A light scalar WIMP?
Evidences vs indirect constraints

Michel H.G. Tytgat

Université Libre de Bruxelles

Belgium

October 18 2010

Max-Planck-Institut für Kernphysik – Particle & Astroparticle Physics

Heidelberg

Based on works done in collaboration with

Chiara Arina

Sarah Andreas

Nicolas Cosme

Thomas Hambye

Fu-Sin Ling

Laura Lopez Honorez

Emmanuel Nezri

Gilles Vertongen

There are some experimental indications of a light WIMP, M ~ few GeV

This is likely to have nothing to do with Dark Matter, but the concordance is intriguing.

Here I consider a very simple model that is (marginally) compatible with current experiments, including WMAP.

First I motivate the model, then I discuss some indirect constraints, mostly based on Fermi-LAT data

Current direct detection indications & exclusion limits

(very briefly)

Indications:

- DAMA annual modulation
- CoGeNT events at low recoil energies
- CRESST events (Oxygen target) (still preliminary)
- CDMS-II two events, low significance

Exclusion limits:

- CDMS-Si
- Xenon 10 & Xenon 100

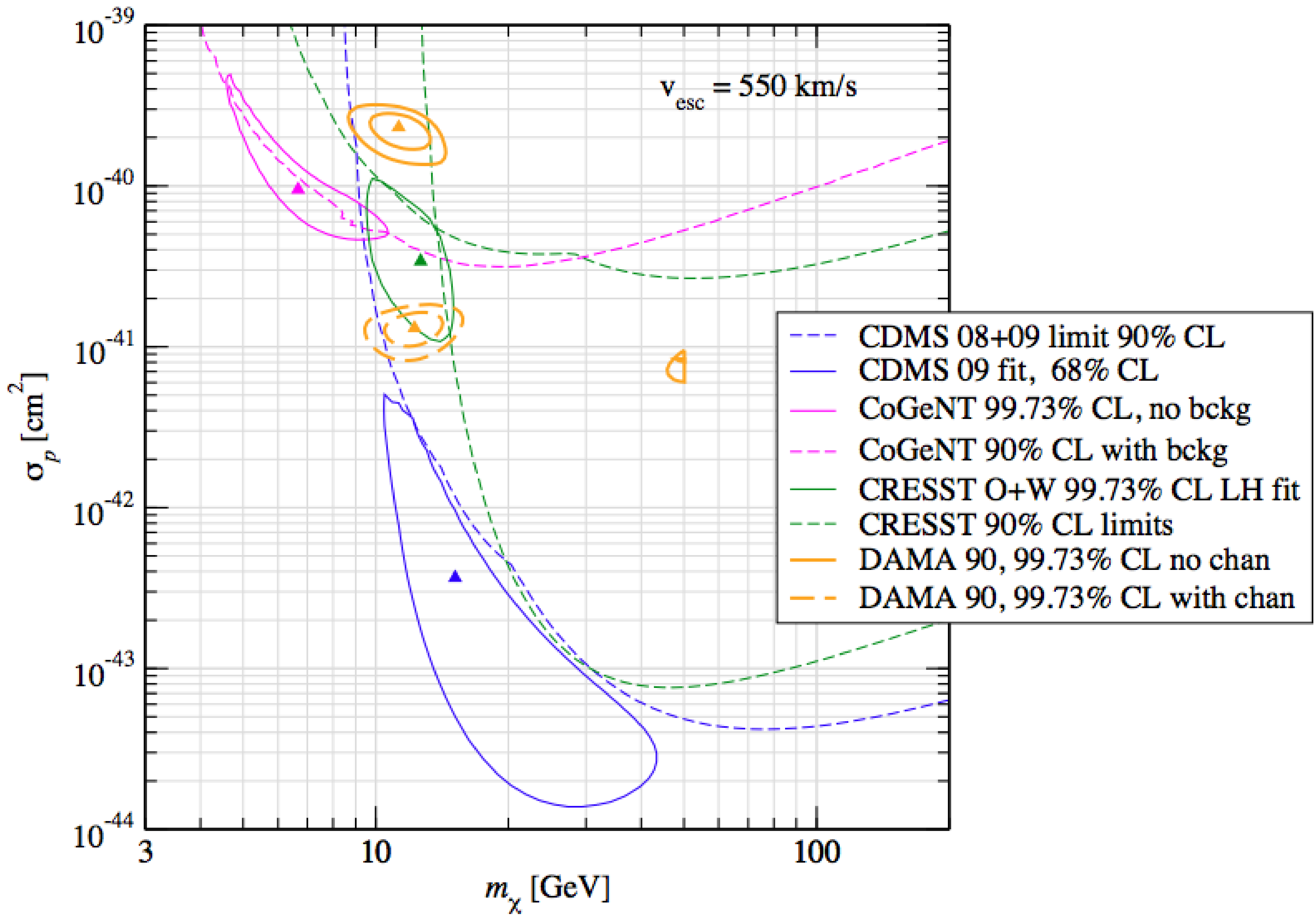
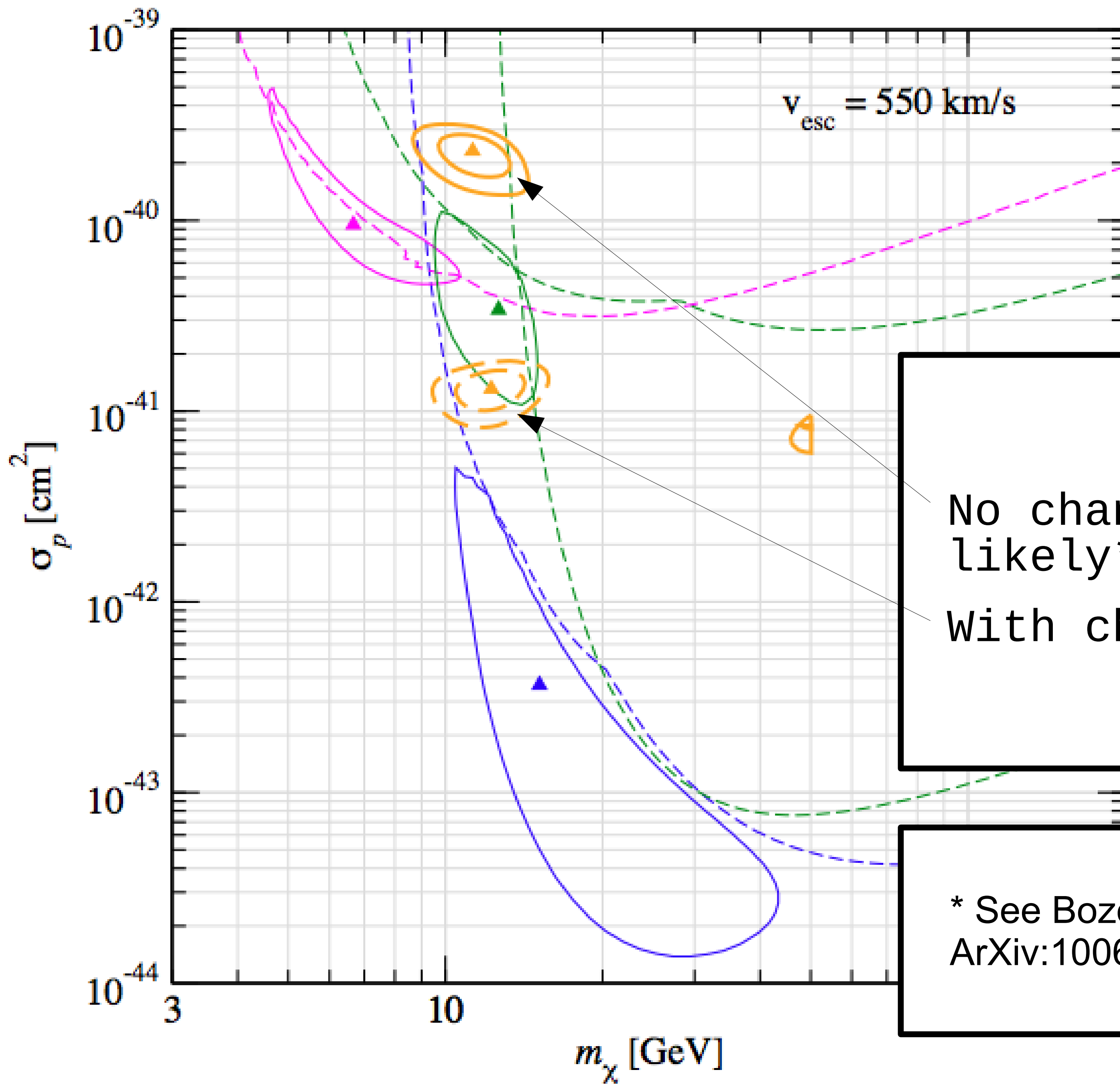


Figure from Th. Schwetz-Mangold (talk at MPIK, June 2010)



DAMA

No channeling (most likely*)

With channeling

* See Bozorgnia, Gelmini, Gondolo ArXiv:1006.3110 + refs therein

Figure from Th. Schwetz-Mangold (talk at MPIK, June 2010)

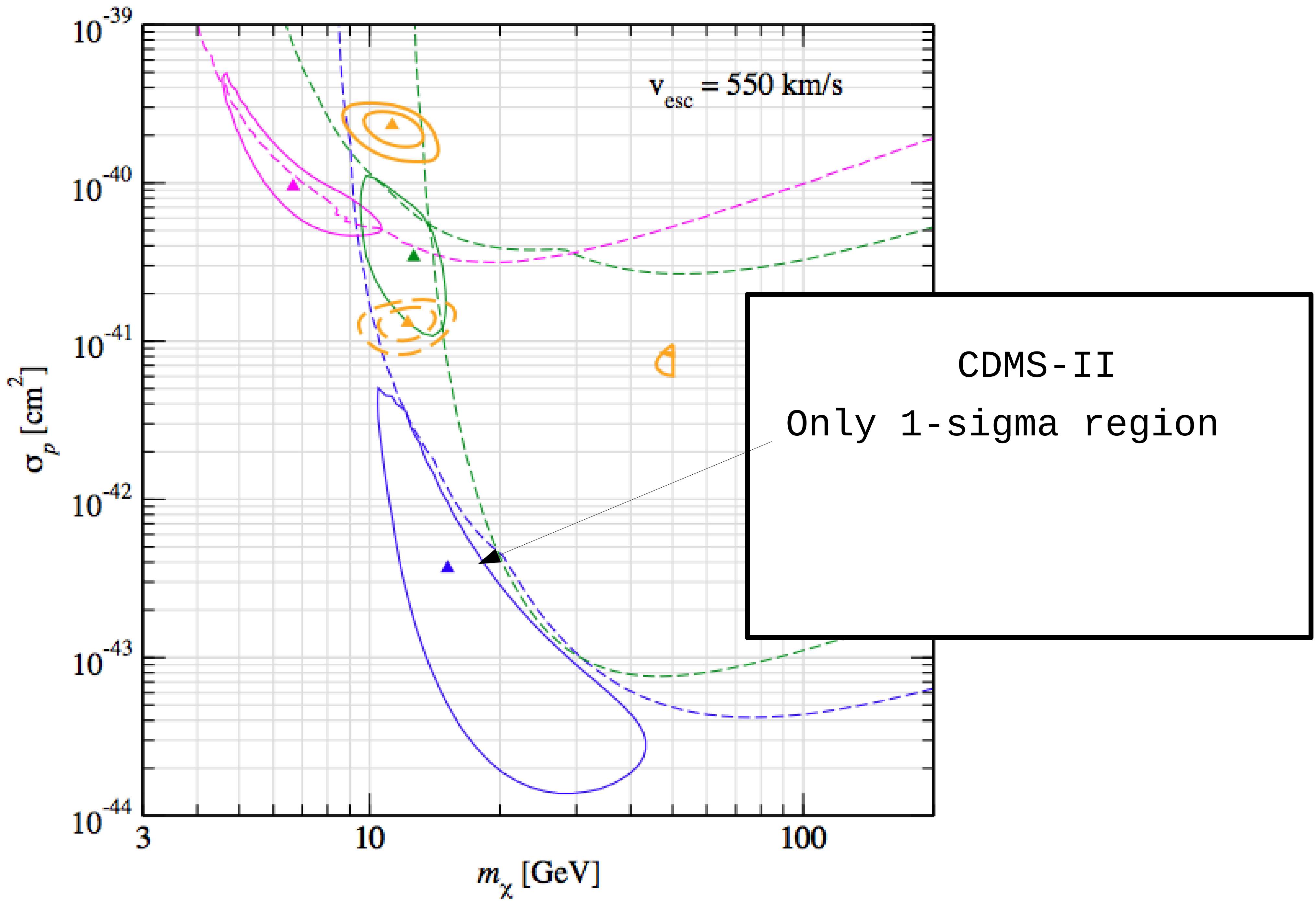


Figure from Th. Schwetz-Mangold (talk at MPIK, June 2010)

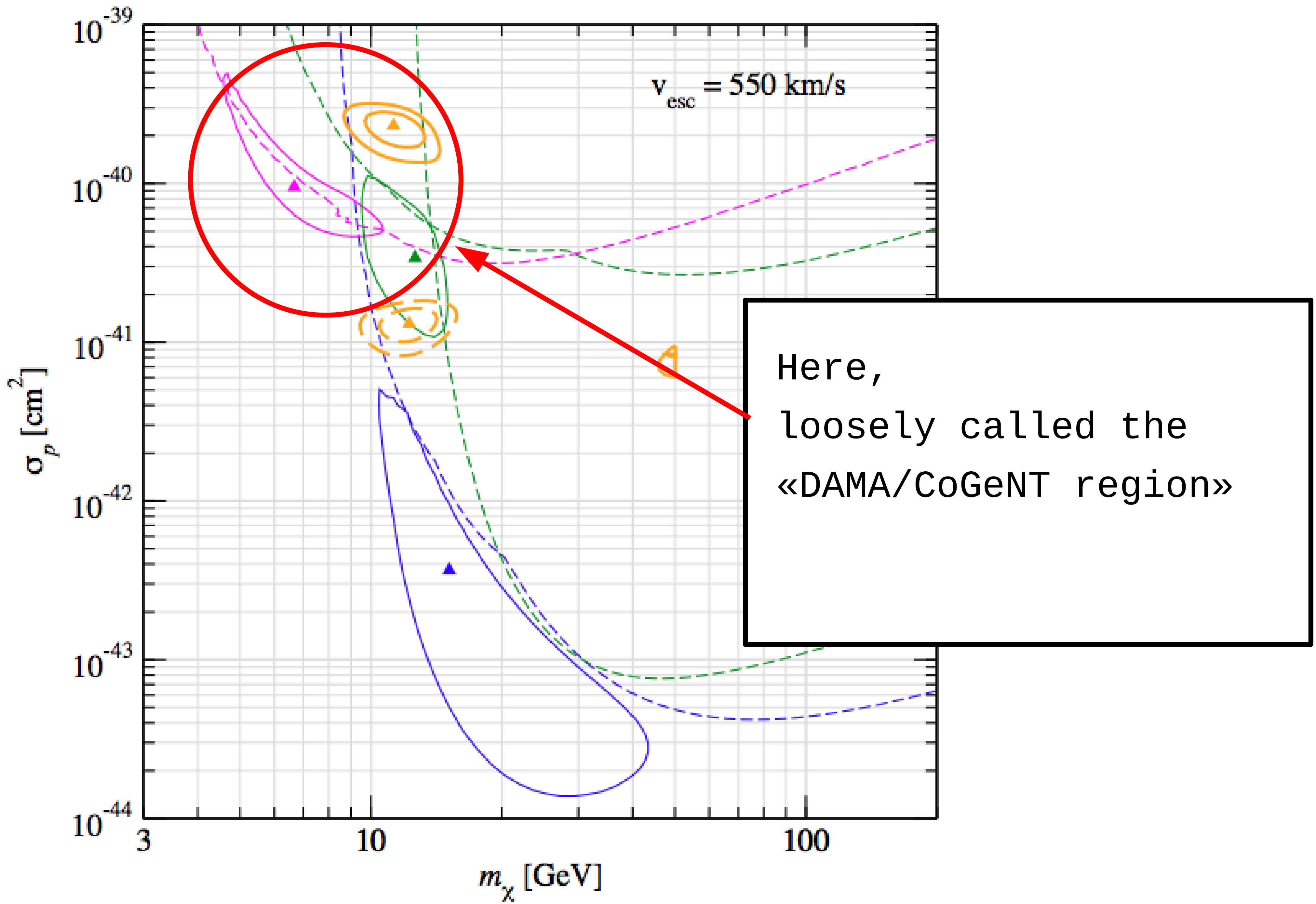


Figure from Th. Schwetz-Mangold (talk at MPIK, June 2010)

A zoom on the DAMA/CoGeNT region and a look at exclusion limits

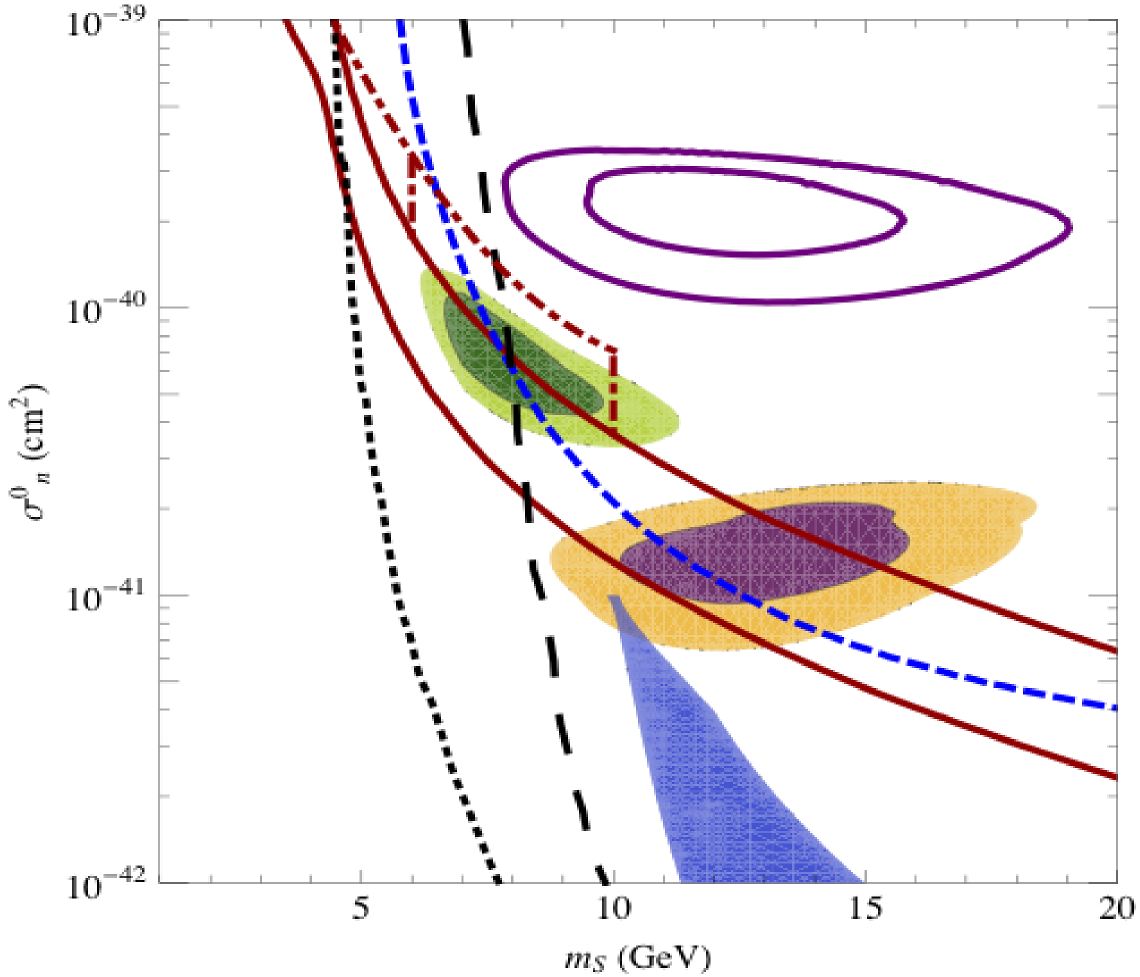


Figure from Andreas, Arina, Hambye, Ling & M.T.   arXiv:1003.2595

A zoom on the DAMA/CoGeNT region and a look at exclusion limits

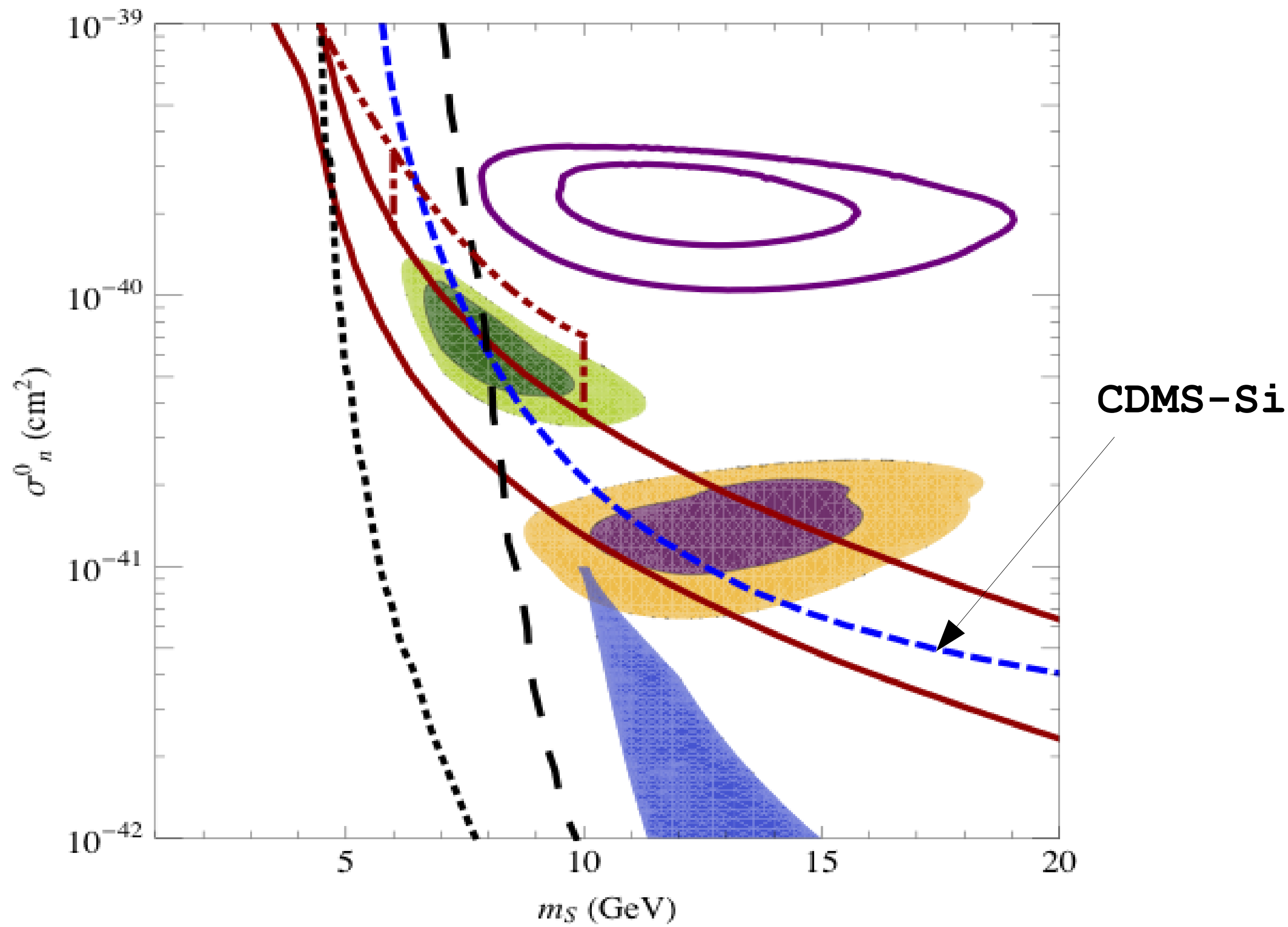
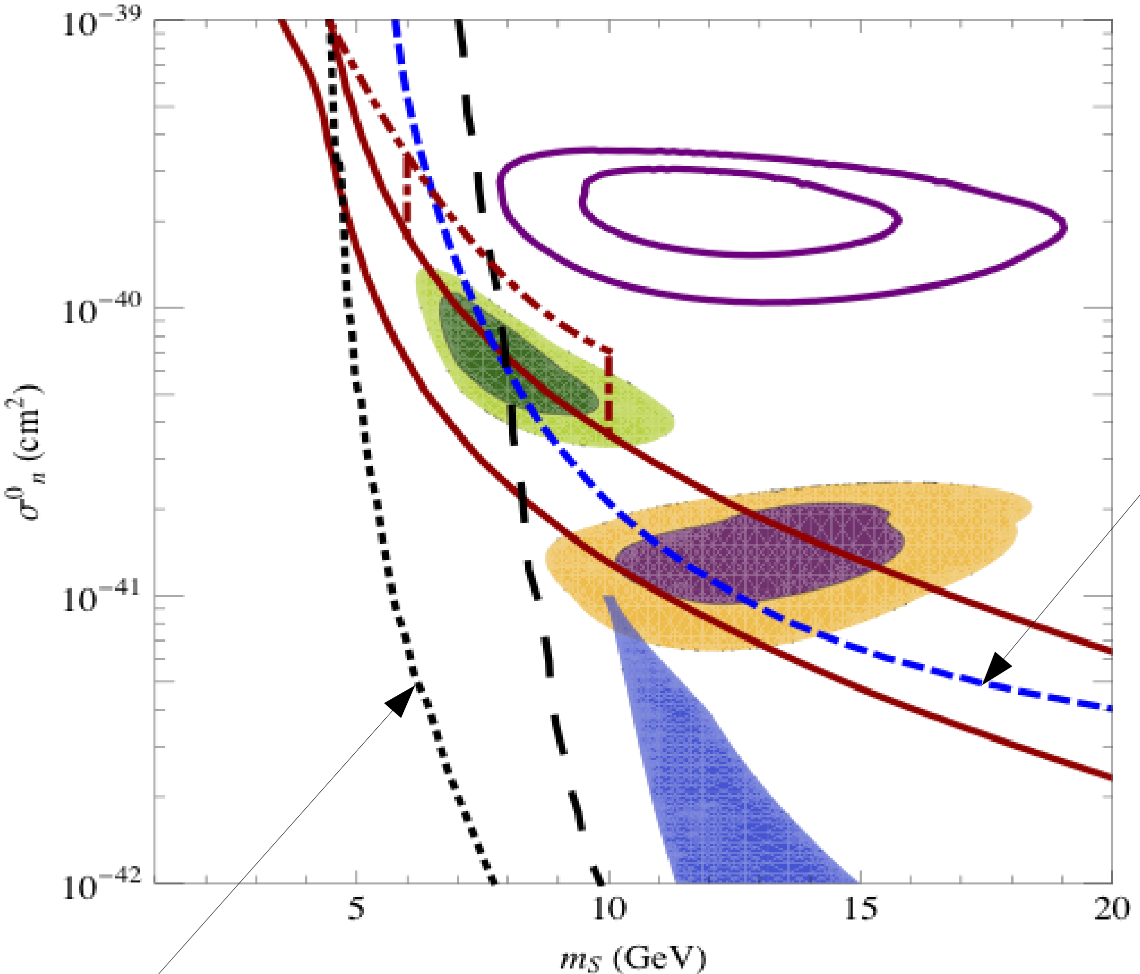


Figure from Andreas, Arina, Hambye, Ling & M.T.   arXiv:1003.2595

A zoom on the DAMA/CoGeNT region and a look at exclusion limits

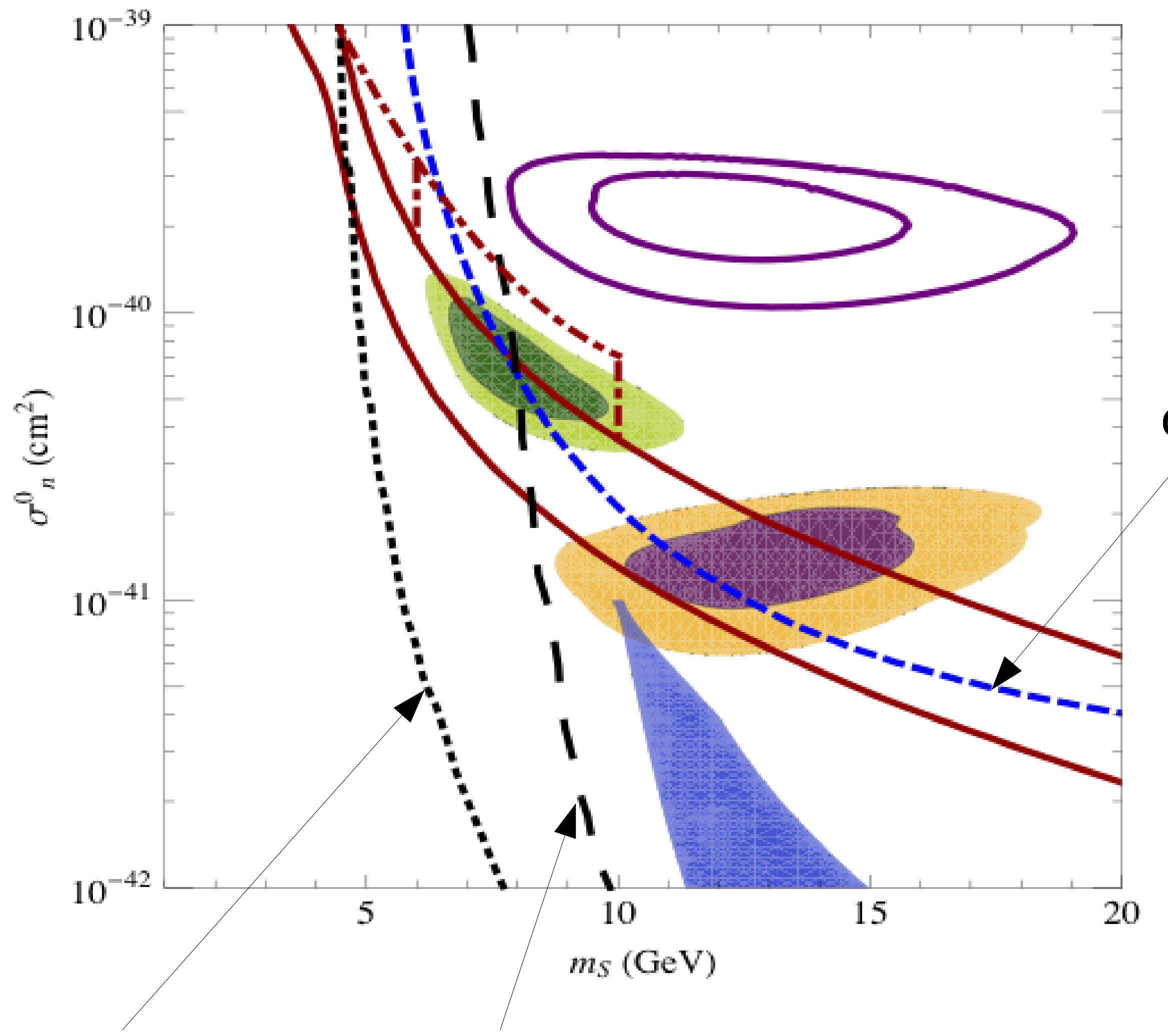


CDMS-Si

Xenon10 (2009) (LeffMed)

Figure from Andreas, Arina, Hambye, Ling & M.T. arXiv:1003.2595

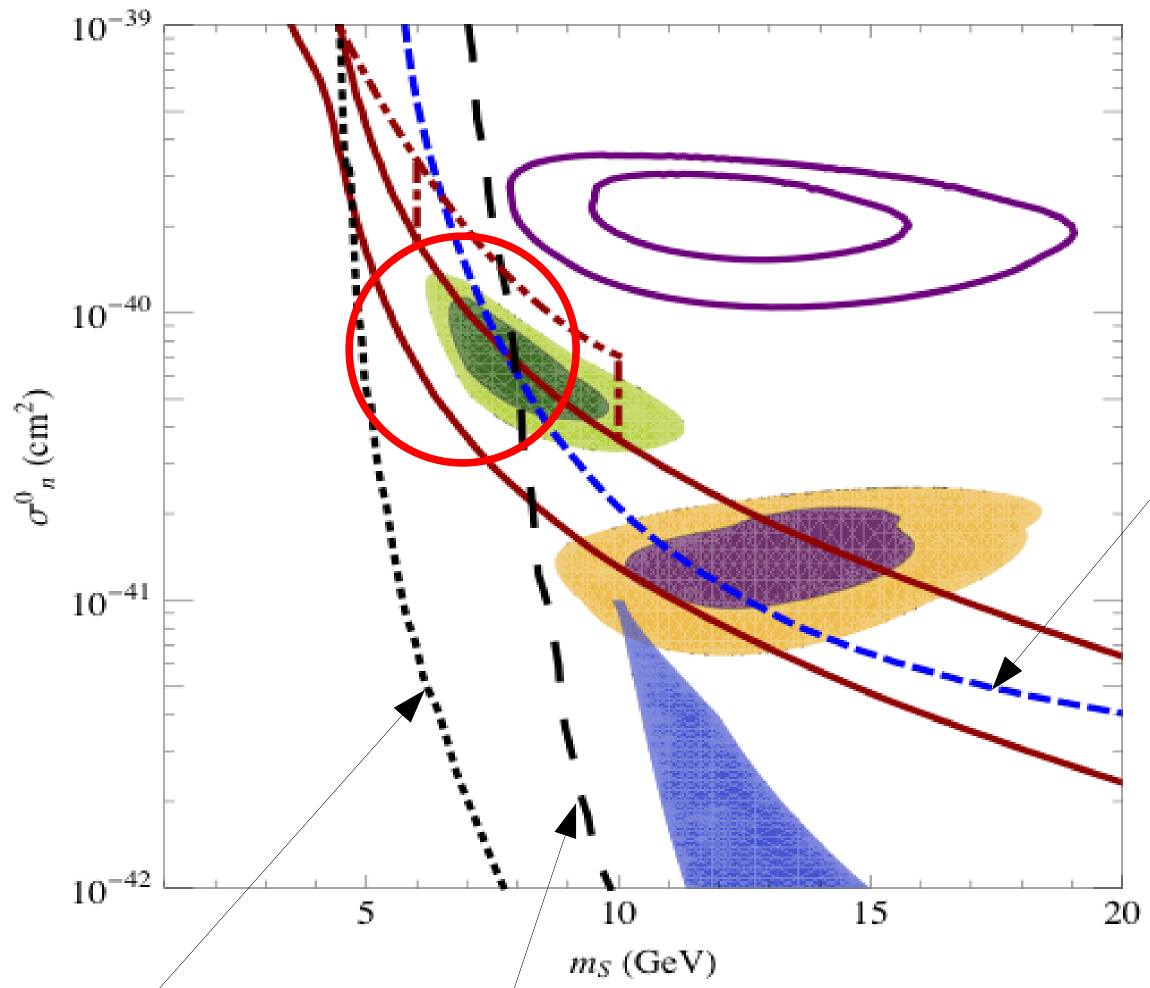
A zoom on the DAMA/CoGeNT region and a look at exclusion limits



Xenon10 (2009) (LeffMed)   **Xenon10** (2009) (LeffMin)

Figure from Andreas, Arina, Hambye, Ling & M.T. arXiv:1003.2595

A zoom on the DAMA/CoGeNT region and a look at exclusion limits



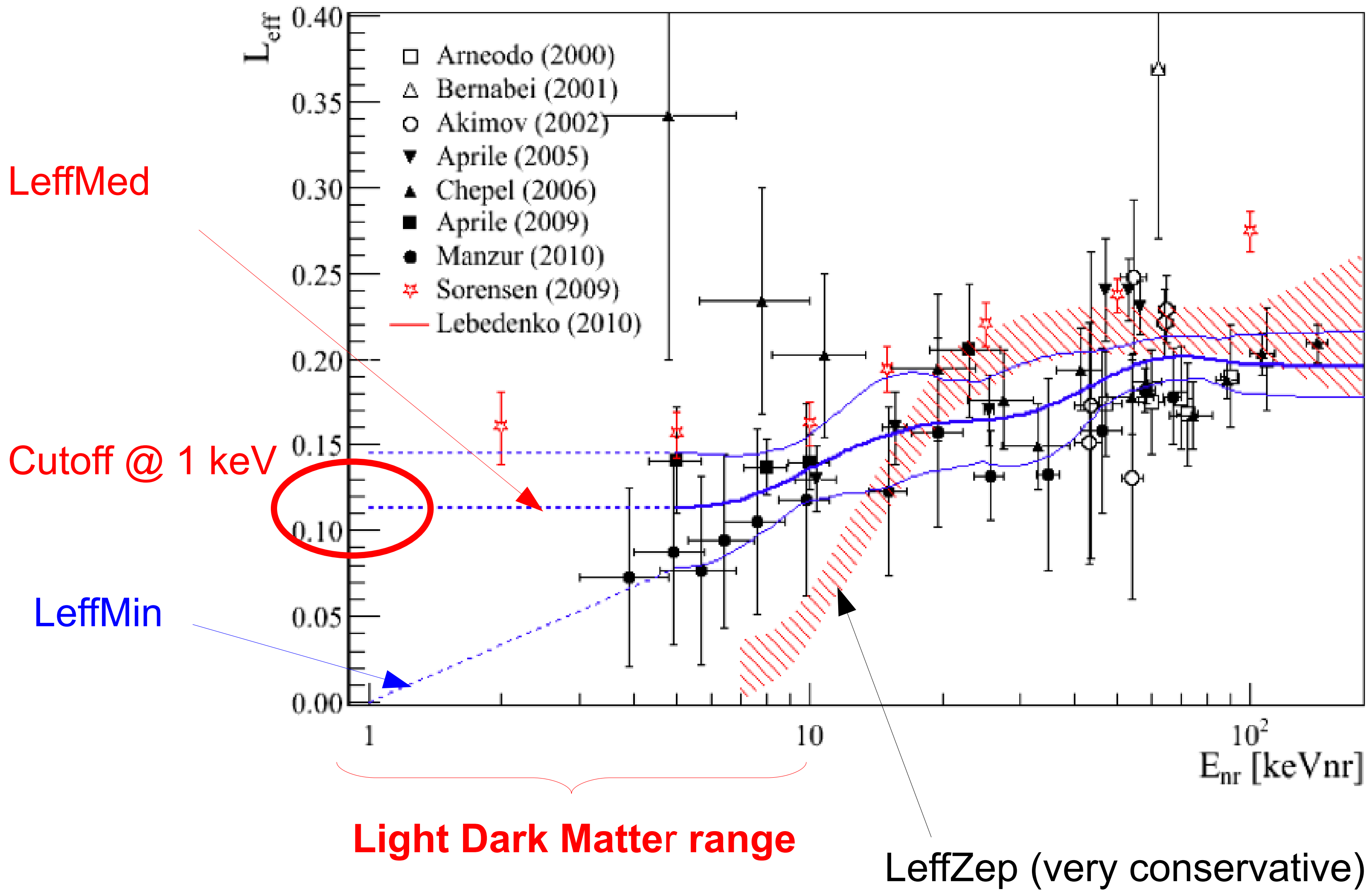
CDMS-Si

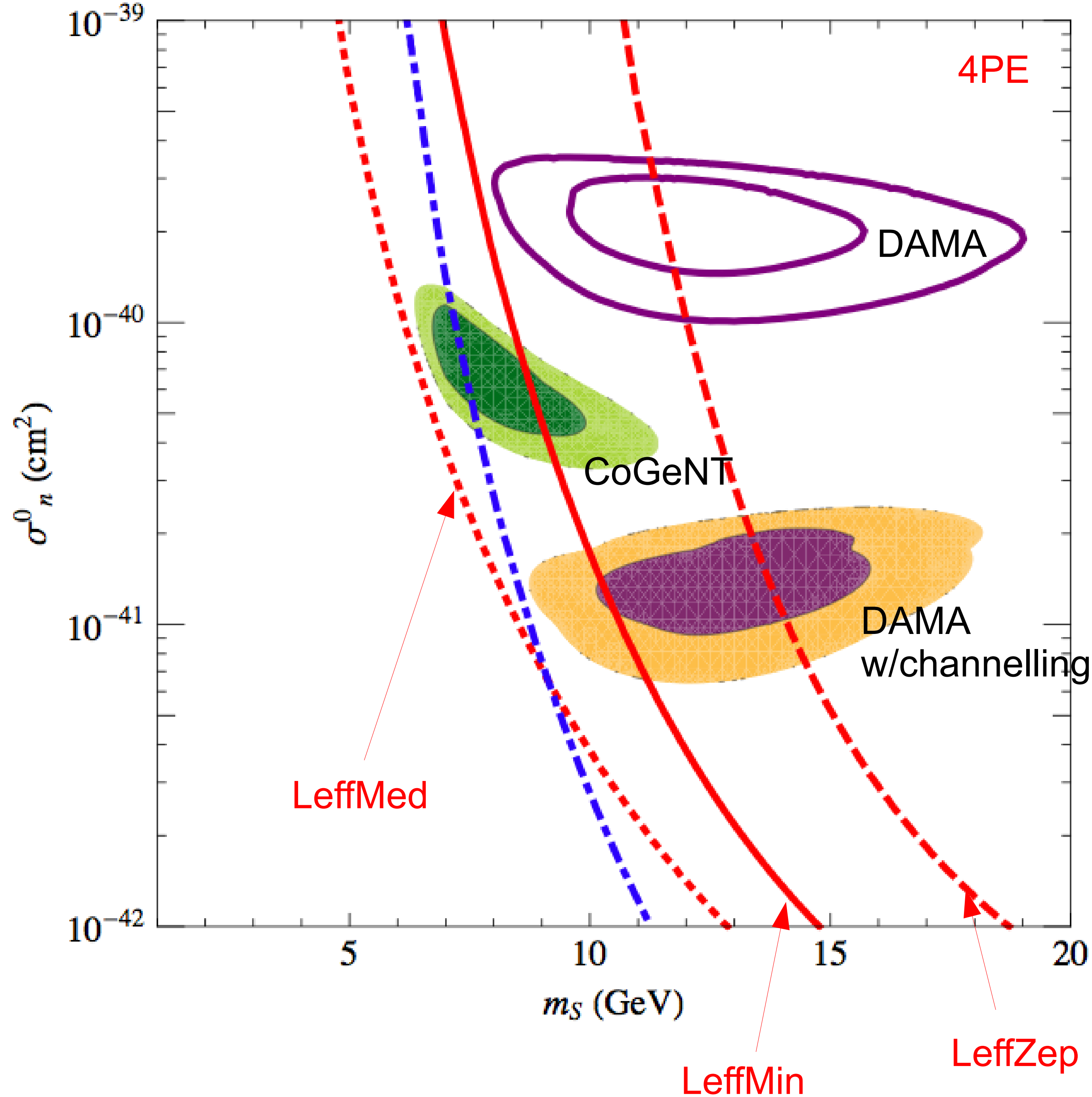
Xenon10 (2009) (LeffMed)   **Xenon10** (2009) (LeffMin)

Figure from Andreas, Arina, Hambye, Ling & M.T.   arXiv:1003.2595

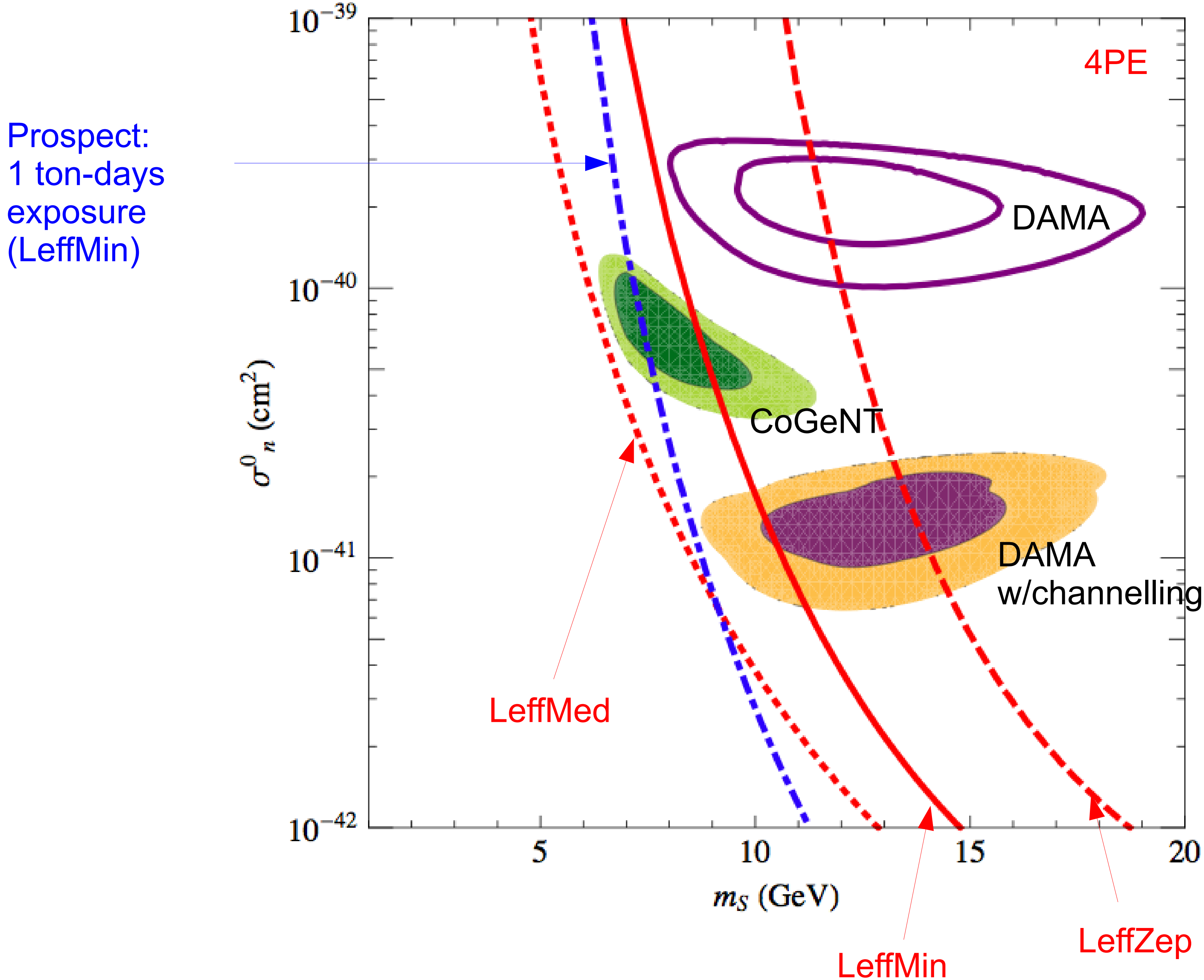
In LXe experiments, mapping of signal (ie photoelectrons PE) to E_{recoil} depends on the so-called Scintillation Efficiency (Leff)

Problem: Leff poorly known at low recoil energies
See Collar & McKinsey vs Xenon100 debate

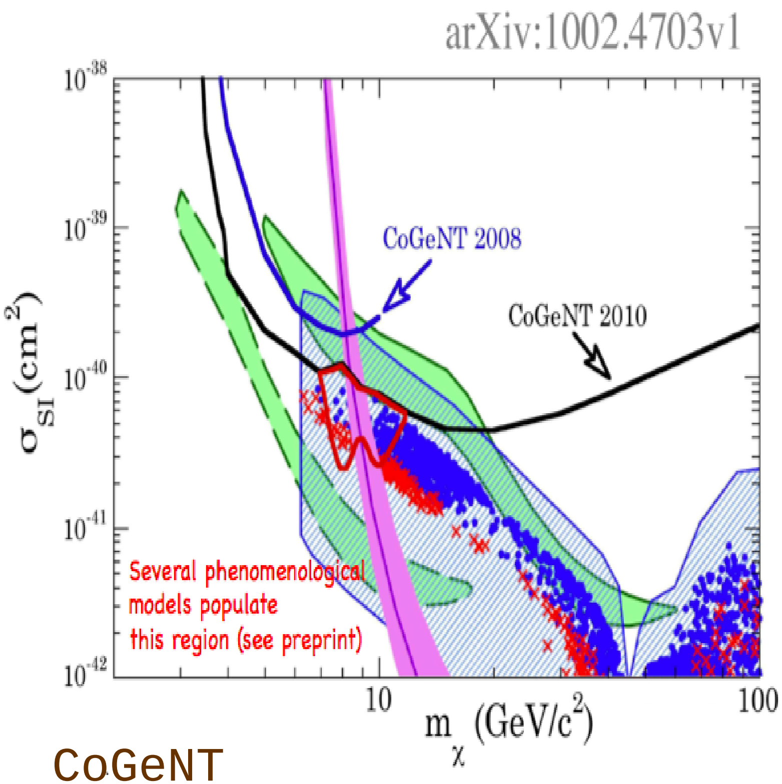




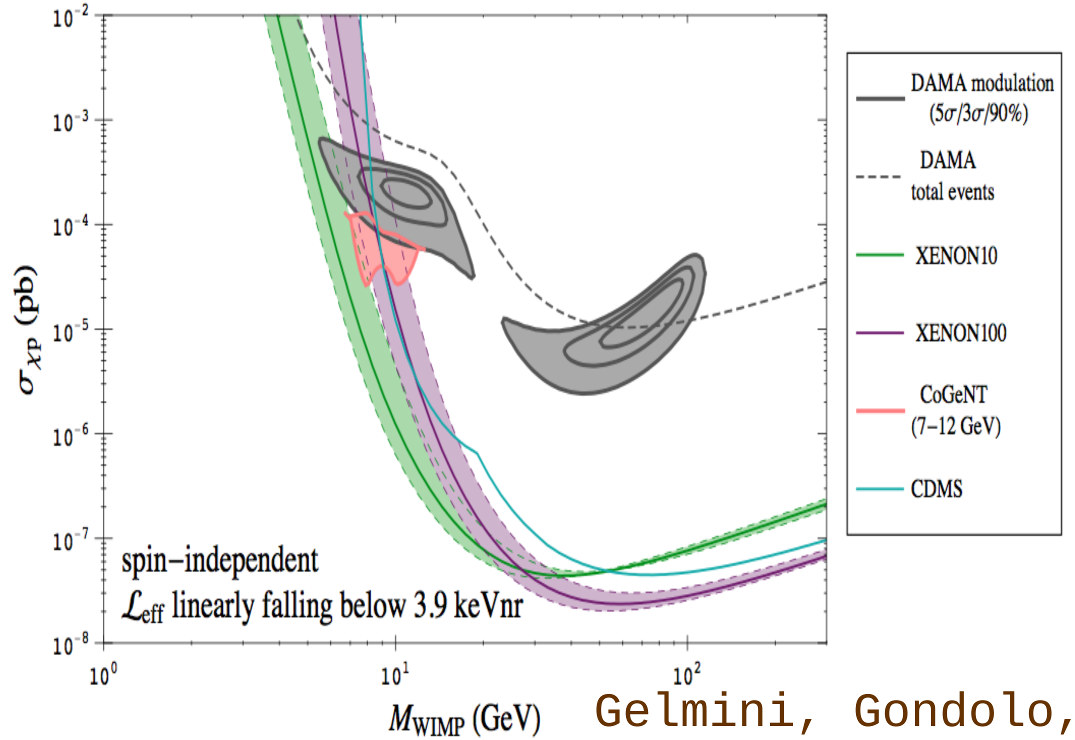
Andreas, Arina, Hambye, Ling, M.T.
(arXiv:1003.2595)



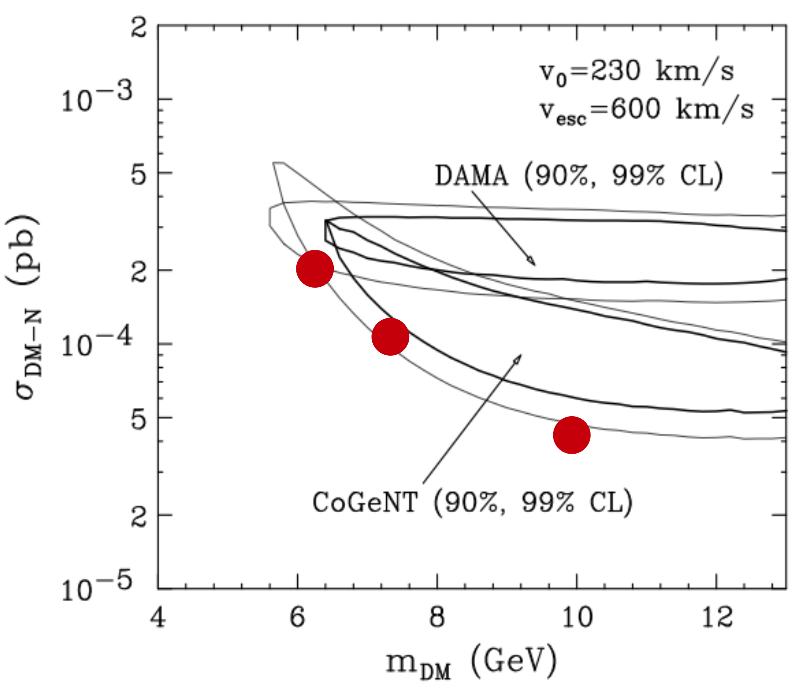
Andreas, Arina, Hambye, Ling, M.T.
(arXiv:1003.2595)



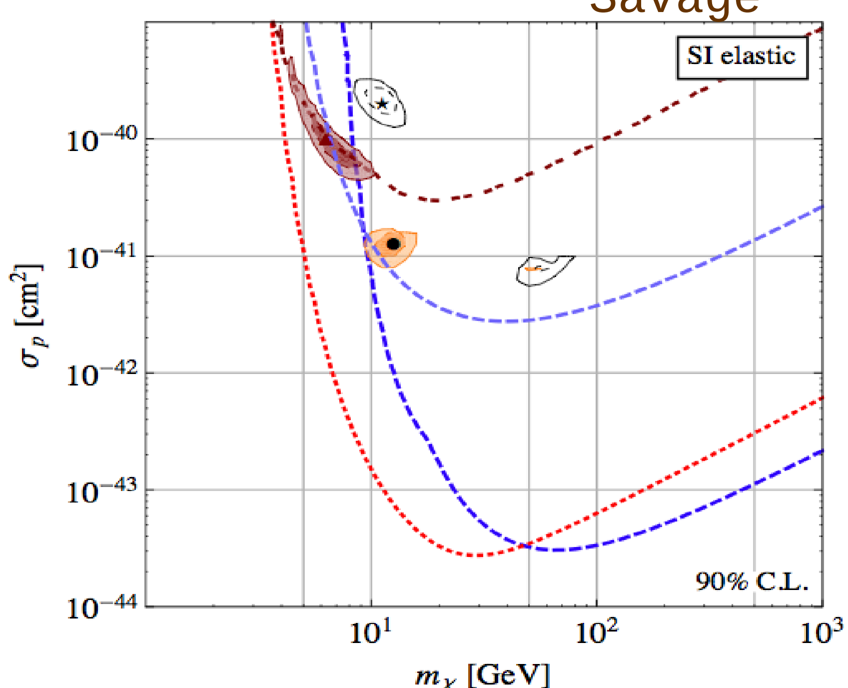
CoGeNT



Gelmini, Gondolo, Savage



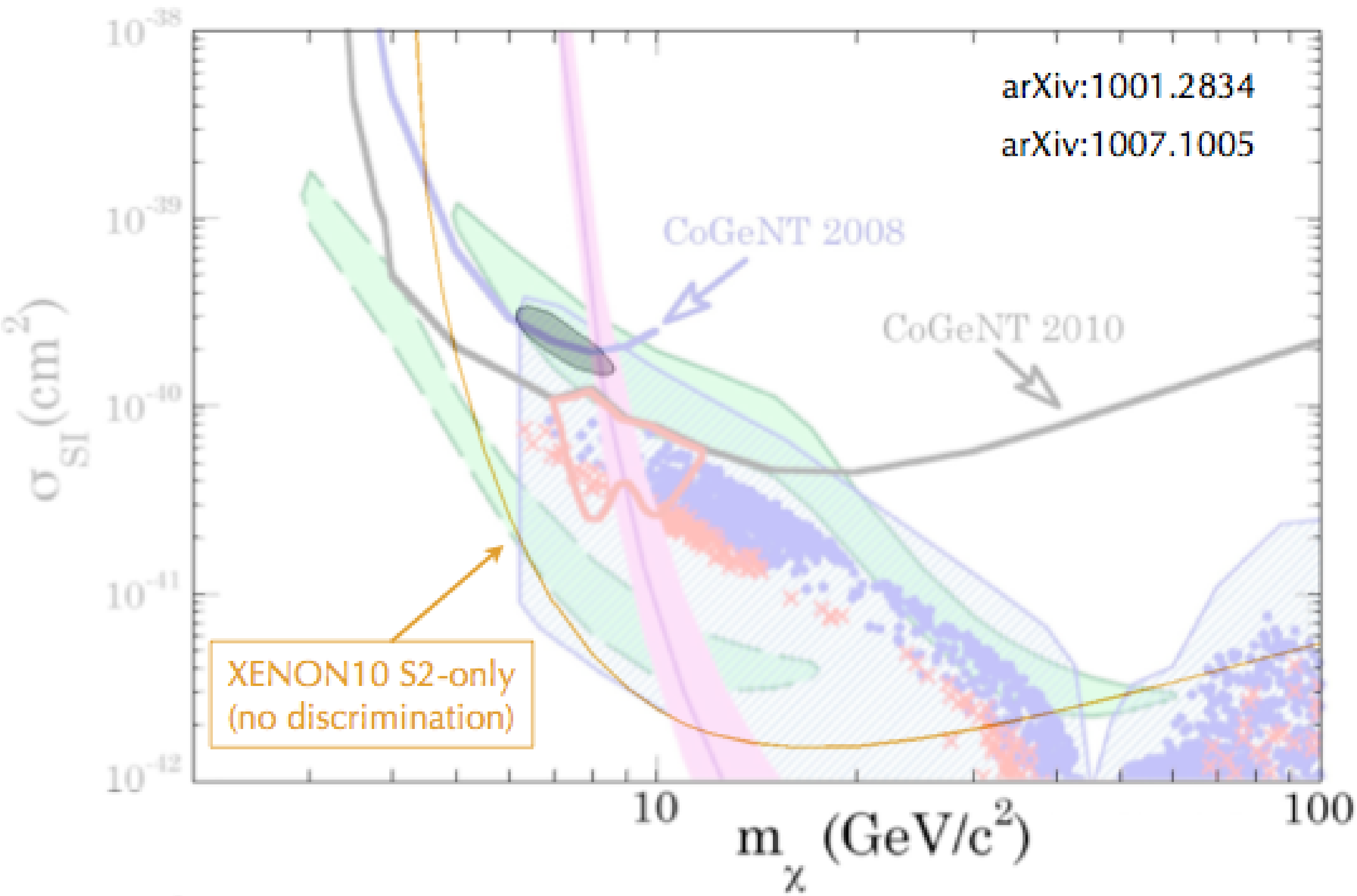
Hooper,Collar,Hall,McKinsey



Kopp, Schwetz, Zupan

(preliminary) dark matter exclusion limits

Notice: this S2-only exclusion limit curve is preliminary, and has not been fully reviewed by the XENON10 collaboration. Pending review it is subject to change.

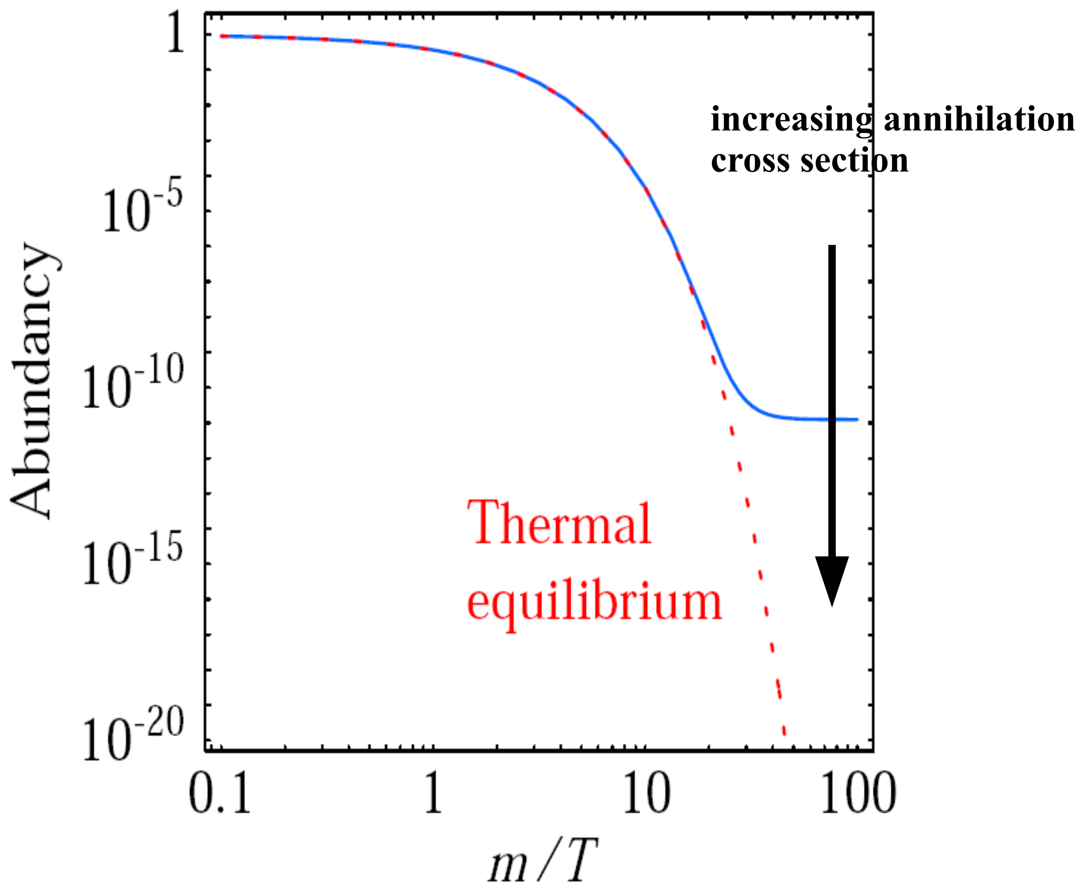


- Max Gap 90% C.L. upper limit between 1.6 keVr and 3.8 keVr
- 12.5 live days
- 1.2 kg target
- conservative -1σ Q_y energy calibration
- no account of resolution (this would improve limits)

The current experimental anomalies might have nothing to do with Dark Matter...

Nevertheless it is fair to look for possible explanations and phenomenological implications

A prejudice* against light WIMPs ?



$$\sigma\ v \sim \alpha^2/M^2$$

$$\rightarrow\ M \sim 10^2\ \mathrm{GeV}$$

*

1 : injury or damage resulting from some judgment or action of another in disregard of one's rights; especially : detriment to one's legal rights or claims

2 a (1) : preconceived judgment or opinion (2) : an adverse opinion or leaning formed without just grounds or before sufficient knowledge b : an instance of such judgment or opinion c : an irrational attitude of hostility directed against an individual, a group, a race, or their supposed characteristics

WIMP → thermal freeze-out

WMAP → σ v ~ pbarn !

Light mass ~ few GeV ?

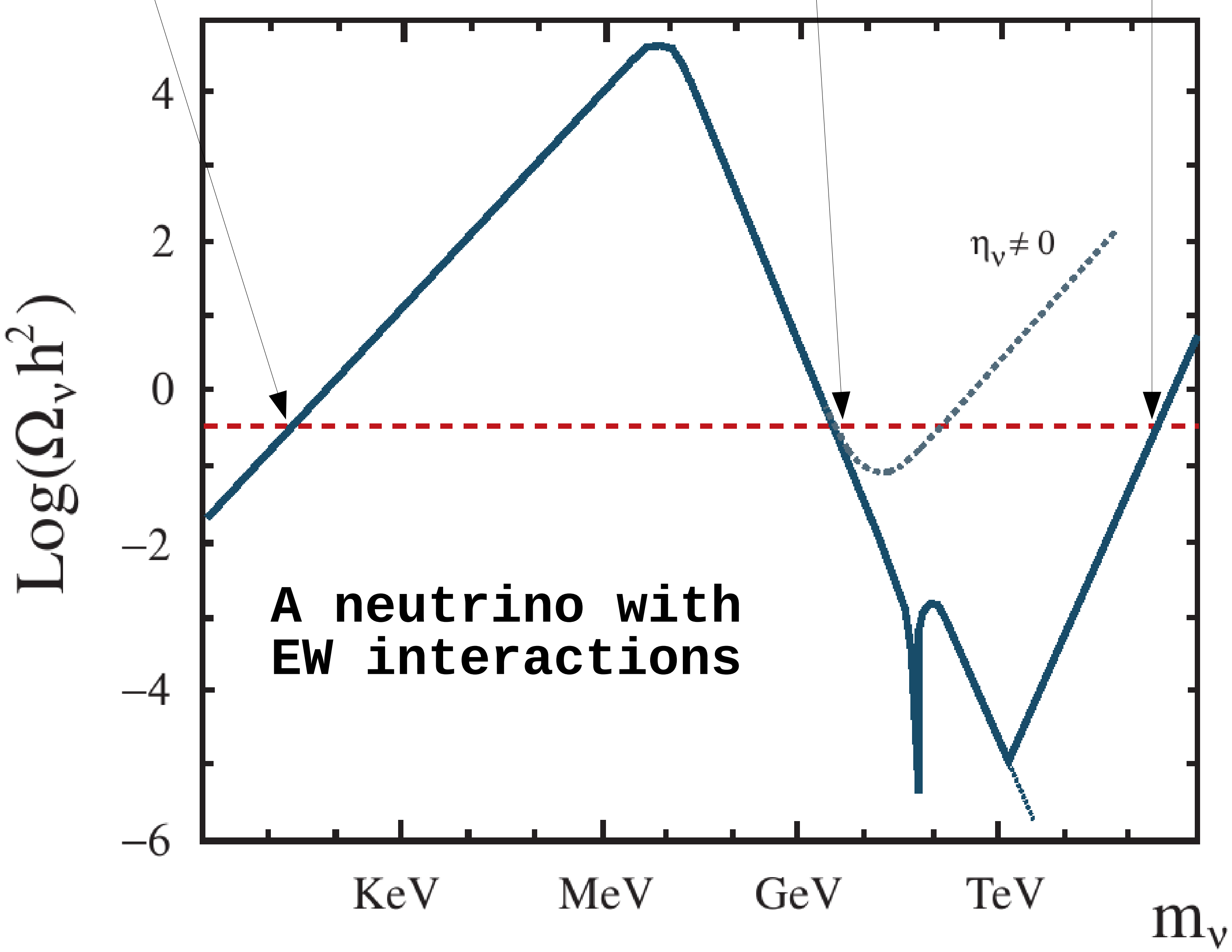
New mass scale!

Unrelated to known/expected new physics (?)

Cowsik-McLelland

Lee-Weinberg

Griest-
Kamionkowski



A neutrino with
EW interactions

Figure from Dolgov

Why I ♥ GeV Dark Matter ?

A cosmological coincidence(?)

$$\Omega_{dm}/\Omega_b = (m_{dm}\, n_{dm})/(m_b\, n_b) \approx 5$$

If m_{dm} ~ few GeV $n_{dm} \sim n_b$

An asymmetry in the dark sector ?

Nussinov; Barr; Kaplan;Gudnasson et al;Dodelson et al;Kitano et al;Farrar et al; Lopez Honorez, Cosme & M.T.; Zurek et al; … and many new scenarios since recently

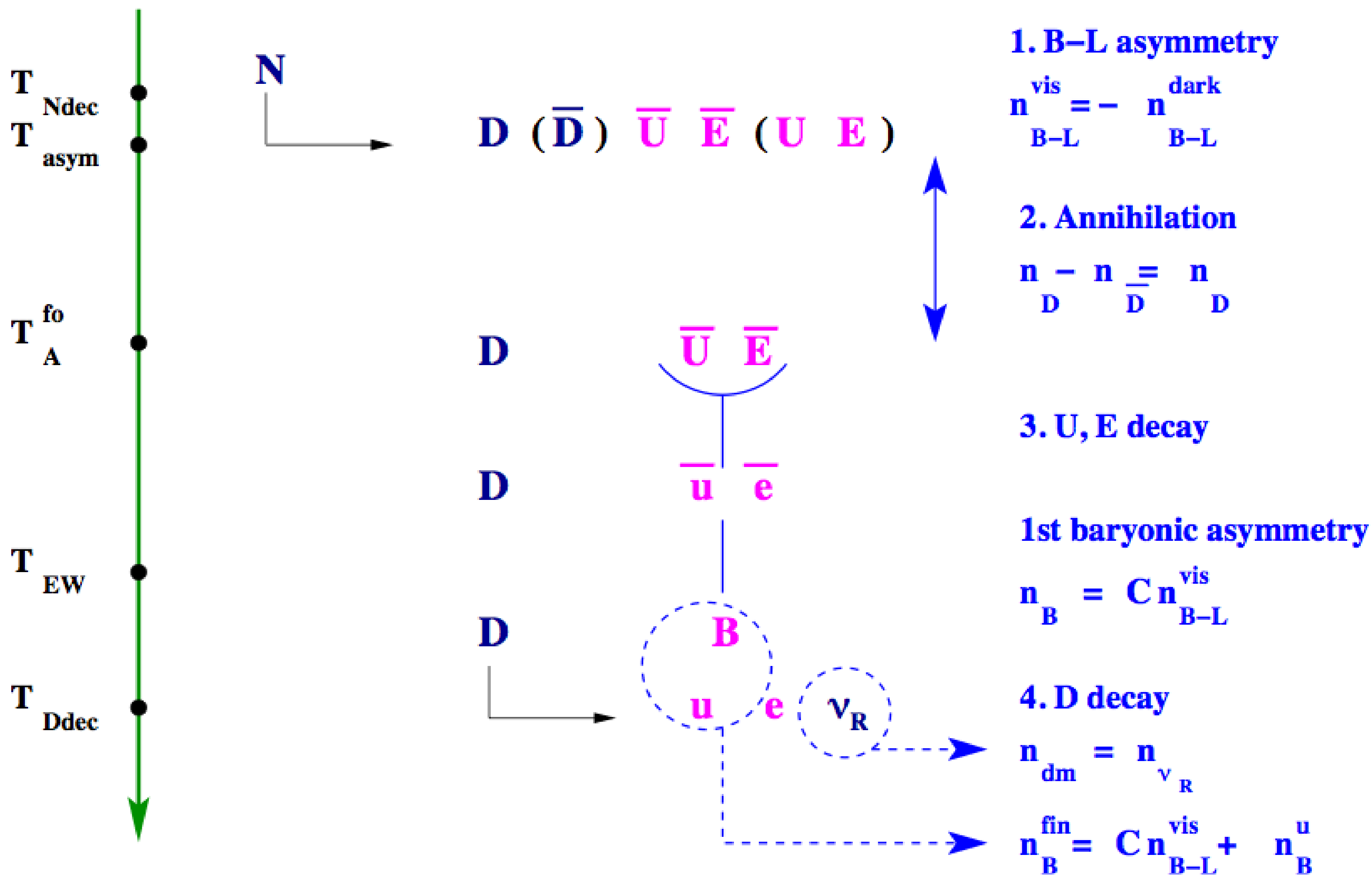


Figure 1: Steps of Matter Genesis

Lopez Honorez, Cosme & M.T. (2005)

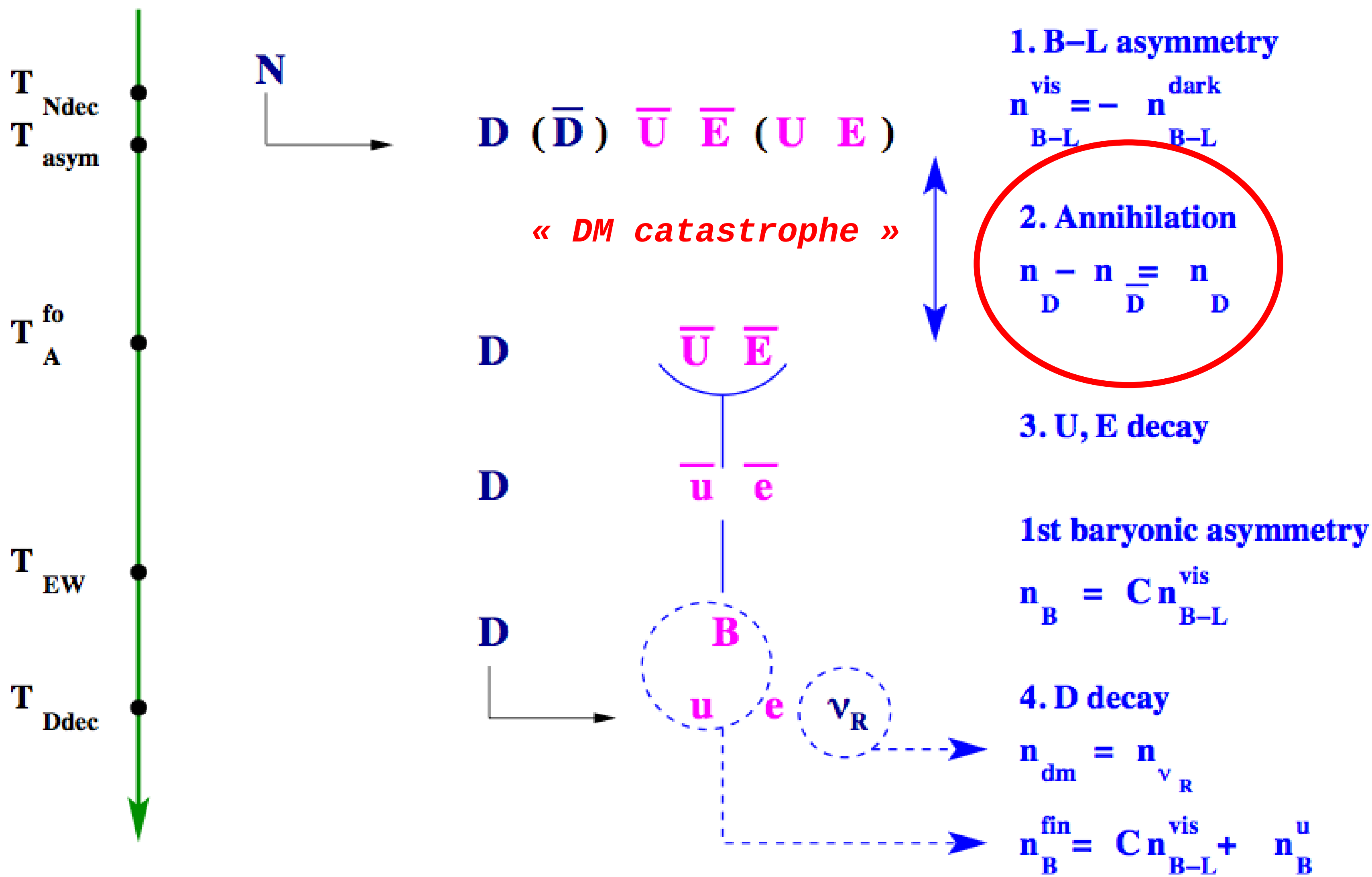


Figure 1: Steps of Matter Genesis

Figure from Lopez Honorez, Cosme & M.T. (2005)

Here, a very simple, conservative model (ie a WIMP)

A real scalar singlet model (SM+3)

$$\mathcal{L} \ni \frac{1}{2}\partial^\mu S \partial_\mu S - \frac{1}{2}\mu_S^2 S^2 - \frac{\lambda_S}{4} S^4 - \lambda_L H^\dagger H S^2$$

Introduce an *ad hoc* parity (with SM dof even)

$$S \rightarrow -S$$

Also assume $\langle S \rangle = 0$

S is a dark matter candidate with mass

$$m_s^2 = \mu_s^2 + \lambda_s v^2$$

Silveira & Zee '85; McDonald '94; Burgess, Pospelov, ter Veldhuis '00; Patt,Wilczek '06; Barger et al '08;...

Why is this st... hum, simple model interesting?

Motivation #1: the simplest instance of Higgs portal

Motivation #2: a one-to-one correspondence between annihilation (ie WMAP) and Spin-Independent (SI)elastic scattering (ie DAMA/CoGeNT)

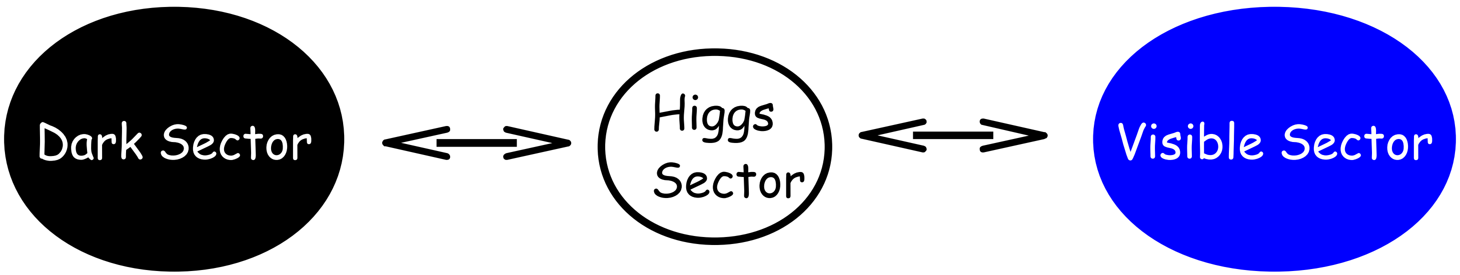
Motivation #3: dramatically affects Higgs physics

Motivation #4: potentially large indirect signals

→ **« works », but falsiable model**

Motivation #1: an instance of Higgs portal

(Patt & Wilczek)



e.g. **Inert Doublet Model**
(Deshpande,Ma;Barbieri,Hall,Ryshkov)

WIMPless scalar (Feng et al)

SO(10) framework (Kadastik,Kannike,
Raidal)

...

Inert Doublet Model

The most general (CP & Z_2 conserving) potential with two Higgs doublets is

$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2$$

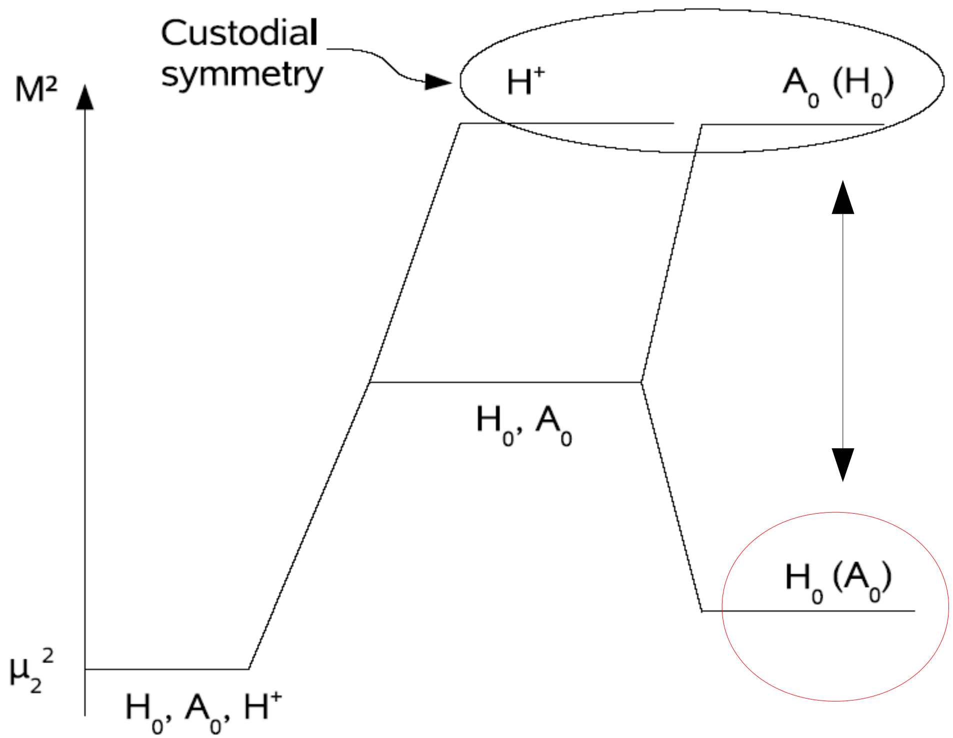
$$+ \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + h.c.\right]$$

Spectrum

$$\begin{aligned}
M_h^2 &= \lambda_1 v^2 \\
M_{H+}^2 &= \mu_2^2 + \lambda_3 v^2/2, \\
M_{H_0}^2 &= \mu_2^2 + (\lambda_3 + \lambda_4 + \lambda_5)v^2/2 \\
M_{A_0}^2 &= \mu_2^2 + (\lambda_3 + \lambda_4 - \lambda_5)v^2/2
\end{aligned}$$

Global custodial SU(2) symmetry if $M_{H+} = M_{H0}$ or $M_{H+} = M_{A0}$

(Gérard, Herquet)



large gap ~ $\lambda_5 v^2$

Effectively H_0 or A_0 like a scalar singlet S

(Andreas, Hambye, T.)

Possible embedding in UED model (Z_2 is KK-parity), but wrong spectrum...

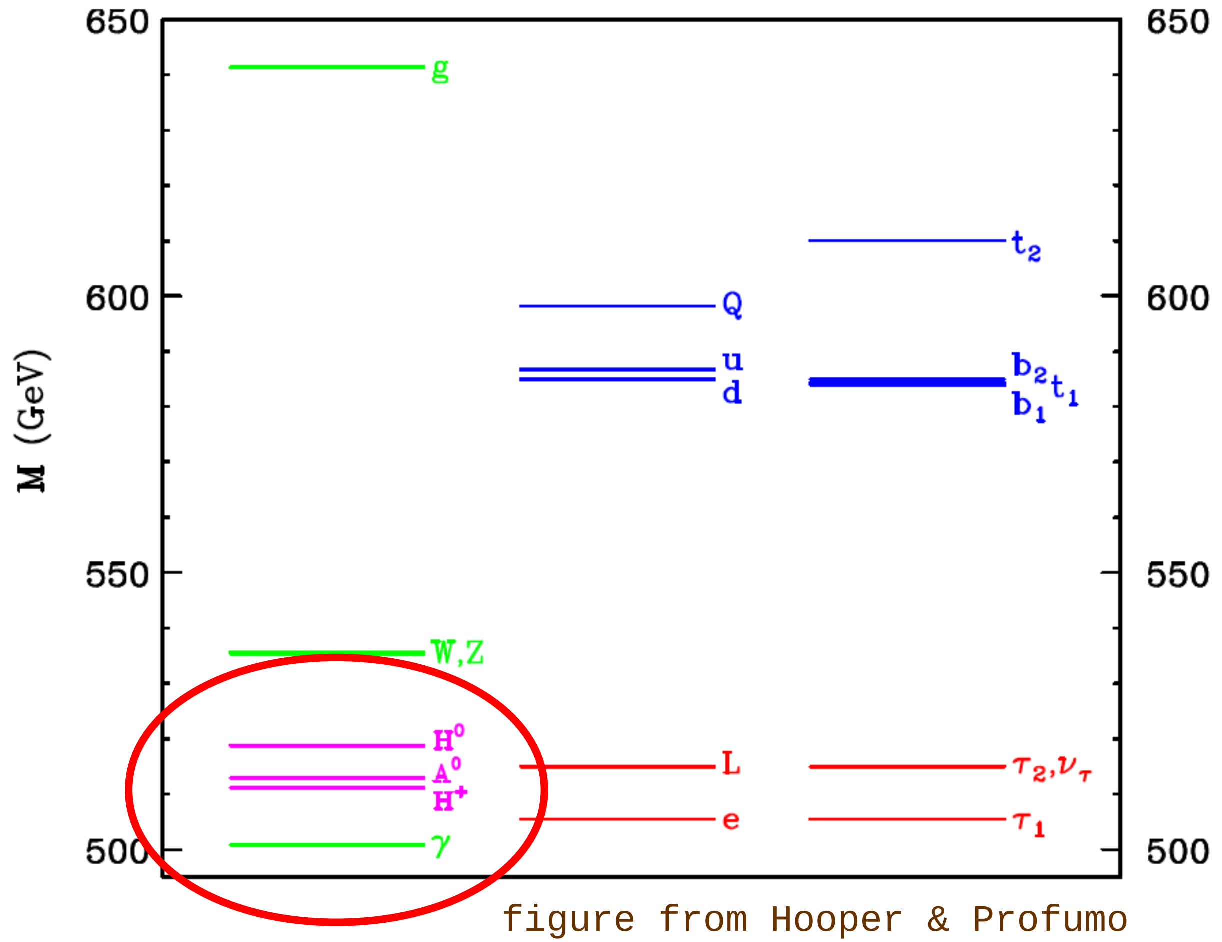
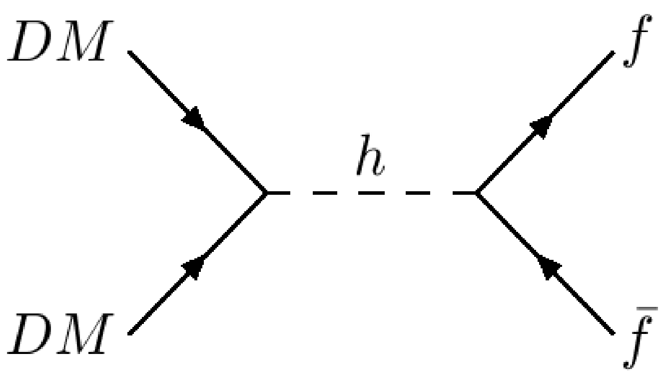


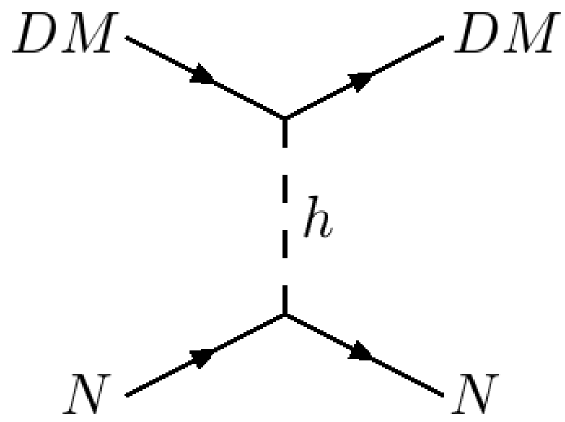
figure from Hooper & Profumo

Motivation #2: a one-to-one correspondence between annihilation and Spin-Independent (SI)elastic scattering

Annihilation



Scattering (SI)



$$\sigma(SS \to \bar{f} f) v_{rel} = n_c \frac{\lambda_L^2}{\pi} \frac{m_f^2}{m_h^4 m_S^3} (m_S^2 - m_f^2)^{3/2}$$

Low energy limit

$$\sigma(SN \to SN) = \frac{\lambda_L^2}{\pi} \frac{\mu_r^2}{m_h^4 m_S^2} f^2 m_N^2$$

$$\boxed{R \equiv \sum_f \frac{\sigma(SS \to \bar{f} f) v_{rel}}{\sigma(SN \to SN)} = \sum_f \frac{n_c m_f^2}{f^2 m_N^2 \mu_r^2} \frac{(m_S^2 - m_f^2)^{3/2}}{m_S}}$$

Ratio depends only on M_S

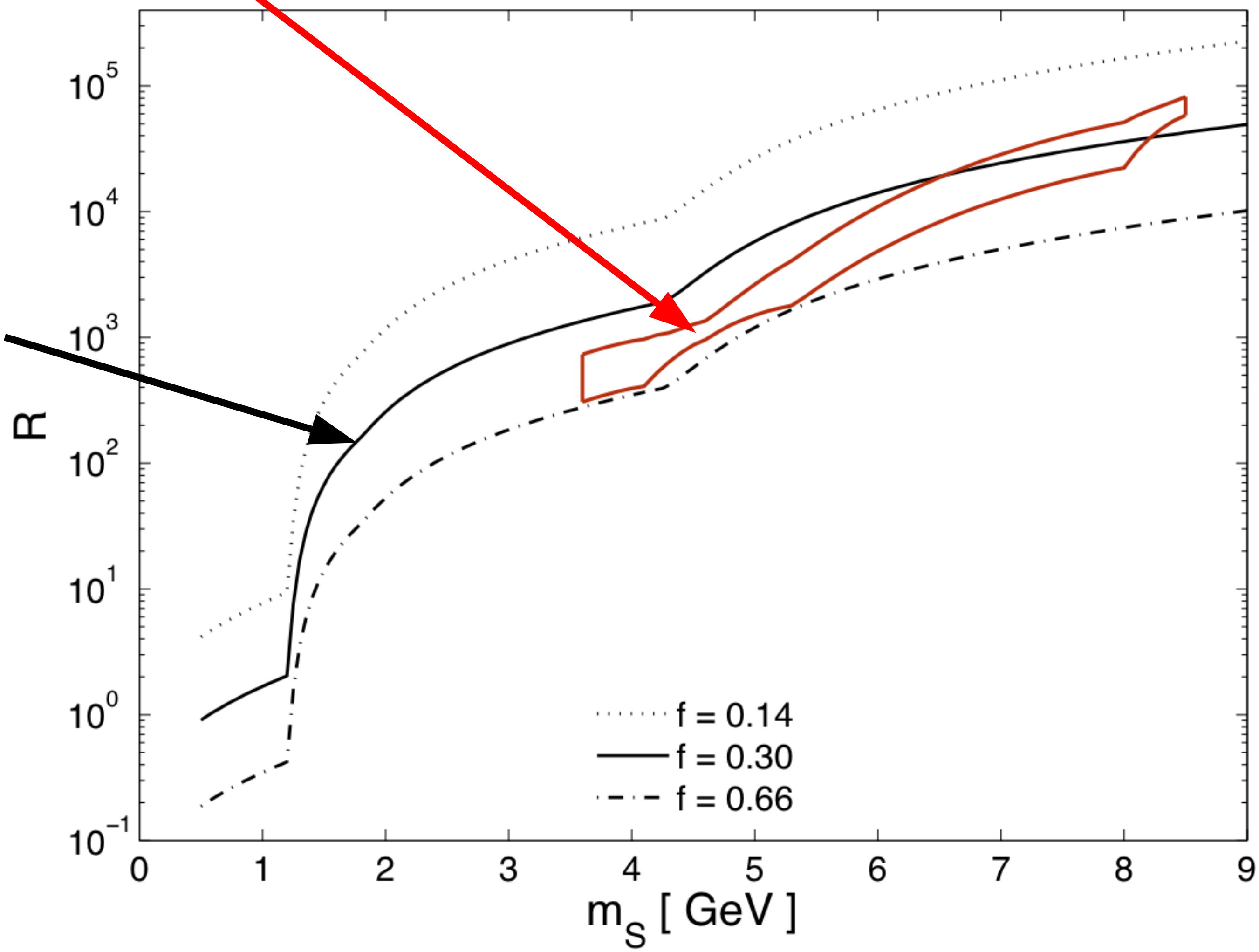
Higgs-Nucleus coupling... large uncertainty (f ~ 0.1-0.6 @ 2σ)

$$f\, m_N = \langle N | \Sigma\, m_q\, \bar{q} q | N \rangle = g_{hNN}\, v$$

DAMA region from Pietrello & Zurek '08
(with channelling & standard halo)

$\frac{\text{WMAP}}{\text{DAMA}}$

Singlet scalar

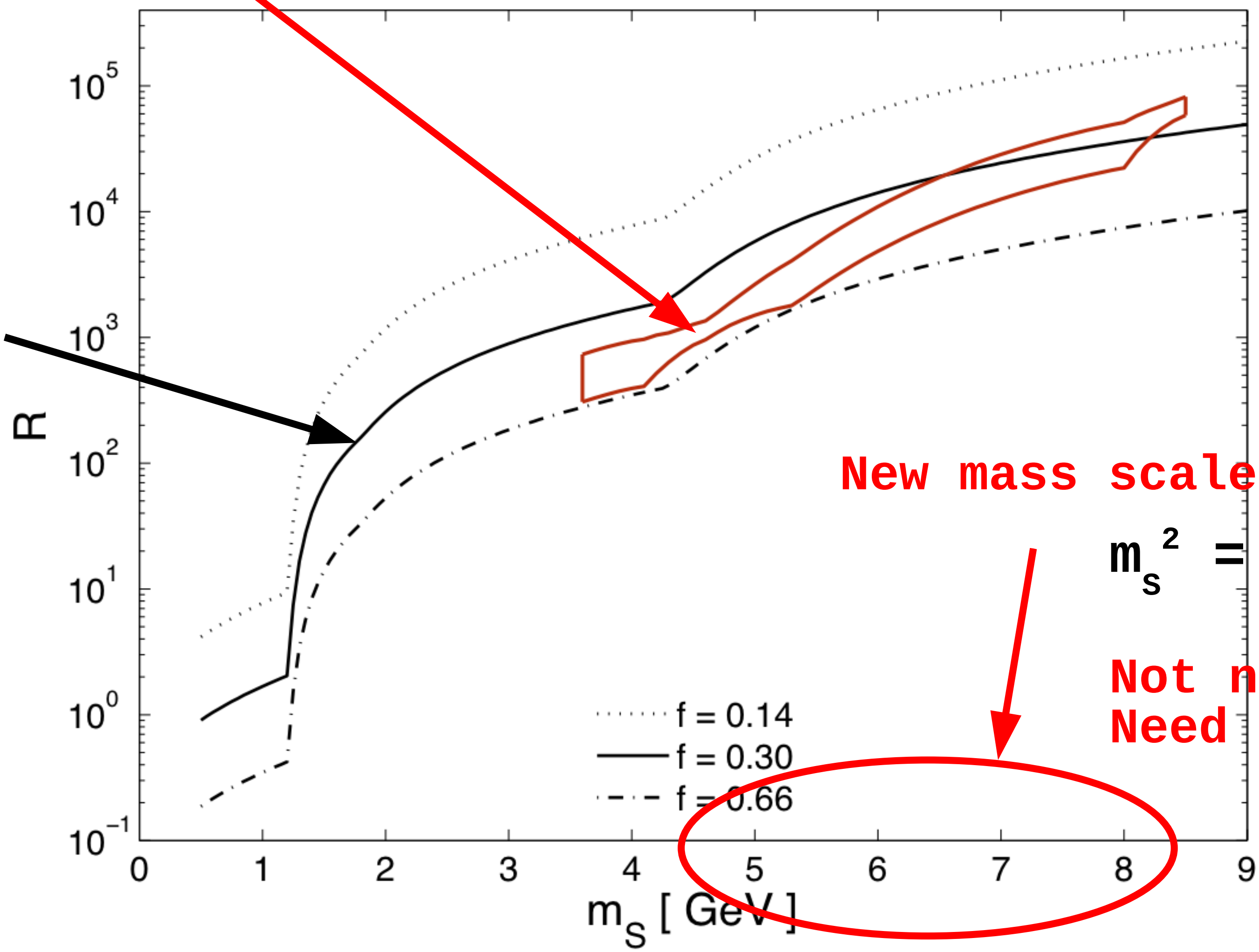


S.Andreas, Th.Hambye, MT '08

$\frac{\text{WMAP}}{\text{DAMA}}$

DAMA region from Pietrello & Zurek '08
(with channelling & standard halo)

Singlet scalar



New mass scale?

$$m_s^2 = \mu_s^2 + \lambda_s v^2$$

Not natural
Need tuning :(

S.Andreas, Th.Hambye, MT '08

SCALAR PHANTOMS

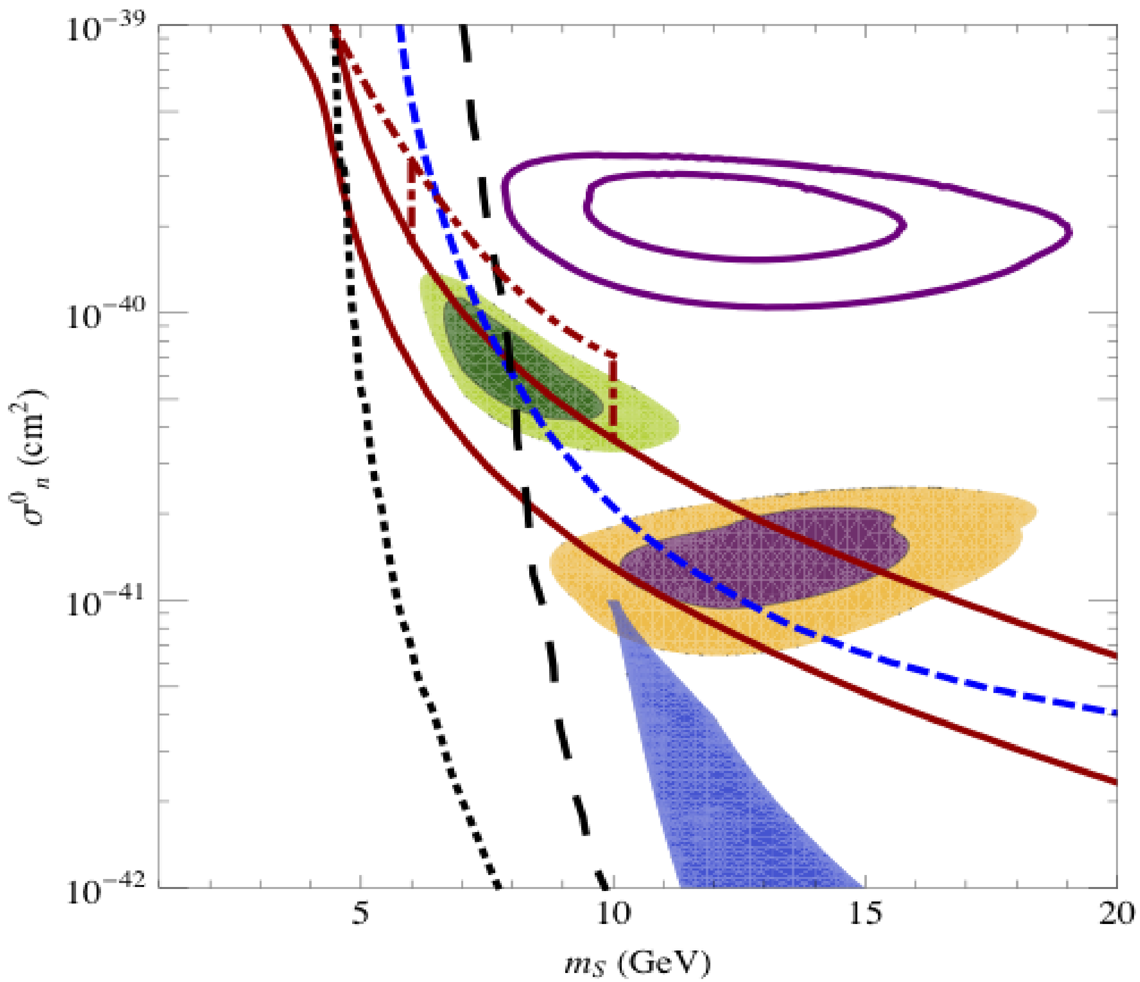
Vanda SILVEIRA[1,2] and A. ZEE
Department of Physics, FM-15, University of Washington, Seattle, WA 98195, USA

Received 17 June 1985

We show that, by a minimal modification of the standard SU(3) × SU(2) × U(1) theory, we can account for the dark matter of the universe. With a reasonable choice of an unknown coupling, the galactic mass scale emerges. We comment on the prospects for laboratory detection of the scalar particle involved and the possible production of anti-protons in cosmic rays.

A striking prediction of the inflationary universe [5] is that Ω is equal to 1. The X particle could saturate Ω if $m_X \simeq 0.75 m_H$. (Let us first take h to be 1.) Thus for m_H in the range 10–30 GeV, the condition $\Omega_X = 1$ requires that m_X lies in the range 7.5–22 GeV and the freezing temperature T_f is in the 0.3–1 GeV range. The value of N_F cited above is roughly the value

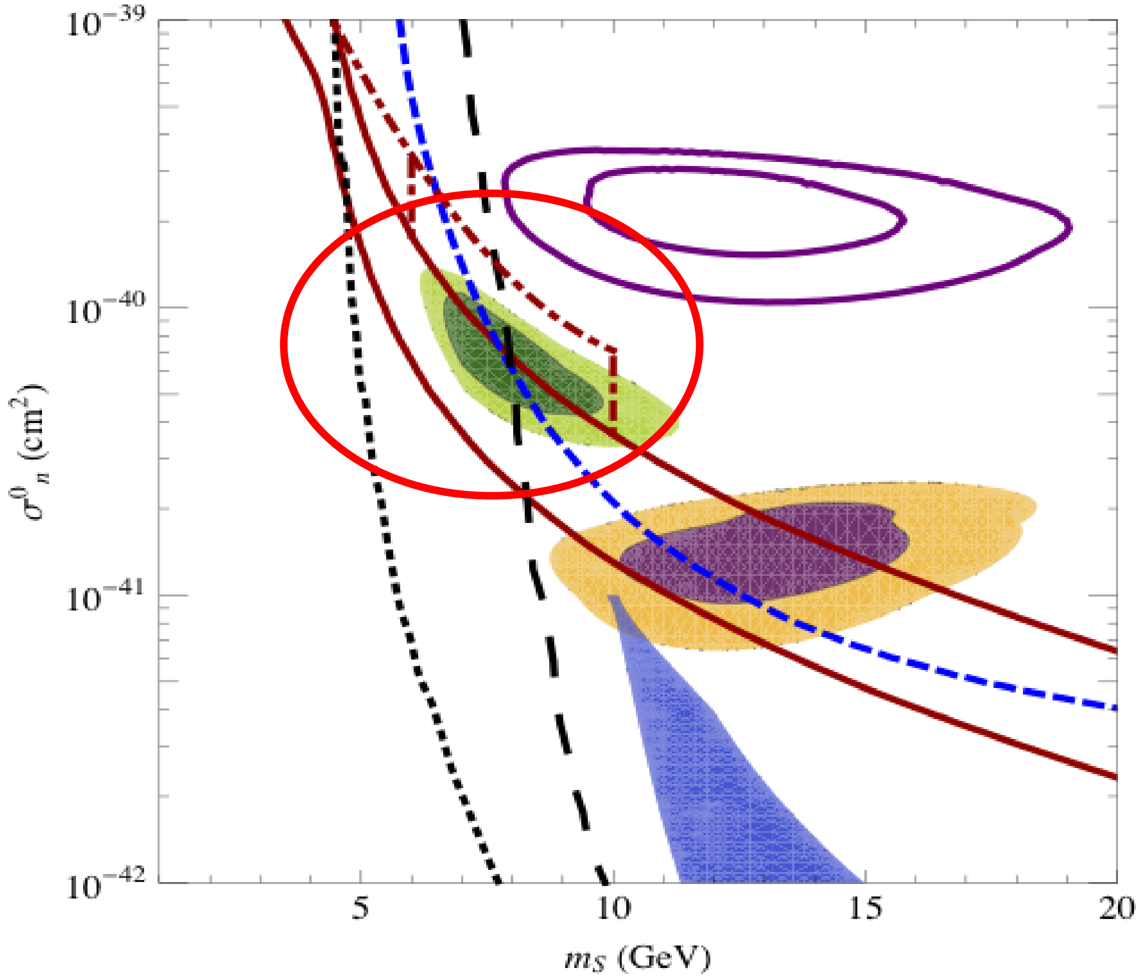
Concordance with CoGeNT and/or DAMA



Singlet scalar Candidates with WMAP abundance

Andreas, Arina, Hambye, Ling & M.T.
arXiv:1003.2595

Concordance with CoGeNT and/or DAMA



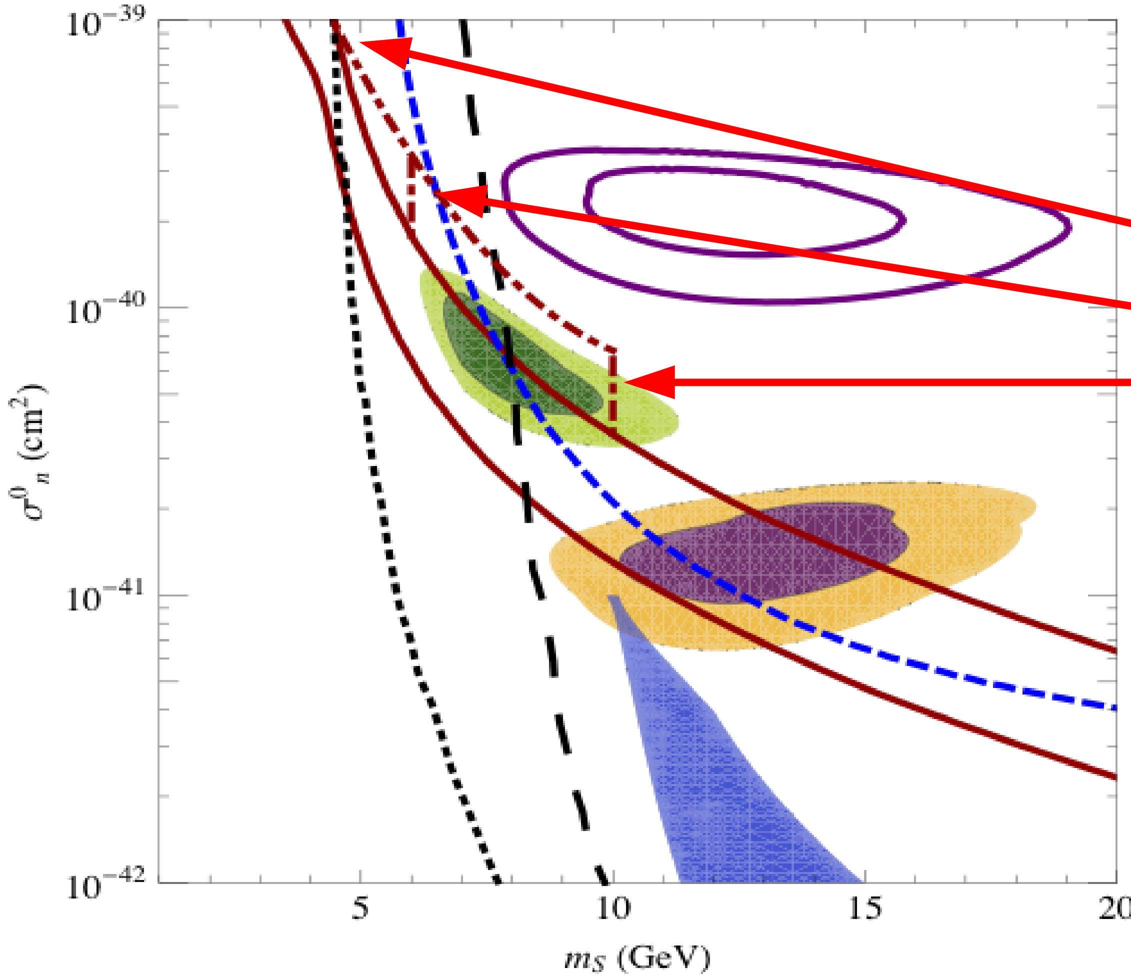
Singlet scalar domain consistent with WMAP abundance

Andreas, Arina, Hambye, Ling & M.T.
arXiv:1003.2595

Concordance with CoGeNT and/or DAMA

QCD phase transition

Smaller g_eff
→ higher abundance
→ need larger
coupling



Tc = 150 MeV
Tc = 300 MeV
Tc = 500 MeV

Singlet scalar domain consistent with WMAP abundance

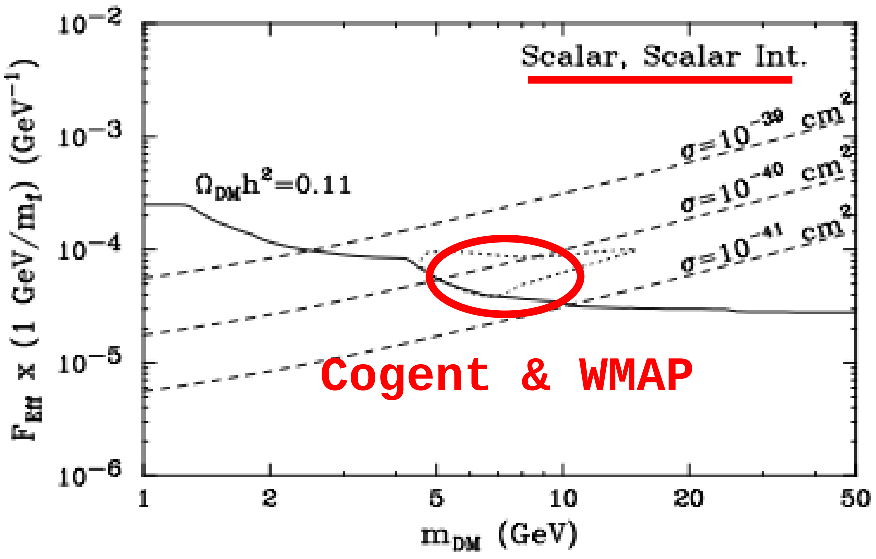
Andreas, Arina, Hambye, Ling & M.T.
arXiv:1003.2595

This is consistent with other recent works

Fitzpatrick, Hooper & Zurek

ArXiv:1003.0014

Effective operators approach

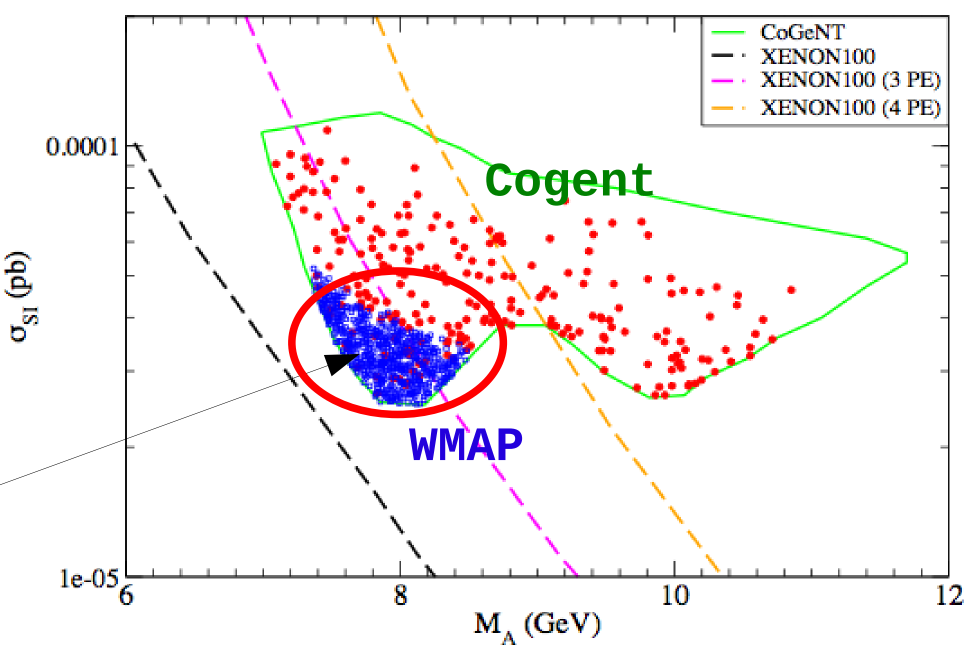


Barger, McCaskey, Shaughnessy

ArXiv:1005.3328

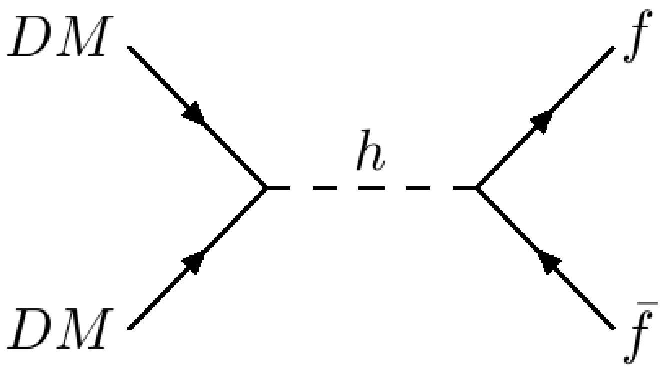
Complex singlet scalar

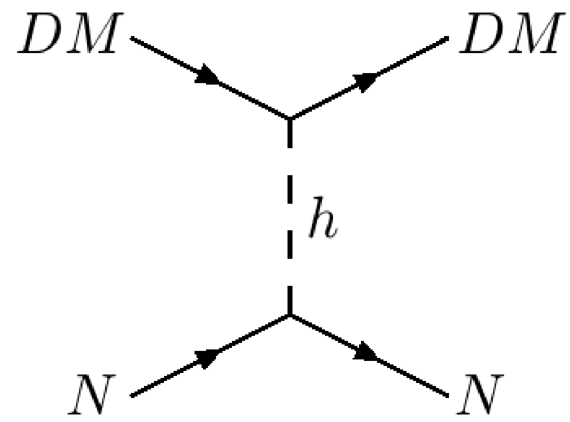
Effectively a **real** singlet scalar



Remark : A fermion (D or M) singlet with Higgs does not work

P odd initial state if S-wave





$$\sigma(\bar\psi\psi \to \bar f f)v_{rel} = n_c \frac{Y_\psi^2}{16\pi} \frac{m_f^2 v_{rel}^2}{v^2 m_h^4} \frac{(m_\psi^2 - m_f^2)^{3/2}}{m_\psi}$$

P-wave suppressed

Thus larger abundance

Typically needs other channels

e.g. light neutralino
(Bottino, Donato, Fornengo & Scopel; others)

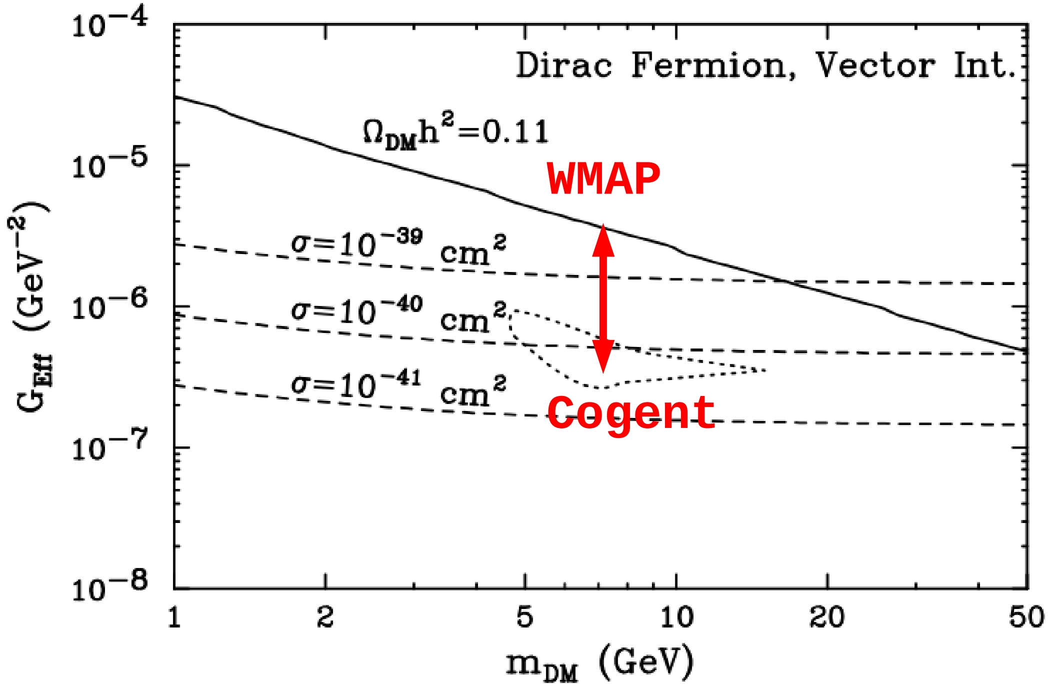
Andreas, Hambye, M.T.

Dirac DM candidate?

Fitzpatrick, Hooper & Zurek

ArXiv:1003.0014

Effective operators approach

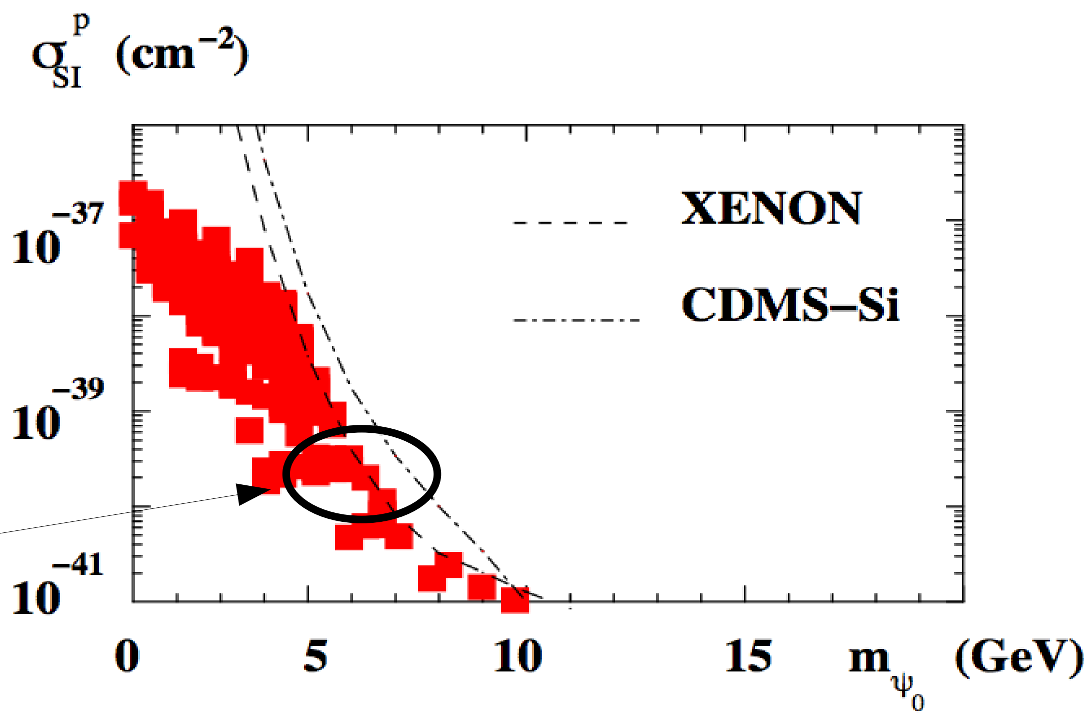


Mambrini ArXiv:1006.3318

Dirac fermion with a

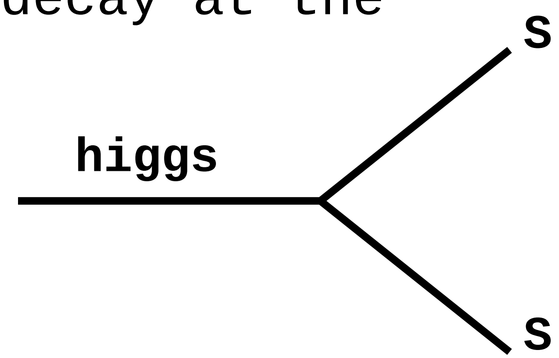
light Z'

OK if use the Z' pole to enhance the annihilation cross section



Motivation 3: affects Higgs physics

Invisible Higgs decay at the LHC



For instance **M_S = 7 GeV** :

For λ_S = 0.2 and m_{higgs} = 120 GeV

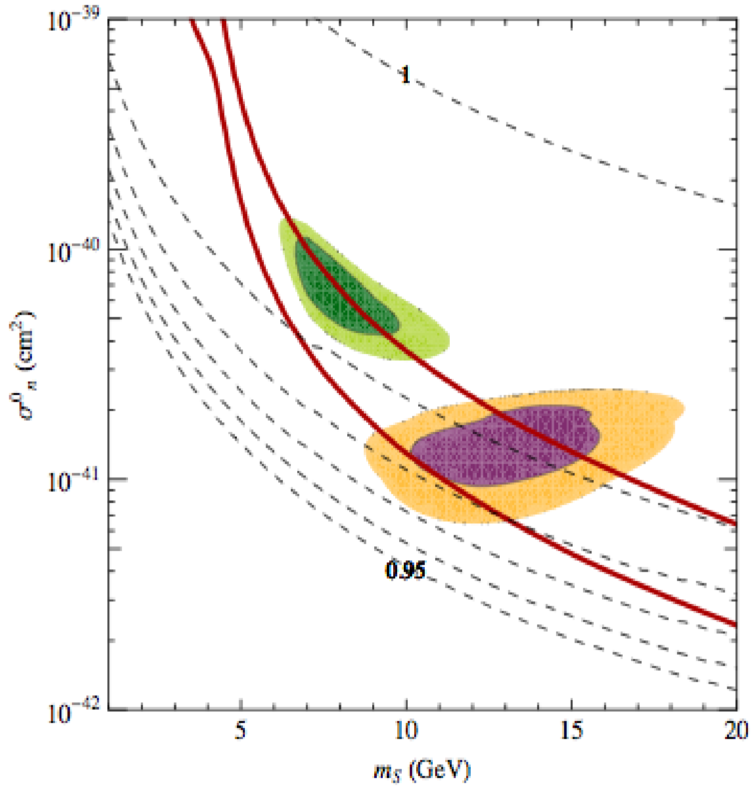
BR(h $\rightarrow$ SS) = 99.5%

For λ_S = 0.55 and m_{higgs} = 200 GeV

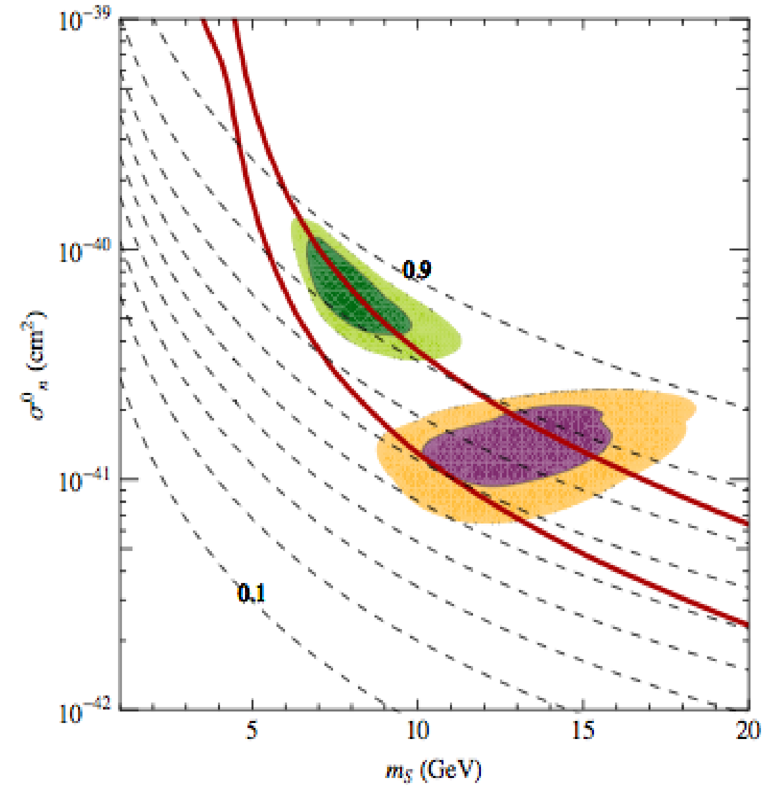
BR(h $\rightarrow$ SS) = 70%

Andreas, Hambye, M.T.

See also Burgess, Pospelov & ter Veldhuis; Barger et al;



m_{higgs} = 120 GeV



m_{higgs} = 180 GeV

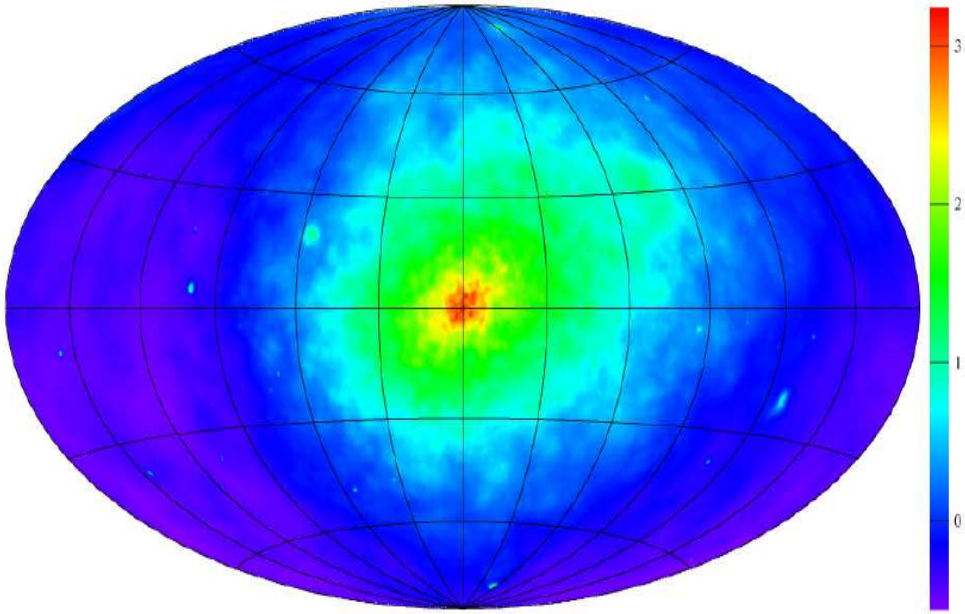
75% < INVIS. BR. < 90 % for CoGeNT with Mhiggs @ 180 GeV

Invisible Higgs search?

Most promising channel@ LHC is Z-boson associated production
ie
di-lepton + missing E_T
(Jets + missing E_T is much less Important)
(Eboli & Zeppenfeld)

Remark: similar problematic for NMSSM light WIMP scenarios
(Gunion, Hooper & West)

Motivation #4: potentially « large » indirect signals



HORIZON simulation
Athanassoula et al

$$\frac{d\Phi_{\gamma,\nu}}{d\Omega} = \frac{1}{4\pi} \underbrace{\frac{1}{\delta}\frac{\langle\sigma v\rangle}{m_{DM}^2} \int_{E_{min}^{\gamma,\nu}}^{E_{max}^{\gamma,\nu}} \sum_i \frac{dN_{\gamma,\nu}^i}{dE_{\gamma,\nu}} BR_i}_{\doteq HEP_{\gamma,\nu}} \underbrace{\int_{l(\vec{\Omega})} \rho_{DM}^2 \, dl}_{\doteq ASTRO} ,$$

Annihilation rate ~ n_{dm}^2 ~ $1/m_{dm}^2$

Flux of gammas, neutrinos, positrons ↗↗

Constraint # 1: gammas rays from dwarf spheroidal galaxies (dSph)

+ Largest galactic dark matter subhalos (we believe)

+ Low gamma-ray background

- low statistics

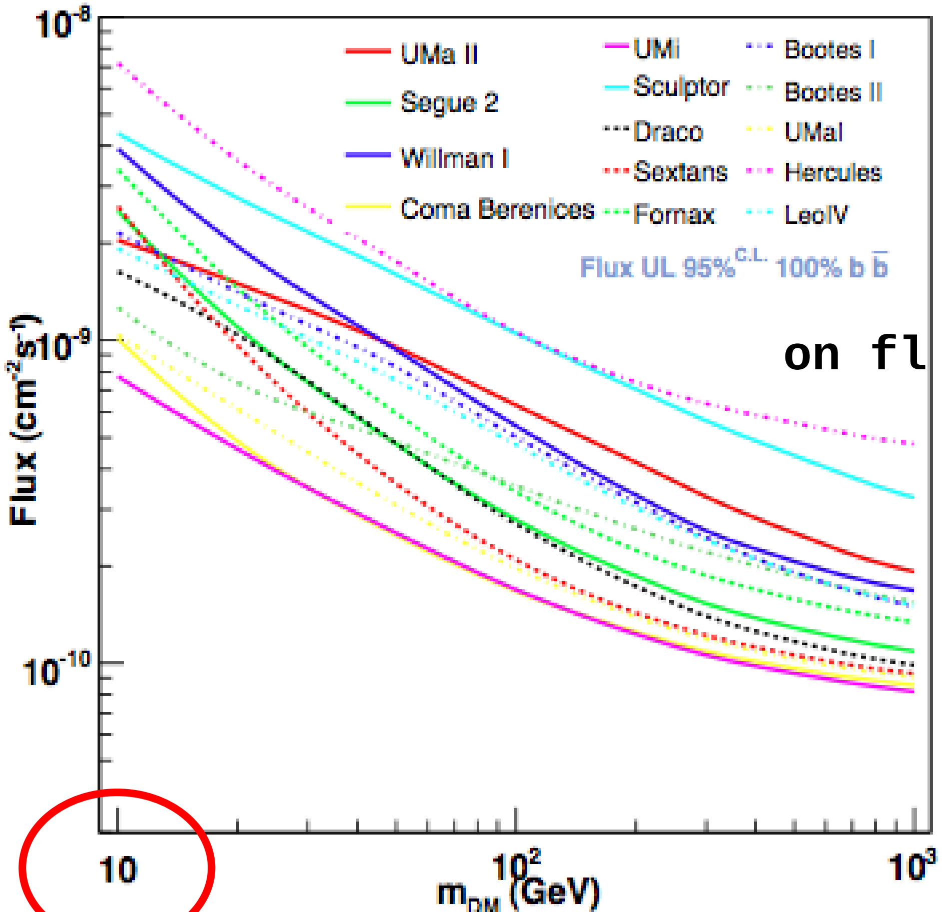
→ analysis by Fermi-LAT collaboration, 11 months of data, with 95% CL on gamma flux from Milky Way dwarf spheroidal galaxies (dSph)

- 14 best candidates dSph
- short distances (< 150 kpc), high latitudes for low background (-30° < b < 30°)
- dSph modelled as point sources
- No observation of gamma from dSph

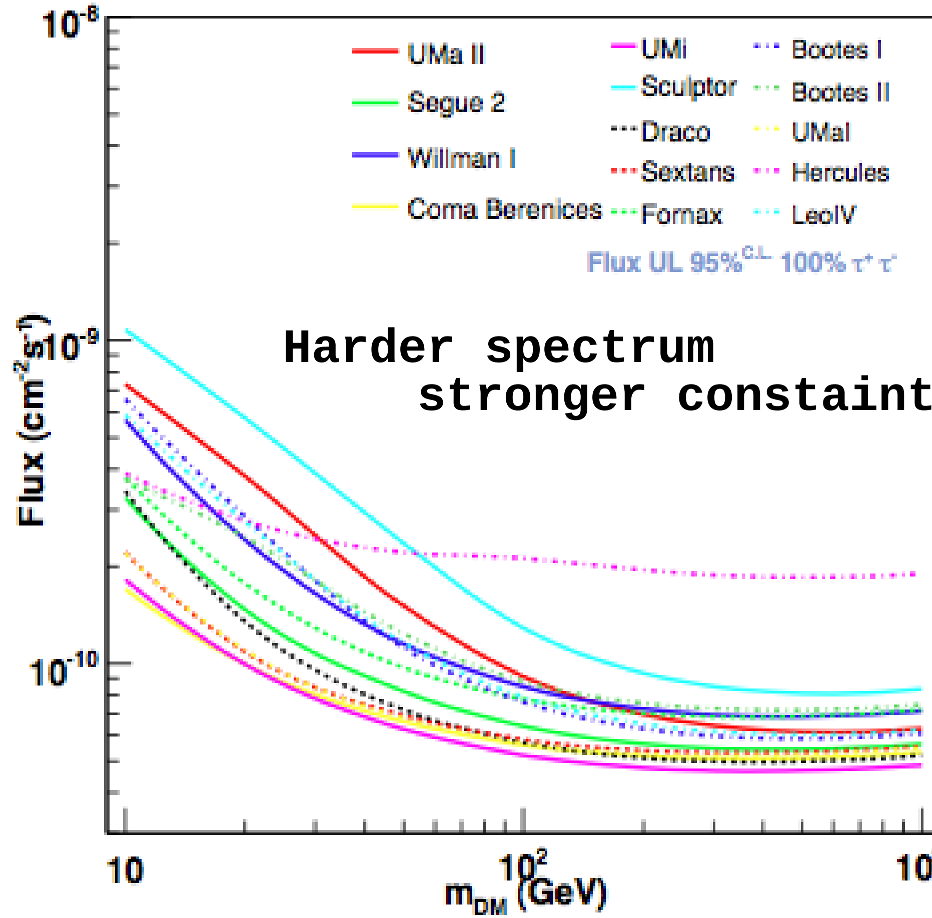
95% CL limits on DM (based on NFW profile)

95% C.L. limits on flux from dSphs between 100 MeV < E < 50 GeV

100% in b-bbar



100% in $\tau^+ \tau^-$



Harder spectrum
stronger constaints

But only published limits for M > 30 GeV neutralino and KK-dm candidates

Figures from Fermi-LAT; Abdo et al, arXiv:1001.4531

New limits on the gamma ray flux from dSphs from a light scalar singlet with WMAP cross section

	Ursa Minor		Draco	
m_S and BR	$\Phi_{\rm pred}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$\Phi_{\rm lim}^{95\%\rm CL}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$\Phi_{\rm pred}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$\Phi_{\rm lim}^{95\%\rm CL}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$
10 GeV $\mathrm{BR}(SS \to \tau^+\tau^-) \simeq 10\%$ $\mathrm{BR}(SS \to b\bar{b} + c\bar{c}) \simeq 90\%$	8.5×10^{-10} >	7.8×10^{-10}	1.6×10^{-9}	1.6×10^{-9}
6 GeV $\mathrm{BR}(SS \to \tau^+\tau^-) \simeq 20\%$ $\mathrm{BR}(SS \to b\bar{b} + c\bar{c}) \simeq 80\%$	1.5×10^{-9} >	1.0×10^{-9}	2.8×10^{-9} >	1.7×10^{-9}

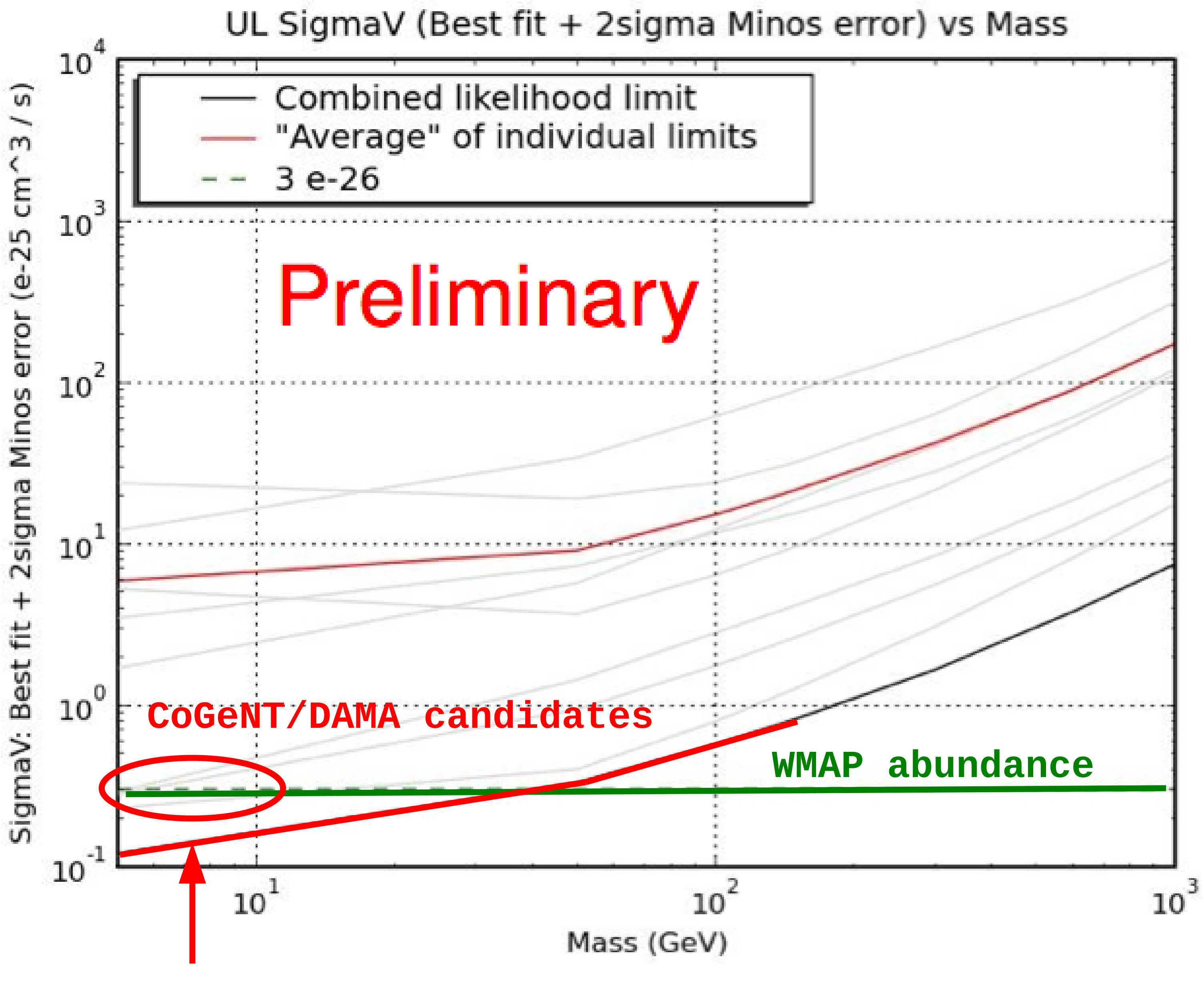
Our predicted fluxes but tentative (e.g. energy resolution, acceptance,... not taken into account)

Our (naive) extrapolations based on Fermi-LAT data

Andreas, Arina, Hambye, Ling, M.T. (arXiv:1003.2595)

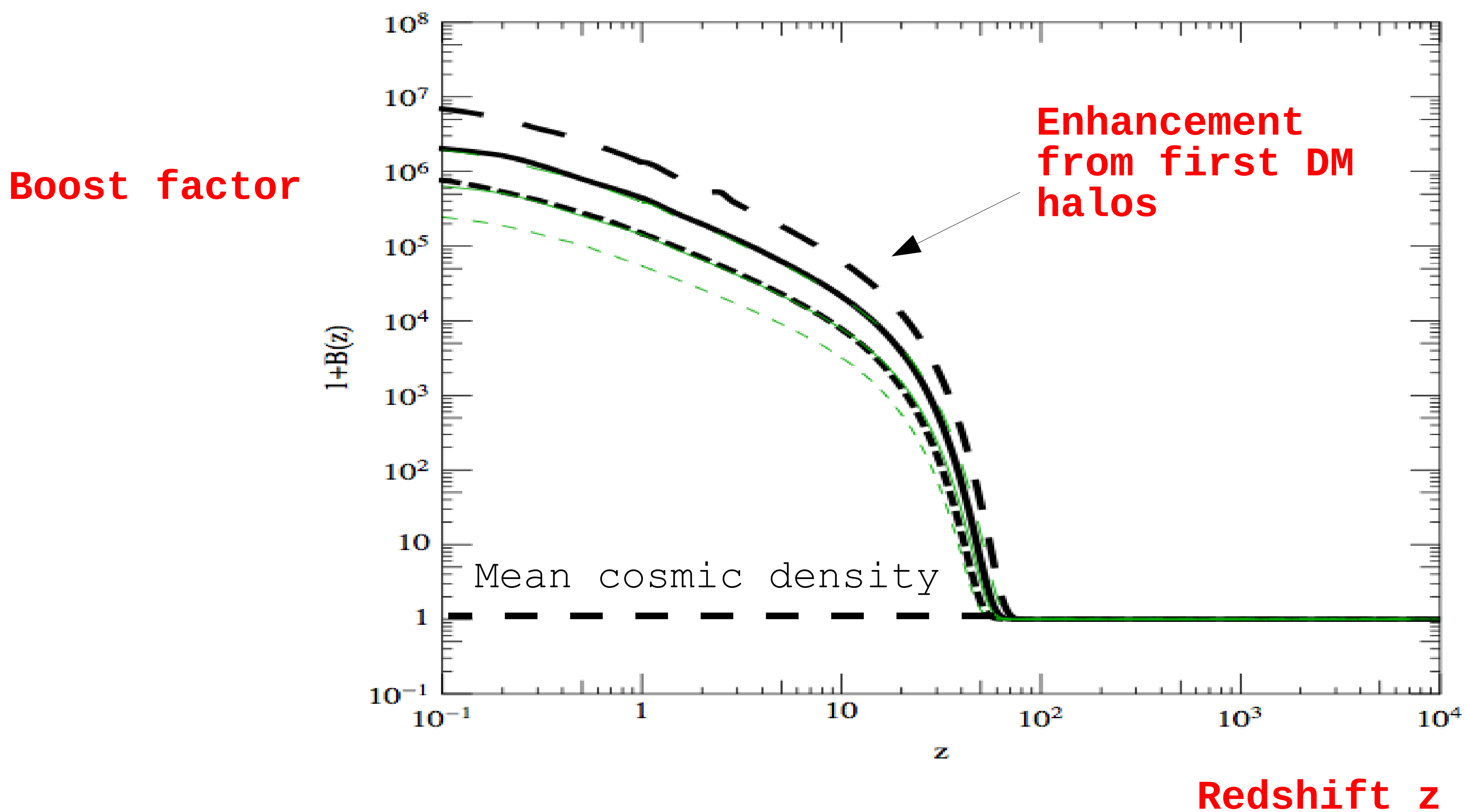
See also Fitzpatrick, Hooper & Zurek

From the talk by Maja LLENA GARDE (Fermi-LAT) @ IDM2010



Stacked analysis → stronger limits: light candidates in b-bbar excluded @ 95% CL

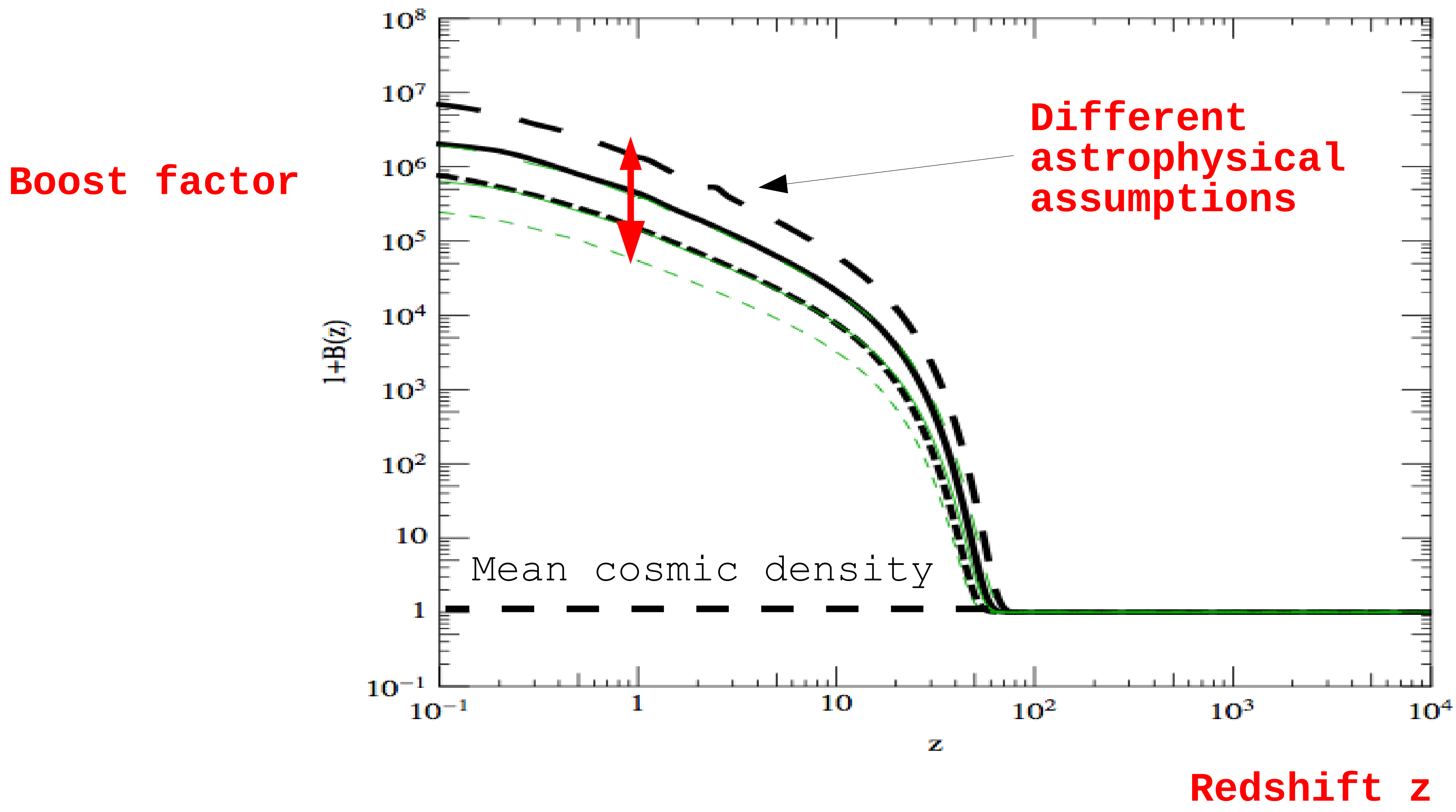
Constraint # 2: Isotropic extragalactic gamma-ray flux



$$\frac{d\Phi_\gamma}{dE} = \frac{c}{4\pi}\frac{<\sigma v>_{ann}}{2M_{DM}^2}\int_0^\infty dz' \frac{1}{H(z')(1+z')^4}\frac{dN_\gamma}{dE'}\mathcal{B}^2(z')e^{-\tau(E',0,z')}$$

Figure from Ch. Arina, M.T. (2010)

Constraint # 2: Isotropic extragalactic gamma-ray flux

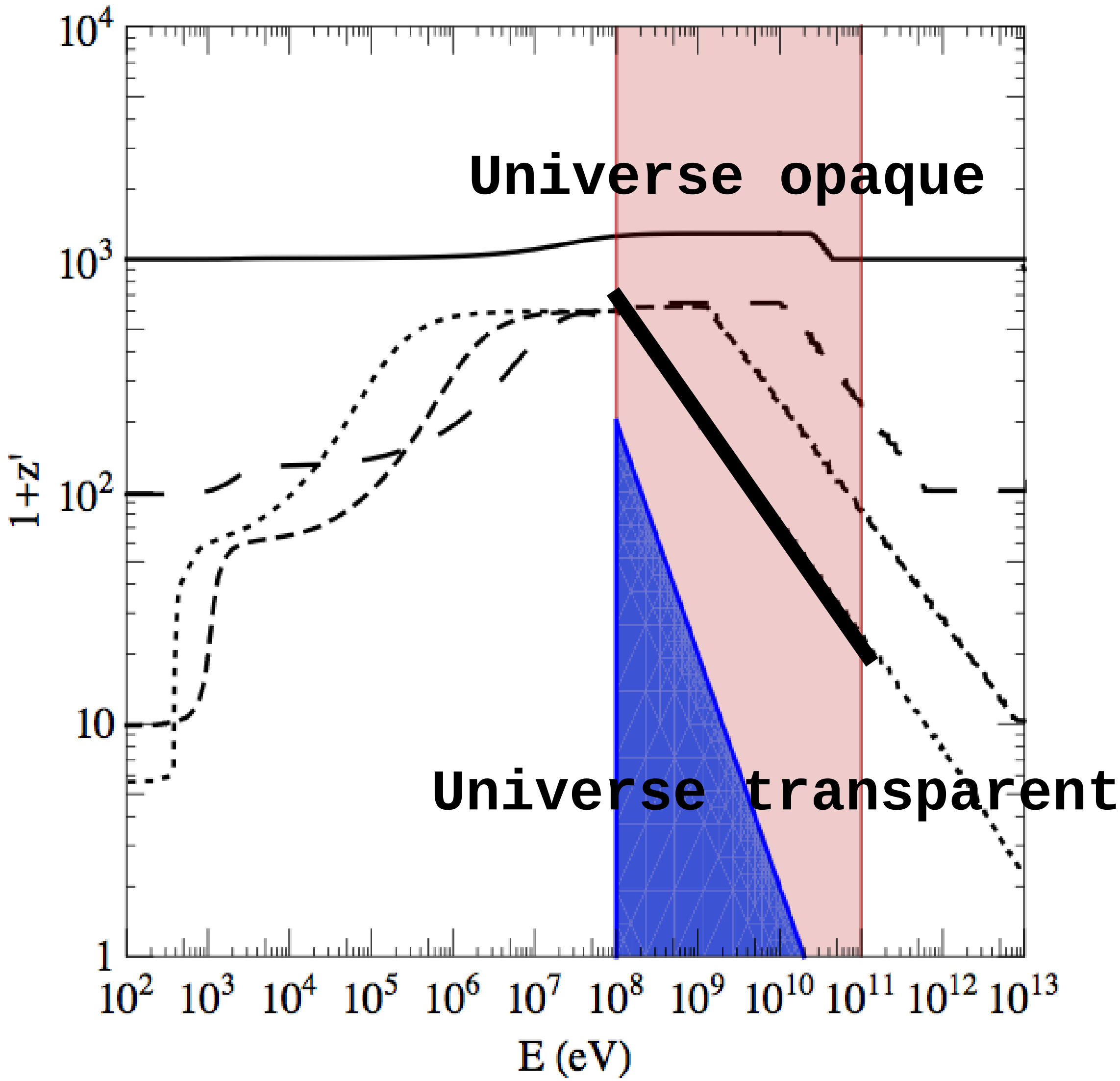


$$\frac{d\Phi_\gamma}{dE} = \frac{c}{4\pi}\frac{<\sigma v>_{ann}}{2M_{DM}^2}\int_0^\infty dz' \frac{1}{H(z')(1+z')^4}\frac{dN_\gamma}{dE'}\mathcal{B}^2(z')e^{-\tau(E',0,z')}$$

Figure from Ch. Arina, M.T. (2010)

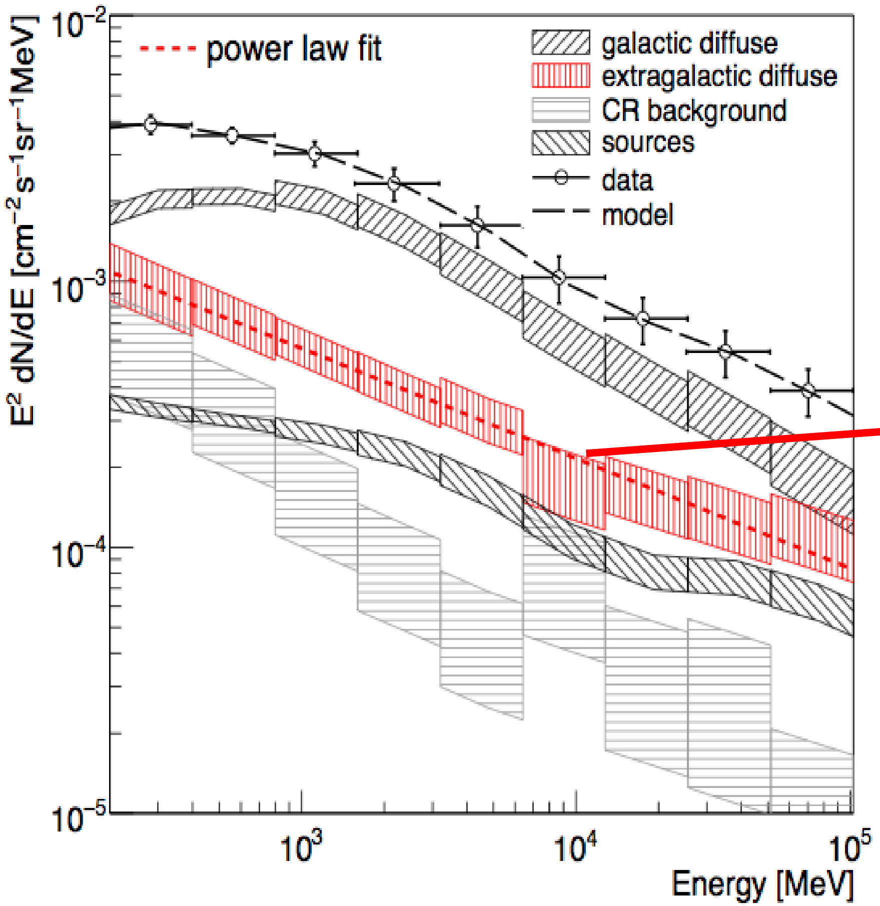
Universe essentially transparent for E < 10 GeV gamma-rays in the Fermi-LAT window (in pink)

Redshift
@
emission



Observed energy

Constraint # 2: Isotropic extragalactic gamma-ray flux



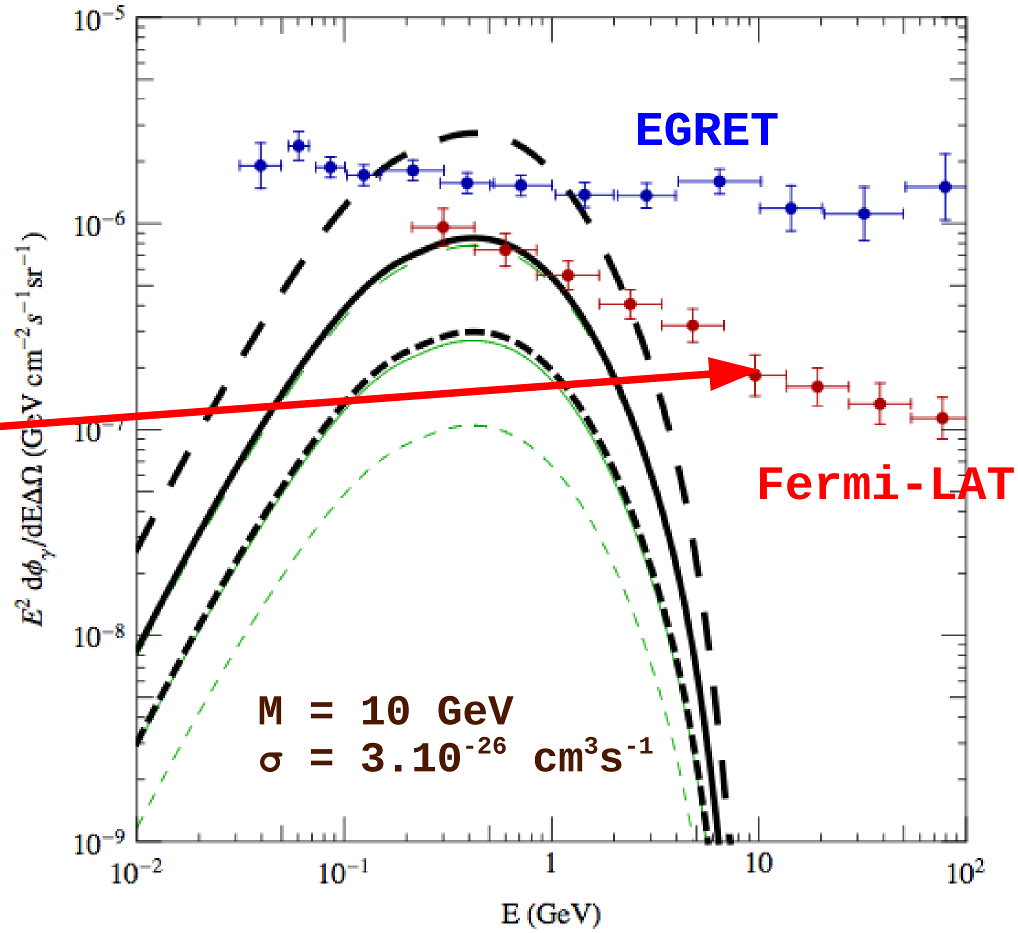
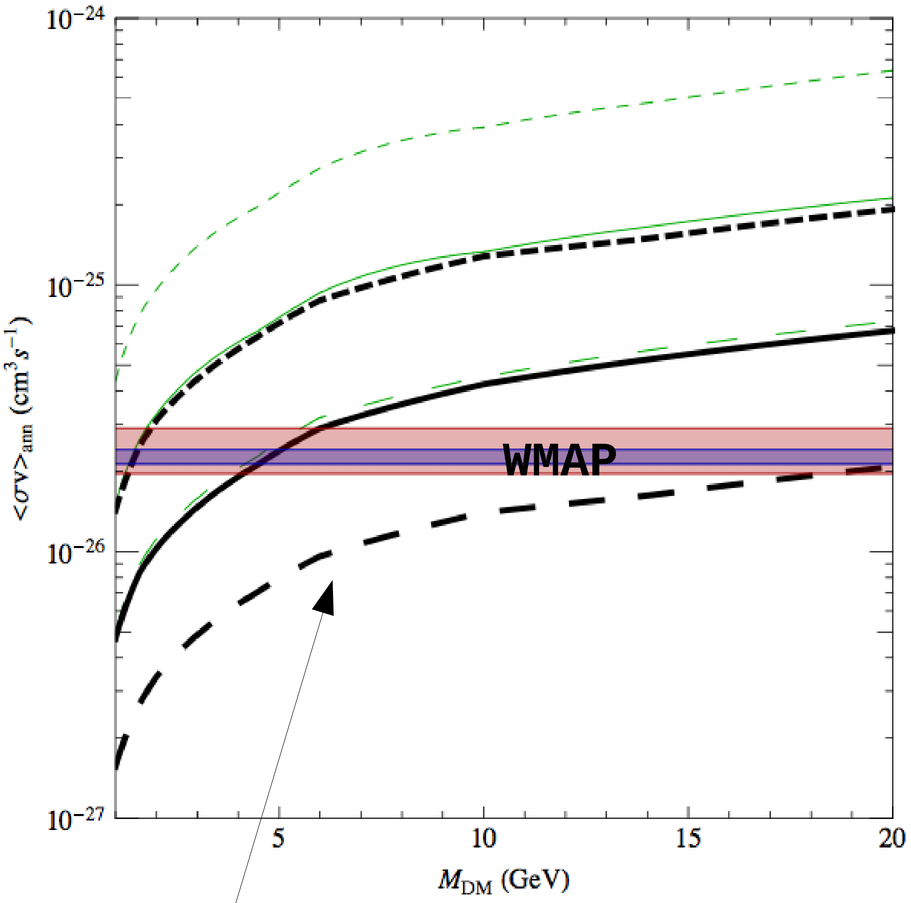


Figure from Fermi-LAT
Abdo *et al* arXiv:1002.3603

Predicted flux,

Fig. from Ch. Arina, M.T. (2010)

Constraint # 2: Isotropic extragalactic gamma-ray flux



Astrophysics uncertainty on distribution of small mass dark matter halos (dn/dM)

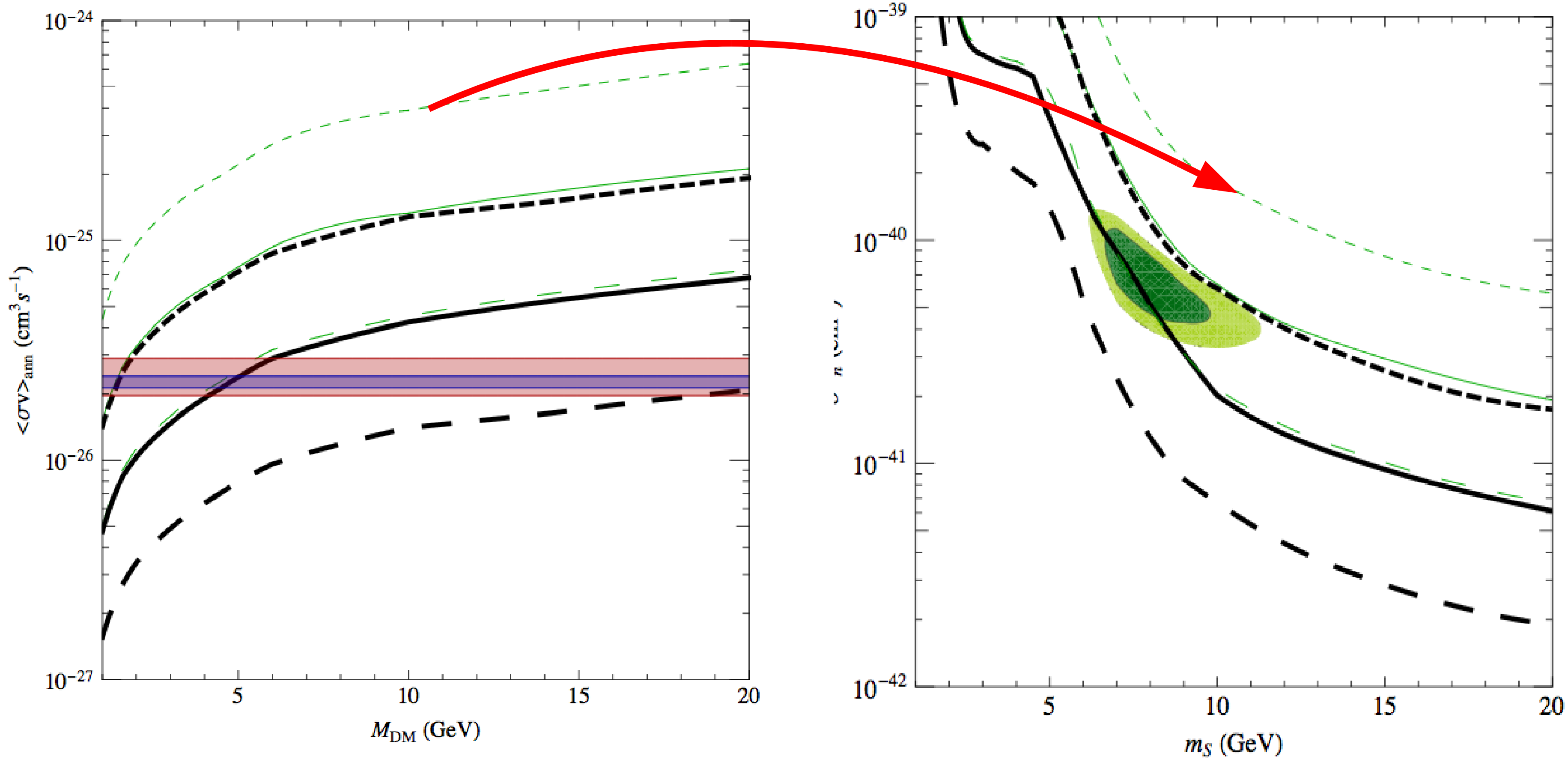
Further uncertainty from the choice of DM profile (here NFW)

95% CL (from no excess in any single bin)

Consistent with many other works, some pre-dating Fermi-LAT

(Abdo et al; Profumo & Tesla; Beacon et al; Yuksel et al;...)

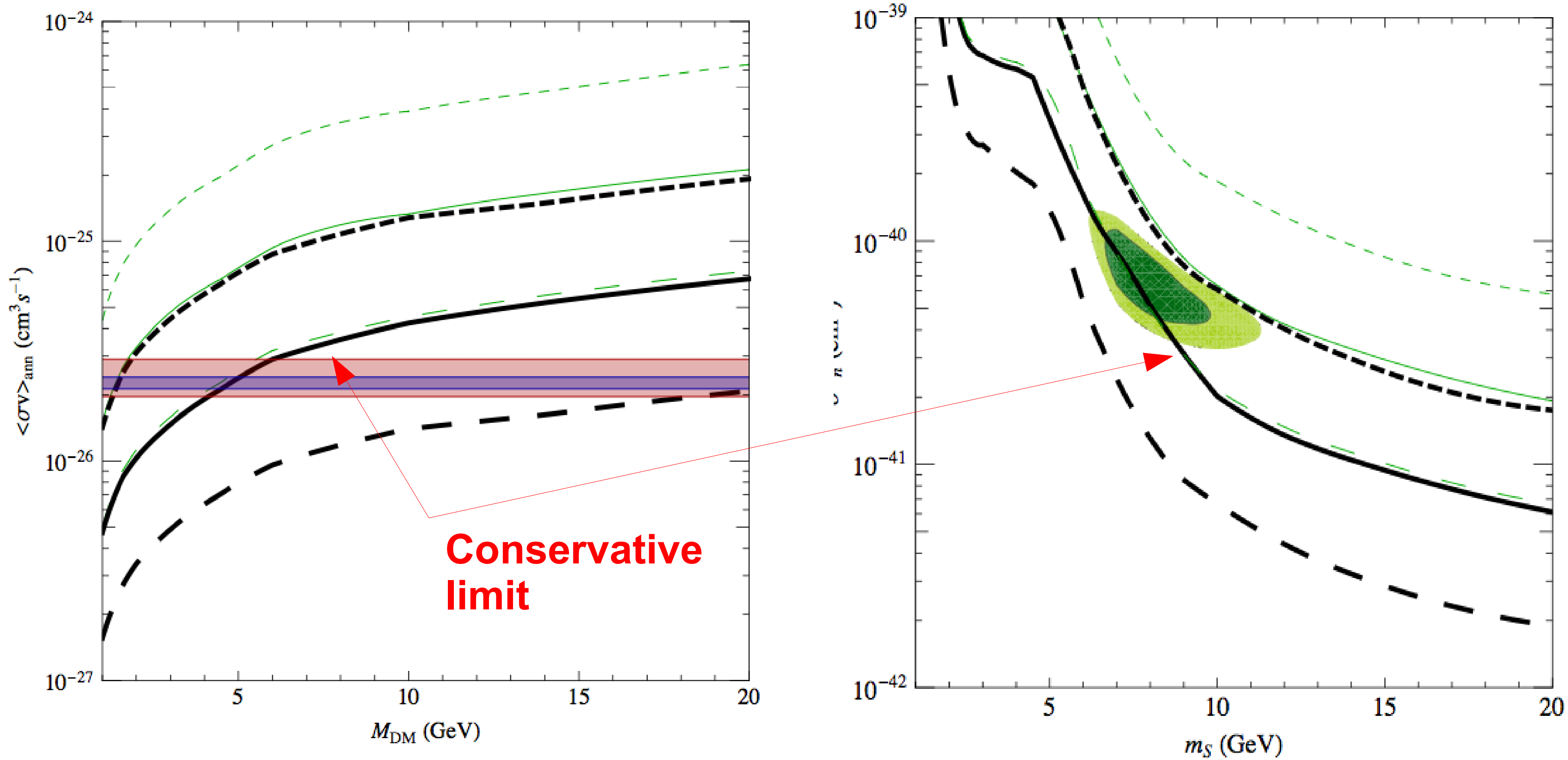
Constraint # 2: Isotropic extragalactic gamma-ray flux



Using the one-to-one correspondence between the annihilation and the SI scattering cross sections

$$\sum_f \frac{\sigma(SS \to \bar{f} f) v_{rel}}{\sigma(SN \to SN)} = \sum_f \frac{n_c m_f^2}{f^2 m_N^2 \mu_n^2} \frac{(m_S^2 - m_f^2)^{3/2}}{m_S}$$

Constraint # 2: Isotropic extragalactic gamma-ray flux



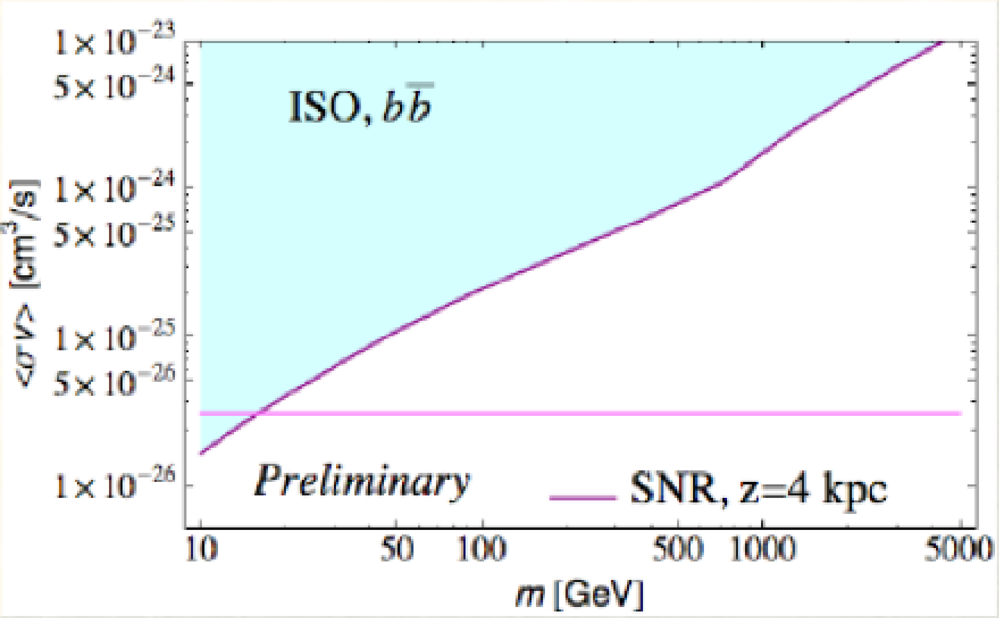
Using the one-to-one correspondence between the annihilation and the SI scattering cross sections

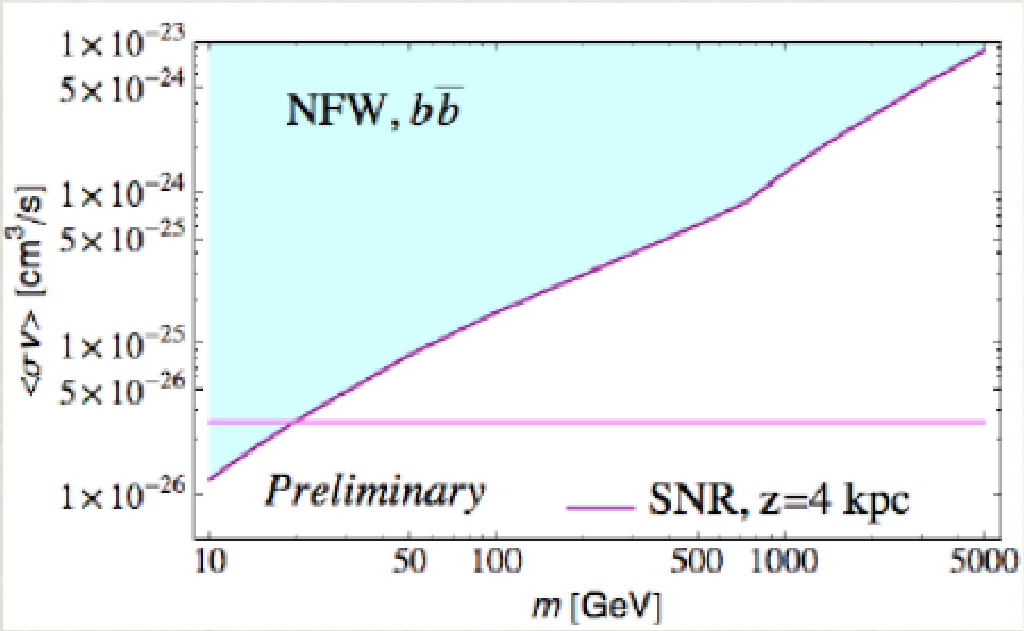
$$\sum_f \frac{\sigma(SS \to \bar{f}f)v_{rel}}{\sigma(SN \to SN)} = \sum_f \frac{n_c m_f^2}{f^2 m_N^2 \mu_n^2} \frac{(m_S^2 - m_f^2)^{3/2}}{m_S}$$

Further constraints: the Diffuse Galactic Halo

DM exclusion limits (2)

FROM ALESSANDRO CUOCO'S TALK @ IDM2010 (SEE ALSO B. ANDERSON)



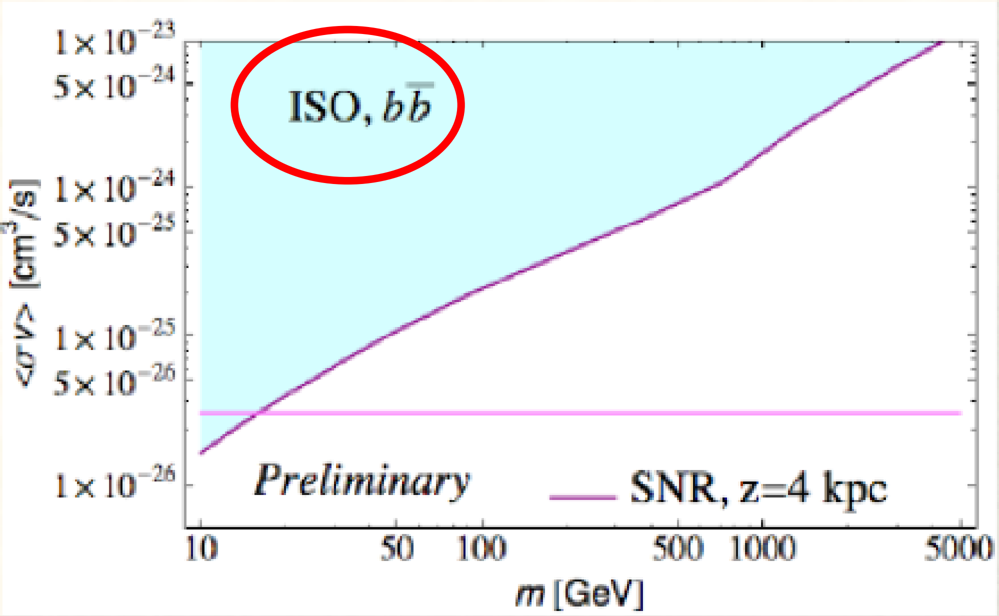


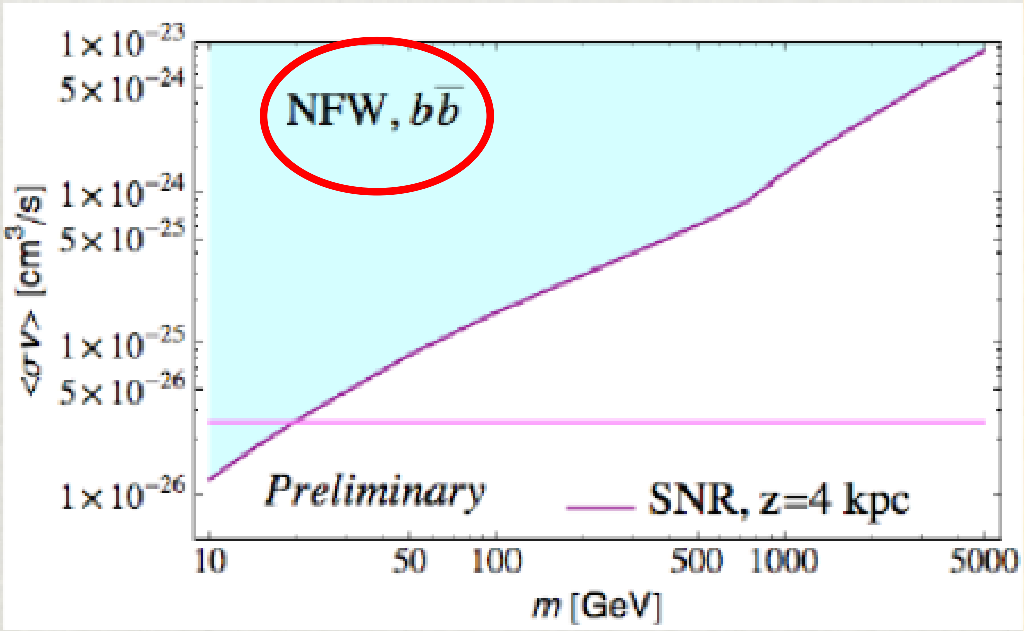
- bbar constrain are also weakly dependent from the DM profile
- Thermal freeze-out cross section probed for low DM wimp masses.

Further constraints: the Diffuse Galactic Halo

DM exclusion limits (2)

FROM ALESSANDRO CUOCO'S TALK @ IDM2010 (SEE ALSO B. ANDERSON)



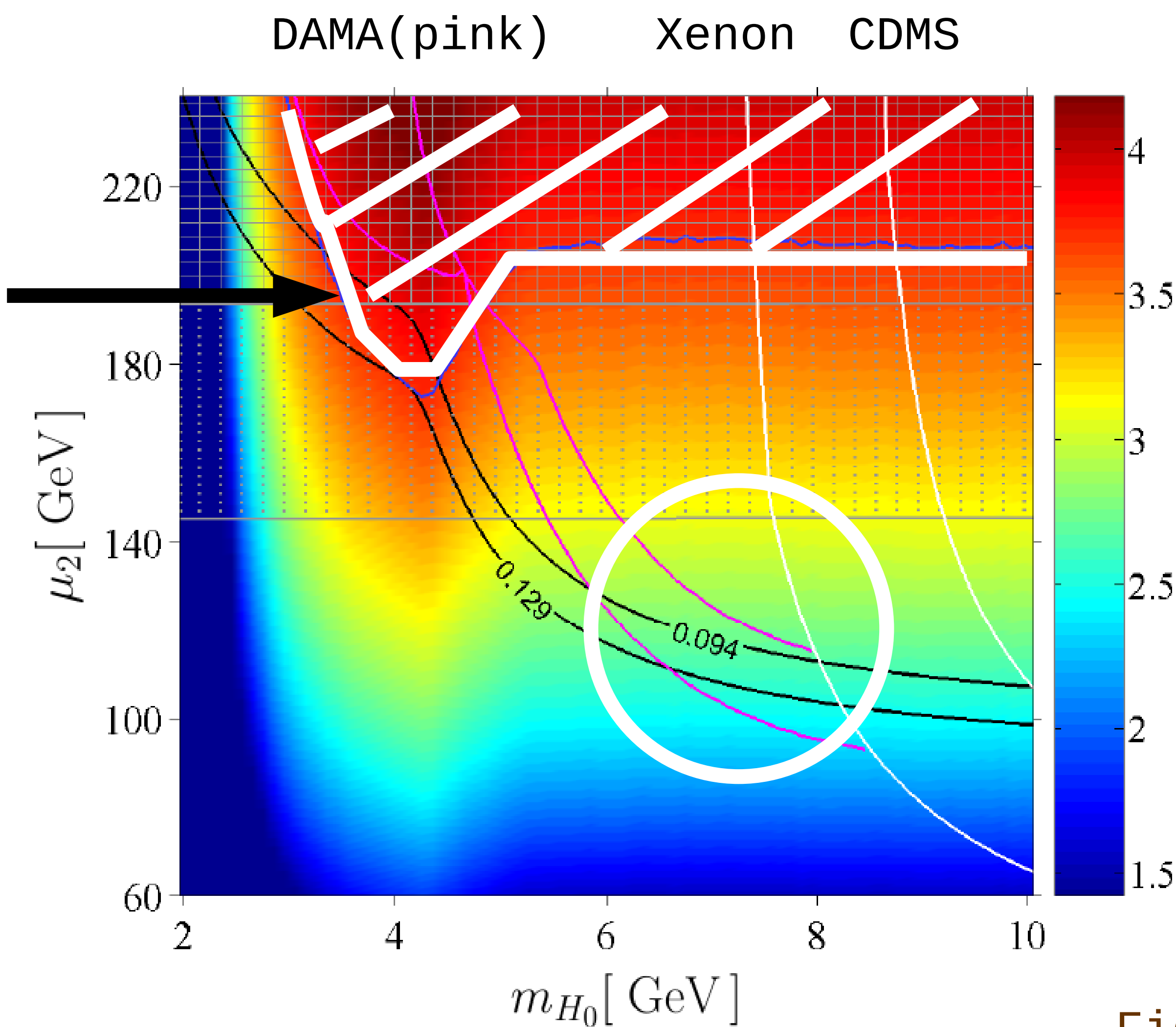


•bbar constrain are also weakly dependent from the DM profile

•Thermal freeze-out cross section probed for low DM wimp masses.

Neutrino flux from ~ GeV DM captured in the Sun

Super-Kamiokande exclusion limit



Log$_{10}$ (Muon flux) per year, per km^2

Figure from S.Andreas, Q.Swillens, M.T. arXiv:0901.1750

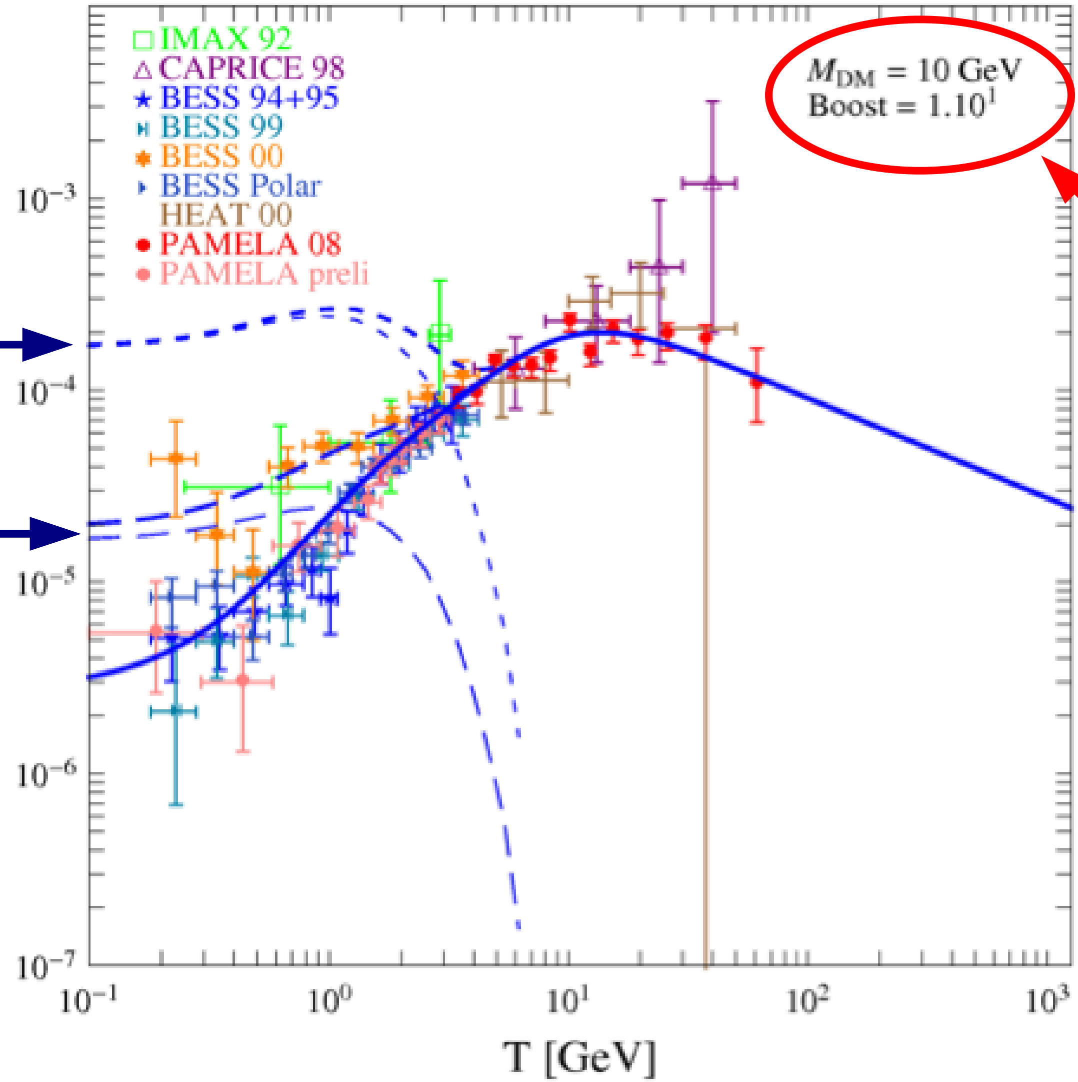
Generic, see also Kumar et al; Freese et al

Limits from Pamela data on antiprotons in cosmic rays

Max

Med

(different choice of diffusion and geometry parameters)



This is clearly excluded

Figure from E.Nezri, G. Vertongen, M.T.

See also J. Lavalle; G. Shaughnessy et al

Remark: a light WIMP could be good for something else ...

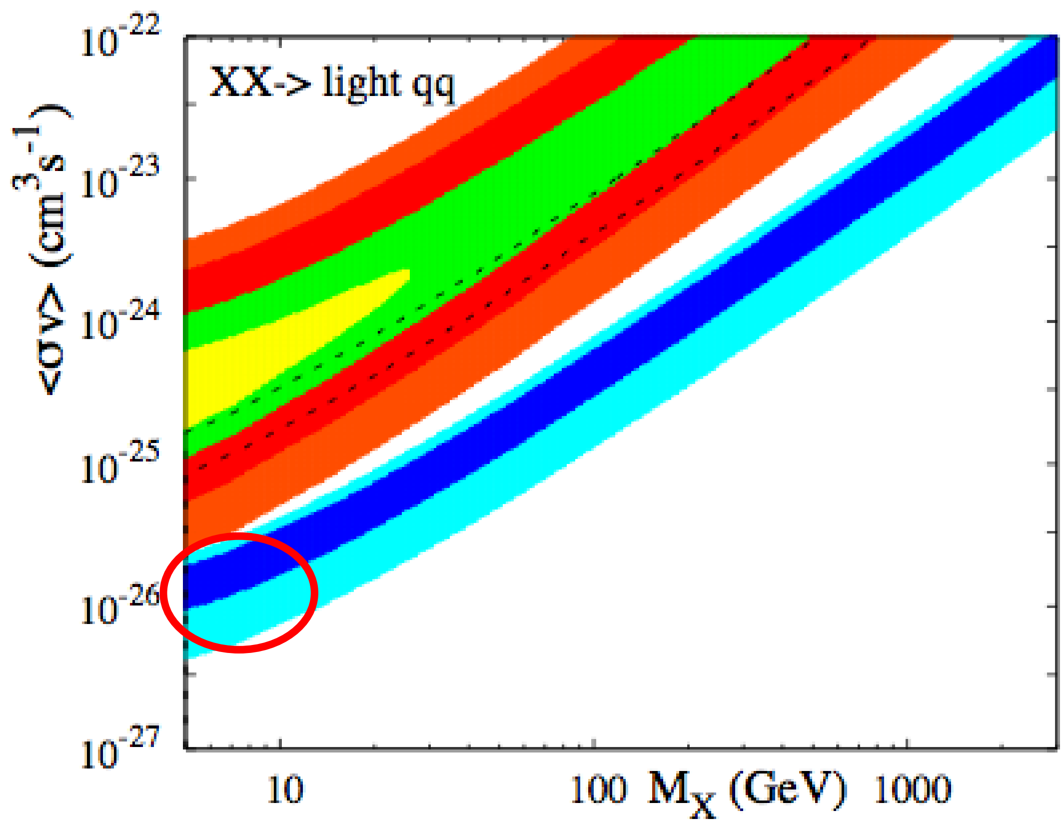


Figure from Jedamzik & Pospelov

Figure 3. Dark matter annihilation rate versus dark matter mass. The blue band shows parameters where ^{6}Li due to residual dark matter annihilation may account for the ^{6}Li abundance as inferred in HD84937 (^{6}Li/^{7}Li$\approx$ 0.014 – 0.09 at 2-σ), whereas the orange-red-green-yellow region shows where ^{7}Li is efficiently destroyed i.e. ^{7}Li/H$<$ 1.5, 2, 3, and 4×10^{-10}, respectively. Above the lower (upper) dashed line D/H exceeds 4×10^{-5} (5.3×10^{-5}), such that parameter space above the upper dashed line is ruled out by D overproduction. Scenarios between this line and the

Conclusions

Singlet scalar model, but quite generic results

May be consistent with CoGeNT and/or DAMA (or CRESST for that matter) and WMAP thermal abundance

Challenged (to say the least) by other direct detection experiments

Dramatic implications for Higgs search (invisible decay)

Also potentially strong indirect constraints from Fermi-LAT data, possibly excluding this (category of) models

Prospects?

A light WIMP requires a new mass scale

This problem is worse for a scalar field ... New ideas?

Expect more constraints from gamma-ray observations, but also from other indirect signatures (some not worked out yet, like synchrotron radio emission)

These constraints are easely evaded by Asymmetric Dark Matter. But then how to probe this scenario?