

New directions in the DM quest

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Explosion of activity (whether it is/was justified or not)

◆ RECENT PAST

Indirect detection

**WMAP (+haze?)
SPI/INTEGRAL
PAMELA,FERMI**

Direct detection

**CDMS/XENON100
vs DAMA/CoGeNT**

◆ PRESENT/FORTHCOMING FUTURE

**LHC
PLANCK
CDMS + XENON
AMS**

**Where do we stand
and
my opinion about where we are going...**

From 1998 to 2011:

Questioning the old hypothesis!

The relic density paradigm

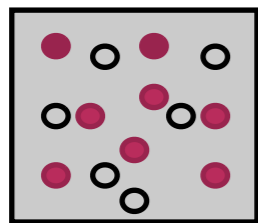
- Hypothesis until the 2000s:

- * thermal (annihilating)

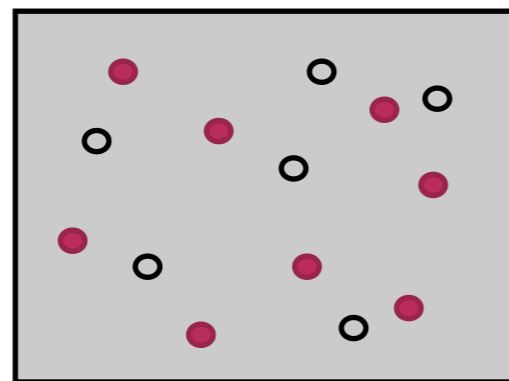
- * symmetric ($n_{\text{DM}} = n_{\text{antiDM}}$)

- * weakly interacting

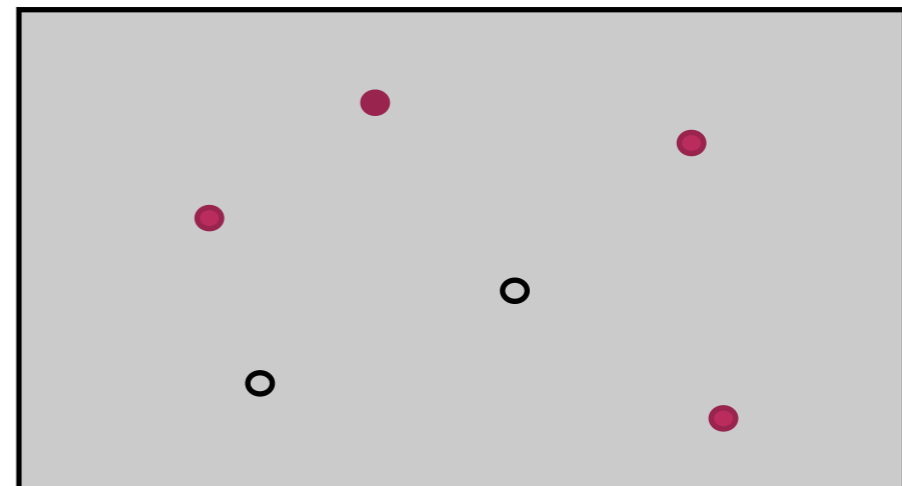
$$\frac{dn}{dt} = -3 H n - \langle \sigma v \rangle (n^2 - n_{\text{eq}}^2)$$



Thermal equilibrium



Expansion



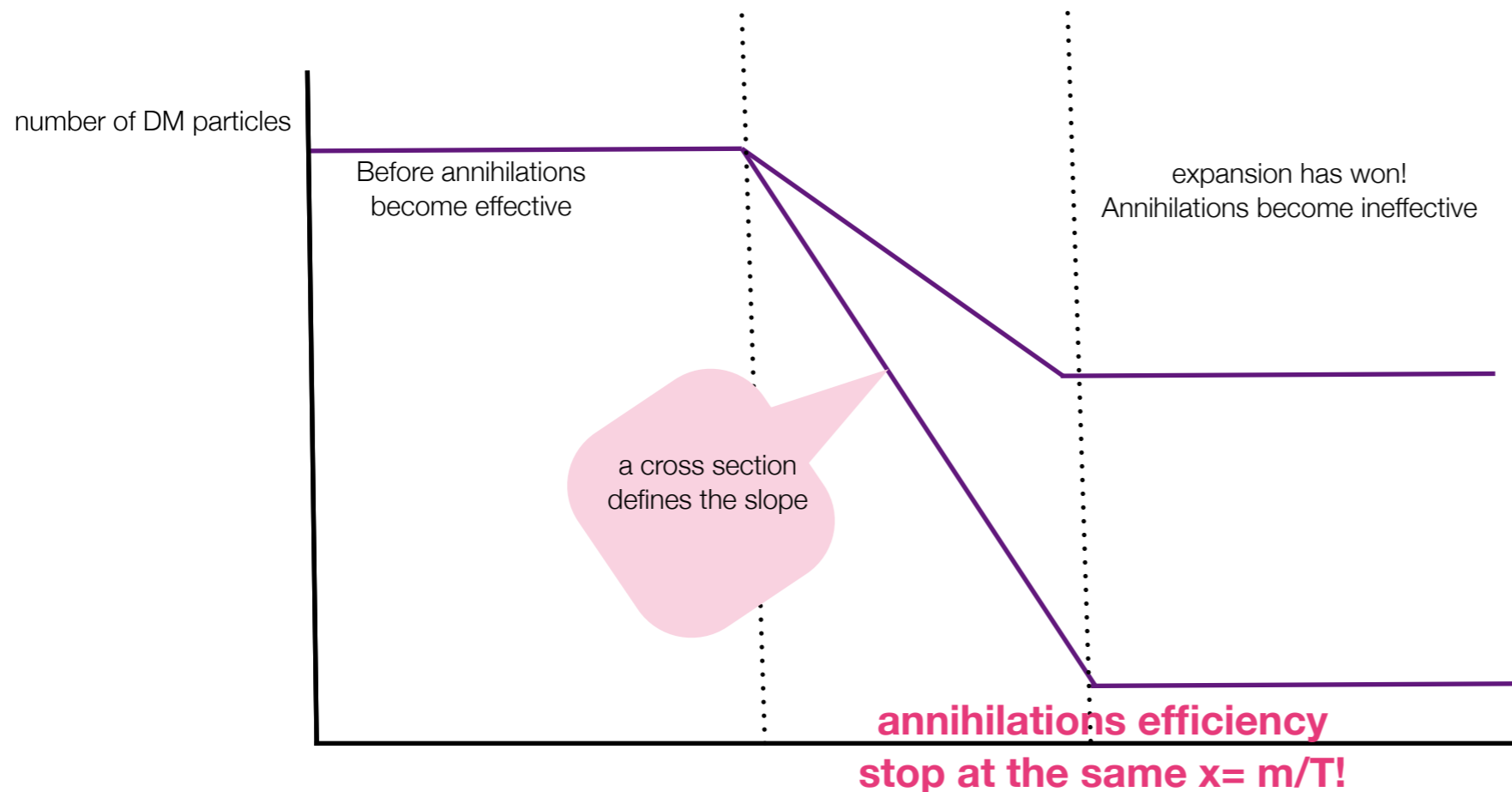
Annihilations

Boltzmann equation
no Particle Physics!

The relic density paradigm

- Solutions of the Boltzmann equation requires no Particle Physics input !
- BUT ... it does give an information about DM particle properties:

$$\langle \sigma v \rangle = \frac{3 \cdot 10^{-27} \text{ cm}^3 / \text{s}}{\Omega_{dm} h^2}$$

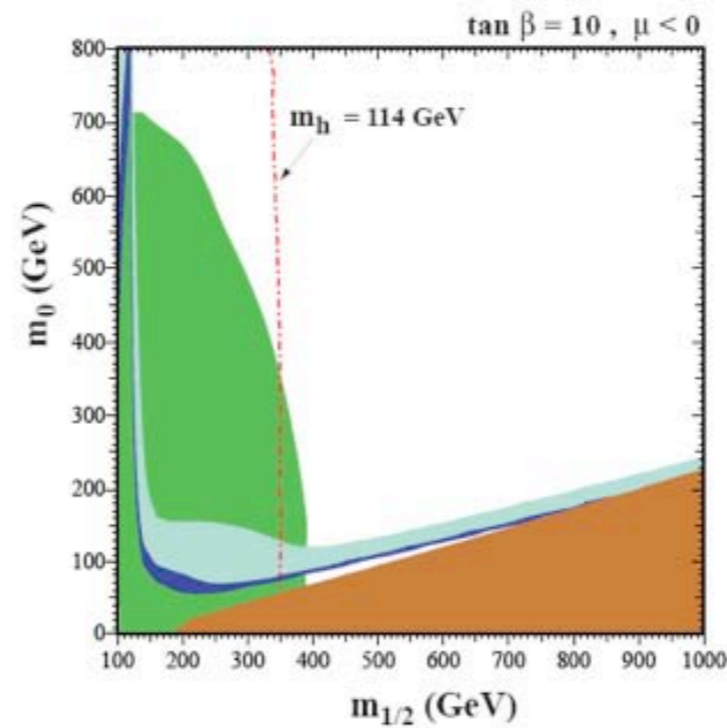
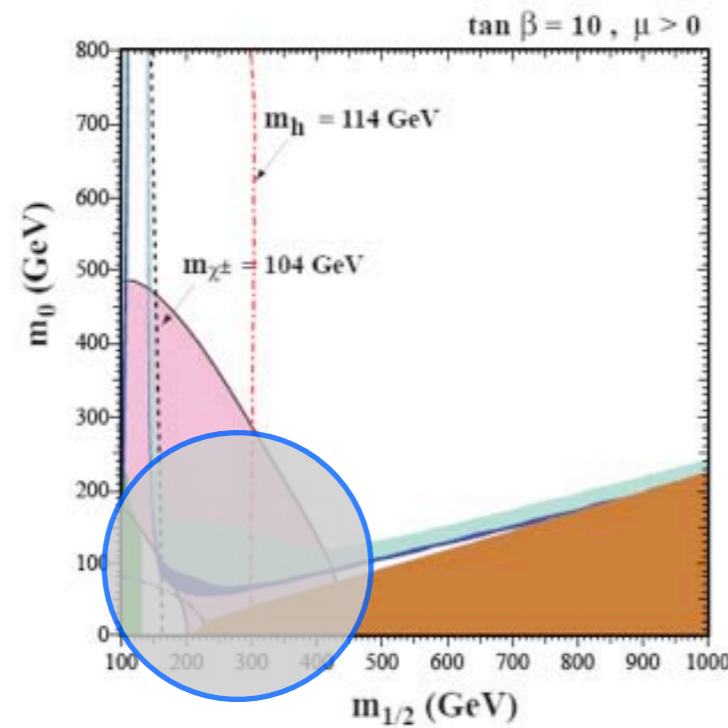


Thus only one value of the cross section works!

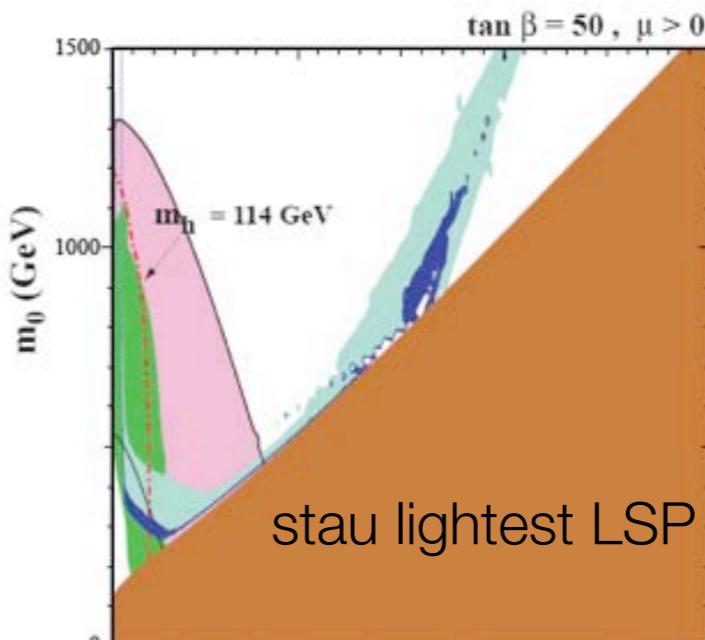
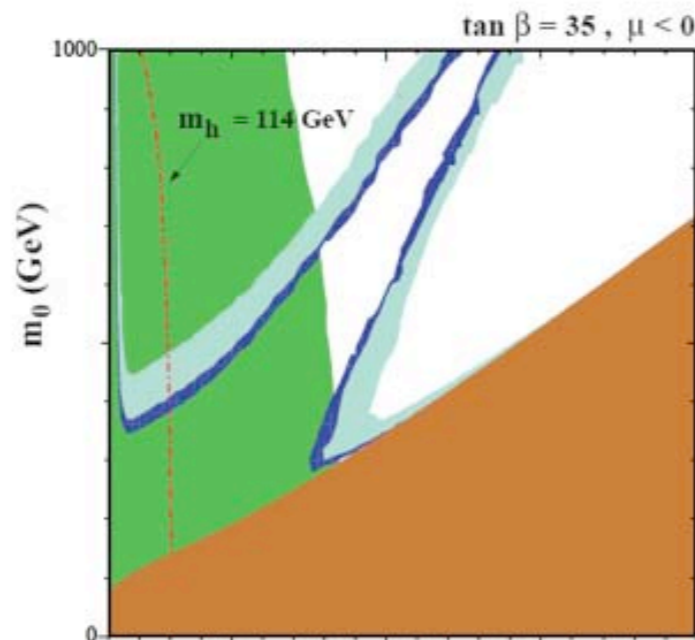
The relic density paradigm

$$\langle\sigma v\rangle = \frac{3 \cdot 10^{-27} \text{ cm}^3 / \text{s}}{\Omega_{\text{dm}} h^2}$$

The so-called Bulk region



Small strip due to e.g. coannihilations



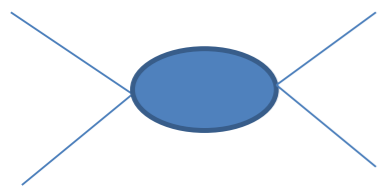
The CMSSM parameter space is being more and more reduced

The relic density paradigm revived

$$\frac{dn_1}{dt} = -3Hn_1 - \langle\sigma v\rangle_{ann}(n_1^2 - n_{1,0}^2) - \langle\sigma v\rangle_{coa}(n_1 n_2 - n_{1,0} n_{2,0})$$

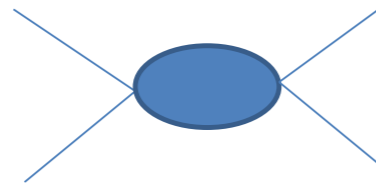
$$\frac{dn_2}{dt} = -3Hn_2 - \langle\sigma v\rangle_{ann}(n_2^2 - n_{2,0}^2) - \langle\sigma v\rangle_{coa}(n_1 n_2 - n_{1,0} n_{2,0})$$

DM = Lightest particle



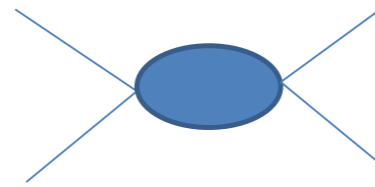
DM

Next to Lightest particle

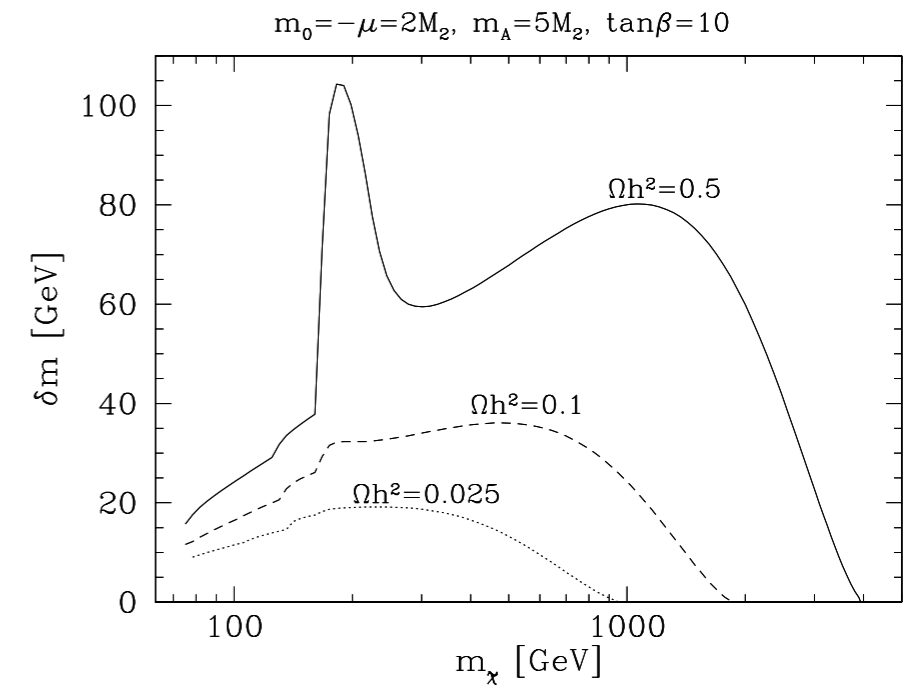


NLSP: Next to lightest

DM



NLSP



$$\frac{\Gamma_{ann}}{\Gamma_{coann}} = \frac{\langle\sigma v\rangle_{ann}}{\langle\sigma v\rangle_{coa}} \frac{n_1}{n_2}$$

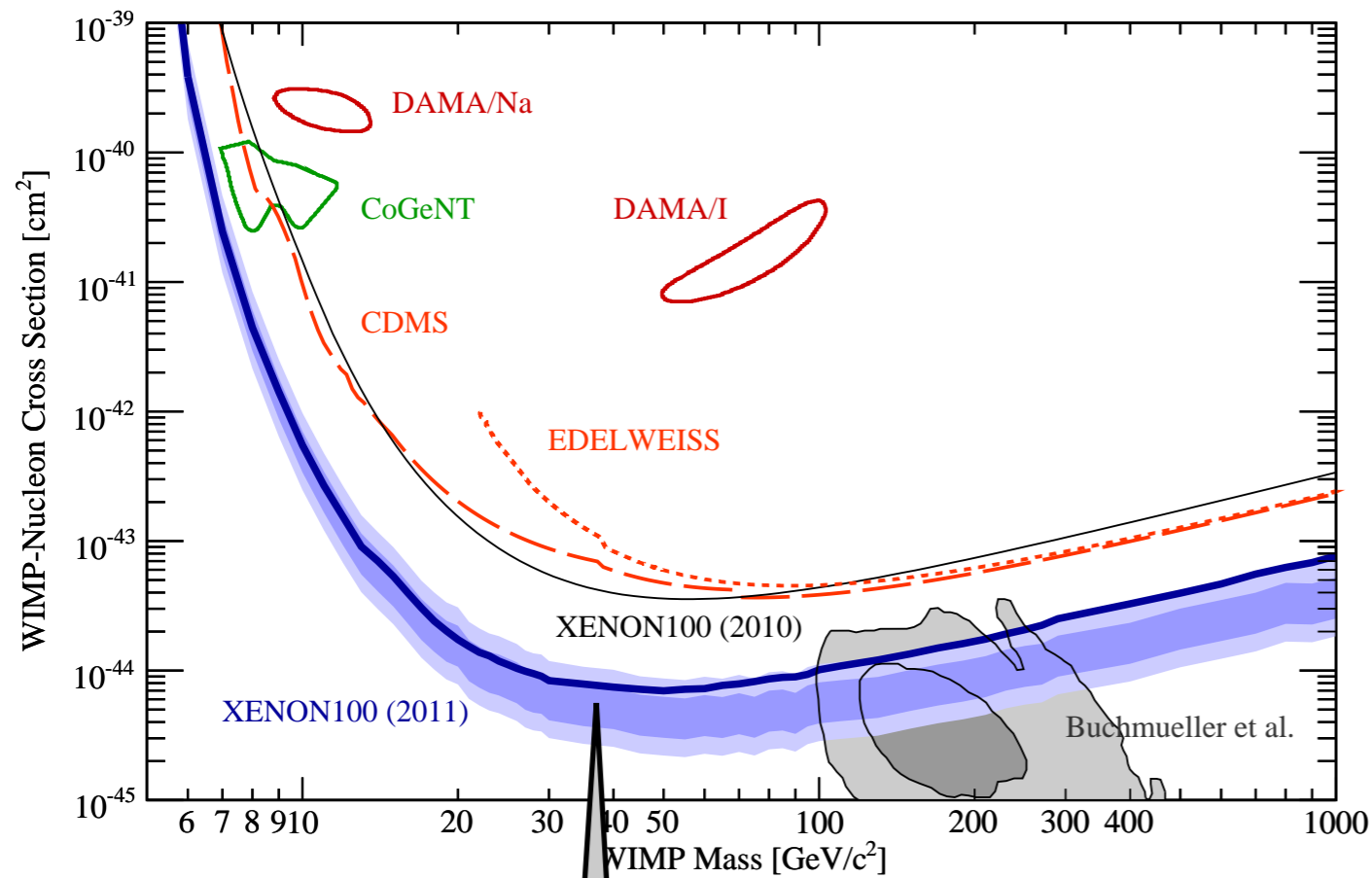
$$= \frac{\langle\sigma v\rangle_{ann}}{\langle\sigma v\rangle_{coa}} \frac{m_{d_1}}{m_{d_2}} e^{-\beta(m_{d_2} - m_{d_1})}$$

And, on top of coannihilations, there are focus points and Higgs resonance

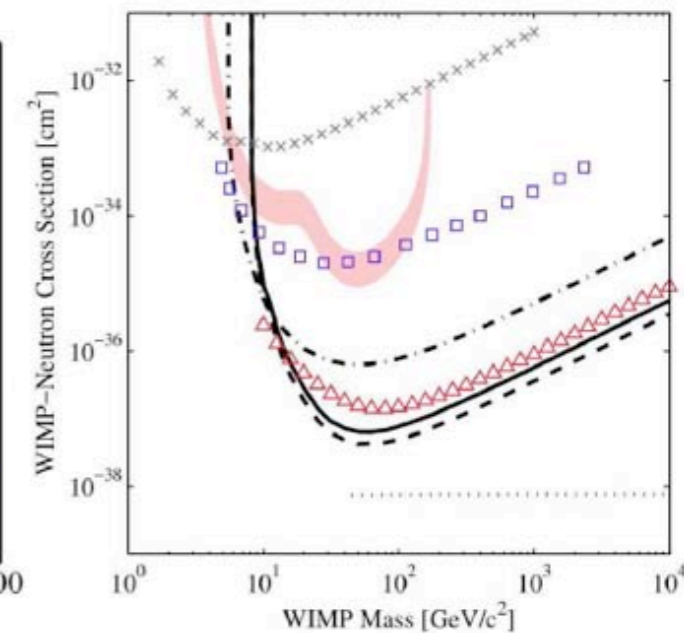
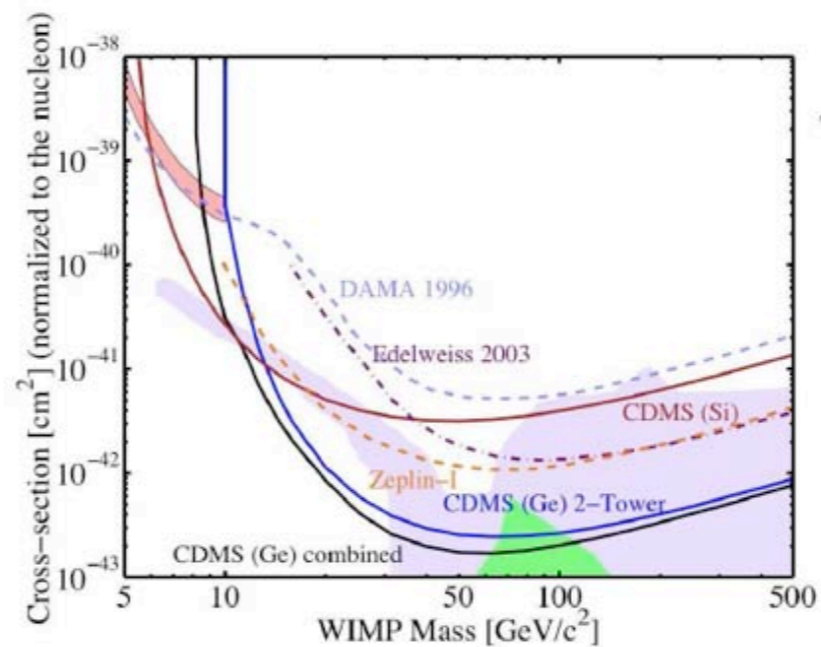
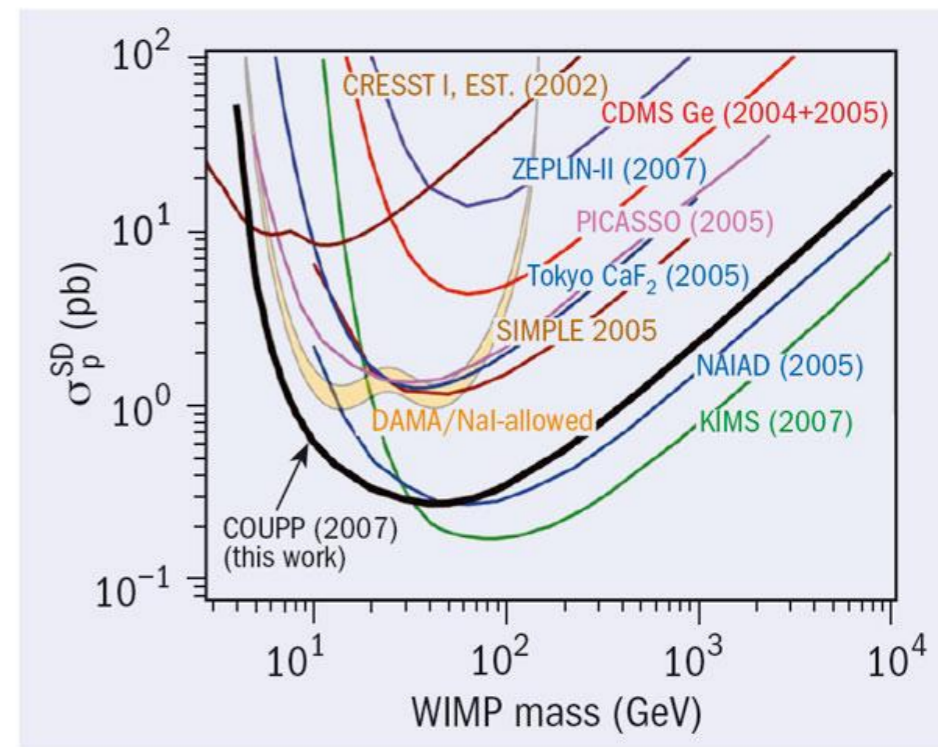
These open up the parameter space again!

Strength of interactions questioned

Plethora of experiments but ...



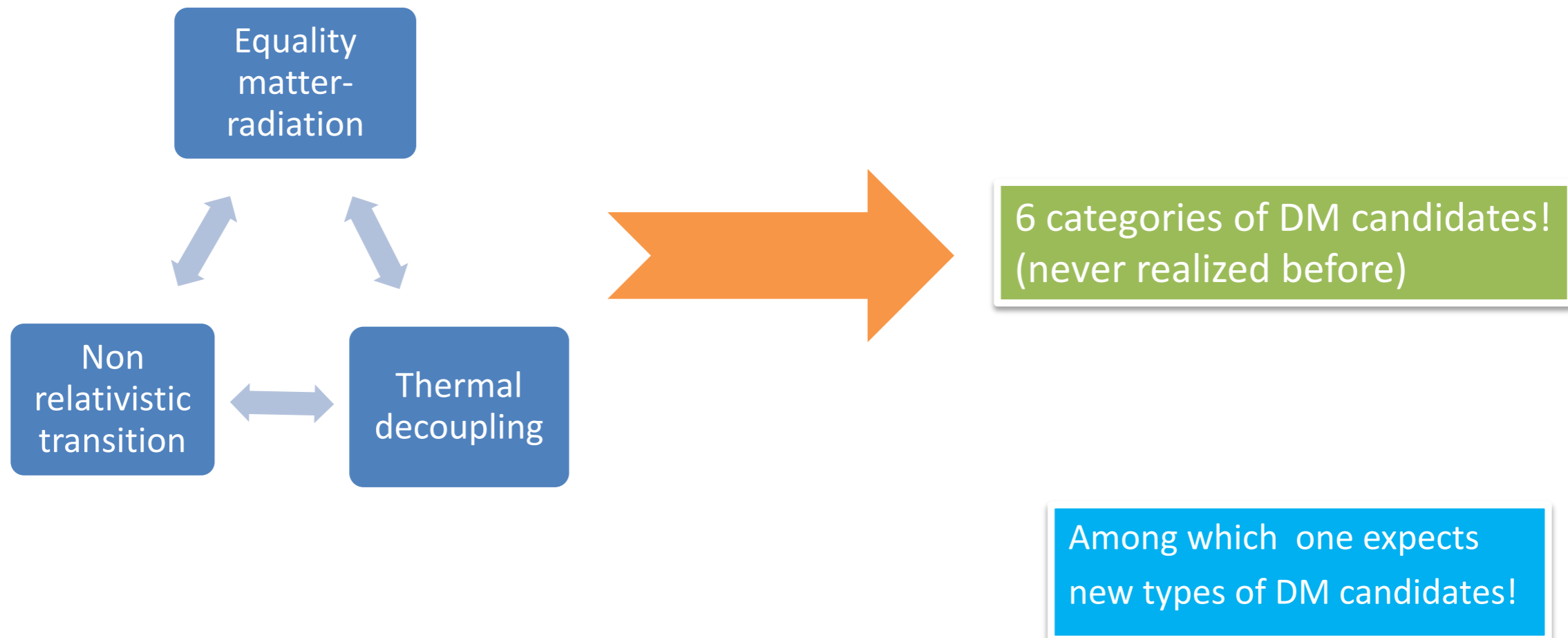
less than
neutrino-e interactions at 1 MeV
I think this tells a lot!



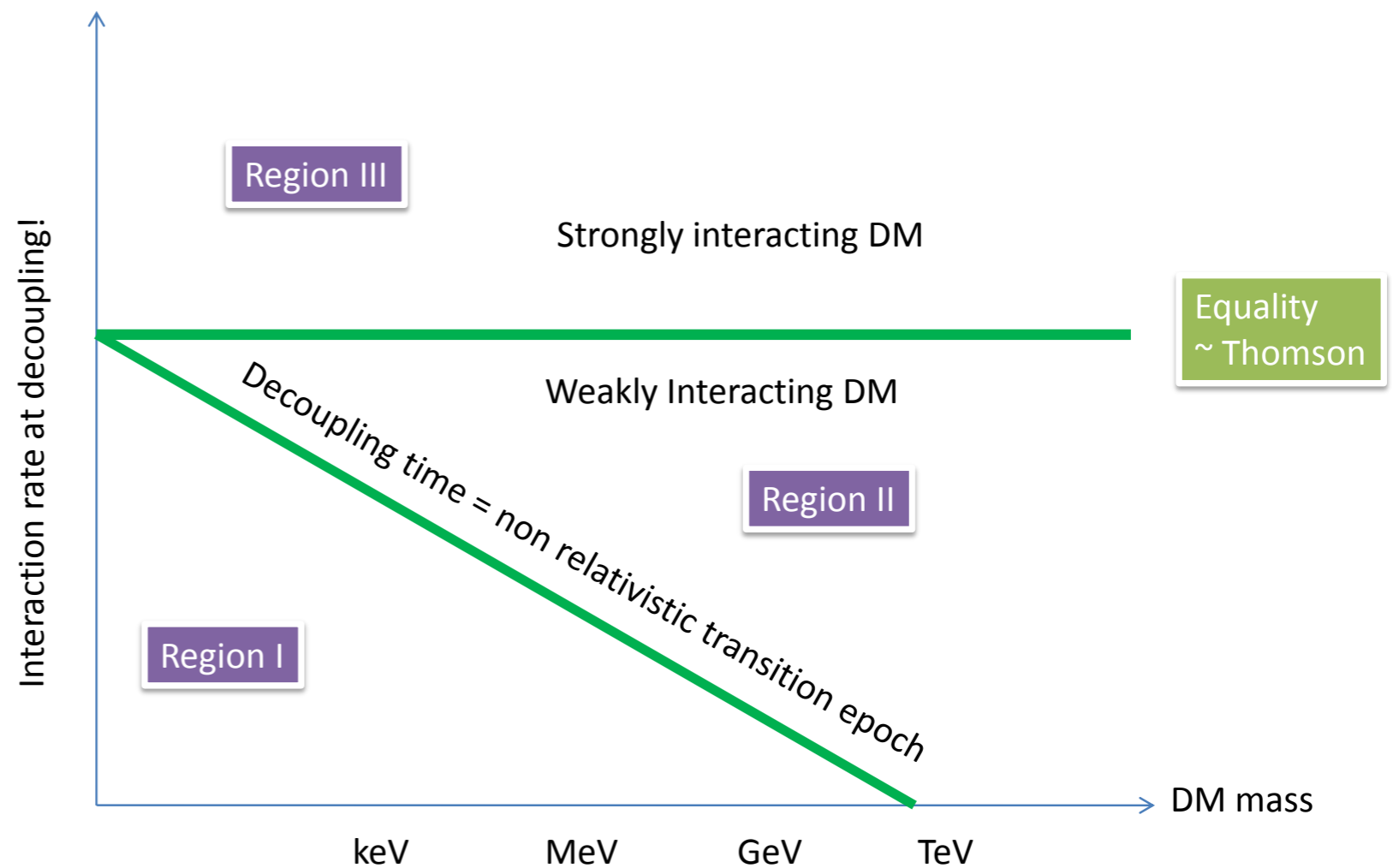
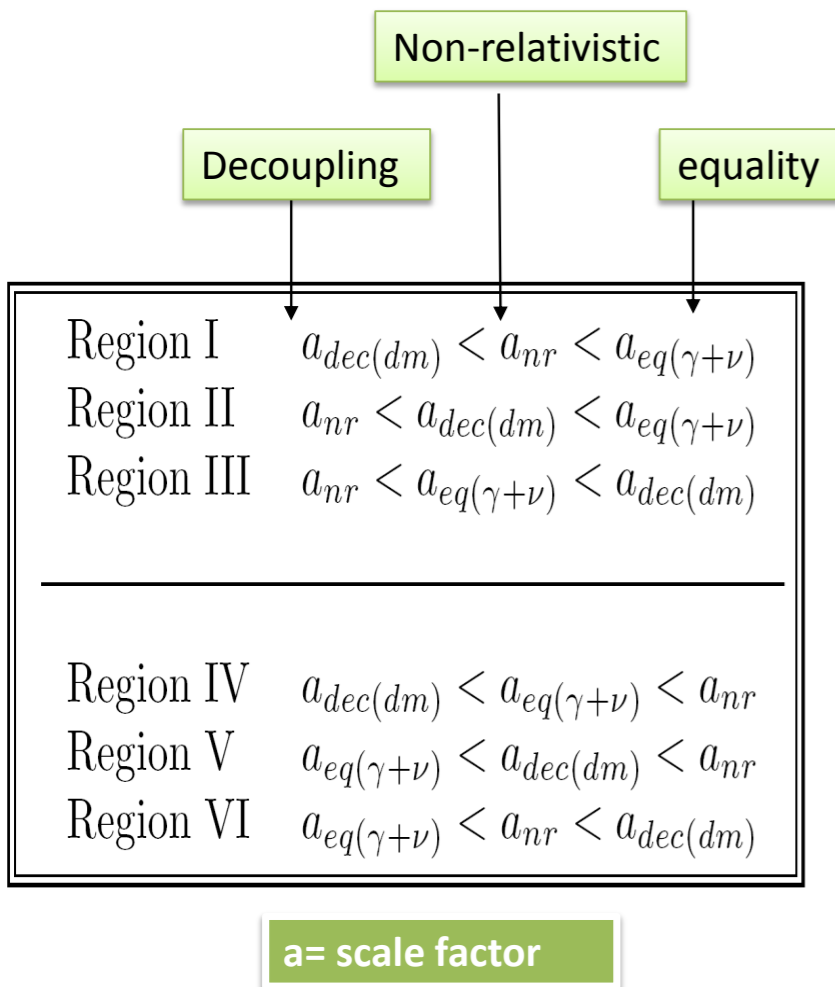
And, in fact, one should question the strength of interactions

- * DM particles must have a mass
- * DM particles must have interactions
- * DM particles experience the thermal history of the Universe

- ✿ mass = non relativistic transition time
- ✿ interactions = decoupling time
- ✿ thermal history = equality time



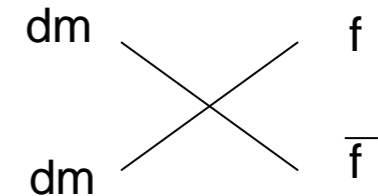
Let us question the strength of interactions



The mass limit dogma

Hut-Lee&Weinberg (massive neutrinos):

$$\sigma v \propto \frac{m_{dm}^2}{m_w^4}$$



general assumptions

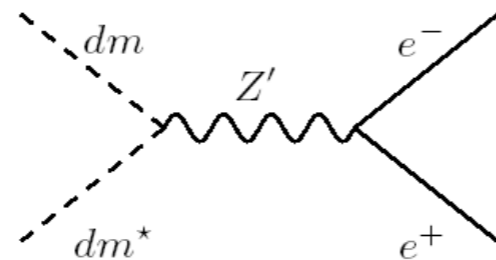
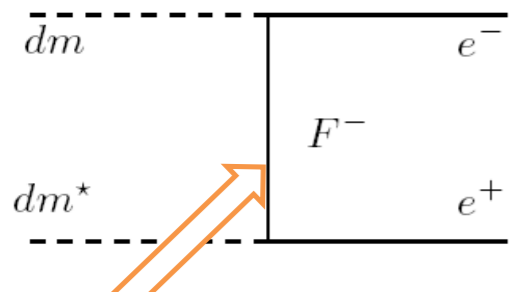
- ❖ DM is a fermion
- ❖ A heavy particle is exchanged

$$\sigma v \propto \frac{m_{dm}^2}{m_F^4} = 3 \cdot 10^{-26} \text{ cm}^3/\text{s}$$

Hence

$$m_{dm} > O(1)\text{GeV}$$

The mass limit dogma



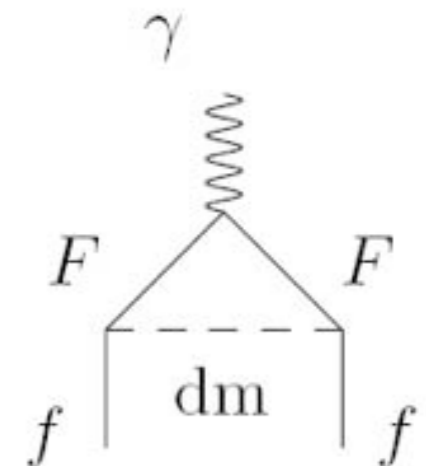
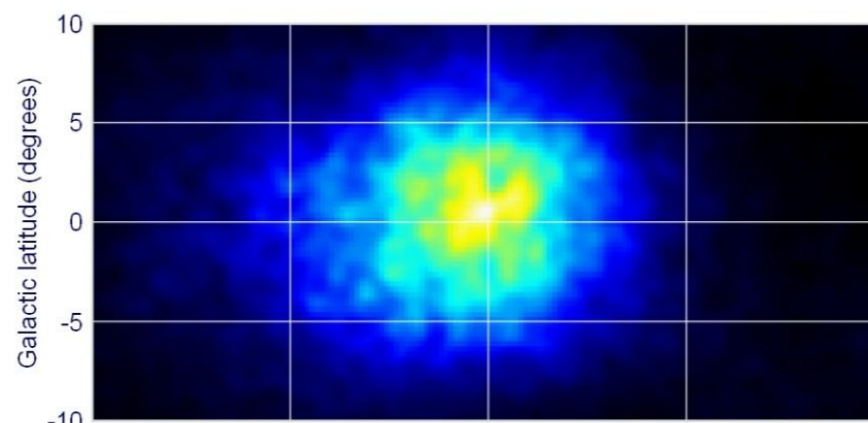
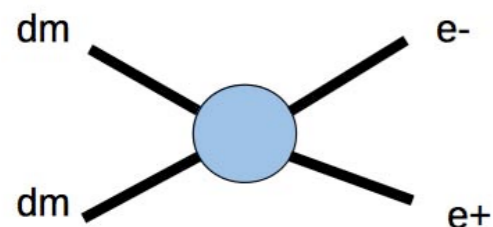
$$\sigma v \propto \frac{1}{m_F^2} = 3 \cdot 10^{-26} \text{ cm}^3/\text{s}$$

m_{dm} is not constrained!

Exceptions to Hut-Lee&Weinberg are possible
Annihilating DM can be lighter than 10 GeV
 In fact, it can be as light as a few keV...

But direct detection experiments cannot easily go down 10 GeV

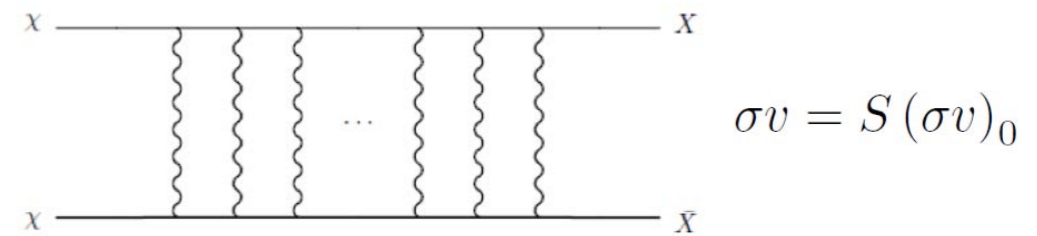
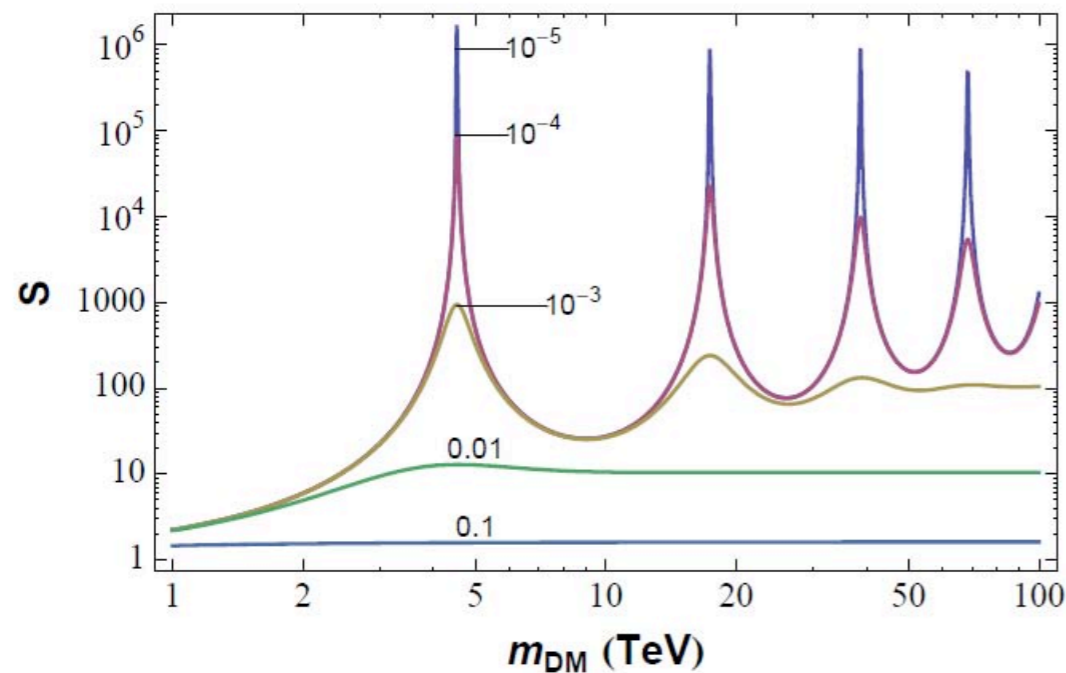
Note that MeV DM could also be interesting (cf 511 keV line)!



The thermal hypothesis questioned?

- Interests for keV (non thermal) sterile neutrinos
- FI mechanism
- Sommerfeld enhancement

Pamela requires larger cross sections than the canonical value!



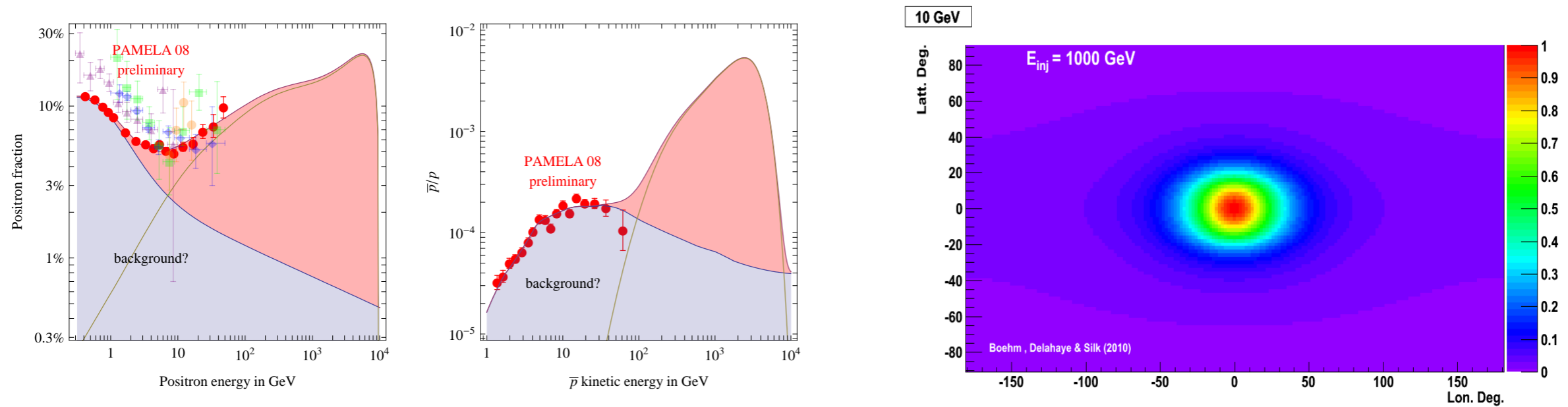
$$d\psi/dr = im\beta\psi$$

$$\frac{1}{m} \frac{d^2\psi(r)}{dr^2} - V(r)\psi(r) = -m\beta^2\psi(r)$$

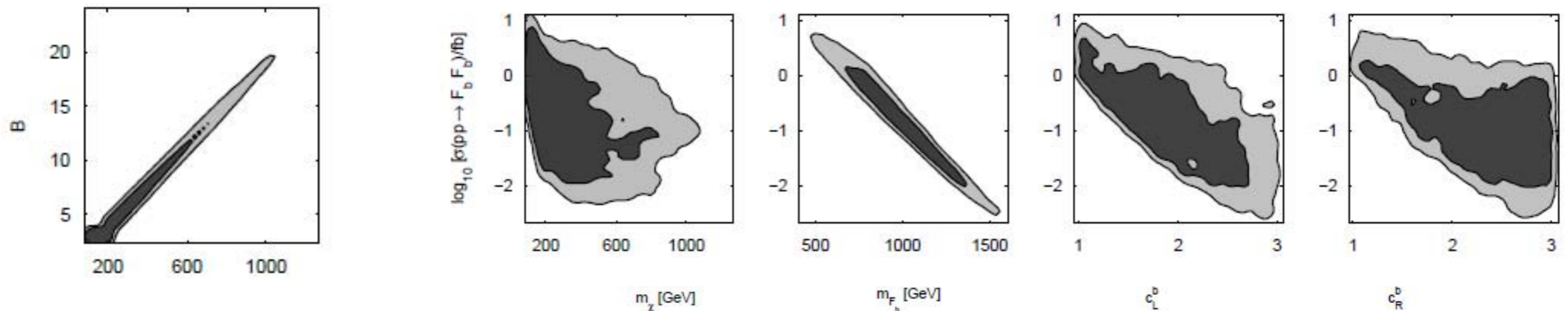
$$-\frac{\alpha}{r} e^{-mvr}$$

The final states of DM annihilations thought again

- Direct Detection based on DM interactions with quarks: **Leptophilic DM could explain the absence of signal!**
- Still a chance to explain PAMELA but FERMI experiment is very constraining!



- Leptophilic maybe ... but not necessarily quarkophobic!

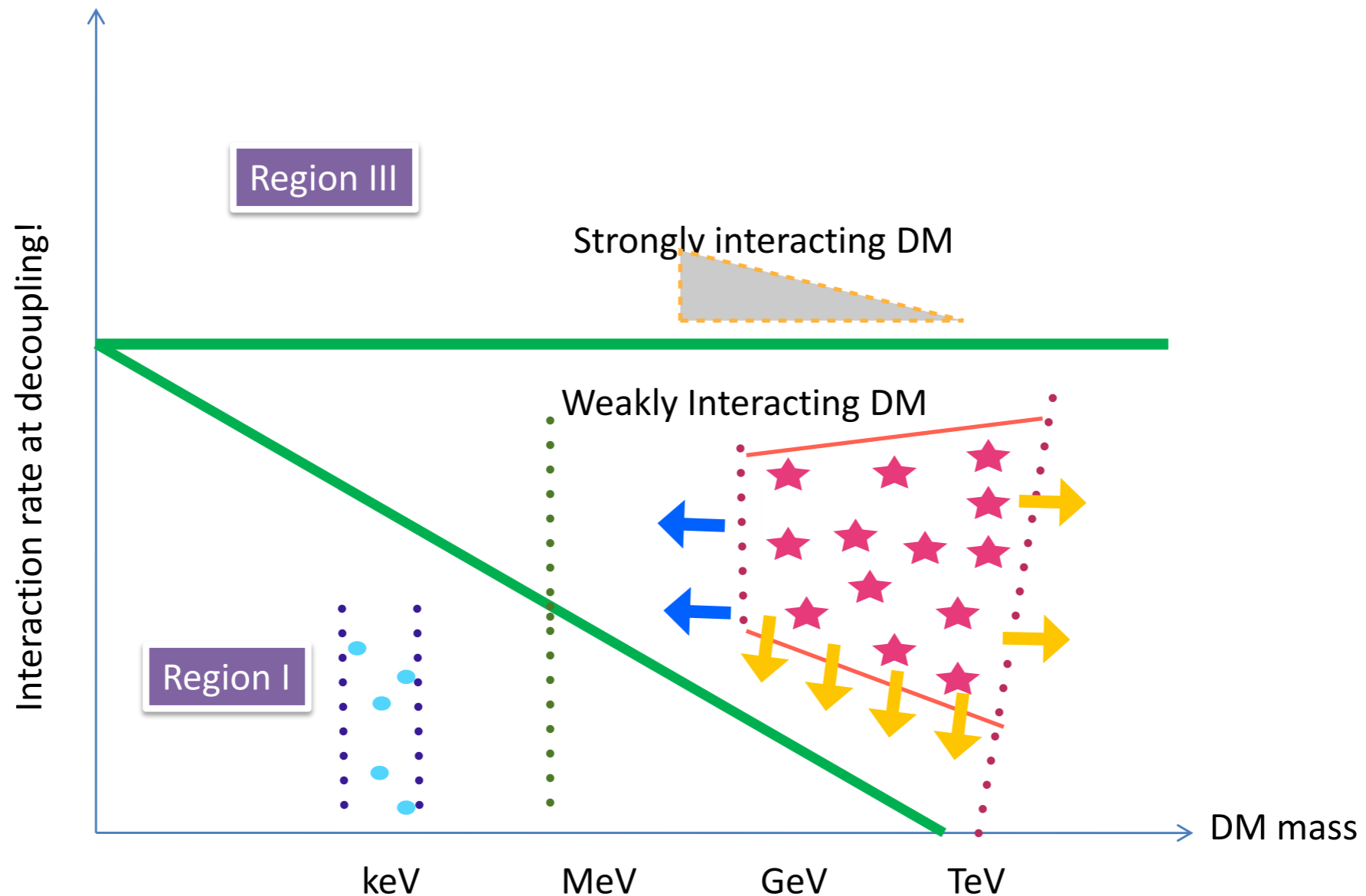


Where are we now?

Time to focus again ...

DM parameter space which has been looked at

Theoretically, we have explored a small region of the parameter space.
Experimentally, we tested an even smaller region
(at least directly) and yet not so many other possibilities in the end...



The Cosmology side

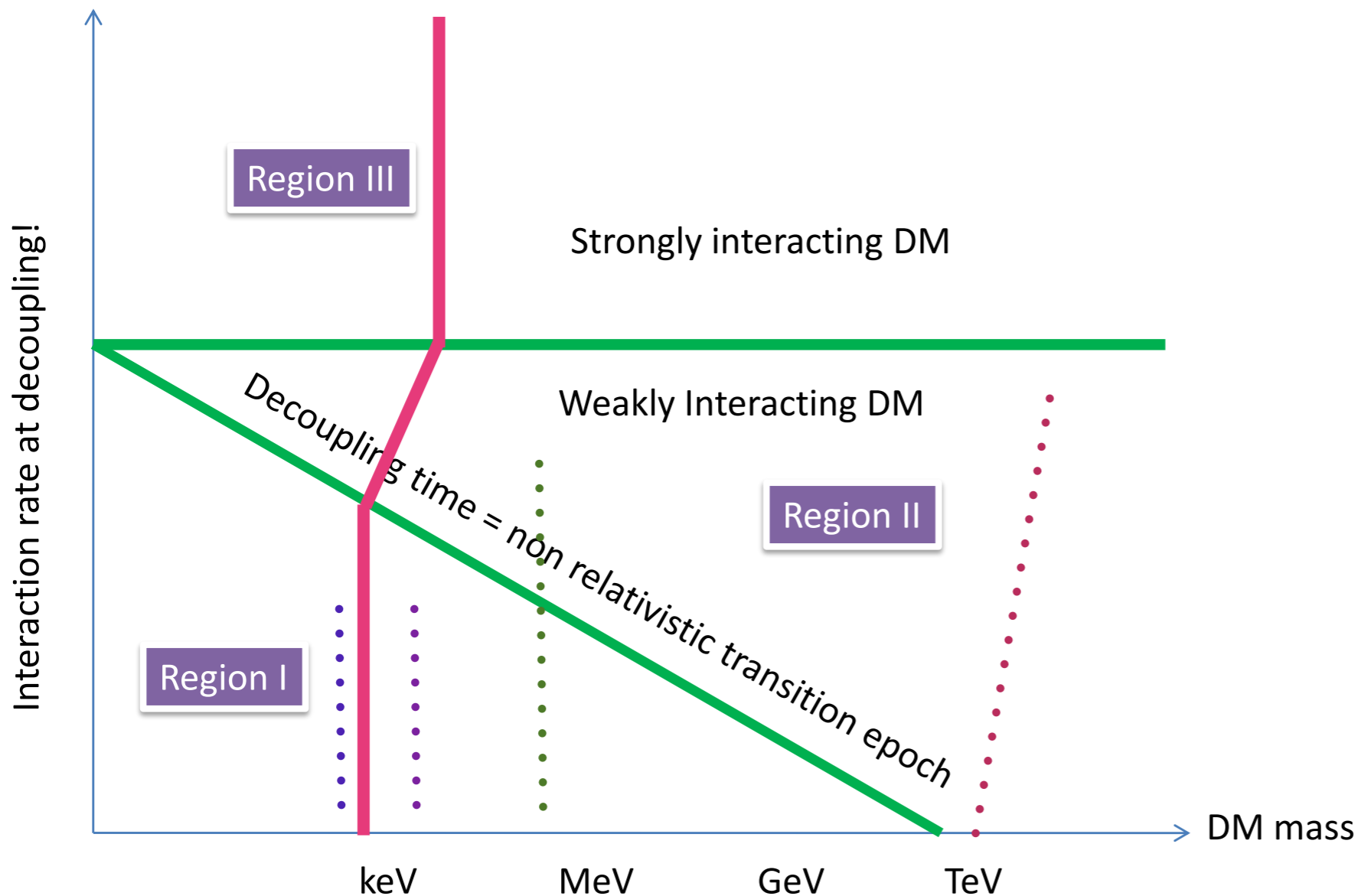
What to expect?

Cosmology can reduce the parameter space further

The sole requirement that the free-streaming length does not exceed the length of the smallest fluctuations needed to survive to explain the formation of objects down to 10^6 Msol cuts part of the parameter space

$$l_{fs(i)} \propto \int_{t_{dec(i)}}^t \frac{v_i dt}{a}$$

The decoupling time is important!!!

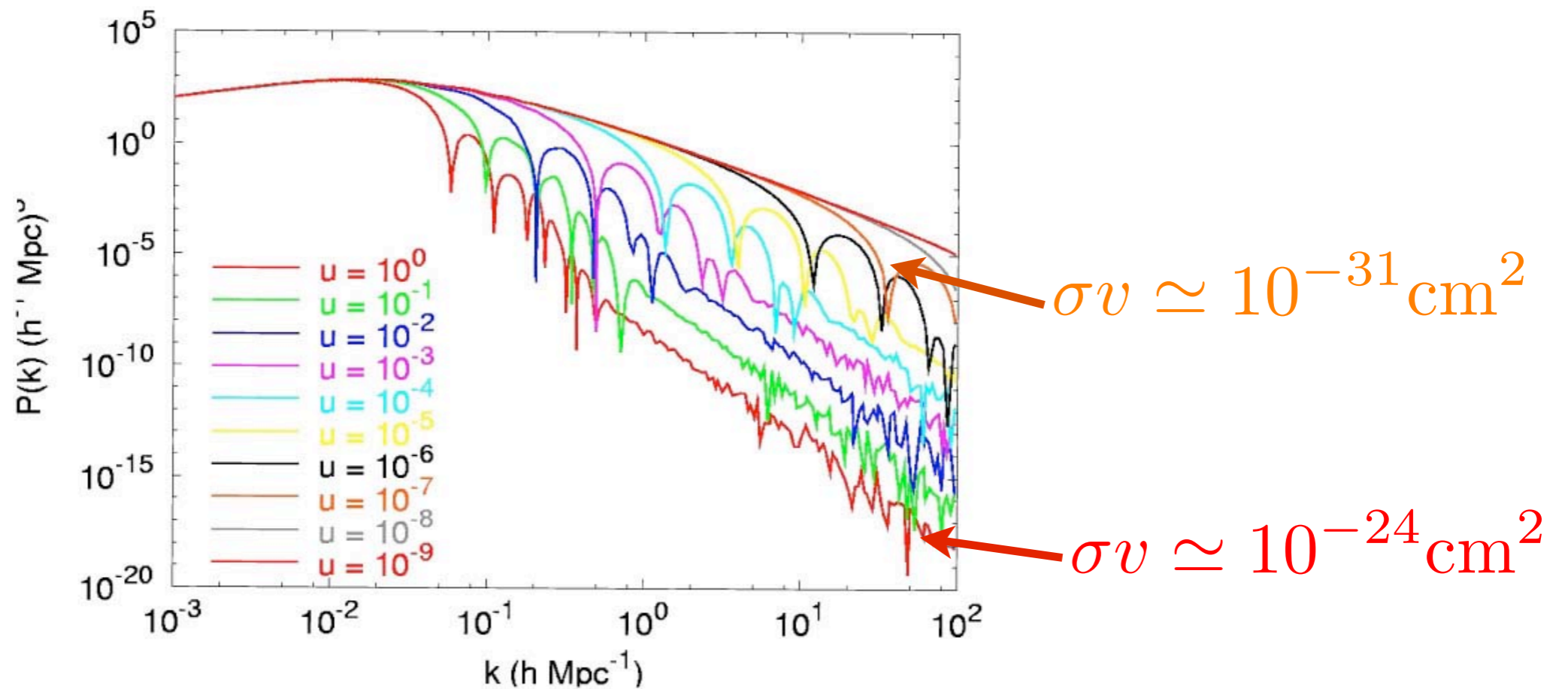


Primordial DM fluctuations are erased if DM freely propagate while still relativistic or so

Cosmology can be even more powerful!

DM interactions cannot be arbitrarily large (even with baryonic matter or themselves, cf self-interactions)

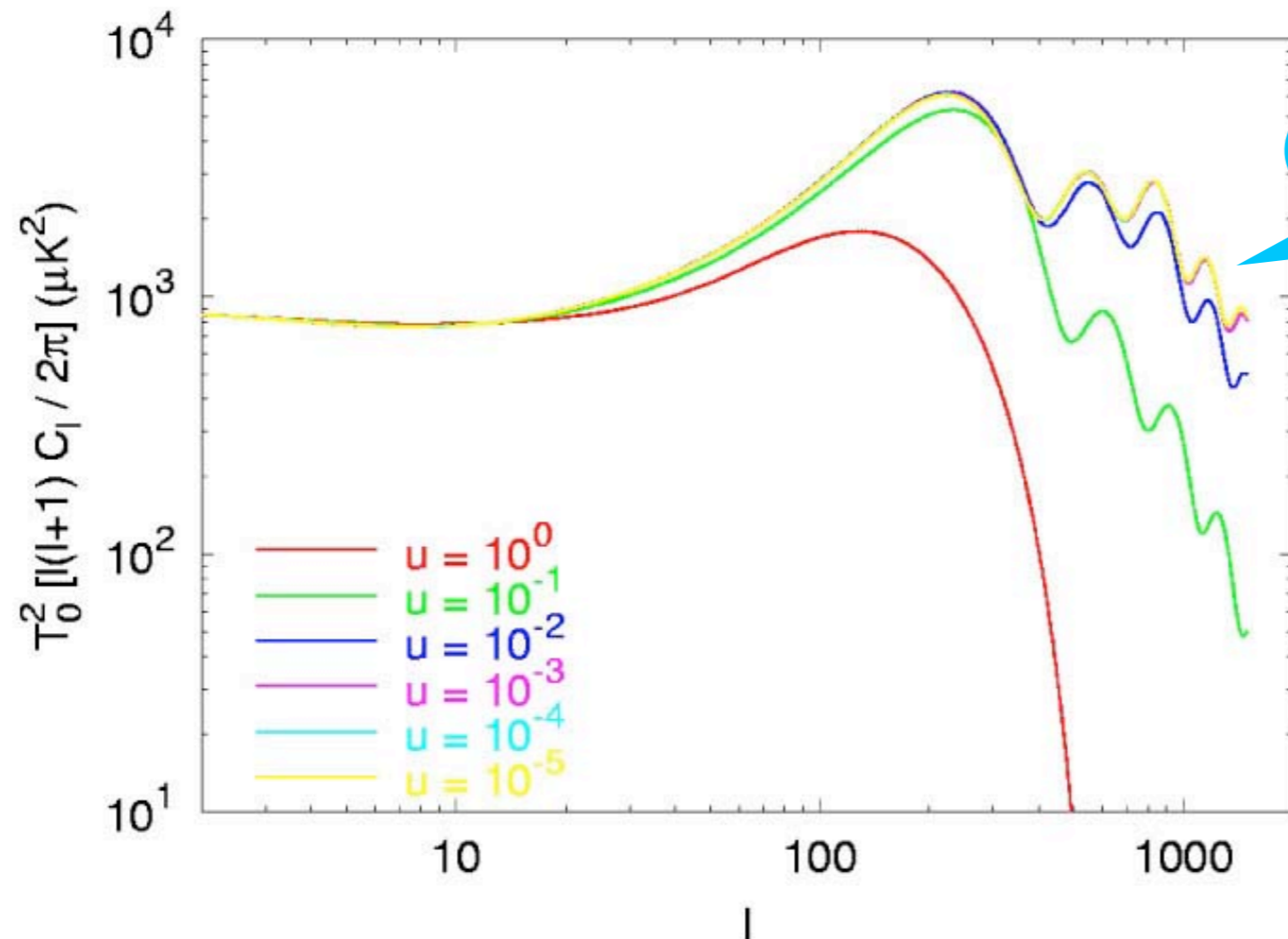
$P(k)$ for DM interactions = $u \cdot \text{Thomson cross section}$



The stronger the interactions, the more pronounced the oscillations

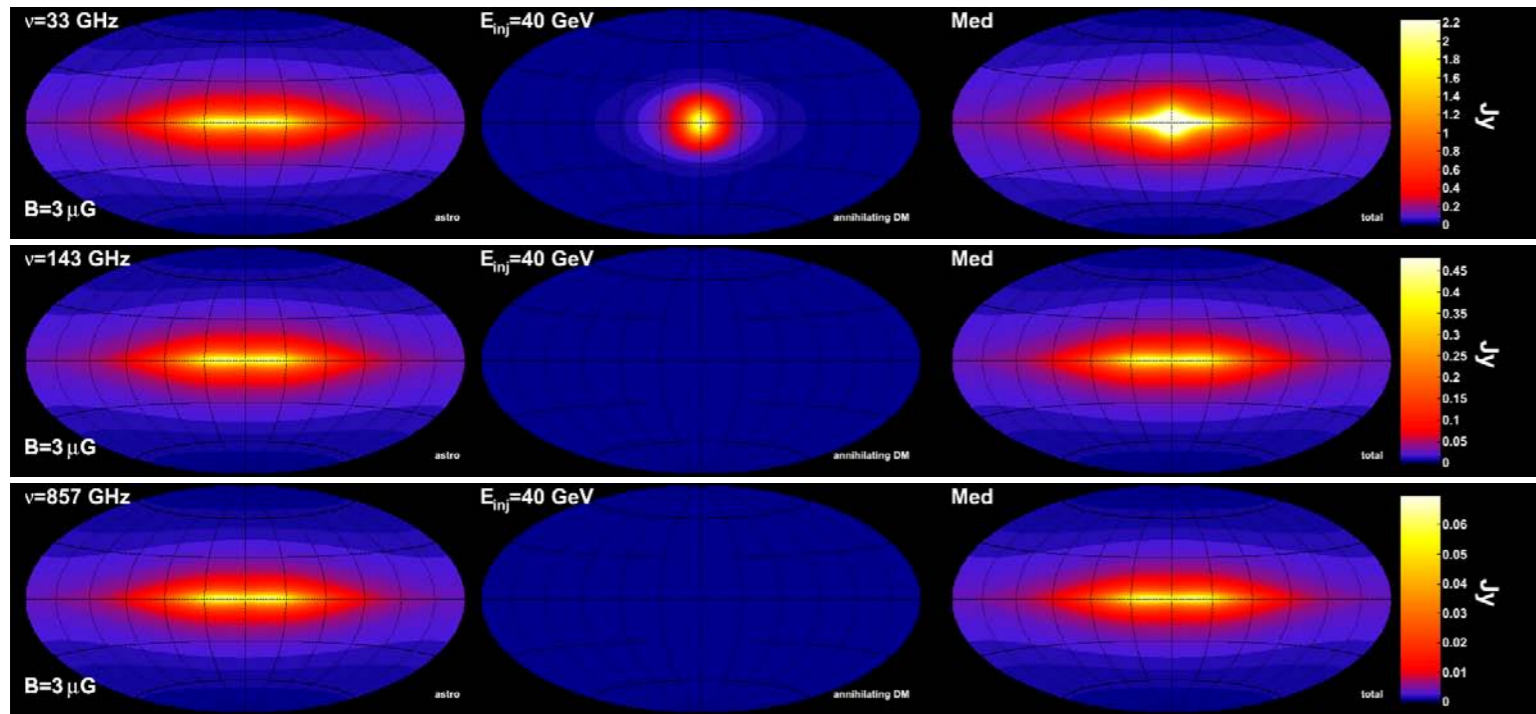
Cosmology can be even more powerful!

Oscillations are a distinctive sign
They should lead to a signature at least
in the Planck Cl

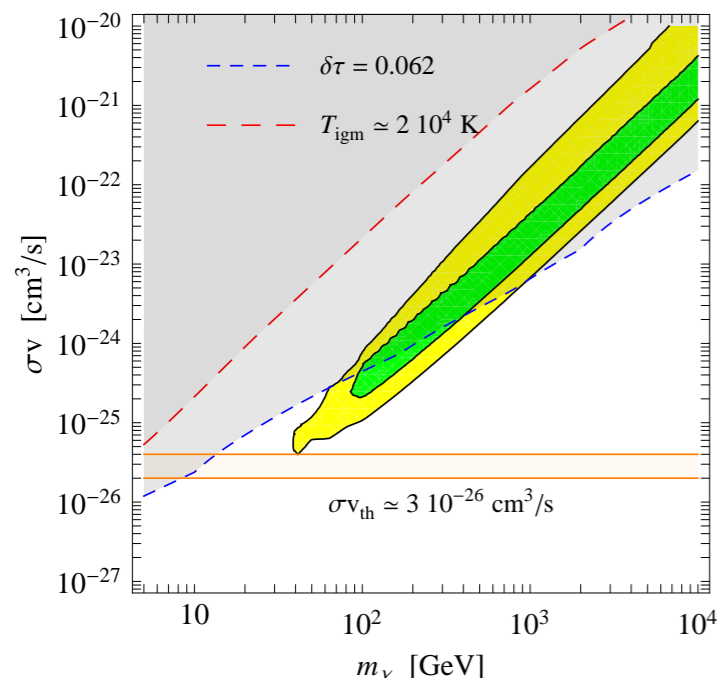


Now time to zoom in!

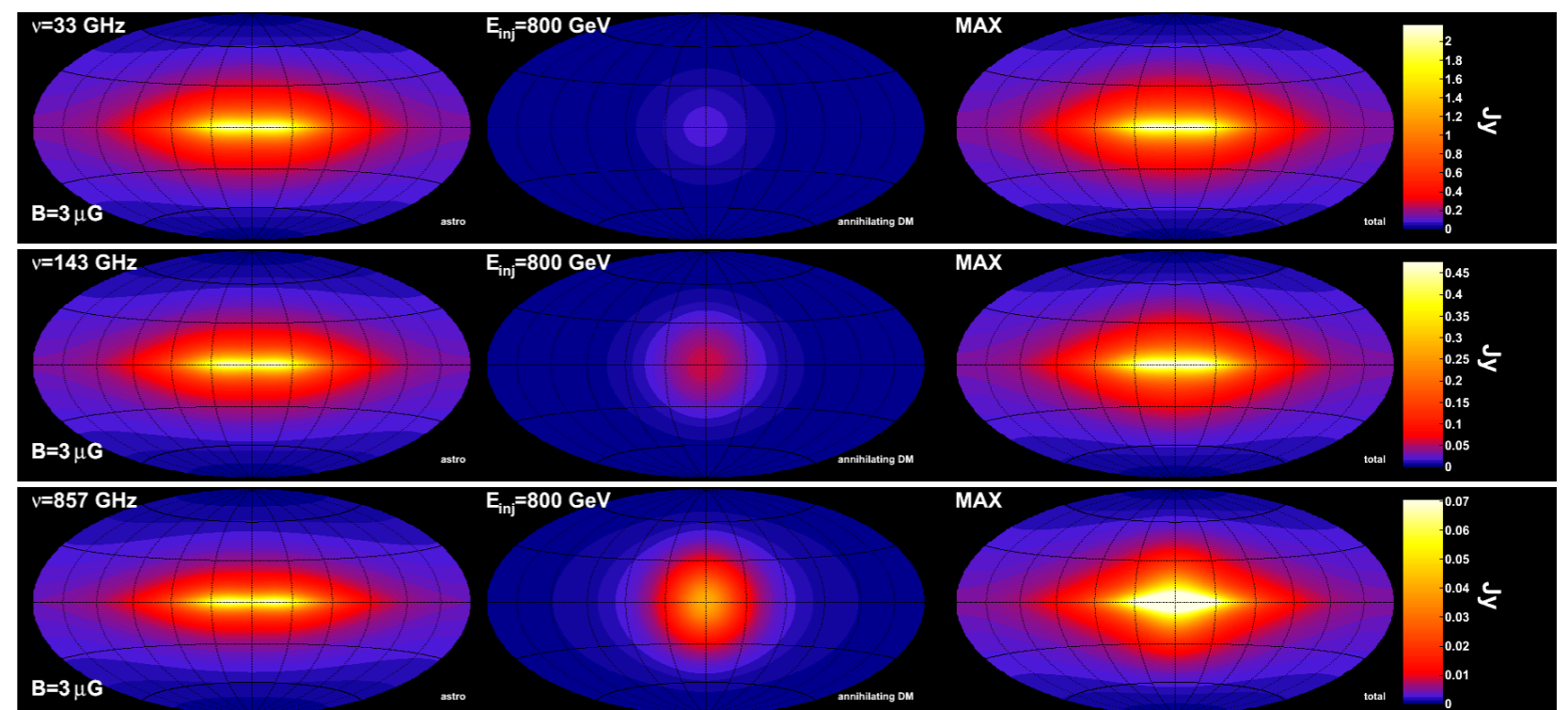
Cosmology can be even more powerful!



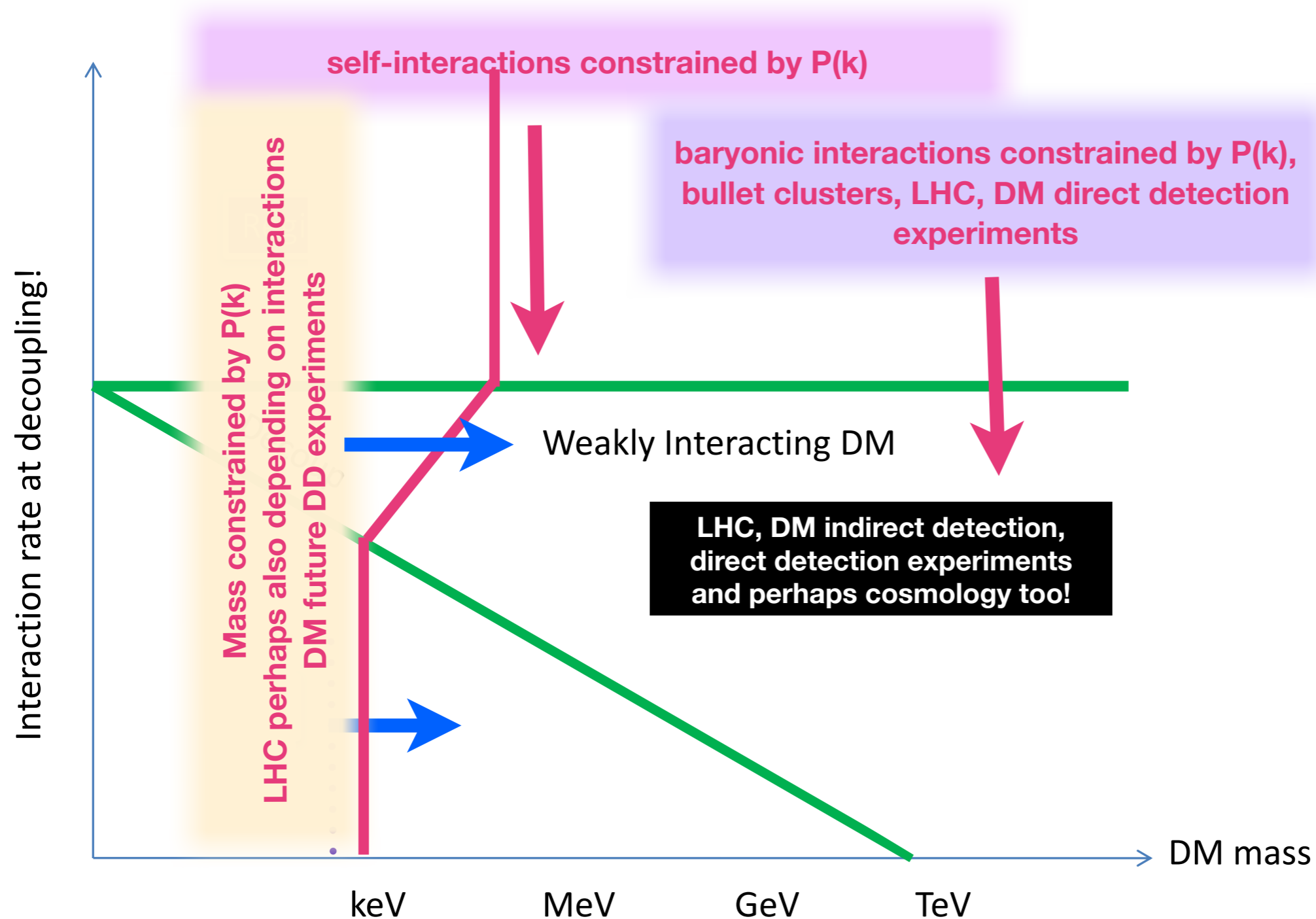
Maybe by exploring the
PLANCK experiment



$\sigma\nu$ [cm^3/c]



Parameter space that should be accessible



Particle and astroparticle physics:

Will there be a discovery?

One important assumption (fact?):

We live in a DM halo!

✿ Direct detection may be possible

DM + Nuclei \rightarrow DM+Nuclei + energy/light/crystal excitation

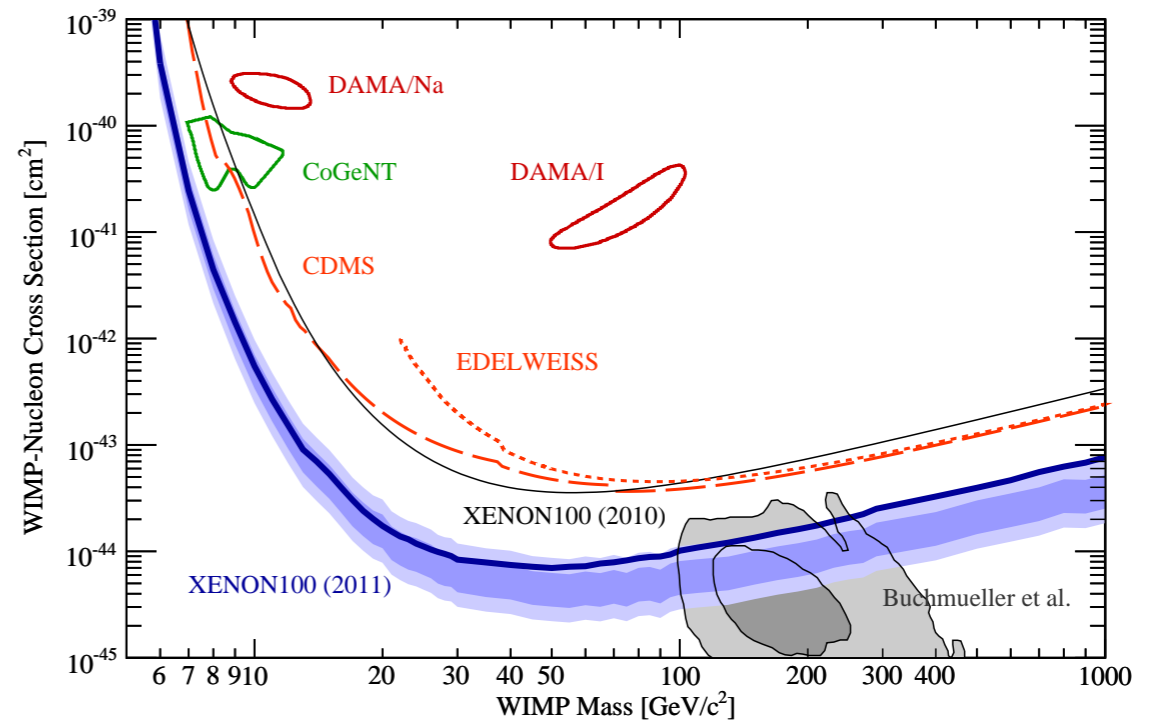
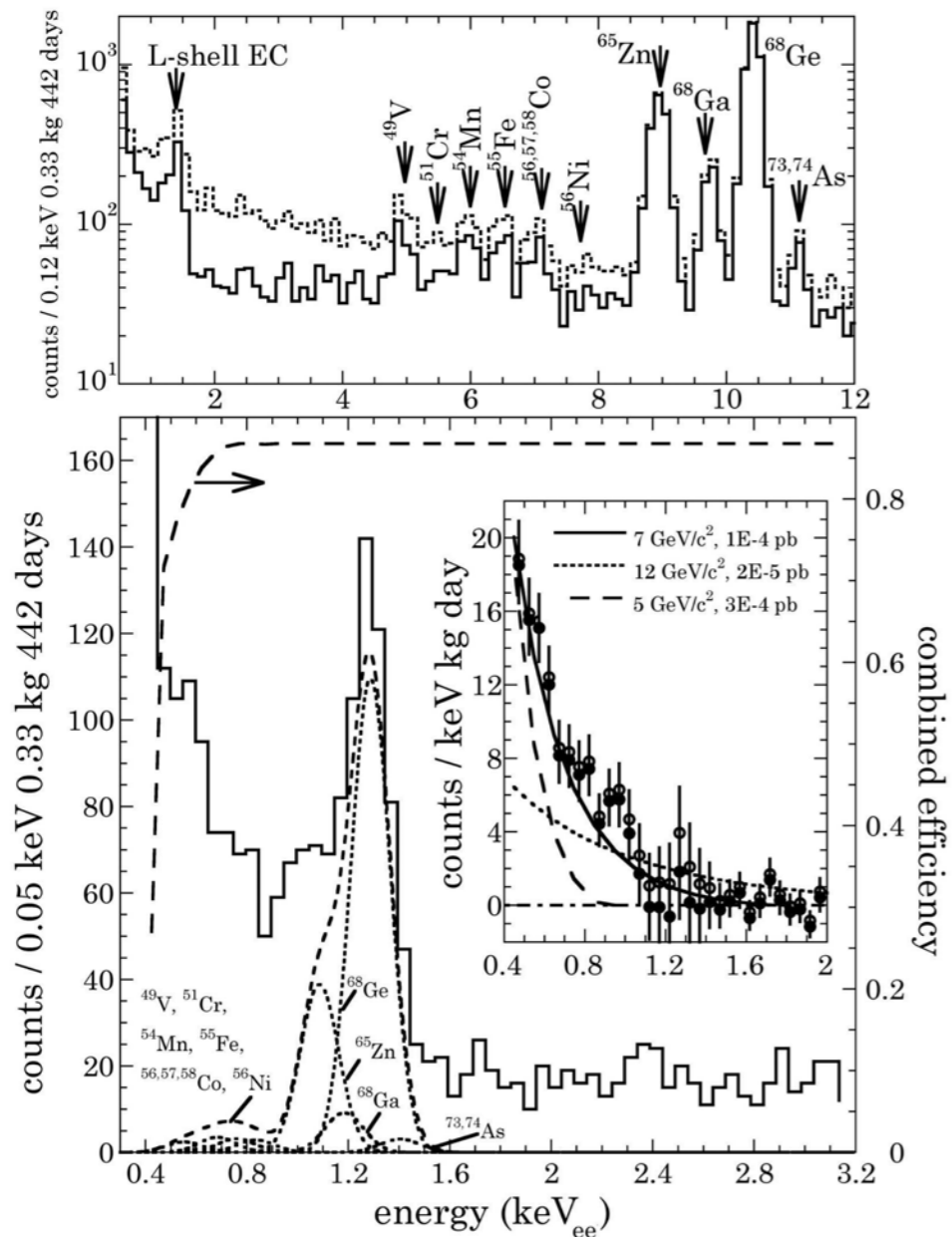
✿ Indirect detection may also occur

DM + DM \rightarrow cosmic rays

DM \rightarrow cosmic rays

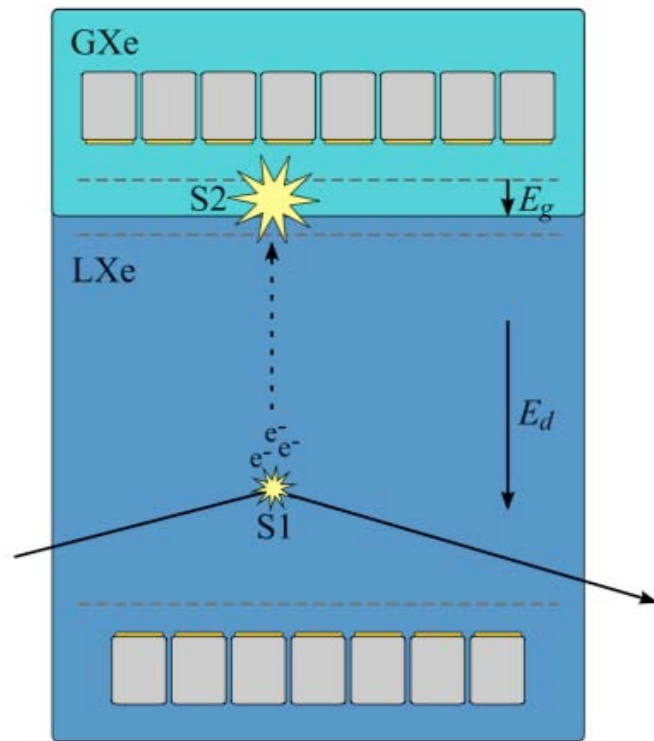
An example Supersymmetric DM: is it still viable?

DM has not been discovered yet but things happened recently

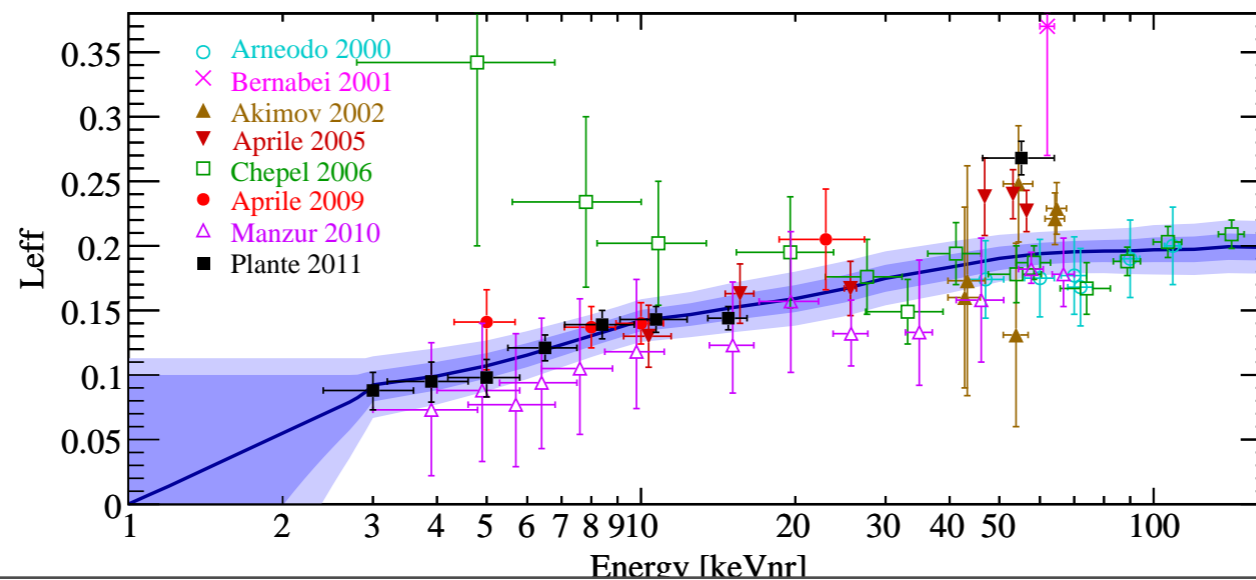
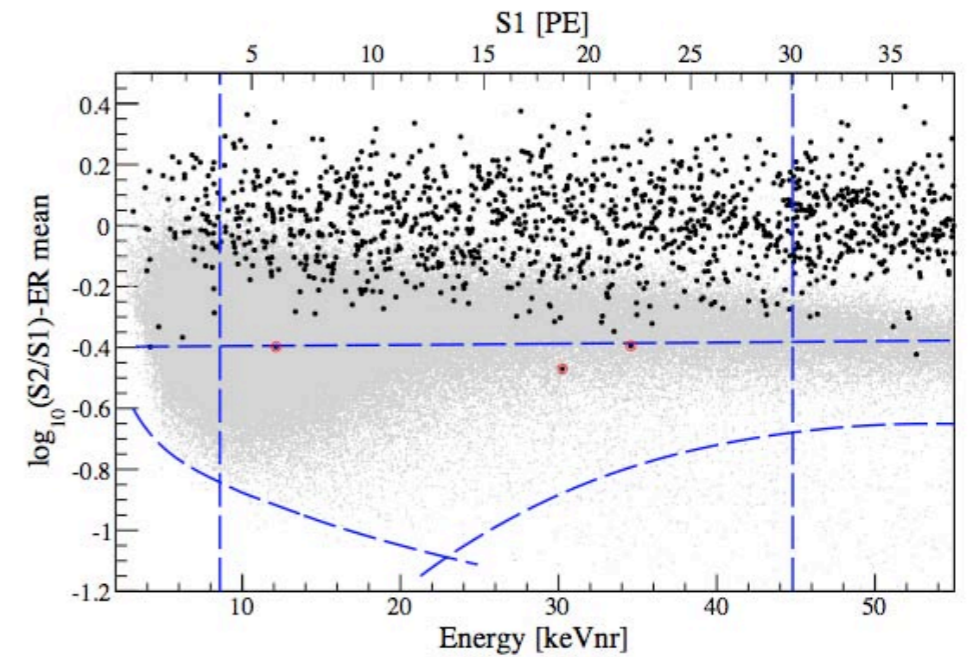
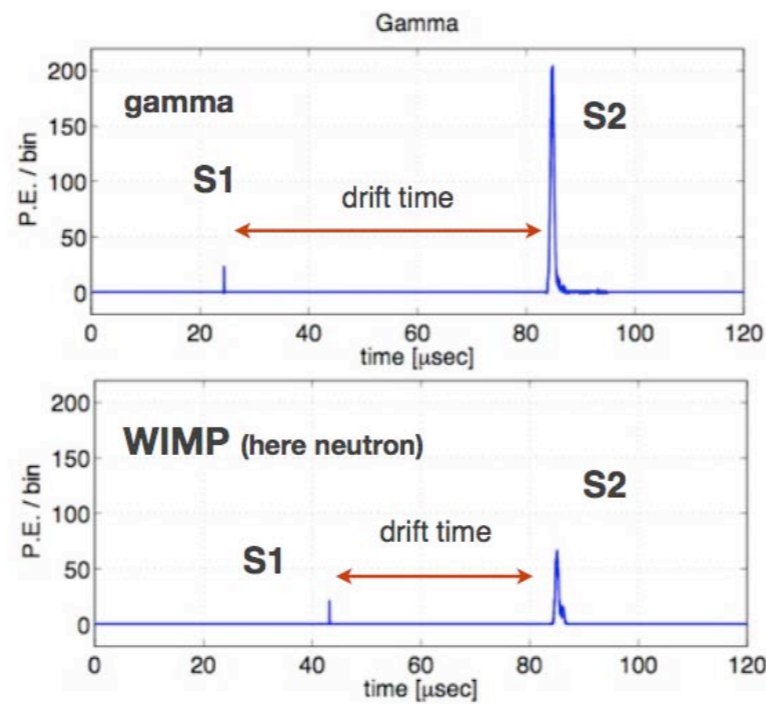


Unfortunately controversy!

Dispute over the low mass range but ...



S2: ionization
S1: scintillation

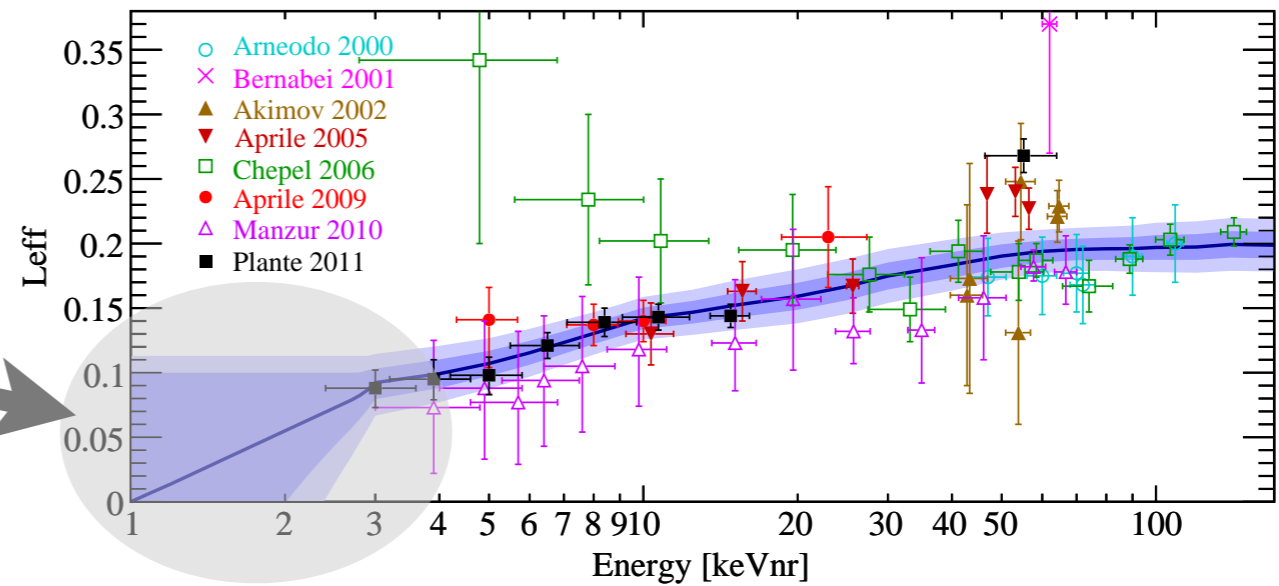
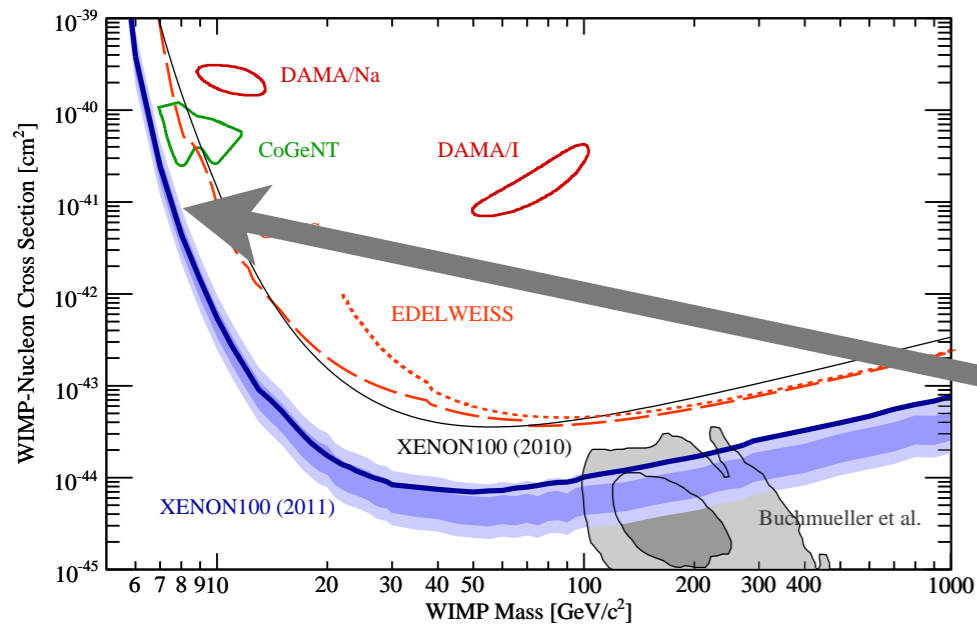


$$E_{nr} = \frac{1}{L_{eff}} \frac{S_1}{L_y} \frac{S_{ee}}{S_{nr}}$$

L_{eff} : scintillation efficiency

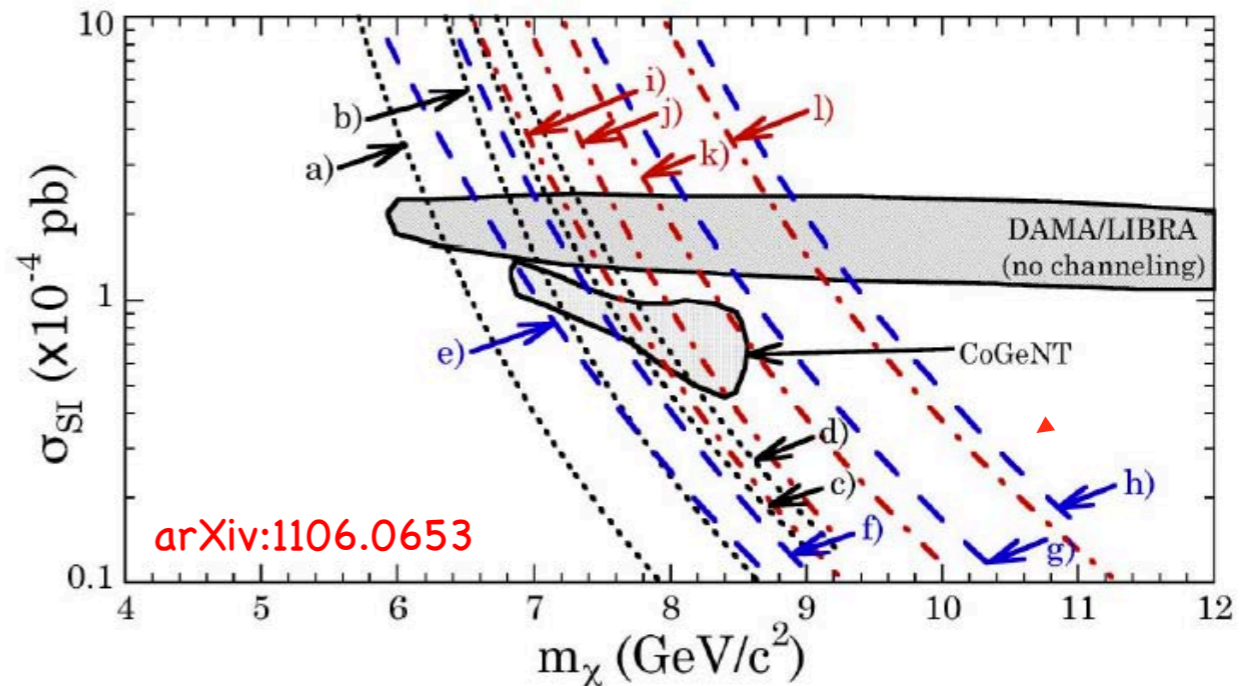
Ionization yield $E_{nr} = \frac{S_2}{L_y}$

We need to use present experiments to help us



* To obtain this curve, XENON100 has assumed no scintillation below 3keVnr!

* The dark blue curve is not the median of the blue region because XENON100 had 3 unidentified events



There are also (astrophysical) uncertainties on the detection rate

Can SUSY DM be still in the game?

At low mass?

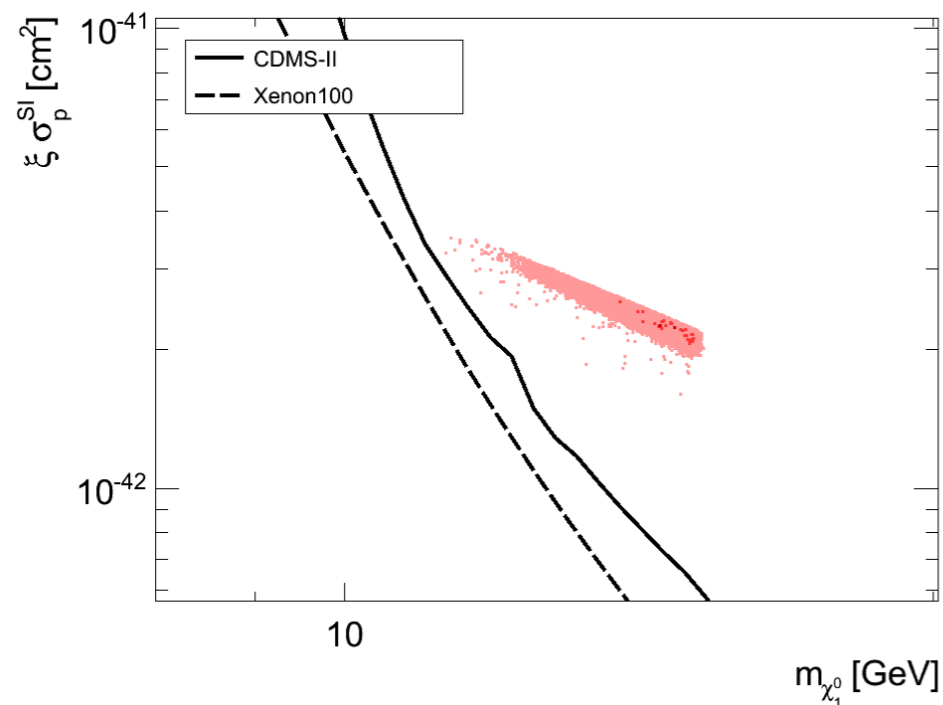


FIG. 3: MSSM-EWSB scenario with $\mu > 0$ and $m_\chi < 15$ GeV. Spin-independent cross section on proton times the fraction of neutralinos in the Milky Way dark halo (ξ) versus the neutralino mass m_χ . The dark red (light pink) points have a likelihood greater than 99.4% (68%).

constraint	value/range	tolerance	applied
Smasses	-	none	both
$\Omega_{WMAP} h^2$	0.01131 - 0.1131	0.0034	both
$(g-2)_\mu$	$25.5 \cdot 10^{-10}$	stat: $6.3 \cdot 10^{-10}$ sys: $4.9 \cdot 10^{-10}$	both
$\Delta\rho$	≤ 0.002	0.0001	MSSM
$b \rightarrow s\gamma$	$3.52 \cdot 10^{-4}$ [38, 39]	th: $0.24 \cdot 10^{-4}$ exp: $0.23 \cdot 10^{-4}$	both
$B_s \rightarrow \mu^+ \mu^-$	$\leq 4.7 \cdot 10^{-8}$	$4.7 \cdot 10^{-10}$	both
$R(B \rightarrow \tau\nu)$	1.28 [38]	0.38	both
m_H	≥ 114.4	1%	MSSM
$Z \rightarrow \chi_1 \chi_1$	≤ 1.7 MeV	0.3 MeV none	MSSM NMSSM
$e^+ e^- \rightarrow \chi_1 \chi_{2,3}$	≤ 0.1 pb [40]	0.001 pb none	MSSM NMSSM
ΔM_s	$117.0 \cdot 10^{-13}$ GeV	th: $21.1 \cdot 10^{-13}$ GeV exp: $0.8 \cdot 10^{-13}$ GeV	NMSSM
ΔM_d	$3.337 \cdot 10^{-13}$ GeV	th: $1.251 \cdot 10^{-13}$ GeV exp: $0.033 \cdot 10^{-13}$ GeV	NMSSM

Light MSSM neutralinos are out...

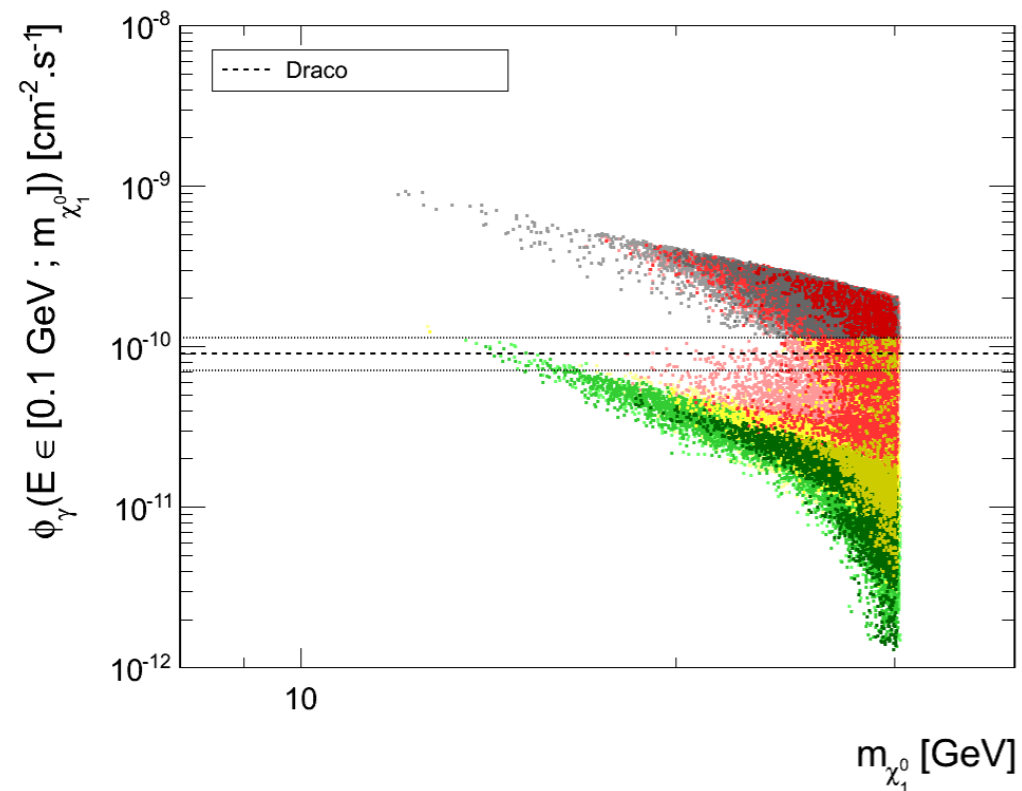


FIG. 5: Integrated γ -ray flux from the Draco dwarf spheroidal galaxy as a function of the neutralino mass in the $m_{\chi_1^0} < 30$ GeV search. We show limits from Fermi-LAT. Same color code as Fig. 4.

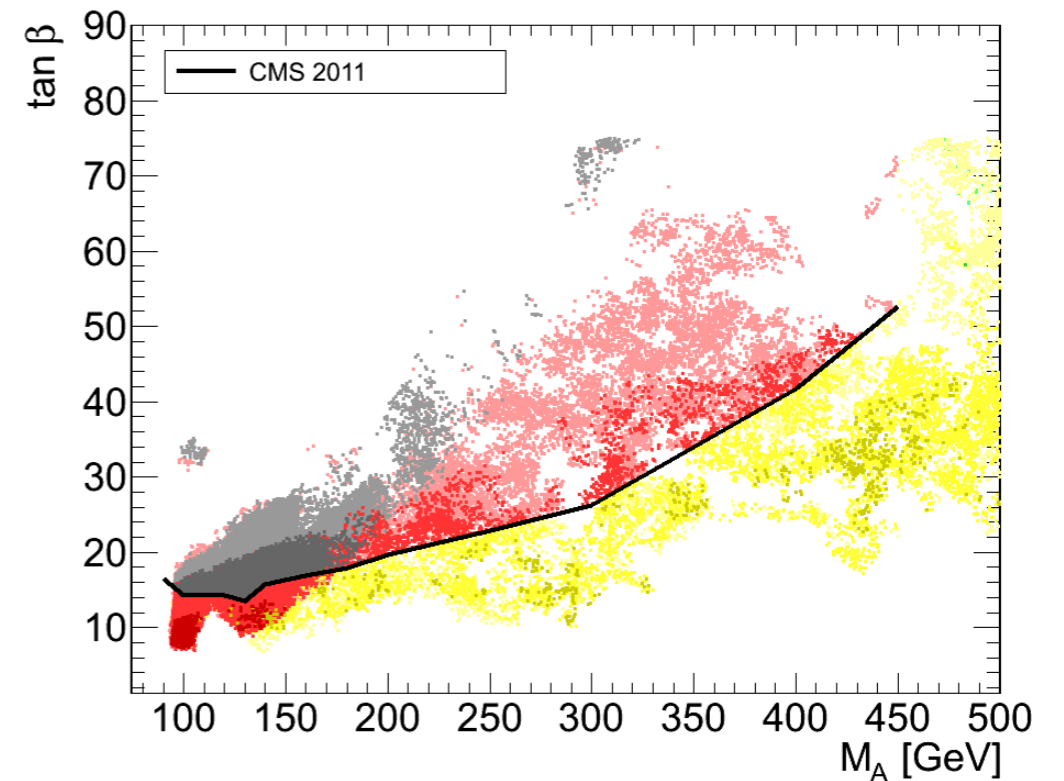


FIG. 2: Allowed points in the $\tan\beta$ vs. M_A plane in the $m_{\chi_1^0} < 30$ GeV search. We show only the region where $M_A < 500$ GeV. The exclusion limit from CMS is also displayed. In yellow (red), points excluded by one (two) constraint and in black those excluded by three constraints (CMS, XENON100 and dSph as described in section III A). The shading represents Q : weights of darker points are at most at 1σ from Q_{\max} while the lighter points are at most at 2σ and 3σ .

**LHC + Direct Detection+ Indirect detection:
the perfect gun machine?**

Complementarity of the 3 types of experiments

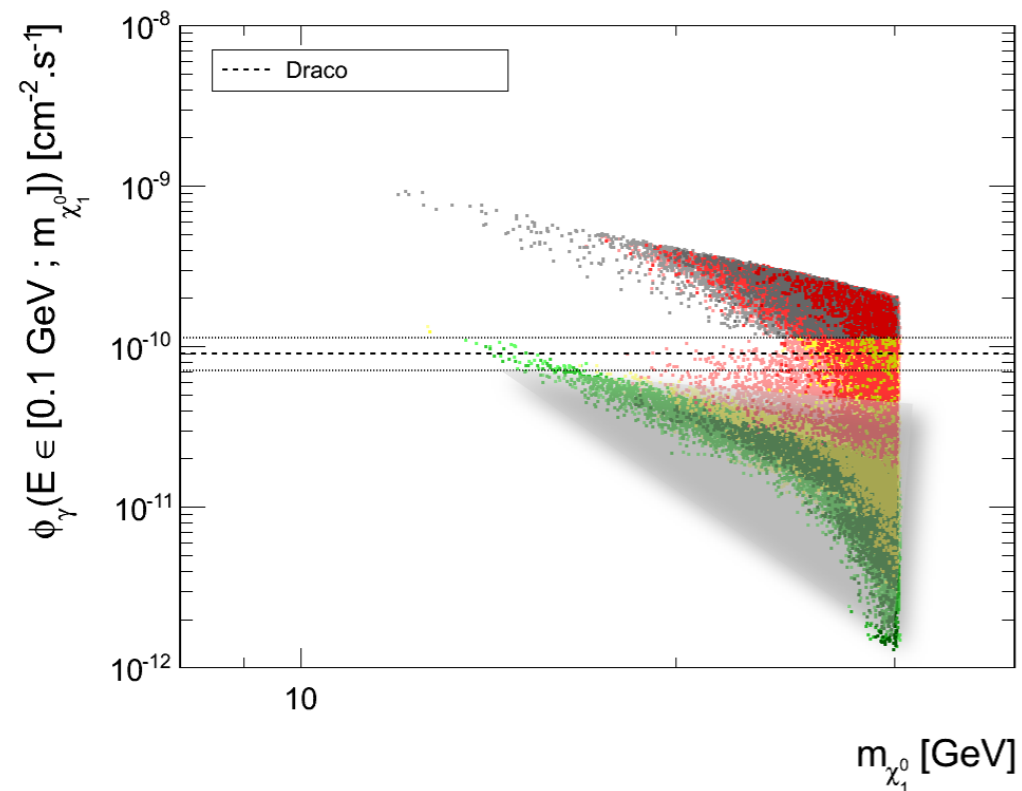


FIG. 5: Integrated γ -ray flux from the Draco dwarf spheroidal galaxy as a function of the neutralino mass in the $m_{\chi_1^0} < 30$ GeV search. We show limits from Fermi-LAT. Same color code as Fig. 4.

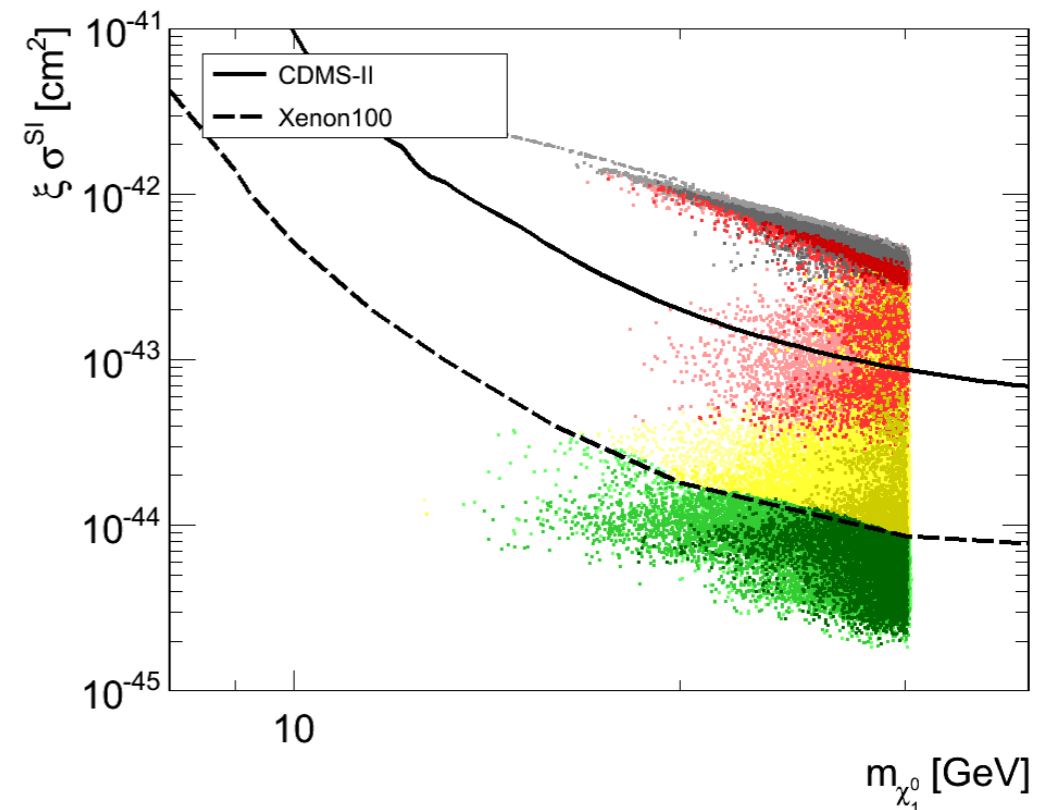
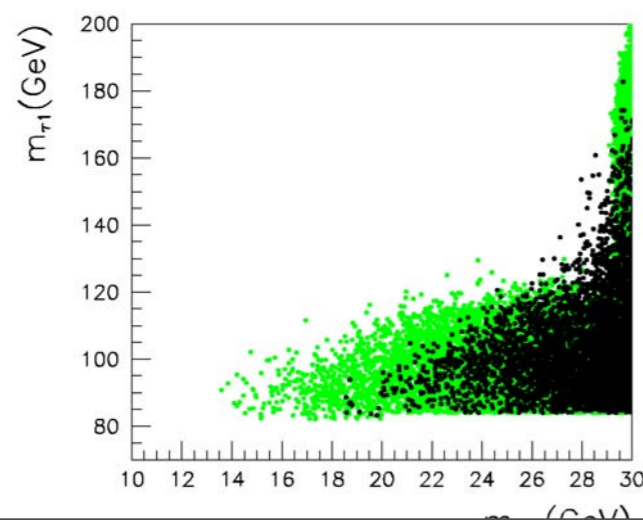


FIG. 4: Points of the $m_{\chi_1^0} < 30$ GeV search represented in the $\xi\sigma^{SI}$ vs. neutralino mass plane. Exclusion limits from CDMS-II [29] and XENON100 are shown. The color code is the same as in Fig. 2, green points are allowed.



Light MSSM neutralinos should not resist a very long time...

Another SUSY example: NMSSM

$$W = \lambda S H_u H_d + \frac{1}{3} \kappa S^3 \quad \mu = \lambda \langle S \rangle$$

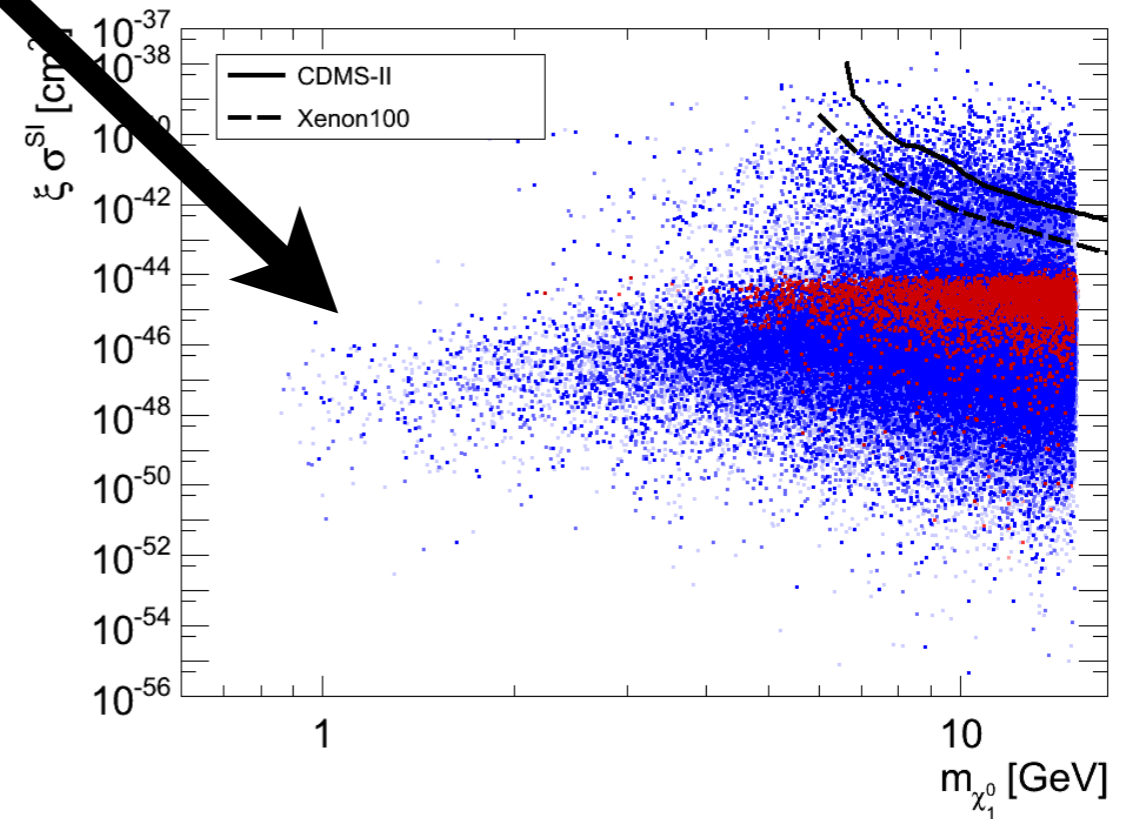
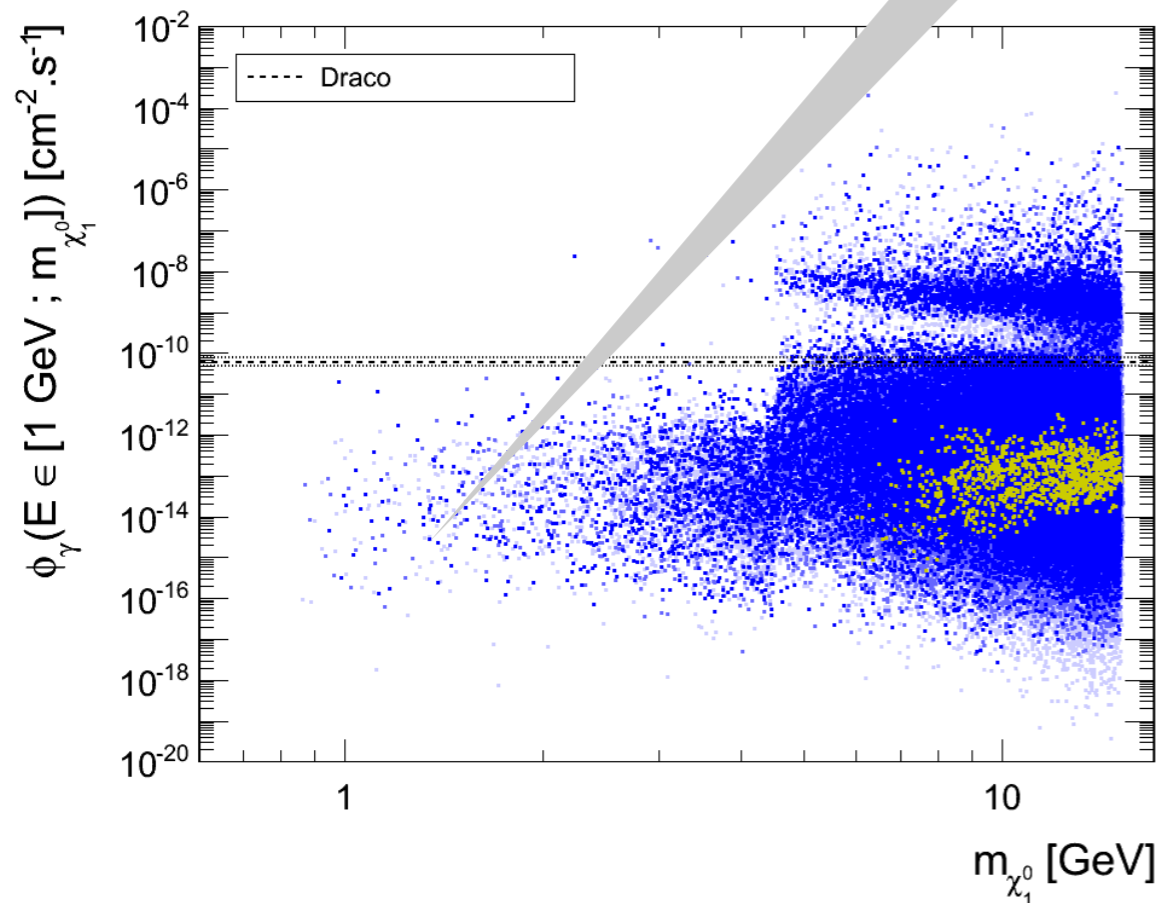
$$\mathcal{L}_{\text{soft}} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2$$

$$+ (\lambda A_\lambda H_u H_d S + \frac{1}{3} \kappa A_\kappa S^3 + h.c.)$$

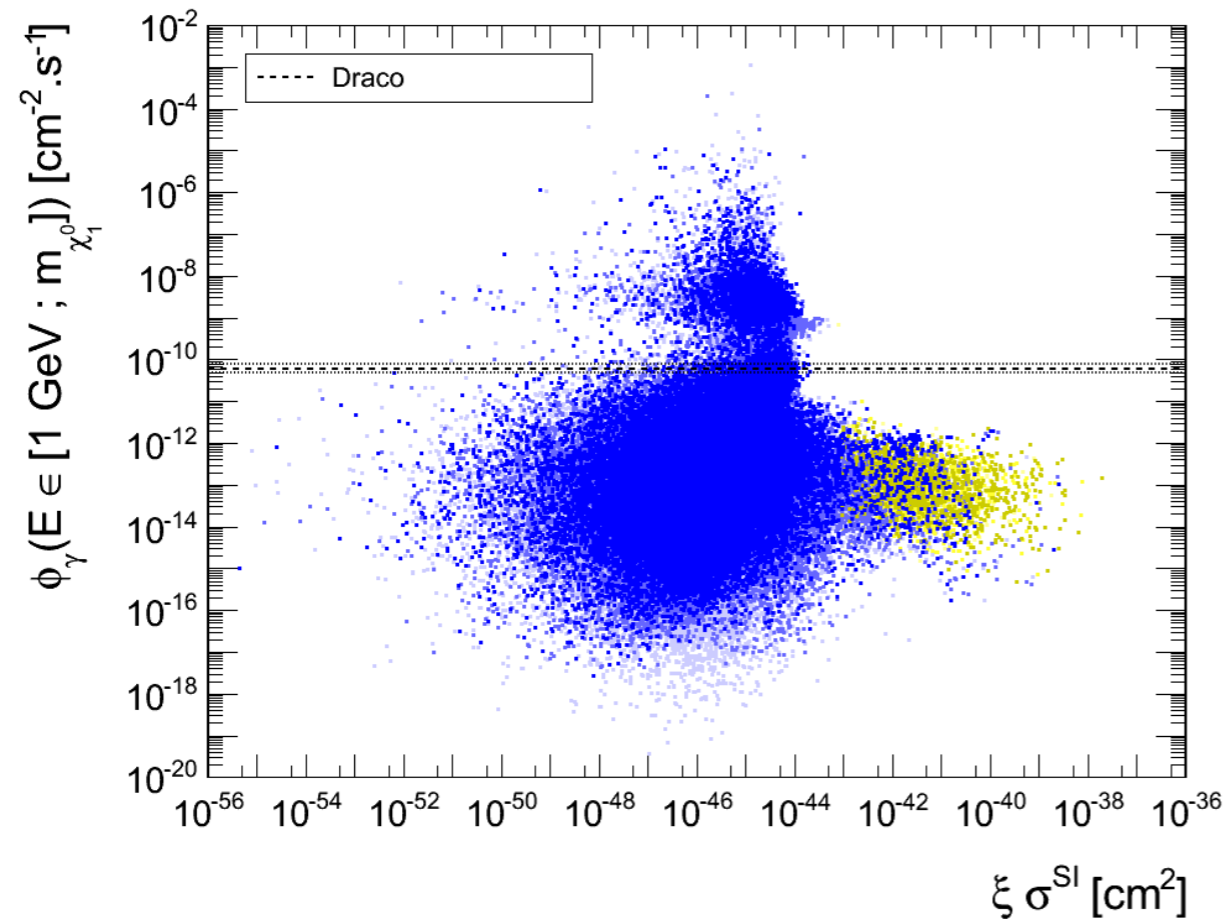
$\mu, \tan \beta$ as well as $\lambda, \kappa, A_\lambda, A_\kappa$

Here we are, light neutralinos...

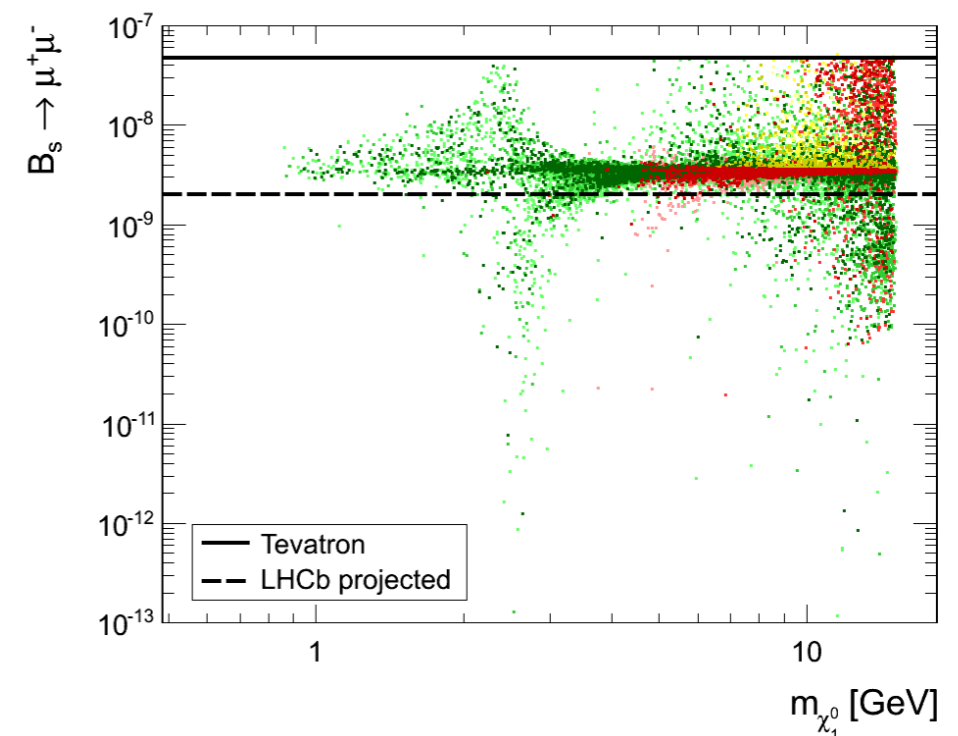
But...



But may never be discovered in fact!



Although LHC might help...



Conclusion

Should we be worried?

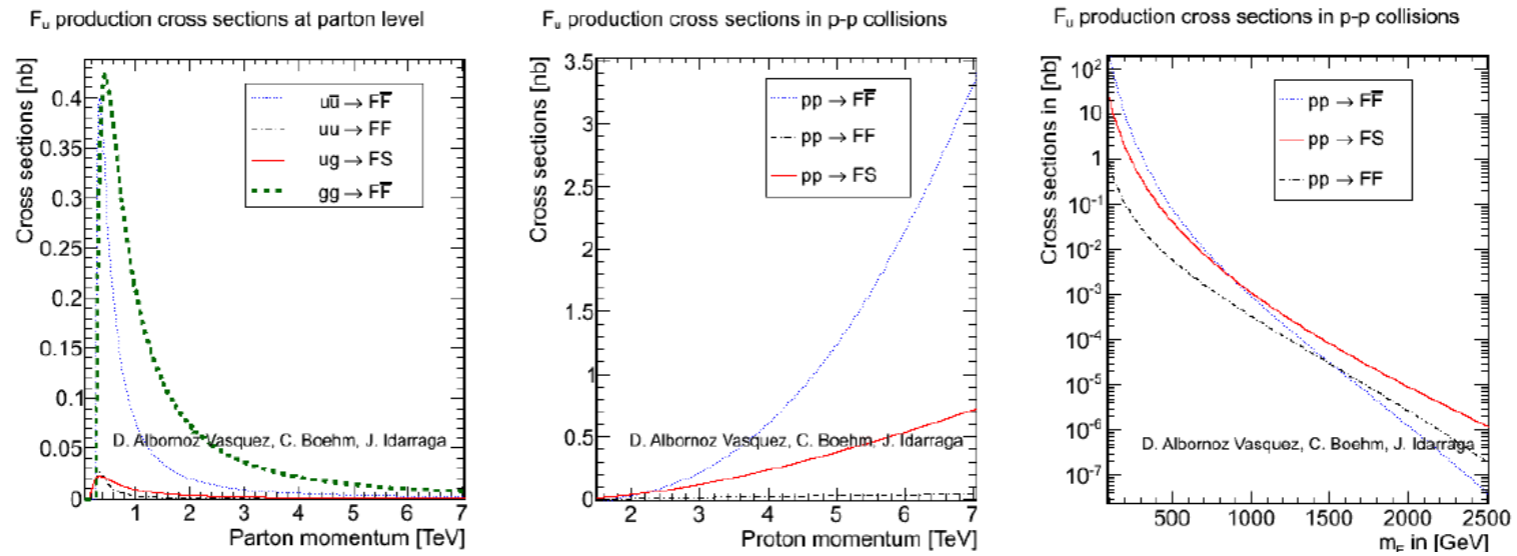
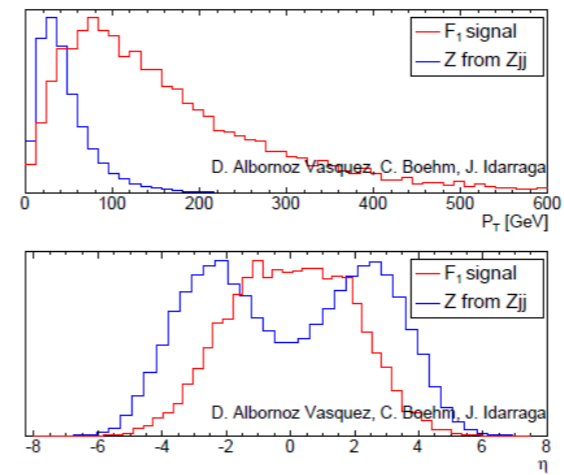
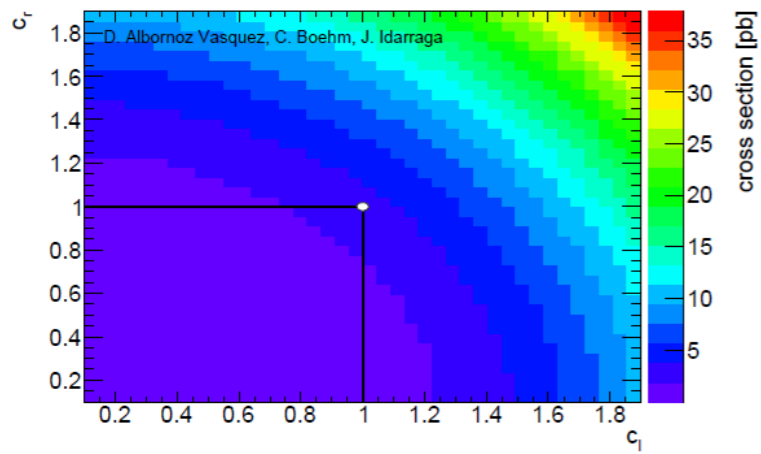
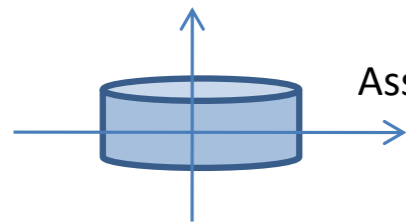


FIG. 1: F_q production cross sections. Left panel: at the parton level, assuming $m_F = 300$ GeV, $c_{l,r} = 1$ and obtained by using the function *cs22* implemented in micrOMEGAS. Middle panel: at the proton level, with $m_F = 300$ GeV, $c_{l,r} = 1$ and obtained by using hCollider. Right panel: dependence of the cross section with m_{F_q} . Same parameters as middle panel but $\sqrt{s} = 10$ TeV.



More on propagation

Deianaye et al 2007



Assume that diffusion zone is well approximated by a cylinder

$$\tilde{I}(\lambda_D) = \sum_{i=1}^{\infty} \sum_{n=1}^{\infty} J_0(\alpha_i r / R_{\text{gal}}) \varphi_n(z) \exp \left\{ -\tilde{C}_{i,n} (\tilde{t} - \tilde{t}_S) \right\} R_{i,n}$$

Bessel in r_cyl
Fourier in z_cyl
Propagation length
Source term

$$\lambda_D^2 = 4K_0 \tau_E \left\{ \frac{\epsilon^{\delta-1} - \epsilon_S^{\delta-1}}{1 - \delta} \right\}$$

$$K(x, E) = K_0 \epsilon^{\delta} \text{ where } \epsilon = E/E_0$$

Finally flux is proportional to the integral over l.o.s (and dE) of $\tilde{I}(\lambda_D)$