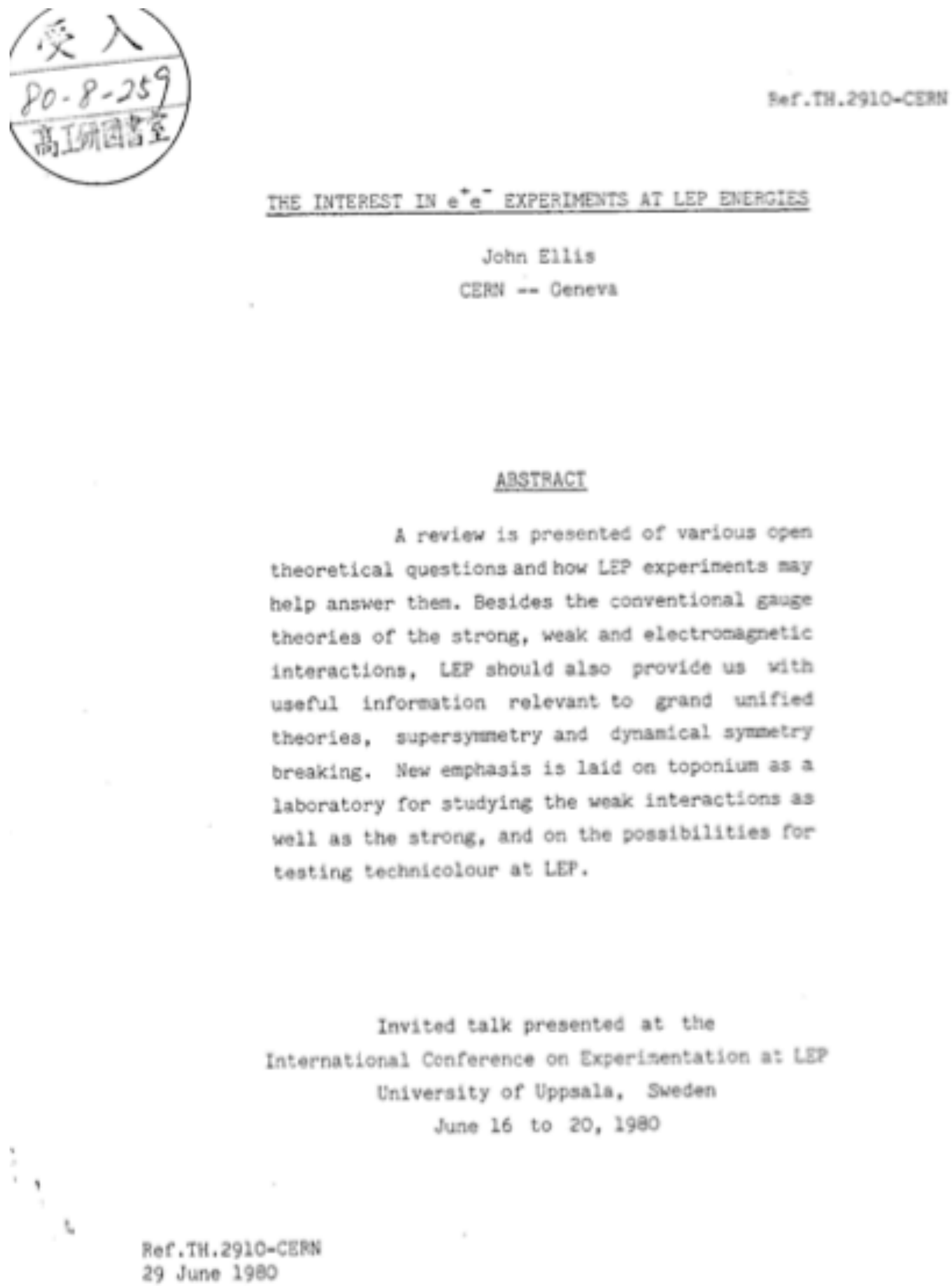
# Can one elucidate the dark matter problem if no new physics is found at LHC?

Celine Boehm, IPPP Durham, UK/ CNRS, Annecy, FR

# “Long lived” expectations since the 1980s





Ref.TH.2910-CERN

THE INTEREST IN $e^+e^-$ EXPERIMENTS AT LEP ENERGIES

John Ellis
CERN -- Geneva

ABSTRACT

A review is presented of various open theoretical questions and how LEP experiments may help answer them. Besides the conventional gauge theories of the strong, weak and electromagnetic interactions, LEP should also provide us with useful information relevant to grand unified theories, supersymmetry and dynamical symmetry breaking. New emphasis is laid on toponium as a laboratory for studying the weak interactions as well as the strong, and on the possibilities for testing technicolour at LEP.

Invited talk presented at the
International Conference on Experimentation at LEP
University of Uppsala, Sweden
June 16 to 20, 1980

Ref.TH.2910-CERN
29 June 1980

## The interest in e+e- experiments at LEP energies

LEP should also provide us with useful information relevant to grand unified theories, supersymmetry and dynamical symmetry breaking

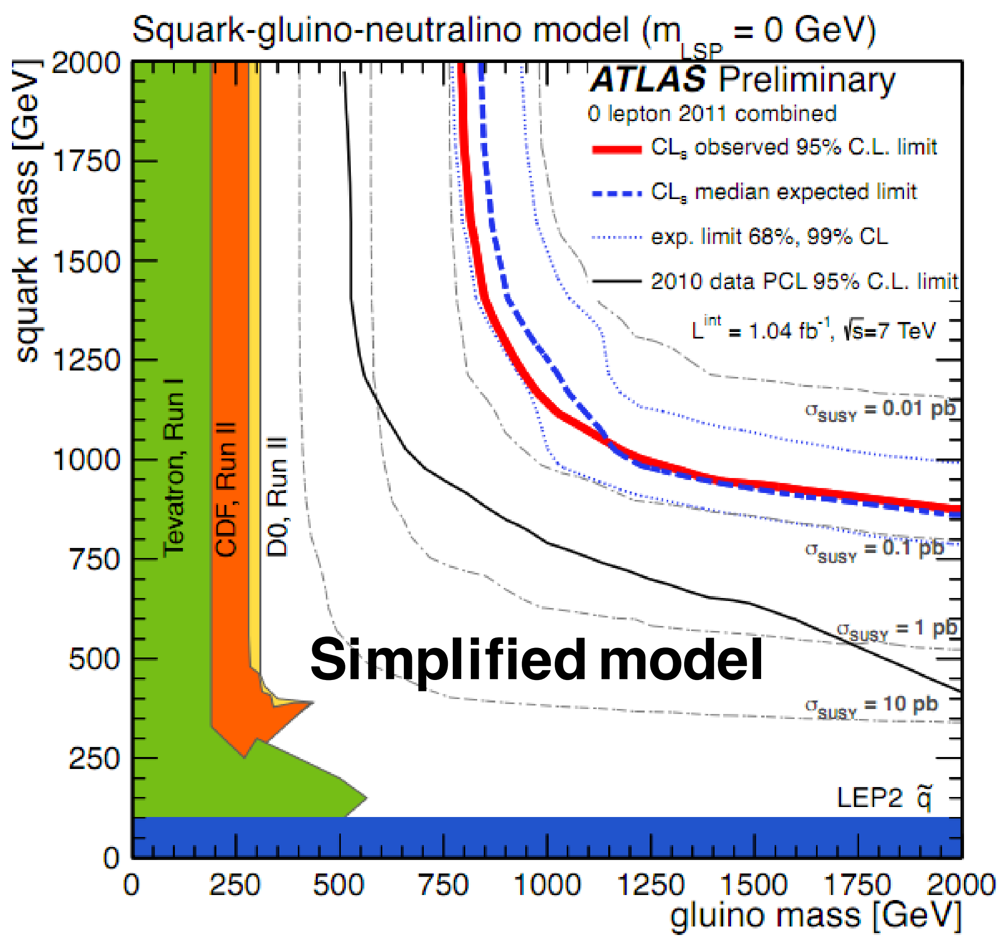
J. R. Ellis, 16th June, 1980

# Would the LHC be the ultimate "kill-hope" machine ?

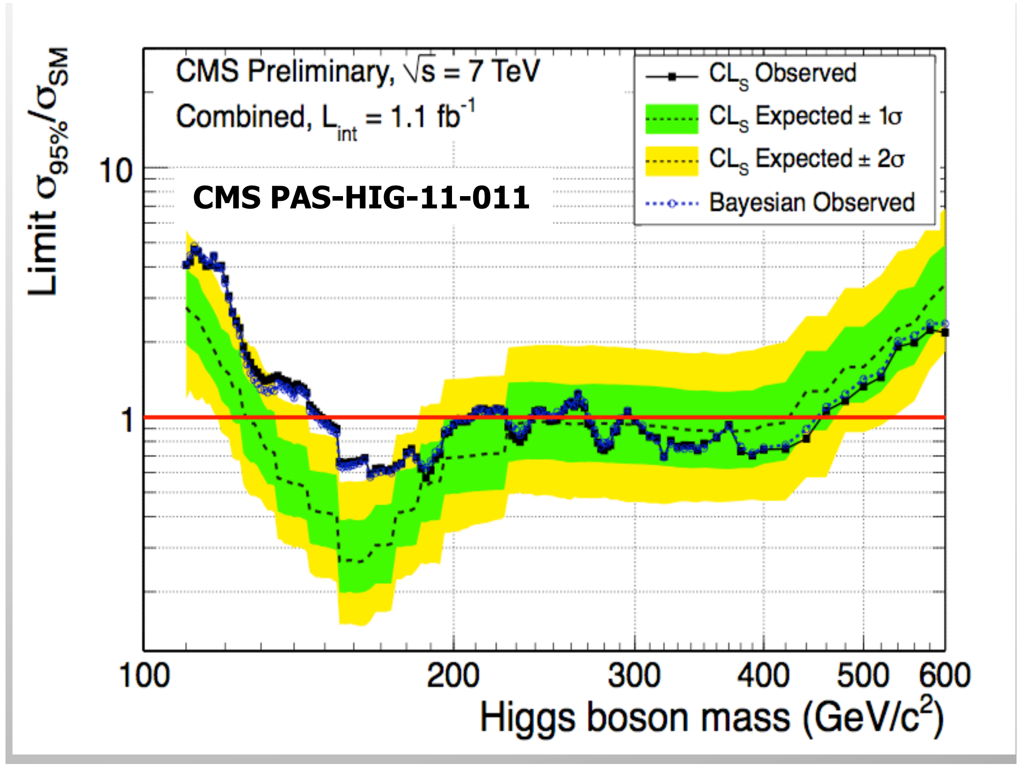
## Quid of LHC?

LEP has not provide us with useful information relevant to grand unified theories, supersymmetry and dynamical symmetry breaking

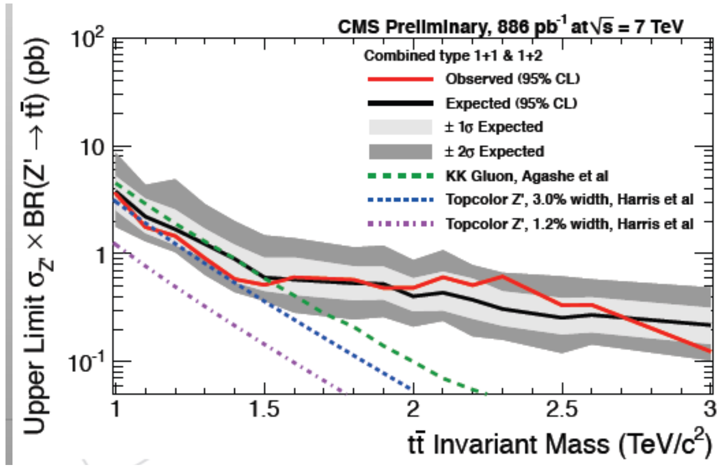
SUSY?

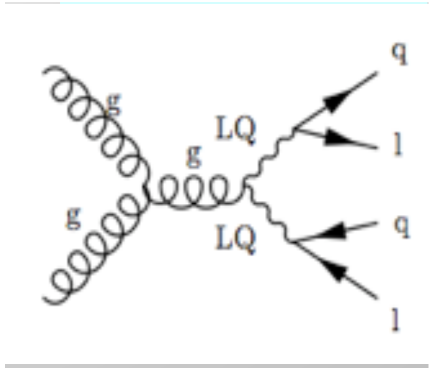



Higgs?

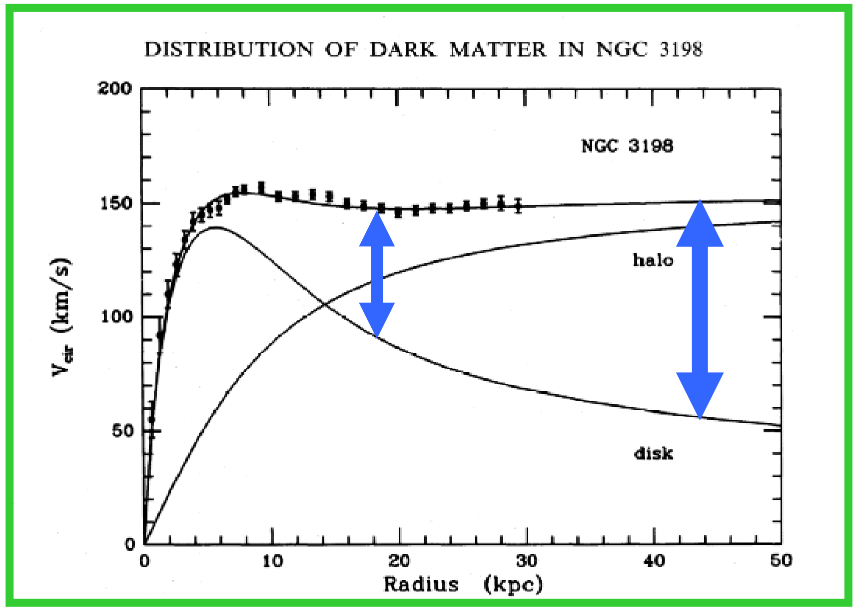


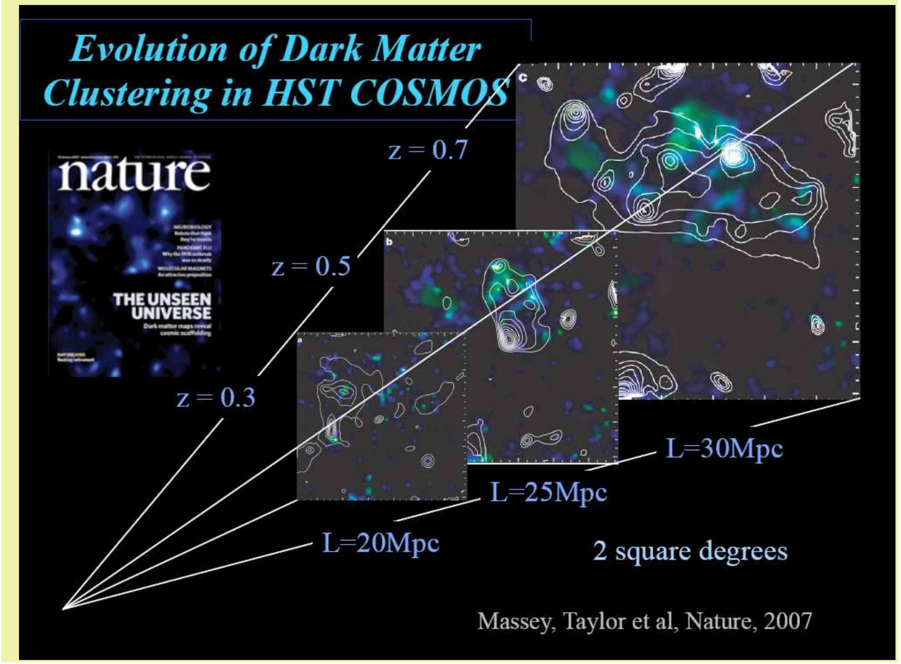

Others?

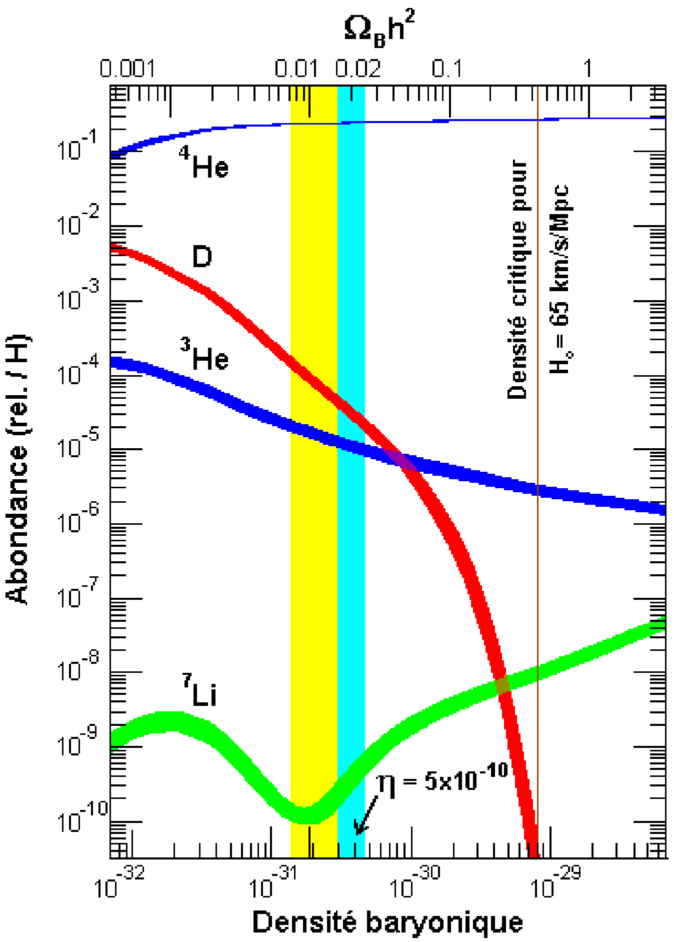


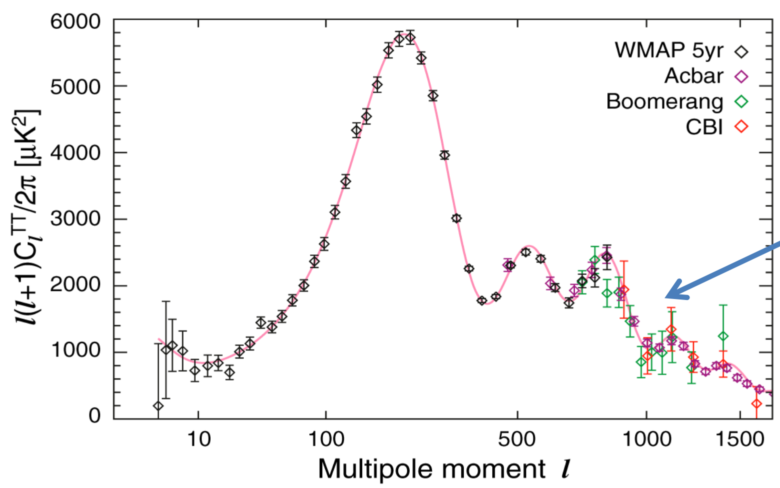



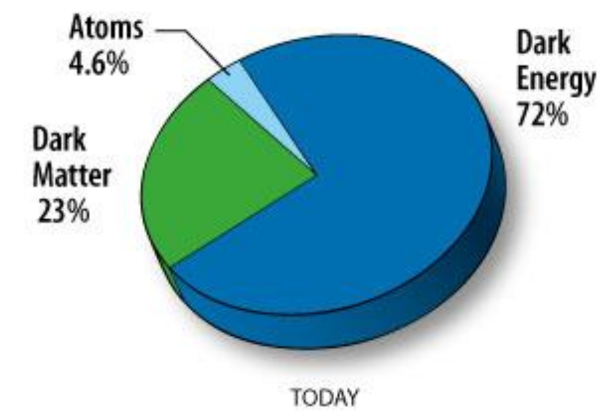
# But there is definitely new physics (whatever it is...)




# Two possible explanations...

## Modifying gravity:

**Bekenstein's theory (TeVeS)**

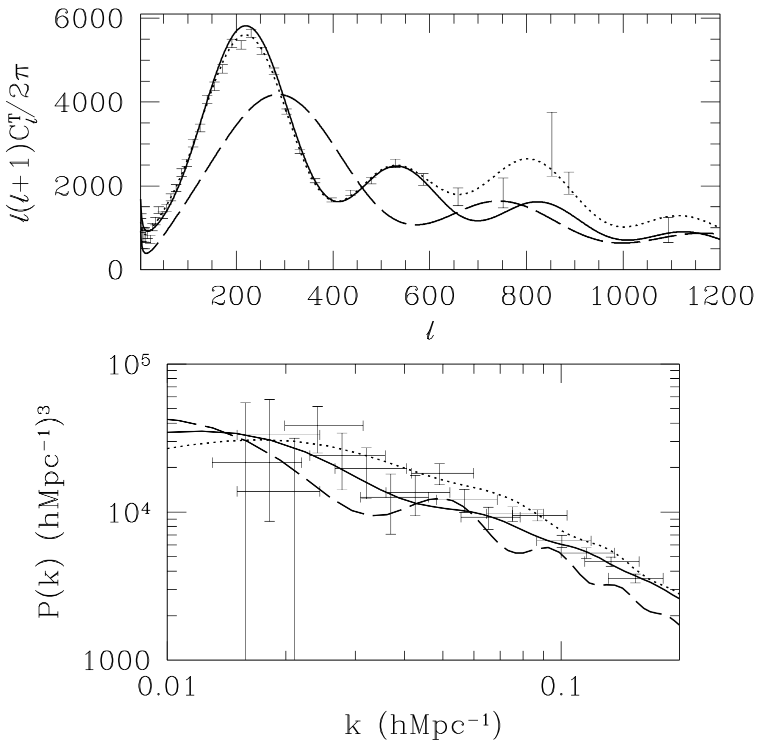



FIG. 4: The angular power spectrum of the CMB (top panel) and the power spectrum of the baryon density (bottom panel) for a MOND universe (with $a_0 \simeq 4.2 \times 10^{-8} cm/s^2$) with $\Omega_\Lambda = 0.78$ and $\Omega_\nu = 0.17$ and $\Omega_B = 0.05$ (solid line), for a MOND universe $\Omega_\Lambda = 0.95$ and $\Omega_B = 0.05$ (dashed line) and for the $\Lambda$-CDM model (dotted line). A collection of data points from CMB experiments and Sloan are overplotted.

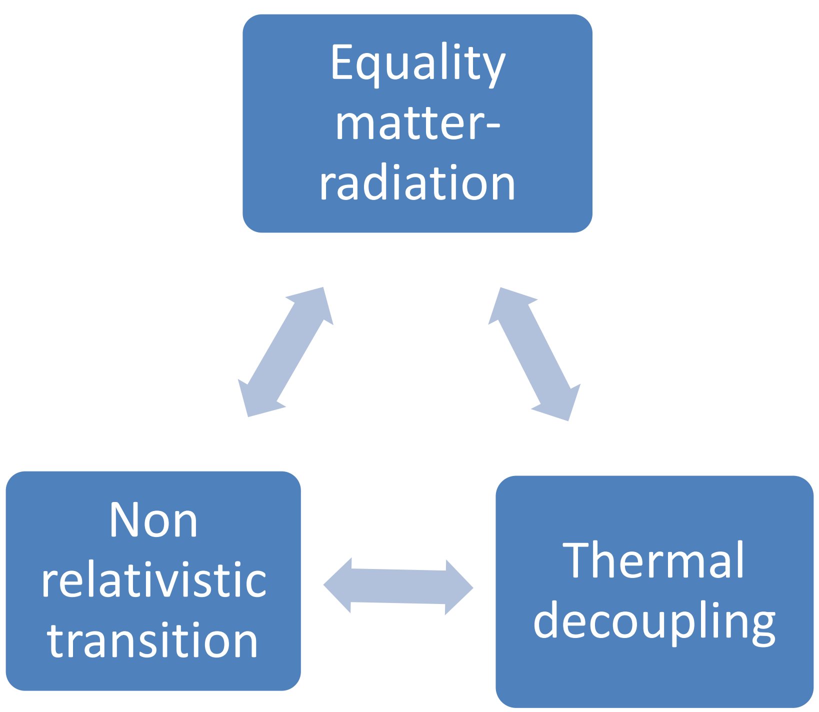
## New neutral particles:

Hence "weakly" interacting when it comes to emitting photons but perhaps not that weakly interacting...

# What kind of neutral particle?

- 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




6 categories of DM candidates!
(never realized before)

Among which one expects
new types of DM candidates!

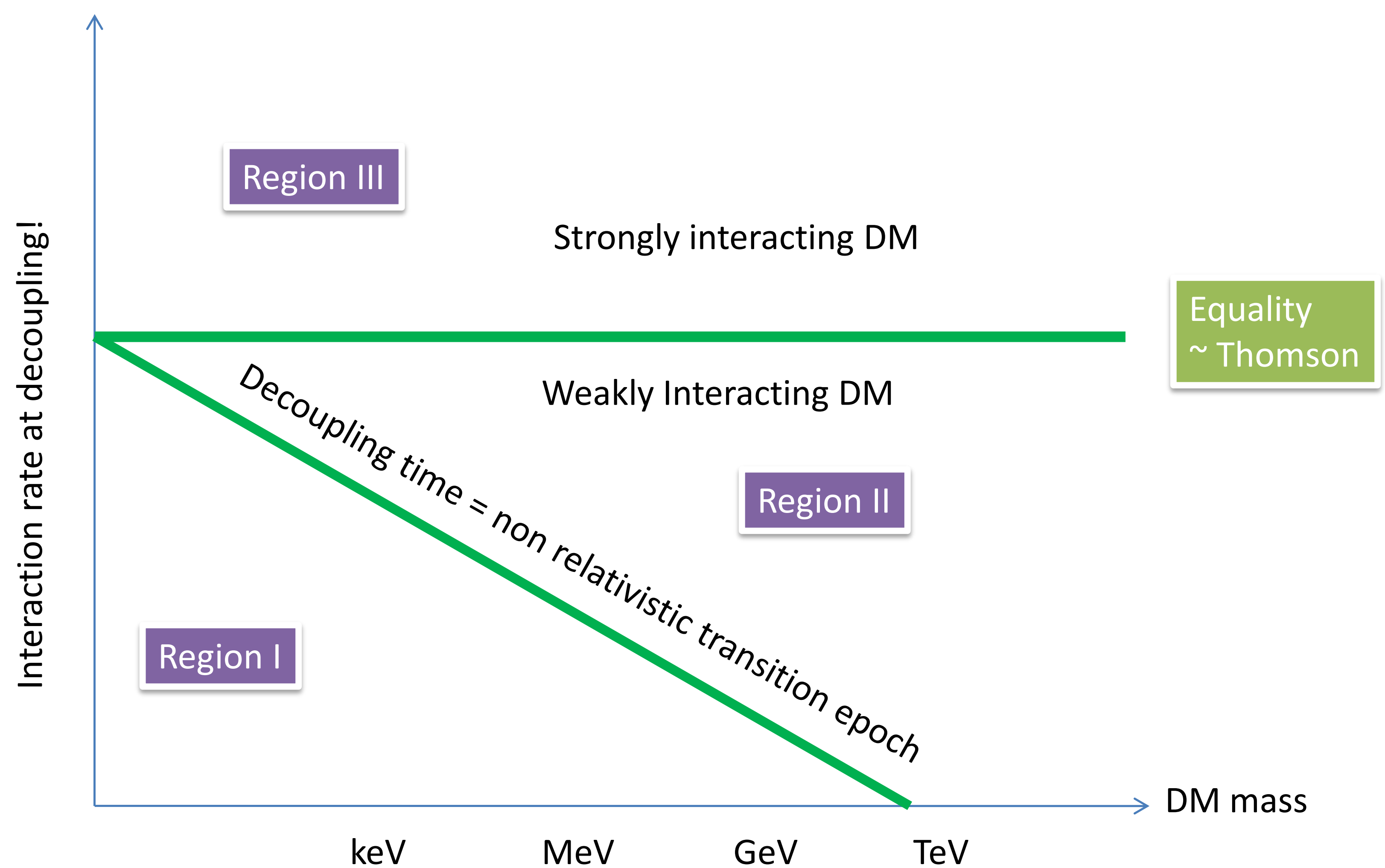
# Need for a neat classification of all types of DM candidates

CB, P. Fayet and R. Schaeffer, astro-ph/0012504

Decoupling — Non-relativistic — equality

| | |
|---|---|
| Region I | $a_{dec(dm)} < a_{nr} < a_{eq(\gamma+\nu)}$ |
| Region II | $a_{nr} < a_{dec(dm)} < a_{eq(\gamma+\nu)}$ |
| Region III | $a_{nr} < a_{eq(\gamma+\nu)} < a_{dec(dm)}$ |
| Region IV | $a_{dec(dm)} < a_{eq(\gamma+\nu)} < a_{nr}$ |
| Region V | $a_{eq(\gamma+\nu)} < a_{dec(dm)} < a_{nr}$ |
| Region VI | $a_{eq(\gamma+\nu)} < a_{nr} < a_{dec(dm)}$ |

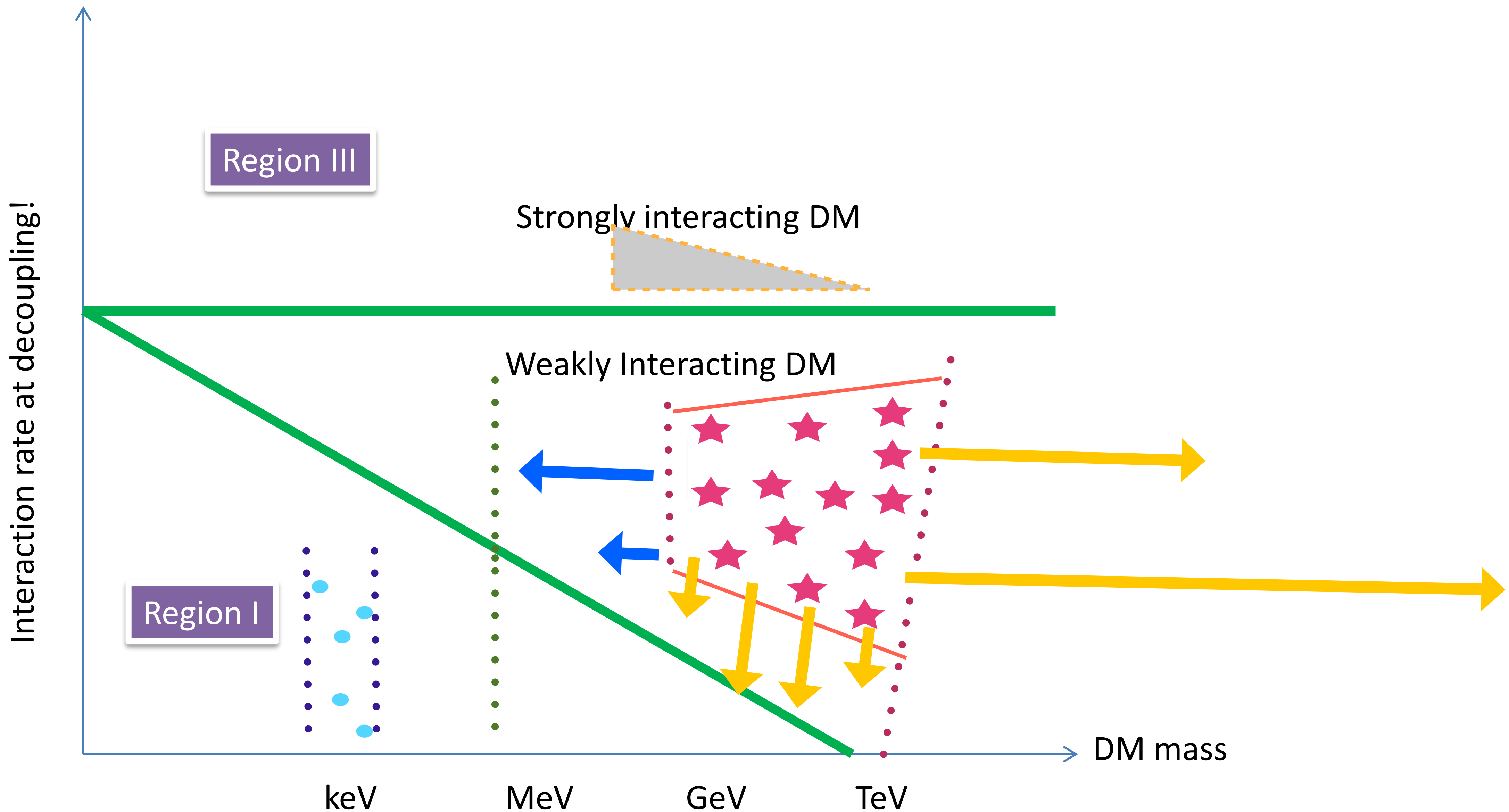
a= scale factor



Locate your favourite DM candidates

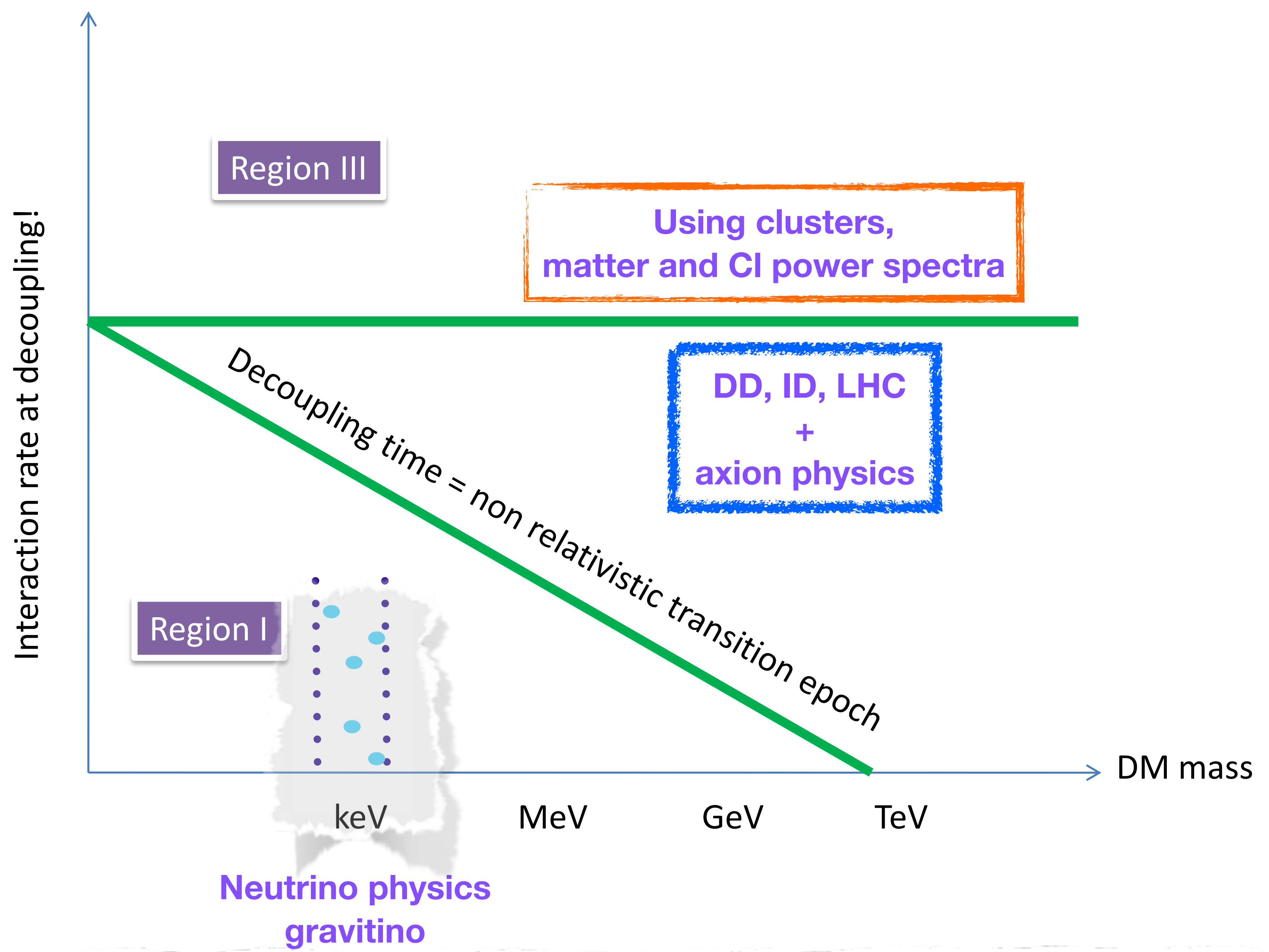
**(forget about CDM and WDM for the moment)**

# Theoretical parameter space



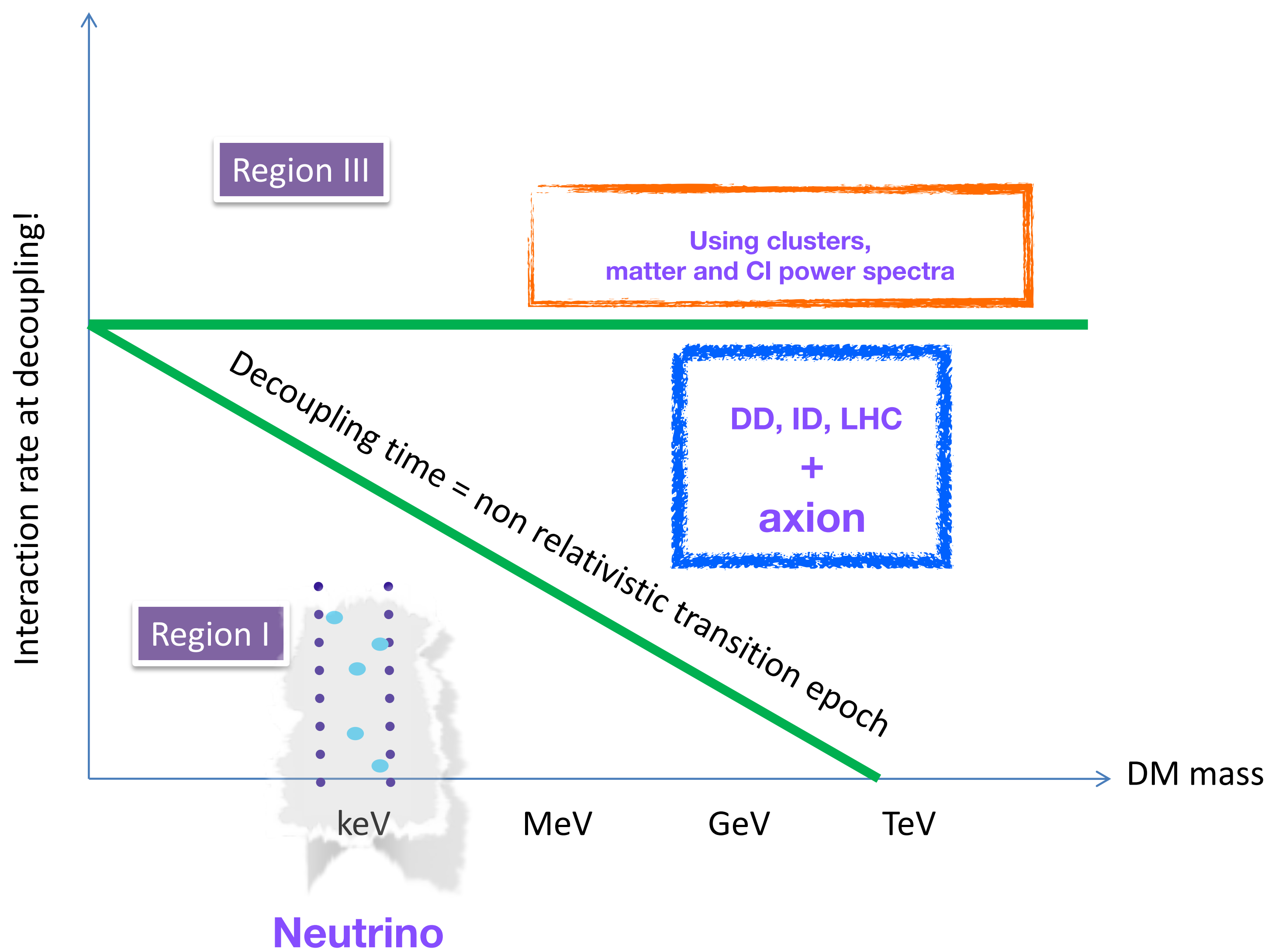

**Theoretically, we have explored a small region of the parameter space.**

# DM parameter space investigated experimentally/observationally




**Experimentally, explored about the same although a bit tricky**

# We have to be very LUCKY for the DM to be the type of particles that we can discover with our present tools!



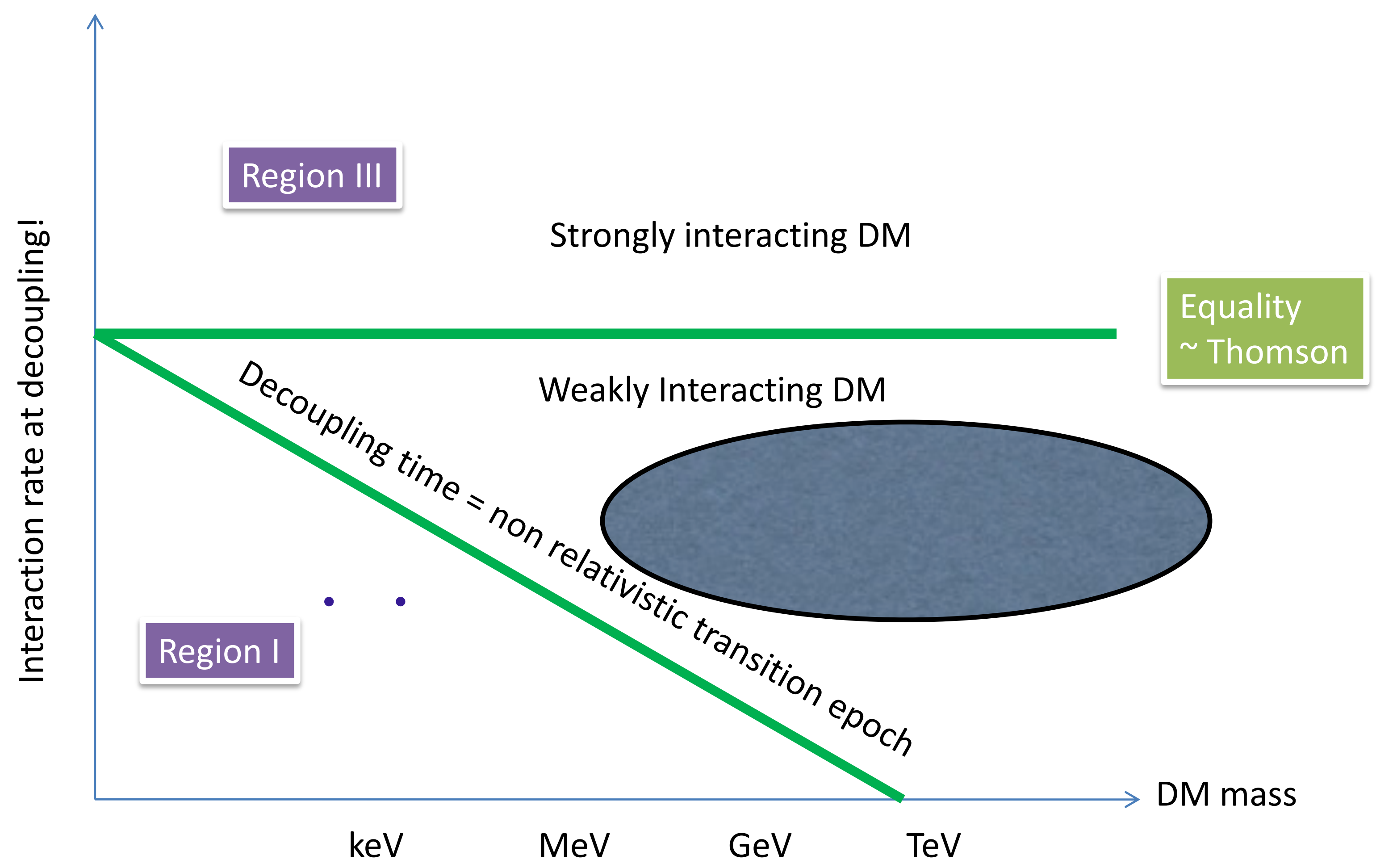

**Experimentally, explored about the same although a bit tricky**

LHC

~~LEP~~ should ~~also~~ provide us with useful information relevant to grand unified theories, supersymmetry and dynamical symmetry

# The WIMP region

**'thermal' bulk only;**
**I am discarding non-thermal candidates**

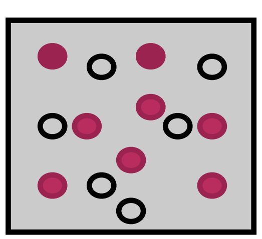


# The relic density paradigm

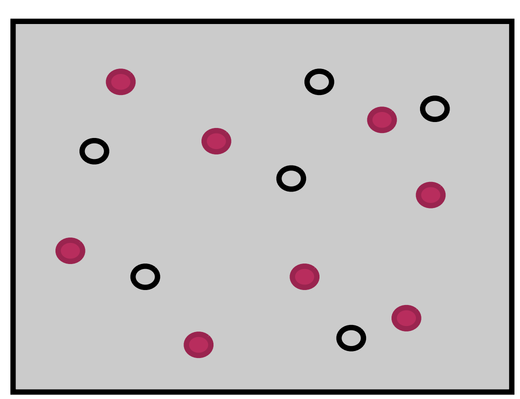
- Hypothesis until the 2000s, working hypothesis:
  - ✳thermal (annihilating)
  - ✳symmetric (n_DM = n_antiDM)
  - ✳weakly interacting

Boltzmann equation
no Particle Physics!

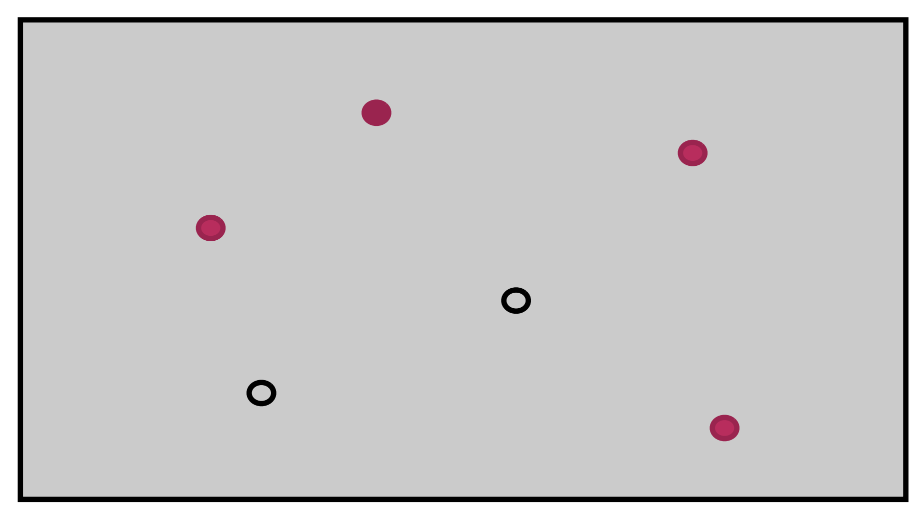
$$\frac{dn}{dt} = -3\,H\,n - <\sigma v>(n^2 - n_{eq}^2)$$



Thermal equilibrium



Expansion

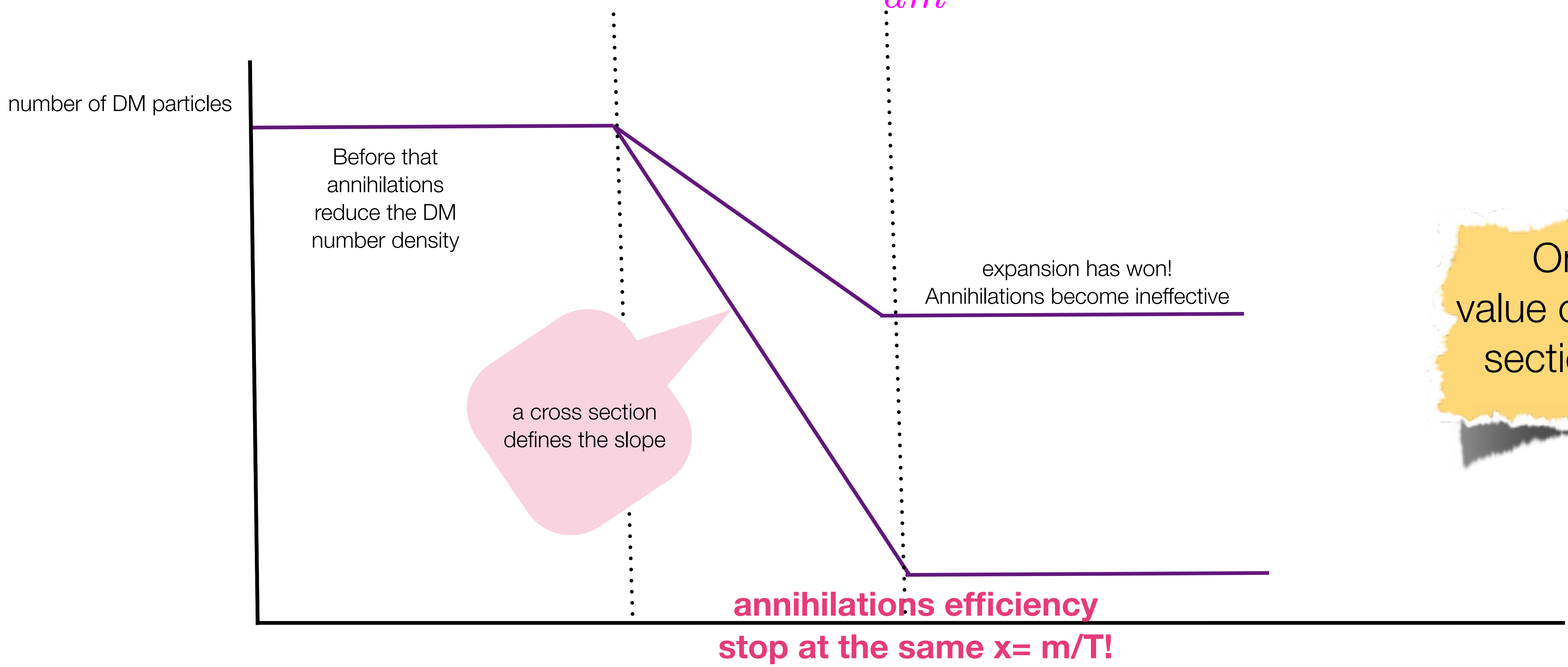


Annihilations

# Why is/was the thermal hypothesis so popular?

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

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



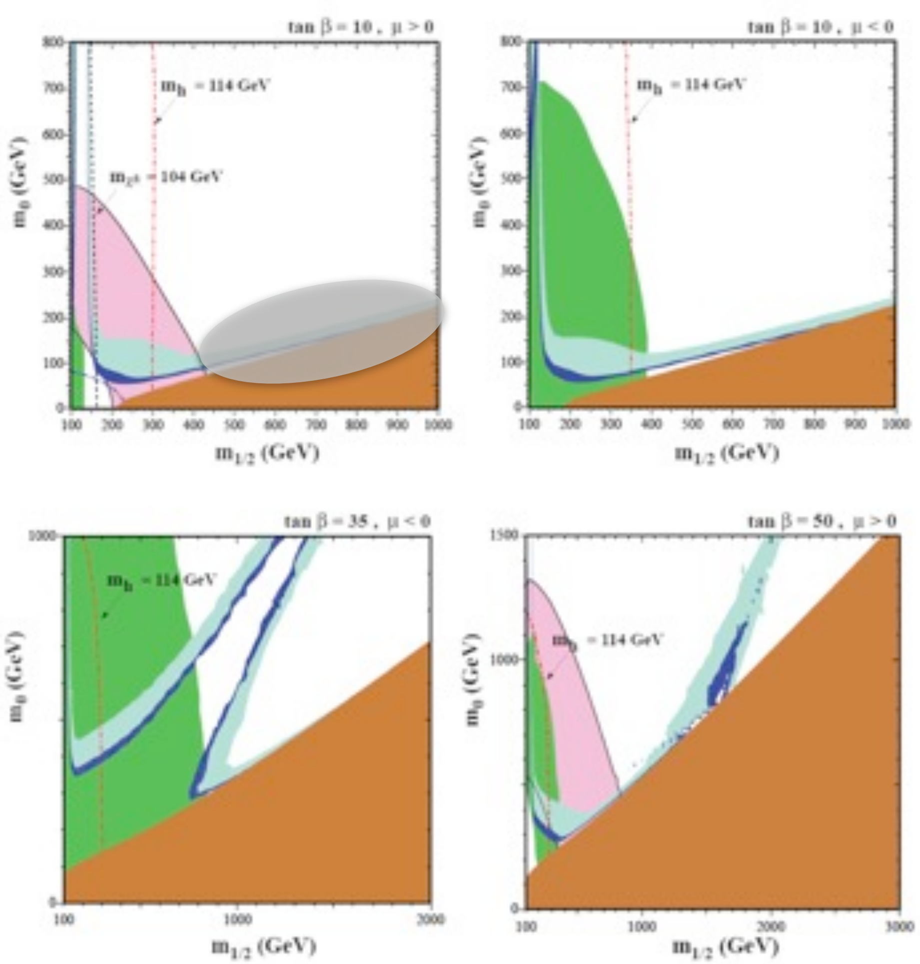

Only one value of the cross section works!

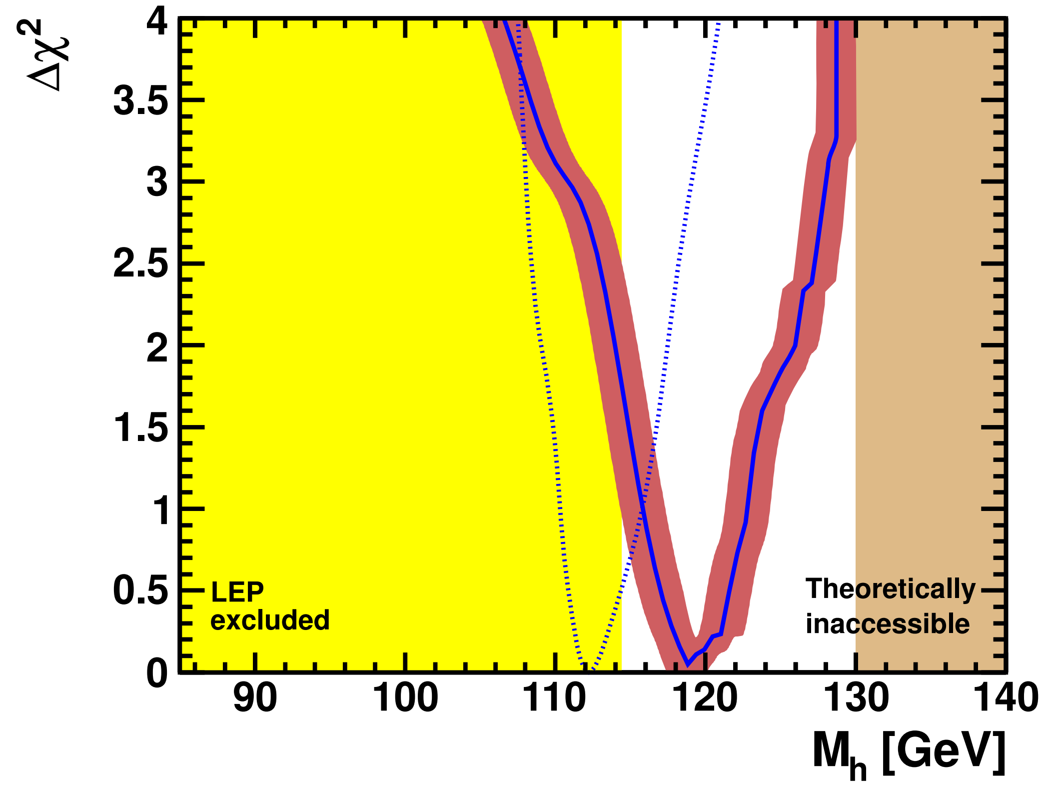
# Will the CMSSM/mSUGRA survive?

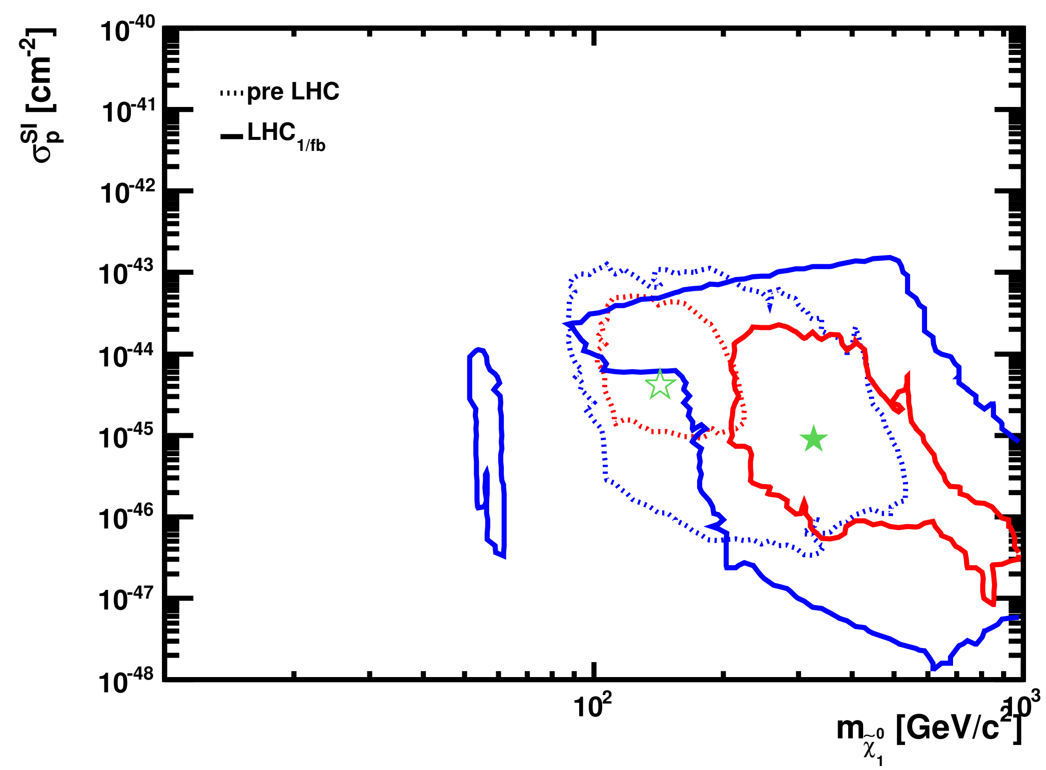
Predictions are being tested at LHC: quid of the light Higgs?

arXiv:1110.3568

$$\frac{dn_1}{dt} = -3Hn_1 - \langle\sigma v\rangle_{ann}(n_1^2 - n_{1,0}^2) - \langle\sigma v\rangle_{coa}(n_1\, n_2 - n_{1,0}\, n_{2,0})$$
$$\frac{dn_2}{dt} = -3Hn_2 - \langle\sigma v\rangle_{ann}(n_2^2 - n_{2,0}^2) - \langle\sigma v\rangle_{coa}(n_1\, n_2 - n_{1,0}\, n_{2,0})$$

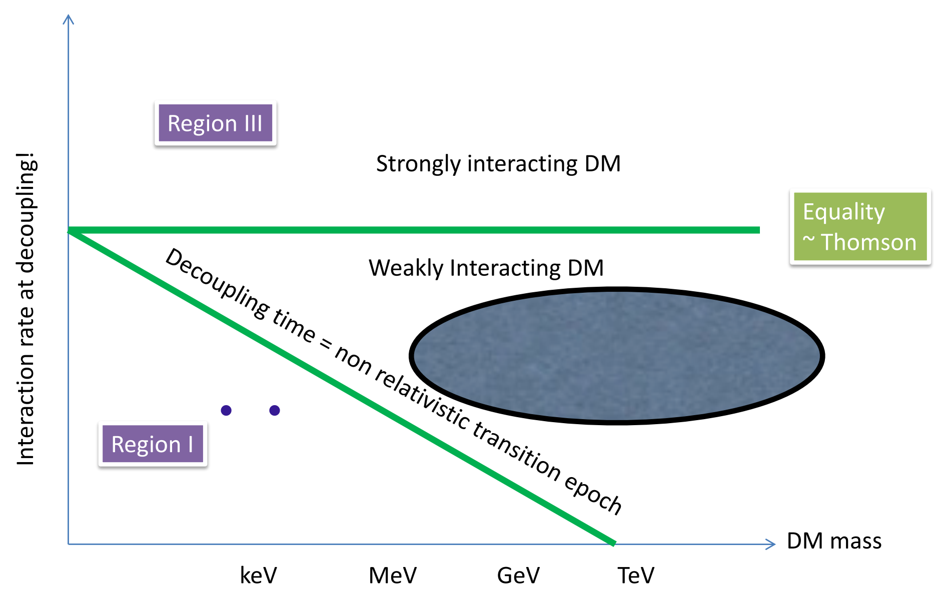


# Summary for CMSSM

Likely to be excluded, we have to move on

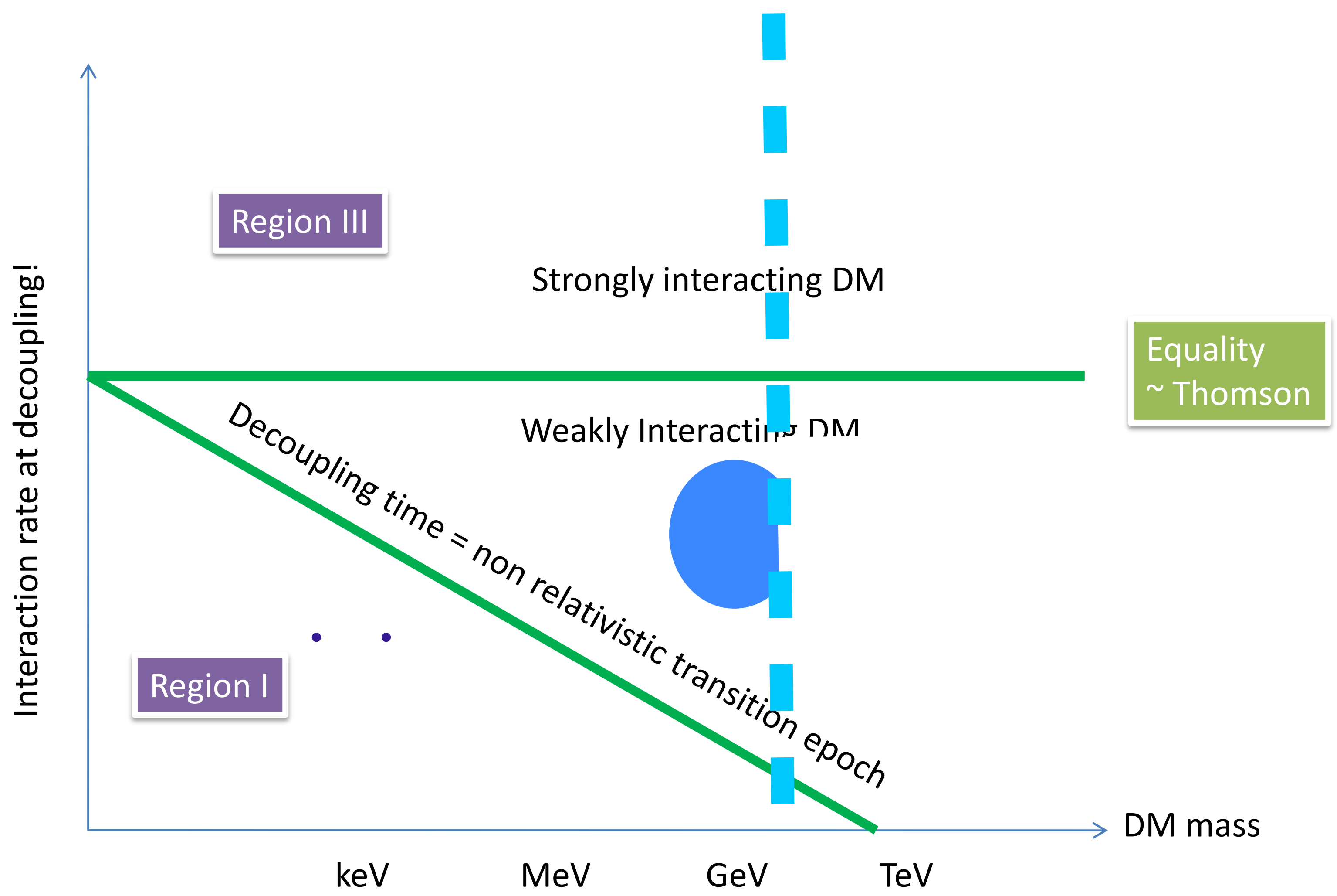


What (conventional) else in the thermal region?

**(Can we still have supersymmetry?)**

CMSSM $\longrightarrow$ pMSSM

# Thermal, low mass, annihilating candidates



# Are there light ([1-10] GeV) neutralinos in the pMSSM?

$$100\%\ \Omega_{WMAP}h^2 > \Omega_\chi h^2 > 10\%\ \Omega_{WMAP}h^2.$$

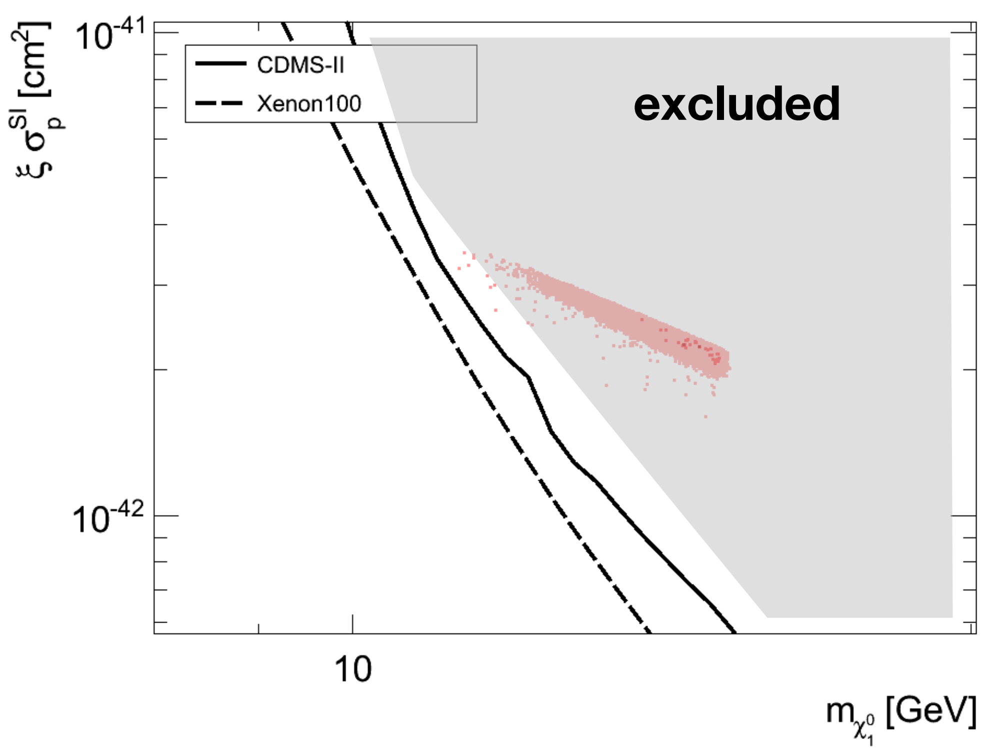



FIG. 3: MSSM-EWSB scenario with $\mu > 0$ and $m_\chi < 15$ GeV. Spin-independent cross section on proton times the fraction of neutralinos in the Milky Way dark halo ($\xi$) versus the neutralino mass $m_\chi$. The dark red (light pink) points have a likelihood greater than 99.4% (68%).

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

**Theoretically: yes,**

**Experimentally: no (?)**

# Very light MSSM neutralinos are out but that is not the end of the story (...yet!...)

1108.1338

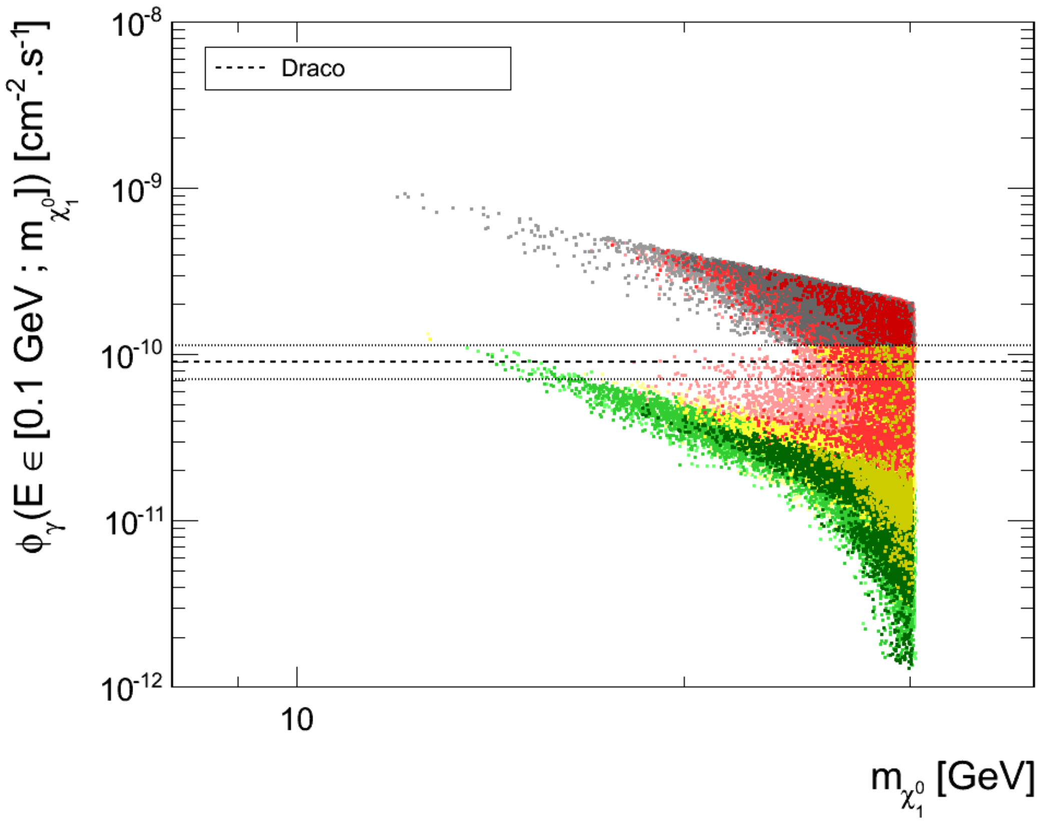



FIG. 5: Integrated γ-ray flux from the Draco dwarf spheroidal galaxy as a function of the neutralino mass in the $m_{\chi_1^0} < 30$ GeV search. We show limits from Fermi-LAT. Same color code as Fig. 4.

| Parameter | Minimum | Maximum | Tolerance |
|---|---|---|---|
| $M_1$ | 1 | 1000 | 3 |
| $M_2$ | 100 | 2000 | 30 |
| $M_3$ | 500 | 6500 | 10 |
| $\mu$ | 0.5 | 1000 | 0.1 |
| $\tan\beta$ | 1 | 75 | 0.01 |
| $M_A$ | 1 | 2000 | 4 |
| $A_t$ | -3000 | 3000 | 100 |
| $M_{\tilde{l}_R}$ | 70 | 2000 | 15 |
| $M_{\tilde{l}_L}$ | 70 | 2000 | 15 |
| $M_{\tilde{q}_{1,2}}$ | 300 | 2000 | 14 |
| $M_{\tilde{q}_3}$ | 300 | 2000 | 14 |

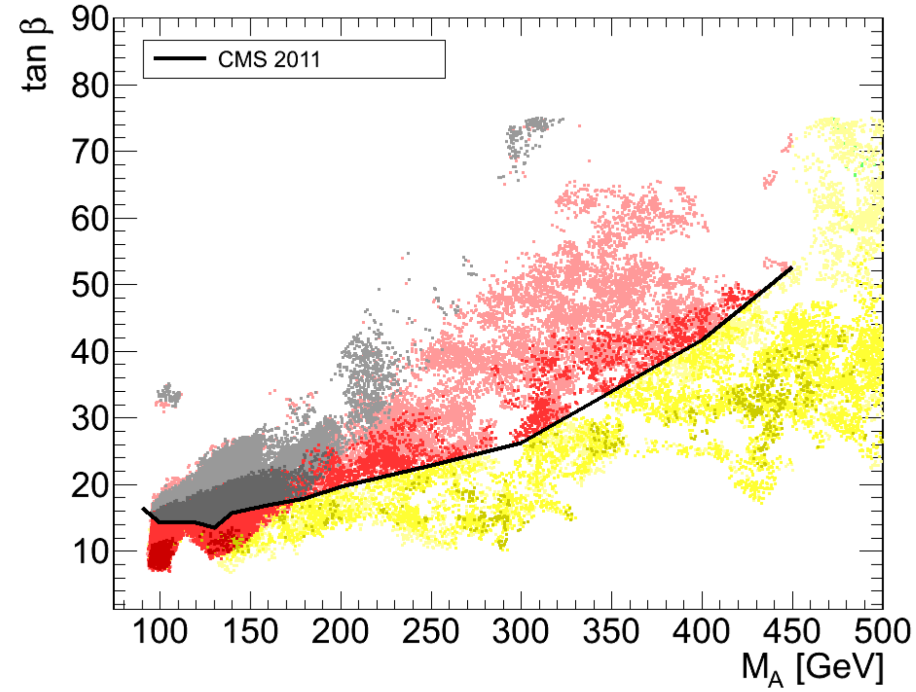
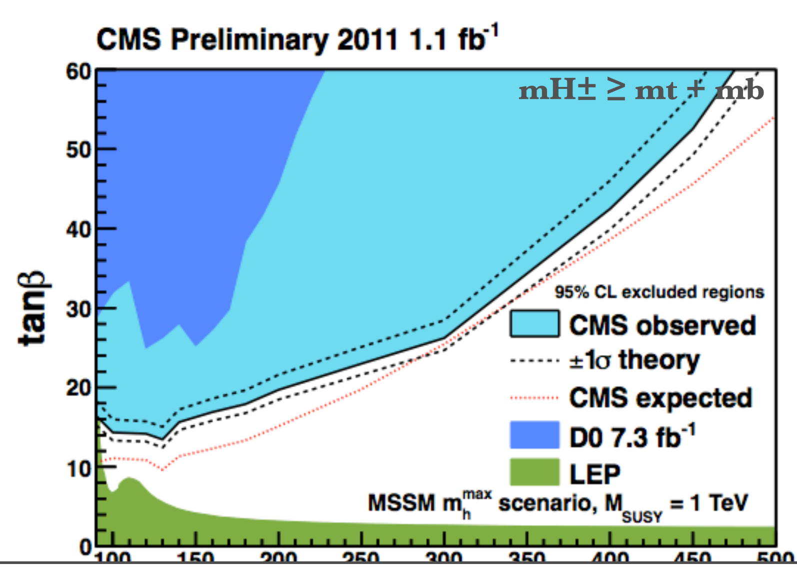



FIG. 2: Allowed points in the $\tan\beta$ vs. $M_A$ plane in the $m_{\chi_1^0} < 30$ GeV search. We show only the region where $M_A < 500$ GeV. The exclusion limit from CMS is also displayed. In yellow (red), points excluded by one (two) constraint and in black those excluded by three constraints (CMS,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



Detectability at the remaining points?

**(Can light neutralino escape constraints?)**

# Complementarity of the 3 types of experiments

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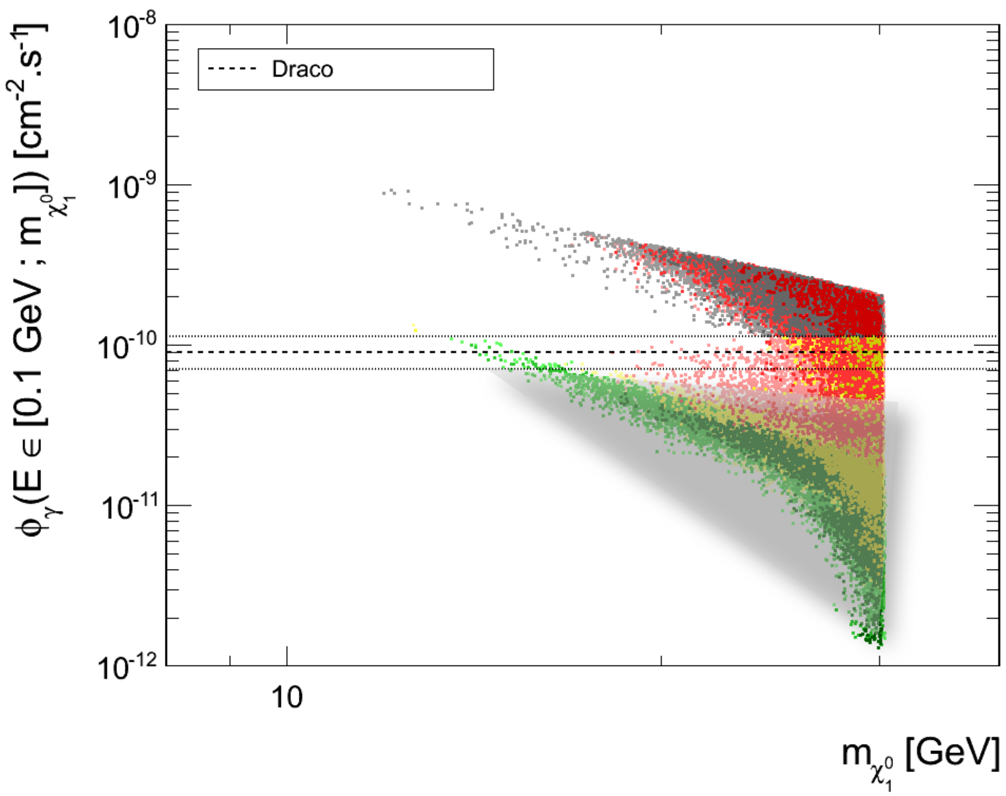



FIG. 5: Integrated γ-ray flux from the Draco dwarf spheroidal galaxy as a function of the neutralino mass in the $m_{\chi_1^0} < 30$ GeV search. We show limits from Fermi-LAT. Same color code as Fig. 4.

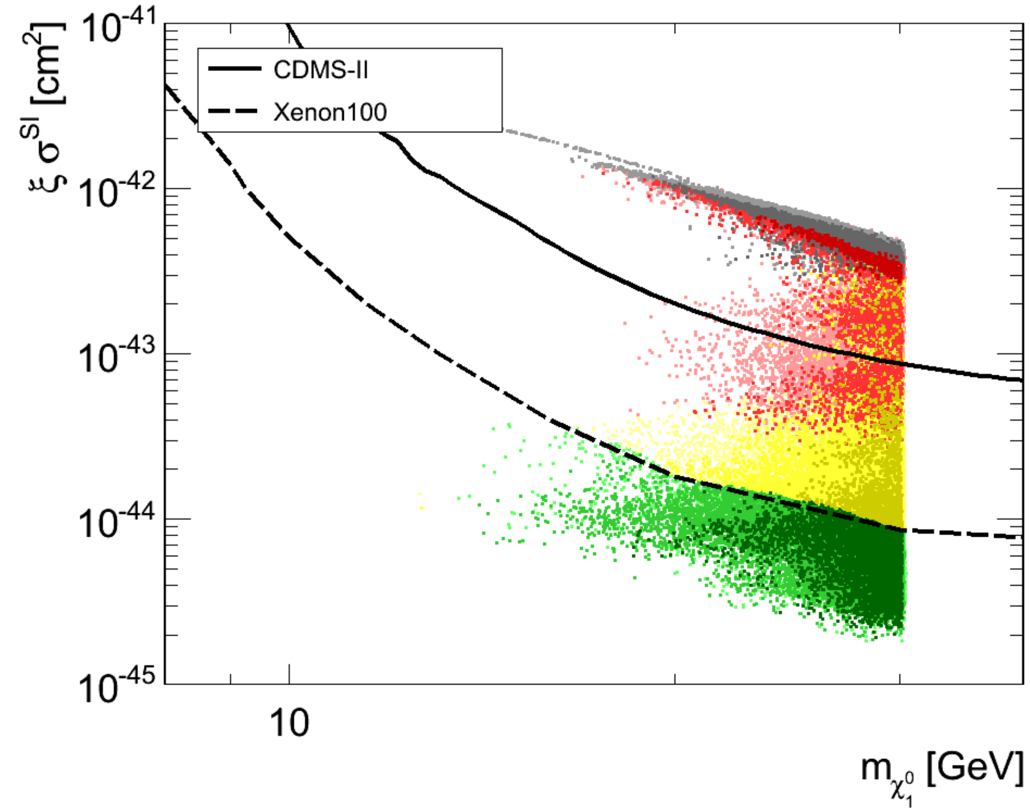
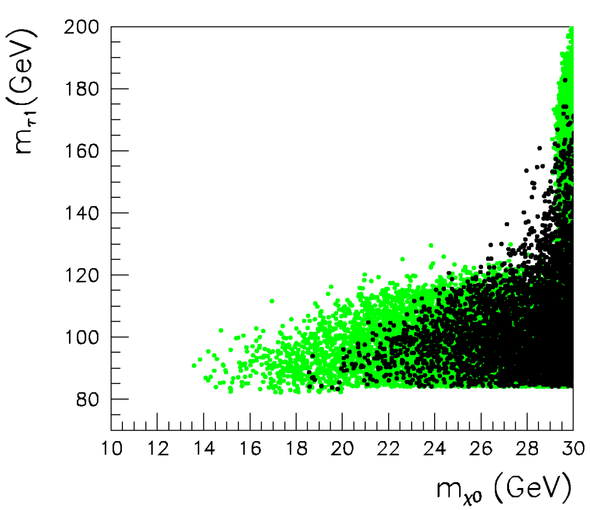
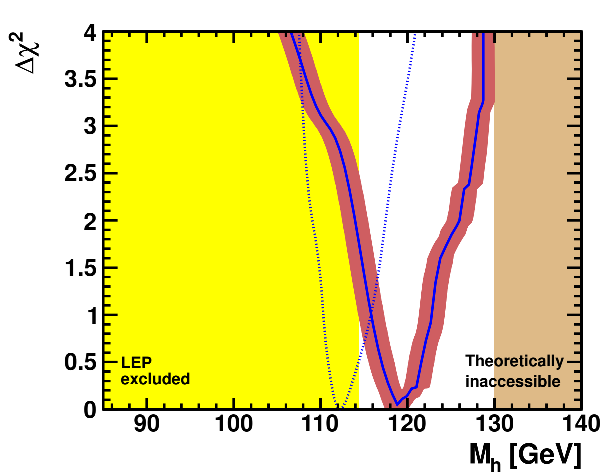



FIG. 4: Points of the $m_{\chi_1^0} < 30$ GeV search represented in the $\xi\sigma^{SI}$ vs. neutralino mass plane. Exclusion limits from CDMS-II [29] and XENON100 are shown. The color code is the same as in Fig. 2, green points are allowed.

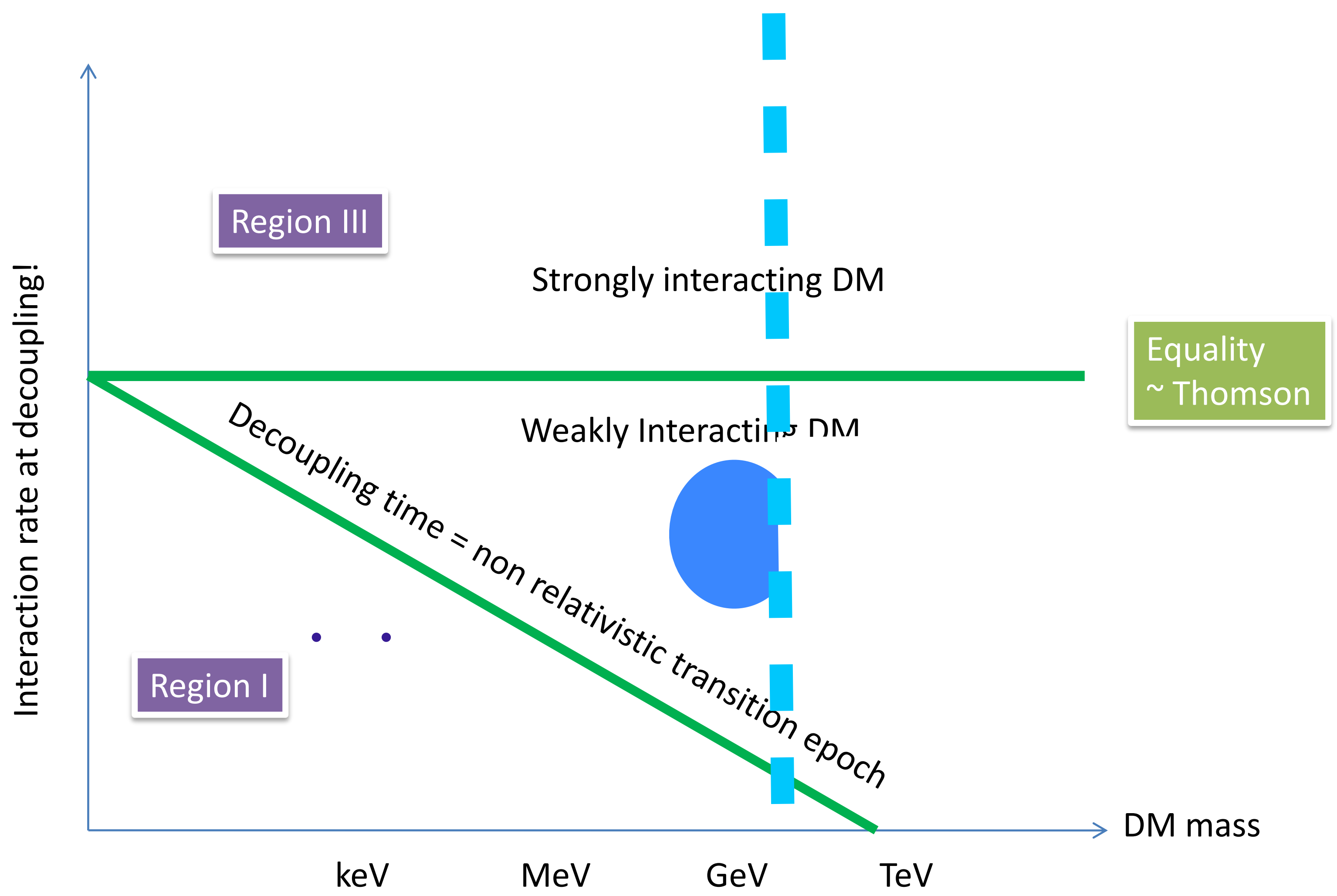



**Light MSSM neutralinos should not resist a very long time...**

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

# Light pMSSM neutralinos? not so sure!



# Another SUSY example: NMSSM

**1107.1614**

fined at the weak scale. The free parameters are taken to be the gaugino masses $M_1, M_2 = M_3/3$, the Higgs sector parameters $\mu, \tan\beta$, $\lambda, \kappa, A_\lambda, A_\kappa$, a common mass for the sleptons $m_{\tilde{l}}$ and the squarks $m_{\tilde{q}}$ as well as only one non-zero trilinear coupling, $A_t$, for more details see [4].

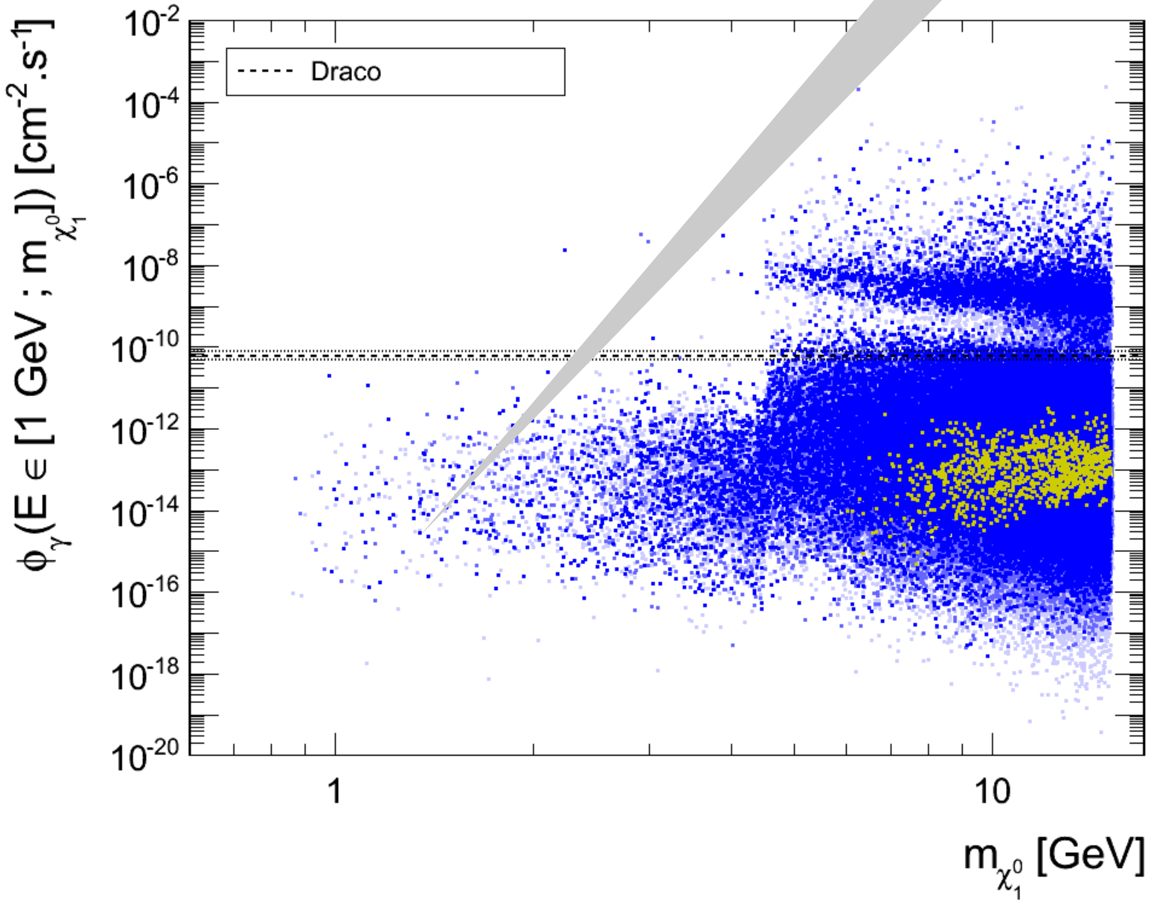
$$W = \lambda S H_u H_d + \frac{1}{3}\kappa S^3 \qquad \mu = \lambda \langle S \rangle$$

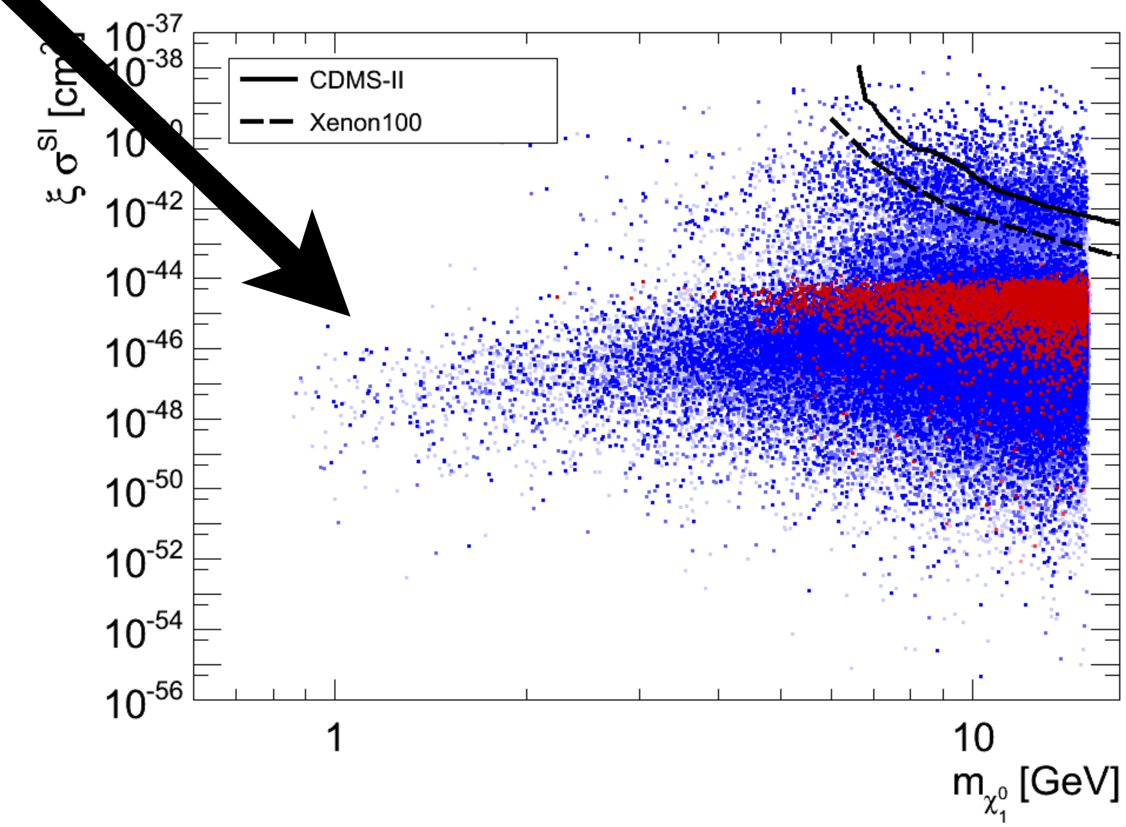
$$\mathcal{L}_{\text{soft}} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + (\lambda A_\lambda H_u H_d S + \frac{1}{3}\kappa A_\kappa S^3 + h.c.)$$

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

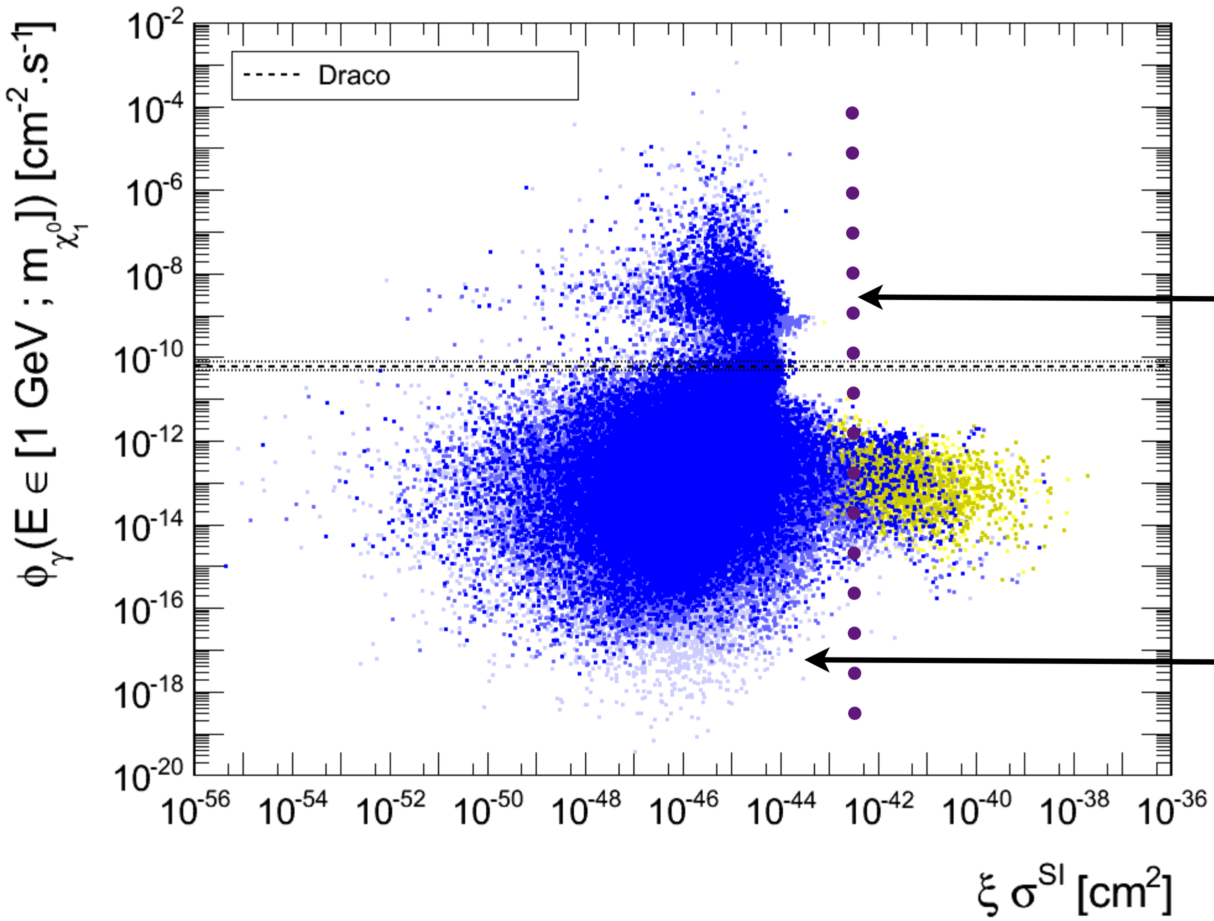
Here we are, light neutralinos...

**But…**



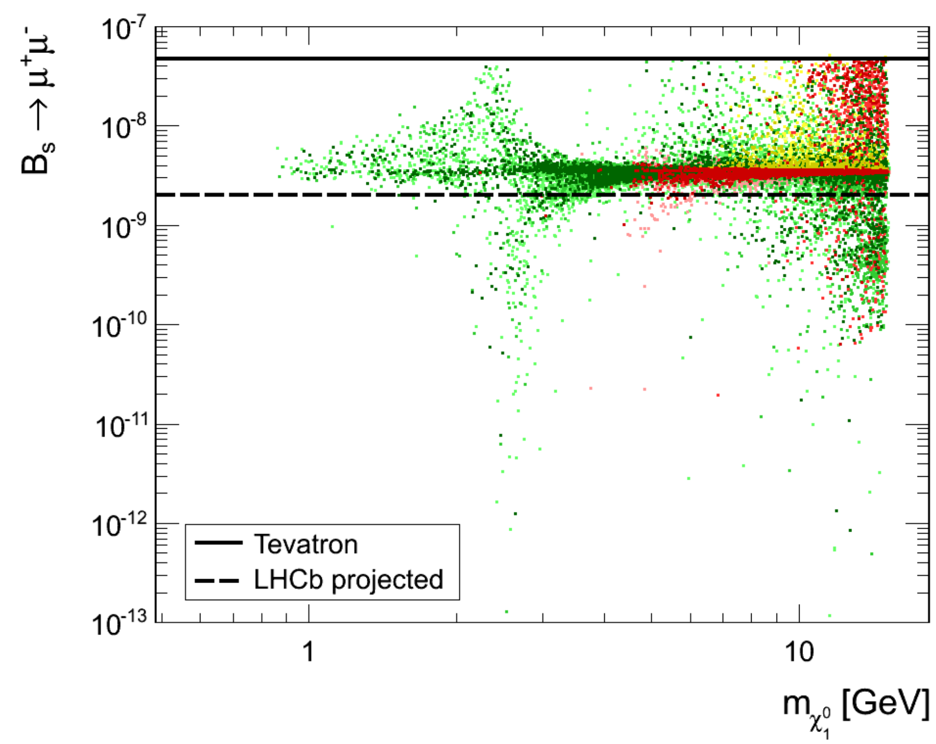
Light NMSSM neutralinos may be hard to discover and could be a solution if no new physics at LHC but easy to exclude if no Higgs!




**Direct Detection**

**But LHC might help...**

Higgs...



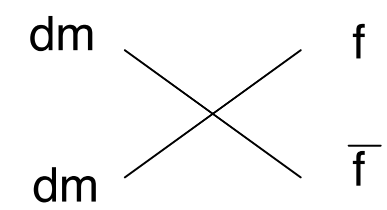
What (unconventional) else in the thermal region?

**(Did we miss something important?)**

# The mass limit dogma

**Hut-Lee&Weinberg (massive neutrinos):**

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




**general assumptions**

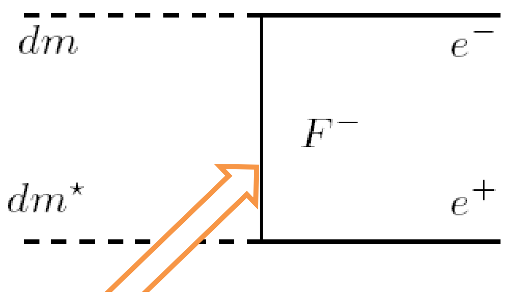
- ✤ **DM is a fermion**
- ✤ **A heavy particle is exchanged**

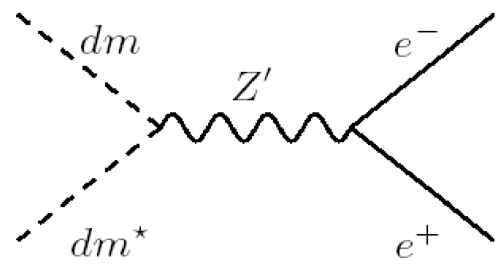
$$\sigma v \propto \frac{m_{dm}^2}{m_F^4} \;=\; 3\ 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

**Hence**

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

# The mass limit dogma



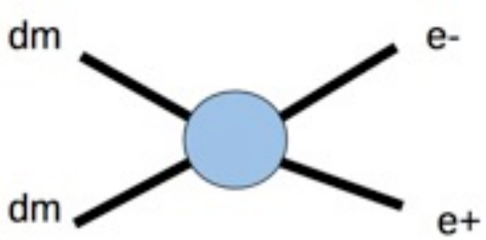

$$\sigma v \propto \frac{1}{m_F^2} = 3\ 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

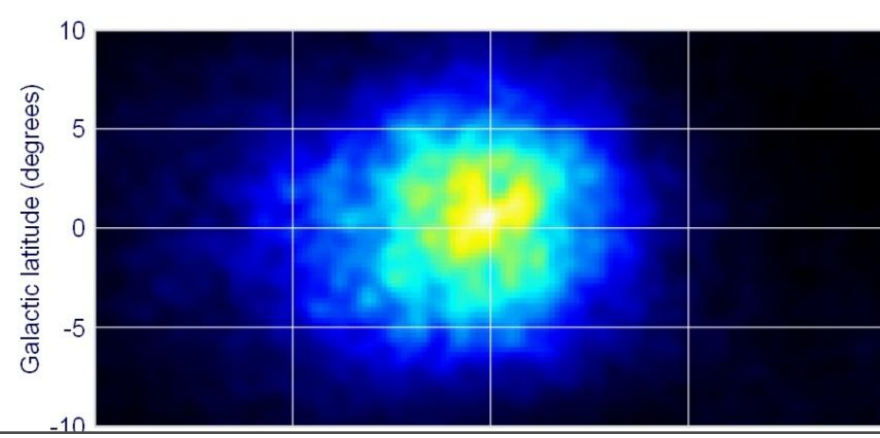
$m_{dm}$ is not constrained!

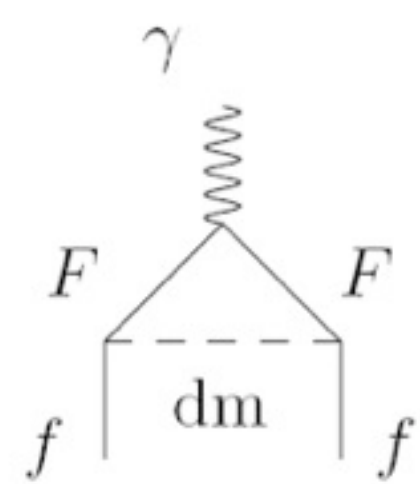
**Exceptions to Hut-Lee&Weinberg are possible**
**Annihilating DM can be lighter than 10 GeV**
**In fact, it can be as light as a few keV...**

**But direct detection experiments cannot easily go down 10 GeV**

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



Anyes Taffard

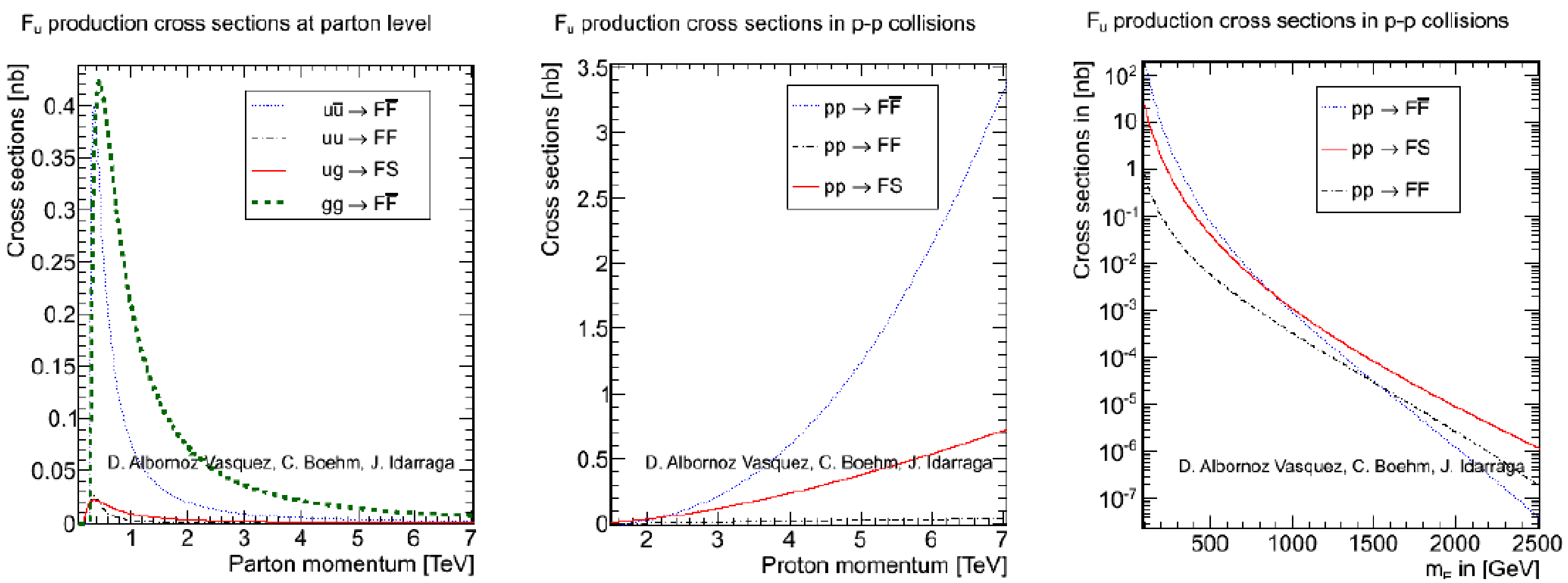
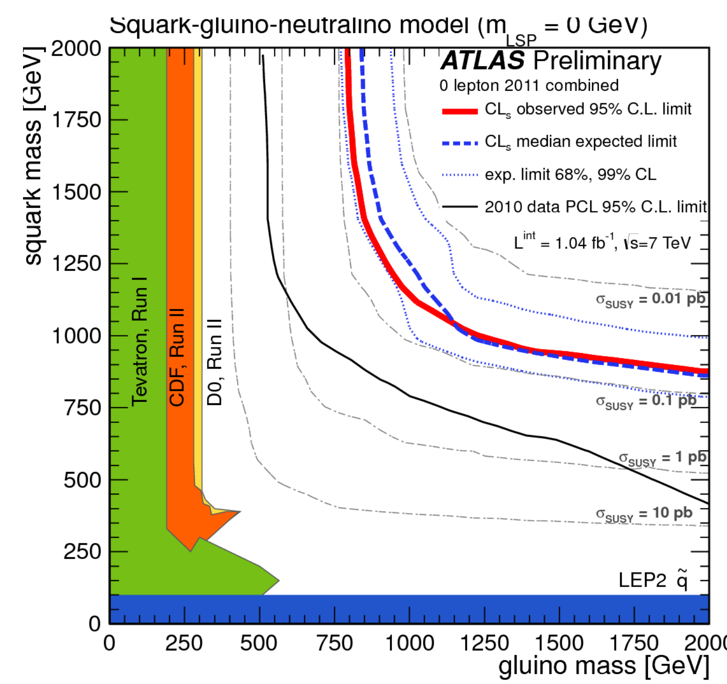


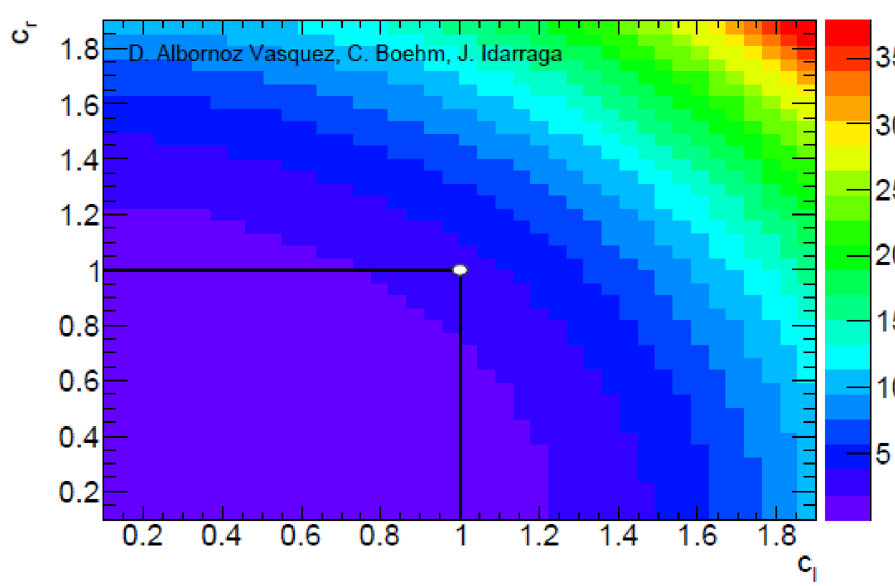

FIG. 1: $F_q$ production cross sections. Left panel: at the parton level, assuming $m_F = 300$ GeV, $c_{l,r} = 1$ and obtained by using the function *cs22* implemented in micrOMEGAs. Middle panel: at the proton level, with $m_F = 300$ GeV, $c_{l,r} = 1$ and obtained by using hCollider. Right panel: dependence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

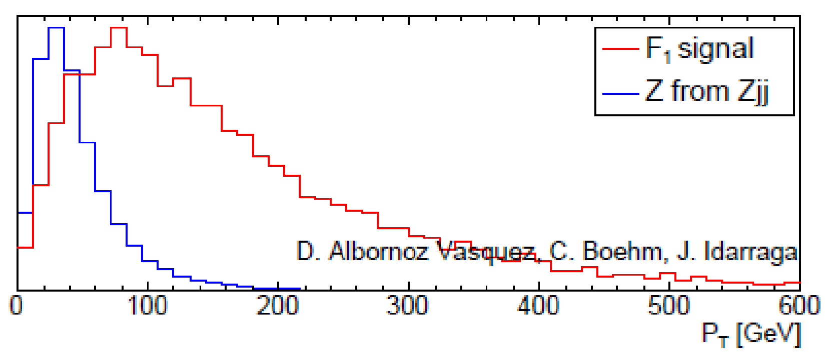


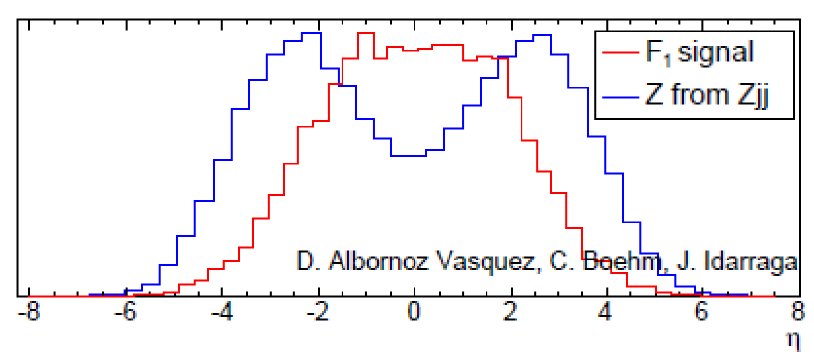

Exclude at 95% C.L

$m_{\tilde{g}} \leq 800$ GeV $m_{\tilde{q}} \leq 850$ GeV

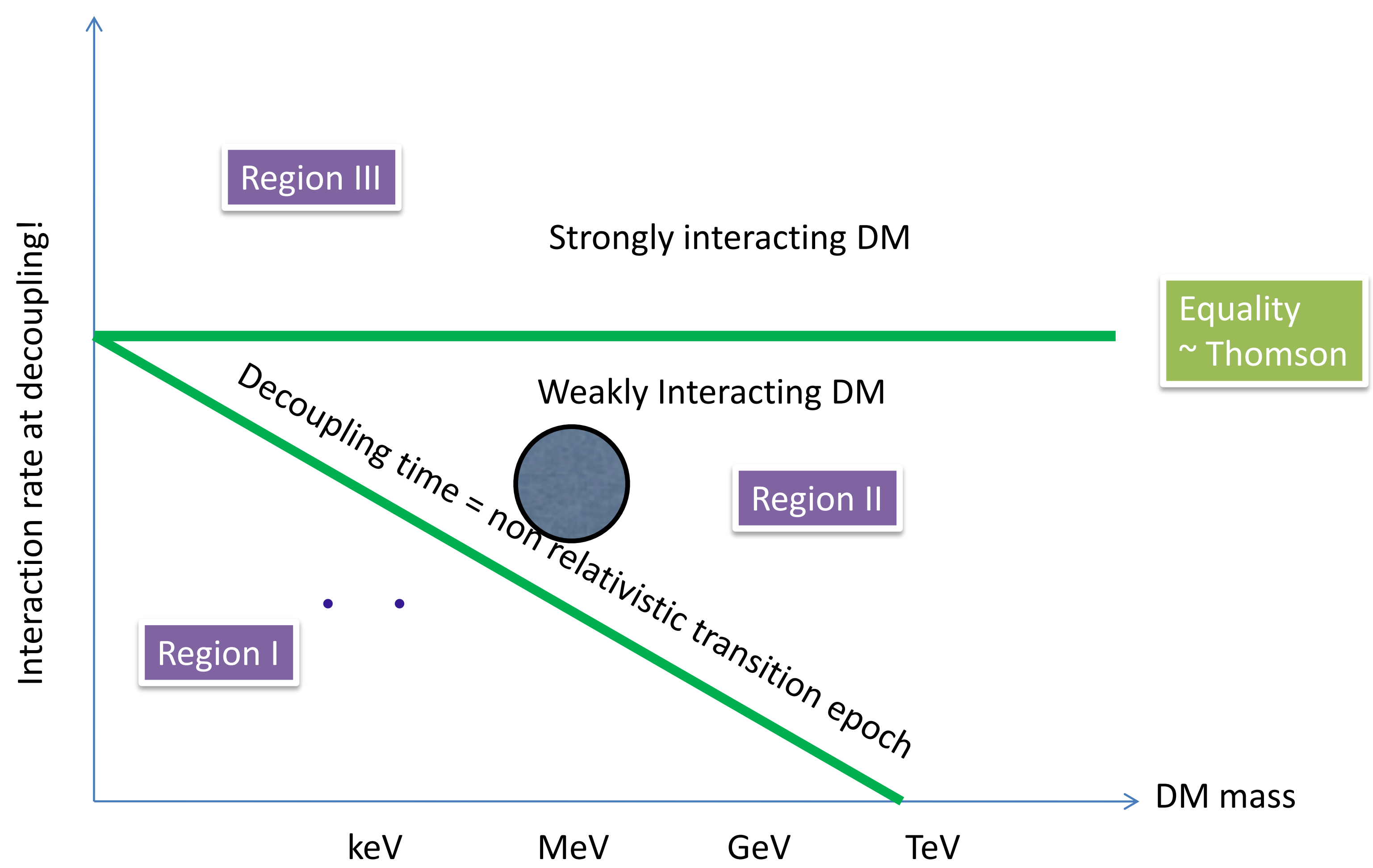
If $m_{\tilde{g}} = m_{\tilde{q}}$, masses < 1075 GeV



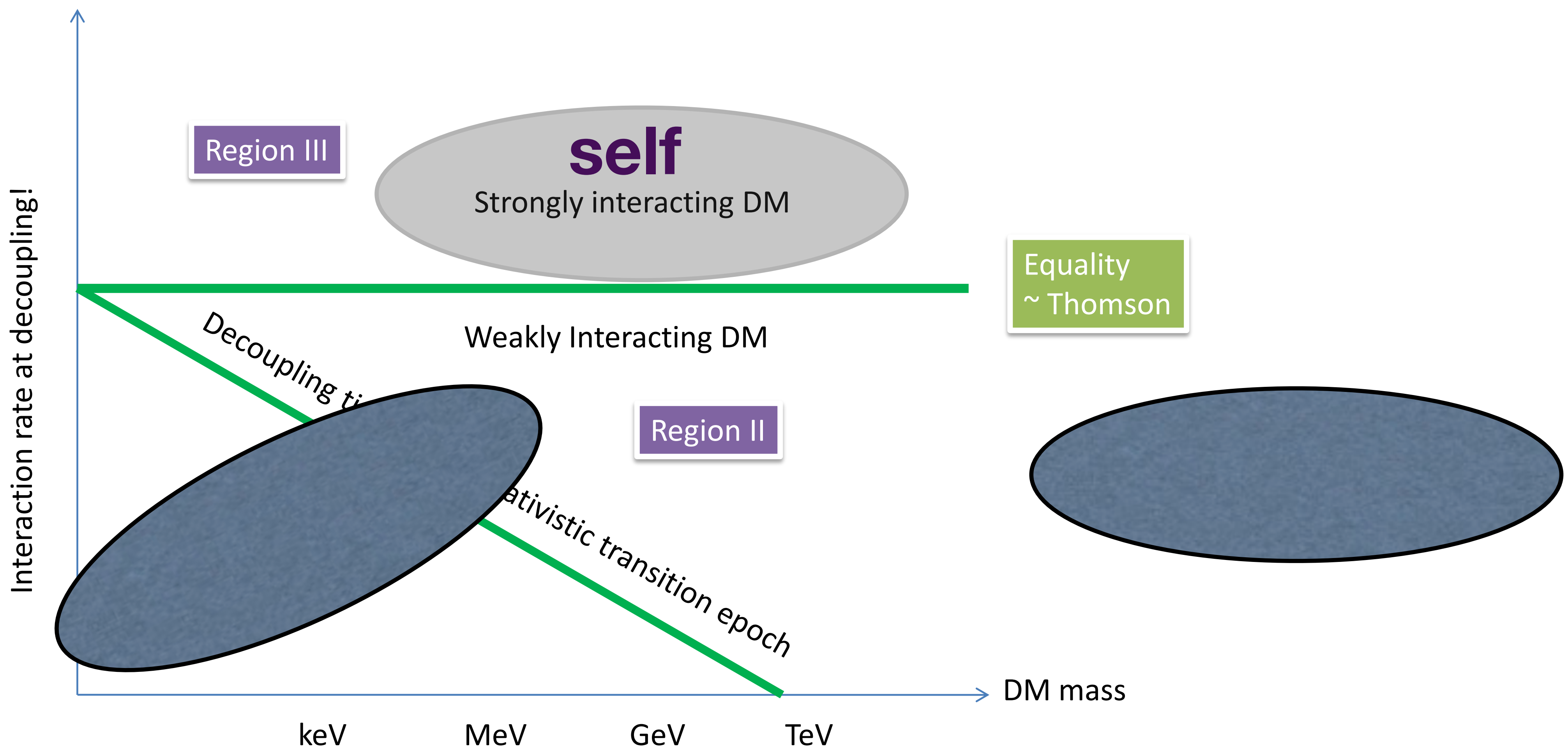
# MeV DM possible but either no charged coloured particles or very heavy ones...



So what do we do if nothing is found at LHC?

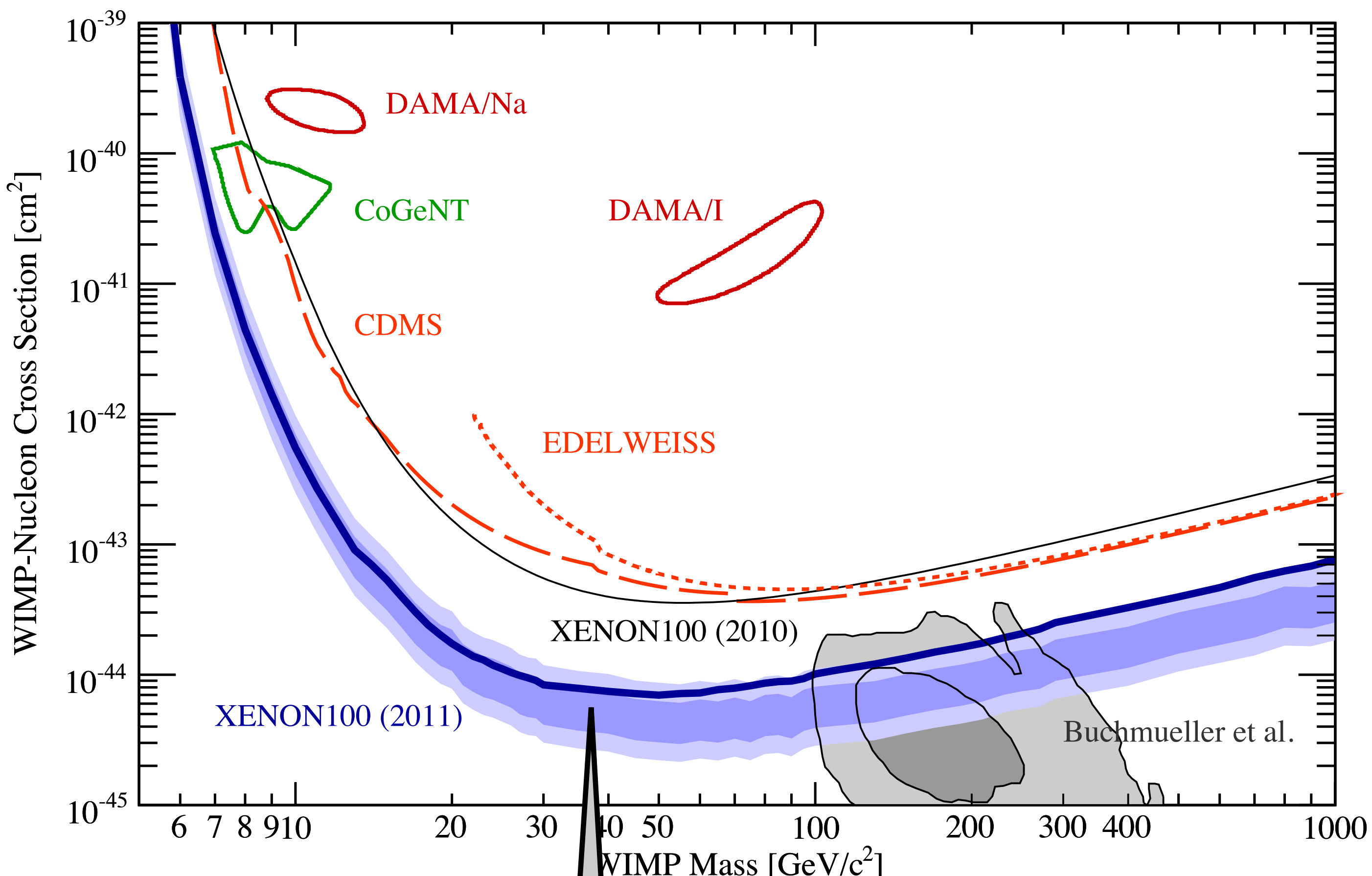
**Implication for DM**

# Start to explore new (and challenging) horizons

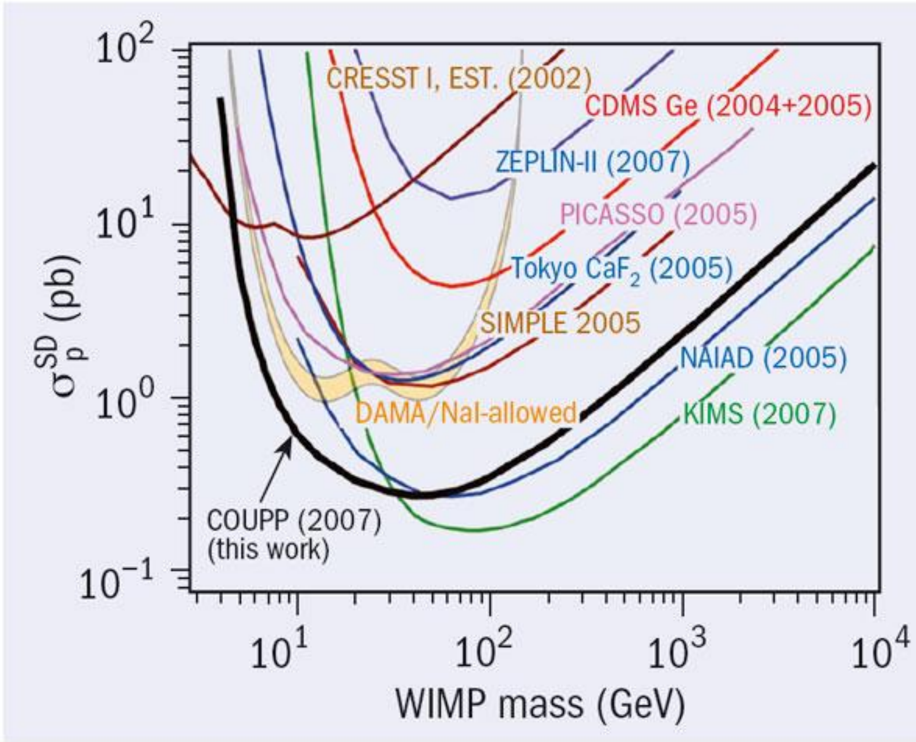


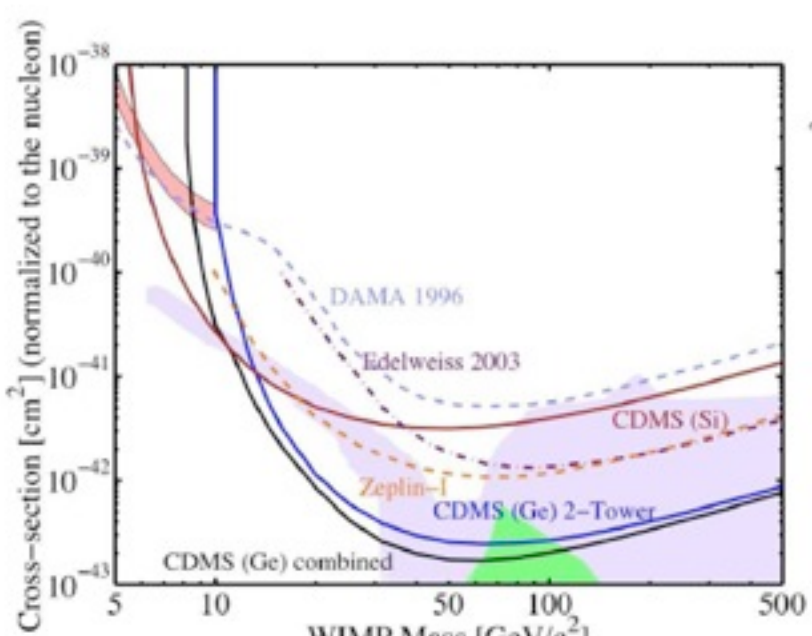
# Dark matter direct detection will become useless...unless...

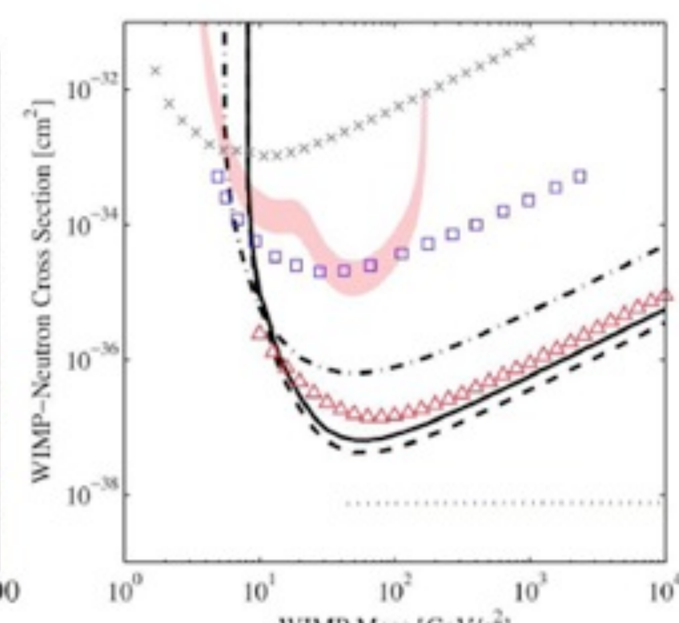
## Plethora of experiments but ...




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

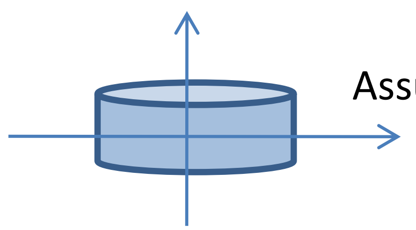


# One will have to explore in detail cosmic ray background!

Delahaye et al 2007



Assume that diffusion zone is well approximated by a cylinder

Radius of the cylinder

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

Bessel in r_cyl

Fourier in z_cyl

Source term

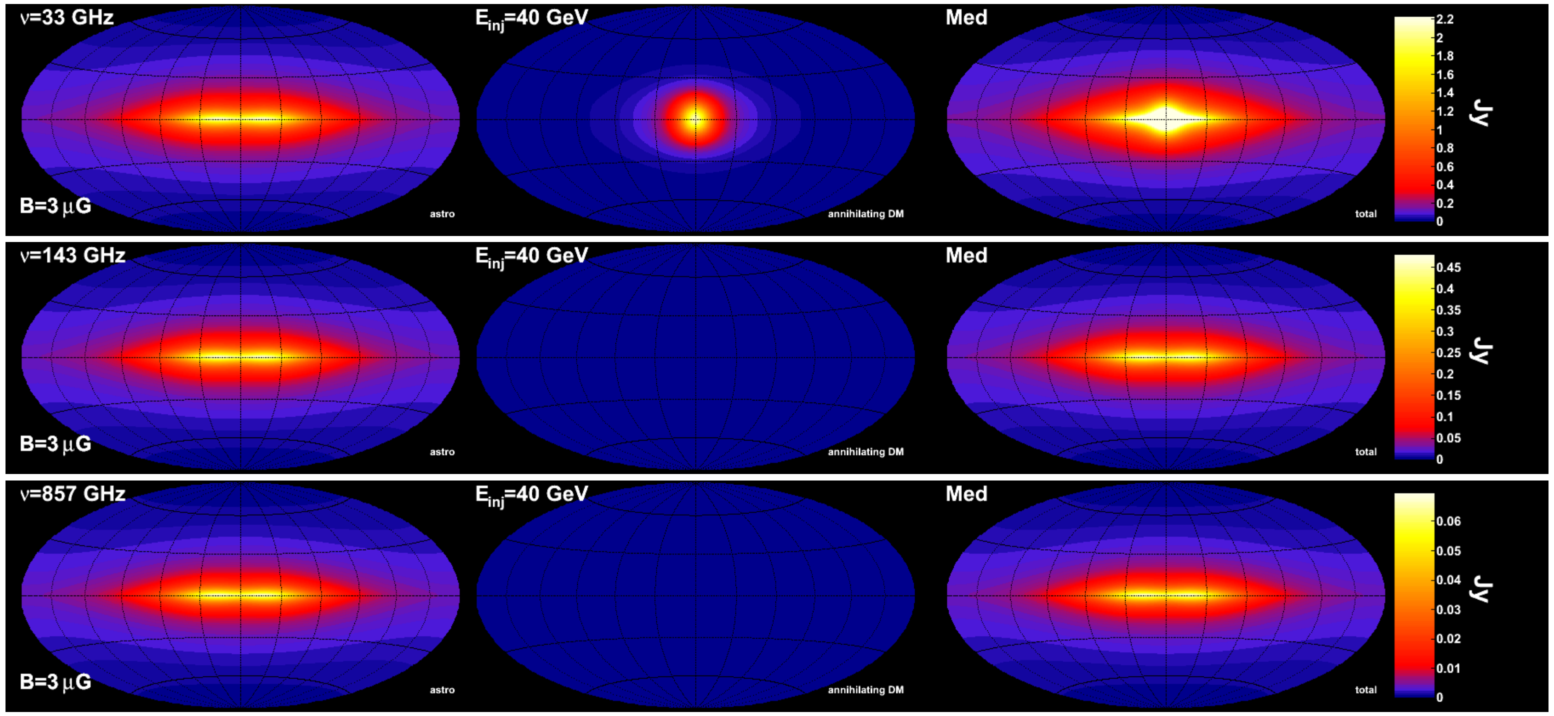
Propagation length

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

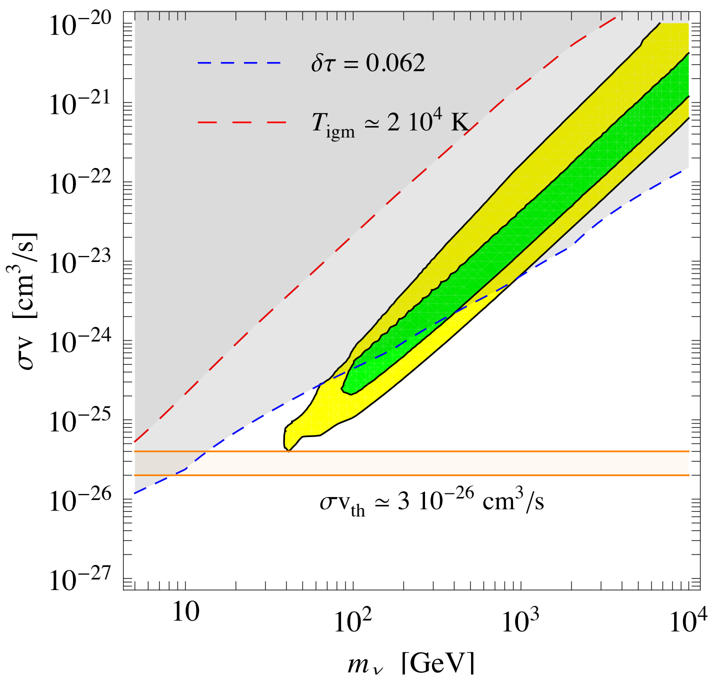
$$K(\mathrm{x}, E) = K_0\, \epsilon^{\delta} \text{ where } \epsilon = E/E_0$$

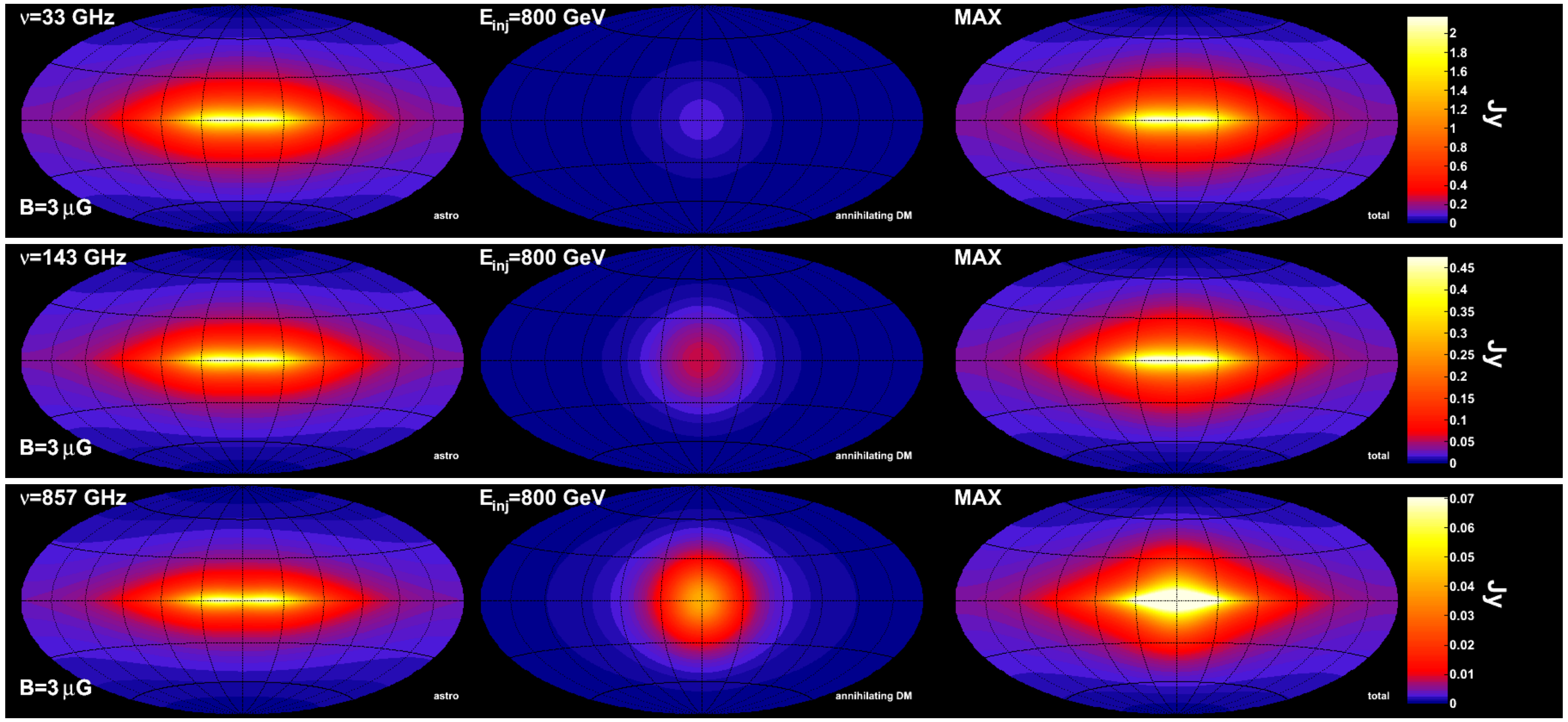
Finally flux is proportional to the integral over l.o.s (and dE) of $\tilde{I}(\lambda_D)$

# And we can still use the EM spectrum (although difficult with Planck foregrounds)




**at submillimetre frequencies but predictions at radio, X and Gamma-ray too..**



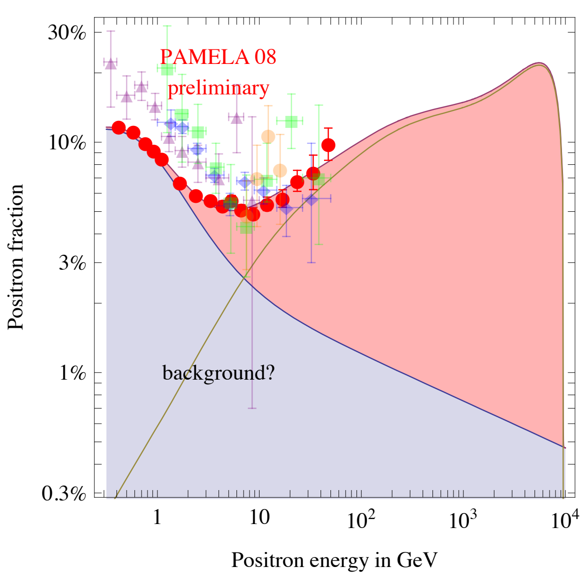



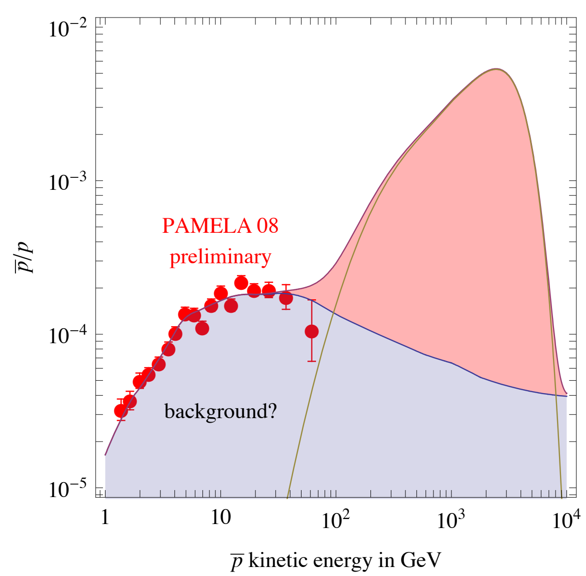

Monday, 14 November 2011

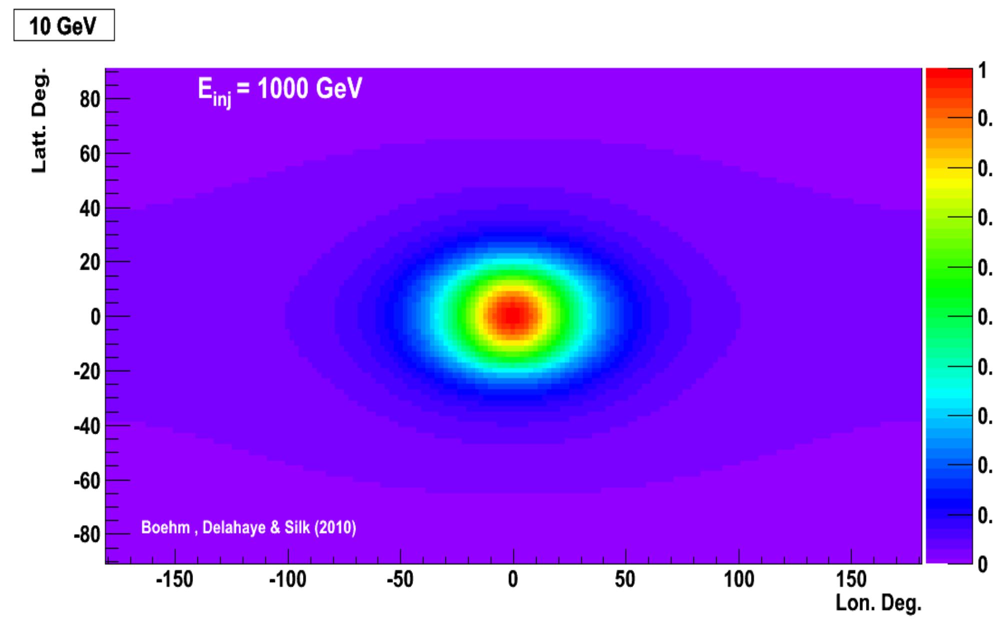
# The final states of DM annihilations thought again

- **Direct Detection based on DM interactions with quarks: Leptophilic DM could explain the absence of signal!**

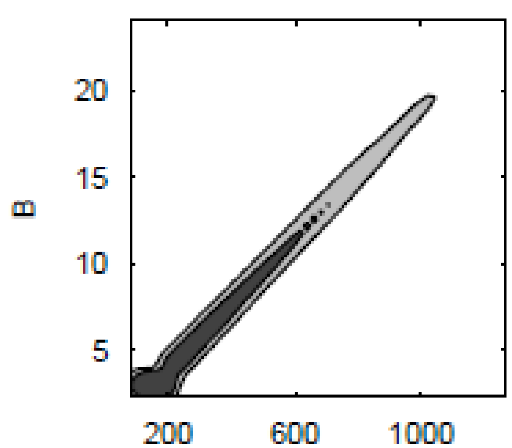
- **Still a chance to explain PAMELA but FERMI experiment is very constraining!**

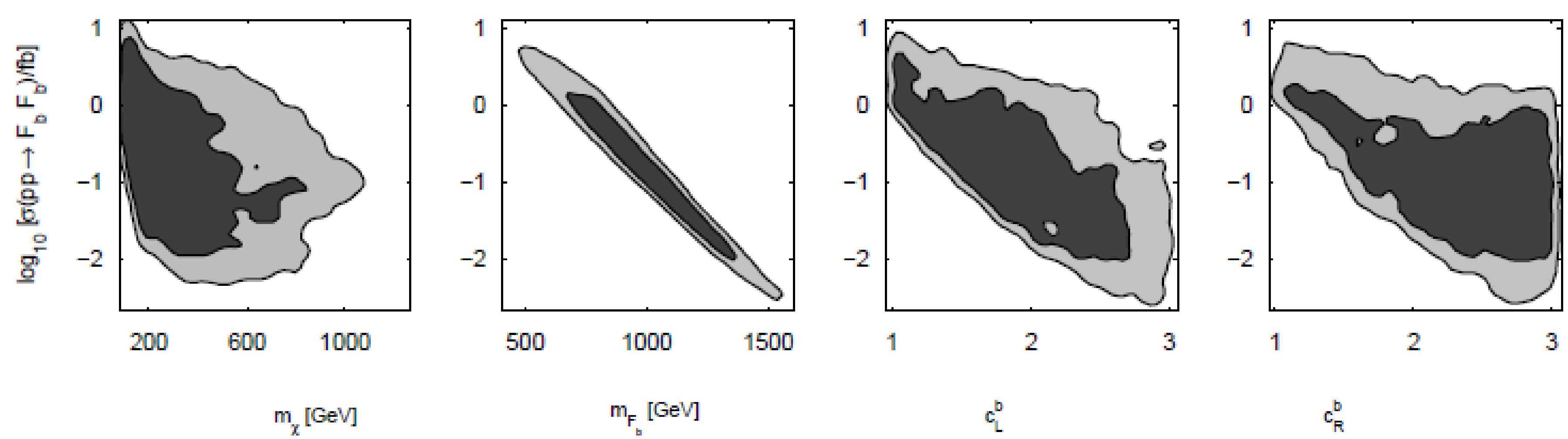



- **Leptophilic maybe ... but not necessarily quarkophobic!**



What else can we do in absence of positive results at LHC?

**Explore WDM/CDM more!**

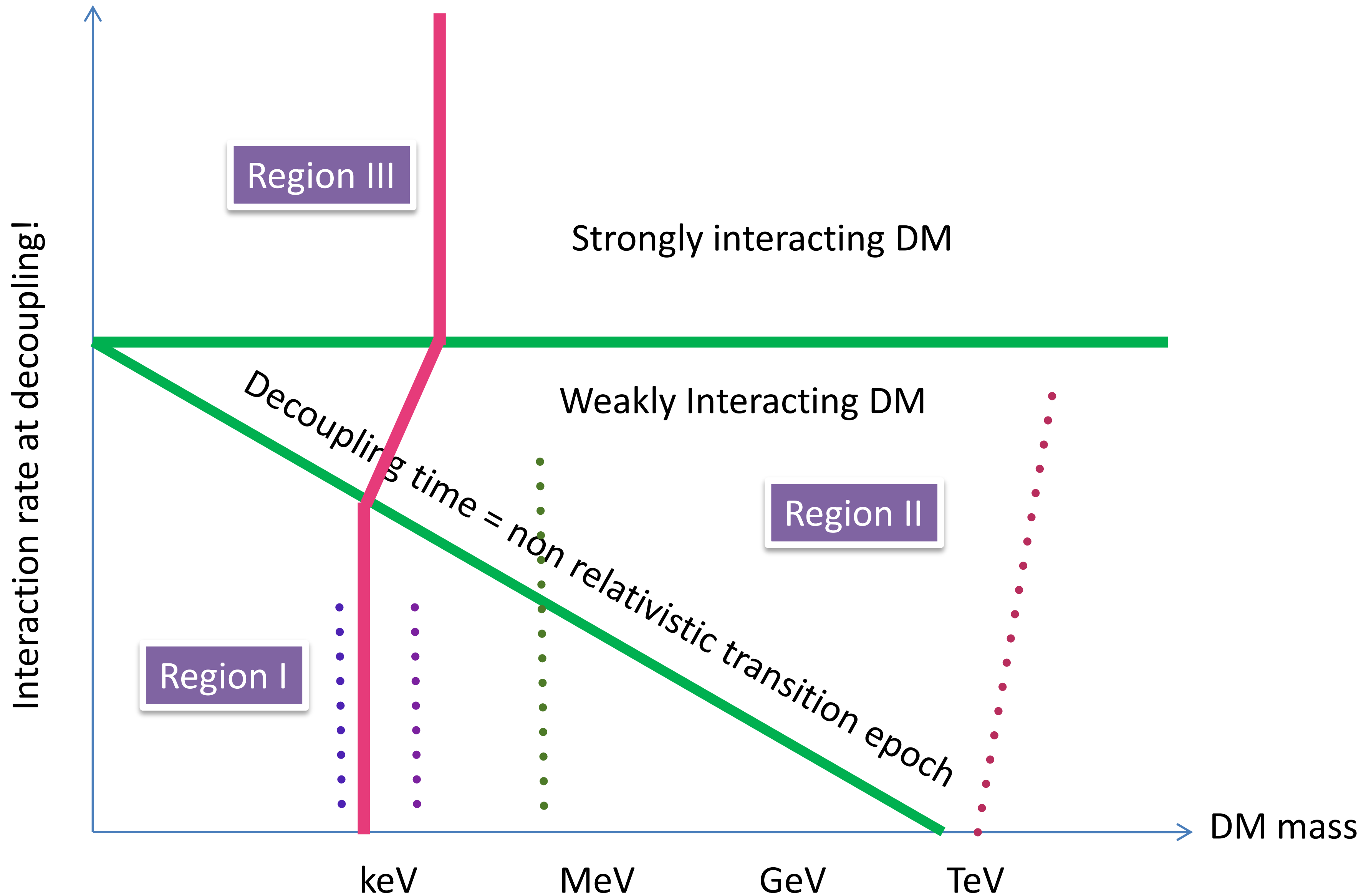
# LSS formation can reduce the parameter space quite a bit!

**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.**

**In particular, it leads to mdm > keV,
not only in region I [that everybody knows] but also for region II and III with an interesting property for region II**

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

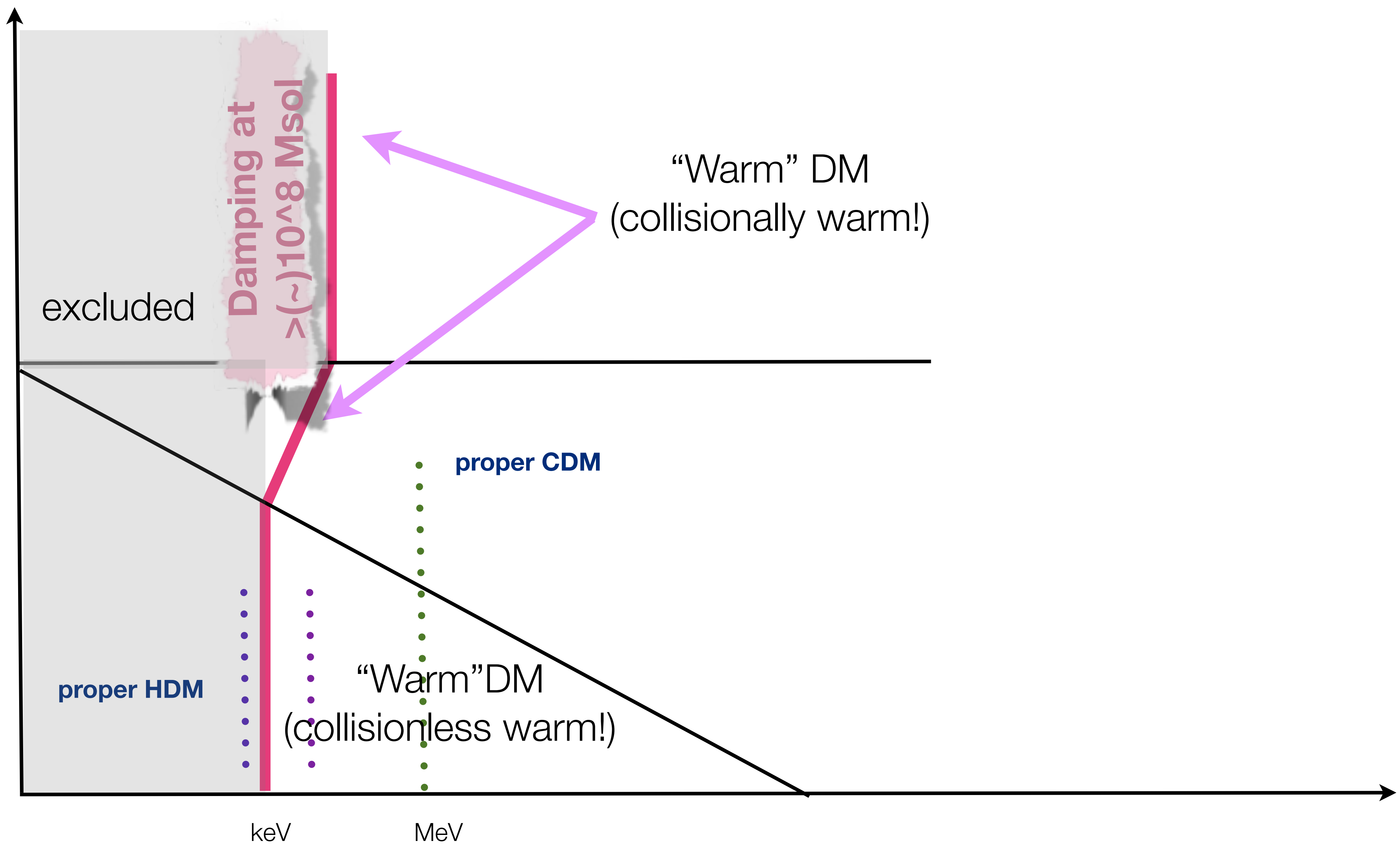
The decoupling time is important!!!




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

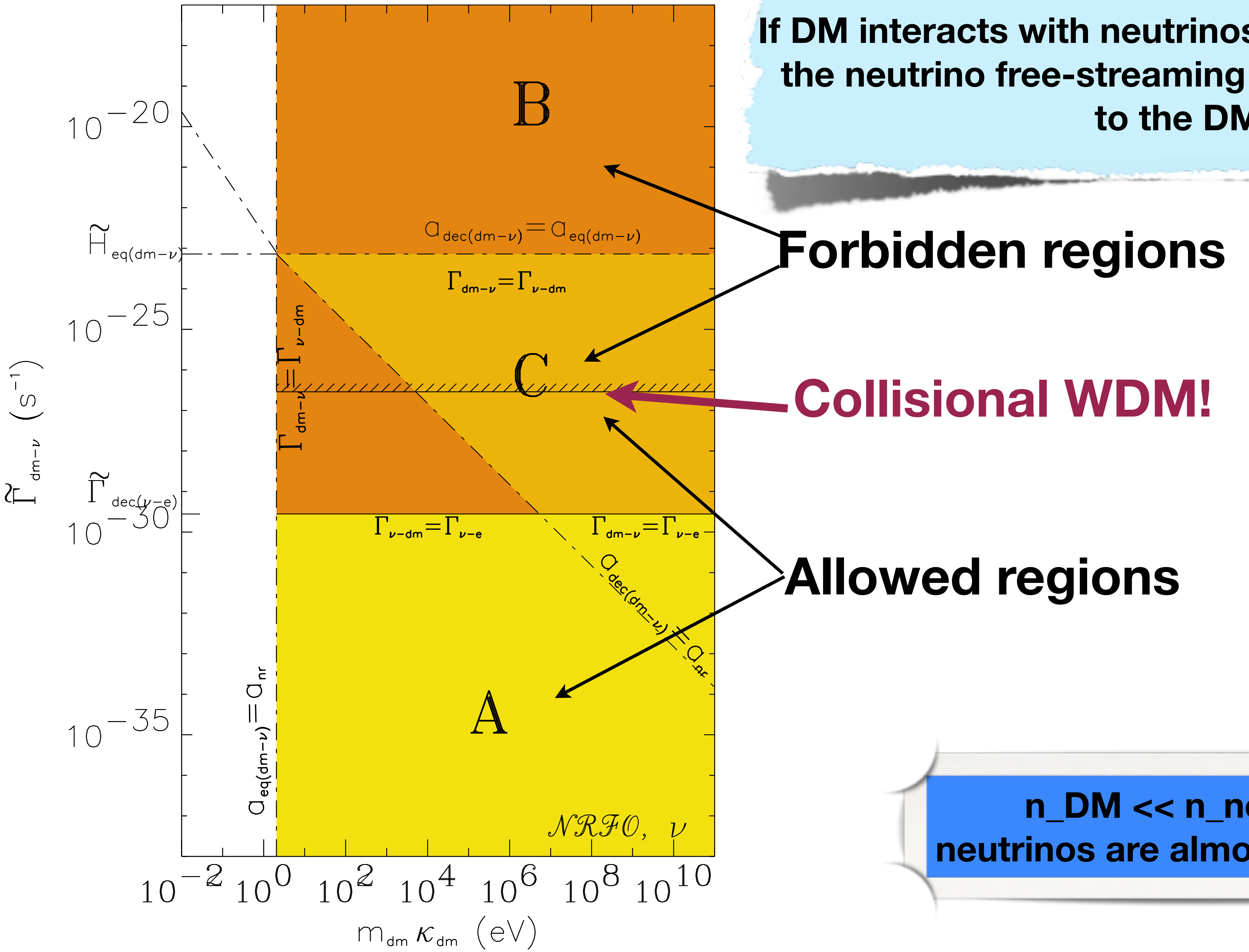
# Definition of WDM revisited....

**astro-ph/0012504; astro-ph/0410591**



# DM-neutrino interactions: a new damping effect

astro-ph/0012504; astro-ph/0410591




**If DM interacts with neutrinos at nu-e decoupling, the neutrino free-streaming can be transmitted to the DM**

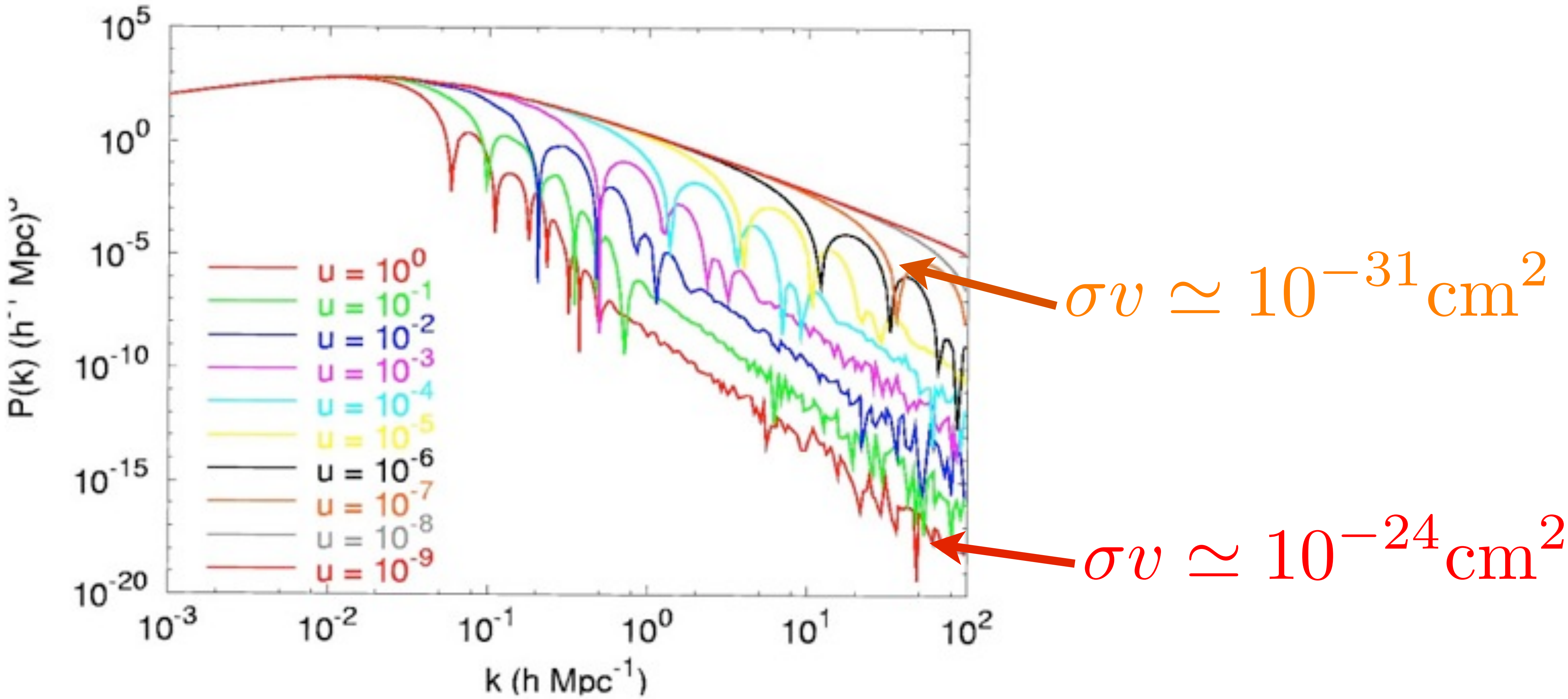
**n_DM << n_neutrinos**
**neutrinos are almost decoupled**

# (Coll)WDM with photons and baryons: Let us now use the Power Spectrum!

**astro-ph/0112522**

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

**P(k) for DM interactions = u * Thomson cross section**

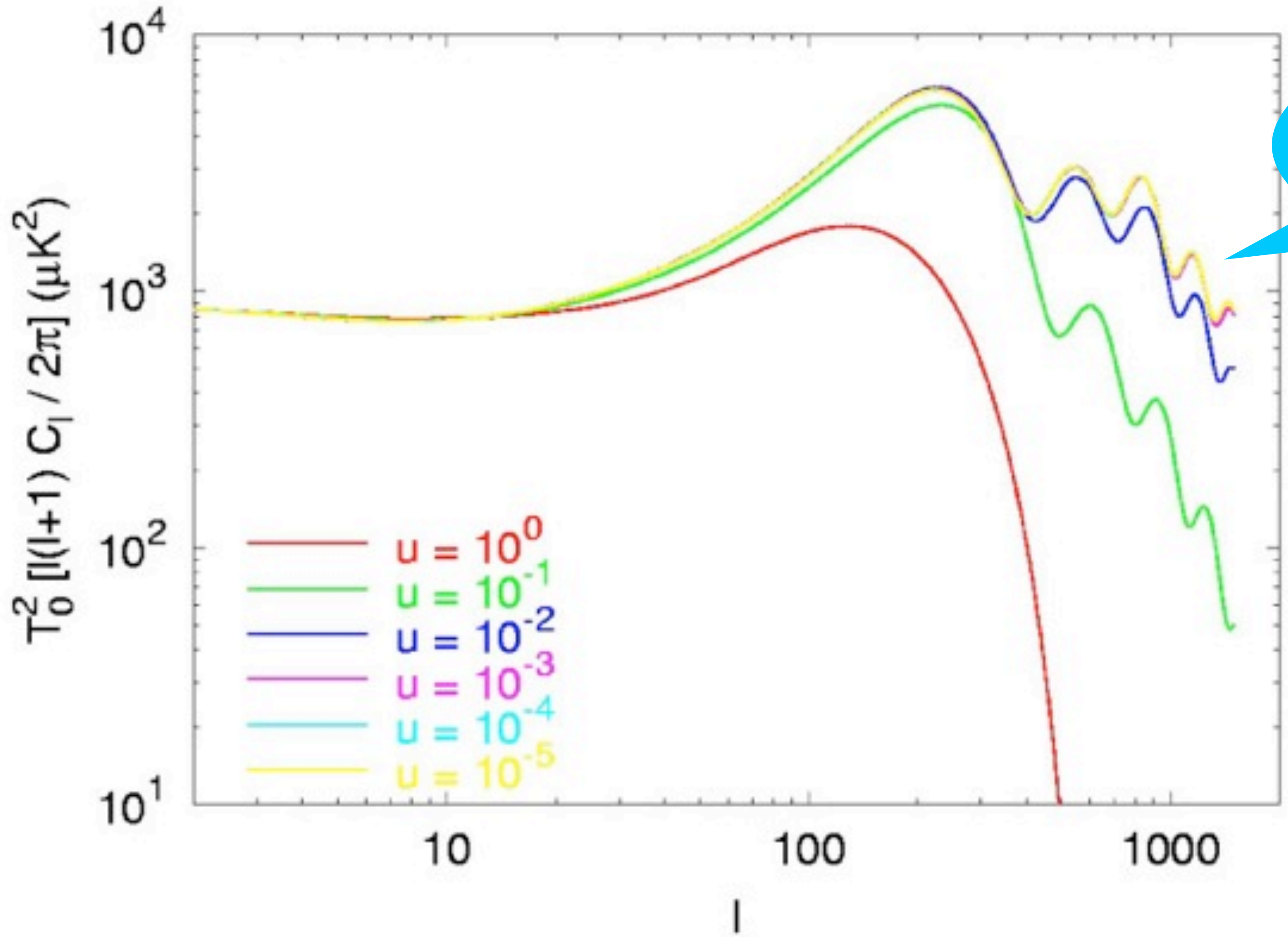



The stronger the interactions, the more pronounced the oscillations

# CMB physics/PLANCK can be used to constrain the DM interactions

astro-ph/0112522

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

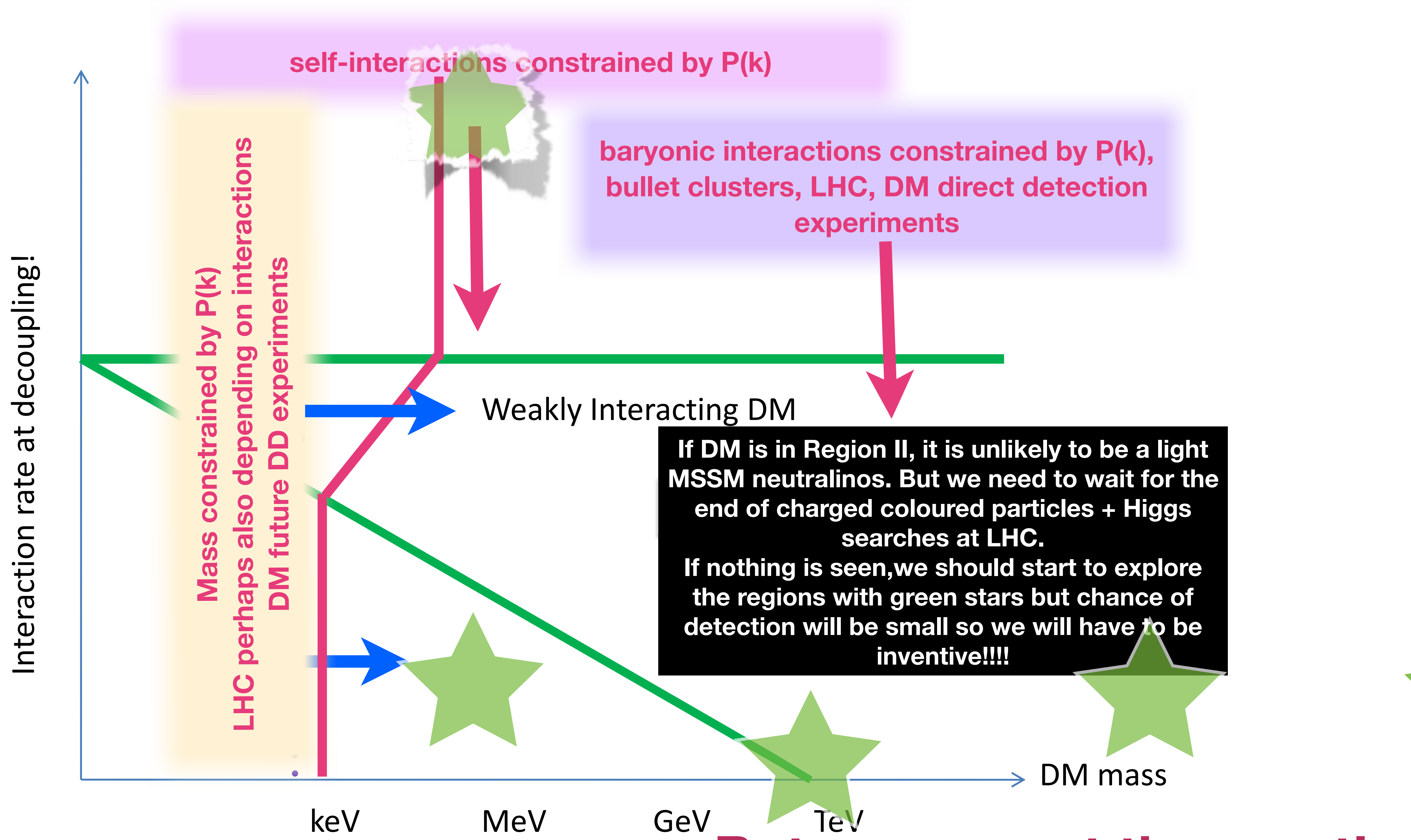



**Now time to zoom in!**

Conclusion

**Should we be worried if no Higgs and new physics is seen at LHC?**

# Conclusion of 10-20-30-40 years of DM hunting




**But we are not there yet!**