# Dark Matter candidates: where do we stand?

Céline Boehm, IPPP

# Many changes happened during the last decade

## Not a 'relic density' driven field anymore

23% not 90% + small uncertainties forced people to look for alternatives and even question the need for using RD

## Instead driven by astrophysical data!

Gamma rays, Xrays, Radio, submillimetre, antiprotons
Direct Detection is fighting hard though

**(DM interacts less than a neutrino with an electron at 1 MeV!!!)**

## Phenomenology overtook the theory

leptophilic DM; sub 10 GeV DM; TeV-10 TeV DM ; etc etc

# A recap of the situation

# Situation 10 years ago

- Typical candidates which used to be considered : SUSY (neutralinos, gravitinos), Axions, KK
- Main paradigm driving the theory: Relic Density

$$\frac{dn}{dt} = -3\ H\ n - <\sigma v> (n^2 - n_{eq}^2) \qquad \langle \sigma v \rangle = \frac{3.\ 10^{-27} cm^3/s}{\Omega_{dm} h^2}$$

As the relic density measurement became more and more precise (WMAP1 to WMAP 7 + others) the uncertainties on the annihilation cross section became smaller and smaller.

In e.g. SUSY models this translates into a mass constraint because

$$\sigma \propto \frac{1}{m^2}$$

**The problem is how to fit a very precise value within a given model.**

**RD constrain the DM mass!**
**mdm > GeV**
**mdm < O(100) GeV if no enhancement of the cross section**

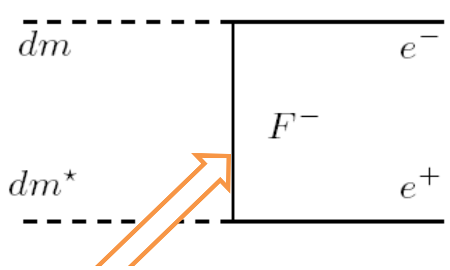
# So what happened to the mass range? (and the type of DM interactions)

| Questions | Possible motivation |
|---|---|
| • Can we go to sub GeV masses? | **511 keV line** |
| • Can we go to TeV masses? | **PAMELA** |
| • Is the 1-10 GeV range interesting? | **CoGeNT/DAMA/...** |
| • Should we go back to the normal/vanilla mass range? | **FERMI-LAT** |

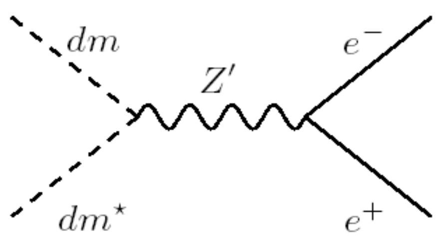
# How can we go to the lower range?

- We need a cross section that is independent of the DM mass or with a light mediator!
- So what about if DM is a boson and/or exchange a light particle?

## Scalar DM

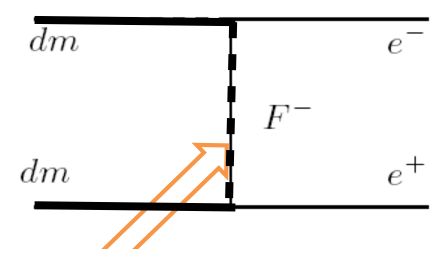



c.s. is independent of
mdm

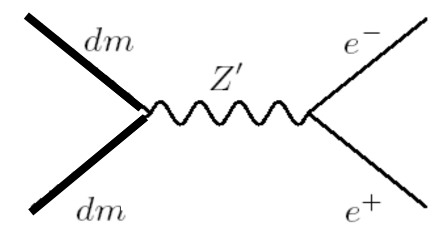



c.s. depends on mDM
but compensated by light Z'

## Fermionic DM




SUSY
case




depends on mdm but
light Z'

+ Higgs exchange

**In principle one can go to low mass**

(down to keV in accordance to structure formation)

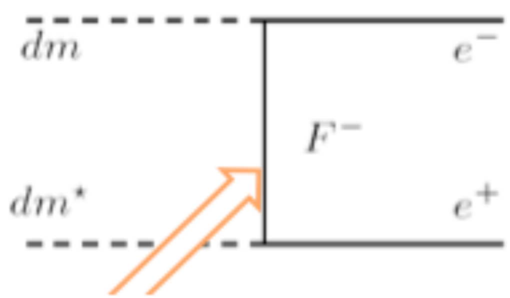
# Beware GAMMA RAYS!

CB, T. Ensslin, J. Silk 2002

Low energy electrons produce gamma rays!

* In 2001, we had good data at low energy and not so many data at high energy.

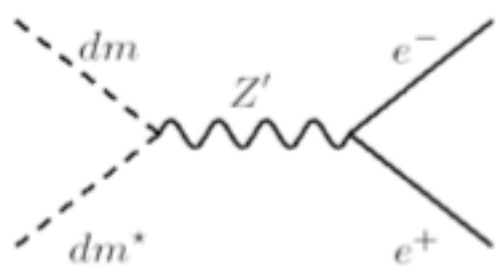
* One needs to suppress the annihilation cross section with respect to the canonical (RD) value by about 10^-4 at least!! So this indicates that the RD would be driven by a Z' exchange.




$\sigma \propto constant < 10^{-31} \mathrm{cm}^3/\mathrm{s}$

assuming 1 electron = 1 photon and 1 MeV DM

at this stage, a needless addition




$\sigma \propto b\, v^2 < 10^{-31} \mathrm{cm}^3/\mathrm{s}$

assuming 1electron = 1 photon and 1 MeV DM

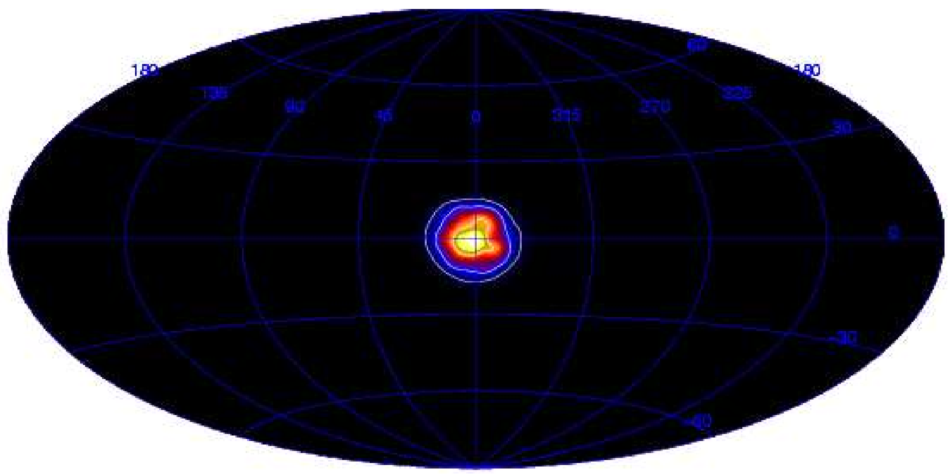
natural solution;
mandatory to achieve the RD

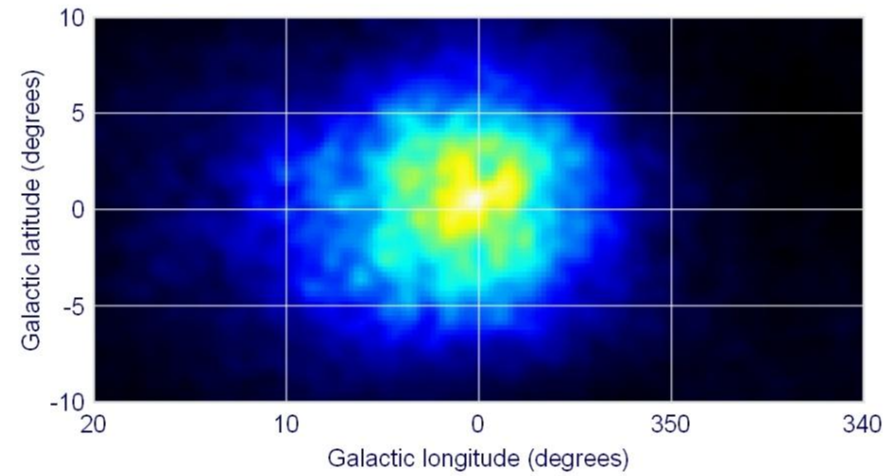
**But this also means that one expects low energy positrons in the galactic bulge!**

# Spin-off: 511 keV line

CB,Hooper,Silk, Casse 2004
0309686

And such low energy positrons have been seen!!! The question is do they really originate from Light DM??






If so: we have found manifestation of BSM physics
If not: we have found new astrophysical sources

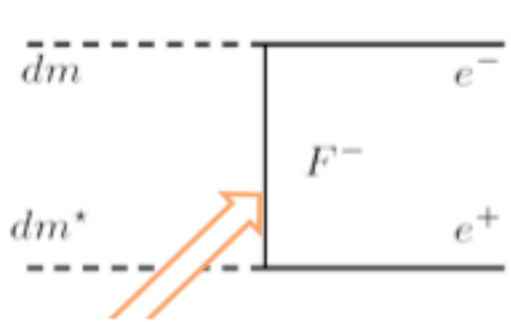
**Many Light DM models were proposed! (0702587,0703128, ...)**

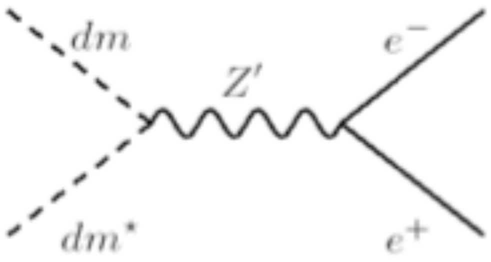
Analysing INTEGRAL/SPI data, the conclusion is that if DM is responsible for the bright 511 keV signal in the galactic centre then DM must be

*** Annihilating DM fits the data**
*** Decaying DM does not fit the data : ruled out!**
*** Annihilating DM must have an annihilation cross section that is constant: the Z' explanation was also ruled out!**

# Conclusions from fitting INTEGRAL/SPI data

astro-ph/0507142

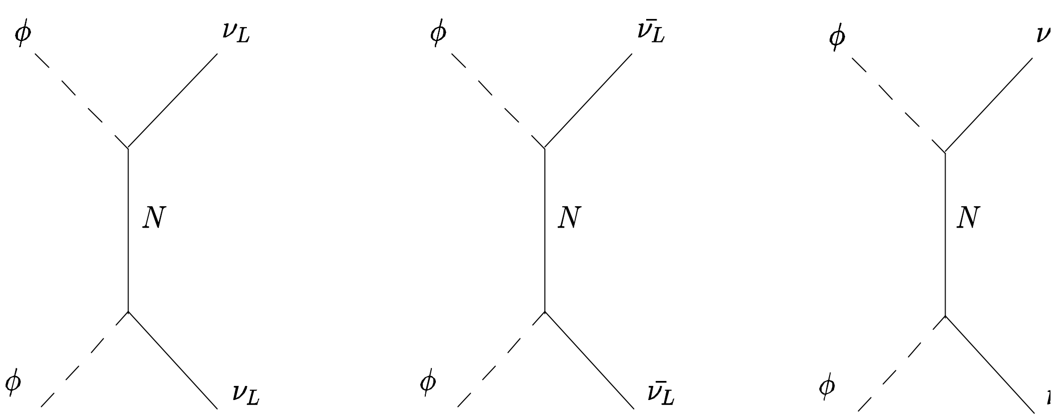


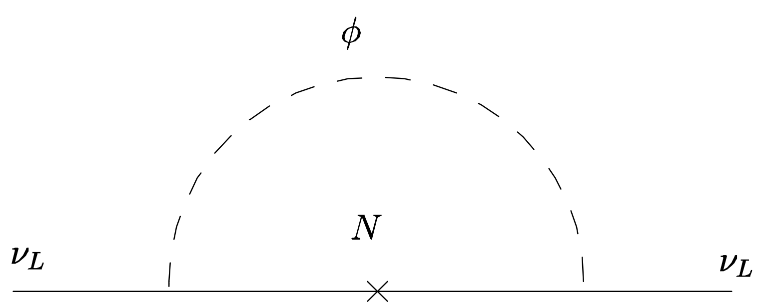




$$\sigma v = 2.6\ 10^{-30} \left(\frac{m_{dm}}{\text{MeV}}\right)^2 \text{cm}^3/\text{s}$$

**Needed to fit the 511 keV data**

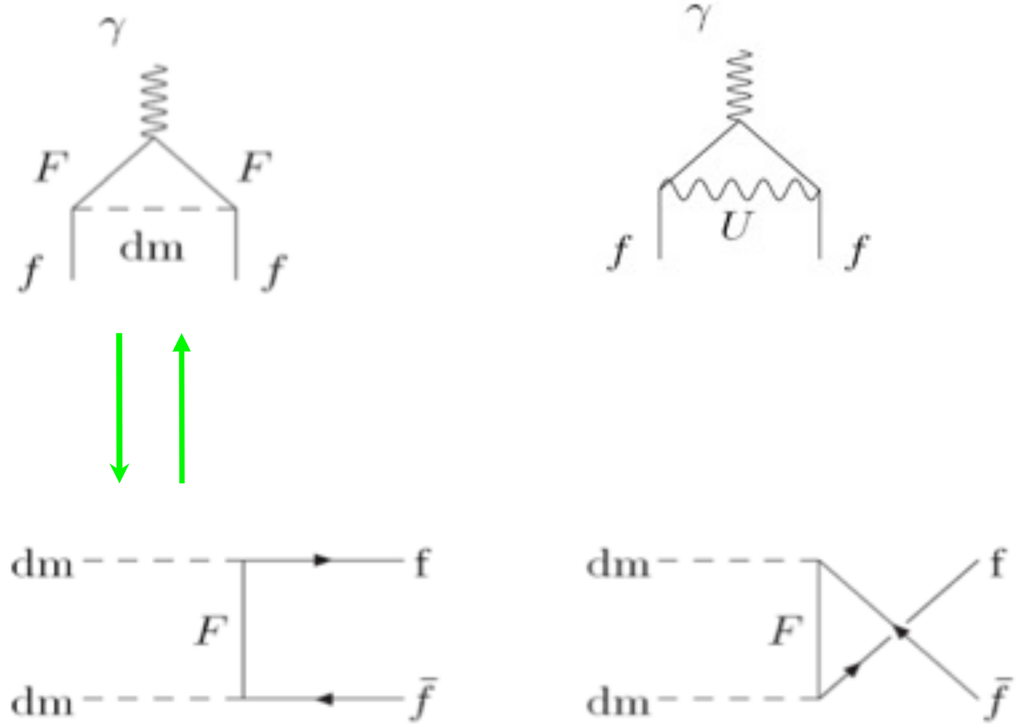
**Not needed to fit the data but needed for RD, although ...**

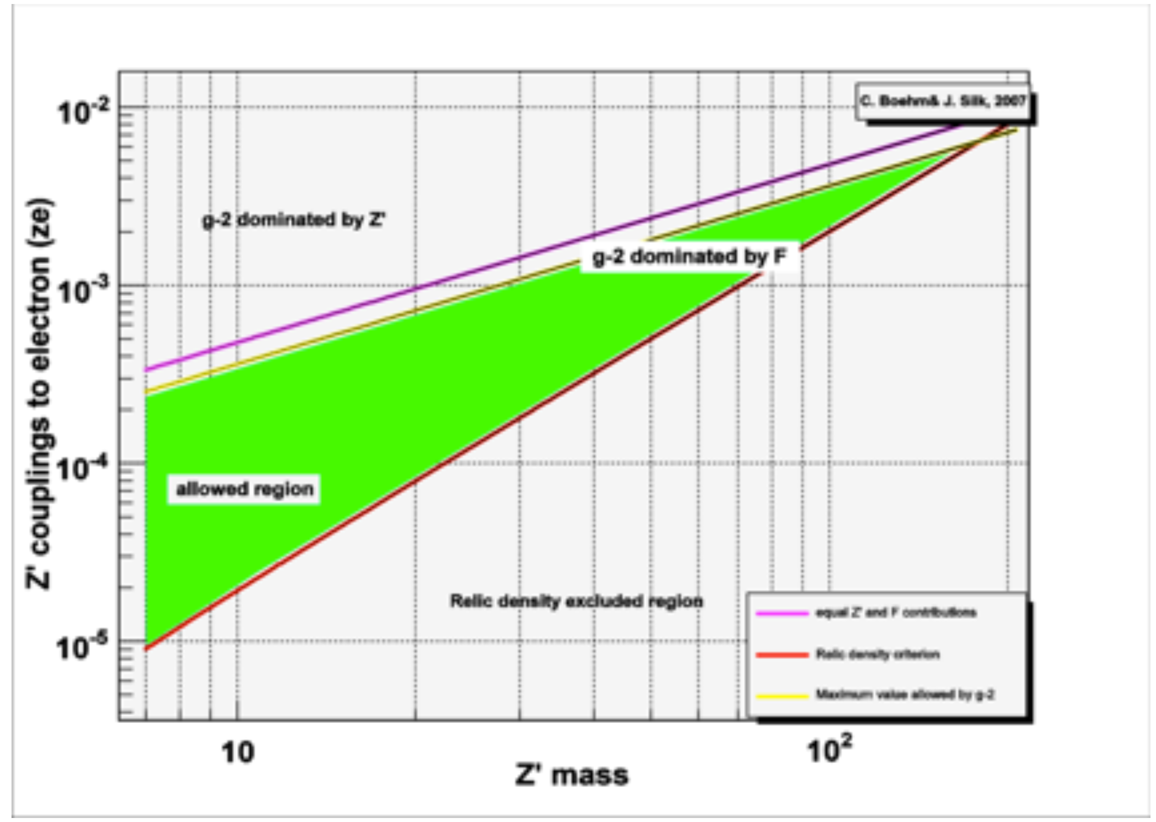



This is another way to explain the RD; yet constraining Z' is very useful!

(even if we forget the 511 keV line)




| | $F_e$ | $Z'$ |
|---|---|---|
| $a_e$ | $\frac{c_l c_r}{16\pi^2}\frac{m_e}{m_{F_e}}$ | $\frac{z_e^2}{12\pi^2}\frac{m_e^2}{m_{Z'}^2}$ |
| = | $5.10^{-12}\sqrt{f}\left(\frac{m_{dm}}{\mathrm{MeV}}\right)$ | $10^{-11}\left(\frac{z_e}{7\,10^{-5}}\right)^2\left(\frac{m_{Z'}}{\mathrm{MeV}}\right)^{-2}$ |

## Experimental results

$$\delta a_{CS06} = a_e^{th}(\alpha_{Cs06}) - a_e^{exp,06} = -7.9\ (9.3)\ 10^{-12}$$

and

$$\delta a_{Rb06} = a_e^{th}(\alpha_{Rb06}) - a_e^{exp,06} = 1.9\ (7.7)\ 10^{-12}$$

**+ new constraint (cf W. Marciano's talk)**

$$\delta a_e^{mean} = -1.06\ 10^{-12}$$

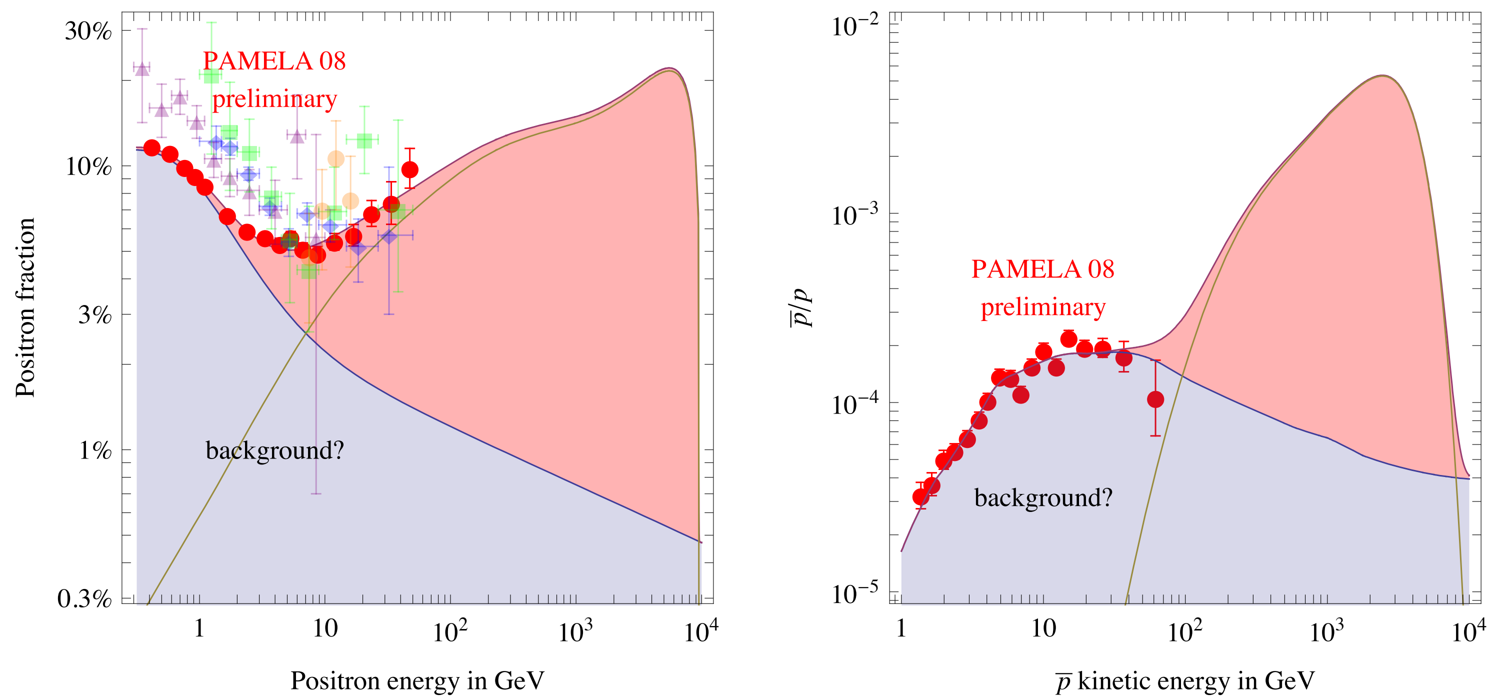
## Theoretical predictions (CB,Silk 2007)

$$\delta a_e^F > 5\ \sqrt{f}\ 10^{-12}$$

**One can therefore exclude this scenario by using the electron g-2**

# How to go to higher masses?

- Need to increase the “effective” annihilation cross section
- resonance or mass degeneracy is the way
- Sommerfeld effect or DM clumps became fashion



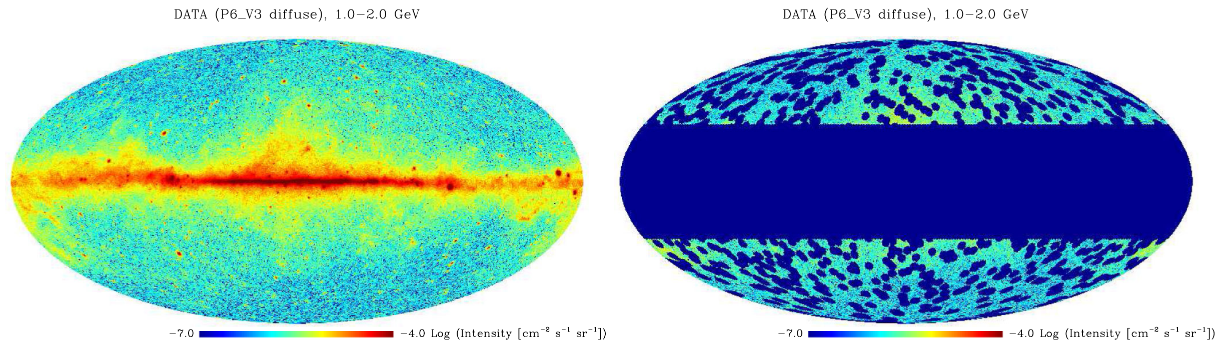

Cirelli et al 2009

**PAMELA: excess of positrons; no excess in antiprotons**

One needs to make sure that the anti proton production by DM occurs at very high energy so one needs to boost the annihilation cross section

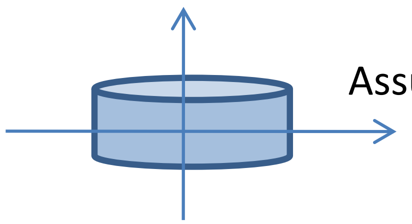
## Gamma ray predictions!!!

(FERMI, HESS, AMS, ...)



# Byproduct of PAMELA: Revisiting cosmic ray propagation

Delahaye et al 2007



Assume that diffusion zone is well approximated by a cylinder

Radius of the cylinder

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

Bessel in r_cyl

Fourier in z_cyl

Source term

Propagation length

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

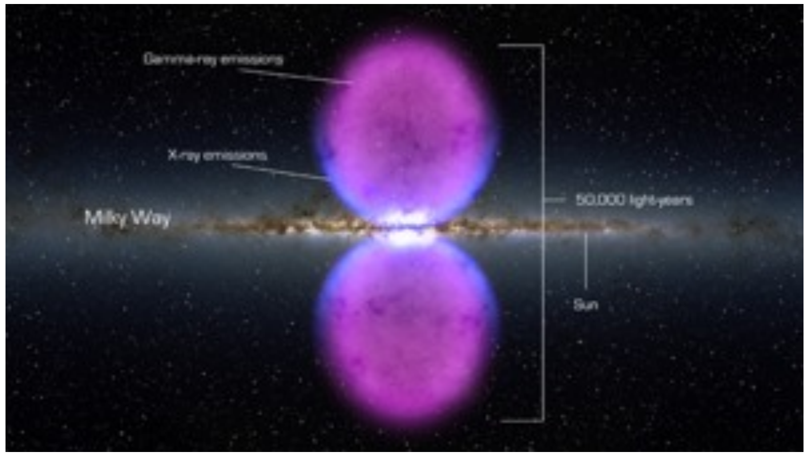
$$K(\mathrm{x}, E) = K_0\, \epsilon^{\delta} \text{ where } \epsilon = E/E_0$$

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

**Astrophysical characterisation of galactic sources merged with DM searches**

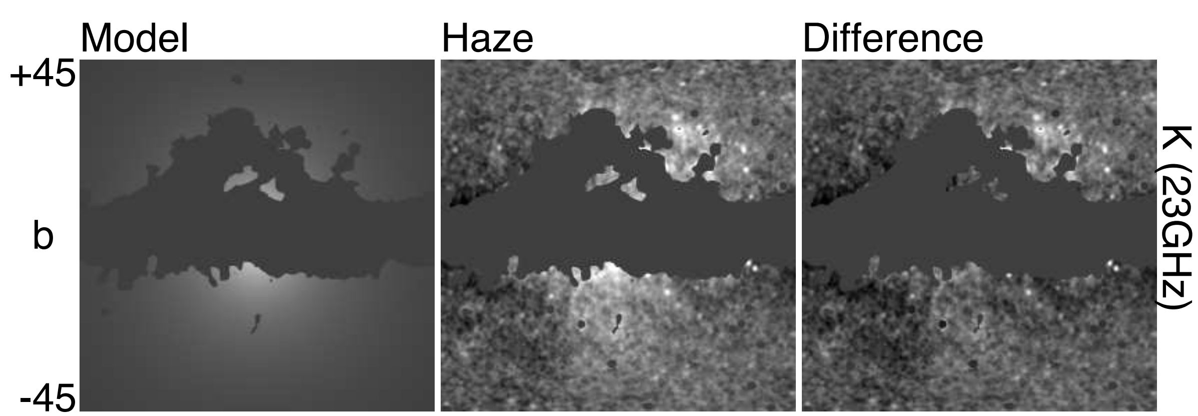
# But once background and foreground astrophysical sources are known, one can look for anomalous features in EM sectrum

**FERMI Bubble: excess in gamma rays..** (Finkbeiner et al)




Bubbles also seen in radio, submillimetre and X-rays
Likely due to pulsars but ???

**WMAP Haze: excess in submillimetre (synchrotron)**




T. Delahaye,CB,J.Silk 2011

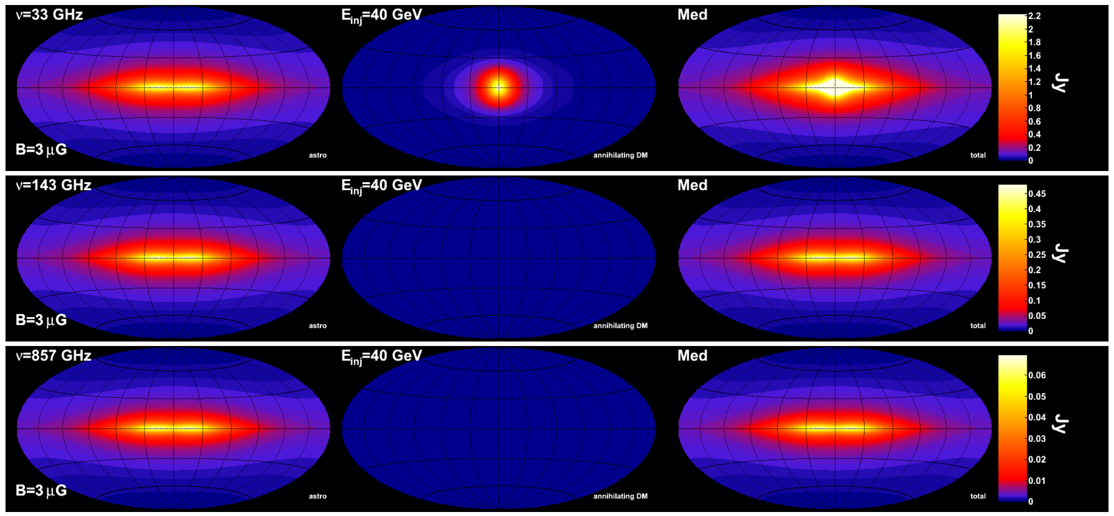


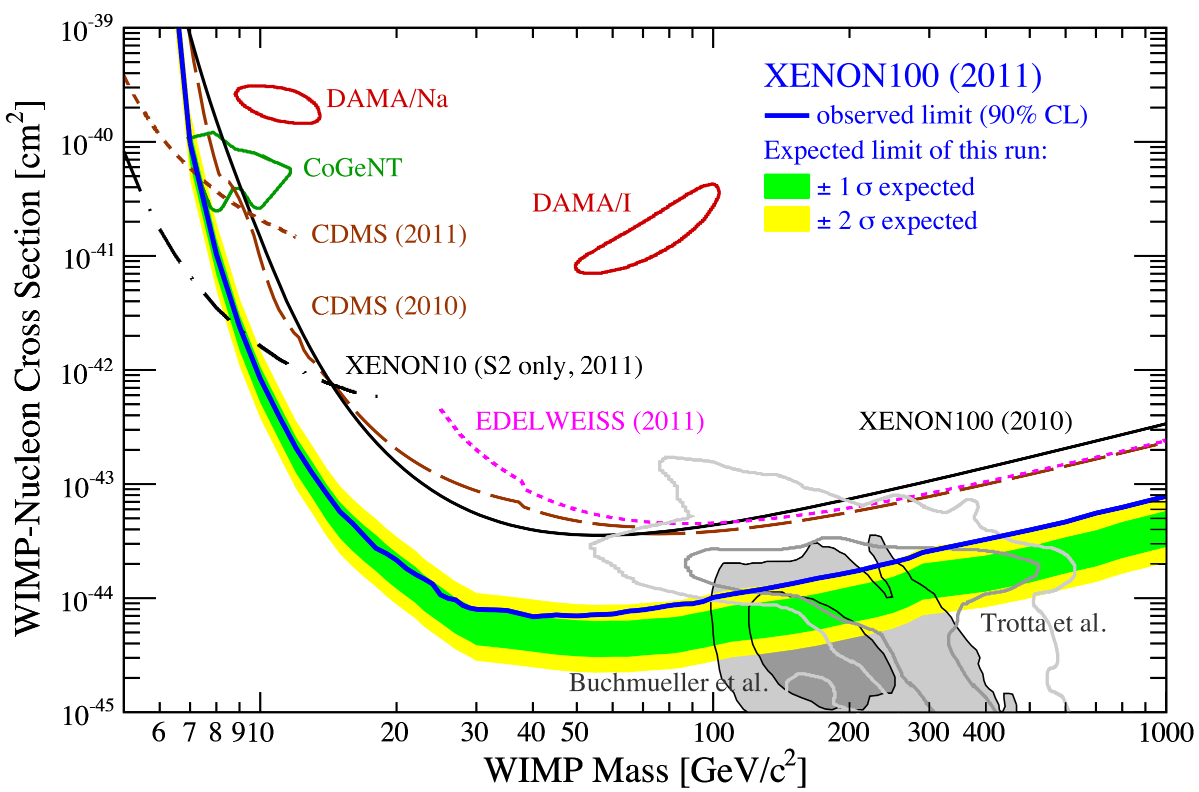

**Figure 2.** Synchrotron maps for 40 GeV dark matter particles $B = 3\mu$G. We use the MED parameter set and assume annihilating particles.

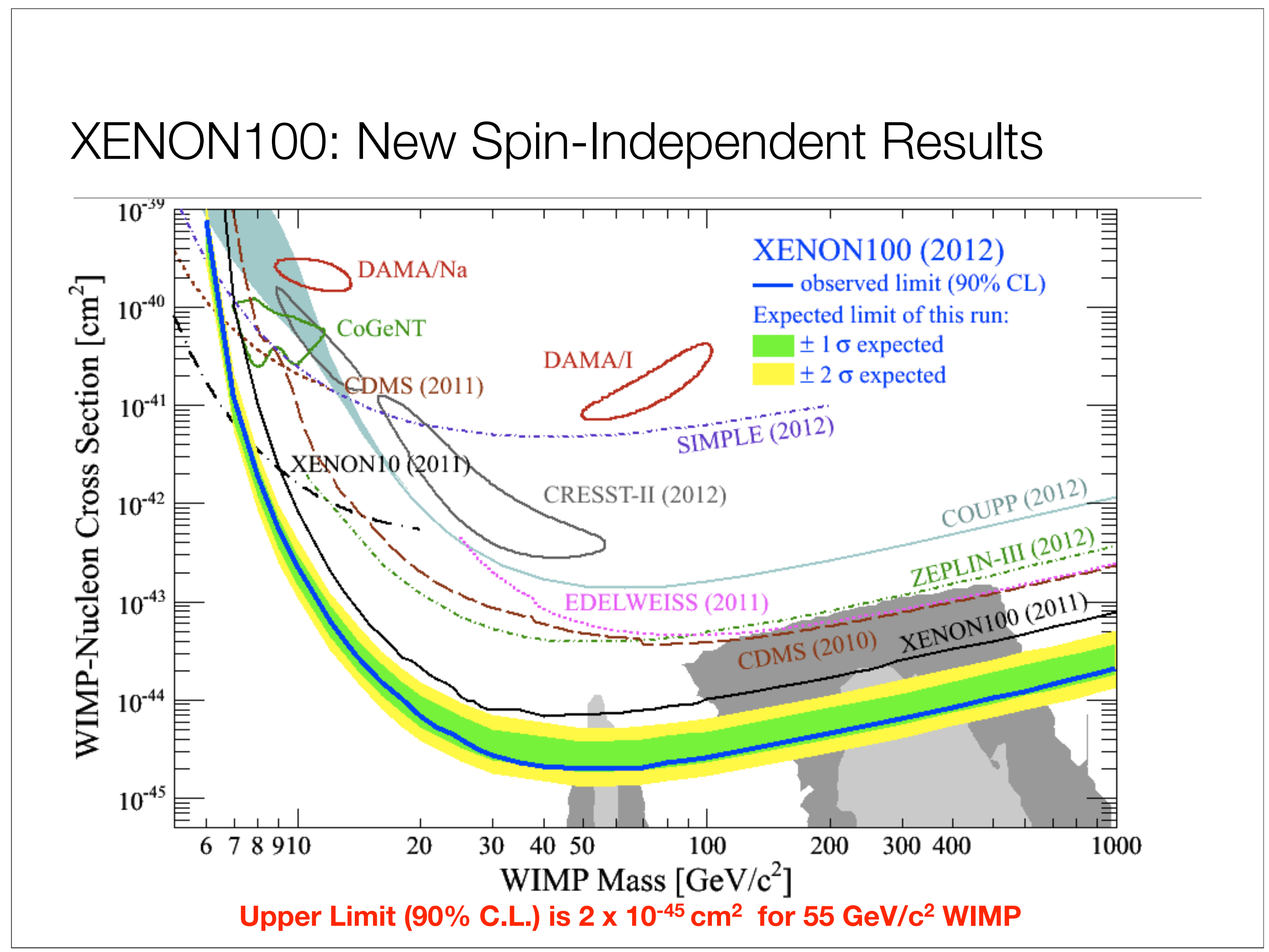
# Should we go back to the Vanilla model?

# The Direct detection experiments revolution

* ***15 years ago***, there was the so-called 'DAMA claim' (40-60 GeV DM; relatively large sigma)
* ***15 years ago***, the DD limits were above the expected SUSY region

* ***Now*** we know that a 'vanilla' WIMP interact less than a neutrino with electrons at 1 MeV
* ***Now*** we can kill a big chunk of the SUSY parameter space...

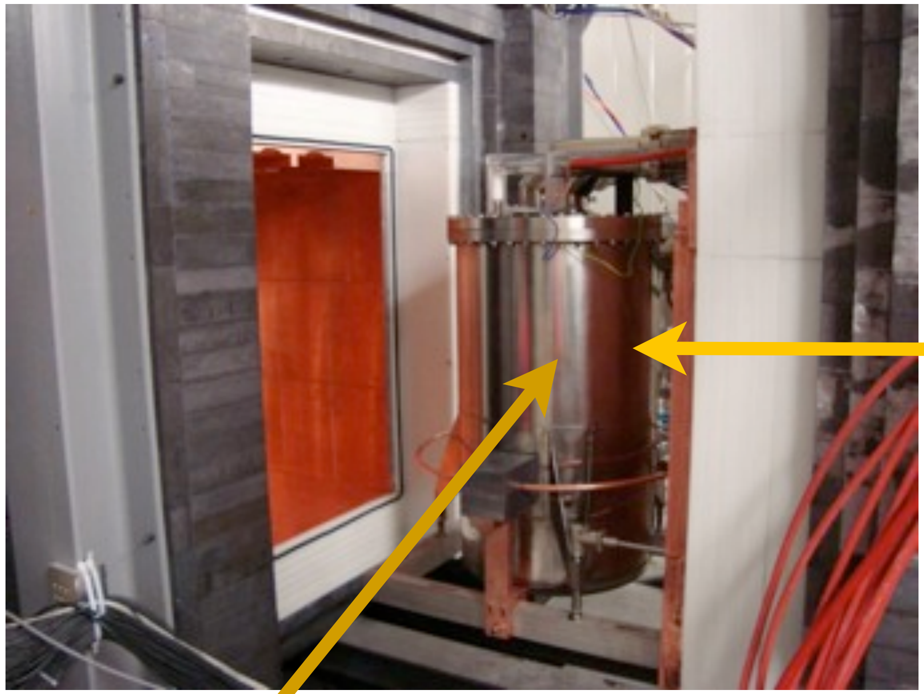


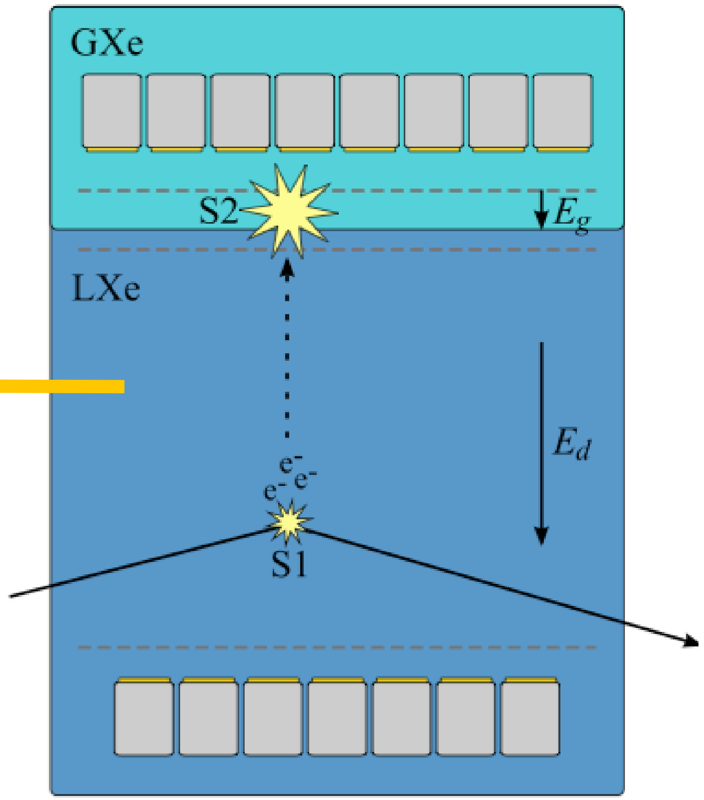

Wednesday, July 18, 2012

Tremendous progress ... the SUSY parameter space is definitely shrinking

# The XENON100 case



detector inside (shielded from radioactivity)




2 phase detector:

upper part = gas

lower part= liquid

S1 = primary scintillation signal

S2 = secondary scintillation signal
(originates from the drift of electrons from ionised Xenon

Exploiting S1 gives an information about the interaction of DM with Xenon nuclei but it depends on the scintillation efficiency of Xenon nuclei. It is very difficult to know the absolute yield so instead one needs to use calibration measurements
**=> relative scintillation efficiency (Leff)**

Recoil energy

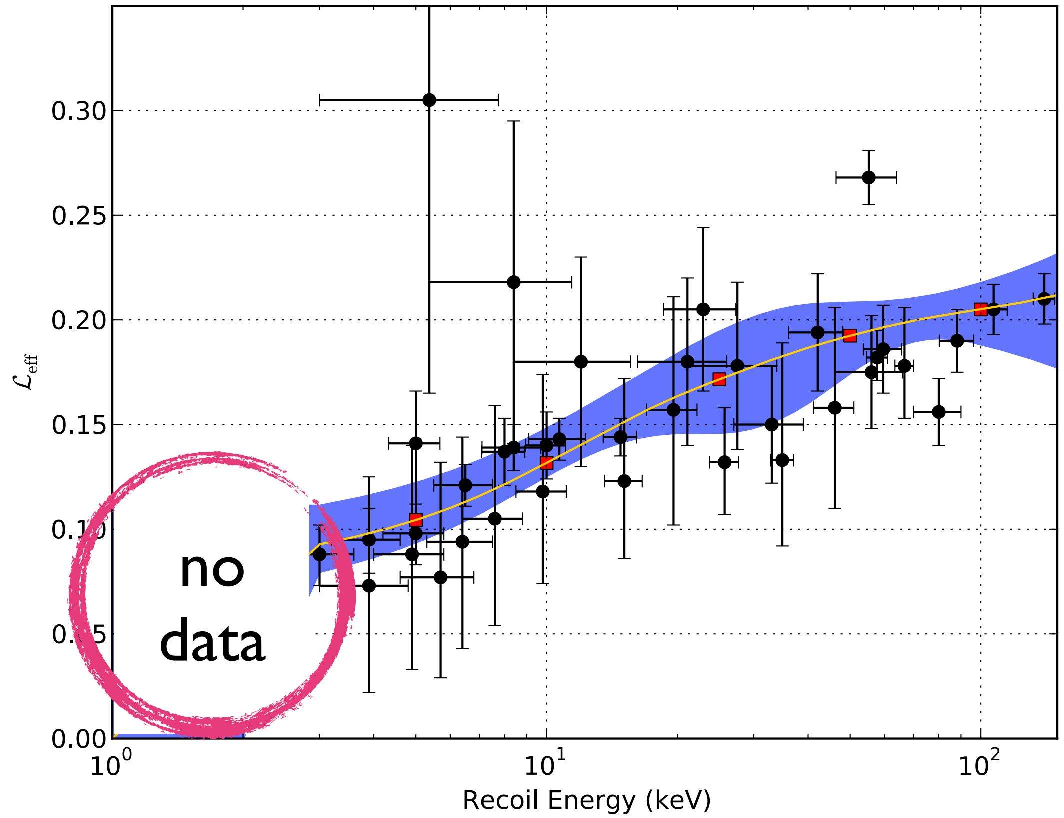
$$E_{nr} = \frac{S_1}{L_y \, \mathcal{L}_{\text{eff}}} \frac{S_{er}}{S_{nr}},$$

quenching factors, related to the electric field

Light yield for the calibration source emitting gammas

**Recoil energy depends crucially on Leff**

# One needs to assume the same Leff as for neutrons



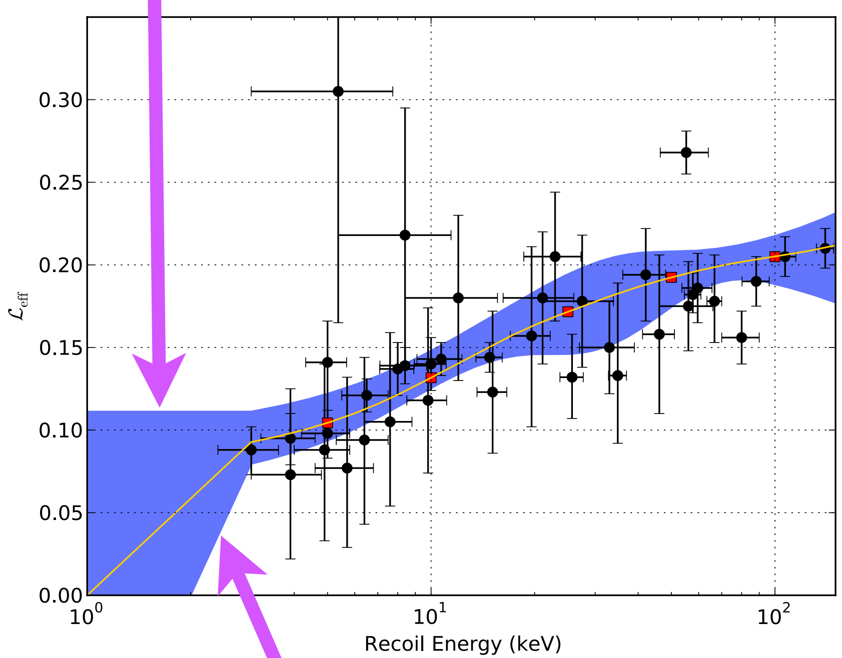

none of them are really consistent and there is no theoretical expression to use for Leff to perform a best fit
so the solution is to perform a cubic spline interpolation

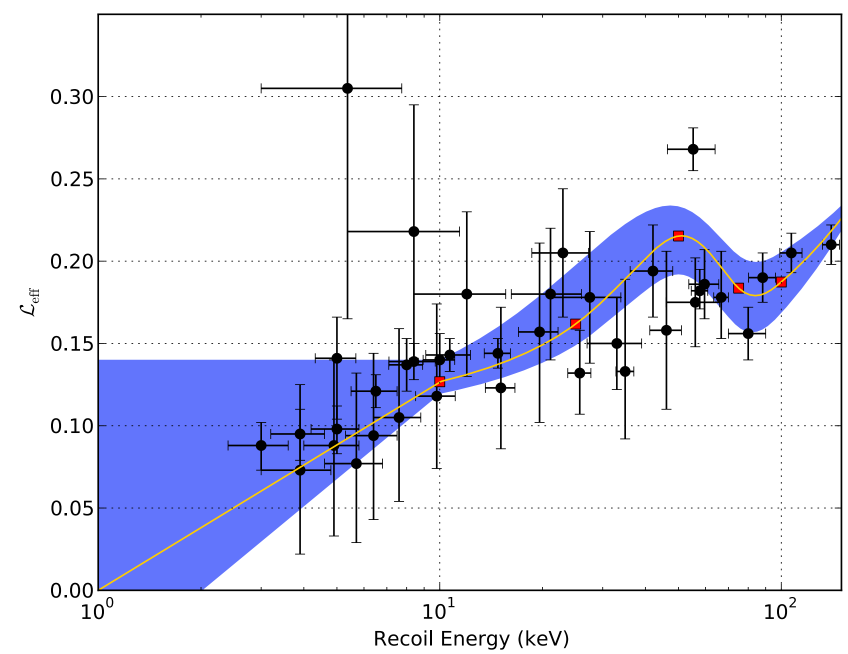
# The XENON100 controversy

$$E_{nr} = \frac{S_1}{L_y \, \mathcal{L}_{\mathrm{eff}}} \frac{S_{er}}{S_{nr}},$$

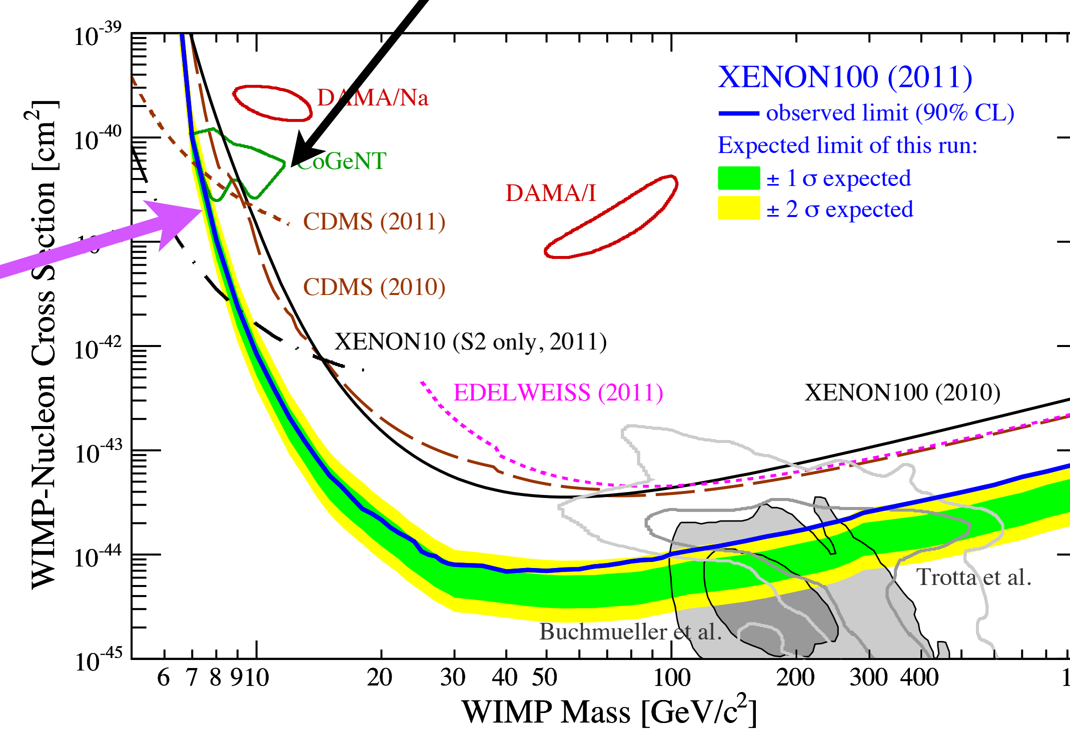
Recoil energy depends crucially on Leff **but lack of data below 3keV**

**One option is to extrapolate the fit of data below 3 keV...but there is some choice!**




**fn,fp**




How come such an uncertainty
does **not** translate
into the exclusion curve?

black curve = exclusion limit;
yellow/green colour band= what XENON100 expected

# The importance of measuring Leff at low Enr

**arXiv:1203.6823**

$$\mathcal{L} = \mathcal{L}_1(\sigma, N_b, \epsilon_s, \epsilon_b, L_{eff}, v_{esc}; m_\chi) \times \mathcal{L}_2(\epsilon_s) \times \mathcal{L}_3(\epsilon_b) \times \mathcal{L}_4(L_{eff}) \times \mathcal{L}_5(v_{esc})$$

Dark Matter likelihood

NR likelihood

ER likelihood

Uncertainties on the energy scale

Uncertainties on the escape velocity

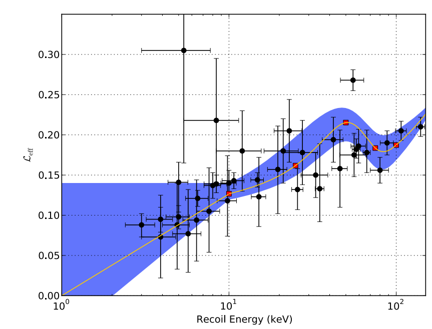
$$\mathscr{L} = \prod_{j=1}^{K} \mathrm{Poiss}(n^j | \epsilon_s^j N_s + \epsilon_b^j N_b)$$

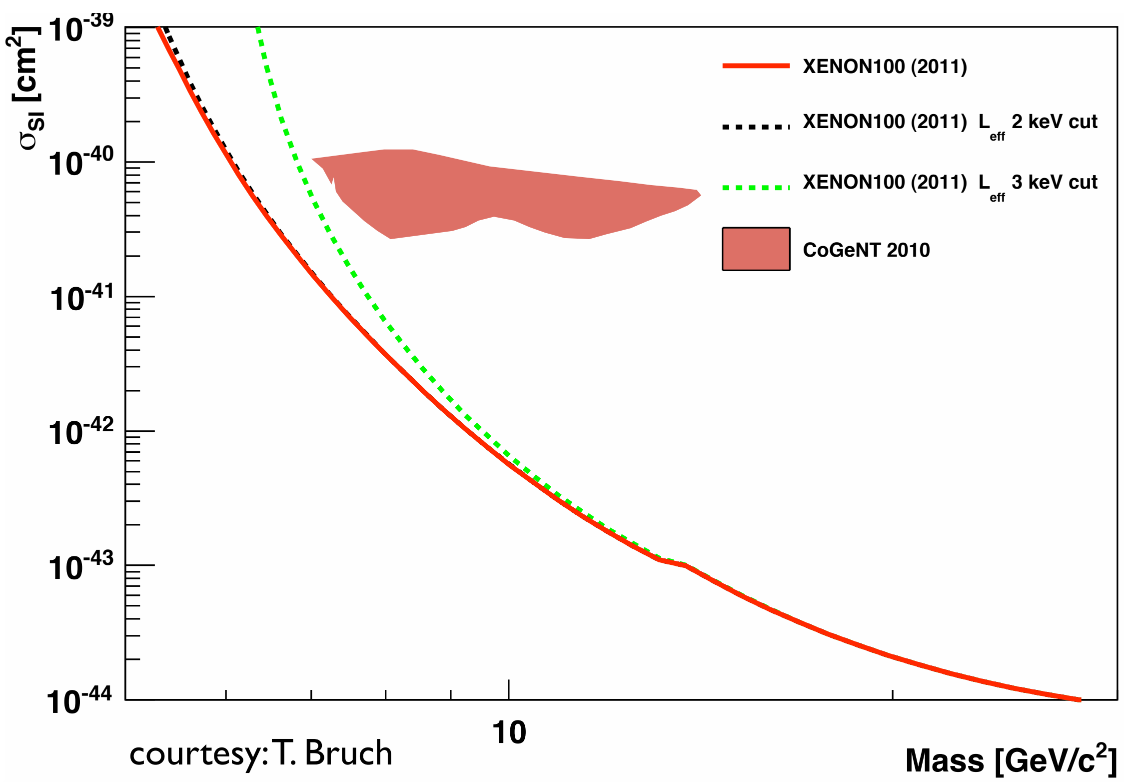
$$\times \prod_{i=1}^{n^j} \frac{\epsilon_s^j N_s f_s(S1) + \epsilon_b^j N_b f_b(S1)}{\epsilon_s^j N_s + \epsilon_b^j N_b}$$

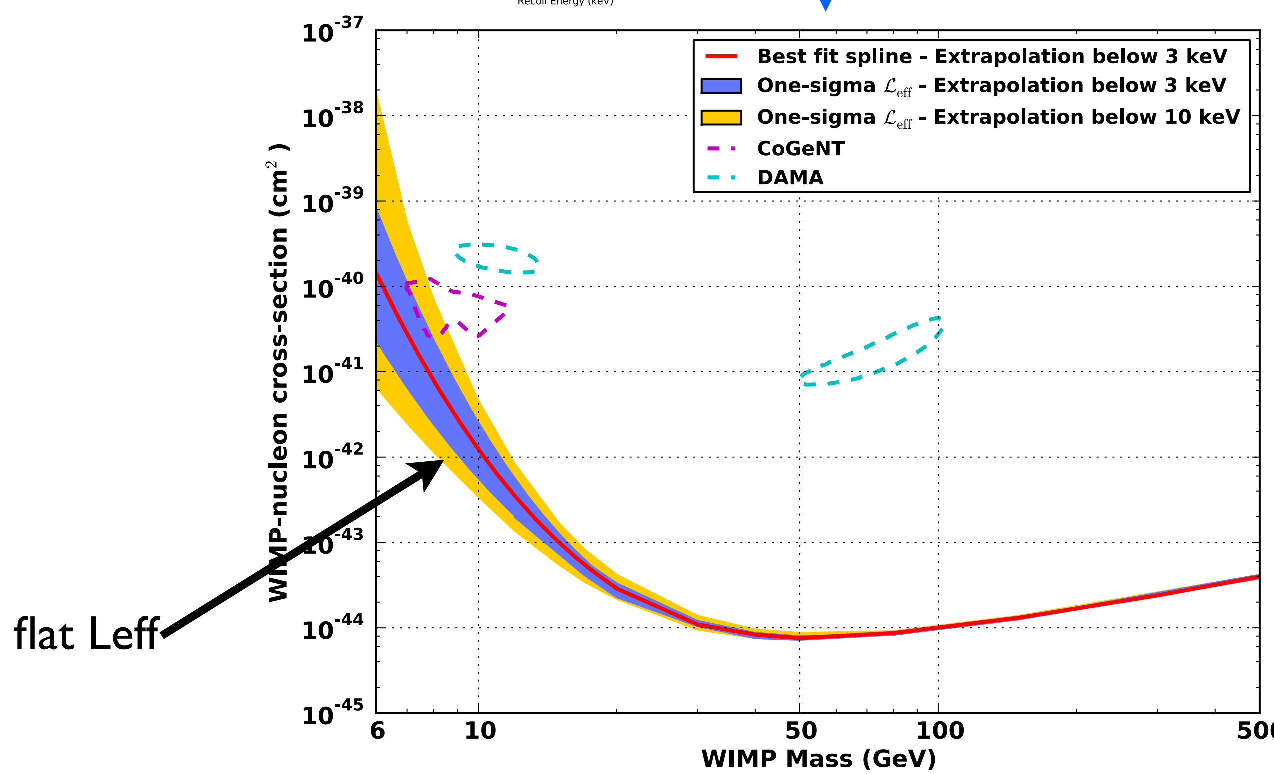
$$\times \mathrm{Poiss}(m_b^j | \epsilon_b^j M_b) \times \mathrm{Poiss}(m_s^j | \epsilon_s^j M_s)$$

$$\times e^{-(t - t^{\mathrm{obs}})^2/2} \times f_v(v_{\mathrm{obs}} | v_{\mathrm{esc}}).$$

Same Likelihood but without the parameterisation for Leff



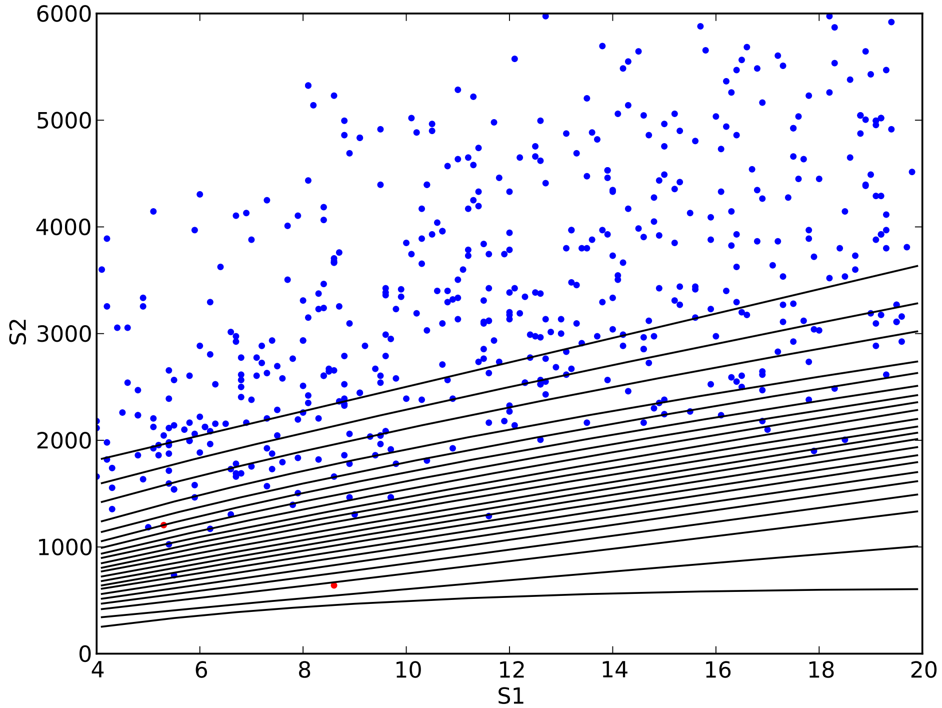
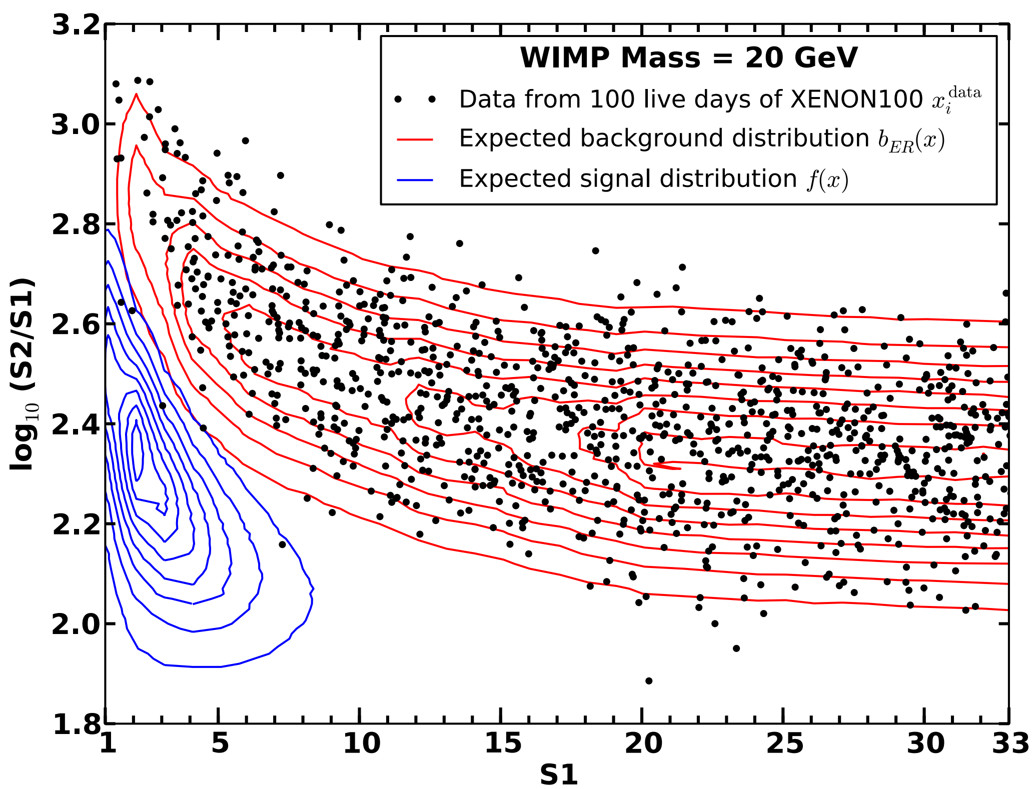
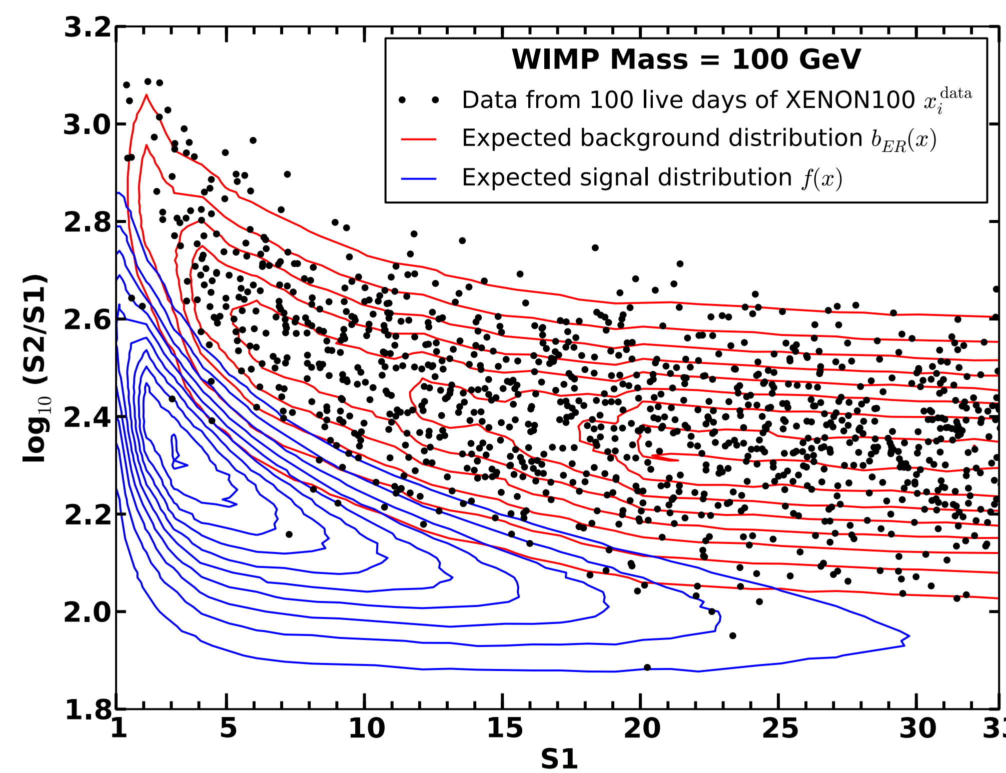



FIG. 5: An example of a simulated dataset, with two nuclear-recoil (signal) events, shown in red. The rest of the points are electronic-recoil (background), shown in blue. The black lines divide the S1-S2 plane into the bands used for the analysis.

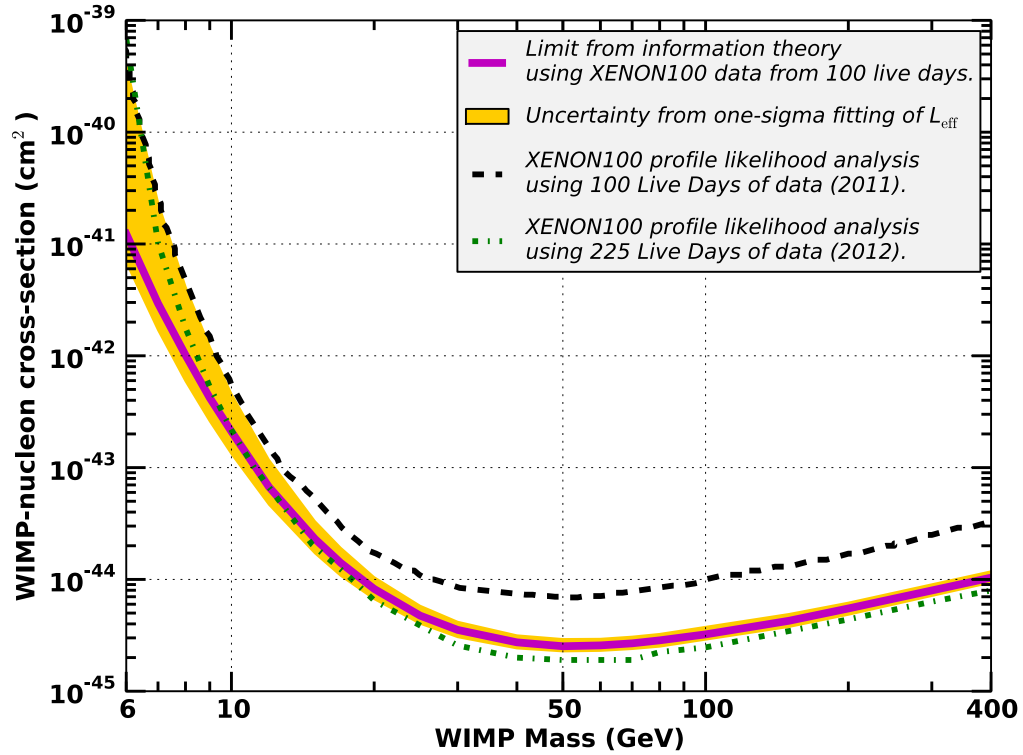
$$\frac{dR}{dE} = \frac{\sigma(q)}{2m\mu^2}\,\rho\,\eta(E,t) \qquad \eta(E,t) = \int_{v_{\min}(E)}^{\infty} \frac{f(v, u_e(t))}{v}\, d^3v$$

We proposed a new analysis bases on pixel discretisation of the data instead of using bands in order to be sensitive to the DM signature

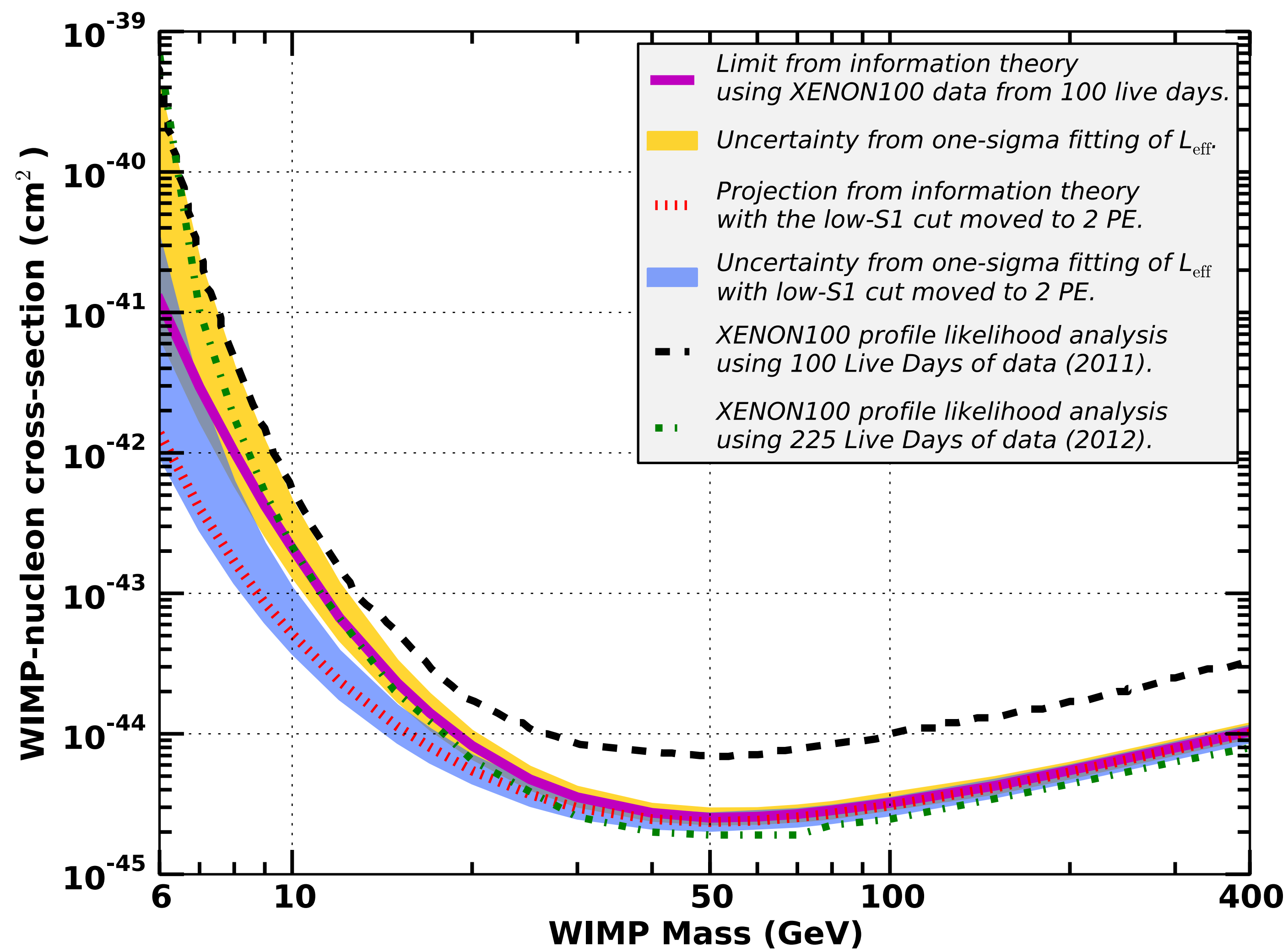


# We obtained a new limit using the 2011 data which is in fact competitive with the XENON100 limit based on the 2012 data!

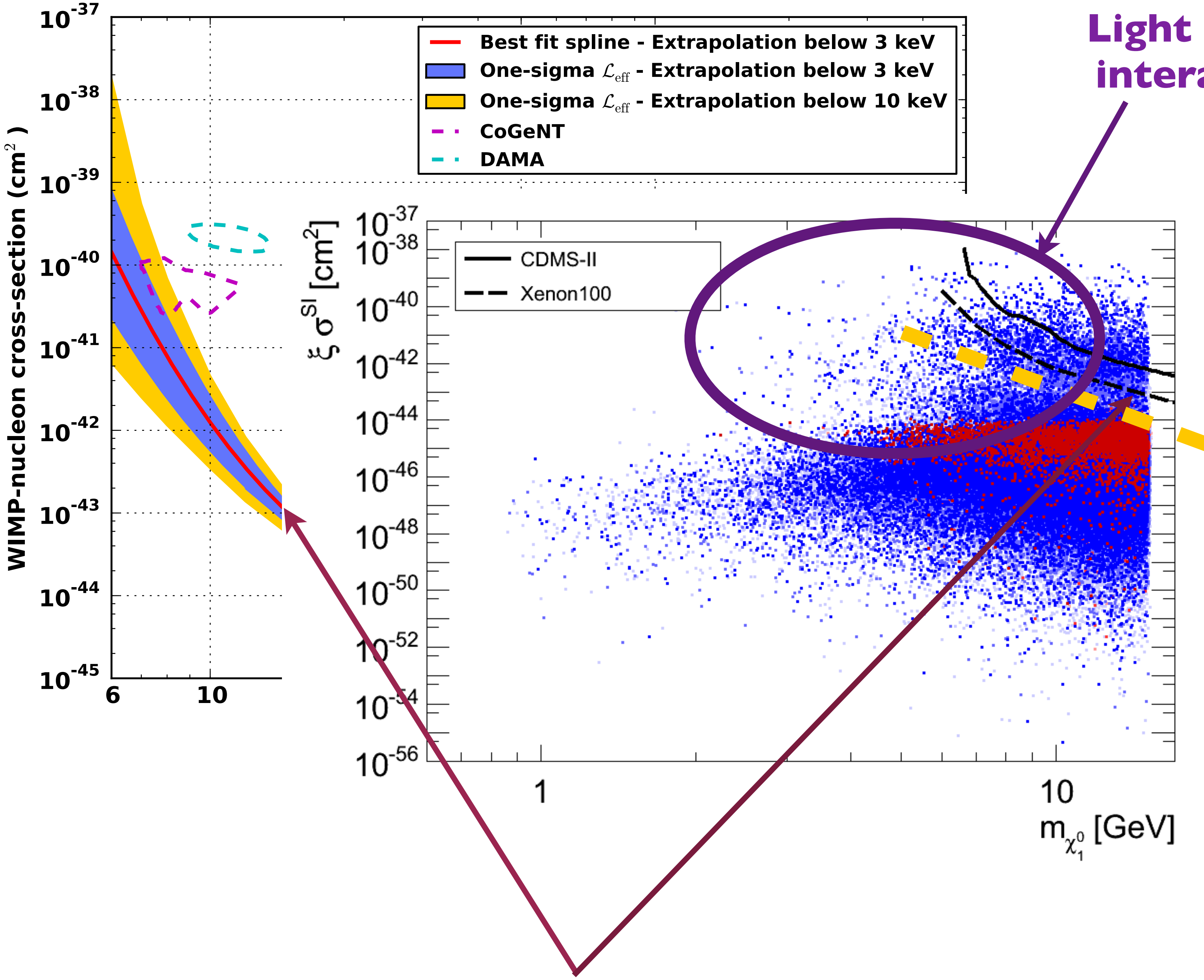



**J. Davis. T. Ensslin&CB 2012**



# Impact on DM model building?
# SUSY example

Light candidates interact weakly




XENON10 may probe to be useful (cf R. Essig)

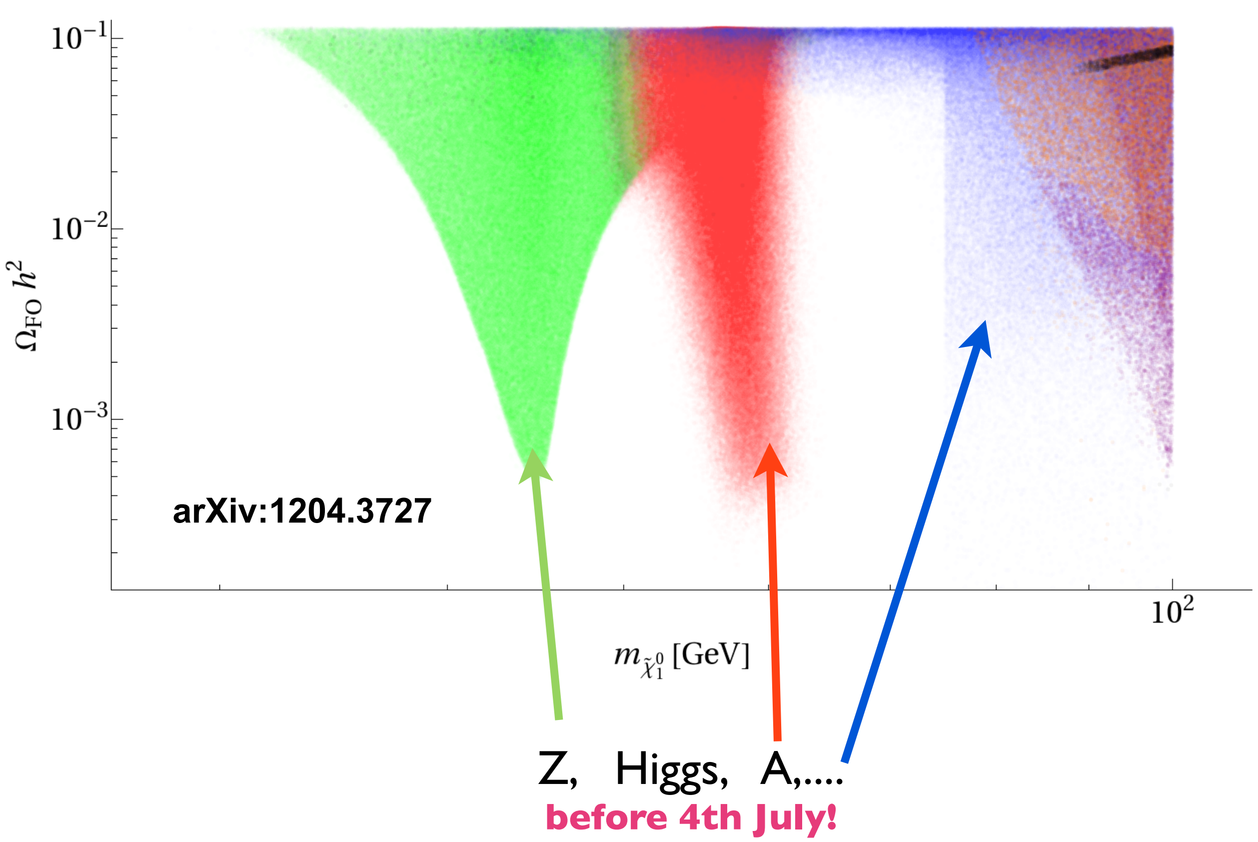
**mean value of Leff** (with extrapolated fit but not necessarily physical Leff)

## What else has changed? The notion of Relic density

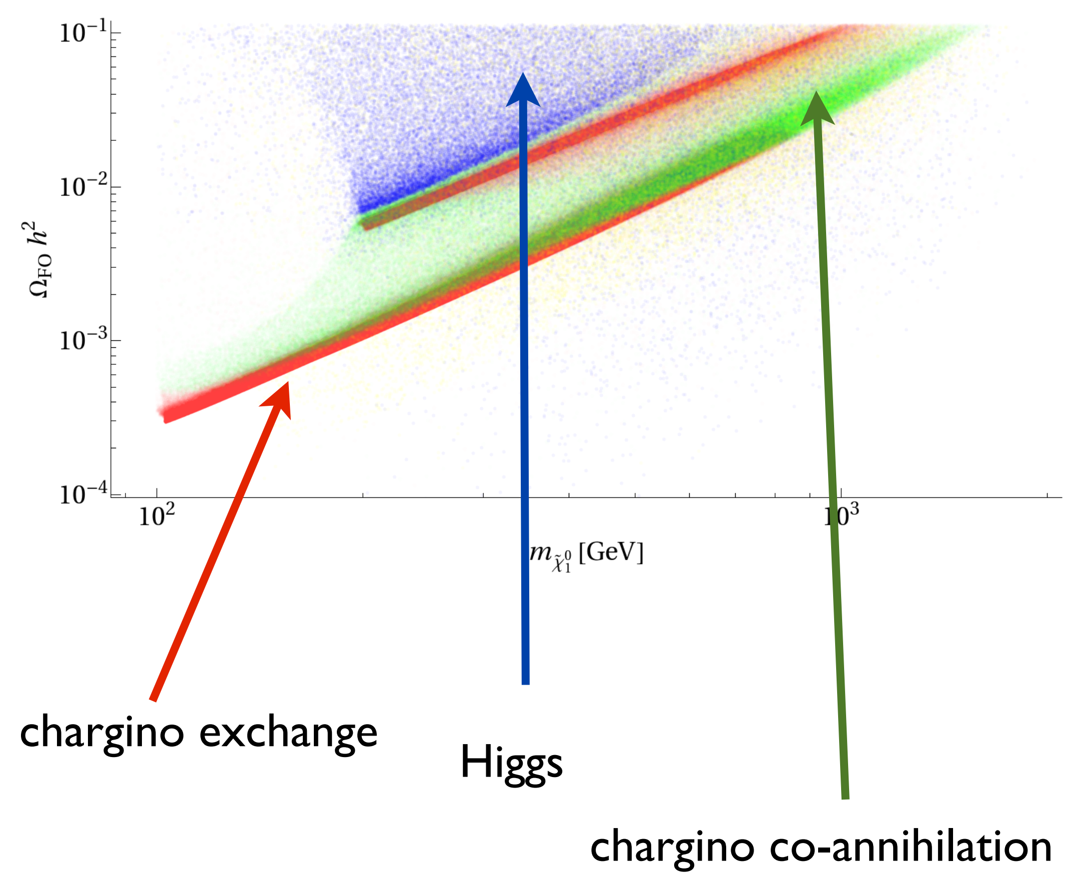
* A candidate can be a subdominant DM component (multi DM)

* DM particles could be regenerated (FI, reannihilation)

**Low mass neutralino**



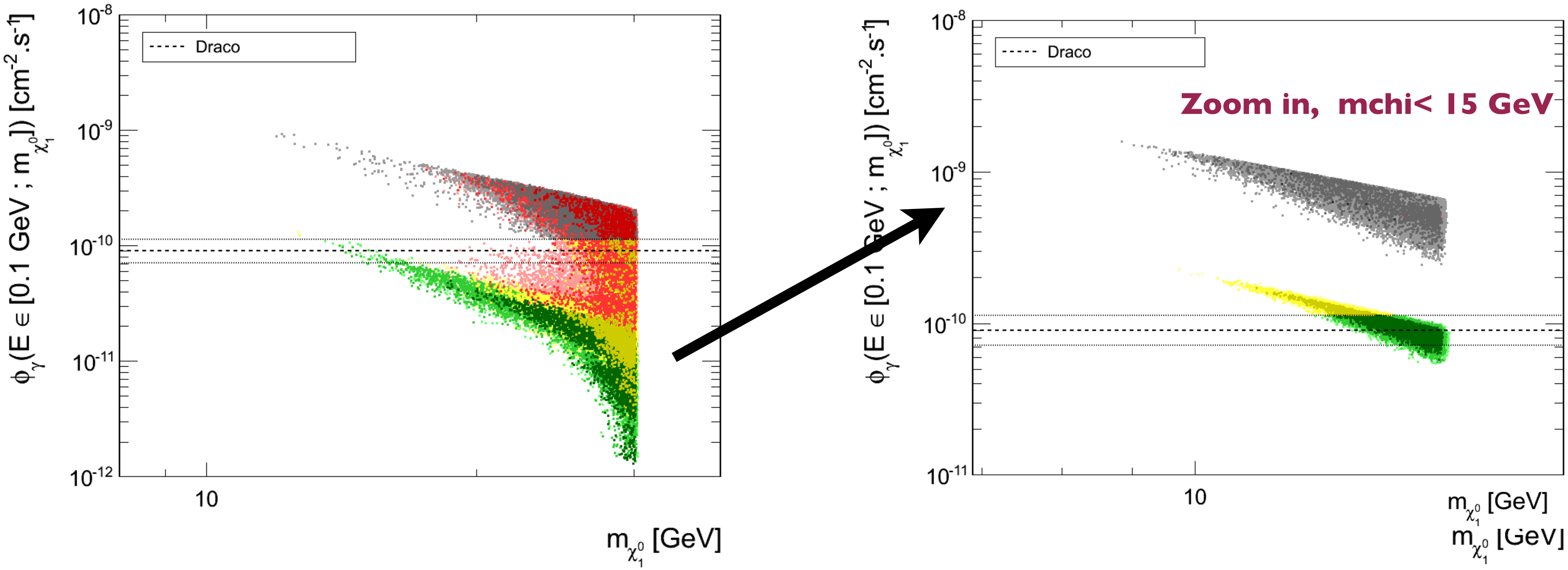

**High mass neutralino**




To some extent this means that one does not need to worry too much about the FO relic density!
One can consider larger cross section, i.e. in particular larger degenracies

# Astrophysical constraints

## low mass




**black** : excluded by LHC (tan beta,mA) + FERMI/LAT+XENON100&CDMS
**red**: excluded by 2 of these 'experiments'
**yellow**: excluded by 1 of these 'experiments'
**green**: ok

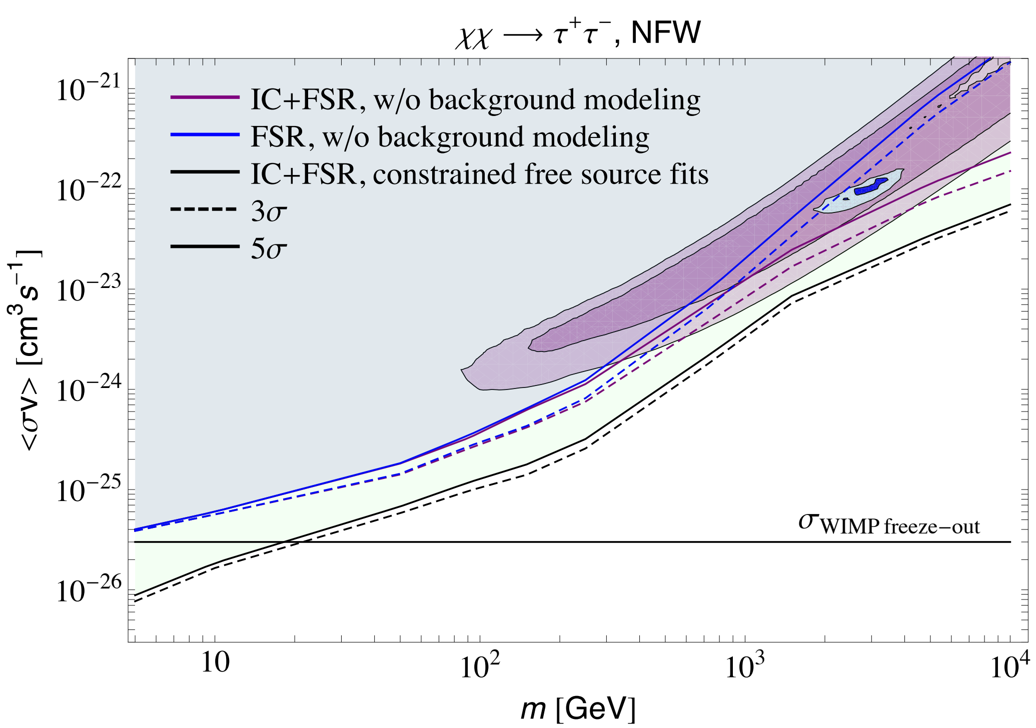
**Relatively light DM (but not sub GeV) could be excluded by FERMI-LAT data**
**Thi needs to be checked for each individual model !!!**

# Should we go back to 100 GeVish DM?

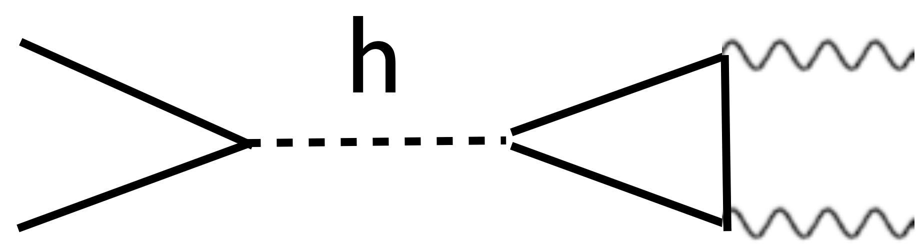
Possible evidence for 2 lines: 130 and 111 GeV

signal offset: 1deg from GC but compatible with new simulations

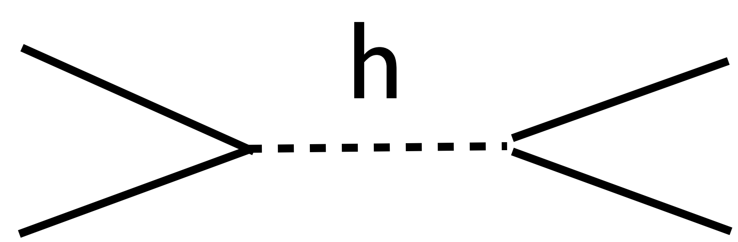
## **Problem:** Gamma-ray continuum




Needs to be boosted

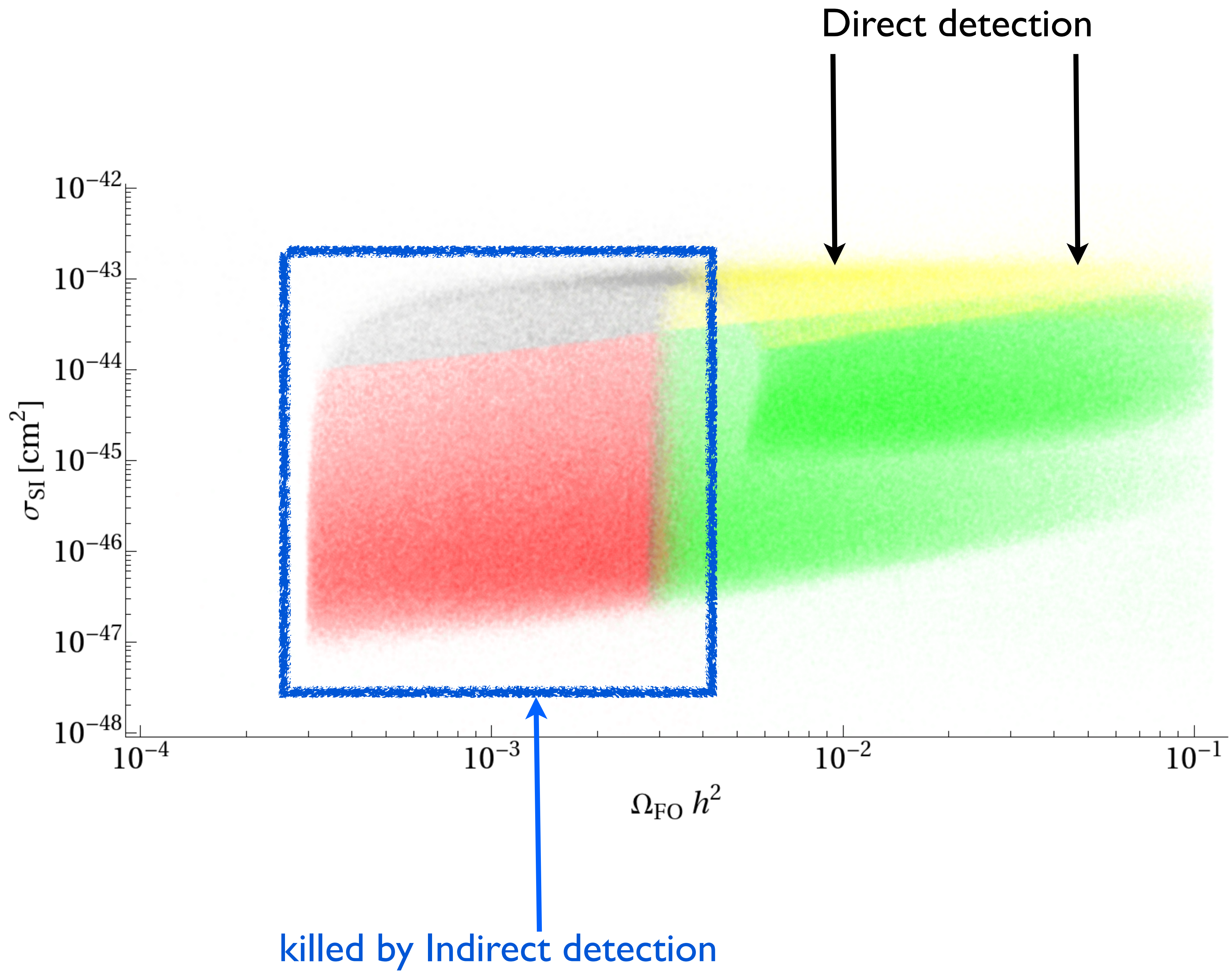



but then ...




## Impossible to fit in the MSSM but ...

# One cannot boost the cross section arbitrarily mdm>100 GeV




**XENON1T (or similar) again welcome+LHC analysis**

# Conclusion

- Whole mass range looked at but there is still a lot of work to do (especially if we forget about possible astrophysical evidence and check which models are really plausible)
- Astrophysical constraints must now be taken into account (they kill many models)!
- Direct detection results also kill many models now; Claims of possible evidence but exclusion limit from XENON100 and CDMS should not be forgotten!
- The relic density argument is not so much driving the field now. Experimental& astrophysical constraints + possible anomalies became more important.

LHC searches (including displaced vertex, mono photon/jet, Higgs) are becoming crucial

**Let us hope that the field will be soon 'positive data' driven!!!**

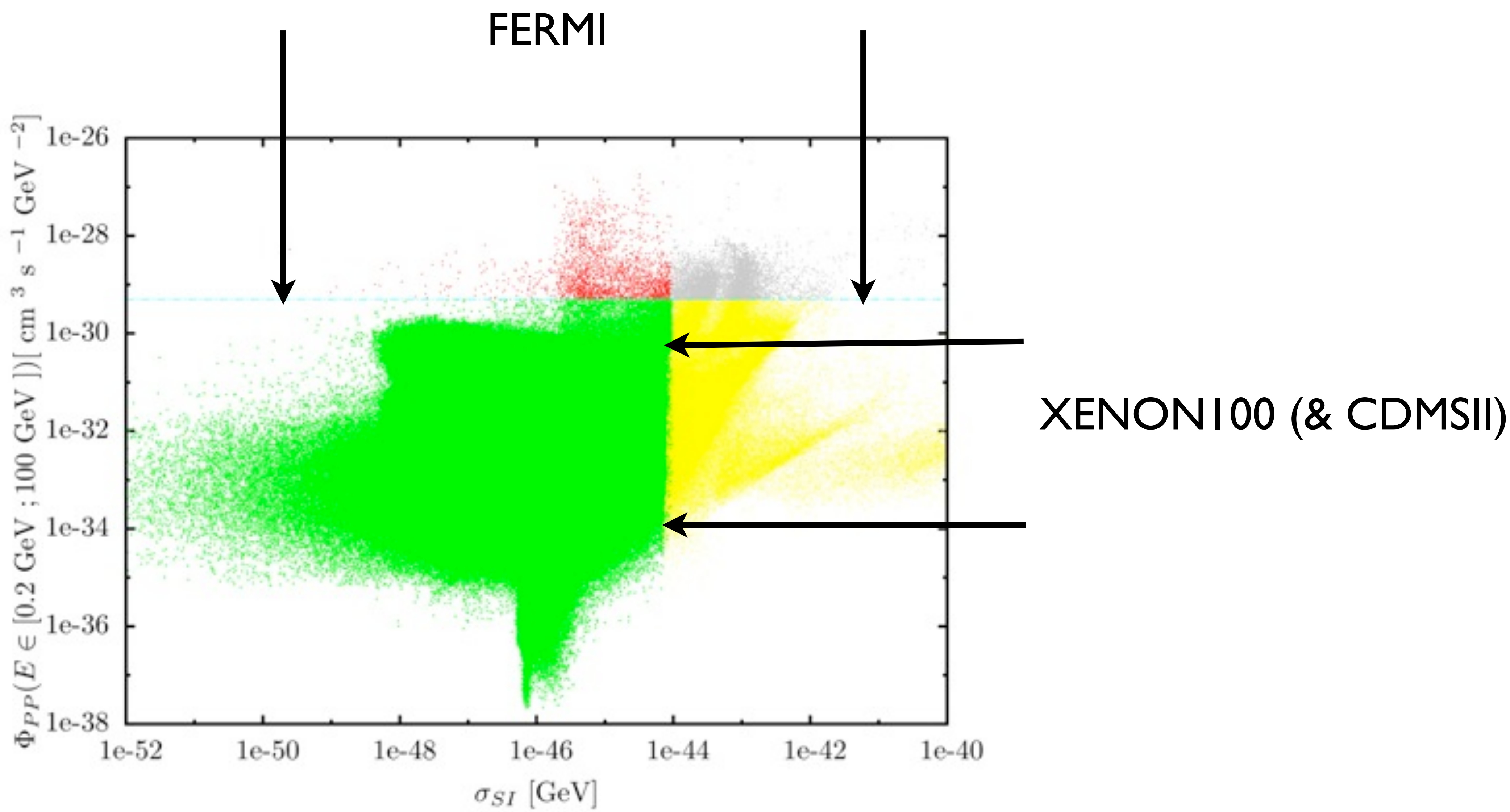
# Back up slides

## Increasing the mass range:
## Cross-correlating Indirect and Direct Detection

**red/black**: excluded

**yellow**: excluded by 1 experiment

**green**: ok

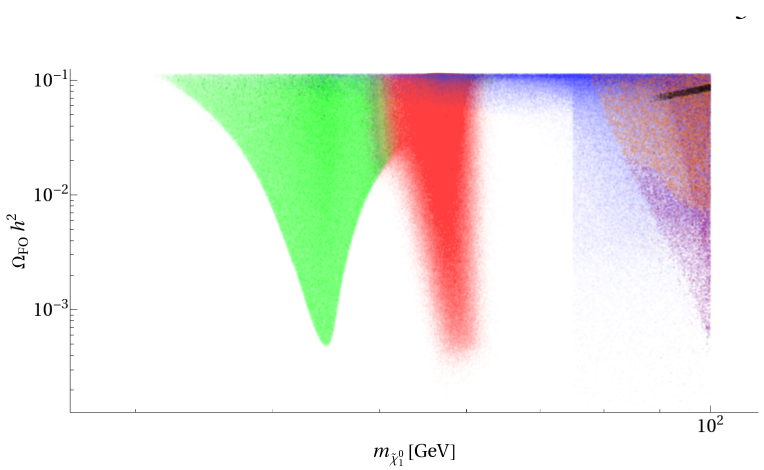



Model = pMSSM + relic density > 3% WMAP, mdm < 100 GeV (no mass below 20 GeV)

**Combining both types of limits, one excludes a region that was not explored previously but there is still progress to do.**

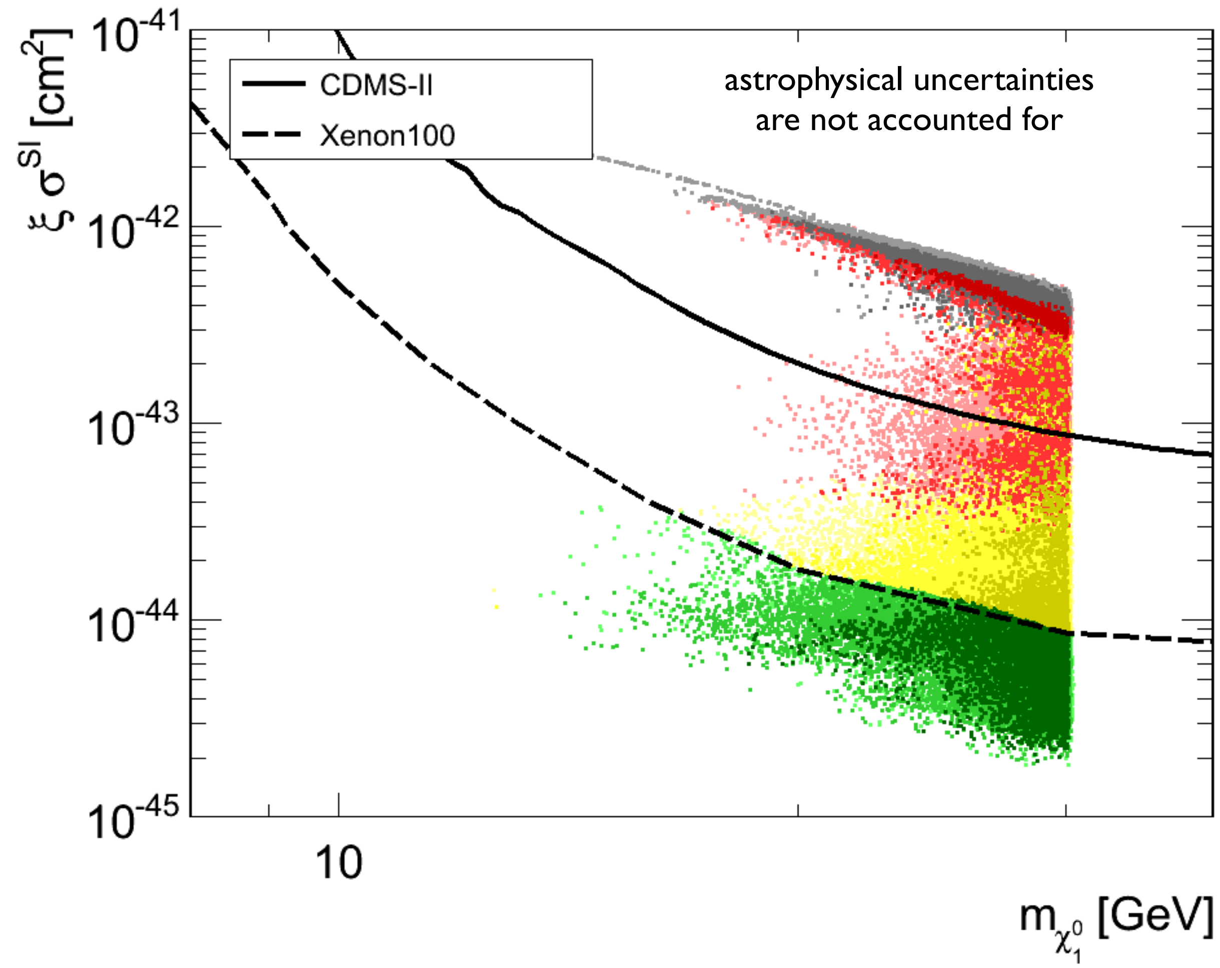
XENON1T (or experiments with similar potential) welcome!

# Zoom in the small mass region (pMSSM)




| 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 |

TABLE I: Intervals for MSSM free parameters (GeV units).




MSSM-EWSB; scans with mdm<30 GeV

**black** : excluded by LHC (tan beta,mA) + FERMI/LAT+XENON100&CDMS
**red**: excluded by 2 of these 'experiments'
**yellow**: excluded by 1 of these 'experiments'
**green**: ok

1) **There are points below 30 GeV but not that much below 20 GeV**
(caveat: light neutralinos with very light sbottoms; may not be killed by monophoton searches, arXiv:1205.2557)

2) **most of the points are excluded by XENON100 (but...) and CDMS**

3) **An improvement of the XENON100 limit at low mass would be extremely useful to probe these scenarios**

# How light can neutralinos be? (pMSSM)

1108.1338

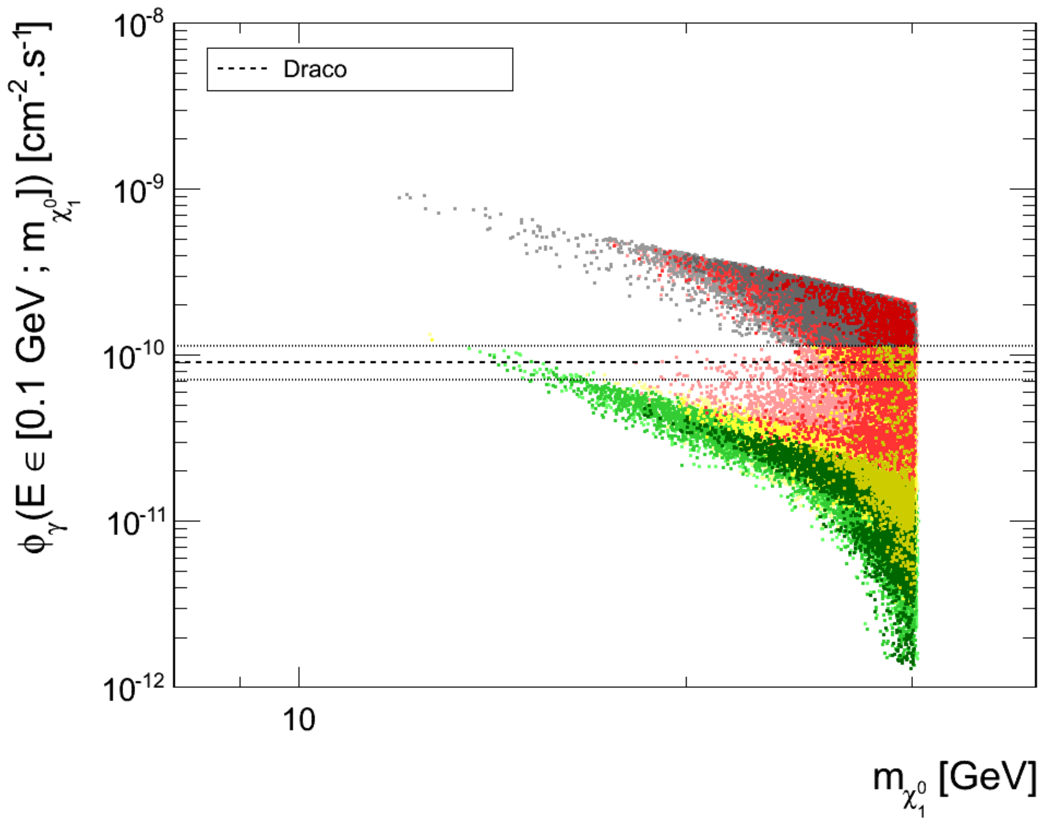



FIG. 5: Integrated γ-ray flux from the Draco dwarf spheroidal galaxy as a function of the neutralino mass in the $m_{\chi_1^0} < 30$ GeV search. We show limits from Fermi-LAT. Same color code as Fig. 4.

| 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 |
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| $M_{\tilde{q}_{1,2}}$ | 300 | 2000 | 14 |
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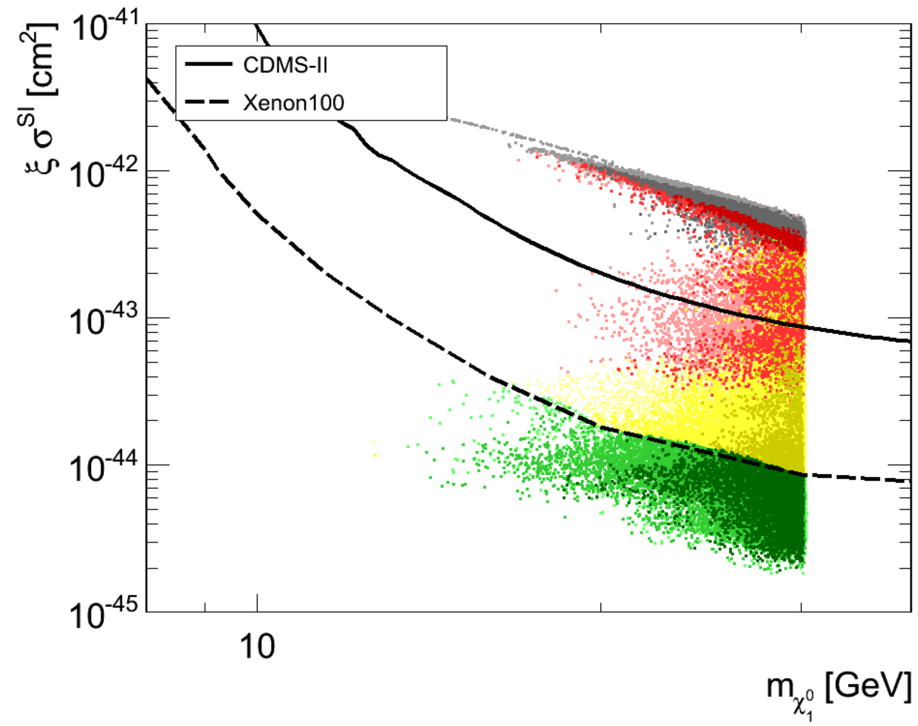
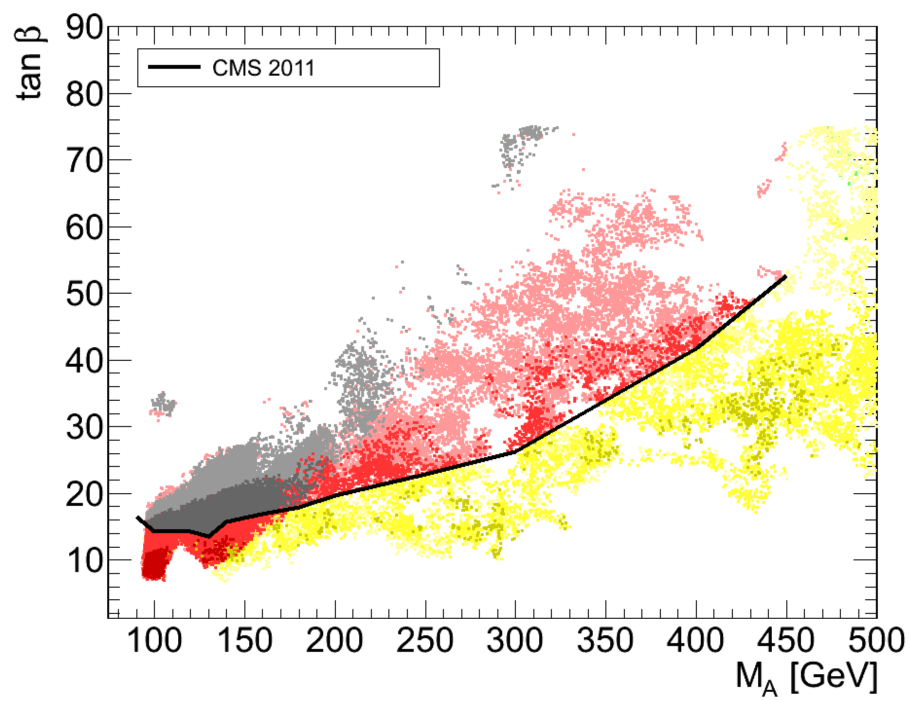
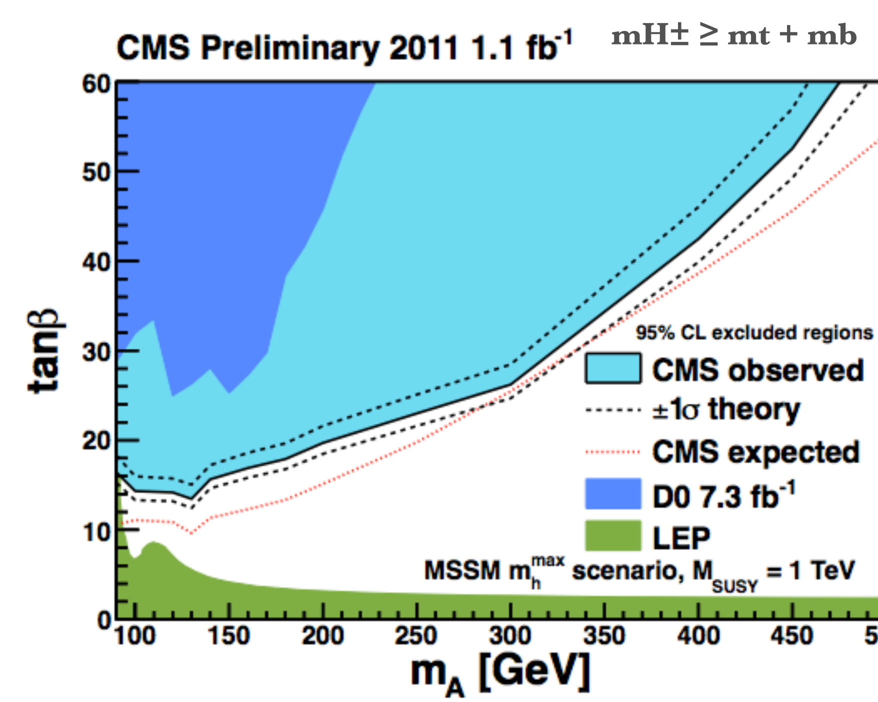



FIG. 4: Points of the $m_{\chi_1^0} < 30$ GeV search represented in the $\xi\sigma^{SI}$ vs. neutralino mass plane. Exclusion limits from CDMS-II [29] and XENON100 are shown. The color code is the same as in Fig. 2, green points are allowed.



# How to get the exclusion curve?

$$\frac{dR}{dS_1}$$ : rate per number of photo-electrons detected

This rate is proportional to the rate per number of photo-electrons that are generated in the detector

$$\frac{dR}{dn} = \int dE \ \frac{dR}{dE} P(n,\nu(E)) \quad \text{with } \mathrm{P}(\mathrm{n}, \nu(\mathrm{E})) = \frac{\nu^{\mathrm{n}} \ \mathrm{E}^{-\nu}}{\mathrm{n}!}$$

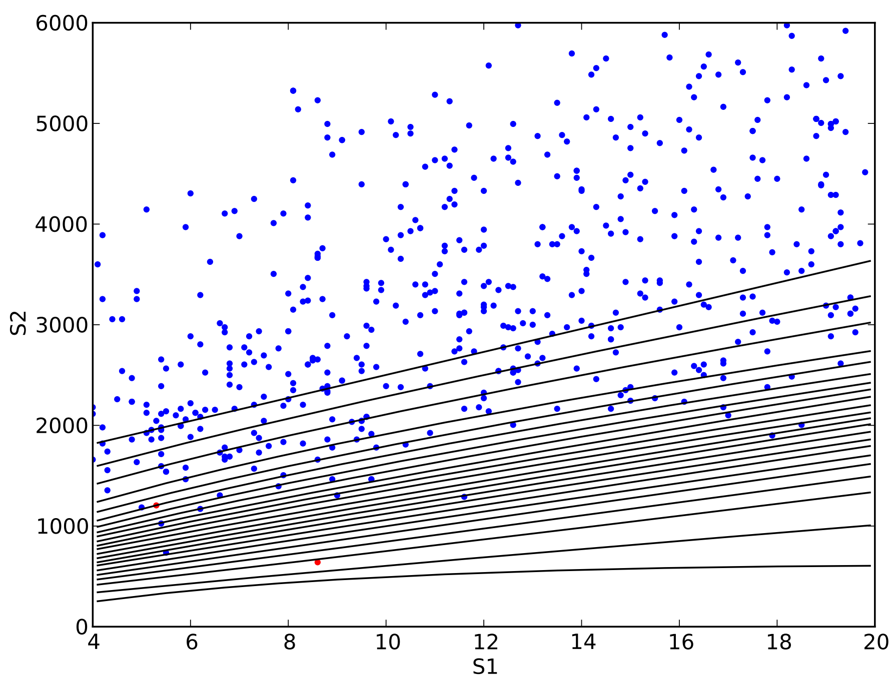



FIG. 5: An example of a simulated dataset, with two nuclear-recoil (signal) events, shown in red. The rest of the points are electronic-recoil (background), shown in blue. The black lines divide the S1-S2 plane into the bands used for the analysis.

$$\nu(E) = E \ L_y \ \mathcal{L}_{eff} \frac{S_{nr}}{S_{er}}$$

number of photo-electrons expected for a given recoil energy

To obtain the exclusion curve, XENON100 uses a profile Likelihood ratio

Likelihood maximised without $\sigma$

$$\lambda = \frac{\mathcal{L}_{max}(\sigma)}{\mathcal{L}_{max}(\hat{\sigma})}$$

$$\lambda(\sigma) = \frac{\max\limits_{\sigma \text{ fixed}} \mathscr{L}(\sigma; \mathcal{L}_{\rm eff}, v_{\rm esc}, N_b, \epsilon_s, \epsilon_b)}{\max \mathscr{L}(\sigma, \mathcal{L}_{\rm eff}, v_{\rm esc}, N_b, \epsilon_s, \epsilon_b)}$$

Likelihood maximised with $\sigma$

$$q_\sigma = -2\ln\sigma \text{ if } \sigma > \hat{\sigma}$$

$$q_\sigma = 0 \text{ if } \sigma < \hat{\sigma}$$

→ $\lambda = 1$ when $\sigma = \hat{\sigma}$

For the present data, for a given mass and vesc, one obtains $q_{\sigma_{obs}}$

But one experiment so not enough statistics...to compensate, XENON100 simulated Mock data giving rise to many values of $q_\sigma$

$$p_s = \int_{q_{\sigma_{obs}}}^{\infty} f(q_\sigma, H_\sigma) dq_\sigma$$

**p-value**

$$p'_s = \frac{p_s}{1 - p_b} = 10\%$$

$$1 - p_b = \int_{q_\sigma^{\rm obs}}^{\infty} f(q_\sigma | H_0)\, {\rm d}q_\sigma$$