When Astrophysics starts to constrain the Supersymmetric parameter space:

what is left for the neutralino?

Trying to close the neutralino window with all available tools...

Céline Boehm, IPPP/Durham

Scanning over the SUSY parameter space

Why considering SUSY DM?

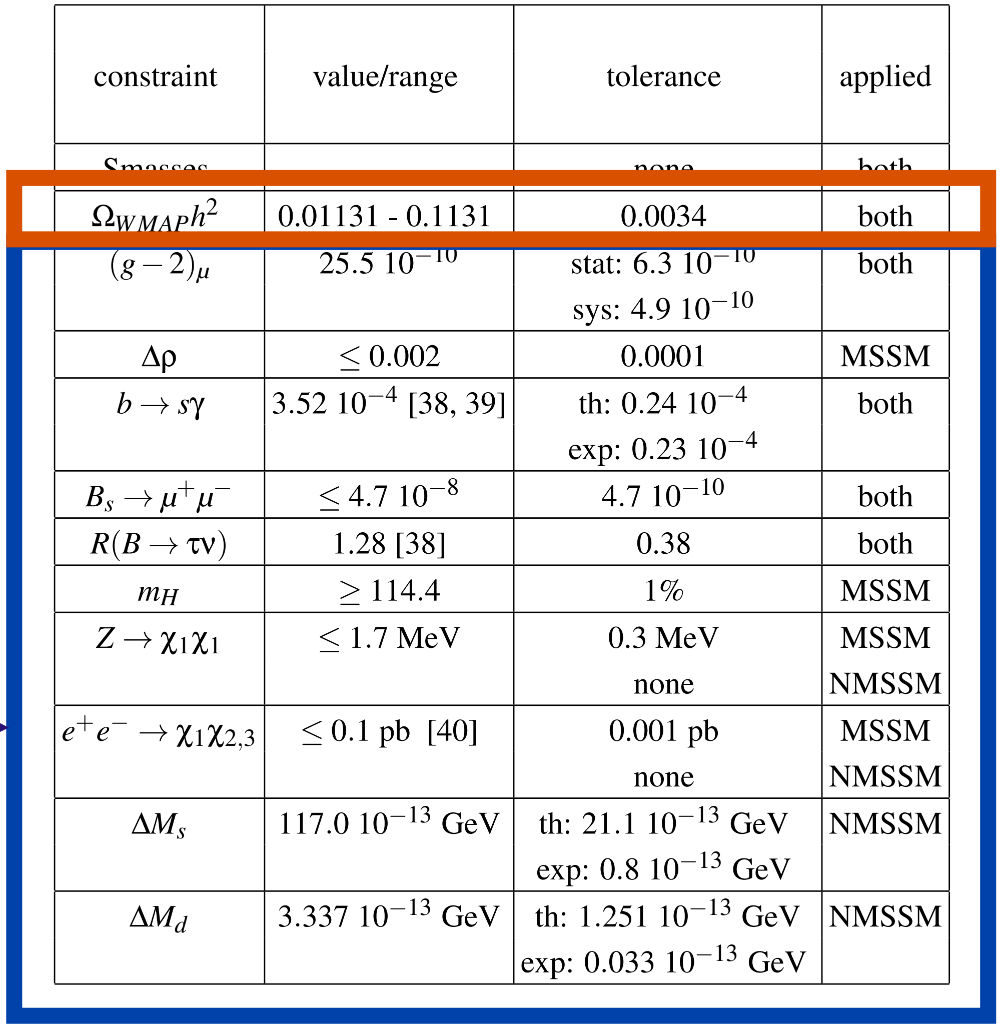
large framework; conclusions valid for other 'SM'-like model
Useful for SUSY searches (complement LHC) but also for DM in general

Which SUSY Model?

pMSSM (17/19 parameters), NMSSM (11 parameters),...

Which constraints?

Particle physics (SUSY dependent but used for the scan)
Relic density (only upper bound)
DM direct detection and indirect detection
(they are applied after the scans)



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: $6.3\ 10^{-10}$ sys: $4.9\ 10^{-10}$	both
$\Delta\rho$	≤ 0.002	0.0001	MSSM
$b \to s\gamma$	$3.52\ 10^{-4}$ [38, 39]	th: $0.24\ 10^{-4}$ 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	≥ 114.4	1%	MSSM
$Z \to \chi_1\chi_1$	≤ 1.7 MeV	0.3 MeV none	MSSM NMSSM
$e^+e^- \to \chi_1\chi_{2,3}$	≤ 0.1 pb [40]	0.001 pb none	MSSM NMSSM
ΔM_s	$117.0\ 10^{-13}$ GeV	th: $21.1\ 10^{-13}$ GeV exp: $0.8\ 10^{-13}$ GeV	NMSSM
ΔM_d	$3.337\ 10^{-13}$ GeV	th: $1.251\ 10^{-13}$ GeV exp: $0.033\ 10^{-13}$ GeV	NMSSM

Scans are done with Particle Physics constraints
Only one 'astro/cosmo': **the relic density but we only care about the upper bound.**

Which mass range/which candidate?

neutralinos as light as a few GeV and as heavy as a few TeV

Principle of the scans

MCMC (i.e. based on Likelihood)

Start at a given point of the parameter space;
Jumps to other point if they provide better likelihood [or random]
used micrOMEGAs, SoftSUSY,Higgsbounds

Constraints set as

neutralino must be the LSP
Parameters must be in agreement with Particle Physics measurements/limits
The rest is prediction ...

Likelihoods

We use a Gaussian distribution for all observables with a preferred value $\mu \pm \sigma$,

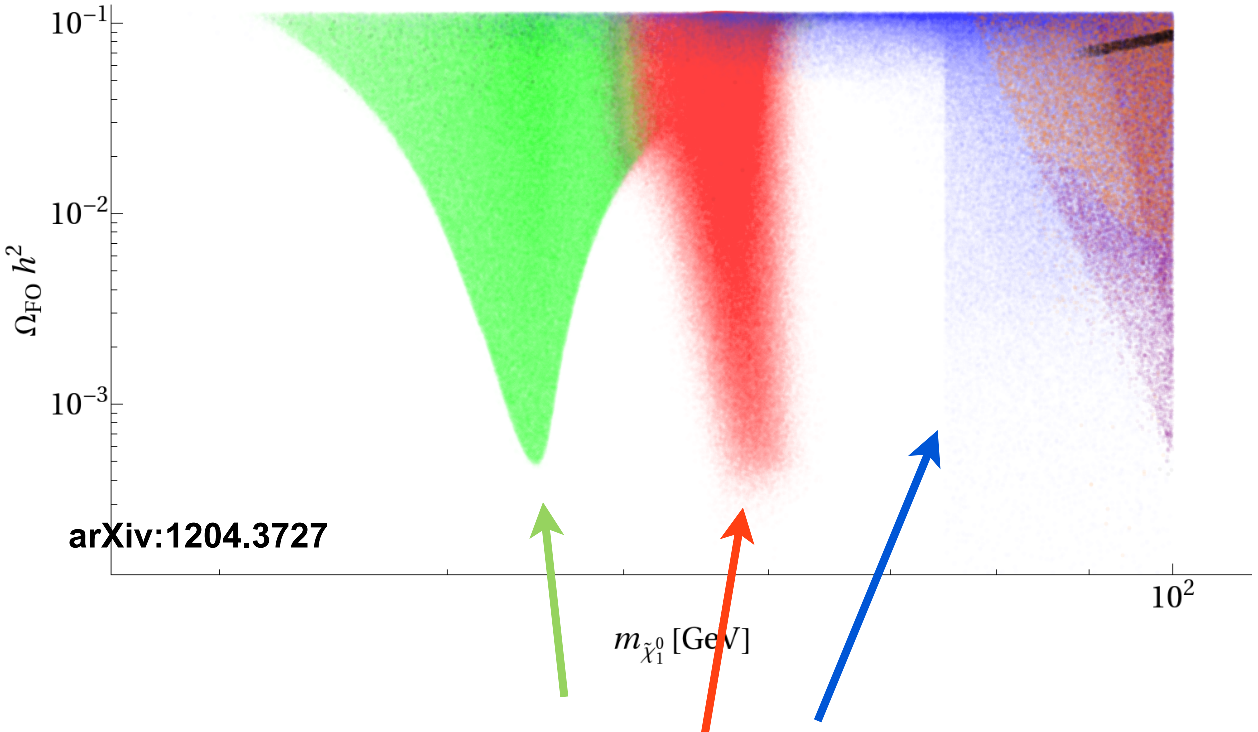
$$F_2(x,\mu,\sigma) = e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{1}$$

$$F_3(x,\mu,\sigma) = \frac{1}{1+e^{-\frac{x-\mu}{\sigma}}}. \tag{2}$$

for observables which only have lower or upper bounds. The tolerance, σ, is negative (positive) when one deals with an upper (lower) bound.

Relic density can still be a guide to scan the parameter space though: Typical 'annihilation' channels to be expected:

Low mass neutralino

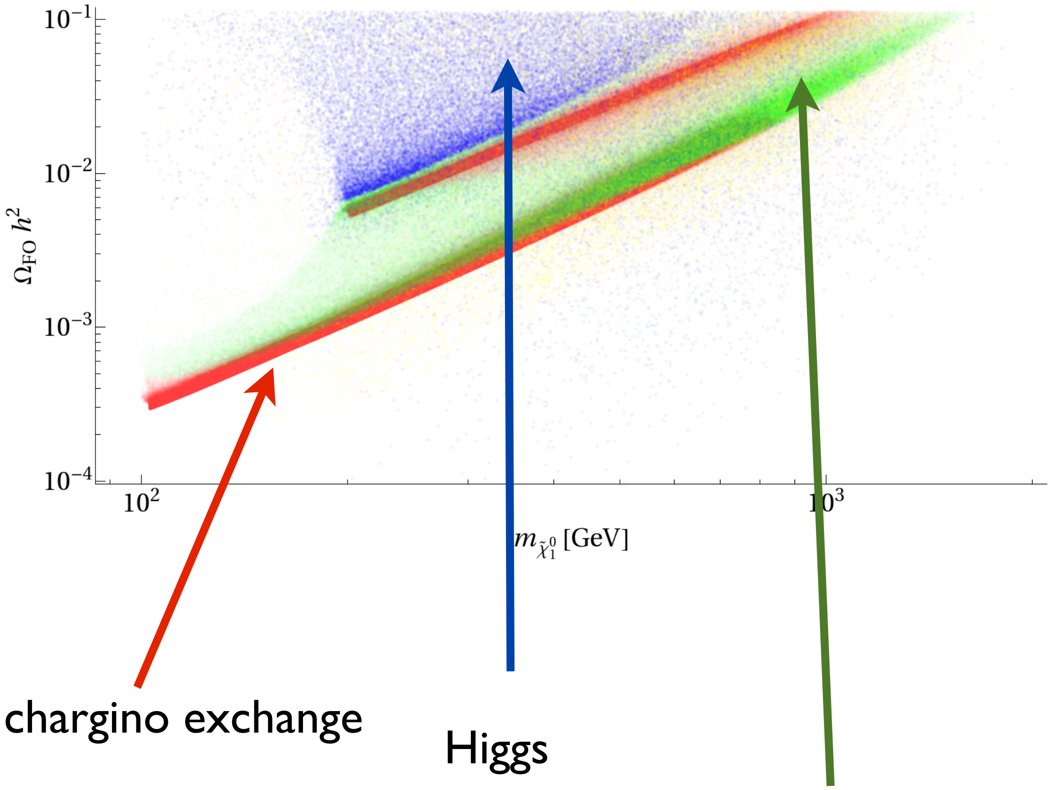


arXiv:1204.3727

Z, Higgs, A,....

before 4th July!

High mass neutralino



chargino exchange

Higgs

chargino co-annihilation

To compensate resonance effects, one can decrease the couplings.

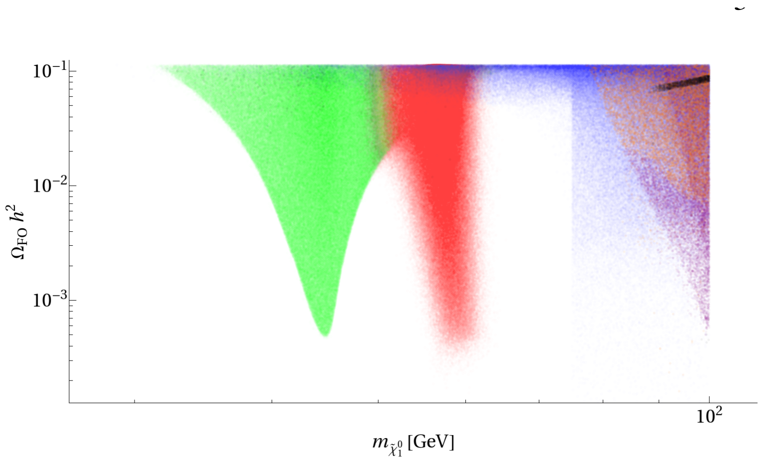
In the 'SUSY' language this translates into Bino/Wino/Higgsino fraction.
In a generic framework, this is related to the strength of the coupling...

Relic density can be extremely small if the DM mass corresponds to a value right on a Higgs or Z resonance

This is not necessarily a problem: neutralino could be a sub-dominant DM species or one could invoke regeneration mechanisms such as Freeze-In, ...

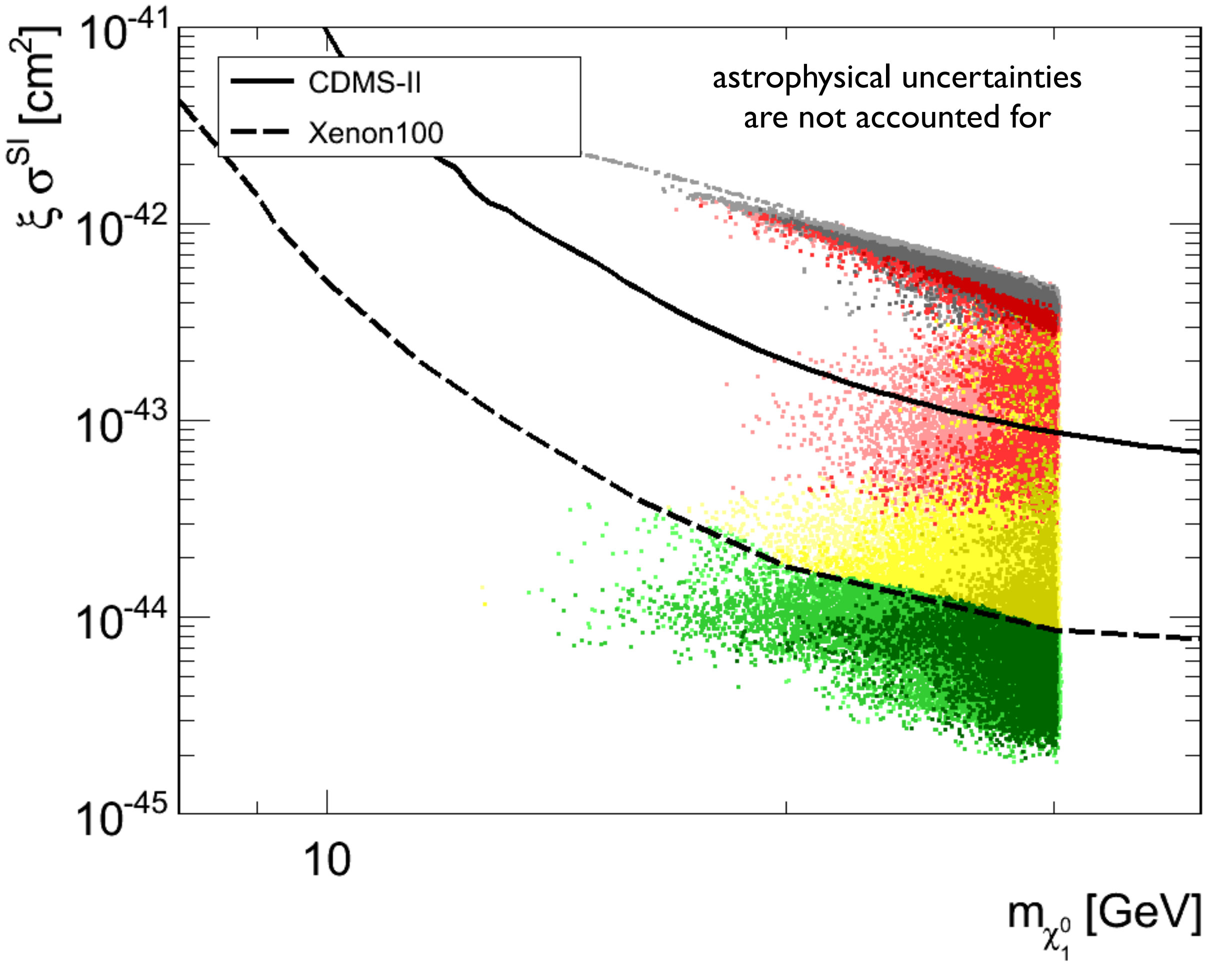
Small masses

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
μ	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

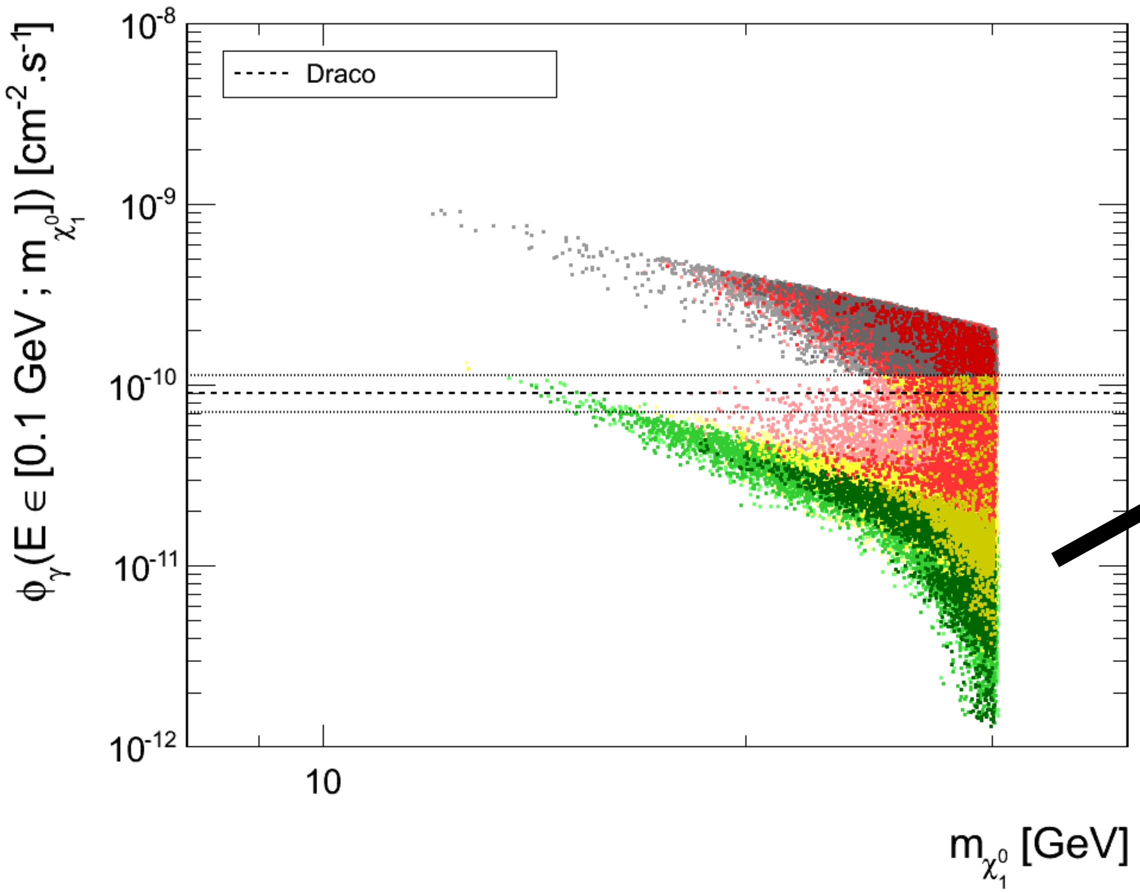
1) **There are points below 30 GeV but not that much below 20 GeV** (caveat: light neutralinos with very light sbottoms; may not be killed by monophoton searches, arXiv:1205.2557)

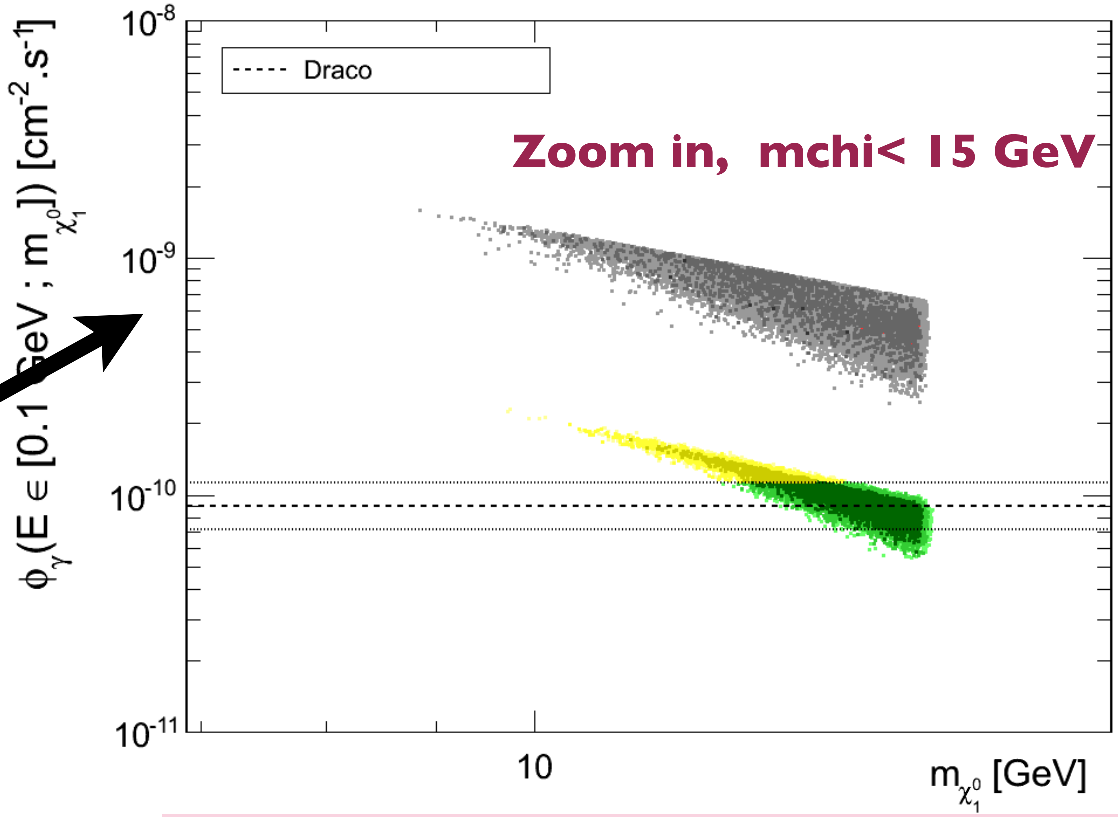
2) **most of the points are excluded by XENON100 (but...) and CDMS**

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

Astrophysical constraints

low mass





Zoom in, mchi< 15 GeV

In the exclusion region for FERMI/LAT
so this possibility should be ruled out/proved soon

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

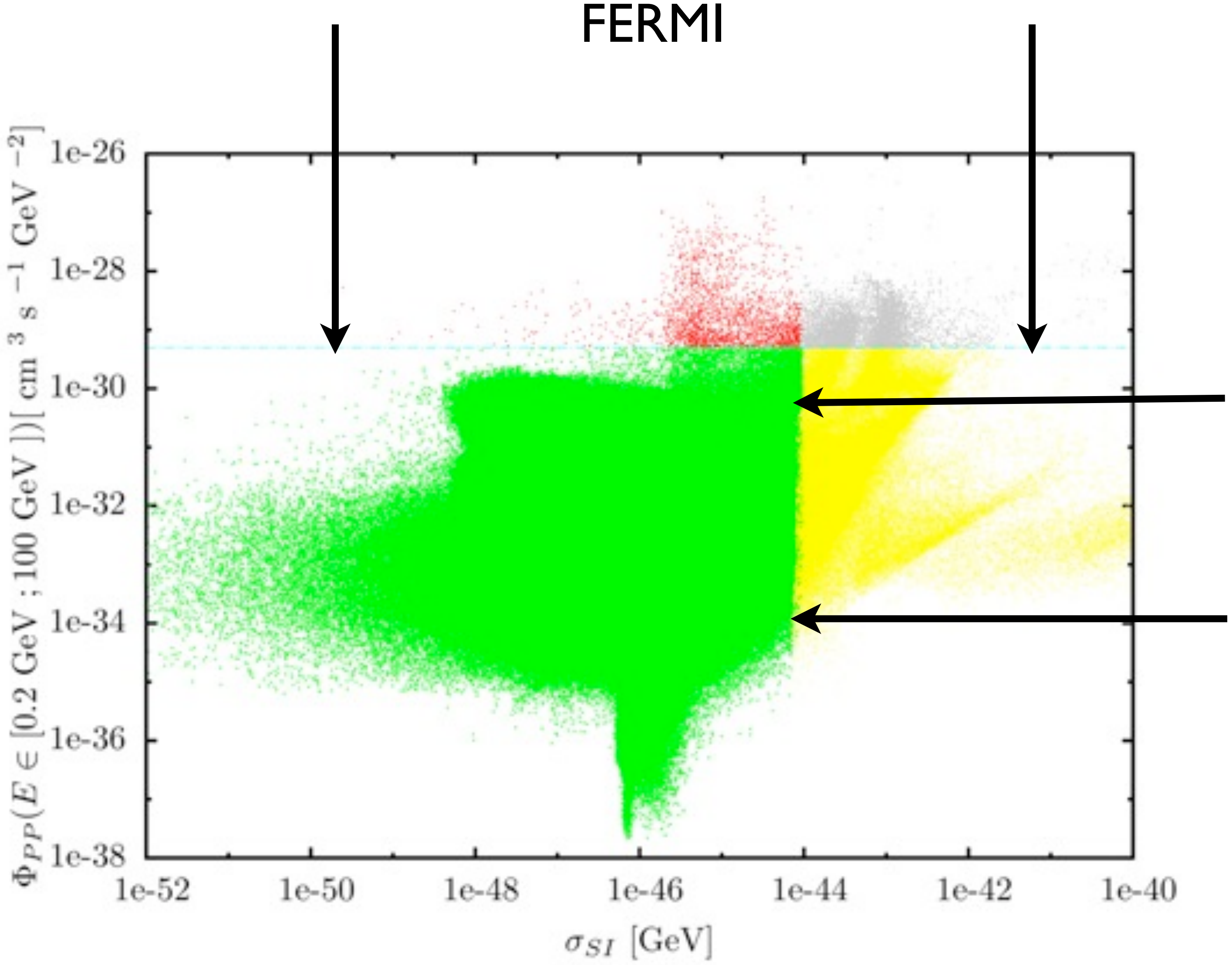
Increasing the mass range:
Cross-correlating Indirect and Direct Detection

FERMI

red/black: excluded

yellow: excluded by 1 experiment

green: ok



XENON100 (& CDMSII)

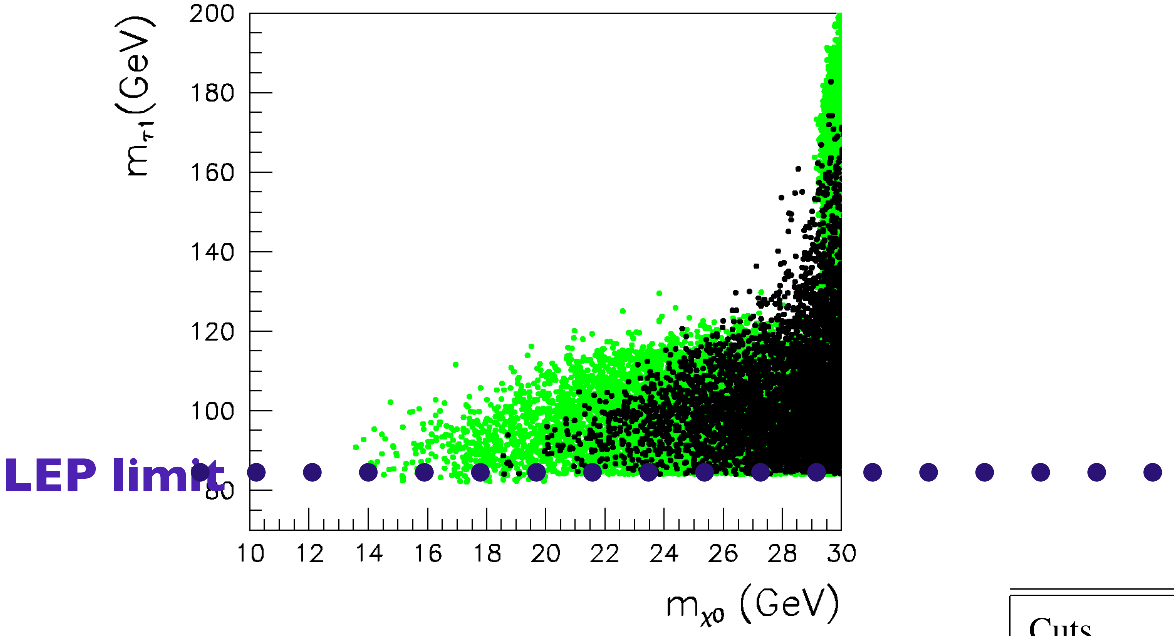
Model = pMSSM + relic density > 3% WMAP, mdm < 100 GeV (no mass below 20 GeV)

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!

Light staus are associated with light neutralinos (<28 GeV)
Are there signatures at LHC?

(Higgs coupling not efficient enough and no other sparticle to help the annihilations)



staus are produced by gluino and squark decays

They further decay into neutralino (not LSP) or chargino which decay into taus. This can give same sign di and tri-tau signatures.

these are the main channels to consider after cuts

arXiv:1206.5404

Cuts	SSDτ_j					Triτ_j				
	B	BP1	Sig.	BP2	Sig.	B	BP1	Sig.	BP2	Sig.
basic cuts	2368	355	7.12	39	0.799	138	82	6.41	14	1.17
$\not{E}_T > 150$ GeV	376	259	12.15	22	1.12	19	60	10.25	8	1.72
$\Sigma\lvert p_T\rvert > 1000$ GeV	482	294	12.29	19	0.86	18	69	11.67	7	1.56
$\Sigma\lvert p_T\rvert > 1100$ GeV	319	280	13.96	19	1.05	12	67	12.79	7	1.86
$M_{eff} > 1100$ GeV	326	296	14.55	19	1.04	14	69	12.55	7	1.74
$M_{eff} > 1200$ GeV	257	287	15.5	19	1.17	10	68	13.58	7	2.01
$\Sigma\lvert p_T\rvert > 1000$ GeV+$\not{E}_T >$ $max(150,\ 0.1\Sigma\lvert p_T\rvert)$ GeV	106	208	16.31	15	1.42	8	52	11.74	7	2.20
$M_{eff} > 1000$ GeV+$\not{E}_T >$ $max(150,\ 0.1M_{eff})$ GeV	157	246	16.36	19	1.49	10	58	12.03	8	2.27

Table 2: *Number of signal and background events for the $2\tau_j$+3-jets+$\not{E}_T$ and $3\tau_j$+3-jets+$\not{E}_T$ final states, considering all SUSY processes, with E_{cm}=14 TeV at an integrated luminosity of 10 fb^{-1} assuming tau identification efficiency of 50% and a jet rejection factor of 100. The series of cuts are applied independently.*

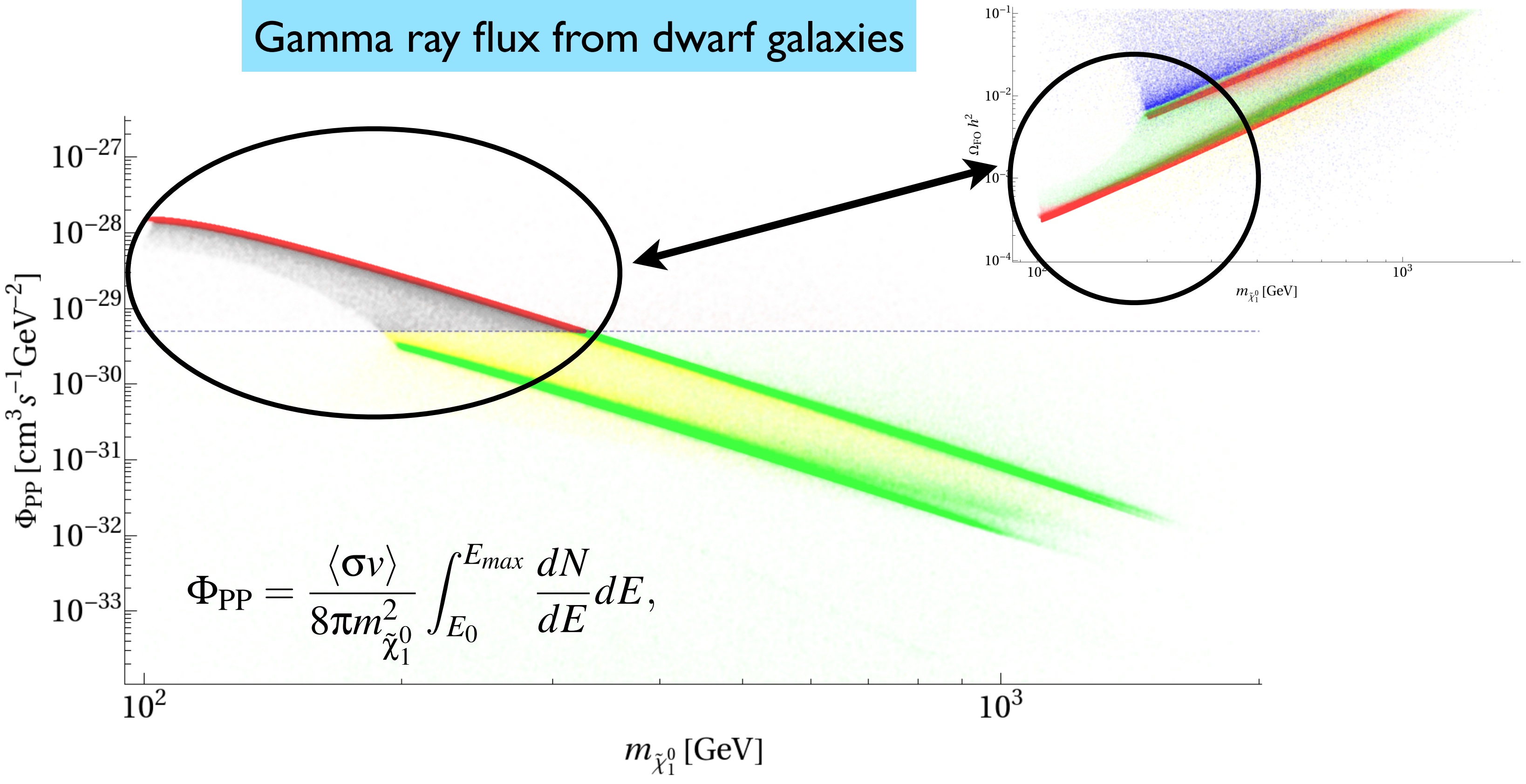
neutralinos with a mass below 28 GeV should be easy to rule out with LHC (if 14 TeV, 10 fb-1).

Higher masses

Astrophysical constraints

High mass

Gamma ray flux from dwarf galaxies

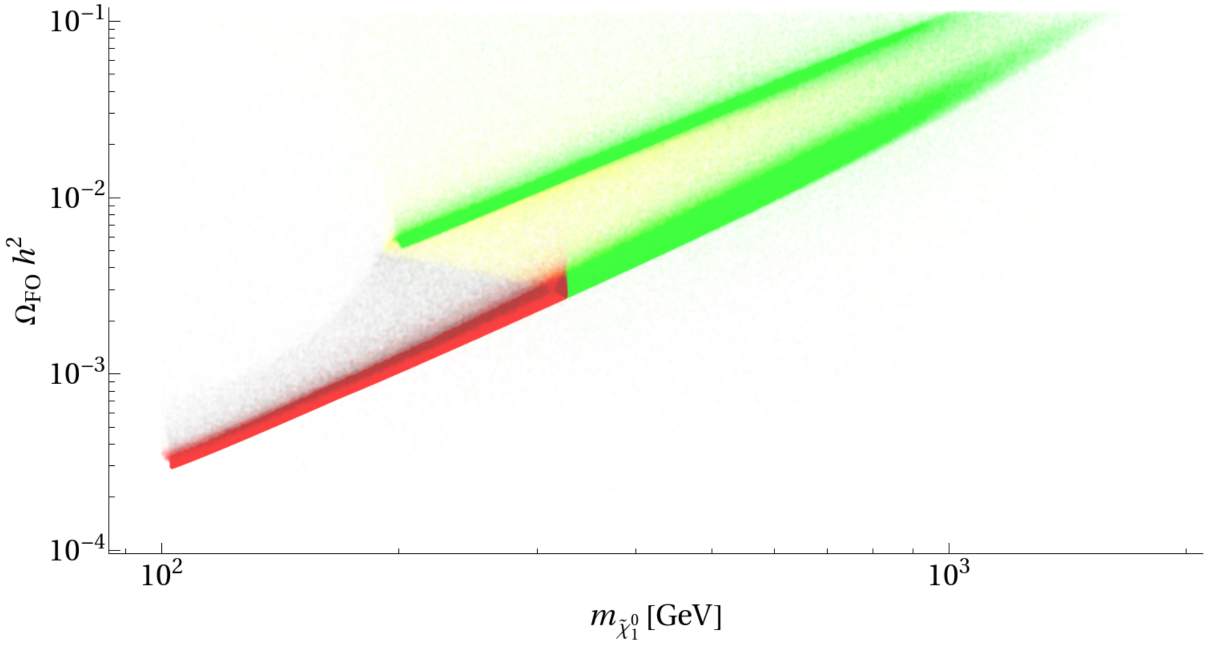


$$\Phi_{PP} = \frac{\langle\sigma v\rangle}{8\pi m^2_{\tilde\chi^0_1}} \int_{E_0}^{E_{max}} \frac{dN}{dE}\, dE,$$

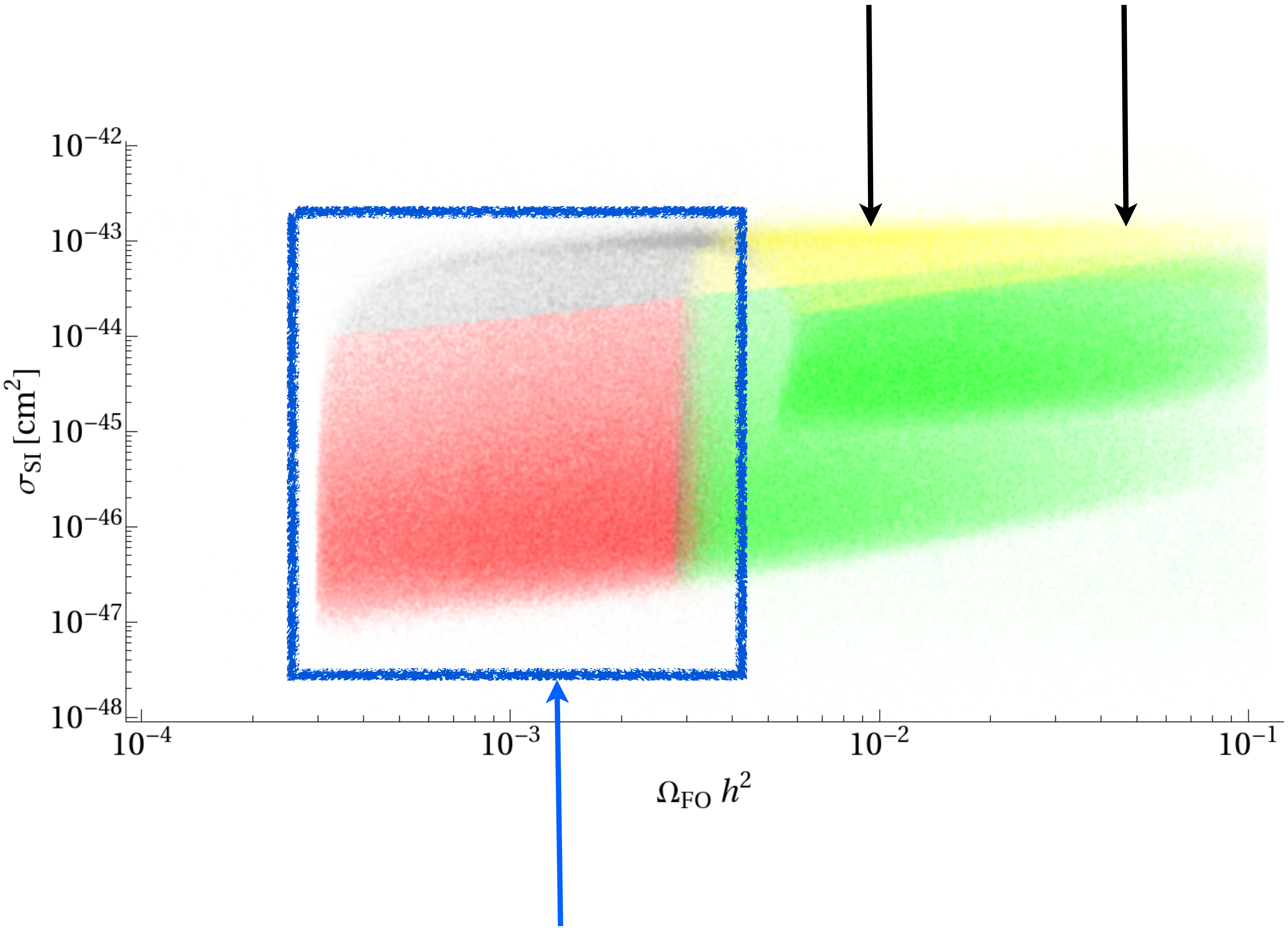
Red: excluded by Indirect detection
yellow: excluded by XENON100
black : excluded by both contraints
green : not excluded

FERMI/LAT do not kill all the points
but they do kill many if we assume
a regeneration mechanism!

As a result, scenarios with very
large cross section at Freeze-Out
cannot be regenerated!



mdm>100 GeV



Direct detection

killed by Indirect detection

XENON1T (or similar) again welcome+LHC analysis

Change of Framework

Another example of complentarity between all experiments: NMSSM

extra singlet enable to have a very light Higgs
enable to have light neutralinos with a FO relic density

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].

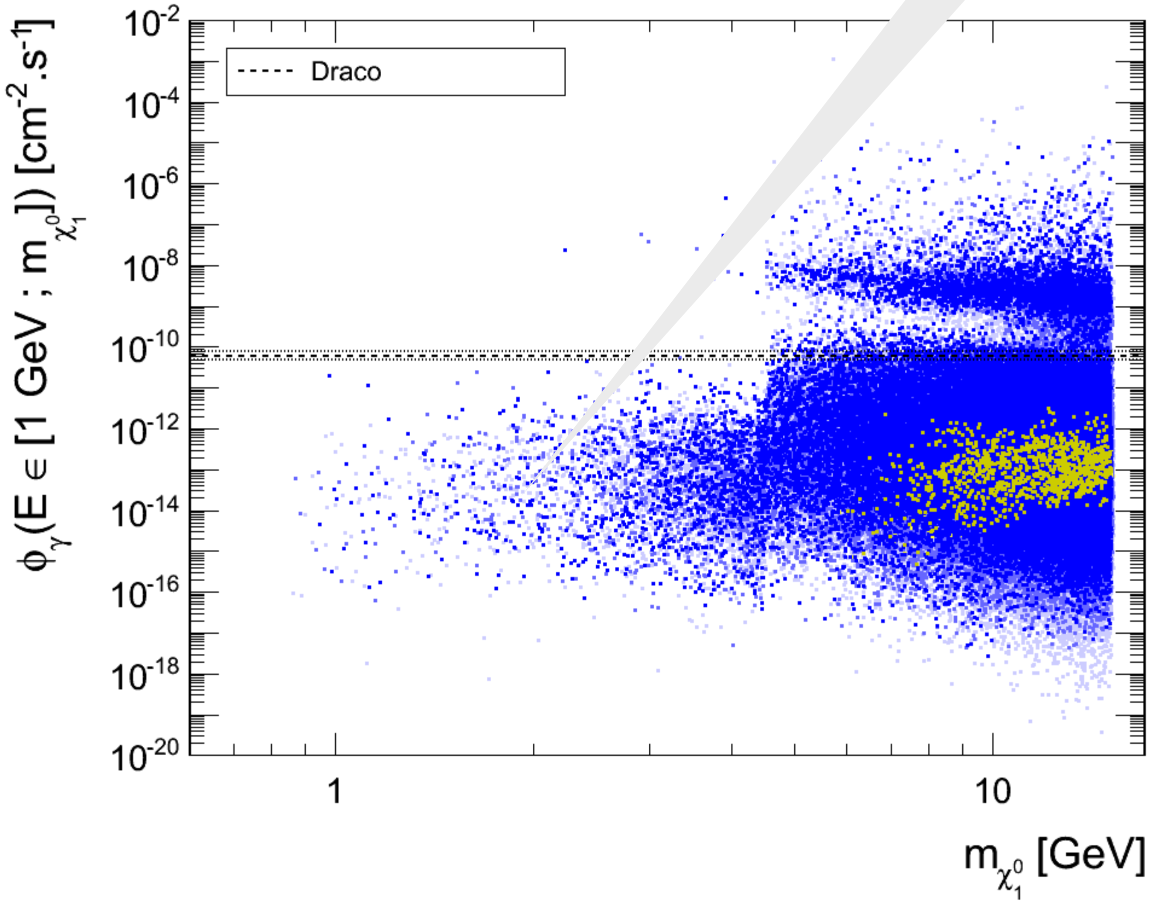
M_1	M_2	$M_{\tilde{l}}$	$M_{\tilde{q}}$	μ	$\tan\beta$	λ	κ	A_λ	A_κ	A_t

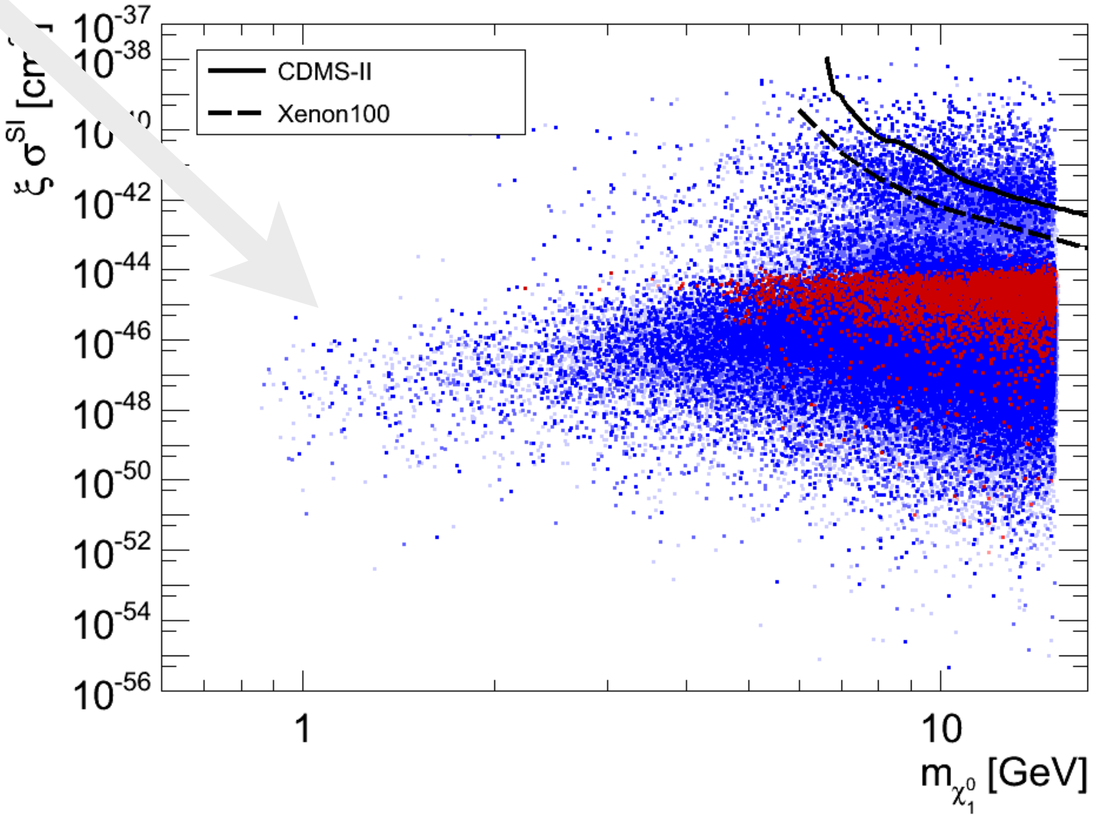
$$W = \lambda S H_u H_d + \frac{1}{3}\kappa S^3 \qquad \mu = \lambda\langle S\rangle$$

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

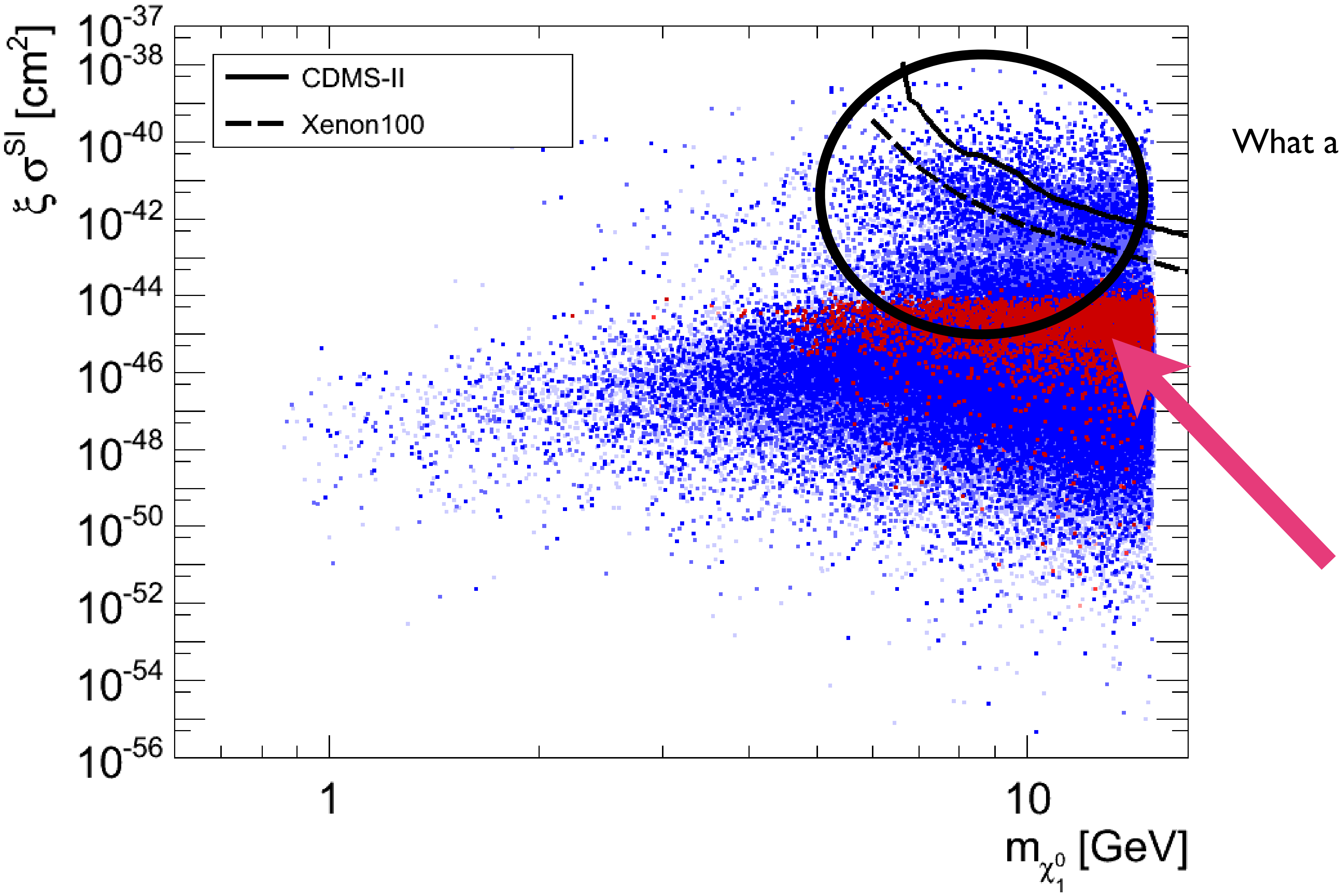
$\mu, \tan\beta$ as well as $\lambda, \kappa, A_\lambda, A_\kappa$

light neutralinos...





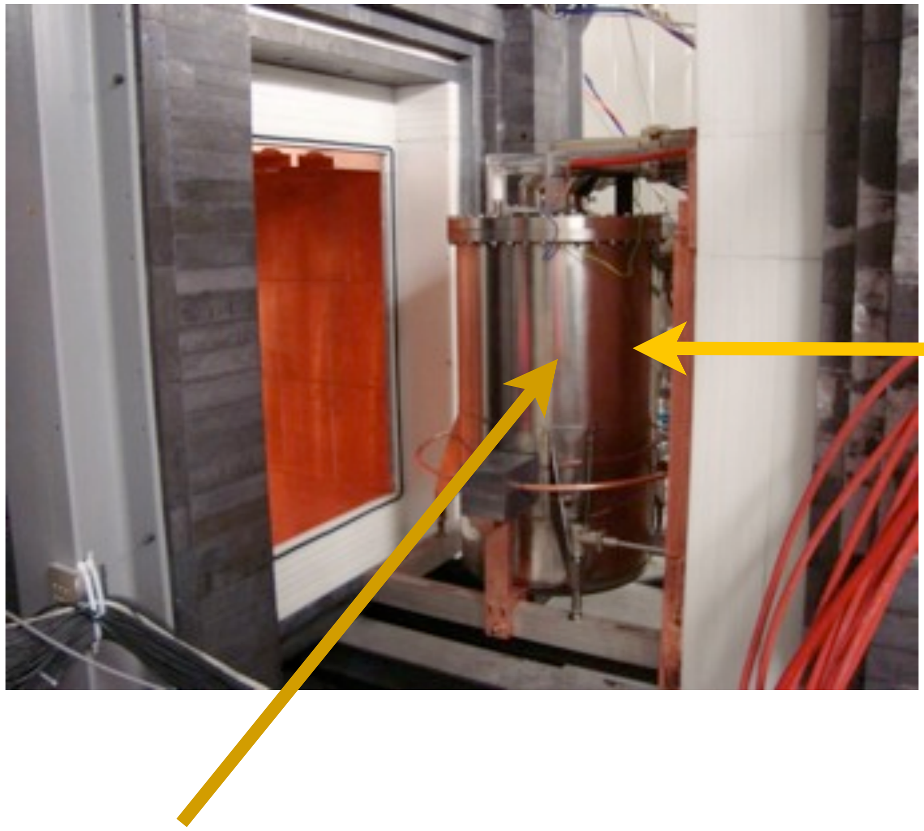
How far are the points close to the XENON100 limit close to be excluded?



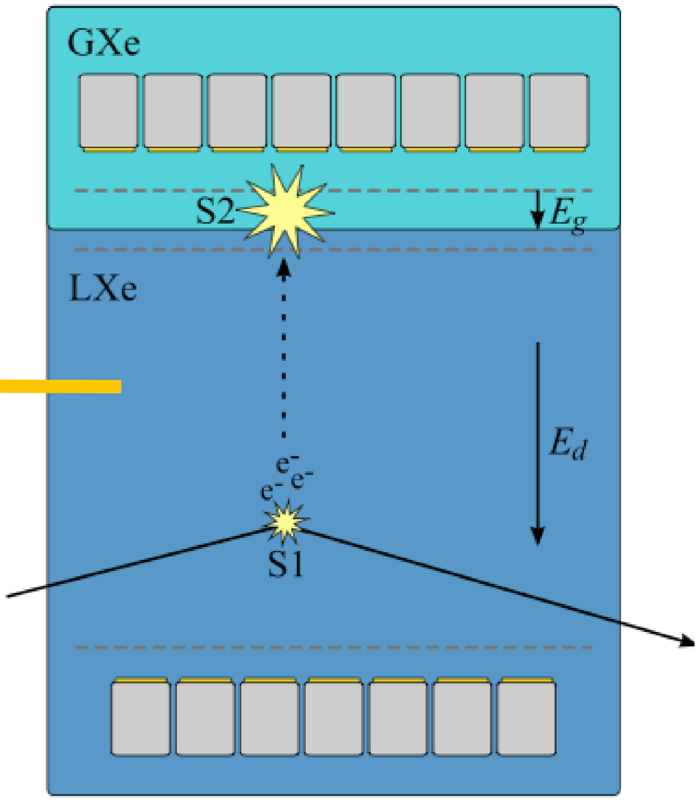
What are the uncertainties?

already excluded by
indirect detection

Re-investigating the XENON100 experiment



detector inside (shielded from radioactivity)



2 phase detector:

upper part = gas

lower part= liquid

Exploiting S1 gives an information
about the interaction of DM with Xenon nuclei
but it depends on the scintillation efficiency
of the Xenon nuclei.

Problem:
nobody has seen a DM particle so
we do not know is the scintillation efficiency
of a DM particle colliding with a Xenon nucleus.
One needs to use calibration measurements
=> relative scintillation efficiency (Leff)

S1 = primary scintillation signal

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

S1, S2 measured in photo-electrons

Sensitivity of XENON100 limit at low mass

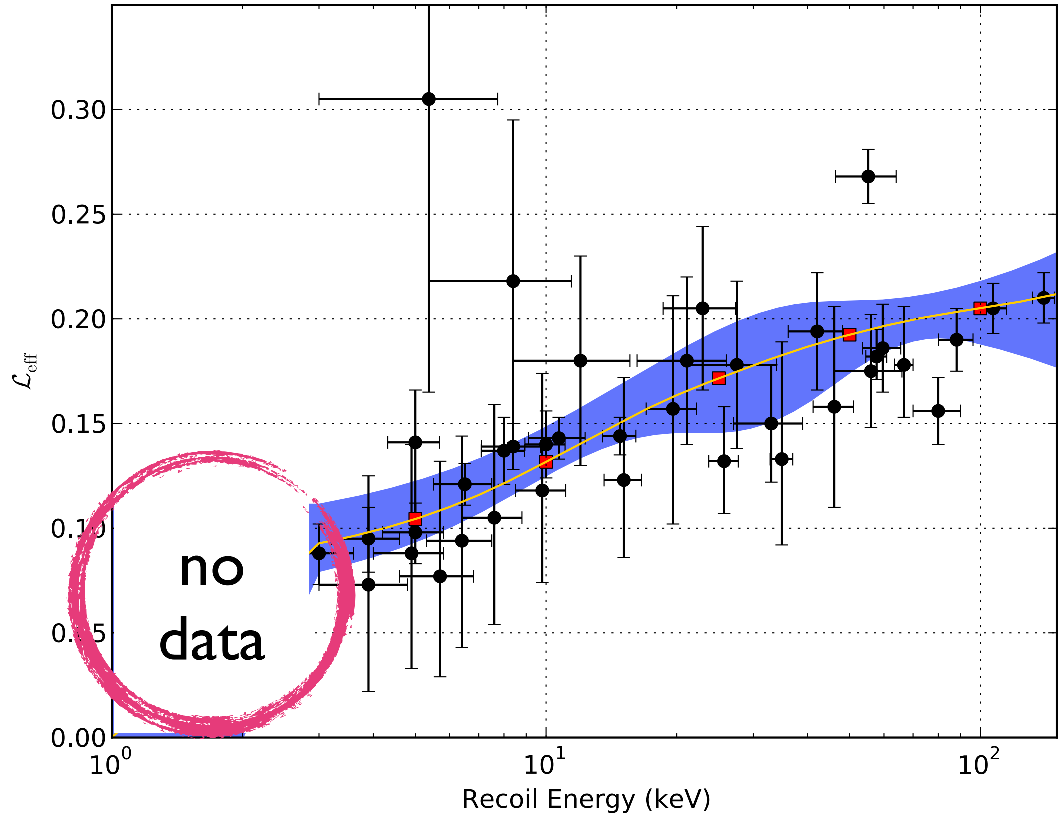
Recoil energy $$E_{nr} = \frac{S_1}{L_y\ \mathcal{L}_{\text{eff}}} \boxed{\frac{S_{er}}{S_{nr}}},$$

Recoil energy depends crucially on Leff

Light yield for the calibration source emitting gammas

quenching factors, related to the electric field

One needs to measure Leff but here are the data:

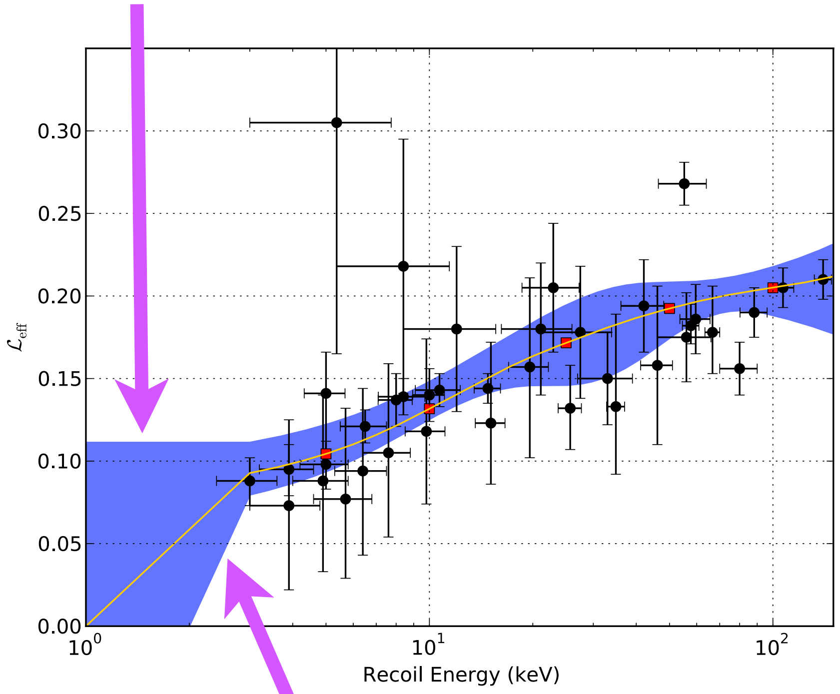


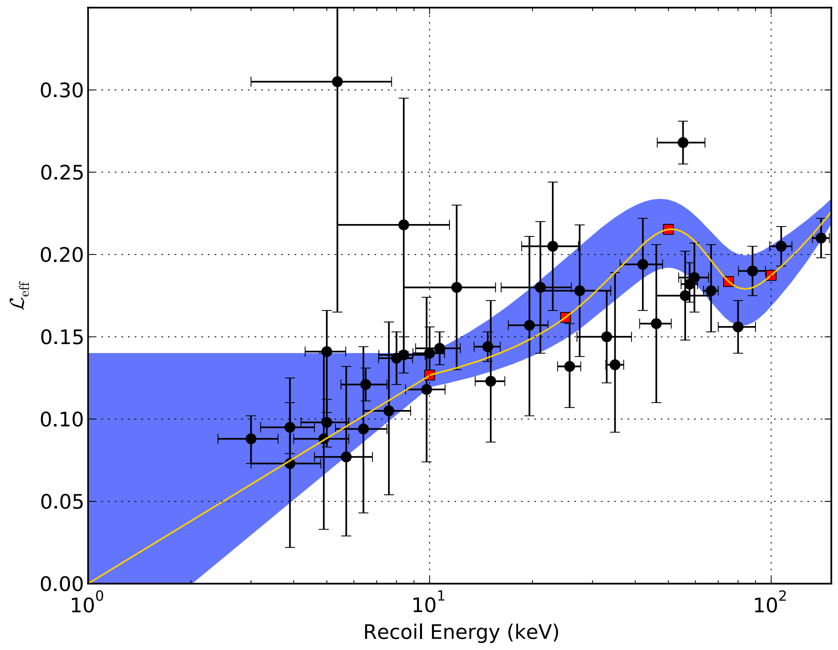
none of them are really consistent and there is no theoretical expression to use for Leff to perform a best fit so the solution is to perform a cubic spline interpolation

Sensitivity of XENON100 limit at low mass

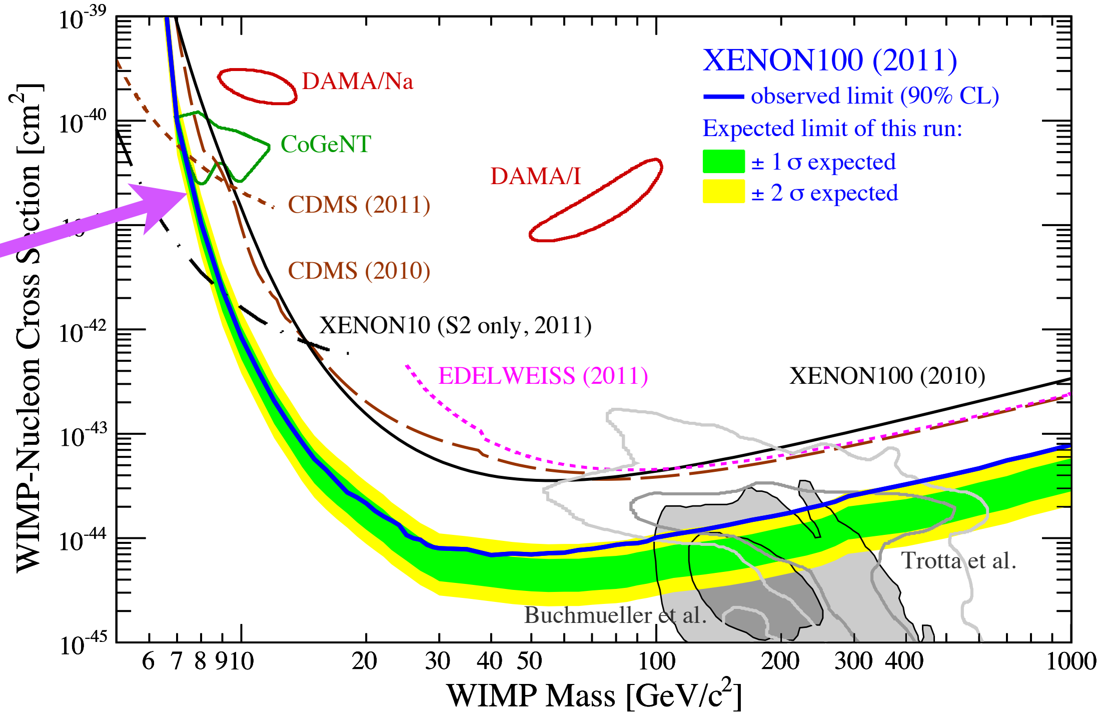
Recoil energy depends crucially on Leff **but lack of data below 3keV**

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





But 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

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

Dark Matter likelihood

NR likelihood

ER likelihood

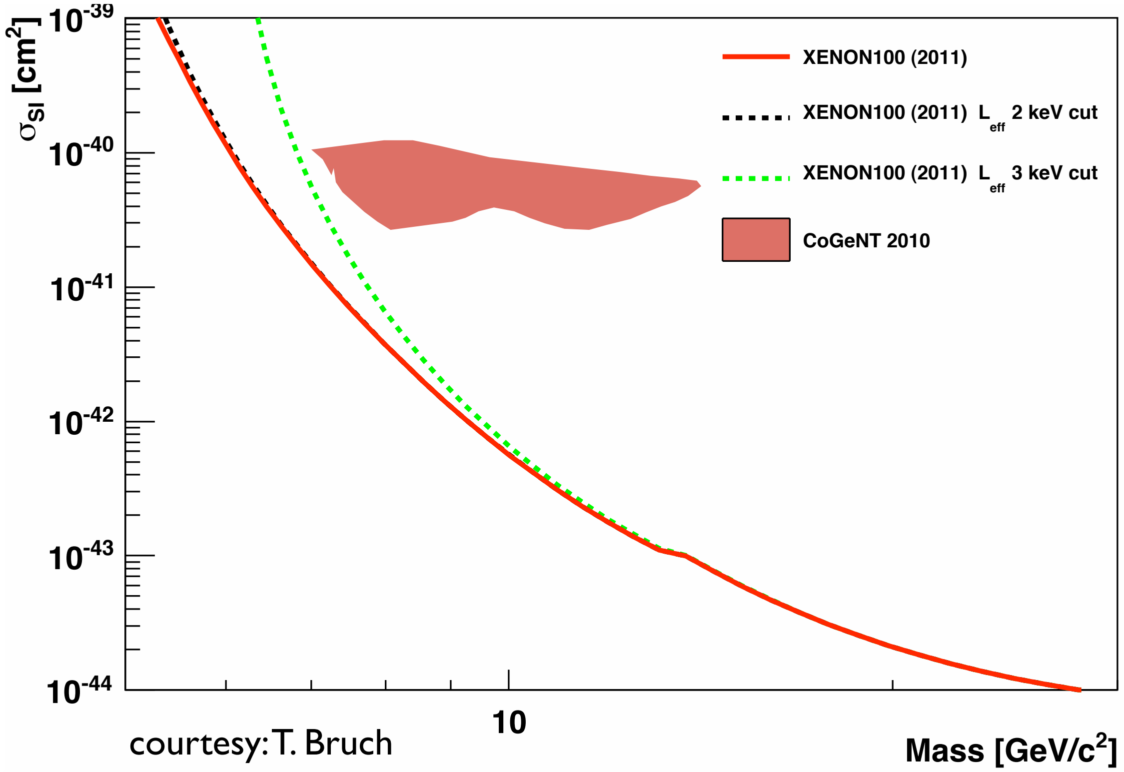
Uncertainties on the energy scale

Uncertainties on the escape velocity

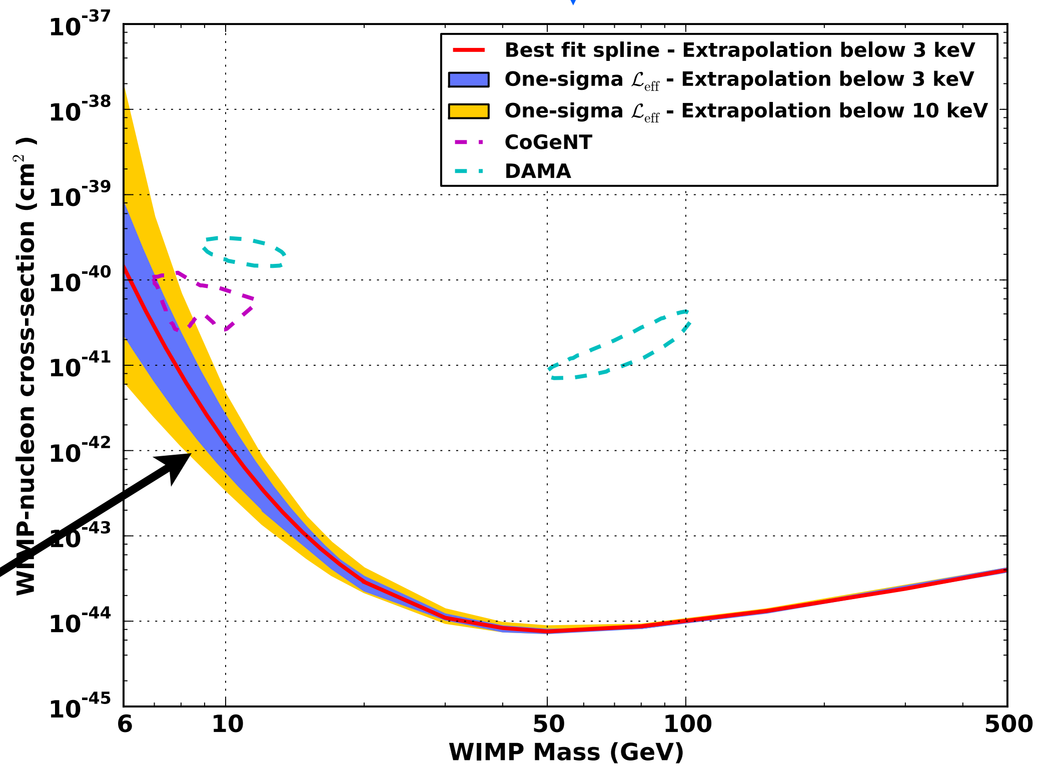
$$\begin{aligned}\mathscr{L} &= \prod_{j=1}^{K} \mathrm{Poiss}(n^j|\epsilon_s^j N_s + \epsilon_b^j N_b)\\ &\times \prod_{i=1}^{n^j} \frac{\epsilon_s^j N_s f_s(S1) + \epsilon_b^j N_b f_b(S1)}{\epsilon_s^j N_s + \epsilon_b^j N_b}\\ &\times \mathrm{Poiss}(m_b^j|\epsilon_b^j M_b) \times \mathrm{Poiss}(m_s^j|\epsilon_s^j M_s)\\ &\times e^{-(t-t^{\mathrm{obs}})^2/2} \times f_v(v_{\mathrm{obs}}|v_{\mathrm{esc}}).\end{aligned}$$

Same Likelihood but without the parameterisation for Leff

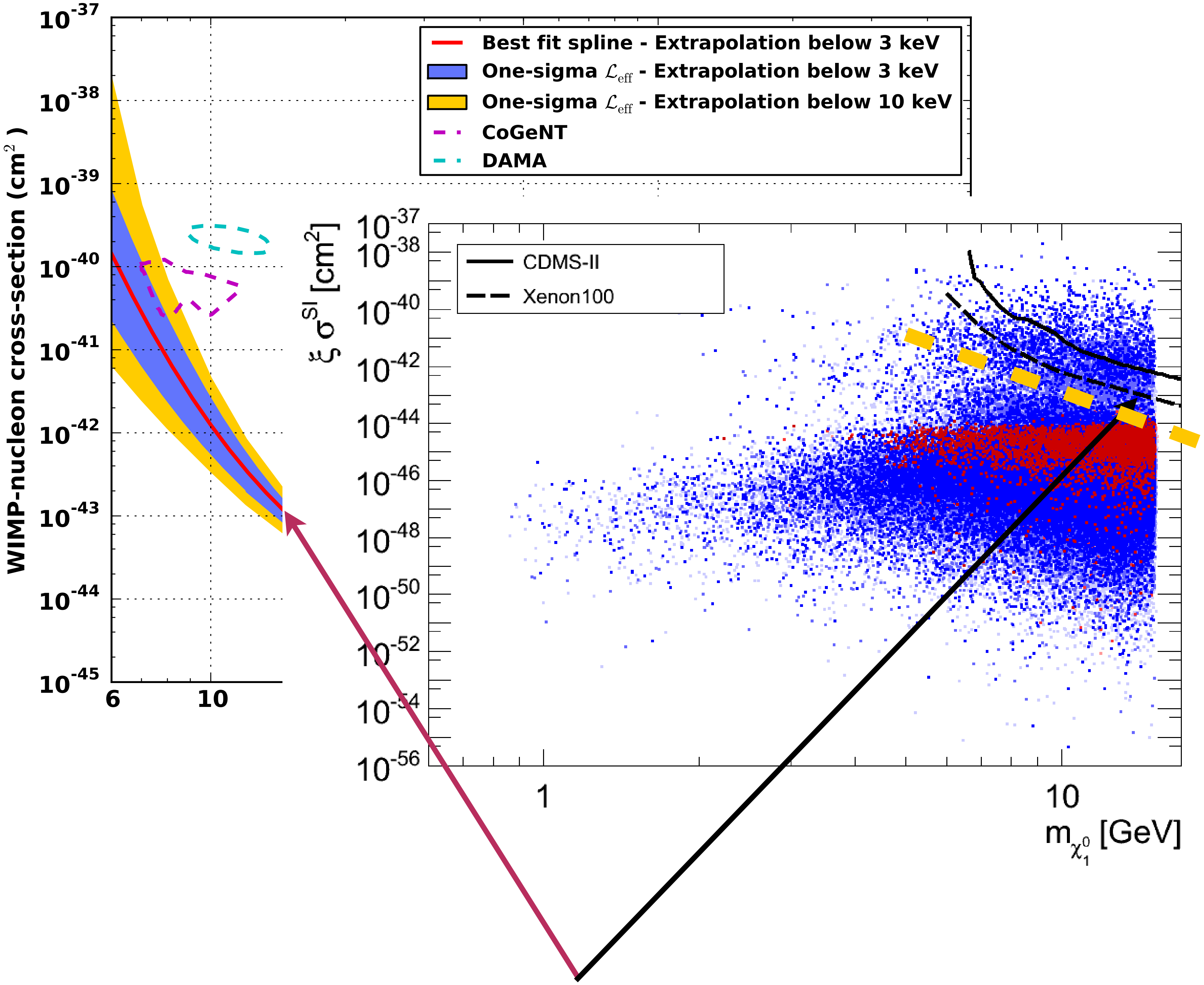
arXiv:1203.6823



courtesy: T. Bruch



flat Leff



XENON100 2011 data could dig even more into this region

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

Conclusion

Not so many very light neutralinos (hard to find below 15 GeV)

Combining direct, indirect detection is already reducing the parameter space

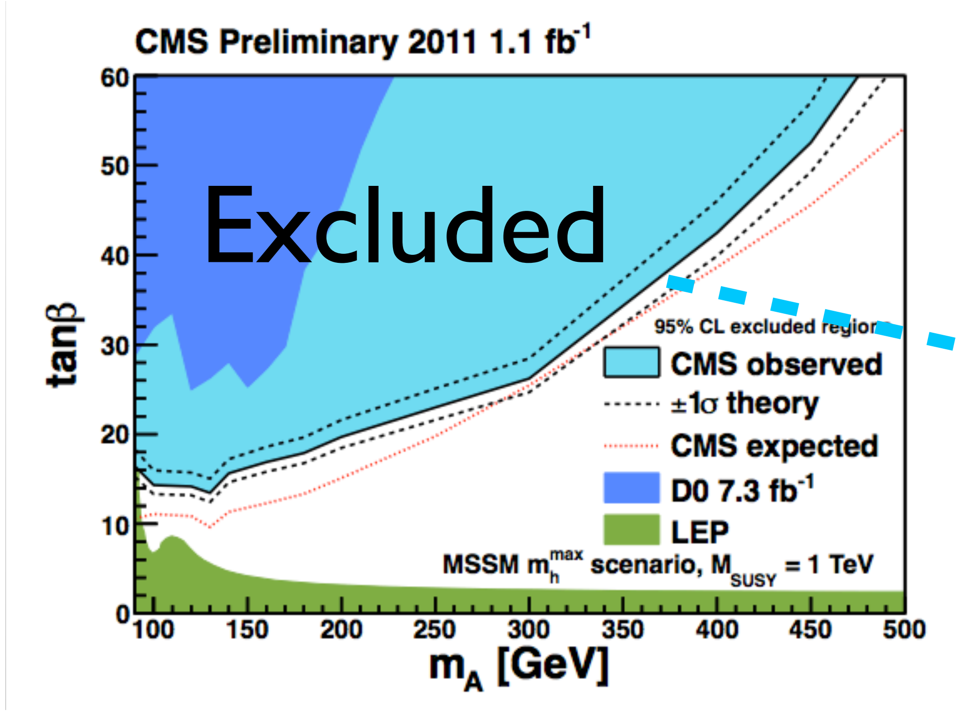
Even if we relax the lower bound on the relic density, one can set exclusion with INDIRECT detection but DIRECT detection is becoming complementary too!

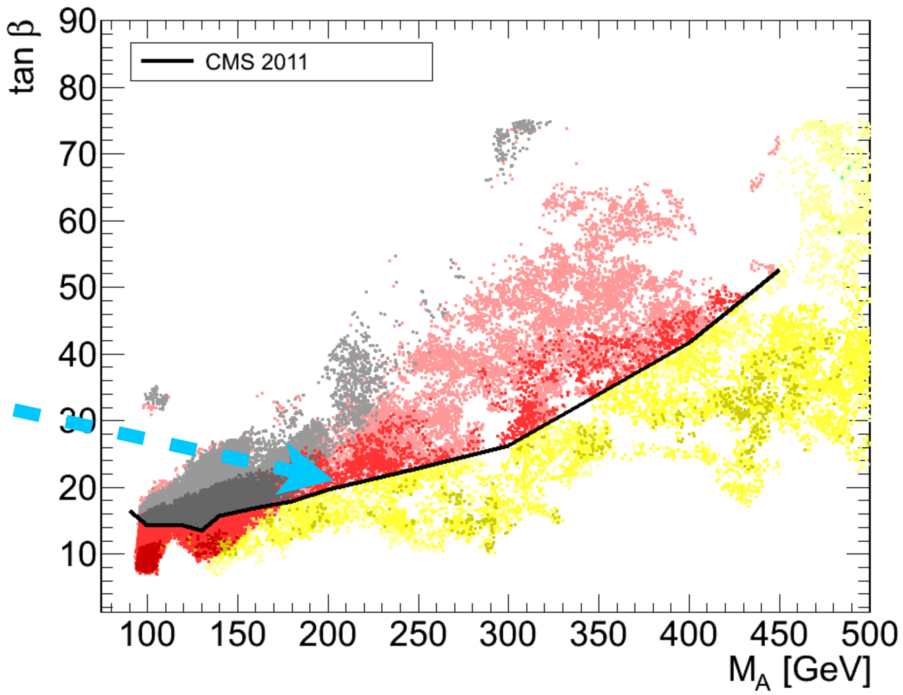
SUSY searches at LHC will definitely help to reduce the parameter space
(di and tri-taus signatures)

Waiting for the XENON100 new data,
but please remove the parameterisation of Leff

Waiting for LHC new results (including Higgs, **arXiv:1203.3446**)!

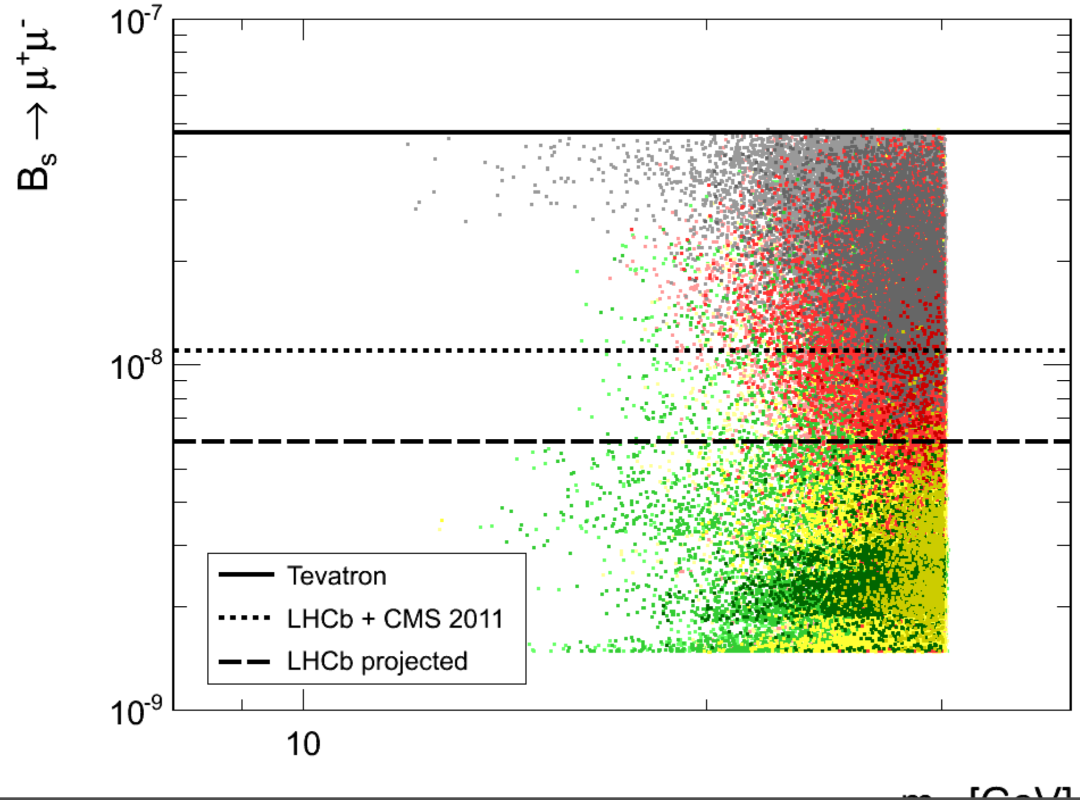
Astro-LHC





mH± ≥ mt + mb

FIG. 2: Allowed points in the tan β 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.

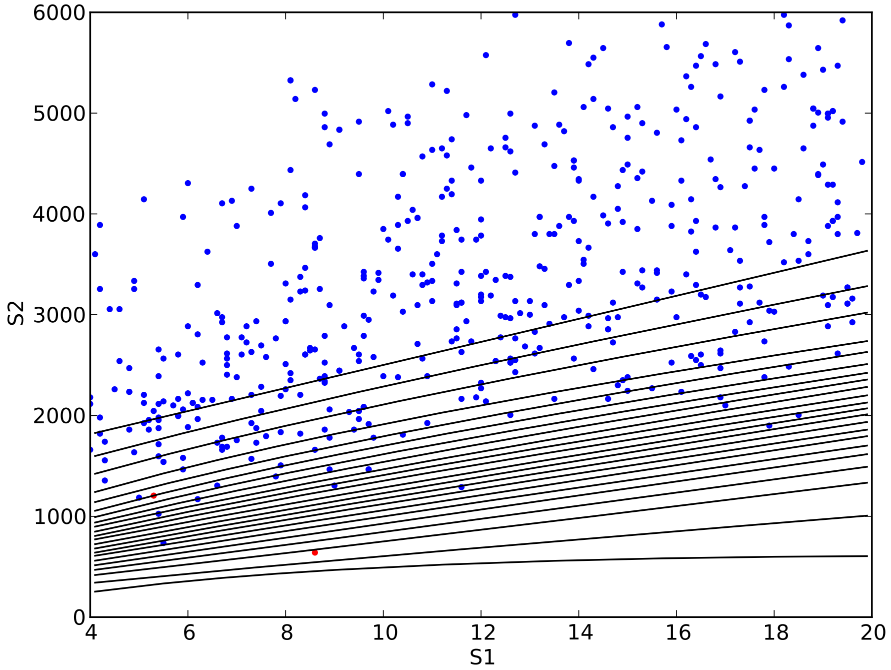


How to get the exclusion curve?

$$\frac{dR}{dS_1}$$: 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

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



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

number of photo-electrons expected for a given recoil energy

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.

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

Likelihood maximised without σ

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

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

Likelihood maximised with σ

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

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

$\longrightarrow$ $\lambda = 1$ 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_σ

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

p-value

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

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