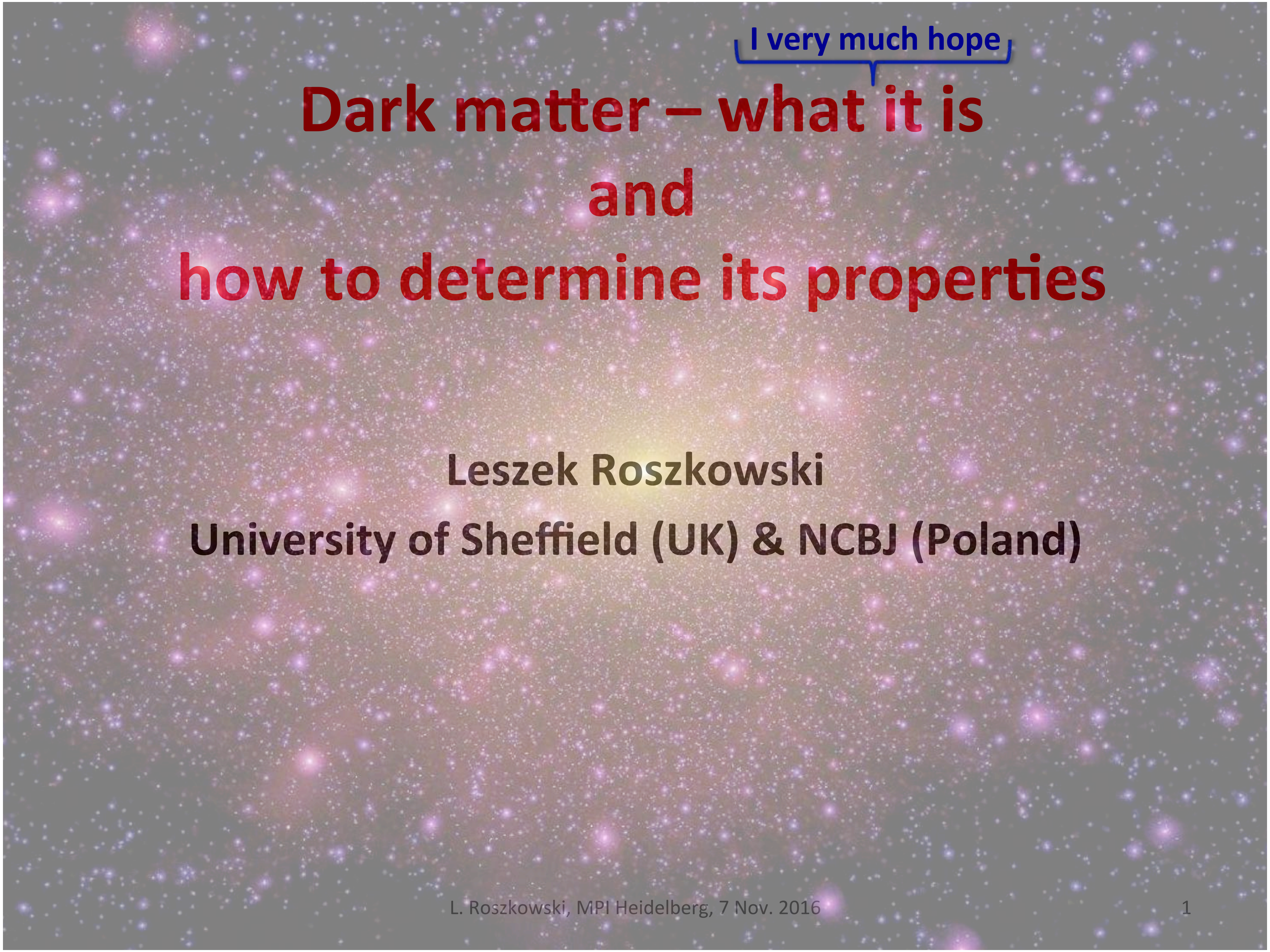


I very much hope

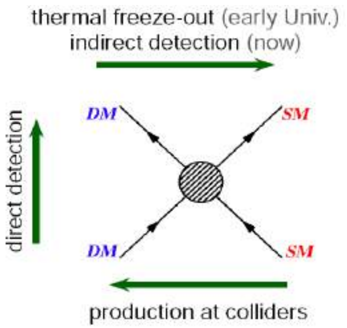
Dark matter – what it is
and
how to determine its properties

Leszek Roszkowski

University of Sheffield (UK) & NCBJ (Poland)

Three approaches:

- **Direct, indirect, collider**



Different motivations:

- **Curiosity driven**
- **Data driven**
- **Theory driven**

Can partly overlap, specific models can be the same, but very different ``philosophy"

After WIMP discovery…

- **Inferring DM particle properties**

The different approaches may possibly remain, or even intensify

Three ways to identify DM WIMP

Curiosity driven:

- Any interactions allowed by basic principles and data
- Not necessarily complete models
- Usually not addressing other issues
- Simplified models
- …

Data driven:

- Fermi LAT GC excess
- 3.5 keV X-ray line
- Positron fraction excess
- Self-interacting DM

- 130 GeV GR line
- DAMA/LIBRA annual modulation effect
- 0.5 MeV excess (Integral)
- …

Particle theory driven approach

WIMP is part of a more complete framework…

- Solves more than one (DM) problem
  - Gauge hierarchy problem
  - Unification of SM forces (+gravity?)
  - Unification of SM matter (quarks, leptons), …
  - Strong CP problem
  - Naturalness of some sort?
  - …

- Provides promising framework for Big Bang physics
  - Cosmic inflation (+reheating)
  - Baryo/leptogenesis
  - DM (production and abundance)
  - …

- Is compatible with data:
  - All limits on new physics (masses, precision measurements of radiative corrections to EW observables
  - Higgs boson

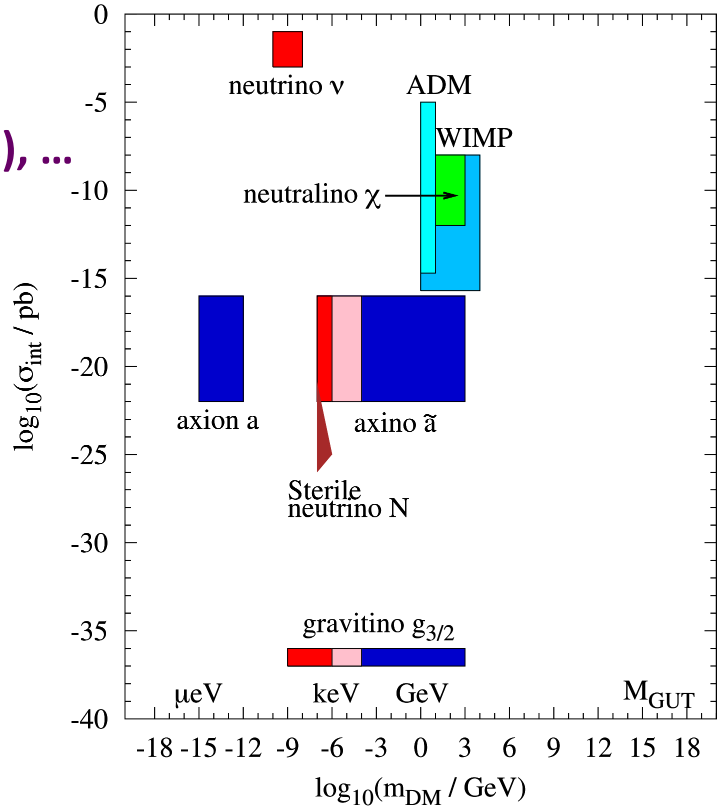
SM is not enough.
Need ``new physics”.

Particle theory motivated approach

WIMP is part of a more complete framework…

- Solves more than one (DM) problem
  - Gauge hierarchy problem
  - Unification of SM forces (+gravity?)
  - Unification of SM matter (quarks, leptons), …
  - Strong CP problem
  - Naturalness of some sort?
  - …

- Provides promising framework for Big Bang physics
  - Cosmic inflation (+reheating)
  - Baryo/lepto-genesis
  - DM (production and abundance)
  - …



- Is compatible with data:
  - All limits on new physics (masses, precision measurements of radiative corrections to EW observables
  - Higgs boson

Need ``new physics”.

SUSY remains most promising framework.

Where is ``new physics”?

- No convincing hint from the LHC

but…

© Ron Leishman * www.ClipartOf.com/1047187

Higgs boson:

- **Fundamental scalar --> SUSY**
- **Light and SM-like --> SUSY**

Low energy SUSY remains the front-runner for ``new physics”

Plan:

- ✧ Implications of Higgs boson m_h~125 GeV and direct limits on SUSY:

DM WIMP: ~1 TeV neutralino (higgsino)

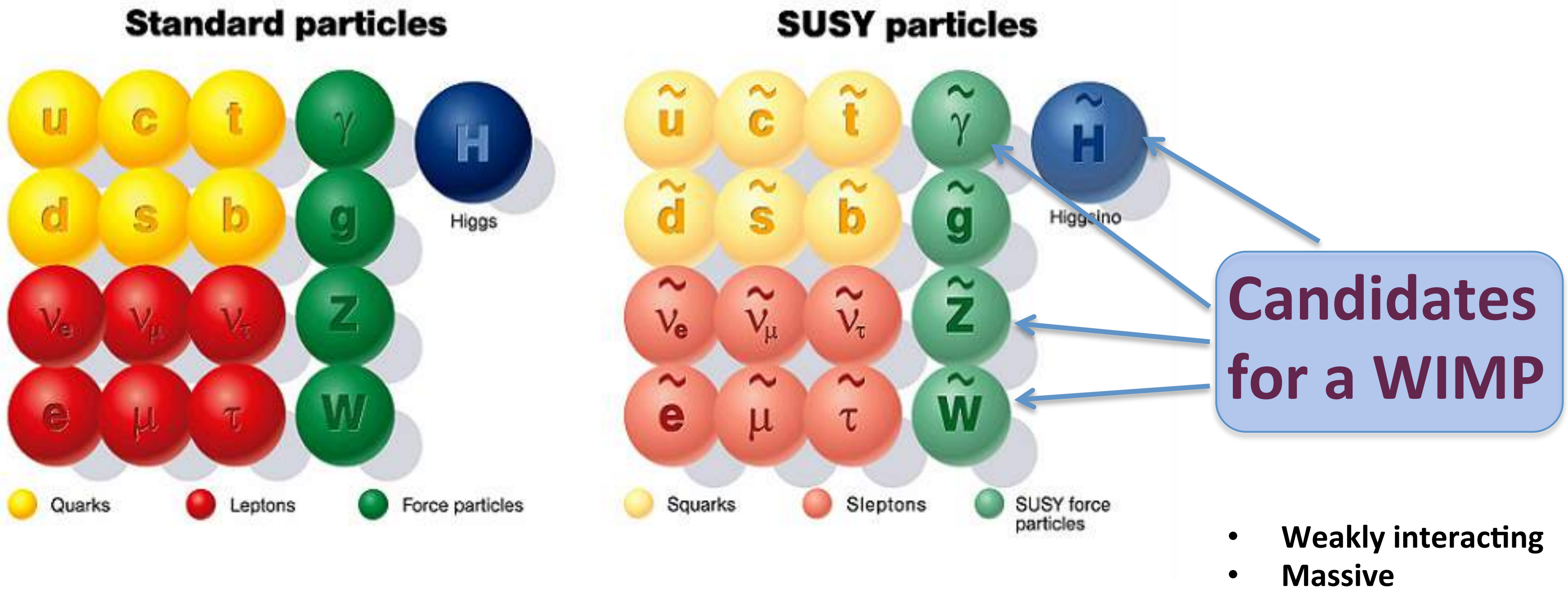
- ✧ Prospects for detection in unified and general SUSY models
  - ✧ complementarity of LHC and DM searches (direct and CTA)

- ✧ Once WIMP detected: challenge of WIMP reconstruction
- ✧ Summary

Based mainly on:

- K. Kowalska, L. Roszkowski, E. M. Sessolo, arXiv:1302.5956, JHEP 1306 (2013) 078
- L. Roszkowski, E. M. Sessolo, A. J. Williams, arXiv:1405.4289 and arXiv:1411.5214 (JHEP)
- K. Kowalska, L. Roszkowski, E. M. Sessolo, S. Trojanowski, 1402.1328 (JHEP)
- K. Kowalska, L. Roszkowski, E. M. Sessolo, A. J. Williams, 1503.08219 (JHEP)
- L. Roszkowski, E. M. Sessolo, S. Trojanowski, A. J. Williams, 1603.06519 (JCAP)

SUSY and dark matter



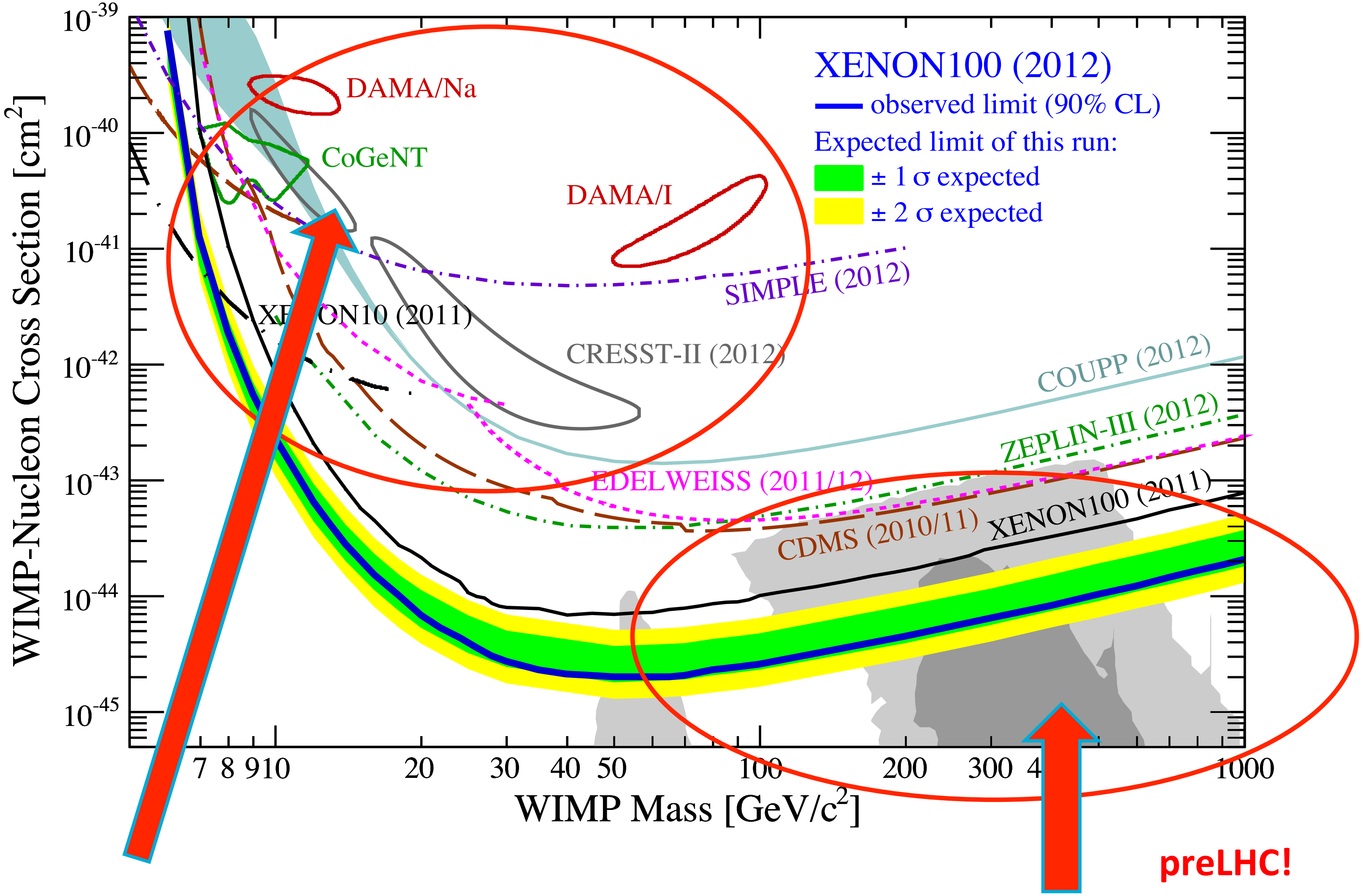
Candidates for a WIMP

- **Weakly interacting**
- **Massive**
- **stable**

With R-parity to keep it stable

WIMP: lightest supersymmetric particle

Direct Detection AD 2011 - Before LHC



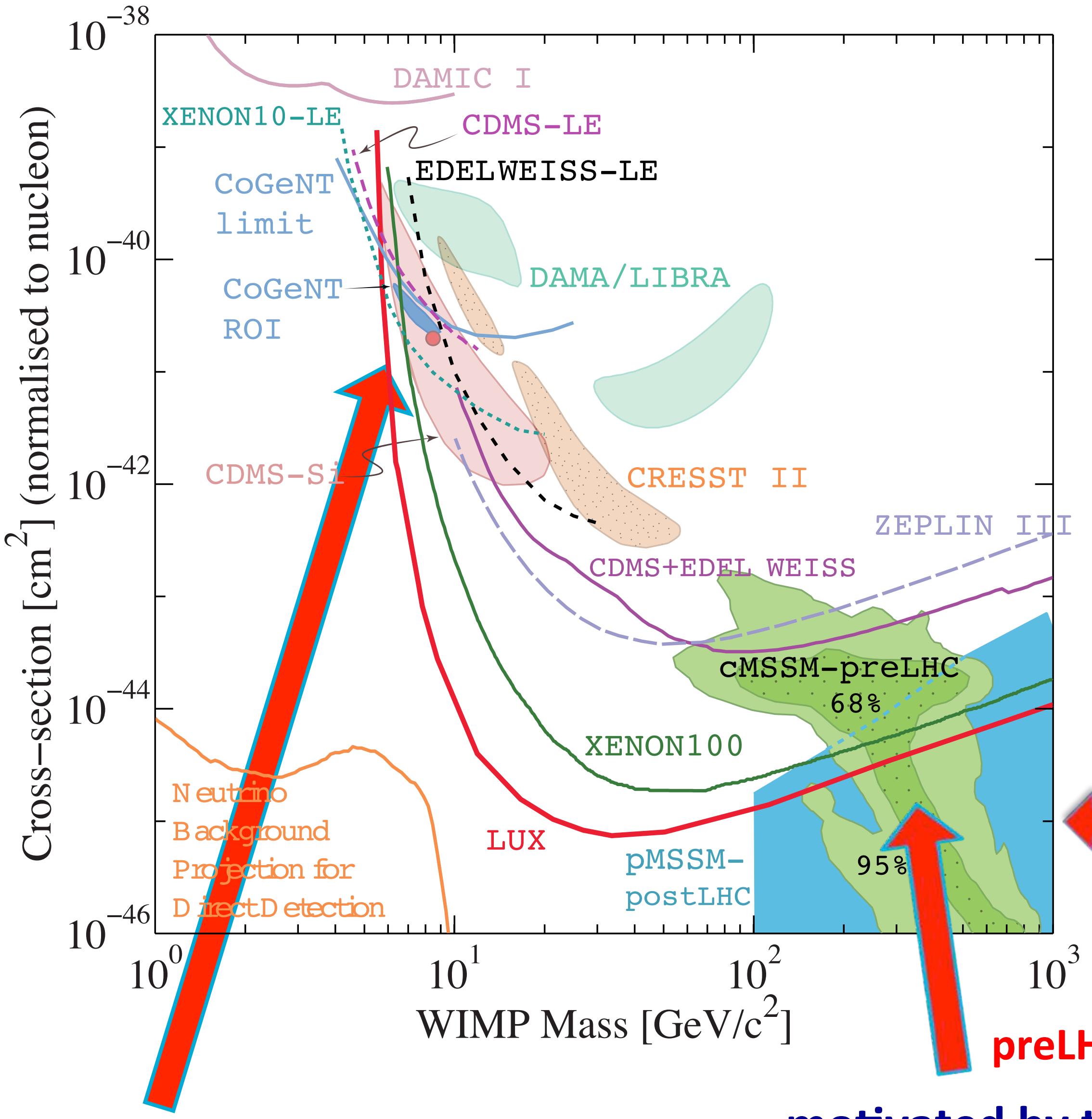
preLHC!

Confusion region

motivated by theory (SUSY)

MasterCode, BayesFITS

Direct Detection Nov. 2013



Since 2011:

- **LHC limits on SUSY**
- **Xenon-100 and LUX limits**

PDG update 2013 (1204.2373)

LHC: theory region has moved down and right

in a very specific way

Smoking gun of SUSY?

preLHC!

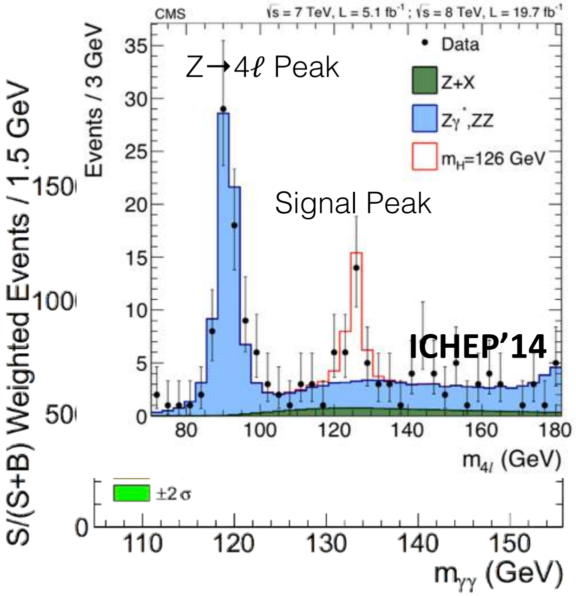
motivated by theory (SUSY)

MasterCode, BayesFITS

Confusion region gone

Main news from the LHC…

- **SM-like Higgs particle at ~125 GeV**



- **No (convincing) deviations from the SM**

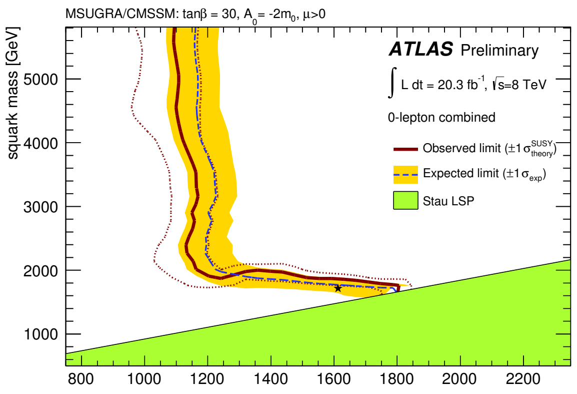
$$\mathrm{BR}(\overline{B}_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

Combined LHCb+CMS

$$\mathrm{SM:}\ 3.54 \pm 0.27 \times 10^{-9}$$

superIso v.3.4

- **Stringent lower limits on superpartner masses**

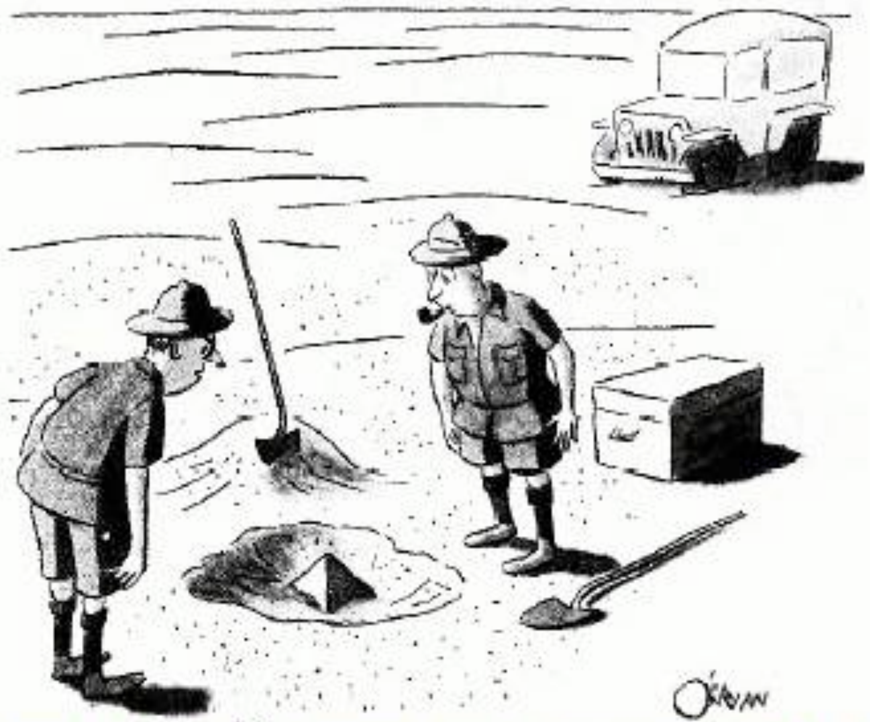


ATLAS-CONF-2013-047

Each independently implies:

SUSY masses pushed to 1 TeV+ scale…

Impact of Higgs boson discovery…



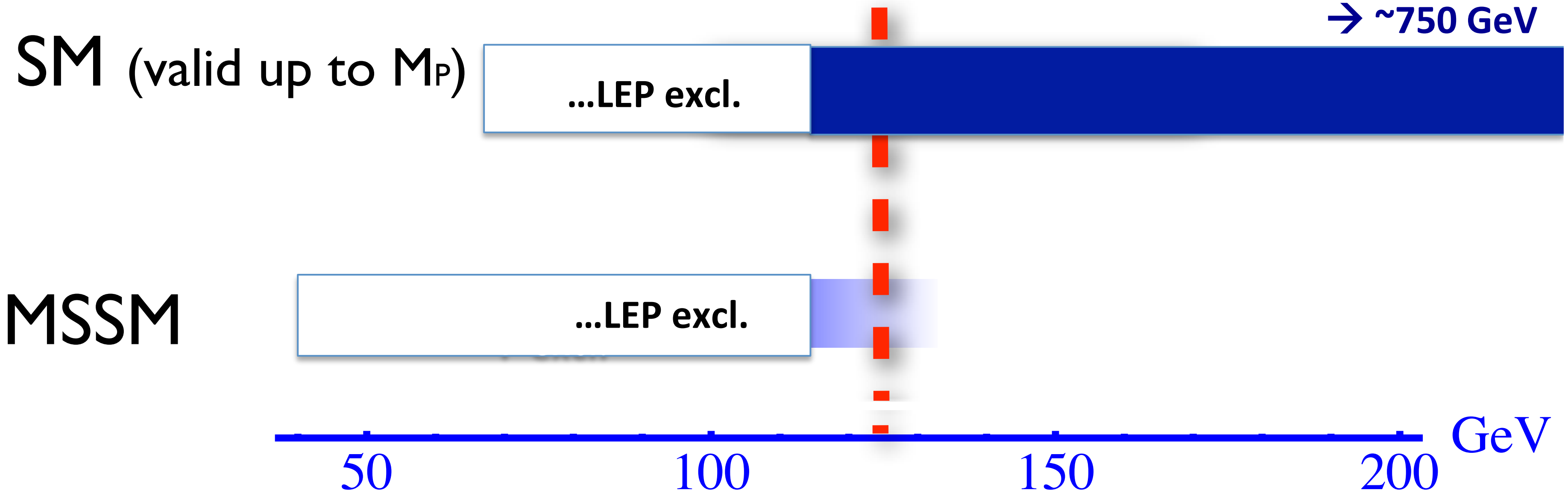
This could be the greatest discovery of the century.
Depending, of course, on how far down it goes.

Higgs boson discovery: Final pages of SM book? or First pages of ``new physics” book?

Standard Model is all that is there.

Higgs -> SUSY -> dark matter->...

The 125 GeV Higgs boson and SUSY



Higgs boson mass of 125 GeV came out to lie in a narrow window allowed by simplest SUSY models (114.4 to ~132 GeV)

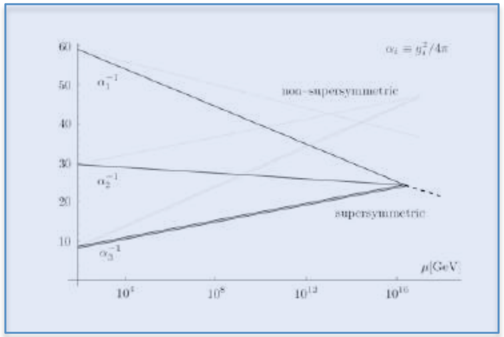
Smoking gun of SUSY?

Higgs boson:

- **fundamental scalar --> SUSY**
- **light and SM-like --> SUSY**

...close to the upper limit: this may have strong implications for DM...

Why SUSY…



IN FAVOUR:

- **Gauge coupling unification**
- **Higgs boson: m_h=125 GeV**
  (SUSY: <~ 130 GeV)

- **Solution to the BIG hierarchy problem**
  (keep M_Z/ M_{GUT} apart)
- **…**

- **Dark matter (neutralino, gravitino, axino)**
- **Inflation, baryo/leptogenesis**
- **Superpartners at ~ TeV scale (consistent with LHC limits, flavor and EW observables)**

AGAINST (???):

- **M_{SUSY}~ few TeV -> too much fine tuning? (small hierarchy problem)**

Unnatural?

But what about naturalness?!

What is natural?

Natural is what is realized in Nature.

LR, Moriond 2015
arXiv:1507.07446

c.f. Frank Wilczek
Stockholm June 2015

How to compare theory with experiment

- **Rigid step-function application of limits/allowed ranges (e.g. DM relic abundance, etc)** **Mahmoudi et al, Hewett et al, …**
- **Frequentist (chi^2-based)** **MasterCode, Fittino, Raby, …**
- **Bayesian** **BayesFITS, Allanach, SuperBayes, Balazs,…**

Frequentist: "probability is the number of times the event occurs over the total number of trials, in the limit of an infinite series of equiprobable repetitions"

Bayesian: "probability is a measure of the degree of belief about a proposition"

Both F and B are based on the likelihood function.

The Likelihood function

Central object: Likelihood function

- **Positive measurements:**

Take a single observable $\xi(m)$ that has been measured

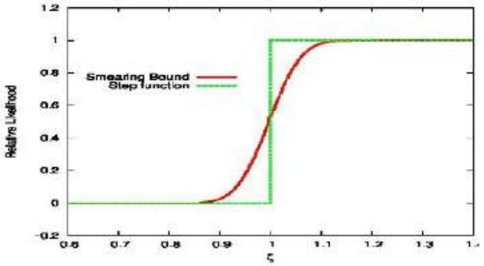
(e.g., M_W)

- c – central value, σ – standard exptal error
- define
$$\chi^2 = \frac{[\xi(m)-c]^2}{\sigma^2}$$
- assuming Gaussian distribution ($d \to (c, \sigma)$):
$$\mathcal{L} = p(\sigma, c|\xi(m)) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{\chi^2}{2}\right]$$
- when include theoretical error estimate τ (assumed Gaussian):
$$\sigma \to s = \sqrt{\sigma^2 + \tau^2}$$

TH error “smears out” the EXPTAL range

- for several uncorrelated observables (assumed Gaussian):
$$\mathcal{L} = \exp\left[-\sum_i \frac{\chi_i^2}{2}\right]$$

- **Limits:**



- Smear out bounds.
- Add theory error.

- **LHC direct limits:**
  - Need careful treatment. Typically use Poisson.

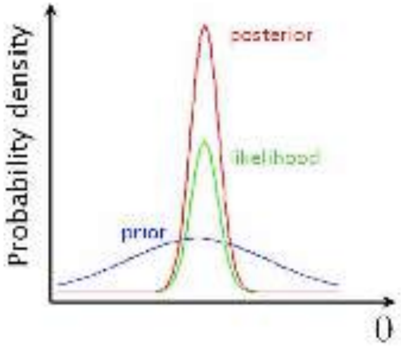
Bayesian statistics

Bayes theorem: $$\boxed{\text{Posterior} = \frac{\text{Prior}\times\text{Likelihood}}{\text{Evidence}}}$$

- **Prior**: what we know about hypothesis BEFORE seeing the data.
- **Likelihood**: the probability of obtaining data if hypothesis is true.
- **Posterior**: the probability about hypothesis AFTER seeing the data.
- **Evidence**: normalization constant, crucial for model comparison.

If hypothesis is a function of parameters, then posterior becomes posterior probability function (pdf).

Posterior → <u>credible regions</u> at chosen CL

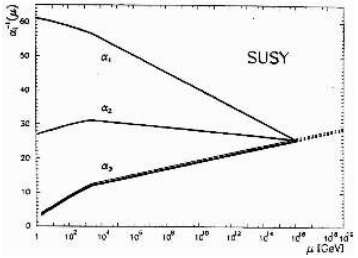


Minimum chi2 approach: find best-fit and draw <u>confidence regions</u> about it

SUSY: Constrained or Not?

Constrained:

Low-energy SUSY models with grand-unification relations among gauge couplings and (soft) SUSY mass parameters



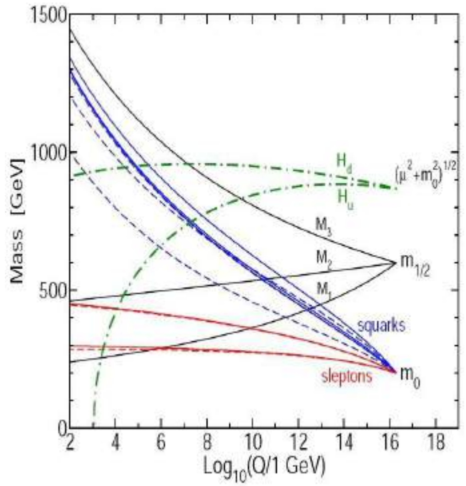


figure from hep-ph/9709356

Virtues:

- Well-motivated
- Predictive (few parameters)
- Realistic

Many models:

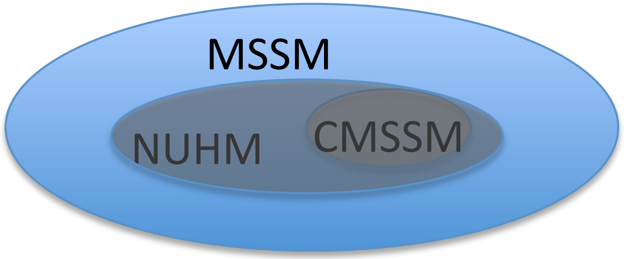
- CMSSM (Constrained MSSM): 4+1 parameters
- NUHM (Non-Universal Higgs Model): 6+1
- CNMSSM (Constrained Next-to-MSSM) 5+1
- CNMSSM-NUHM: 7+1
- etc

Phenomenological:

Supersymmetrized SM…

Features:

- Many free parameters
- Broader than constrained SUSY



Many models:

- general MSSM – over 120 params
- MSSM + simplifying assumptions
- pMSSM: MSSM with 19 params
- p9MSSM, p12MSSM, pnMSSM, …

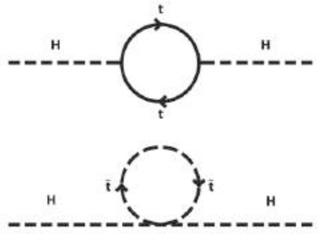
The 125 GeV Higgs Boson and SUSY

A curse…

In SUSY Higgs mass is a calculated quantity

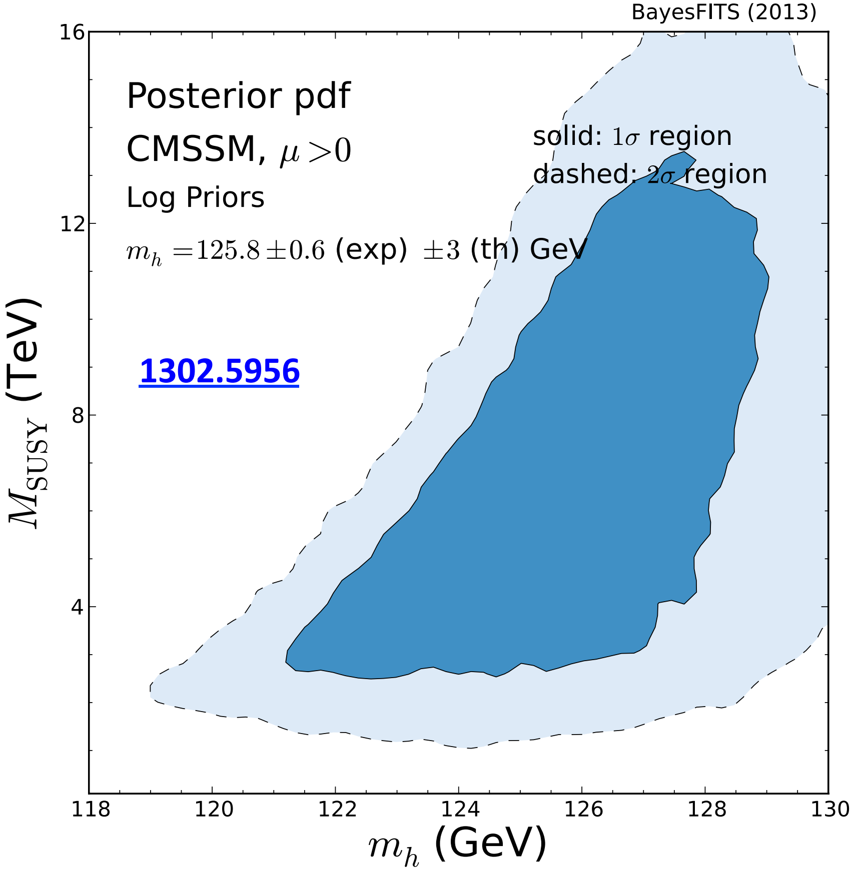
- **1 loop correction**

$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{\rm SUSY}^2}\right)\right]$$



$$X_t = A_t - \mu \cot\beta$$

$$M_{\rm SUSY} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$



Only m_h~125 GeV and CMS lower bounds on SUSY applied here.

$$\mathcal{L} \sim e^{\frac{(m_h - 125.8\,\mathrm{GeV})^2}{\sigma^2+\tau^2}}$$

$\sigma = 0.6$ GeV, $\tau = 2$ GeV

125 GeV Higgs -> multi-TeV SUSY

~125 GeV Higgs and unified SUSY

- Take only m_h~125 GeV and lower limits from direct SUSY searches

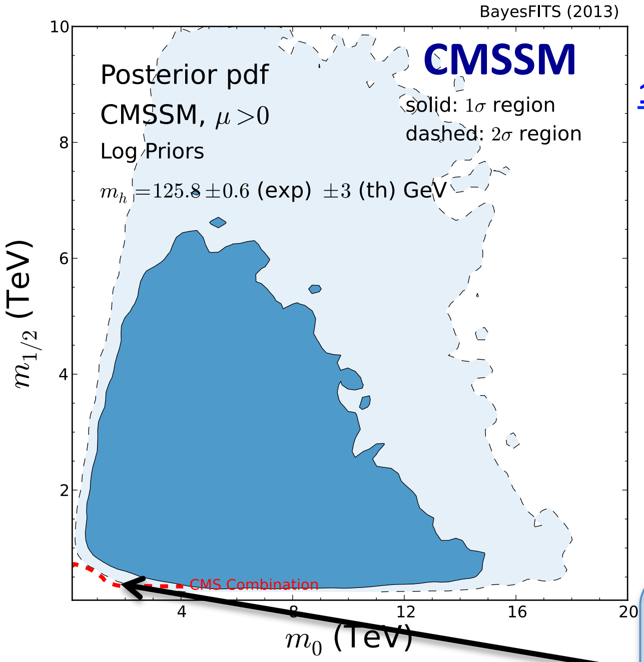
$$\mathcal{L} \sim e^{\frac{(m_h - 125.8\,\mathrm{GeV})^2}{\sigma^2+\tau^2}}$$

$$\sigma = 0.6\ \mathrm{GeV}, \tau = 2\ \mathrm{GeV}$$

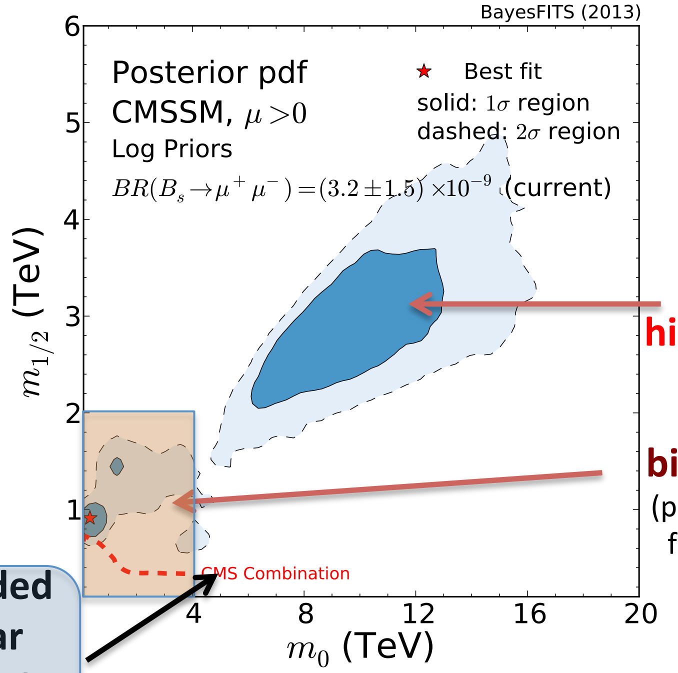
$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\mathrm{SUSY}}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\mathrm{SUSY}}^2}\left(1 - \frac{X_t^2}{12 M_{\mathrm{SUSY}}^2}\right)\right]$$

$$M_{\mathrm{SUSY}} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \qquad X_t = A_t - \mu \cot\beta$$

- Add relic abundance $\Omega_{\mathrm{DM}} h^2 \simeq 0.12$



1302.5956



~1 TeV higgsino DM
(``new")

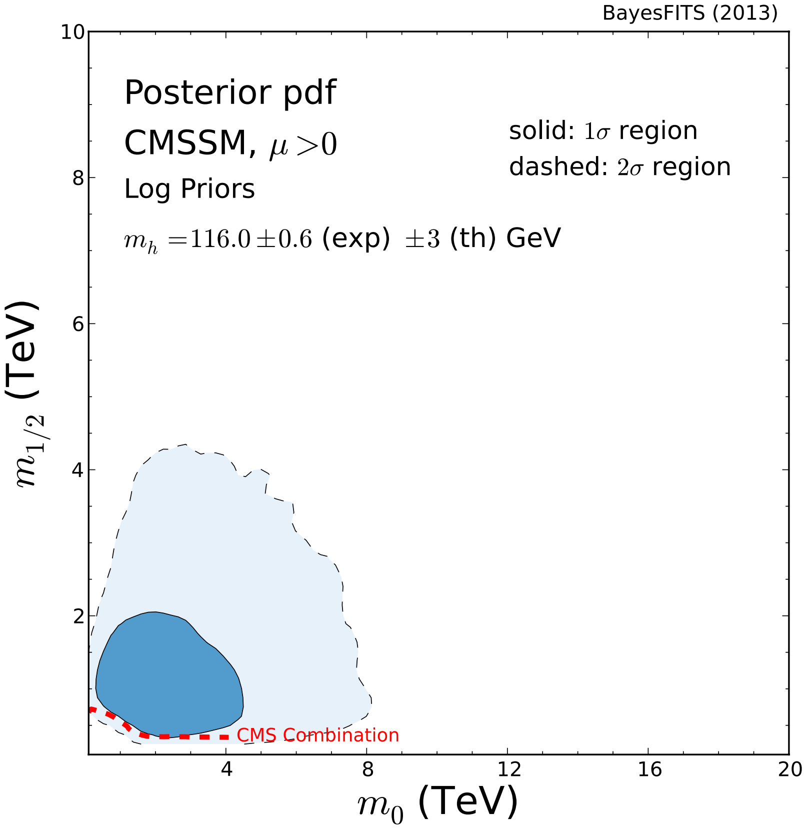
bino DM
(previously favored)

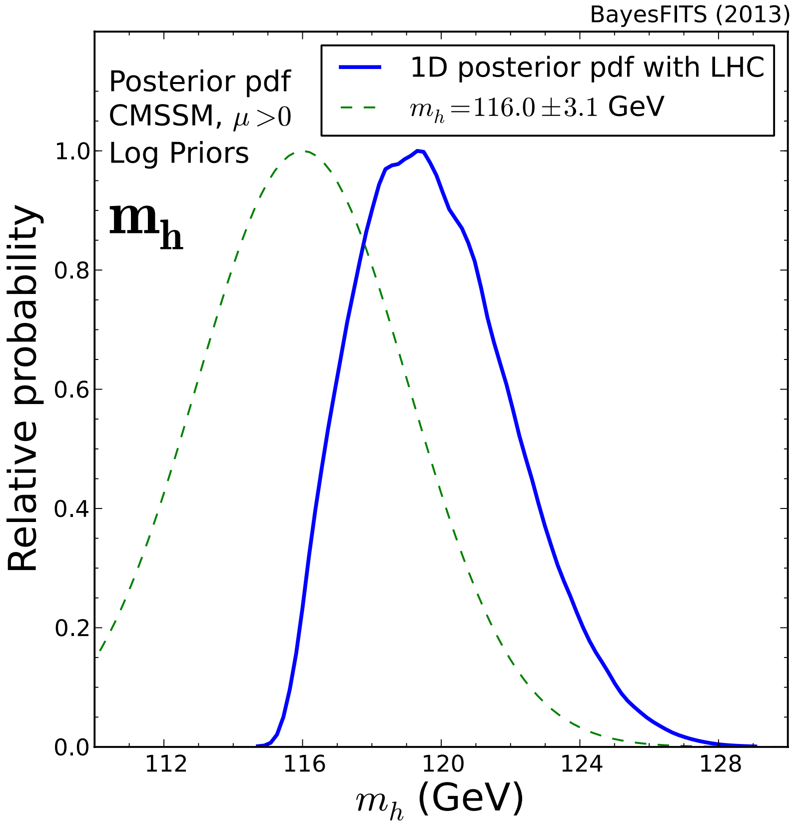
Excluded so far by LHC searches

~125 GeV Higgs mass implies multi-TeV scale for SUSY

Simple unified SUSY:
NO other solutions

If m_h were, say, 116 GeV…



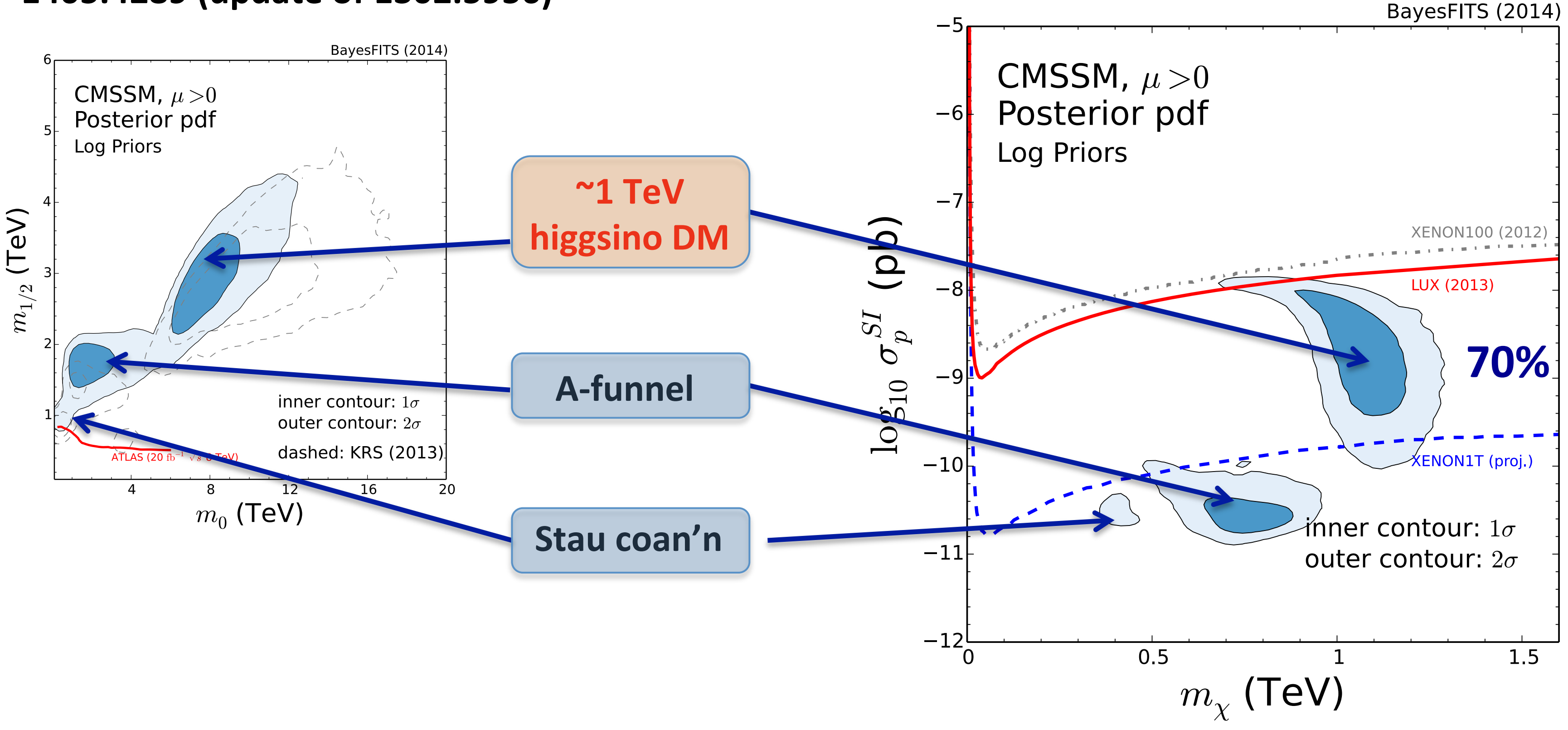


…would have created significant tension with LHC bounds on SUSY

CMSSM and direct DM searches

$\mu > 0$

1405.4289 (update of 1302.5956)



~1 TeV higgsino DM

A-funnel

Stau coan'n

~1TeV higgsino DM: exciting prospects for 1 tonne detectors

CMSSM: numerical scans

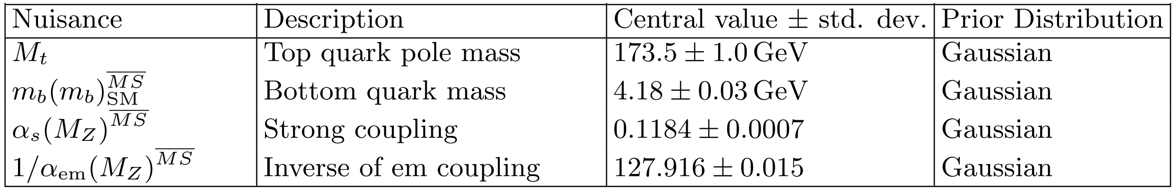
- **Perform random scan over 4 CMSSM +4 SM (nuisance) parameters** ***simultaneously***

- Very wide ranges:

1302.5956

$$100\,\mathrm{GeV} \leq m_0 \leq 20\,\mathrm{TeV}$$
$$100\,\mathrm{GeV} \leq m_{1/2} \leq 10\,\mathrm{TeV}$$
$$-20\,\mathrm{TeV} \leq A_0 \leq 20\,\mathrm{TeV}$$
$$3 \leq \tan\beta \leq 62$$

- Use Nested Sampling algorithm to evaluate posterior
- Use 4 000 live points



Nuisance	Description	Central value ± std. dev.	Prior Distribution
M_t	Top quark pole mass	$173.5 \pm 1.0\,\mathrm{GeV}$	Gaussian
$m_b(m_b)^{\overline{MS}}_{\mathrm{SM}}$	Bottom quark mass	$4.18 \pm 0.03\,\mathrm{GeV}$	Gaussian
$\alpha_s(M_Z)^{\overline{MS}}$	Strong coupling	0.1184 ± 0.0007	Gaussian
$1/\alpha_{\mathrm{em}}(M_Z)^{\overline{MS}}$	Inverse of em coupling	127.916 ± 0.015	Gaussian

Use Bayesian approach (posterior)

SUSY confronting data

The experimental measurements that we apply to constrain the CMSSM's parameters. Masses are in GeV.

Constraint	Mean	Exp. Error	Th. Error
Higgs sector	See text.	See text.	See text.
Direct SUSY searches	See text.	See text.	See text.
σ_p^{SI}	See text.	See text.	See text.
$\Omega_\chi h^2$	0.1199	0.0027	10%
$\sin^2\theta_{\mathrm{eff}}$	0.23155	0.00015	0.00015
$\delta\left(g-2\right)_\mu \times 10^{10}$	28.7	8.0	1.0
$\mathrm{BR}\left(\overline{\mathrm{B}} \to \mathrm{X_s}\gamma\right) \times 10^4$	3.43	0.22	0.21
$\mathrm{BR}\left(\mathrm{B_u} \to \tau\nu\right) \times 10^4$	0.72	0.27	0.38
ΔM_{B_s}	$17.719\ \mathrm{ps}^{-1}$	$0.043\ \mathrm{ps}^{-1}$	$2.400\ \mathrm{ps}^{-1}$
M_W	80.385 GeV	0.015 GeV	0.015 GeV
$\mathrm{BR}\left(\mathrm{B_s} \to \mu^+\mu^-\right) \times 10^9$	2.9	0.7	10%

?

most important (by far)

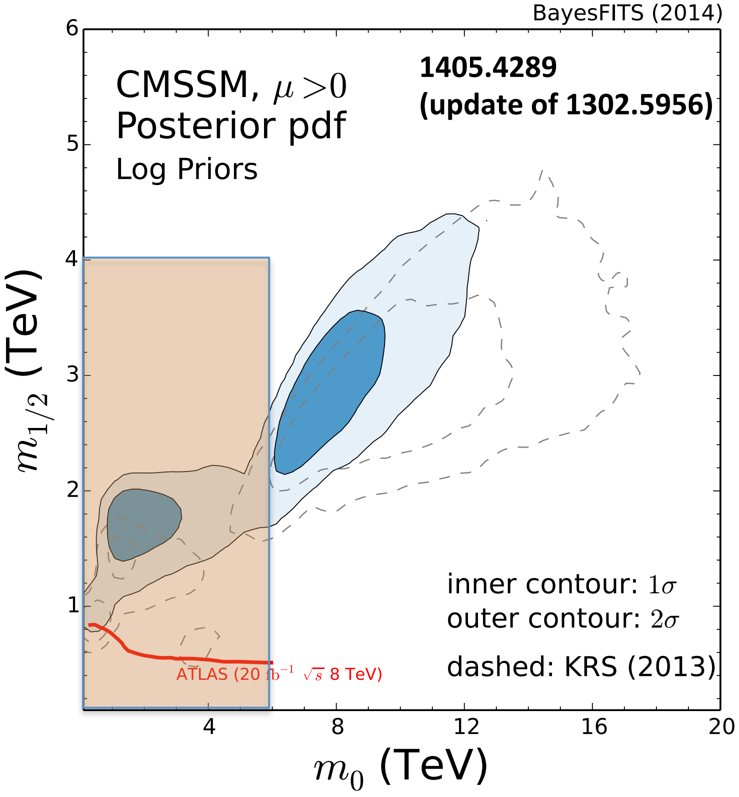
10 dof

SM value: $\simeq 3.5 \times 10^{-9}$

We do simultaneous scan of at least 8 parameters (4 of CMSSM + 4 of SM)

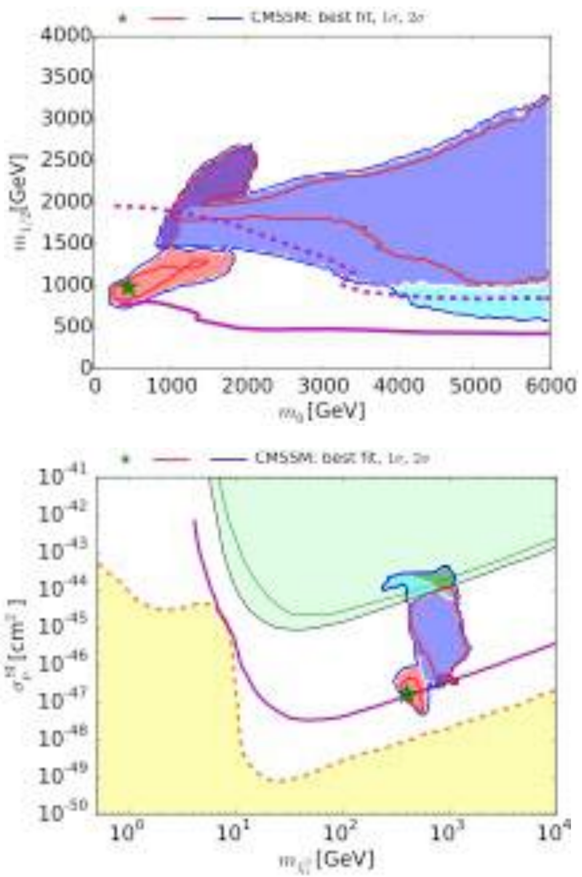
Bayesian vs chi-square analysis

(updated to include 3loop Higgs mass corrs)



1405.4289
(update of 1302.5956)

MasterCode, 1508.01173



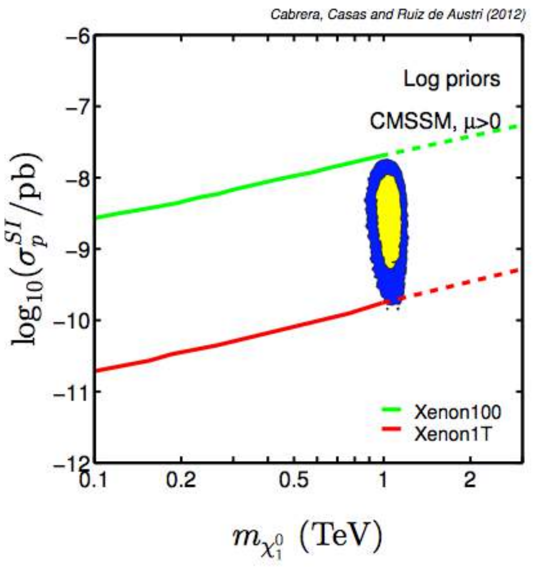
Reasonably good agreement in overlapping region

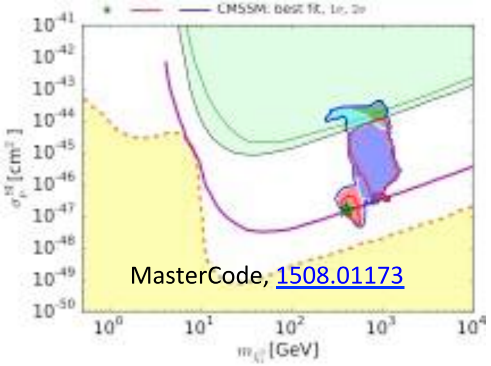
Note: Likelihood fn is rather flat

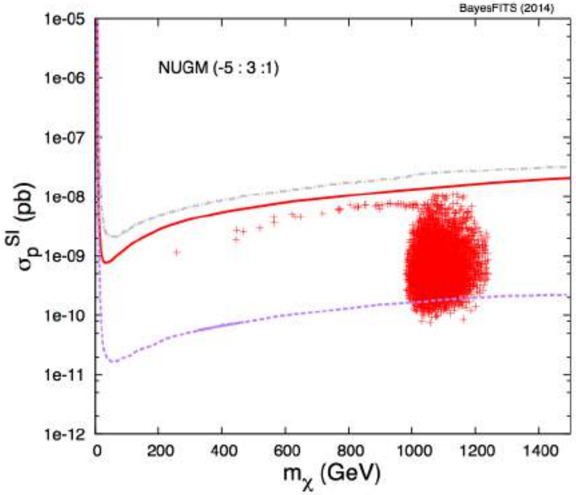
~1 TeV higgsino-like WIMP: implied by ~125 GeV Higgs -> large $m_{1/2}$ and m_0

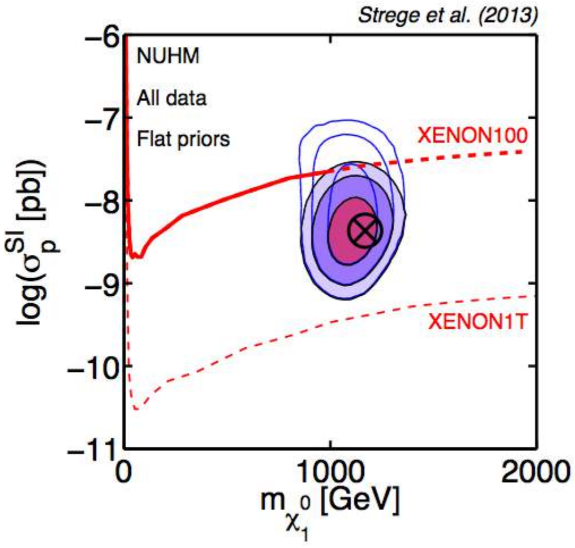
~1 TeV higgsino DM is robust

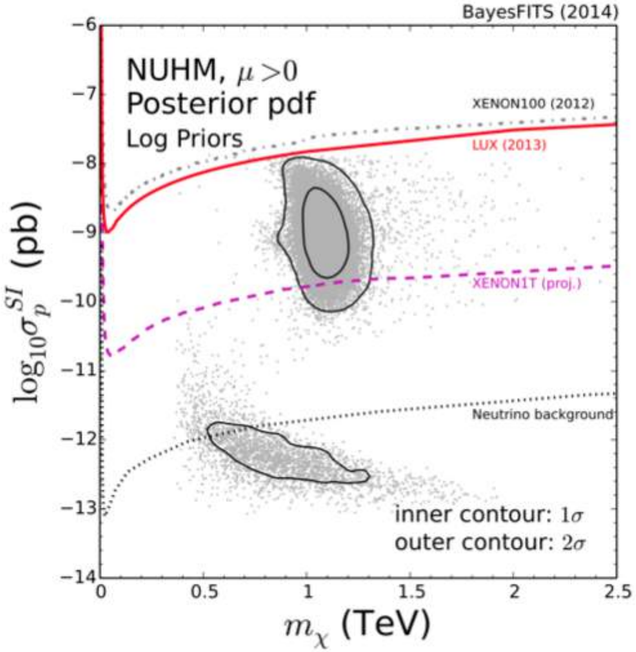
Present in both unified and pheno SUSY models

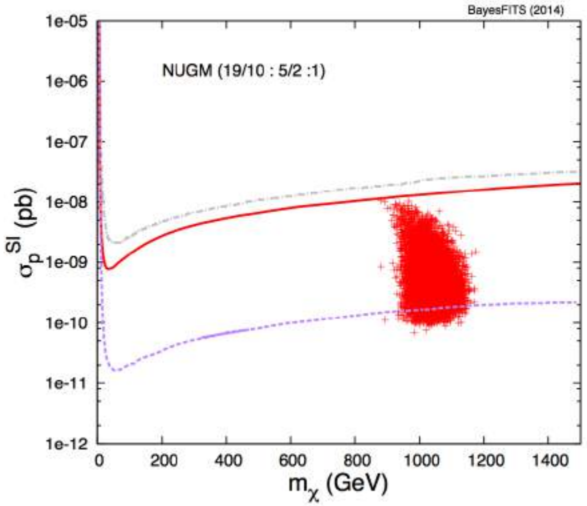

Cabrera, Casas and Ruiz de Austri (2012)


MasterCode, 1508.01173


BayesFITS (2014)


Strege et al. (2013)


BayesFITS (2014)


BayesFITS (2014)

Watch prior dependence and chi2 vs Bayesian

Why ~1 TeV higgsino DM is so interesting

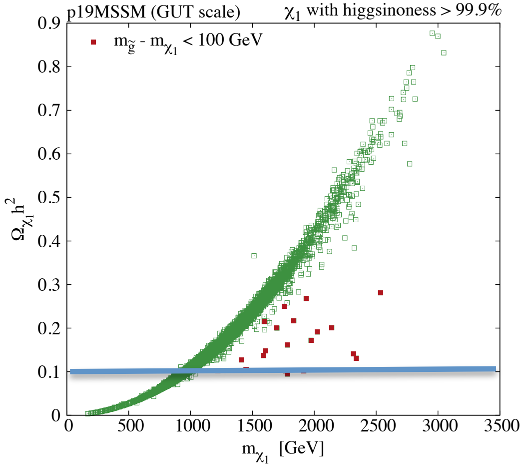
✧ robust, generically present in many SUSY models (both GUT-based and not)

Condition: heavy enough gauginos

When $m_{\tilde{B}} \gtrsim 1\,\mathrm{TeV}$:

easiest to achieve $\Omega_\chi h^2 \simeq 0.1$

when $m_{\tilde{H}} \simeq 1\,\mathrm{TeV}$



✧ implied by ~125 GeV Higgs mass and relic density

No need to employ special mechanisms (A-funnel or coannihilation) to obtain correct relic density

✧ most natural of SUSY DM

✧ smoking gun of SUSY!?

Similarly with wino but mass less determined due to Sommerfeld effect

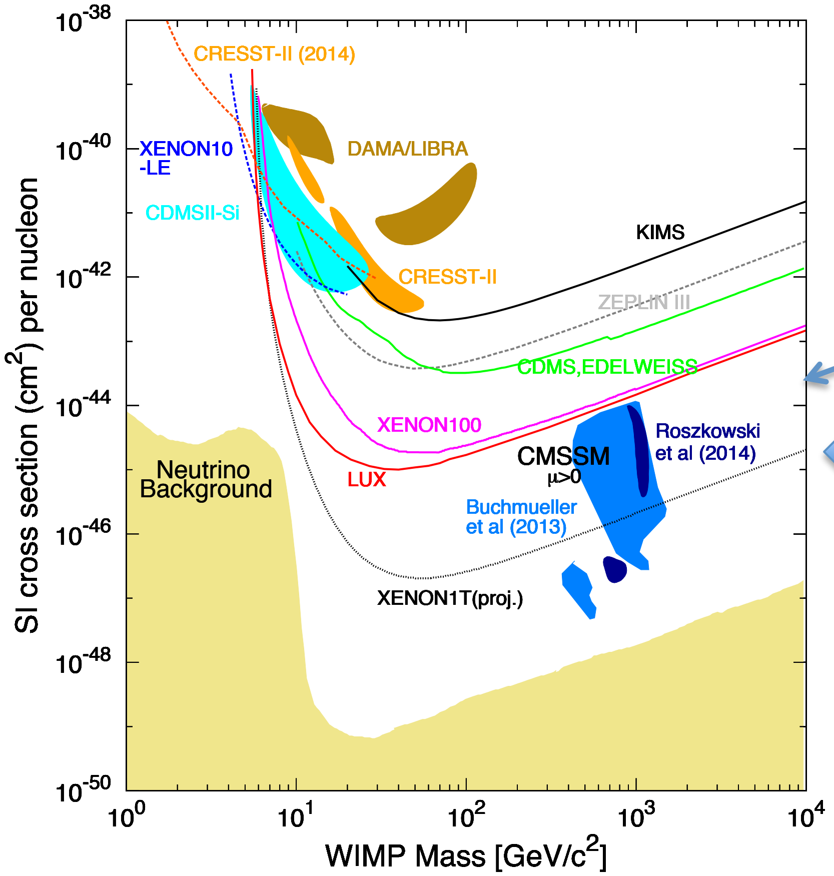
Fine print: How robust is m_{WIMP} ~1 TeV?

m_{WIMP} ~1 TeV if one makes usual assumptions:

- WIMP makes up all DM
  - Could be a x:(1-x) with e.g. axions. Then $m_{WIMP} \sim x^2 \cdot 1$ TeV
- All DM comes from thermal freeze-out
  - Additional (non-thermal) production modes (e.g., from decaying inflaton) --> $m_{WIMP} < 1$ TeV
- Reheating after inflation $T_R >> T_{freeze\text{-}out}$
  - --> allows $m_{WIMP} > 1$ TeV

DM direct detection (2014)

Recent Phys. Rept. (1407.0017)
H. Baer, K.-Y. Choi, J.E Kim, LR



Reach of LUX, PandaX

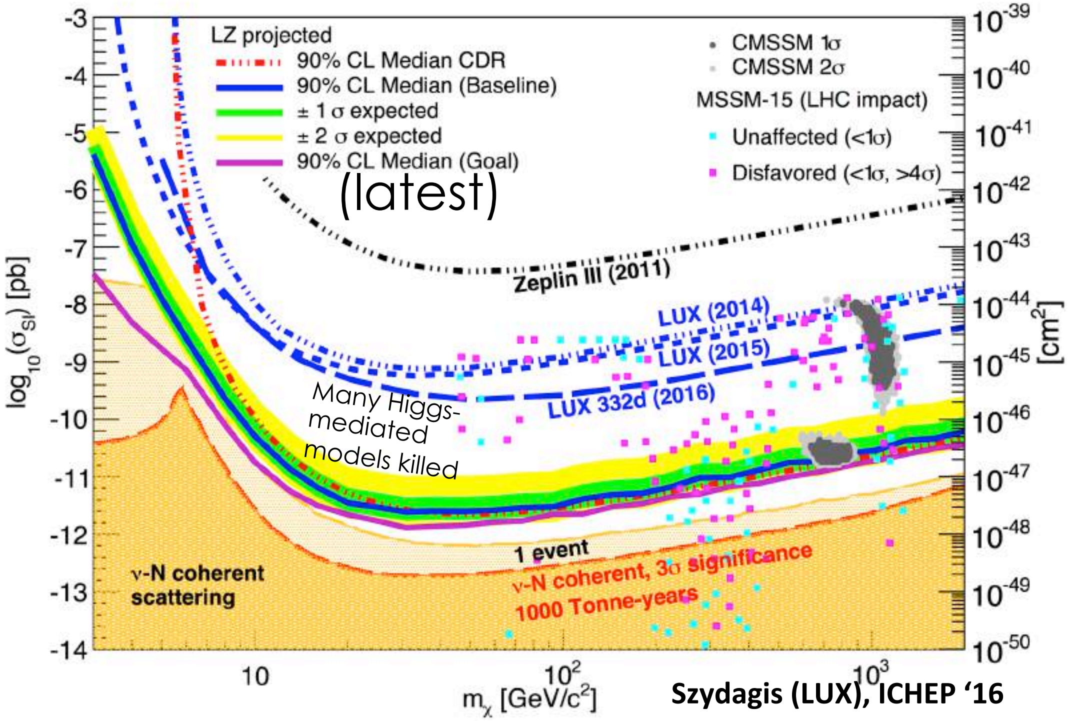
Xenon-1T reach (~2018)

~1 TeV higgsino DM: Excellent prospects!

DM direct detection (2016)

Final limit from LUX, first one from PandaX

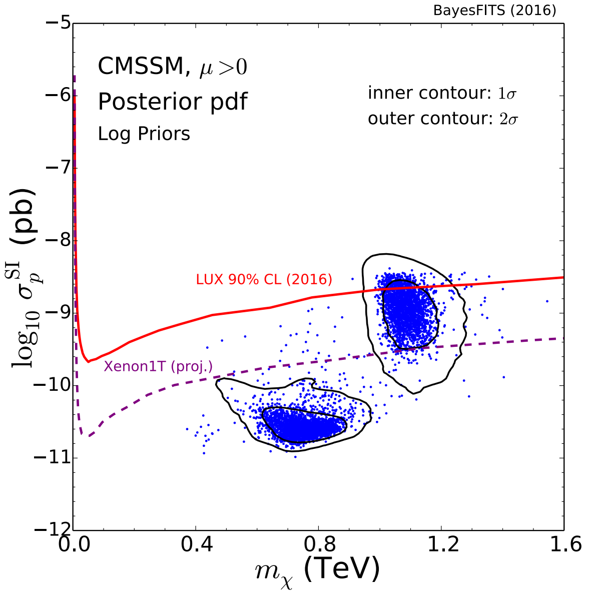
**our update, to appear in
a DM review in ROPP**



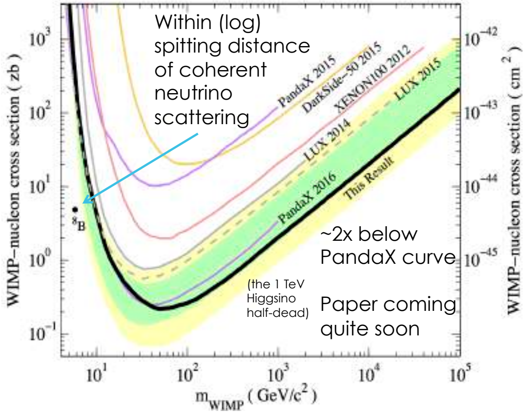
(latest)

Many Higgs-mediated models killed

Szydagis (LUX), ICHEP '16



For comparison, w/o final LUX limit



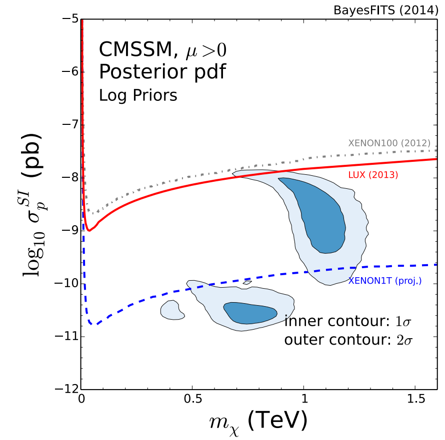
Within (log) spitting distance of coherent neutrino scattering

~2x below PandaX curve

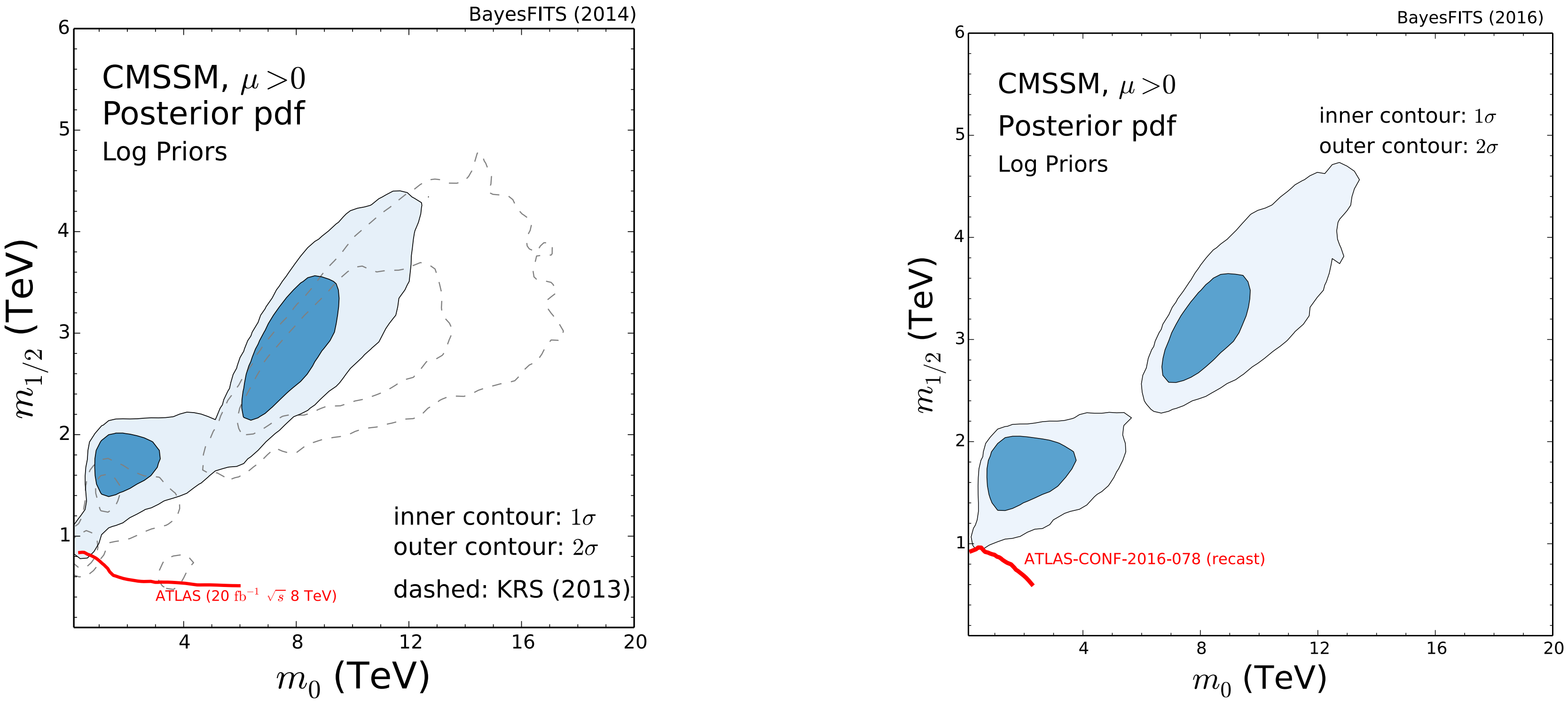
(the 1 TeV Higgsino half-dead)

Paper coming quite soon

LUX, PandaX 90%CL limits: Impact on ~1 TeV WIMP in CMSSM not as big as claimed.



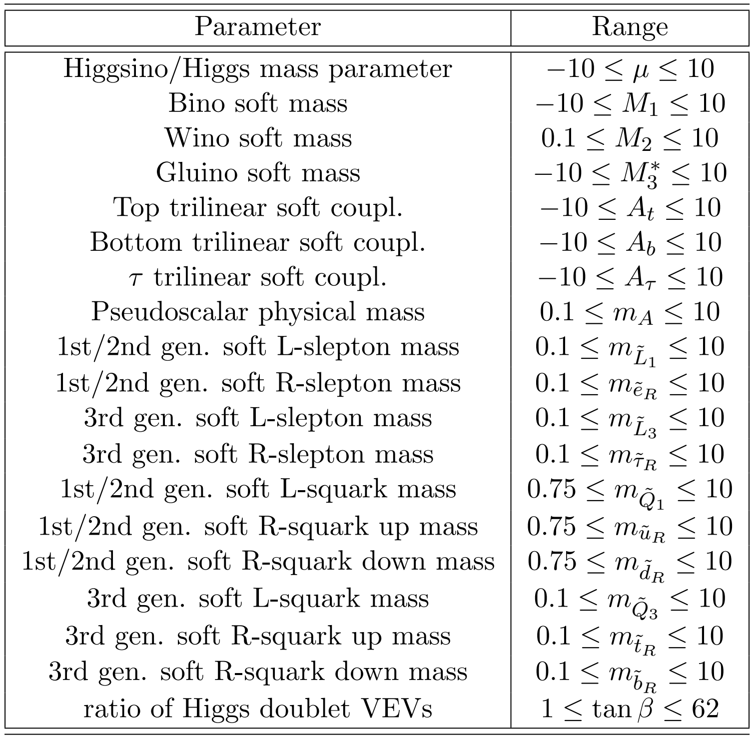
Update - CMSSM After ICHEP’16



Direct Search for DM in general SUSY

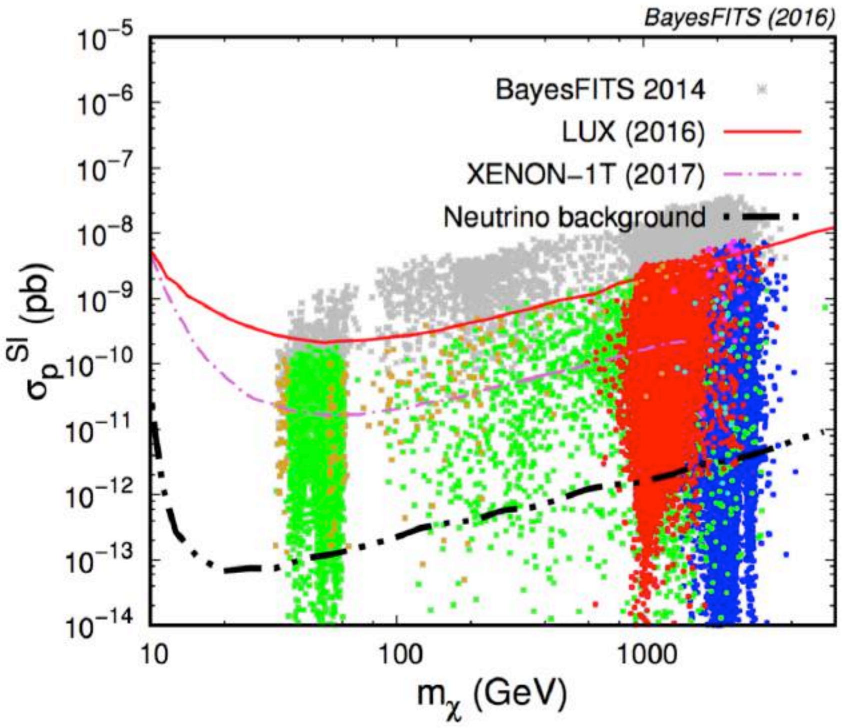
Update of Roszkowski, Sesssolo, Williams, 1411.5214

- **pMSSM** (=p19MSSM)
- **bino (M1) vs wino (M2) masses: free parameters**



Parameter	Range
Higgsino/Higgs mass parameter	$-10 \leq \mu \leq 10$
Bino soft mass	$-10 \leq M_1 \leq 10$
Wino soft mass	$0.1 \leq M_2 \leq 10$
Gluino soft mass	$-10 \leq M_3^* \leq 10$
Top trilinear soft coupl.	$-10 \leq A_t \leq 10$
Bottom trilinear soft coupl.	$-10 \leq A_b \leq 10$
τ trilinear soft coupl.	$-10 \leq A_\tau \leq 10$
Pseudoscalar physical mass	$0.1 \leq m_A \leq 10$
1st/2nd gen. soft L-slepton mass	$0.1 \leq m_{\tilde{L}_1} \leq 10$
1st/2nd gen. soft R-slepton mass	$0.1 \leq m_{\tilde{e}_R} \leq 10$
3rd gen. soft L-slepton mass	$0.1 \leq m_{\tilde{L}_3} \leq 10$
3rd gen. soft R-slepton mass	$0.1 \leq m_{\tilde{\tau}_R} \leq 10$
1st/2nd gen. soft L-squark mass	$0.75 \leq m_{\tilde{Q}_1} \leq 10$
1st/2nd gen. soft R-squark up mass	$0.75 \leq m_{\tilde{u}_R} \leq 10$
1st/2nd gen. soft R-squark down mass	$0.75 \leq m_{\tilde{d}_R} \leq 10$
3rd gen. soft L-squark mass	$0.1 \leq m_{\tilde{Q}_3} \leq 10$
3rd gen. soft R-squark up mass	$0.1 \leq m_{\tilde{t}_R} \leq 10$
3rd gen. soft R-squark down mass	$0.1 \leq m_{\tilde{b}_R} \leq 10$
ratio of Higgs doublet VEVs	$1 \leq \tan\beta \leq 62$

- **Very wide scan**
- **All relevant constraints**
- **Sommerfeld effect included**



bino **higgsino** **wino**

General MSSM: No DM mass restrictions … but different WIMP compositions

Strategies for WIMP Detection

- direct detection (DD): measure WIMPs scattering off a target

go underground to beat cosmic ray bgnd

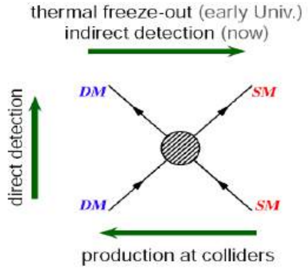
- indirect detection (ID):
  - HE neutrinos from the Sun (or Earth)

    WIMPs get trapped in Sun's core, start pair annihilating, only ν's escape
  - antimatter (e^+, $\bar{p}$, $\bar{D}$) from WIMP pair-annihilation in the MW halo

    from within a few kpc
  - gamma rays from WIMP pair-annihilation in the Galactic center

    depending on DM distribution in the GC
  - other ideas: traces of WIMP annihilation in dwarf galaxies, in rich clusters, etc

    more speculative



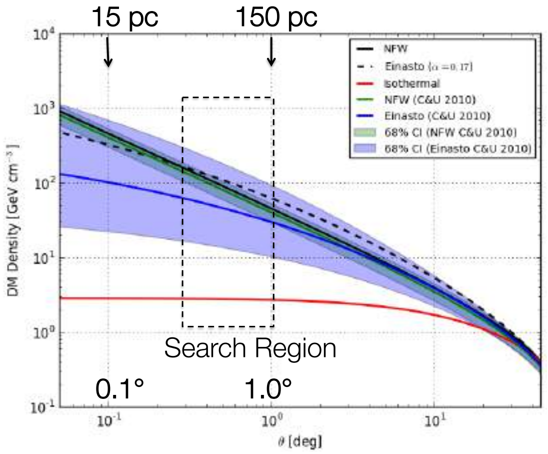
- the LHC

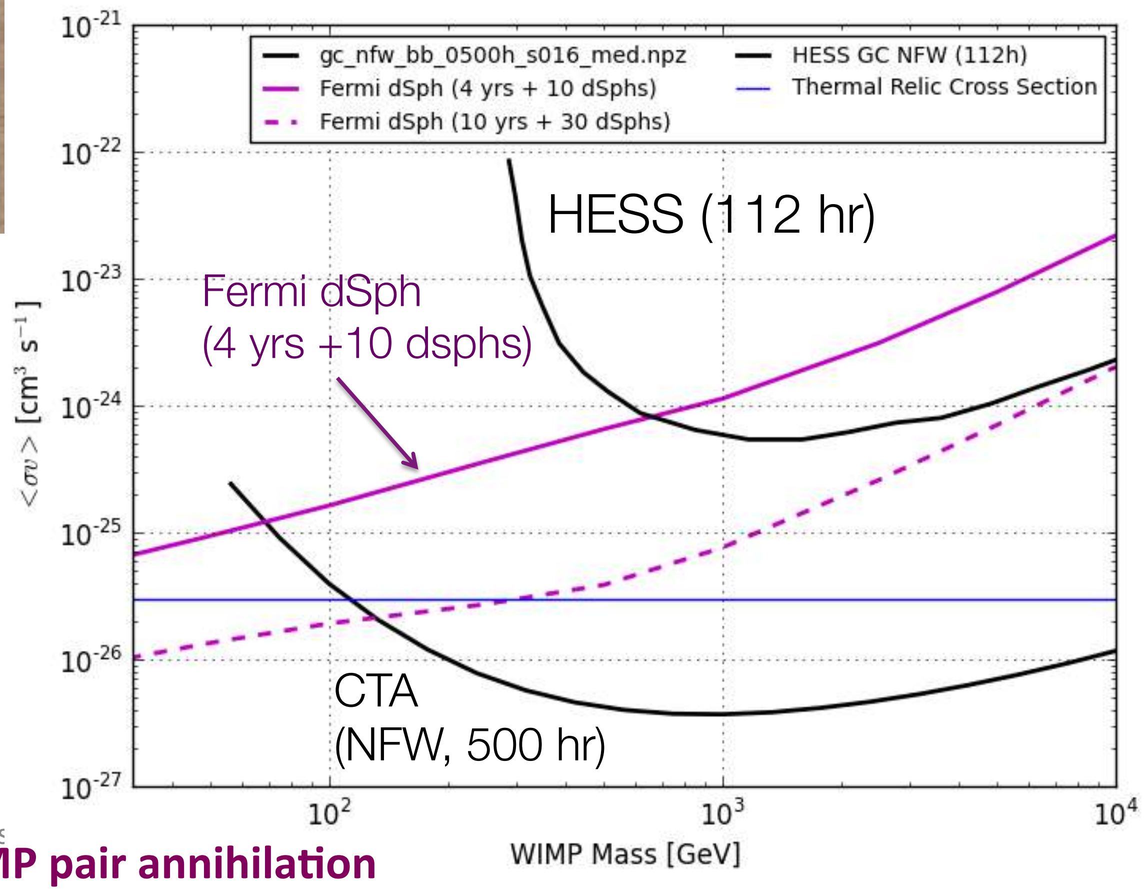
CTA – New guy in DM hunt race

http://www.cta-observatory.org/

- ground-based gamma-ray telescope
- Arrays in southern and northern hemisphere for full-sky coverage
- Energy range: tens of GeV to >100 TeV
- Sensitivity: more than an order of mag improvement in 100 GeV – 10 TeV

Galactic Center DM Halo

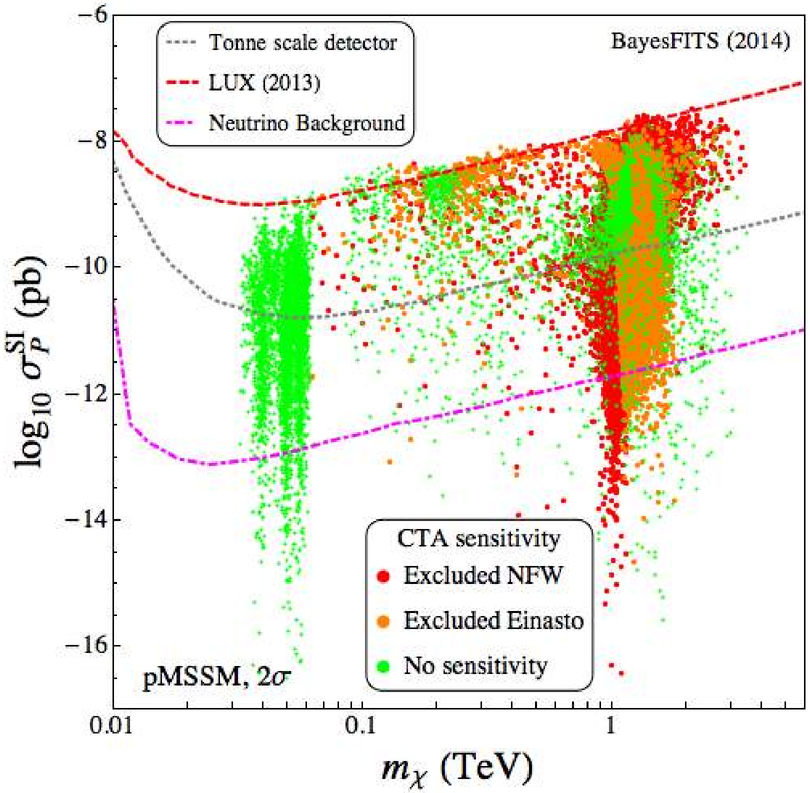




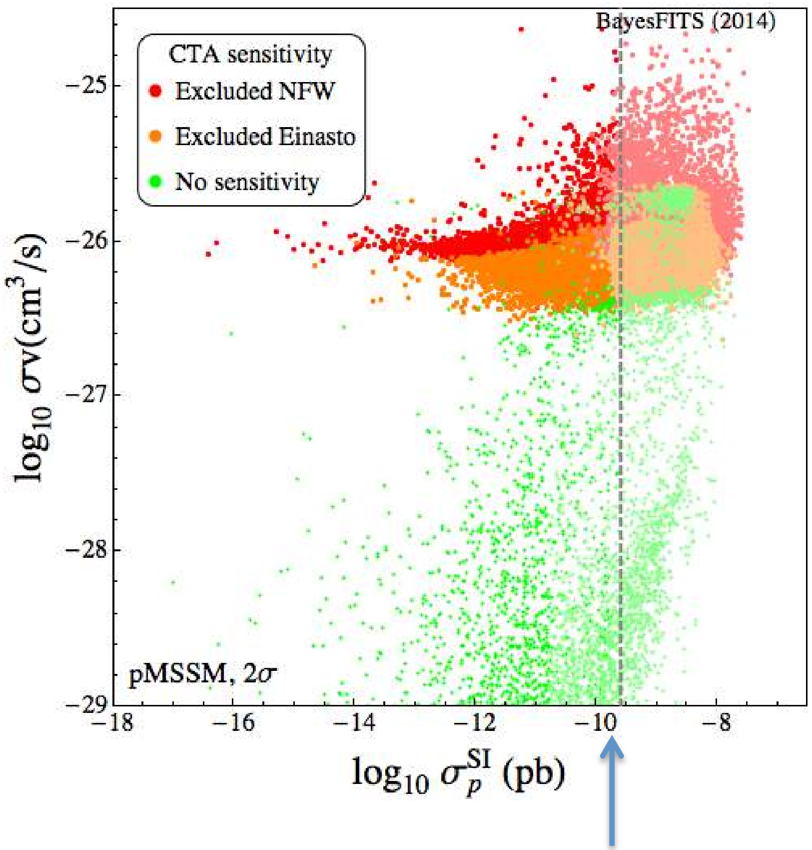
diffuse gamma radiation from WIMP pair annihilation

General SUSY: CTA vs direct detection

p19MSSM



Roszkowski, Sesssolo, Williams, 1411.5214

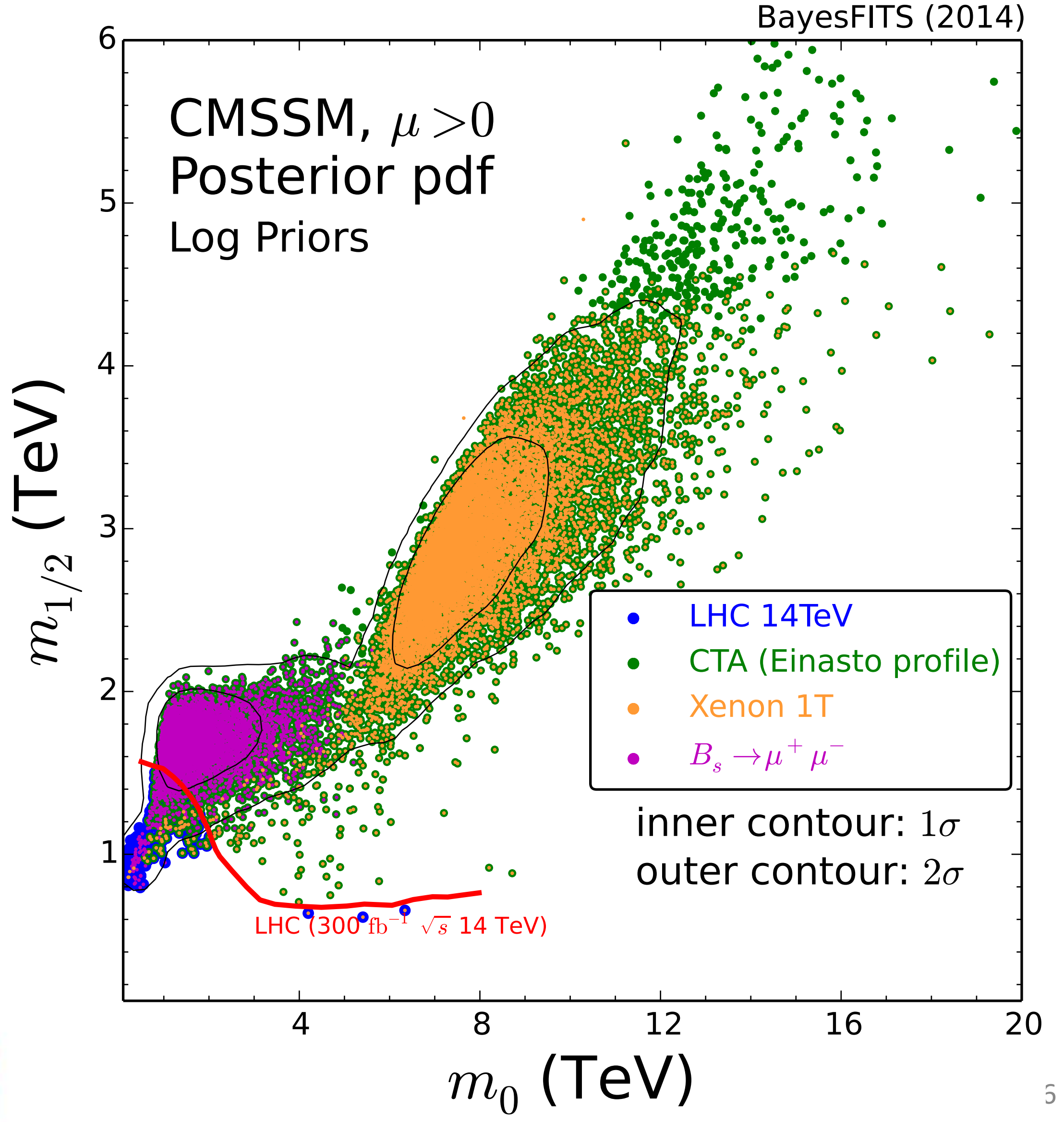


~1 tonne DD reach

General pMSSM:

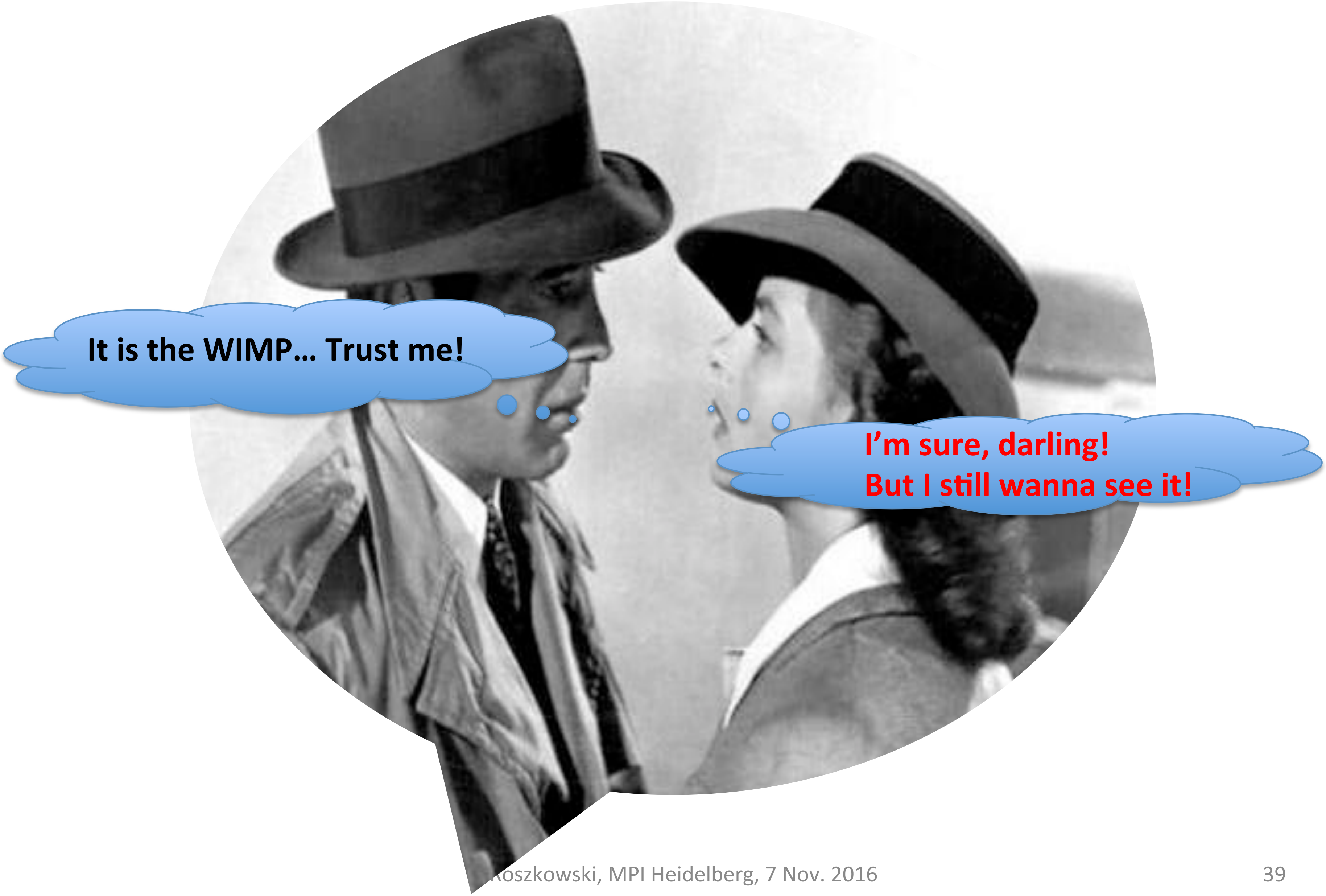
- CTA to probe WIMP regions below reach of ~1 tonne detectors (even below neutrino floor!)
- Good complementarity of DD and CTA

CMSSM: Complementarity of DD, CTA and LHC



..all parameter space covered at 2 sigma

CMSSM can be fully explored by experiment


It is the WIMP… Trust me!
I’m sure, darling!
But I still wanna see it!

Assuming one year (day?) a CDM signal is actually detected…

What can one learn from WIMP signal?

Attempt to reconstruct:

- WIMP mass m_X
- WIMP DD cross-section sigma_p
- WIMP annihilation c.s. sigma*v
- Dominant annihilation channel(s)

- Confirm (thermal?) WIMP hypothesis?
- Compatible with some theory frameworks…

How well?

Likely to be a challenging task!

Will possibly need signal in both DD and ID

…and eventually colliders

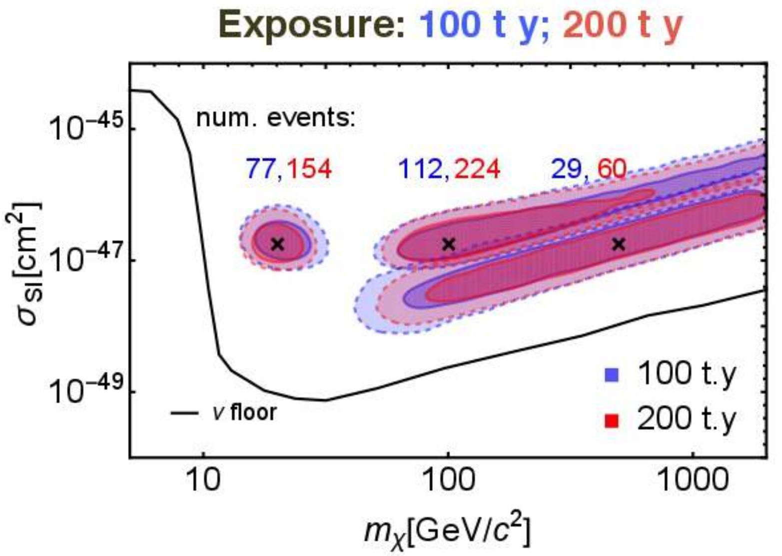
If signal seen in direct detection only

Reconstruction of m_χ and sigma_p^{SI}:

- **Low mass (tens of GeV): good**
- **<~100 GeV: still reasonable**
- **>~200 GeV: poor**

…(?)
Drees and Shan, 0803.4477
Peter, 0910.4765,
Pato, et al, 1006.1322
Bernal, et al., 0804.1976 (DD + ID + ILC)
…

E.g., m_χ= 20, 100, 500 GeV

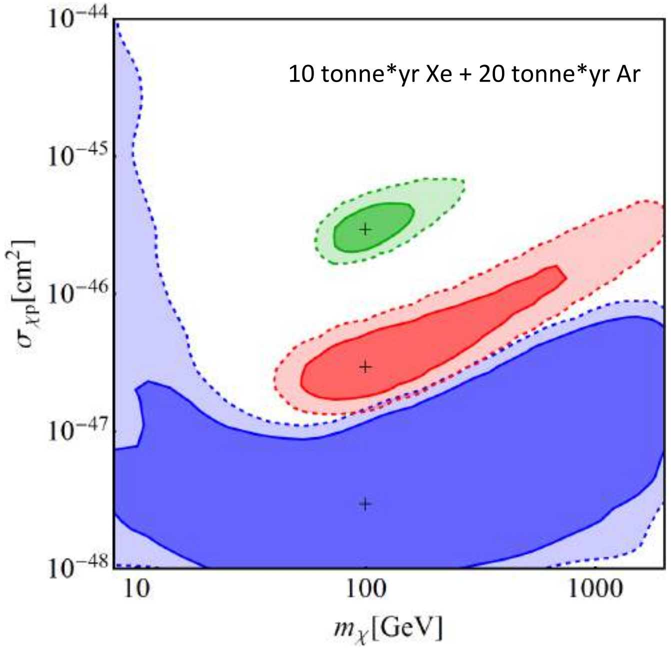


Update of Newstead et al., PRD 8, 076011 (2013)

Schumann @COSMO-15

1 & 2 sigma CI marginalized over astro parameters

When sigma_p^{SI} low: prospects poorer

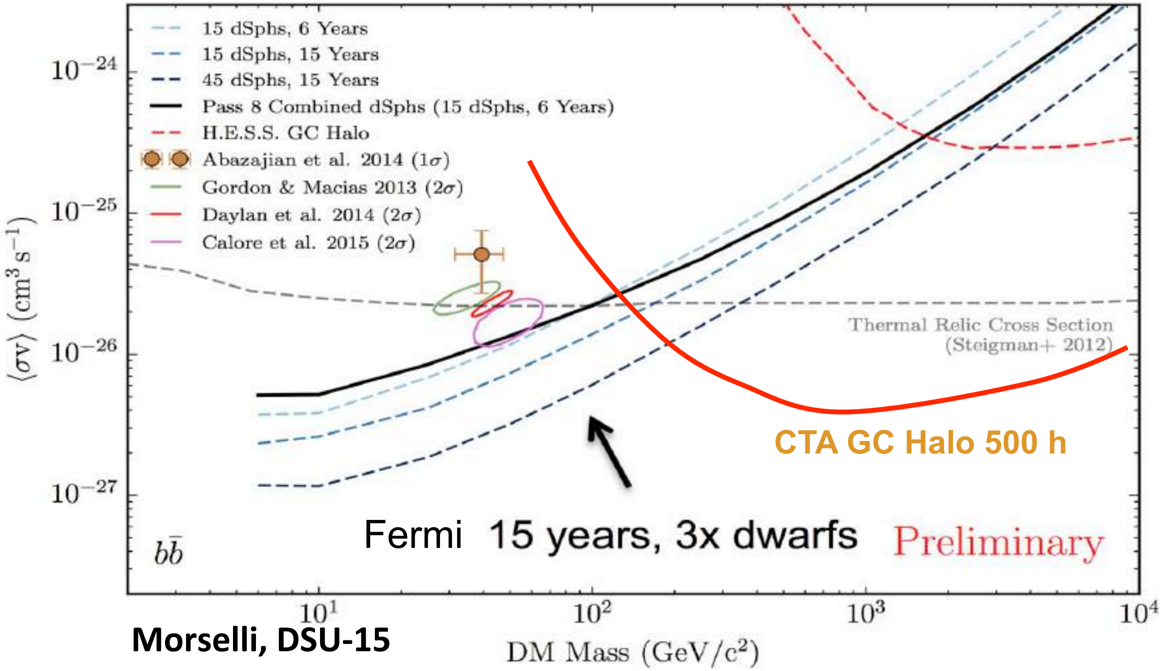


Newstead, 1306.3244

How about diffuse gamma radiation

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\psi) = \sum_i \frac{\sigma_i v}{8\pi m_\chi^2}\,\frac{dN_\gamma^i}{dE_\gamma}\int_{\mathrm{l.o.s.}} dl\,\rho_\chi^2(r(l,\psi))$$

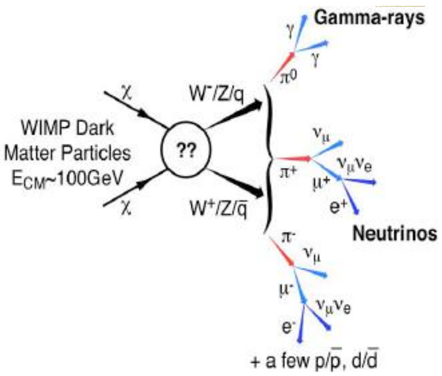
Fermi LAT
CTA - upcoming

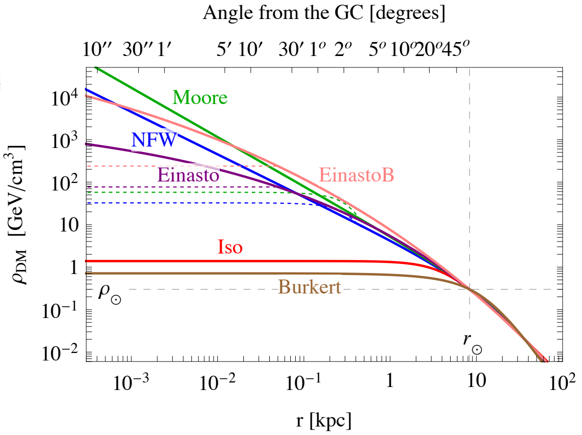


CTA GC Halo 500 h

Fermi 15 years, 3x dwarfs

Morselli, DSU-15



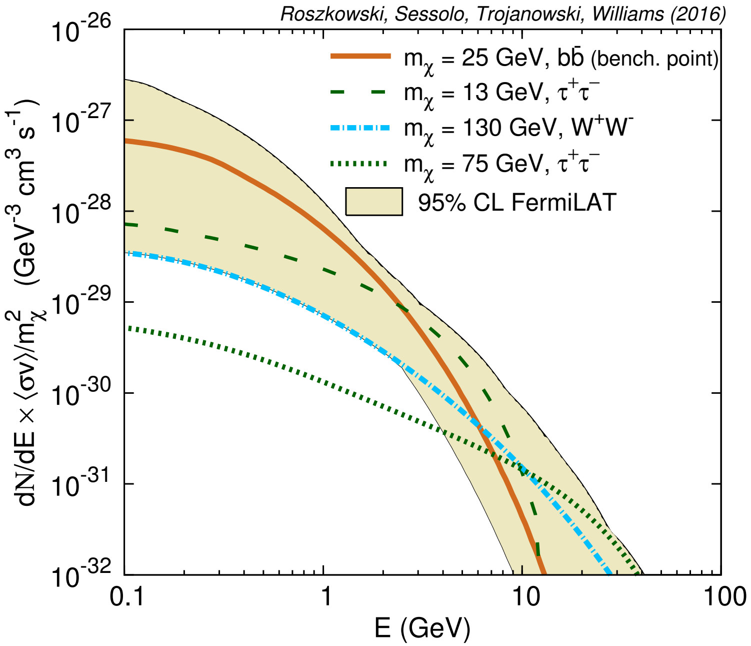


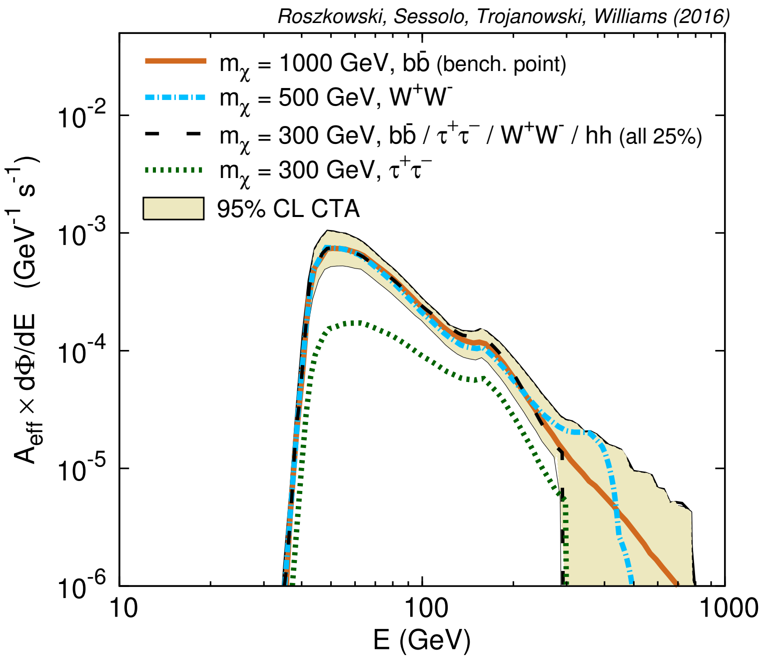
- **Low WIMP mass: Fermi LAT**
- **Mid range: Fermi LAT and CTA**
- **High mass: CTA**

WIMP reconstruction with diffuse gamma radiation

Cirelli et al., 2010

…





- **Differential flux shapes different when vary m_χ**
  but…
- **Similar for different final states (esp. qqbar, VV, hh, but not for ee, mu mu,tau tau)**

Consider direct detection and/or gamma radiation

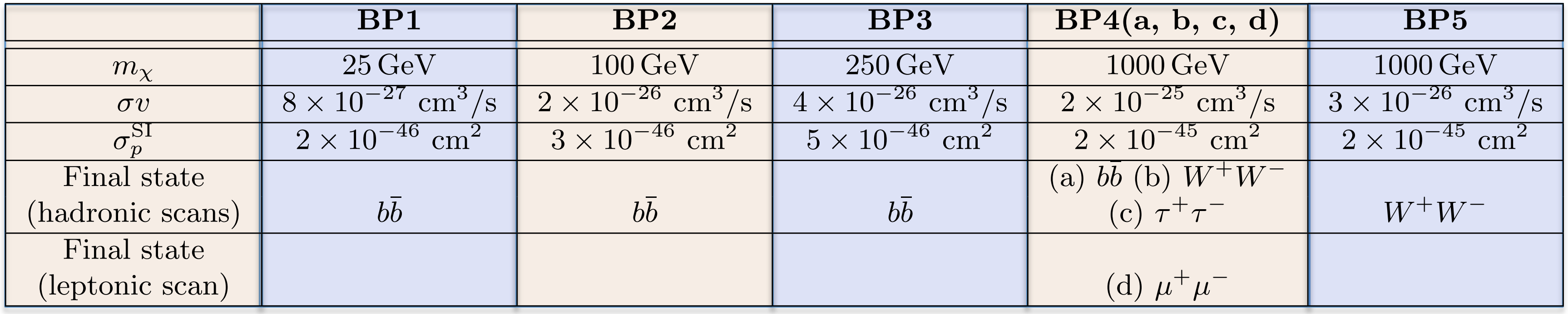
LR + Sessolo + Trojanowski + Williams, 1603.06519

Assume signal detected in DD and/or DGR

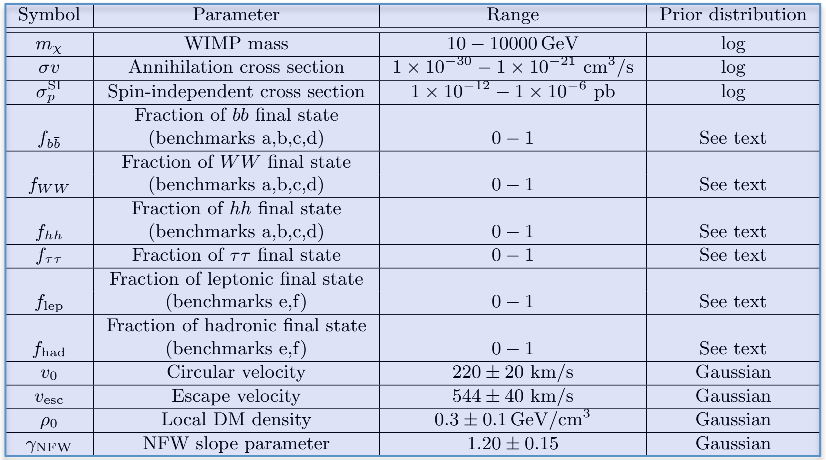
- **Assume WIMP benchmark points:**
  mass, sigma$_p^{SI}$, sigma*v, annihilation BR

Bernal, et al., 0804.1976 (DD + ID + ILC)

DGR: Diffuse Gamma Radiation



	BP1	BP2	BP3	BP4(a, b, c, d)	BP5
m_χ	25 GeV	100 GeV	250 GeV	1000 GeV	1000 GeV
σv	8×10^{-27} cm^3/s	2×10^{-26} cm^3/s	4×10^{-26} cm^3/s	2×10^{-25} cm^3/s	3×10^{-26} cm^3/s
σ_p^{SI}	2×10^{-46} cm^2	3×10^{-46} cm^2	5×10^{-46} cm^2	2×10^{-45} cm^2	2×10^{-45} cm^2
Final state (hadronic scans)	$b\bar{b}$	$b\bar{b}$	$b\bar{b}$	(a) $b\bar{b}$ (b) W^+W^- (c) $\tau^+\tau^-$	W^+W^-
Final state (leptonic scan)				(d) $\mu^+\mu^-$	



Symbol	Parameter	Range	Prior distribution
m_χ	WIMP mass	10 – 10000 GeV	log
σv	Annihilation cross section	$1 \times 10^{-30} - 1 \times 10^{-21}$ cm^3/s	log
σ_p^{SI}	Spin-independent cross section	$1 \times 10^{-12} - 1 \times 10^{-6}$ pb	log
$f_{b\bar{b}}$	Fraction of $b\bar{b}$ final state (benchmarks a,b,c,d)	0 – 1	See text
f_{WW}	Fraction of WW final state (benchmarks a,b,c,d)	0 – 1	See text
f_{hh}	Fraction of hh final state (benchmarks a,b,c,d)	0 – 1	See text
$f_{\tau\tau}$	Fraction of $\tau\tau$ final state	0 – 1	See text
$f_{\rm lep}$	Fraction of leptonic final state (benchmarks e,f)	0 – 1	See text
$f_{\rm had}$	Fraction of hadronic final state (benchmarks e,f)	0 – 1	See text
v_0	Circular velocity	220 ± 20 km/s	Gaussian
$v_{\rm esc}$	Escape velocity	544 ± 40 km/s	Gaussian
ρ_0	Local DM density	0.3 ± 0.1 GeV/cm^3	Gaussian
$\gamma_{\rm NFW}$	NFW slope parameter	1.20 ± 0.15	Gaussian

- **Statistical approach**
- **Construct likelihood function for DD, Fermi LAT dSphs, CTA**
- **Vary four WIMP properties + several astrophysical parameters**
- **Produce mock data**
- **Compare with benchmark point**

$$\rho(r) = \frac{\rho_0 \left(1 + \frac{R_\odot}{r_s}\right)^{3-\gamma_{\rm NFW}}}{\left(\frac{r}{R_\odot}\right)^{\gamma_{\rm NFW}} \left(1 + \frac{r}{r_s}\right)^{3-\gamma_{\rm NFW}}}$$

Diffuse Gamma Radiation: Fermi LAT, CTA

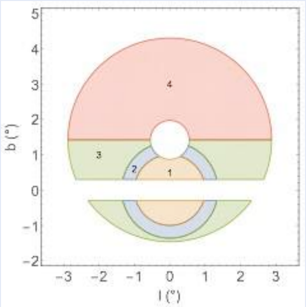
Fermi LAT **Assume 15 yrs and 45 dSphs**

$$\mathcal{L}_{\mathrm{dSphs}} = \prod_{j=1}^{N_{\mathrm{dSphs}}} \left\{ \int \frac{dJ_j}{\log(10)\bar{J}_j\sqrt{2\pi}\sigma_j} \exp\left[-\frac{(\log_{10} J_j - \log_{10} \bar{J}_j)^2}{2\sigma_j^2}\right] \times \left(\prod_{i=1}^{N_{\mathrm{Fermi}}} \frac{1}{\sqrt{2\pi}\overline{\sigma}_{ij}} \exp\left[-\frac{(\Phi_{ij} - \overline{\Phi}_{ij})^2}{2\overline{\sigma}_{ij}^2}\right]\right)\right\}$$

$N_{\mathrm{Fermi}} = 17$ energy bins.

CTA **Assume 500 hrs**

$N_{\mathrm{CTA}} = 30$ energy bins. logarithmically spaced



$$\mathcal{L}_{\mathrm{CTA}} = \prod_{i=1}^{N_{\mathrm{CTA}}} \left\{ \int dR_i^{\mathrm{CR}} e^{-\frac{\left(1-R_i^{\mathrm{CR}}\right)^2}{2\sigma_{\mathrm{CR}}^2}} \int dR_i^{\mathrm{GDE}} e^{-\frac{\left(1-R_i^{\mathrm{GDE}}\right)^2}{2\sigma_{\mathrm{GDE}}^2}} \left[\prod_{j=1}^{3} \frac{\mu_{ij}\left(R_i^{\mathrm{CR}}, R_i^{\mathrm{GDE}}\right)^{n_{ij}}}{n_{ij}!} e^{-\mu_{ij}\left(R_i^{\mathrm{CR}}, R_i^{\mathrm{GDE}}\right)}\right]\right\}$$

mu_ij – expected signal + bgnd

n_ij – observed signal +bgnd

$$\mu_{ij}\left(R_i^{\mathrm{CR}}, R_i^{\mathrm{GDE}}\right) = \mu_{ij}^{\mathrm{DM}} + R_i^{\mathrm{CR}}\mu_{ij}^{\mathrm{CR}} + R_i^{\mathrm{GDE}}\mu_{ij}^{\mathrm{GDE}}$$

Use modified Ring Method: ON, OFF 1, OFF 2

DM: prompt and secondary (ICS from electrons on CMB, starlight and IR)

(Cirelli, et al., Silk et al.)

R - background normalization

CR: isotropic cosmic ray (from CTA)

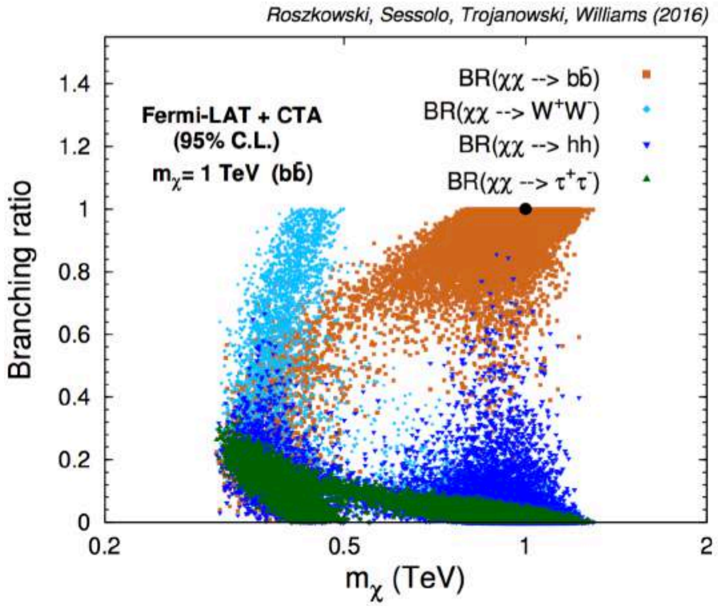
GDE: galactic diffuse emission

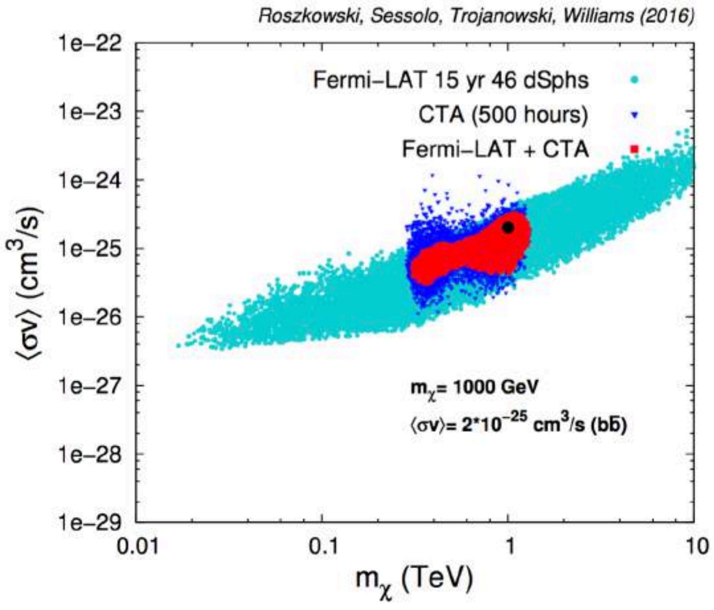
GDE: Extrapolated from Fermi LAT beyond 500 GeV
(Silverwood, et al., Silk et al.)

WIMP reconstruction with Fermi LAT and CTA

Example: BP4a (``generic")
``True" WIMP: m_χ= 1 TeV, BR(b-bbar)=1, sigma*v= 2×10^{-25} cm^3s^{-1}

But other values of m_χ and final states can give very similar spectra!



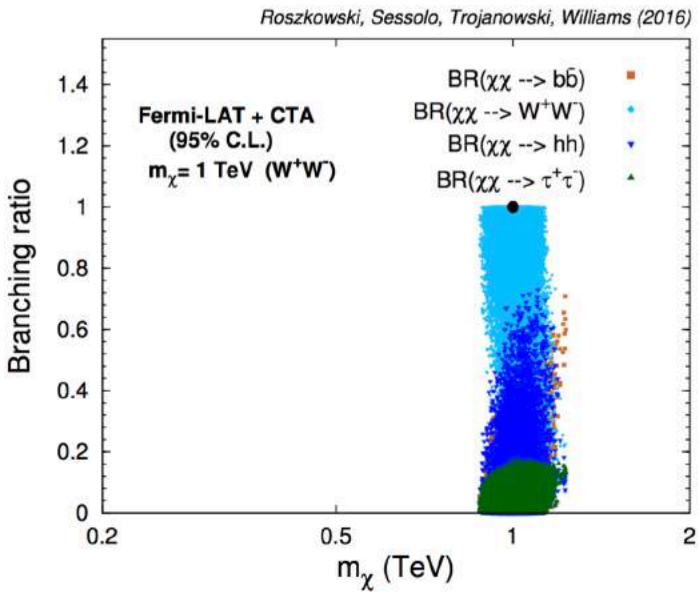


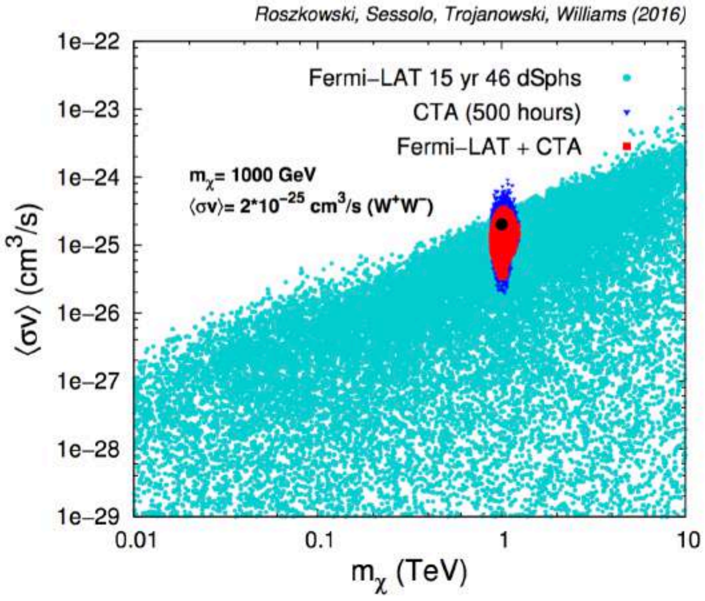
--> Heavy WIMP: Mass reconstruction doable but crude (CTA)
Fermi LAT helps narrow down sigma*v

WIMP reconstruction with Fermi LAT and CTA

Example: BP4b (close to SUSY ~1 TeV higgsino case)
``True" WIMP: m_X= 1 TeV, BR(WW)=1, sigma*v= $2x10^{-25}$ cm^3s^{-1}

Additional spectral feature: spike at E_{gamma}=~ m_X **(caused by W → W+gamma)**


Roszkowski, Sessolo, Trojanowski, Williams (2016)


Roszkowski, Sessolo, Trojanowski, Williams (2016)

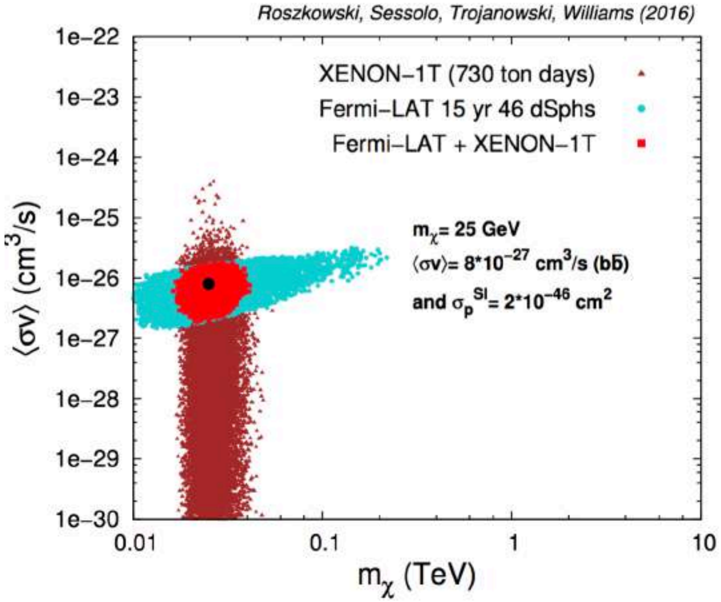
WW final state: both m_X and final states can be reconstructed rather well!

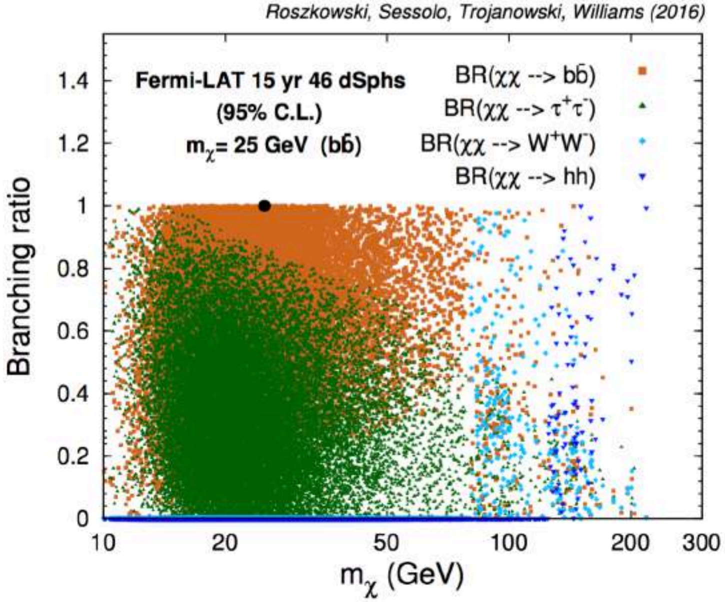
Even more optimistic results for tau-tau and leptonic final states (mu-mu and e-e)

Interplay of direct detection and gamma radiation

Example BP1: m_χ= 25 GeV
sigma$_p$= 9.0 x 10^{-47}cm^2, sigma*v= 8.0 x 10^{-26}cm^{3}s^{-1}
BR(b bbar)=1

Of help only for low m_χ





Direct detection signal can essential in pinpointing WIMP mass but only at low m_χ.

This will in turn help reconstructing final states.

To take home:

- WIMP dark matter is still awaiting a discovery

- SUSY Higgs of 125 GeV + DM abundance + unification:
  - M_{susy} ~ few TeV
  - DM WIMP is preferably ~1 TeV higgsino

- DM ~1 TeV higgsino case will be sensitive to only DM searches (direct + CTA)

Far beyond the reach of LHC
LUX and PandaX started probing it

- WIMP reconstruction: likely to be CHALLENGING

…unless WIMP << 100 GeV (DD)

  - High mass (~1 TeV): CTA signal essential
  - Mid-range (~100 – few hundred GeV): most difficult

The real message:

It is not SUSY that we should worry about.

It's whether we can probe favored SUSY ranges with available experimental tools.

Dark matter searches may come to the rescue.