Three-tier approach to dark matter

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

Leszek Roszkowski
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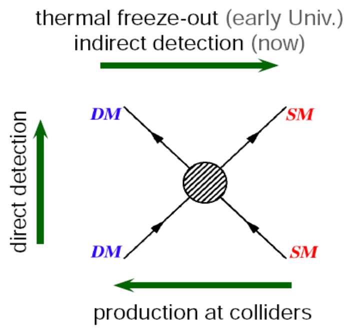
- **Dark matter is made up of WIMPs**
- **DM WIMP is part of some ``new physics” beyond the SM**

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

<u>**Curiosity driven:**</u>

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

Curiosity driven approach

- **(Relatively) model-independent interpretation of experimental bounds**
- (Planck, DD, LHC Mono-jet/photon/..., etc)
- **Minimal set of assumptions (renormalizability, gauge invariance)**
- **Allows for bound comparisons (with care)**
- **Reduced set of parameters**

Cao, Chen, Li, Zhang, 0912.4511 (JHEP), Beltran *et al*. 1002.4137 (JHEP), Goodman, Tait *et al.* 1005.3797 (PLB), 1009.0008 (NPB), Bai, Fox, Harnik *et al*. 1005.3797 (JHEP), 1109.4398 (PRD).... many more

Effective field theory

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2} \qquad \mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

$$\mathcal{O}_g = \alpha_s \frac{(\bar{\chi}\chi)\,(G^a_{\mu\nu}G^{a\mu\nu})}{\Lambda^3} \qquad \mathcal{O}_t = \frac{(\bar{\chi}P_R q)(\bar{q}P_L\chi)}{\Lambda^2} + (L \leftrightarrow R)$$

Busoni, De Simone, Riotto *et al.* 1307.2253 (PLB), 1402.1275 (JCAP), 1405.3101 (JCAP), ...

Portals and simplified models

$$\mathcal{L} \supset -y_\chi\,(h_{\rm SM}\sin\theta + H\cos\theta)\,\bar{\chi}\chi - \frac{1}{\sqrt{2}}(h_{\rm SM}\cos\theta - H\sin\theta)\sum_f y_f \bar{f} f$$

$$\mathcal{L} \supset Z'_\mu \bar{\chi}\gamma^\mu(g^V_\chi - g^A_\chi\gamma_5)\chi + \sum_i Z'_\mu \bar{q}_i\gamma^\mu(g^V_q - g^A_q\gamma_5)q_i$$

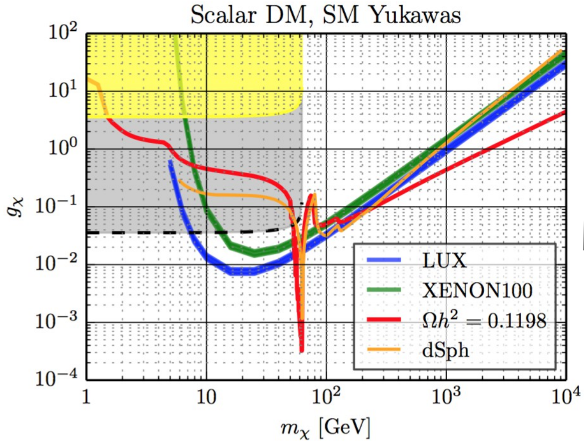
Patt, Wilczek hep-ph/0605188, March-Russel *et al.* 0801.3440 (JHEP), Andreas *et al.* 0808.0255 (JCAP), Djouadi, Lebedev, Mambrini *et al.* 1108.0671 (PRD), 1112.3299 (PLB), 1205.3169 (EPJ), 1411.2985 (JCAP), An *et al.* 1202.2894 (JHEP), Frandsen *et al.* 1204.3839 (JHEP), Bai and Berger 1308.0612 (JHEP), DiFranzo *et al.* 1308.2679 (JHEP).... many more

Curiosity driven approach

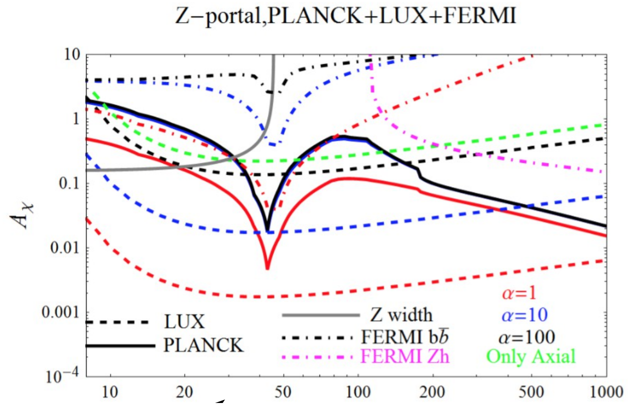
- **Minimal Higgs or Z portals**

e.g.

Bishara, Brod, Uttayarat, Zupan
1504.04022 (JHEP)



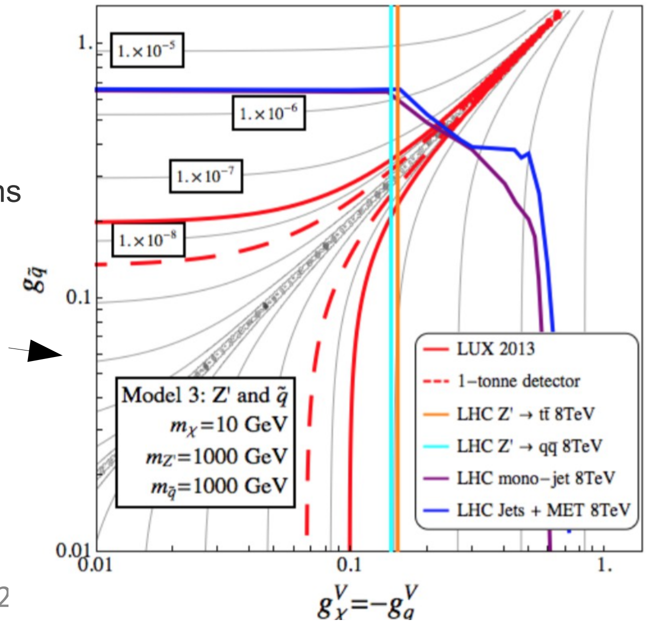
Arcadi, Mambrini, Richard
1411.2985 (JCAP)



- **Less simplified models**

Choudhury, Kowalska, Roszkowski, EMS, Williams
1509.05771 (JHEP)

(less-simplified models: h/H+Z', Z'+t-channel, gauge, unitarity constraints, ...)



See also Baek *et al.* 1405.3530, 1506.06556,
Kahlhoefer *et al.* 1510.02110, and more

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
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- ...

Data driven:

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

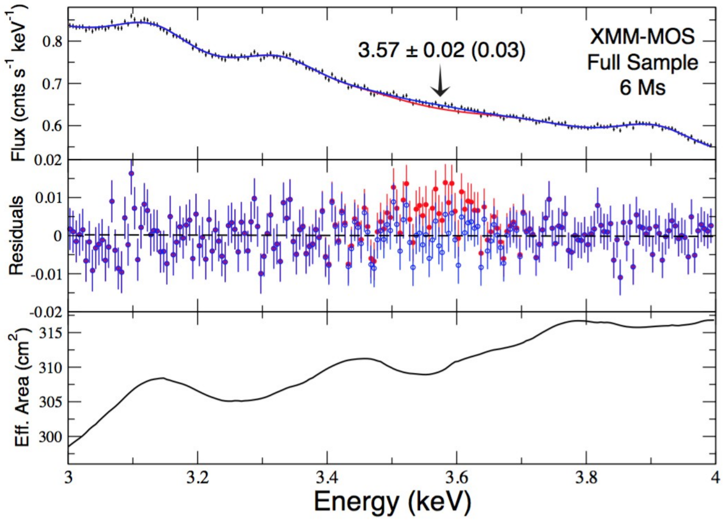
- 130 GeV GR line
- DAMA/LIBRA annual modulation effect
- 0.5 MeV excess (Integral)
- ...

Data driven approach

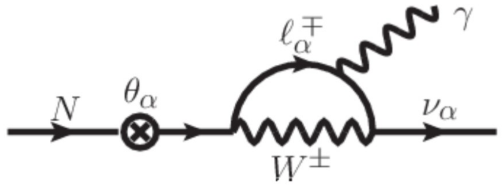
e.g.

- **3.5 keV line claimed to be seen in clusters of galaxies and in M31**

Bulbul, et al., 1402.2301 (ApJ)
Boyarsky, et al., 1402.4119 (PRL)



decaying dark matter?



Sterile neutrino

Boyarsky *et al.* 1402.4119 Ishida, Jeong, Takahishi 1402.5837, Baek, Okada 1403.1710 … and more

Axinos

Park, Park, Kong 1403.1536, Choi, Seto 1403.1782, Liew 1403.6621

Gravitinos

Bomark, Roszkowski 1403.4503

Other

Finkbeiner, Weiner 1402.6671, Queiroz, Sinha 1404.1400, Frandsen *et al.* 1403.1570 … and many more

More recent data (dSphs, ….) have not confirmed, but fully excluded the claim

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

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  - …

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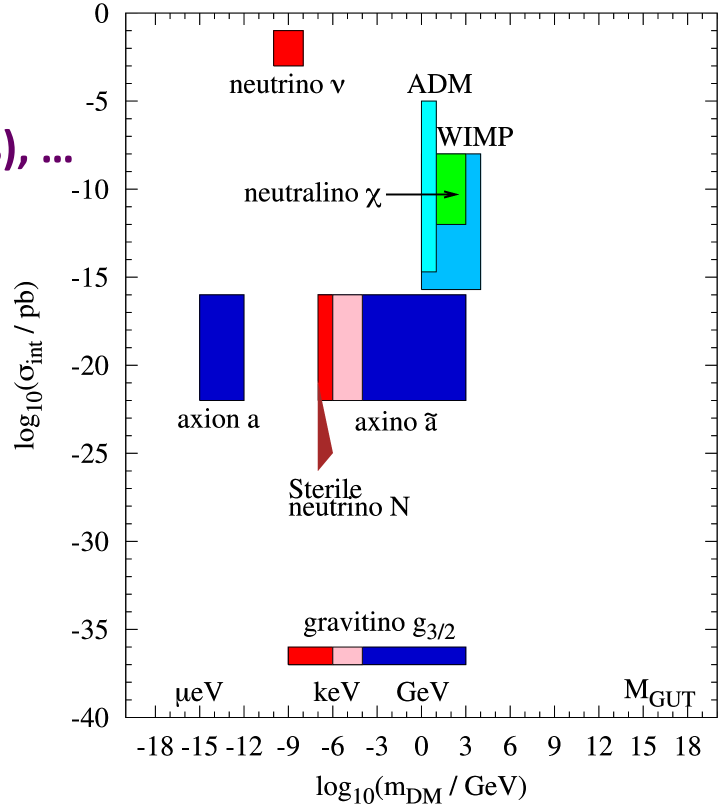

Need ``new physics”.

SUSY remains most promising framework.

Where is ``new physics"?

- No convincing hint from the LHC

but…

Higgs boson:

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

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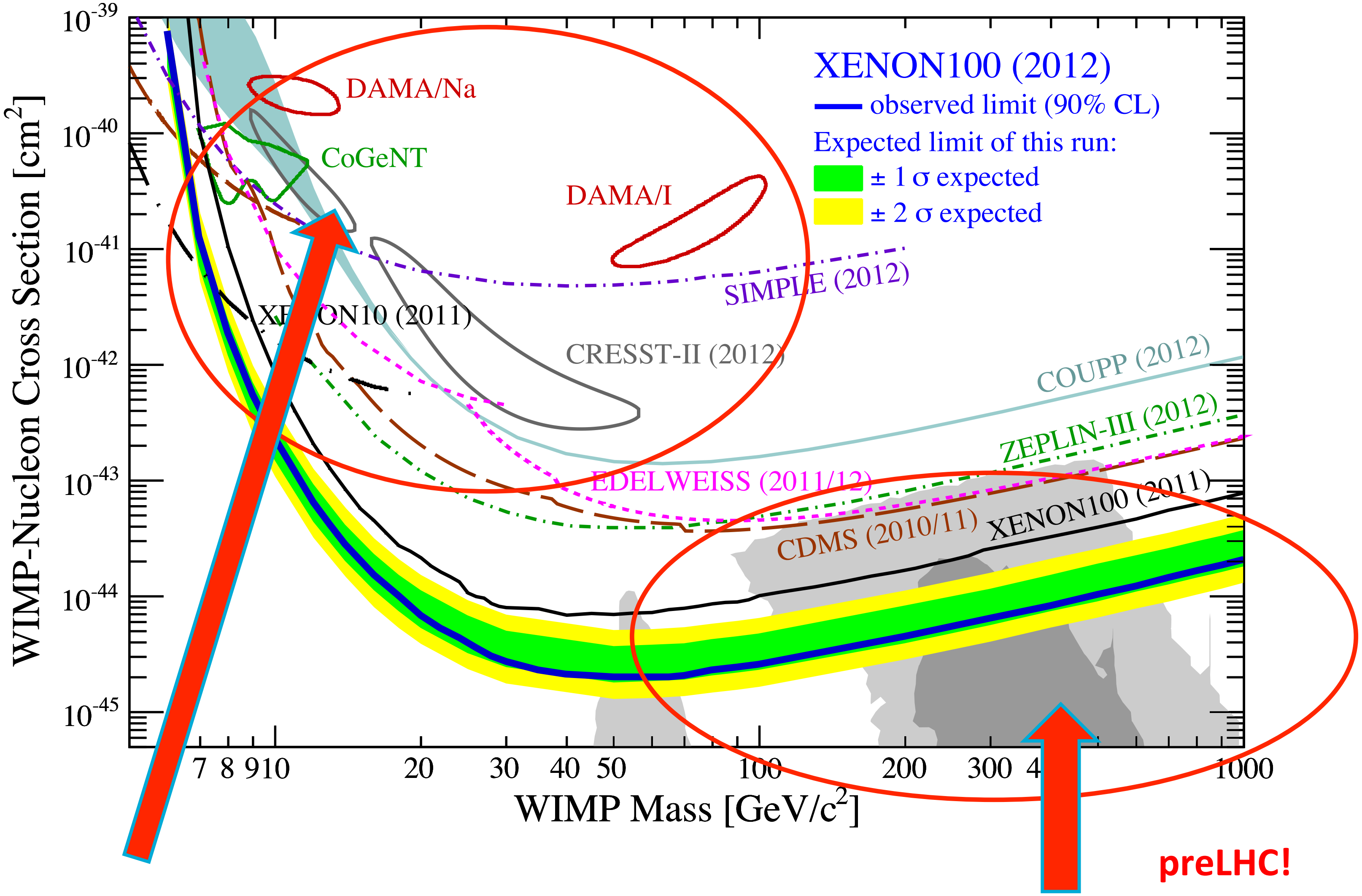
Low energy SUSY remains the front-runner for ``new physics"

Direct Detection AD 2011 - Before LHC

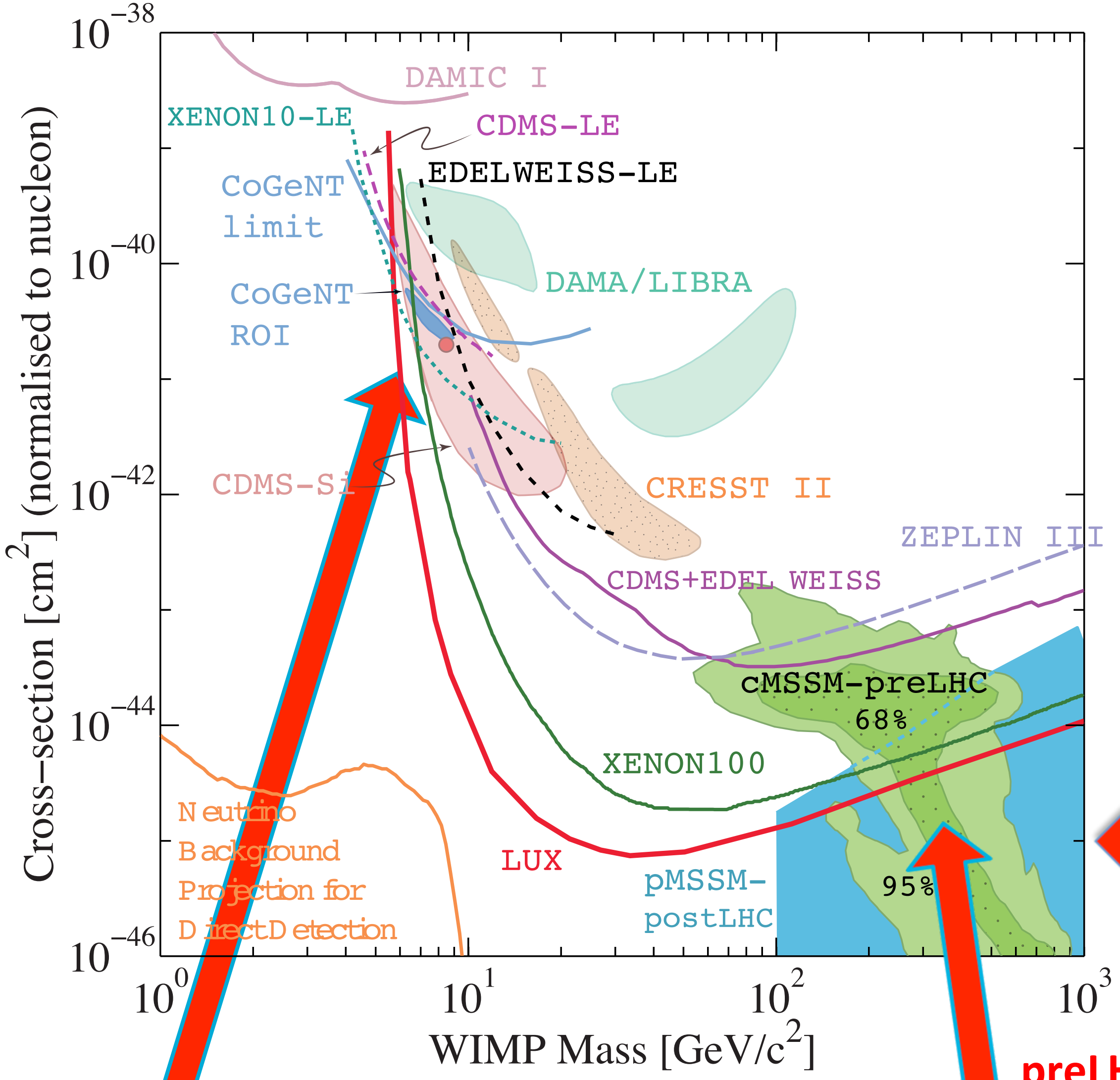


Confusion region

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)

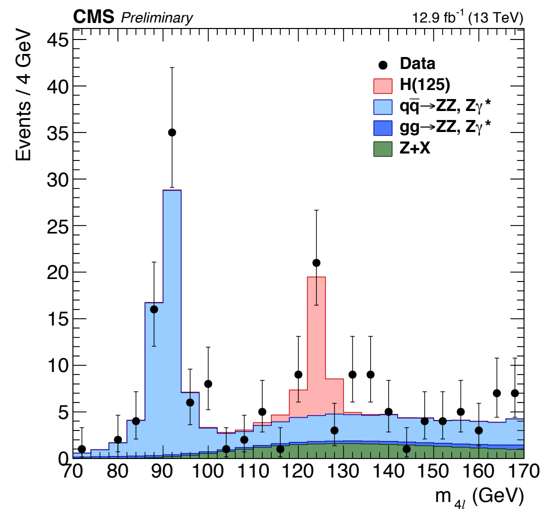
MasterCode, BayesFITS

Confusion region gone

Main news from the LHC…

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

ICHEP'16



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

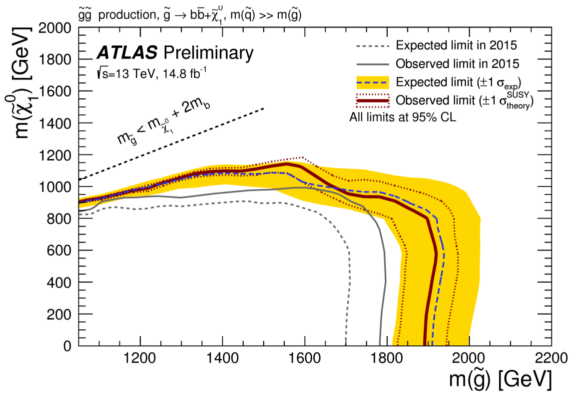
$$\mathrm{BR}(\overline{B}_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

Combined LHCb+CMS

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

superIso v.3.4

ICHEP'16, ATLAS-CONF-2016-052

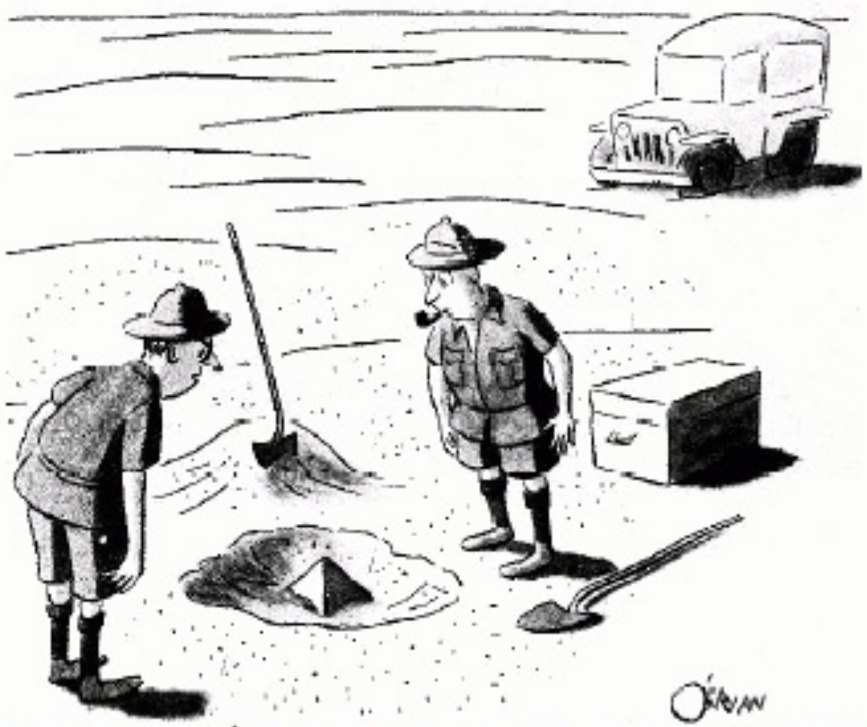


- **Stringent lower limits on superpartner masses**

Each independently implies:

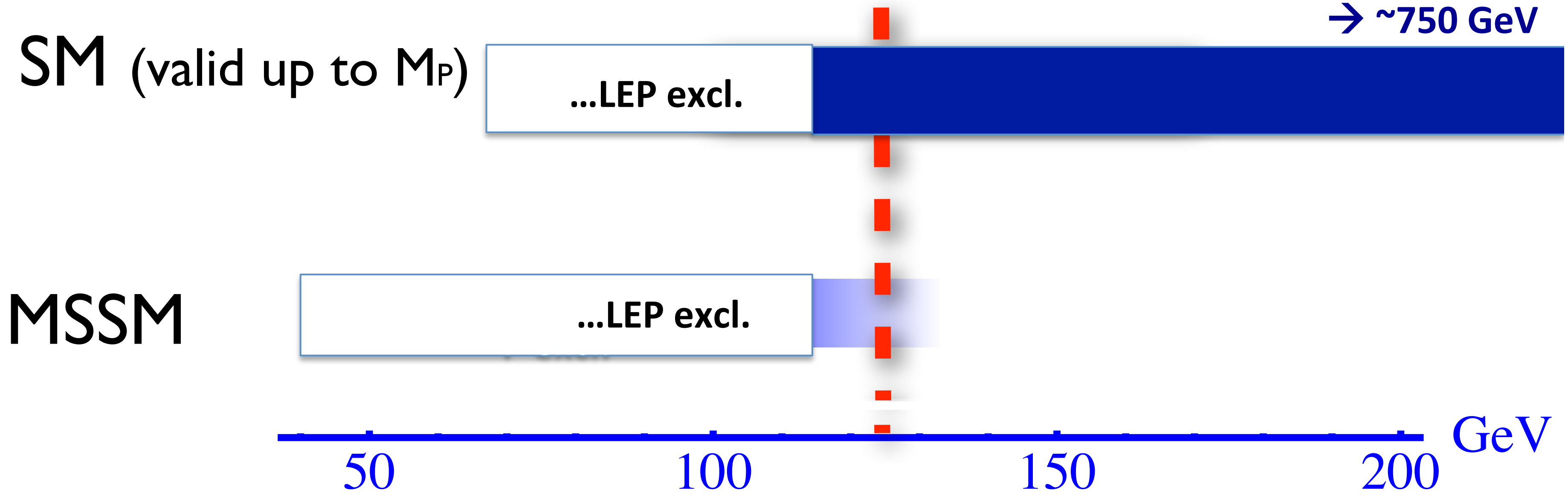
SUSY masses pushed to 1 TeV+ scale…

Impact of Higgs boson discovery…



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

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)

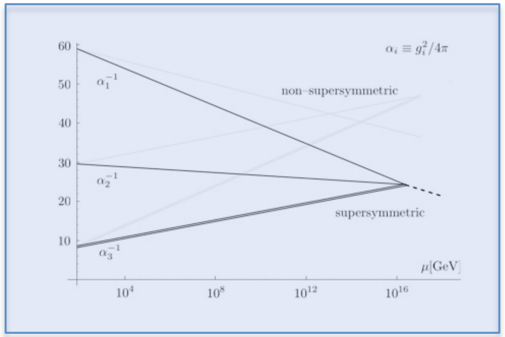
Smoking gun of SUSY?

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.

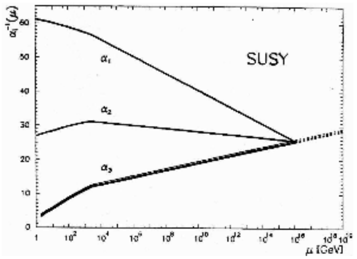
LR, Moriond 2015
arXiv:1507.07446

c.f. Frank Wilczek
Stockholm June 2015

SUSY: Constrained or Not?

- <u>**Constrained:**</u>

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



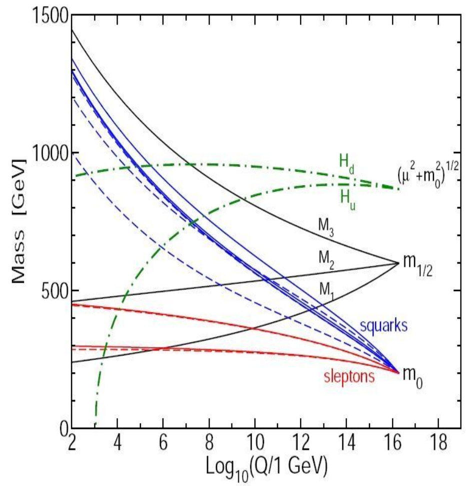


figure from hep-ph/9709356

<u>**Virtues:**</u>

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

Many models:

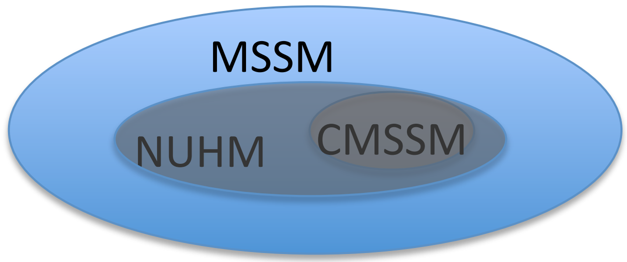
- **CMSSM (Constrained MSSM): 4+1 parameters**
- **NUHM (Non-Universal Higgs Model): 6+1**
- **CNMSSM (Constrained Next-to-MSSM) 5+1**
- **CNMSSM-NUHM: 7+1**
- **etc**

- <u>**Phenomenological:**</u>

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, …**

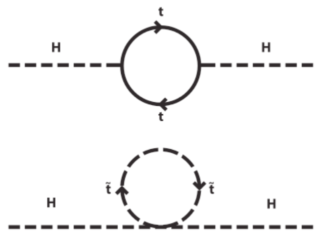
The 125 GeV Higgs Boson and SUSY

A curse…

In SUSY Higgs mass is a calculated quantity

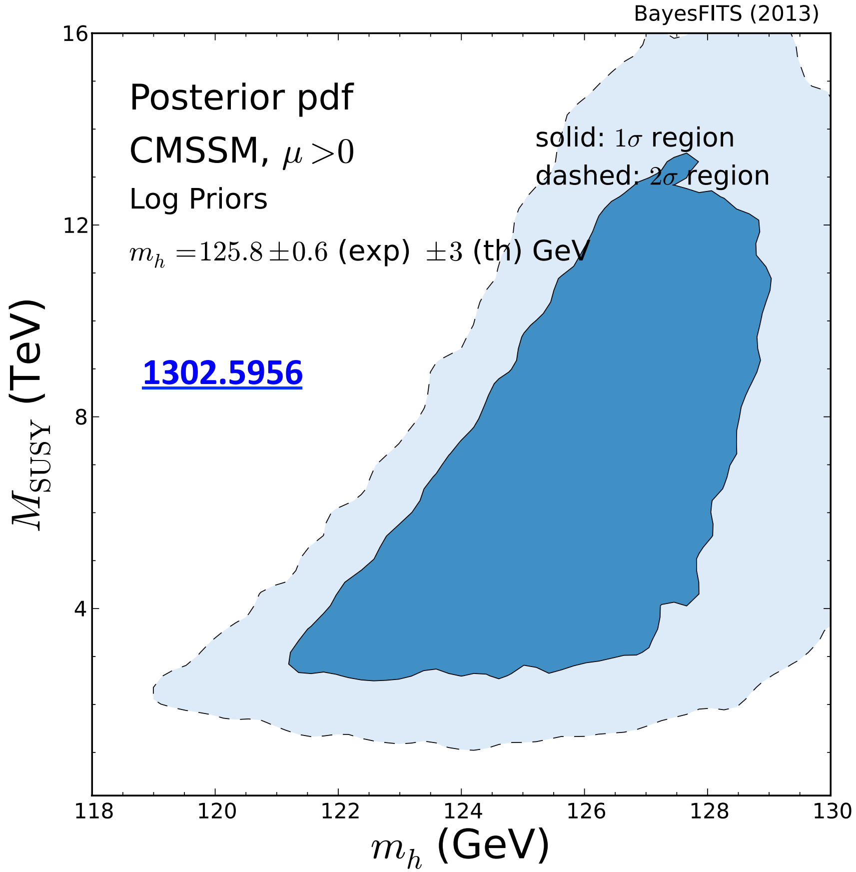
- **1 loop correction**

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



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

$$M_{\rm SUSY} \equiv \sqrt{m_{\tilde t_1} m_{\tilde t_2}}$$



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

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

$\sigma = 0.6$ 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**

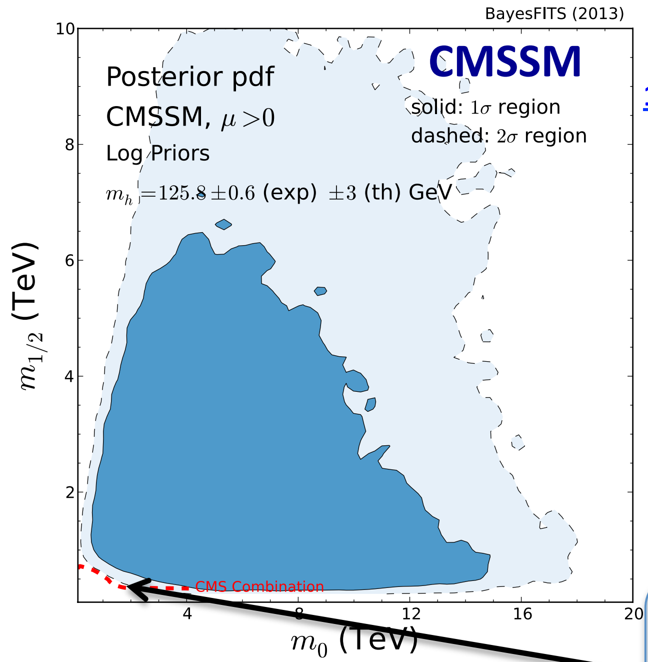
$$\mathcal{L} \sim e^{\frac{(m_h - 125.8\ \mathrm{GeV})^2}{\sigma^2+\tau^2}}$$

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

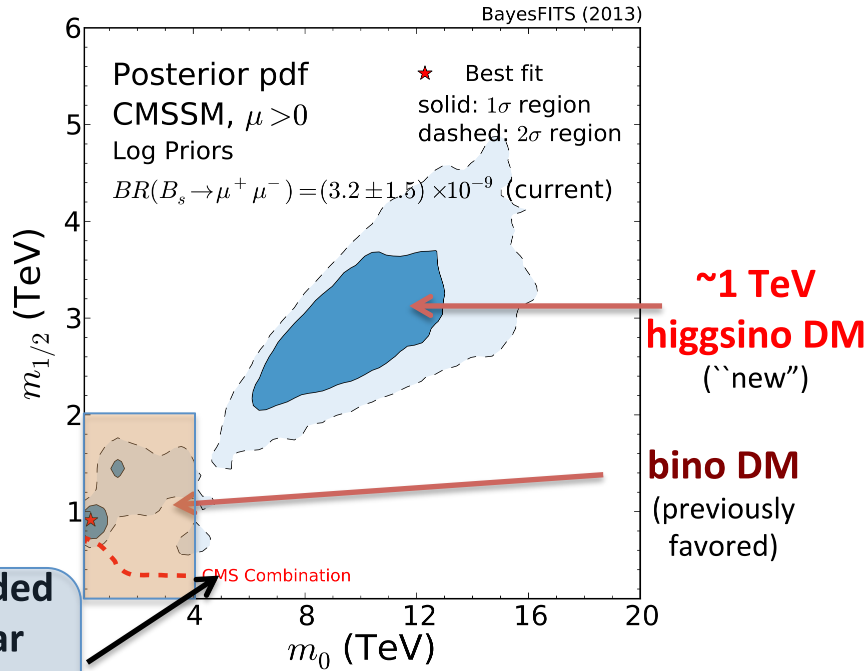
$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm SUSY}^2}\left(1-\frac{X_t^2}{12M_{\rm SUSY}^2}\right)\right]$$

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

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



1302.5956

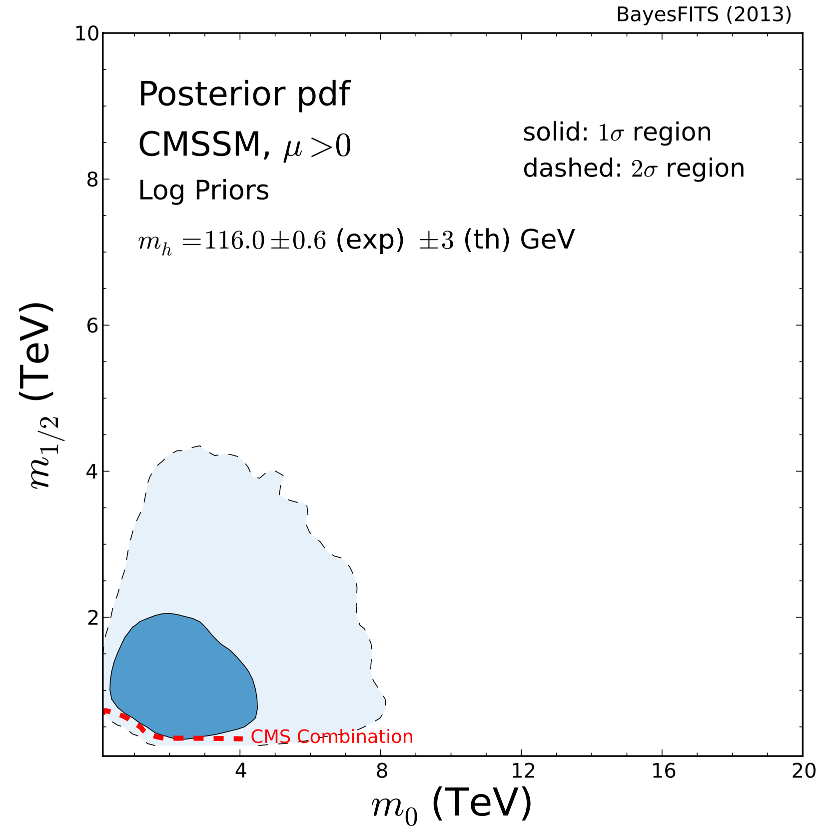


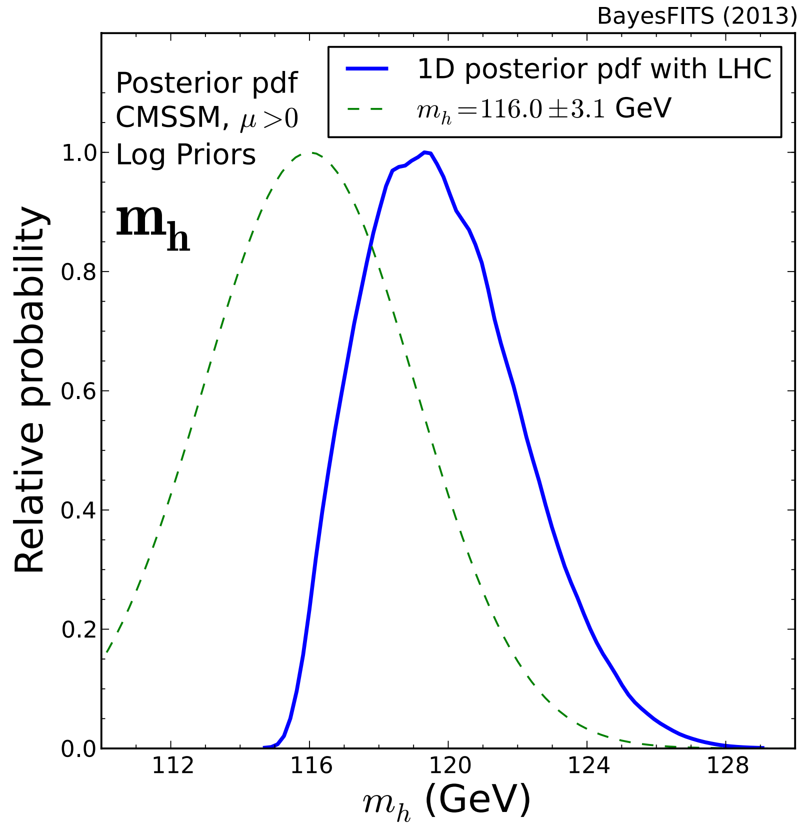
Excluded so far by LHC searches

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

Simple unified SUSY: NO other solutions

If m_h were, say, 116 GeV...



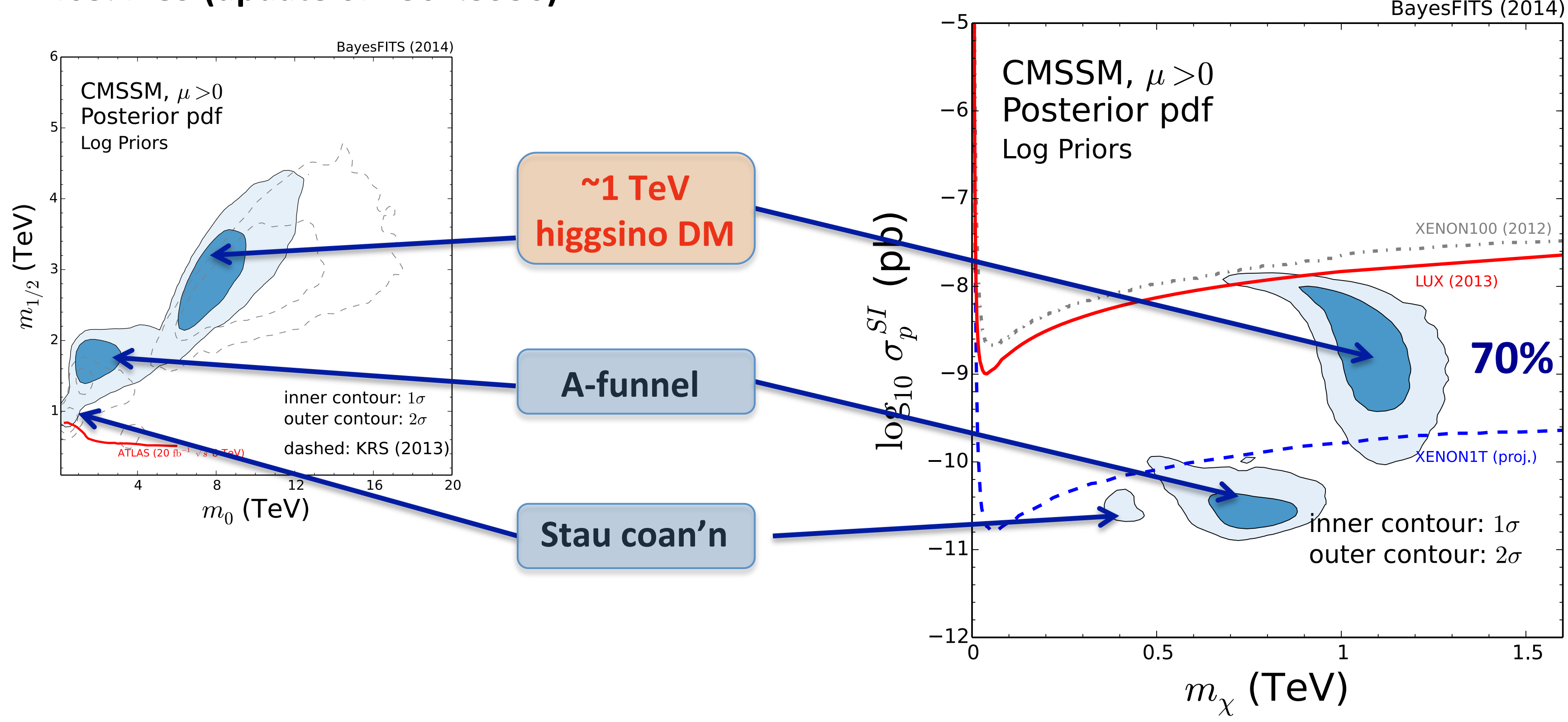


...would have created significant tension with LHC bounds on SUSY

CMSSM and direct DM searches

$\mu > 0$

1405.4289 (update of 1302.5956)



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

CMSSM: numerical scans

- **Perform random scan over 4 CMSSM +4 SM (nuisance) parameters <u>simultaneously</u>**

- Very wide ranges: 1302.5956

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

- 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	$173.5 \pm 1.0\,\text{GeV}$	Gaussian
$m_b(m_b)^{\overline{MS}}_{\text{SM}}$	Bottom quark mass	$4.18 \pm 0.03\,\text{GeV}$	Gaussian
$\alpha_s(M_Z)^{\overline{MS}}$	Strong coupling	0.1184 ± 0.0007	Gaussian
$1/\alpha_{\text{em}}(M_Z)^{\overline{MS}}$	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%
$\sin^2\theta_{\rm eff}$	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 ps^{-1}	0.043 ps^{-1}	2.400 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%

?

10 dof

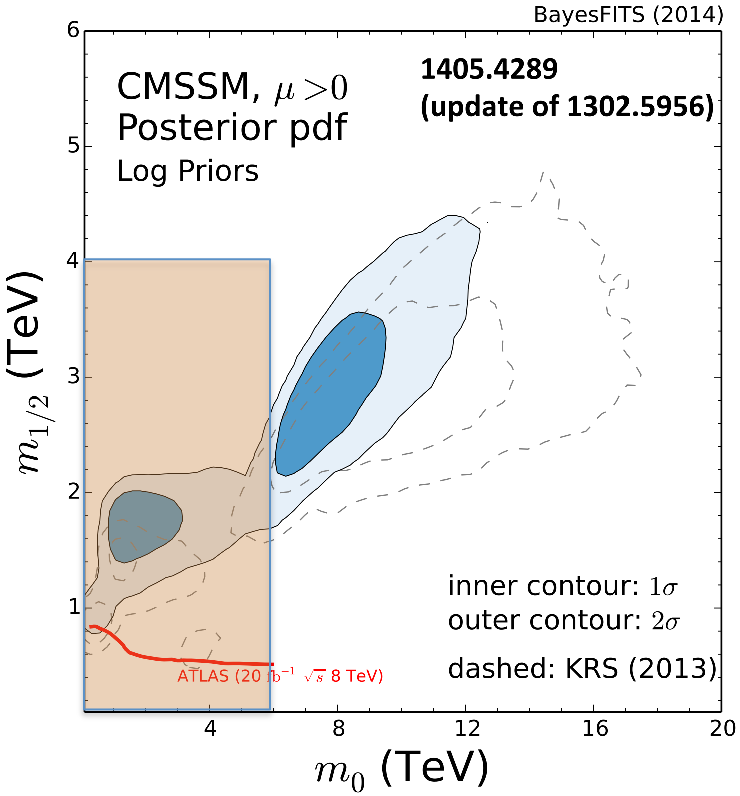
most important (by far)

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

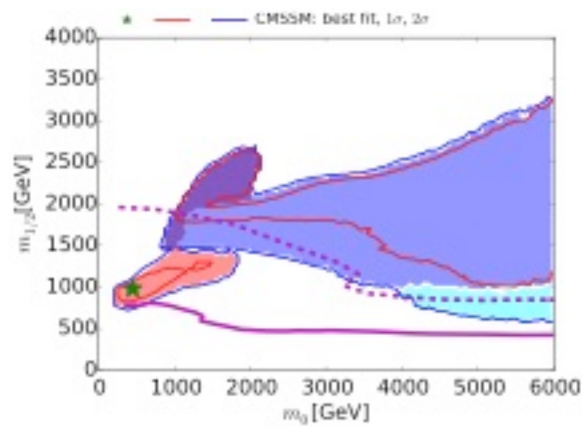
Bayes FITS

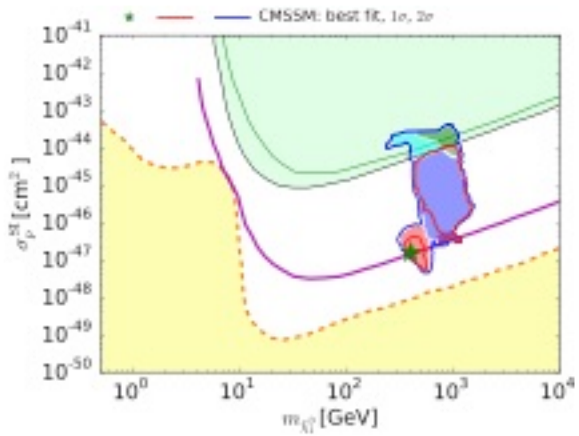
We do simultaneous scan of at least 8 parameters (4 of CMSSM + 4 of SM)

Bayesian vs chi-square analysis
(updated to include 3loop Higgs mass corrs)



MasterCode, 1508.01173





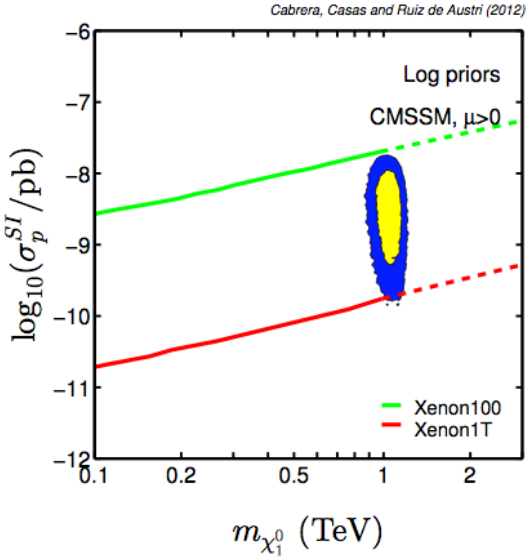
Reasonably good agreement in overlapping region

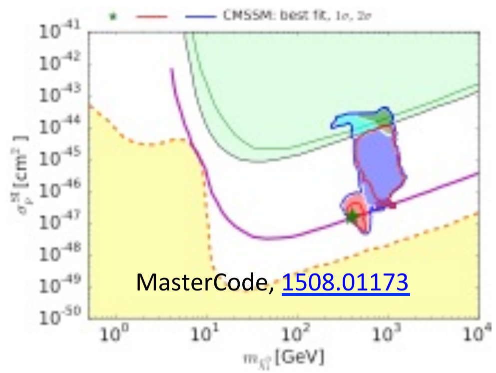
Note: Likelihood fn is rather flat

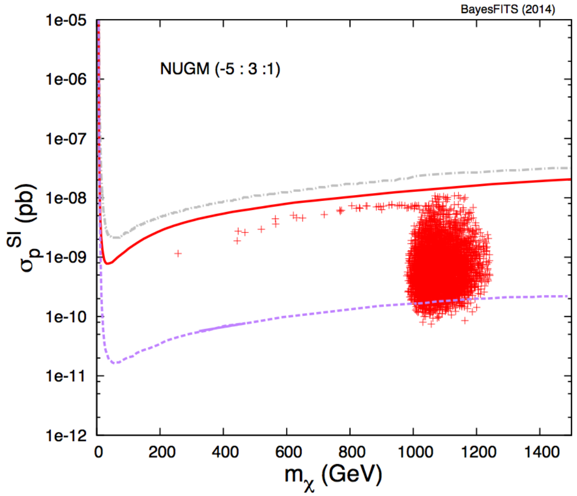
~1 TeV higgsino-like WIMP: implied by ~125 GeV Higgs -> large $m_{1/2}$ and m_0

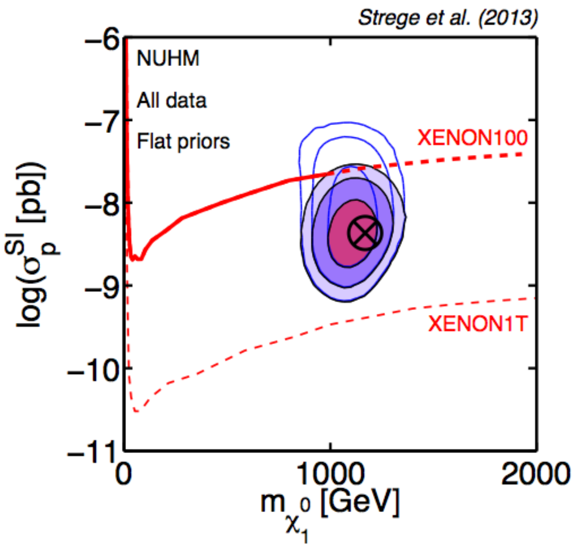
~1 TeV higgsino DM is robust

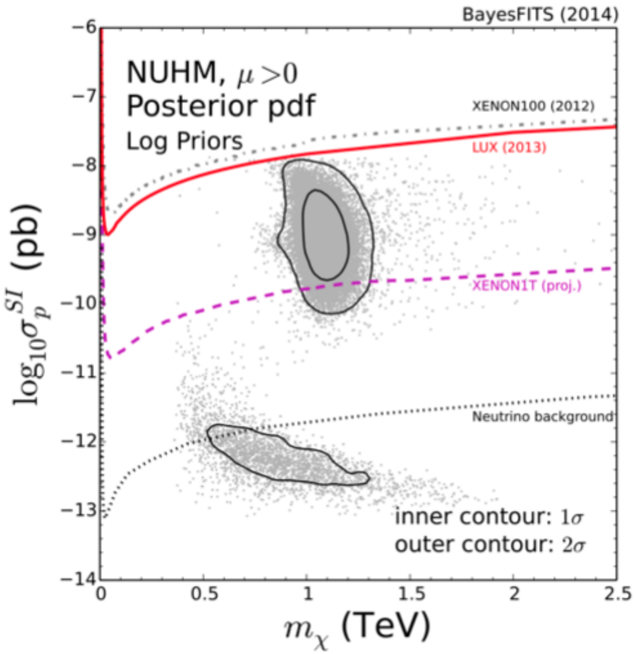
Present in both unified and pheno SUSY models

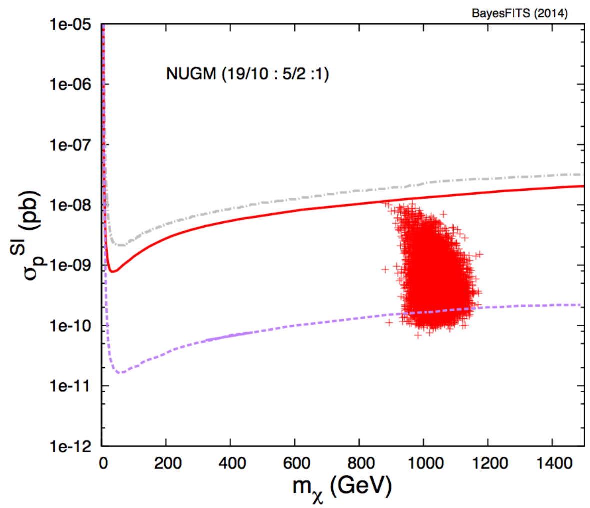












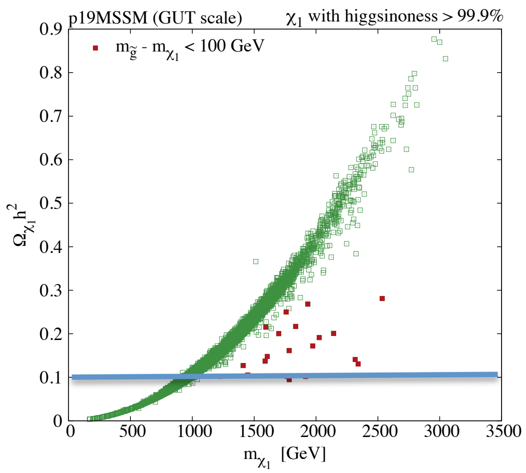
Watch prior dependence and chi2 vs Bayesian

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 <u>and</u> relic density**

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

✧ **most <u>natural</u> of SUSY DM**

✧ **smoking gun of SUSY!?**

Similarly with wino but mass less determined due to Sommerfeld effect

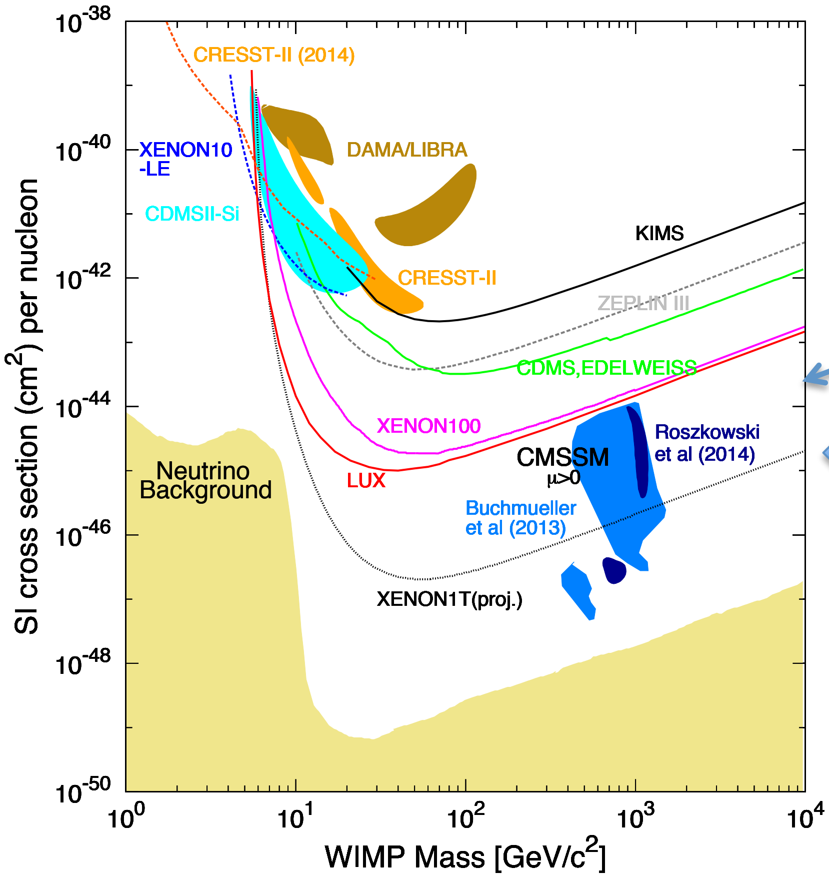
Fine print: How robust is m_{WIMP} ~1 TeV?

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

- **WIMP makes up <u>all</u> 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 $T_R \sim T_{freeze\text{-}out}$**
  - --> allows $m_{WIMP} > 1$ TeV

DM direct detection (2014)

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



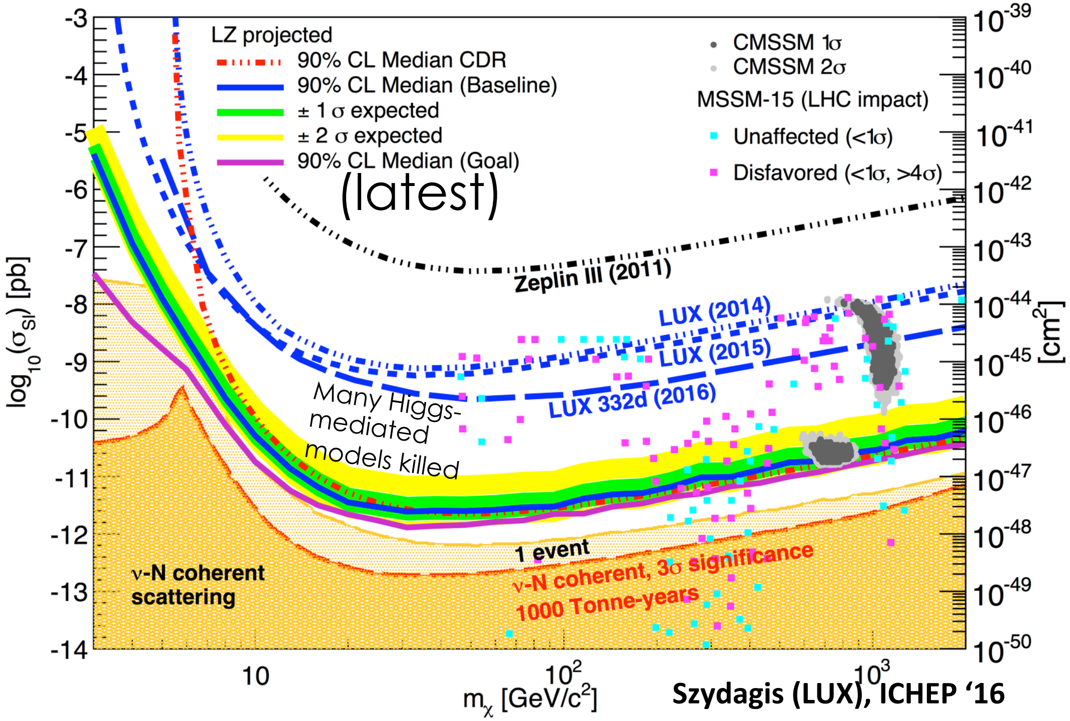
Reach of LUX, PandaX

Xenon-1T reach (~2018)

~1 TeV higgsino DM: Excellent prospects!

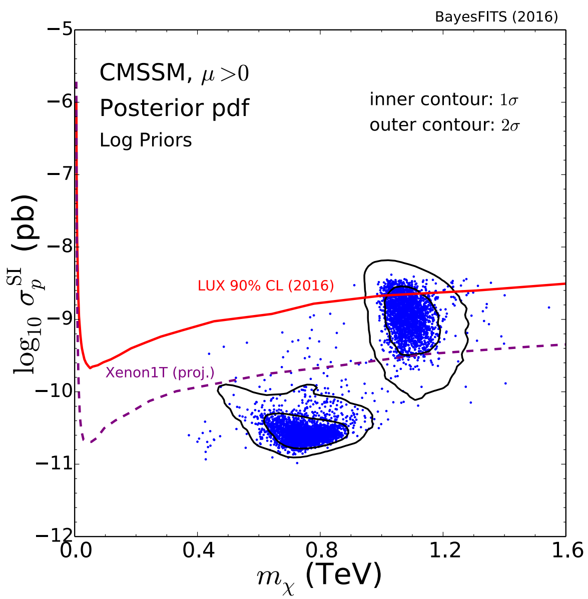
DM direct detection (2016)

Final limit from LUX, first one from PandaX

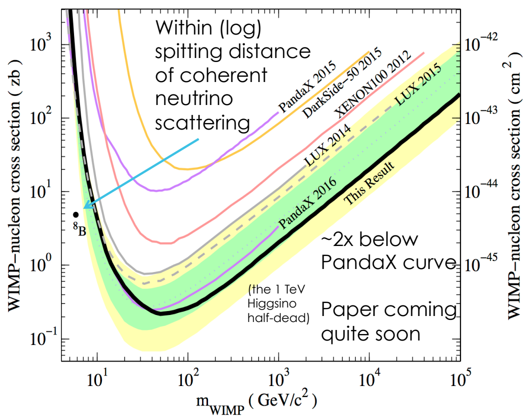


Szydagis (LUX), ICHEP '16

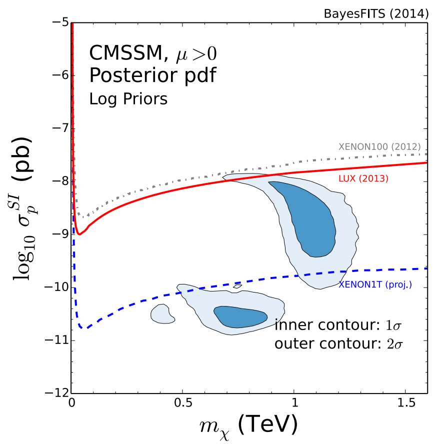
our update, to appear in a DM review in ROPP



For comparison, w/o final LUX limit



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



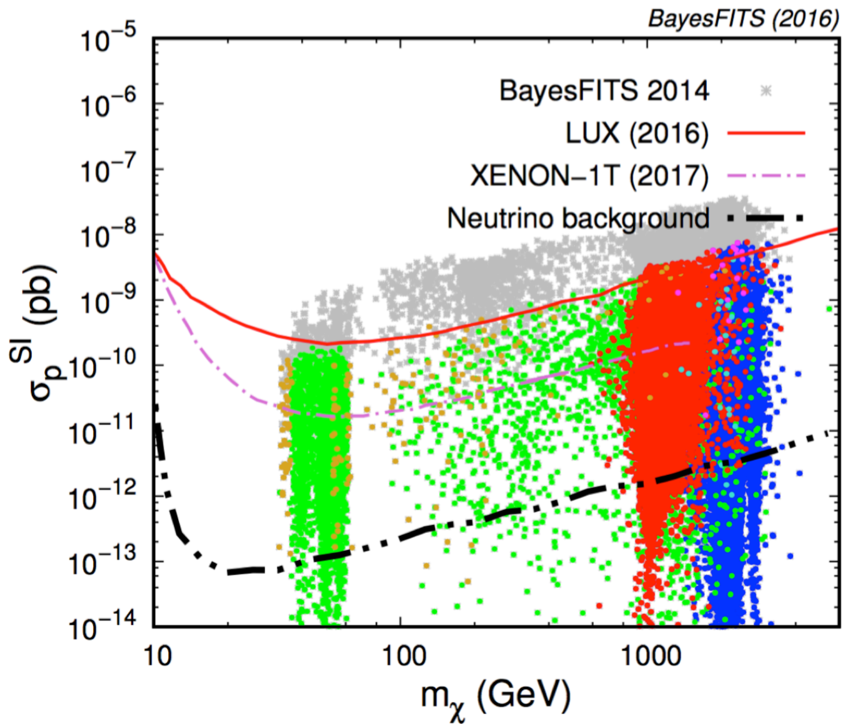
Direct Search for DM in general SUSY

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

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

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

Update of Roszkowski, Sesssolo, Williams, 1411.5214



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

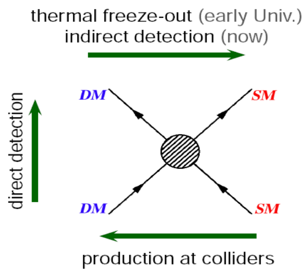
- indirect detection (ID):
  - HE neutrinos from the Sun (or Earth)

    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

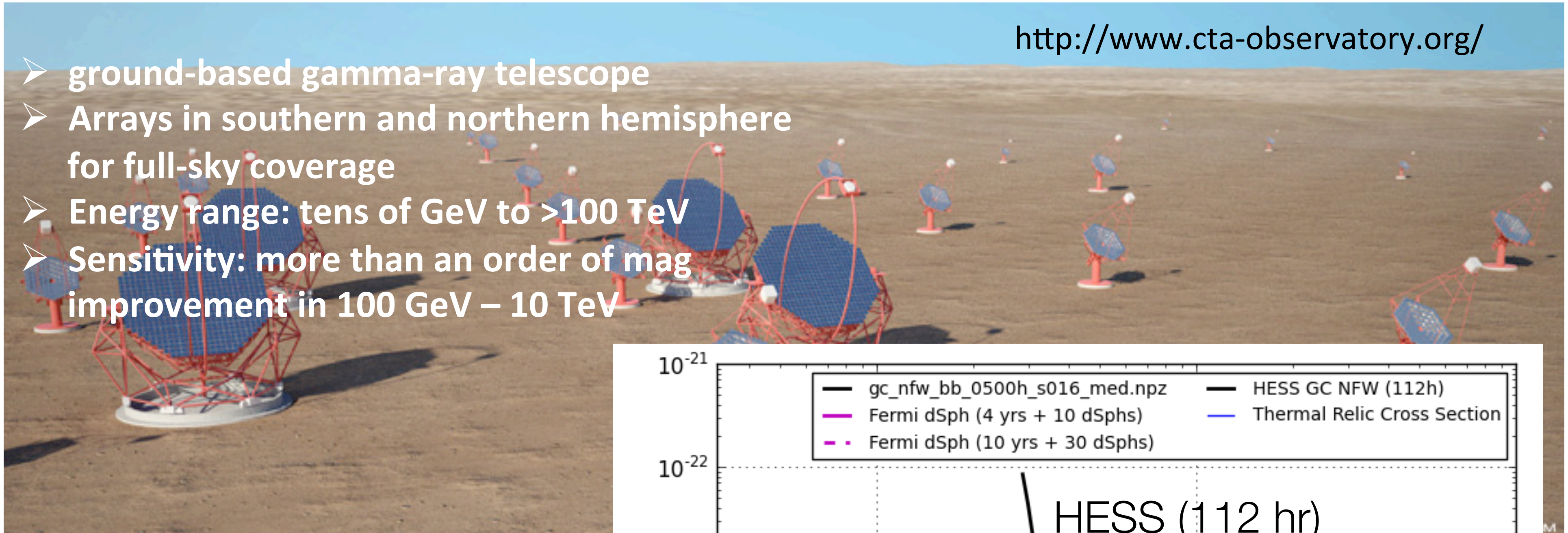
    from within a few kpc
  - gamma rays from WIMP pair-annihilation in the Galactic center

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

    more speculative
- the LHC

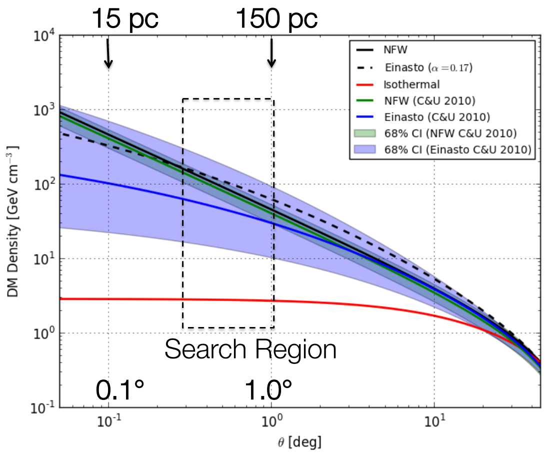


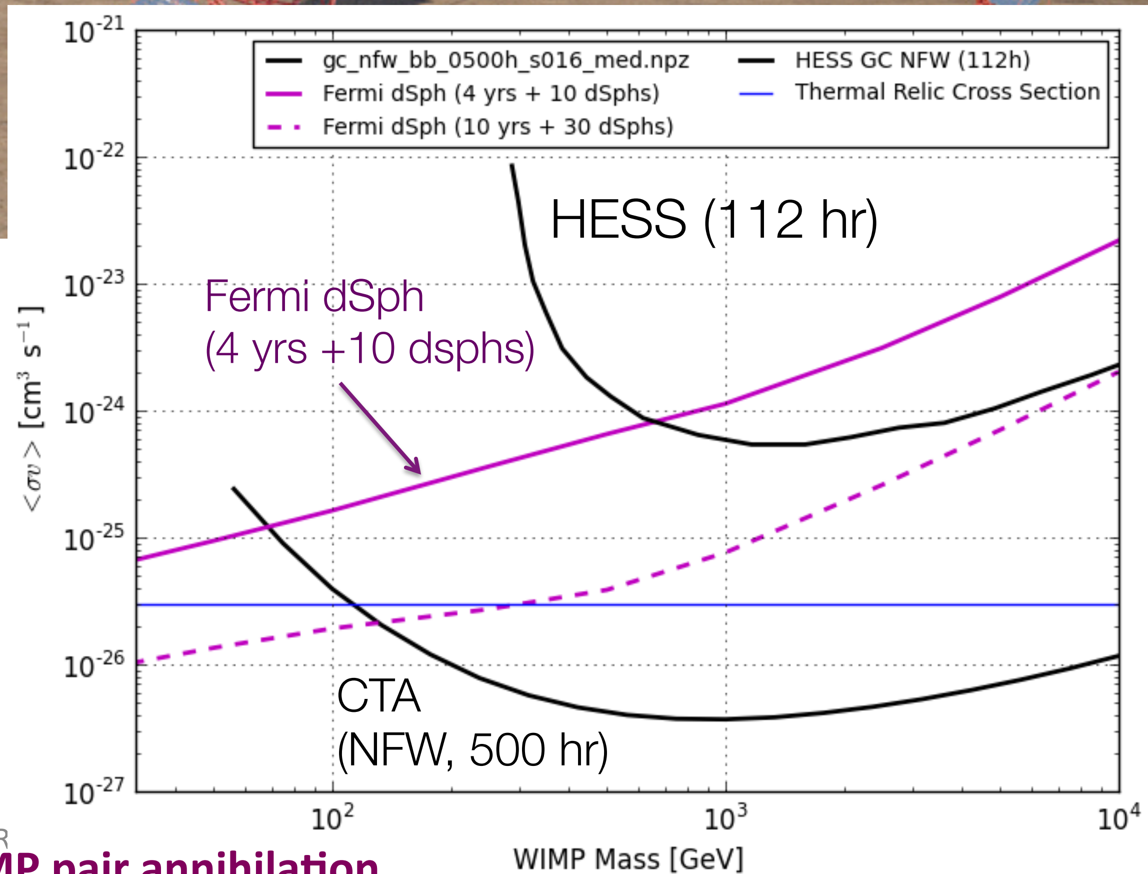
CTA – New guy in DM hunt race



- 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



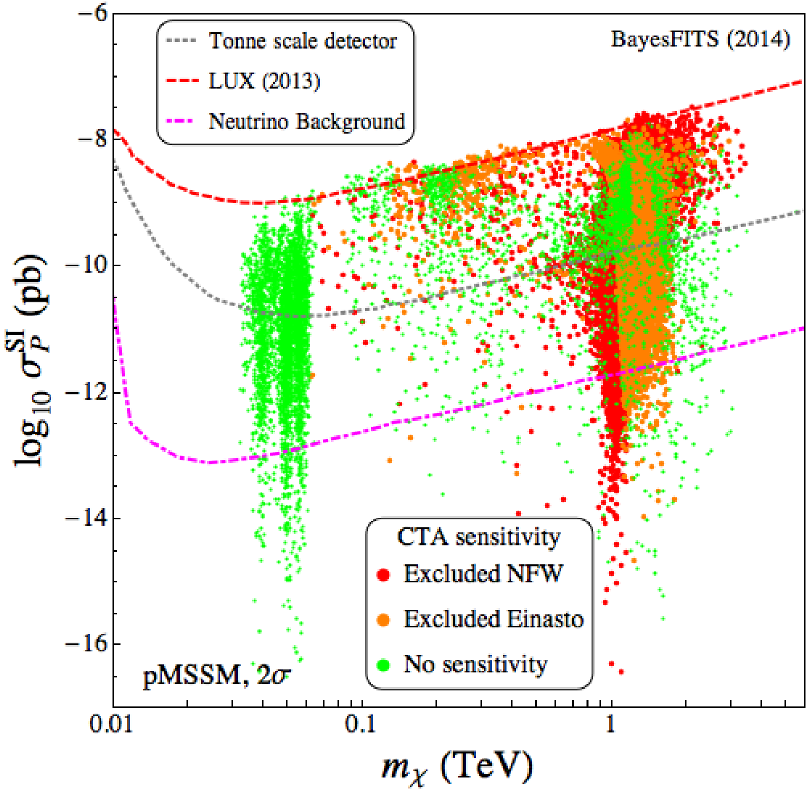


L. R

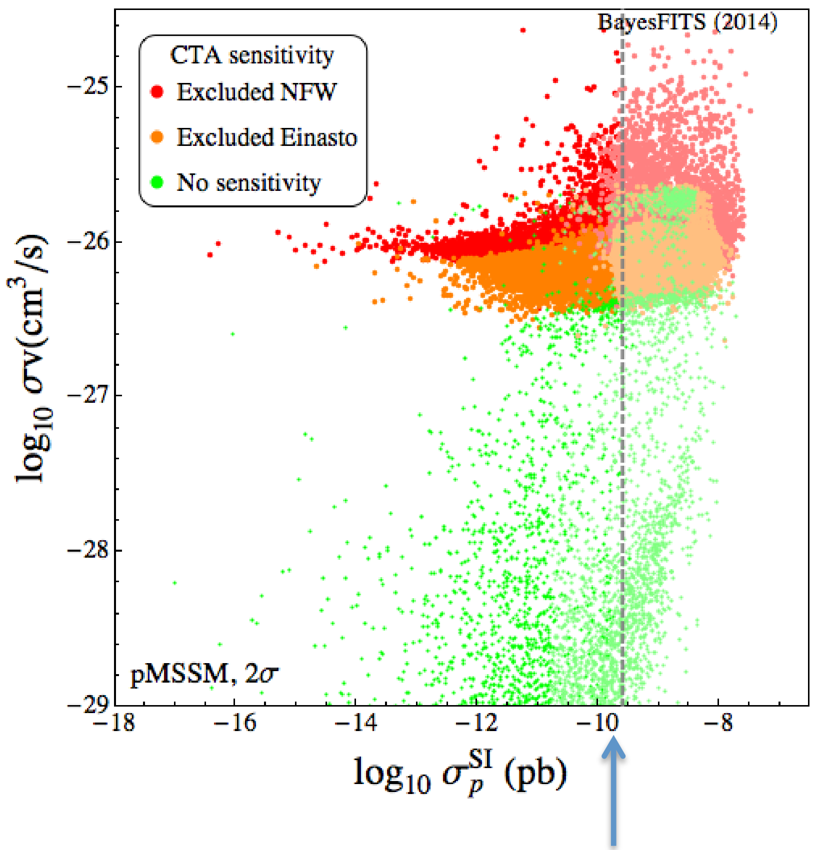
diffuse gamma radiation from WIMP pair annihilation

General SUSY: CTA vs direct detection

p19MSSM



Roszkowski, Sesssolo, Williams, [1411.5214]

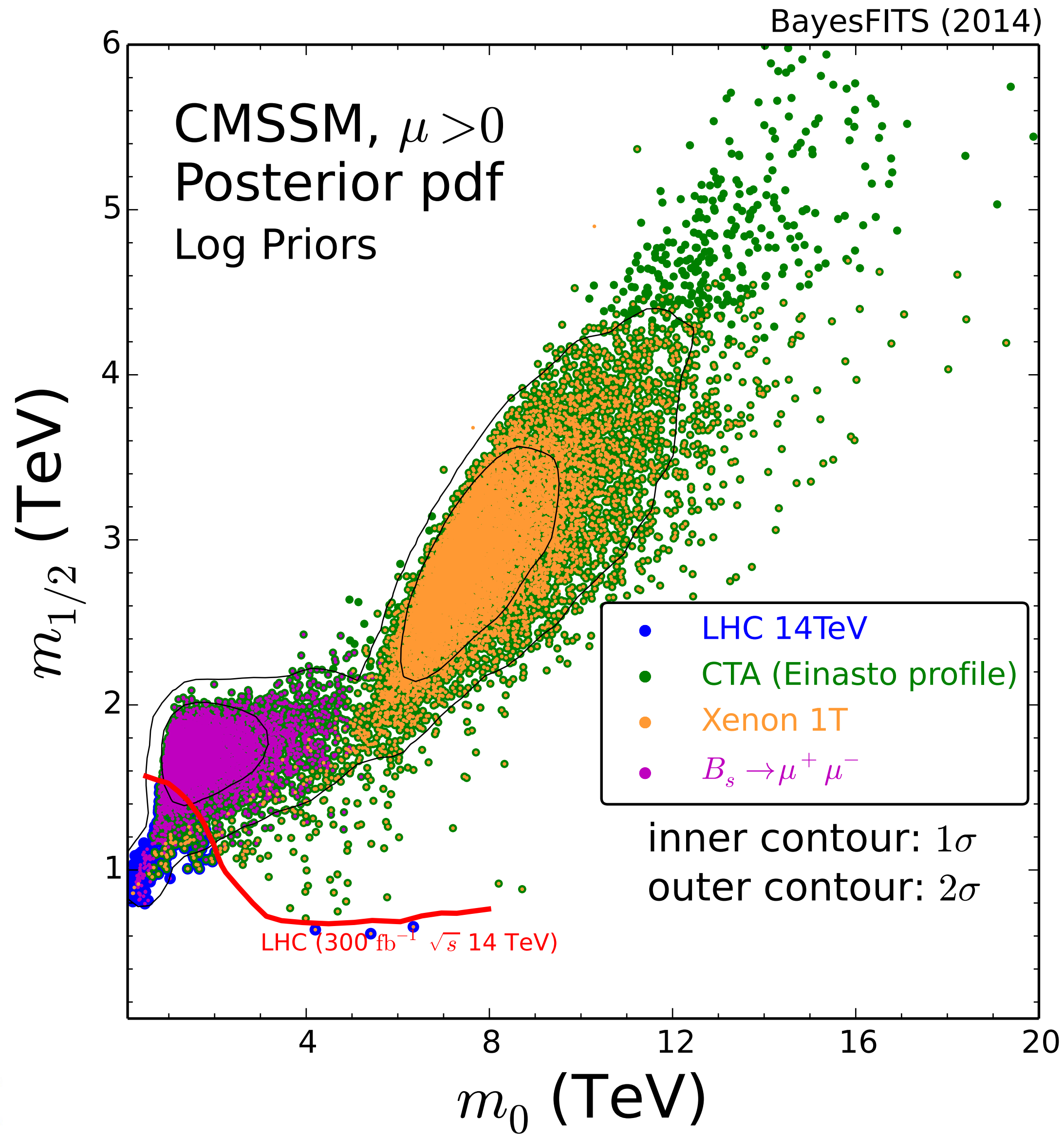


~1 tonne DD reach

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

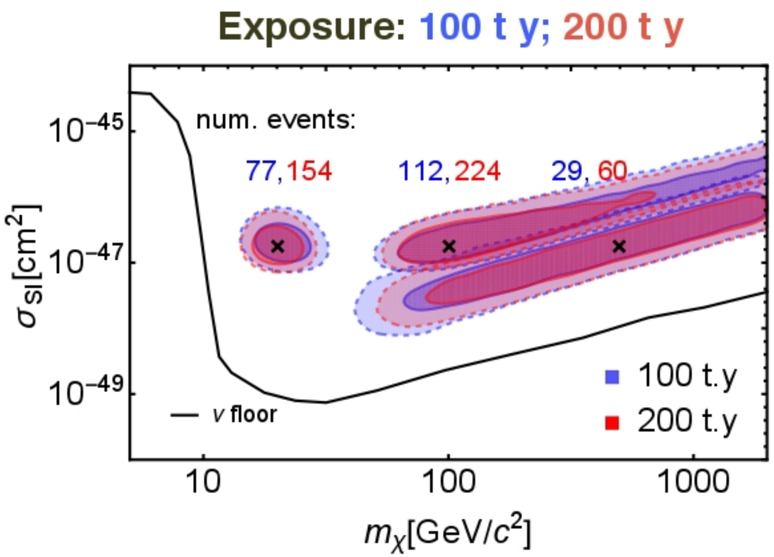
If signal seen in direct detection only

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

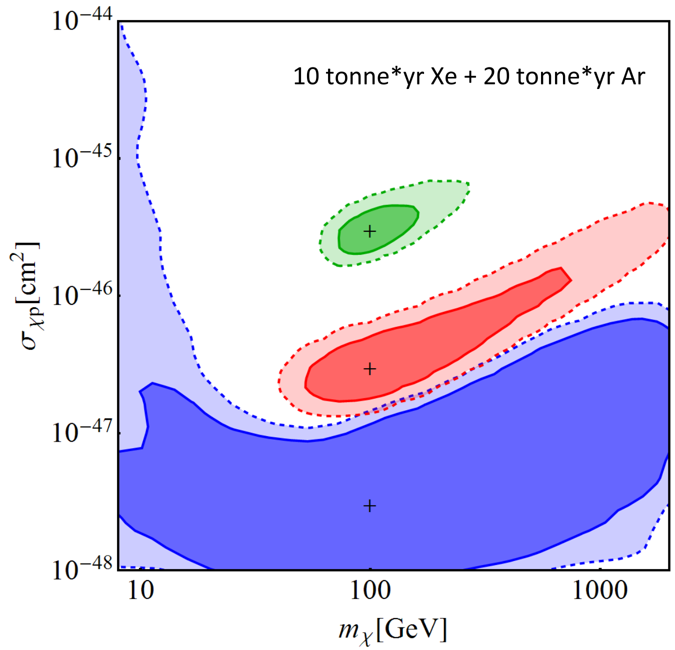


Update of Newstead et al., PRD 8, 076011 (2013)

Schumann @COSMO-15

1 & 2 sigma CI marginalized over astro parameters

When $sigma_p^{SI}$ low: prospects poorer

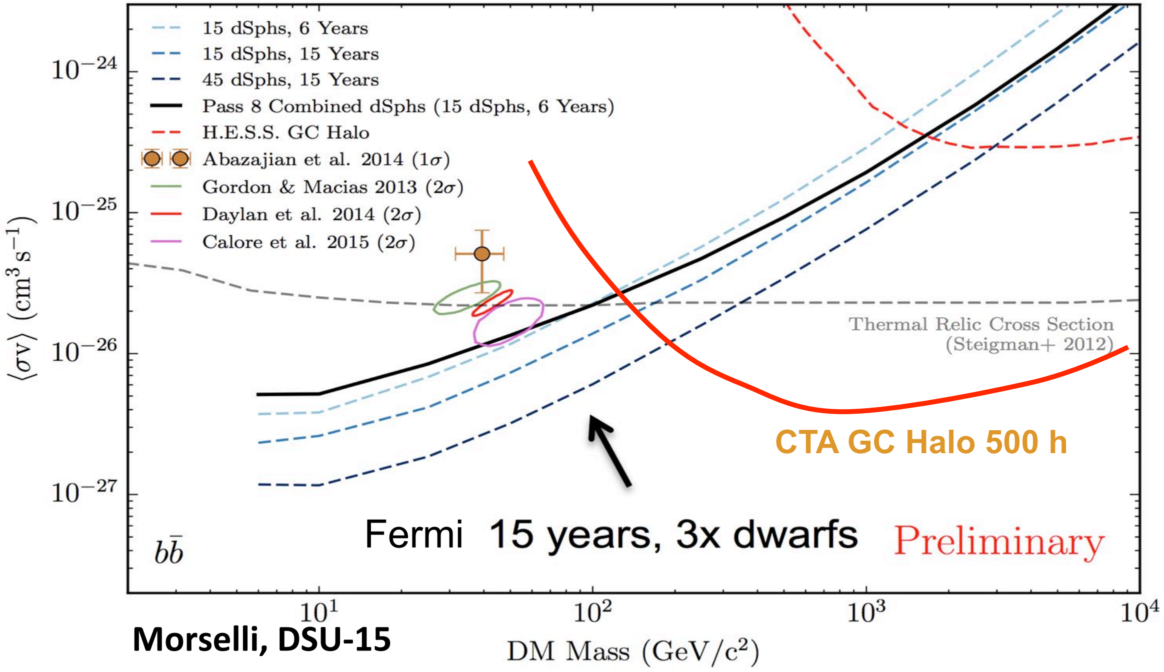


Newstead, 1306.3244

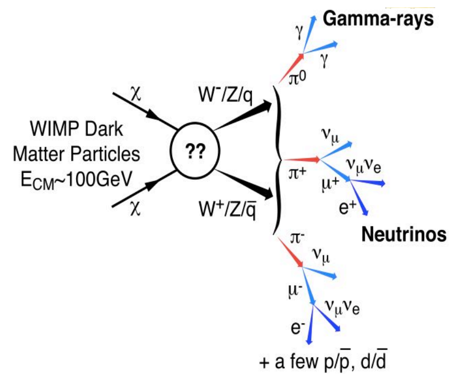
How about diffuse gamma radiation

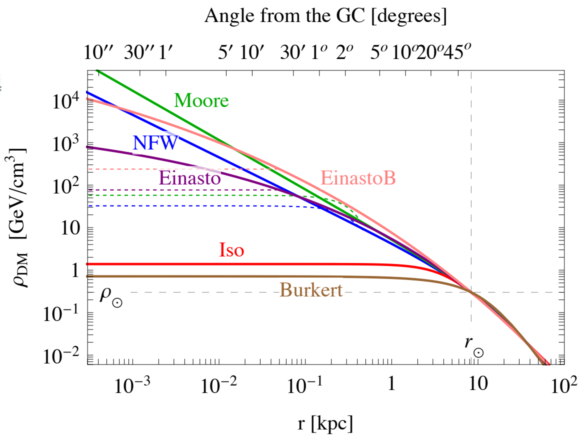
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\psi) = \sum_i \frac{\sigma_i v}{8\pi m_\chi^2}\frac{dN_\gamma^i}{dE_\gamma}\int_{\mathrm{l.o.s.}} dl\,\rho_\chi^2(r(l,\psi))$$

Fermi LAT
CTA - upcoming



Morselli, DSU-15



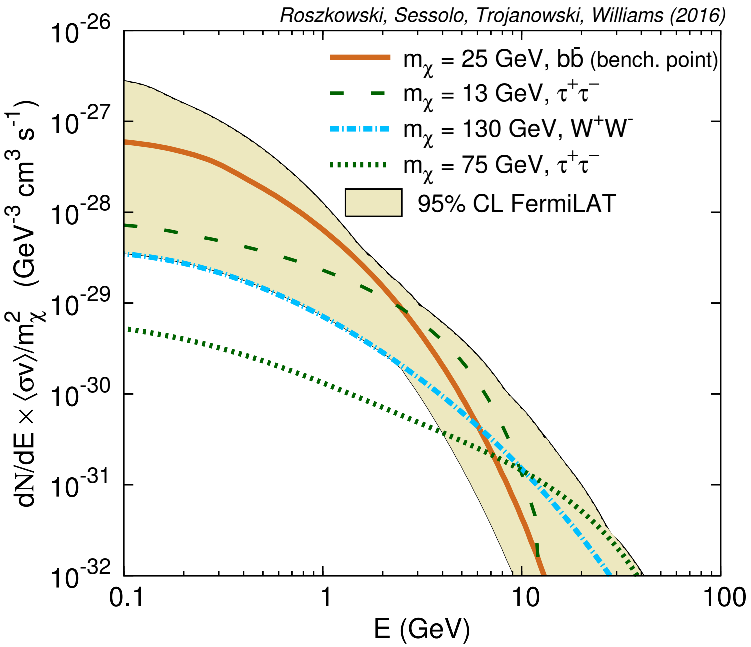


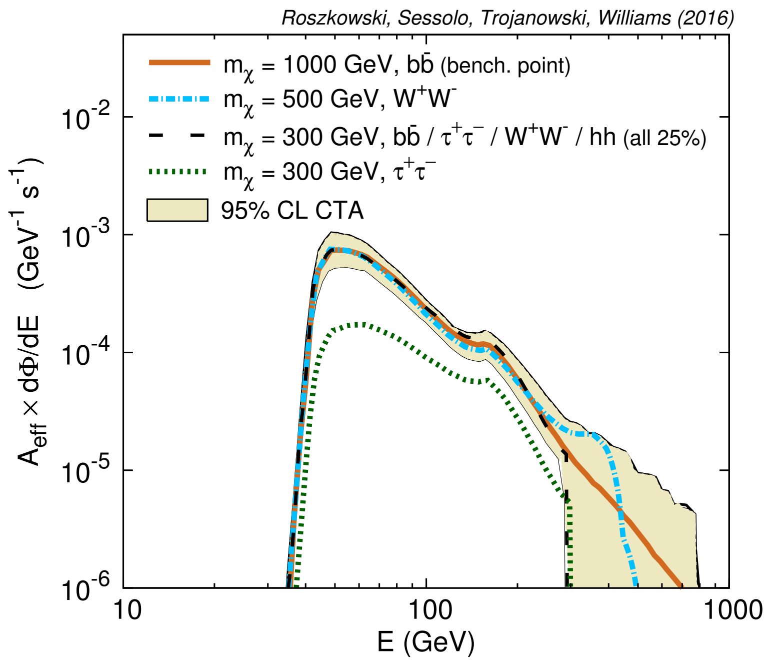
- **Low WIMP mass: Fermi LAT**
- **Mid range: Fermi LAT and CTA**
- **High mass: CTA**

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

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

DGR: Diffuse Gamma Radiation

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

	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	$1\times10^{-30}-1\times10^{-21}$ cm^3/s	log
σ_p^{SI}	Spin-independent cross section	$1\times10^{-12}-1\times10^{-6}$ 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

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

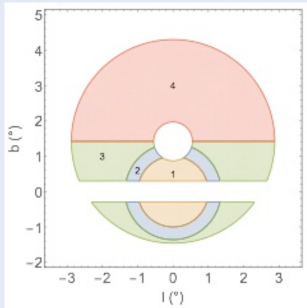
$N_{\rm Fermi} = 17$ energy bins.

CTA

Assume 500 hrs

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

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



mu_ij – expected signal + bgnd

n_ij – observed signal +bgnd

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

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

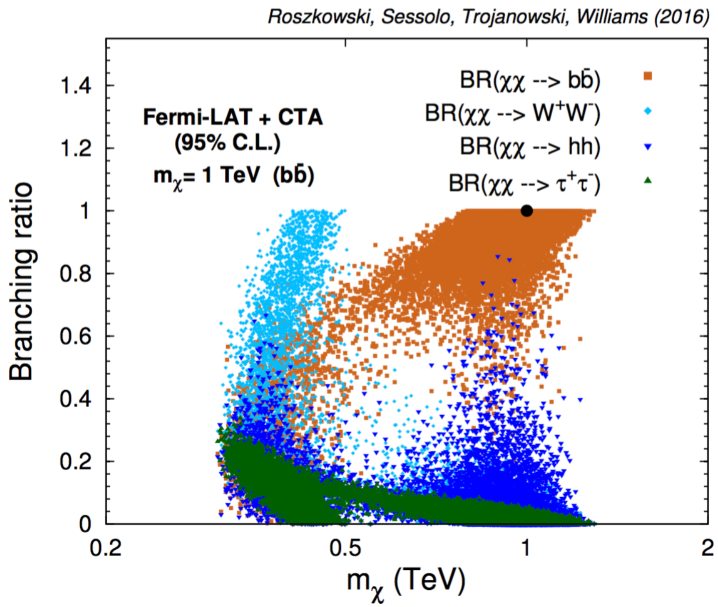
GDE: Extrapolated from Fermi LAT beyond 500 GeV (Silverwood, et al., Silk et al.)

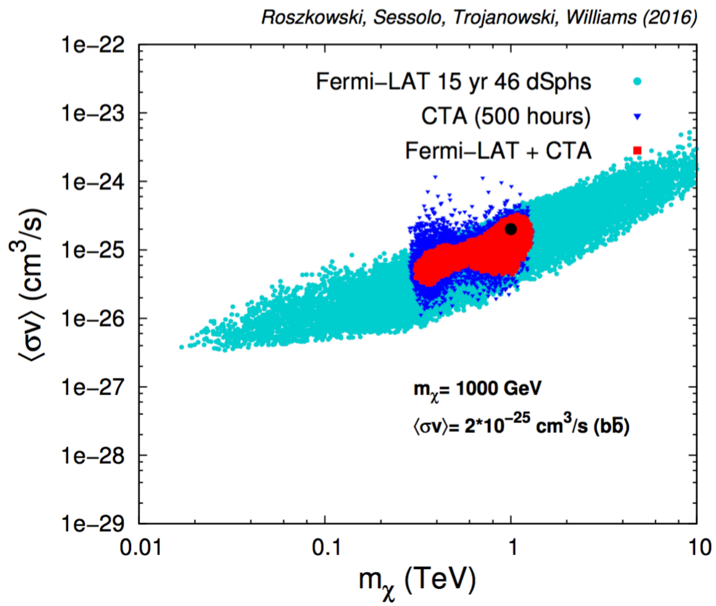
WIMP reconstruction with Fermi LAT and CTA

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!



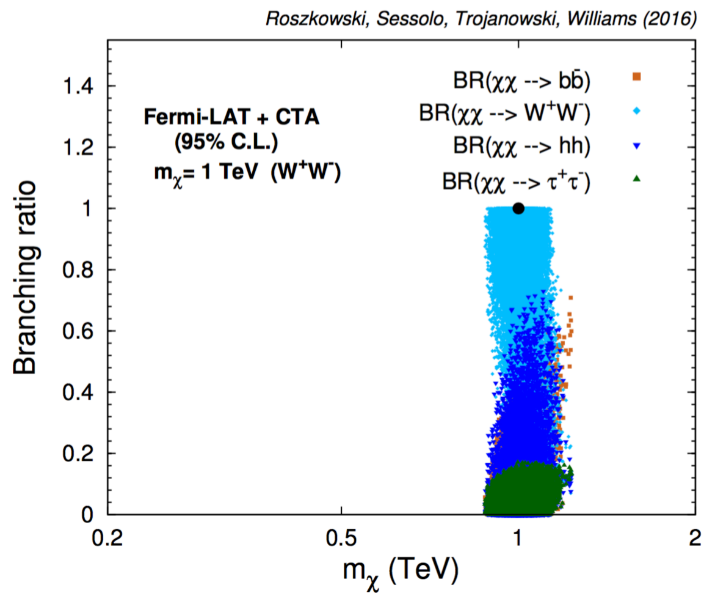


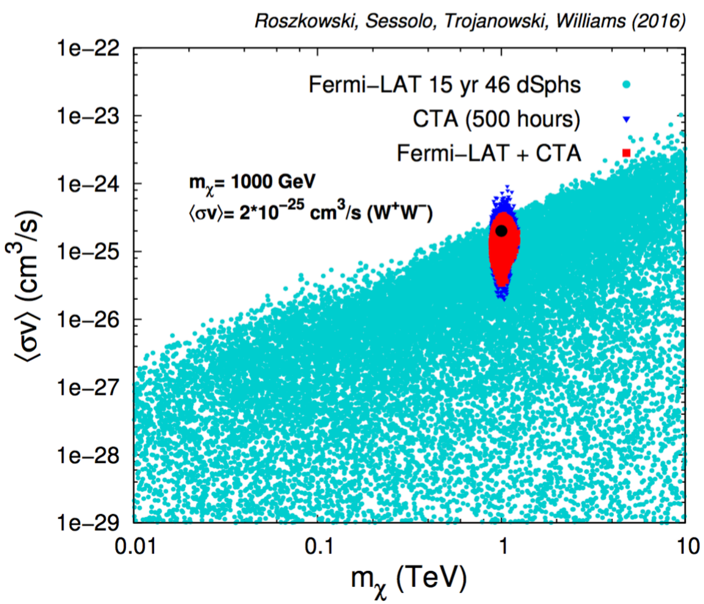
--> Heavy WIMP: Mass reconstruction doable but crude (CTA)
Fermi LAT helps narrow down sigma*v

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^{3}s^{-1}

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





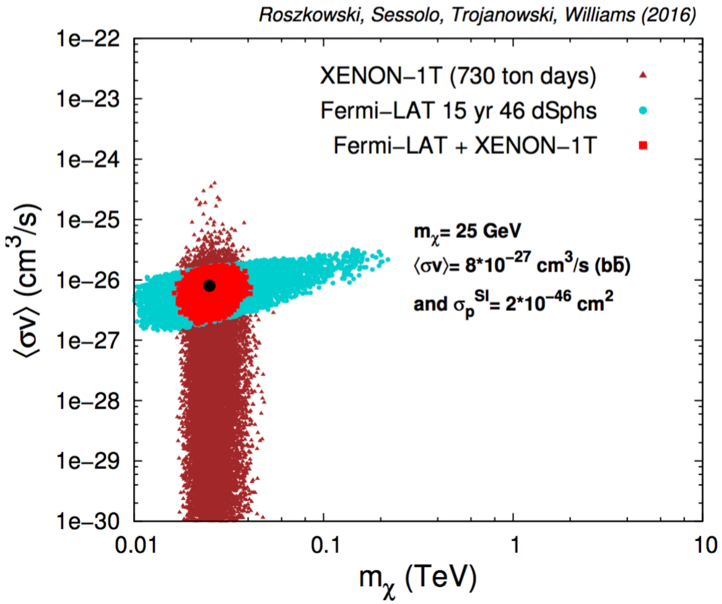
WW final state: both m_X and final states can be reconstructed rather well!

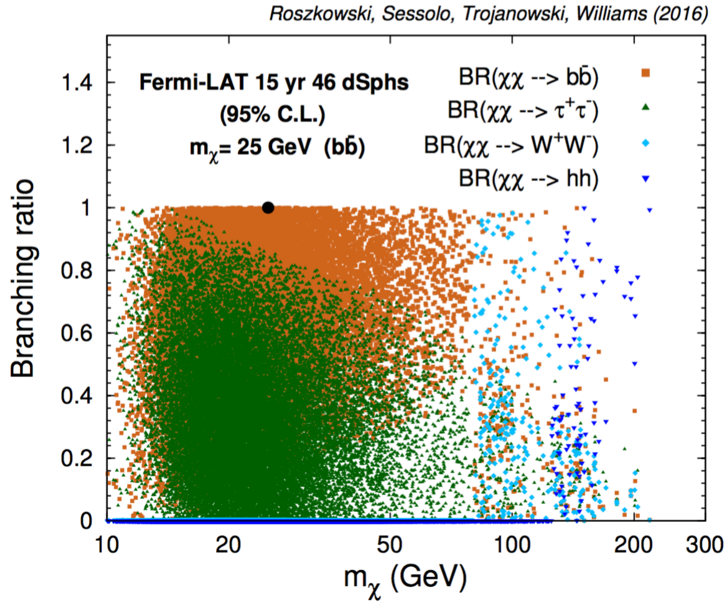
Even more optimistic results for tau-tau and leptonic final states (mu-mu and e-e)

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.

Backup

… a question on many people's mind…

But what about fine-tuning/naturalness?!

- I prefer to follow what the data implies, rather than theoretical prejudice
- Stabilizing mass hierarchy: initial motivation for SUSY but why should we treat it as a sacred cow

Initial motivation for cosmic inflation was to rid the Universe of unwanted relics like monopoles. Now: primordial density perturbation

- Naturalness: fundamental Higgs -> SUSY
- 125 GeV -> generically 1TeV <~ M_SUSY tens of TeV

- Fine-tuning is needed at any scale above the EW scale!

1 TeV is not a magic number

- If SUSY is discovered, large FT issue will have to be understood/accepted
- If SUSY is not discovered, the issue will become irrelevant
- Naturalness argument gone astray:

$$\frac{m_t}{m_b} \sim \frac{m_c}{m_s} \simeq 14 \quad \Rightarrow \quad m_t \simeq 60\,\mathrm{GeV}$$

Fine tuning issue is an expression of our ignorance about the high scale!

Usual definitions measure sensitivity to GUT scale values, and not FT.

- **FT argument:** $$\mu^2 = -\frac{1}{2}M_Z^2 + \frac{m_{H_d}^2(M_{\rm SUSY}) - \tan^2\beta m_{H_u}^2(M_{\rm SUSY})}{\tan^2\beta - 1}$$ $m_{H_{u,d}}^2$: tree + 1L corrs

$m_{H_u}^2$, $m_{H_u}^2$ and μ^2 need to be all fine-tuned to give M_Z^2

Since we don't know them, we expect them to be of order m_Z^2

- **But, imagine they are derived from some <u>fundamental</u> theory and come out to be very large, say of order 100 TeV, but still obey EWSB**

Would one still claim high FT in the theory? **NO!**

Low FT does not have to necessarily imply low M_{SUSY}.

RGE focussing

EWSB at large $\tan\beta$

$$\frac{M_Z^2}{2} \approx -\mu^2 - m_{H_u}^2 - \Sigma_u^u + \mathcal{O}(m_{H_d}^2/\tan^2\beta)$$

Chan, Chattopadhay, Nath '98
Feng, Matchev, Moroi '99
...

$m_{H_u}^2$ at $M_{\rm SUSY}$ stable wrt variations of GUT initial conditions

Dependence on inputs at GUT scale:

Integrate 2-loop RGEs:

$$\begin{aligned} m_{H_u}^2(M_{\rm SUSY}) = & \; 0.645 m_{H_u}^2 + 0.028 m_{H_d}^2 - 0.024 m_{\tilde{Q}_1}^2 - 0.024 m_{\tilde{Q}_2}^2 - 0.328 m_{\tilde{Q}_3}^2 \\ & + 0.049 m_{\tilde{u}_1}^2 + 0.049 m_{\tilde{u}_2}^2 - 0.251 m_{\tilde{u}_3}^2 - 0.024 m_{\tilde{d}_1}^2 - 0.024 m_{\tilde{d}_2}^2 - 0.019 m_{\tilde{d}_3}^2 \\ & + 0.024 m_{\tilde{L}_1}^2 + 0.024 m_{\tilde{L}_2}^2 + 0.024 m_{\tilde{L}_3}^2 - 0.025 m_{\tilde{e}_1}^2 - 0.025 m_{\tilde{e}_2}^2 - 0.025 m_{\tilde{e}_3}^2 \\ & + 0.014 M_1^2 + 0.210 M_2^2 - 1.097 M_3^2 + 0.001 M_1 M_2 - 0.047 M_1 M_3 - 0.089 M_2 M_3 \\ & - 0.113 A_t^2 + 0.010 A_b^2 + 0.006 A_\tau^2 + 0.008 A_t A_b + 0.005 A_t A_\tau + 0.004 A_b A_\tau \\ & + M_1(0.007 A_t - 0.005 A_b - 0.004 A_\tau) + M_2(0.062 A_t - 0.009 A_b + 0.005 A_\tau) \\ & + M_3(0.295 A_t + 0.024 A_b + 0.030 A_\tau) \end{aligned}$$

$m_{H_U}^2, m_{\tilde{Q}_3}^2, m_{\tilde{u}_3}^2$ almost cancel if all $= m_0^2$

$$m_{H_u}^2(M_{\rm SUSY}) = 0.074 m_0^2 - 1.008 m_{1/2}^2 - 0.080 A_0^2 + 0.406 m_{1/2} A_0$$

Some contributions can correlate.

Fine tuning in the CMSSM

J. R. Ellis, K. Enqvist, D. V. Nanopoulos, and F. Zwirner

R. Barbieri and G. Giudice

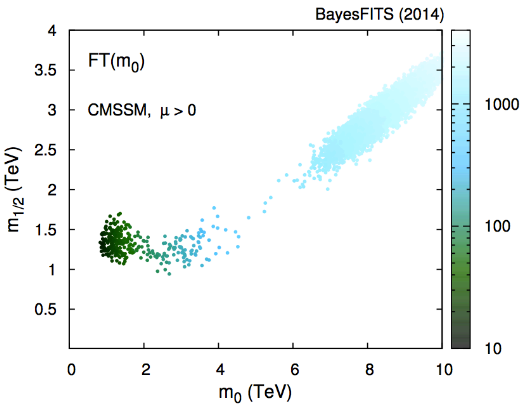
$$\Delta = \max\{\Delta_{p_i}\}$$

$$\Delta_{p_i} = \left|\frac{\partial \ln M_Z^2}{\partial \ln p_i^2}\right| = \frac{1}{2}\left|\frac{\partial \ln M_Z^2}{\partial \ln p_i}\right|$$

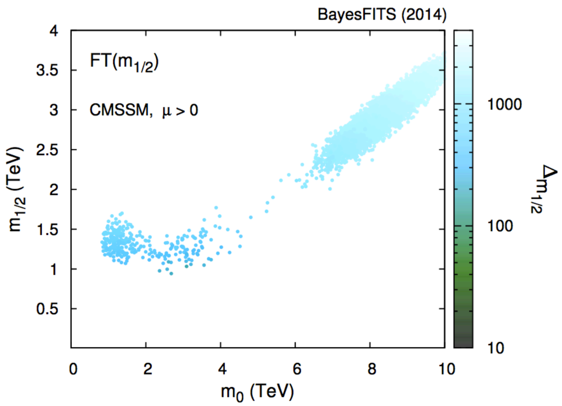
p_i are the defining parameters of the model

K. Kowalska et al., arXiv:1402.1328, JHEP 1404 (2014) 166

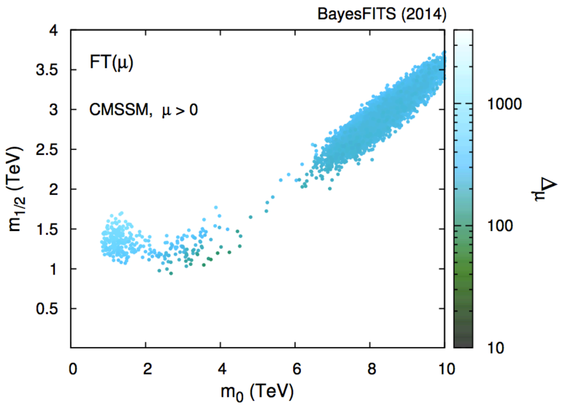
➢ **In ~1 TeV higgsino region:**



$\mathbf{m_0}$: $\mathbf{FT > 1000}$



$\mathbf{m_{1/2}}$: $\mathbf{FT > 1000}$



μ : $\mathbf{FT \simeq 250}$

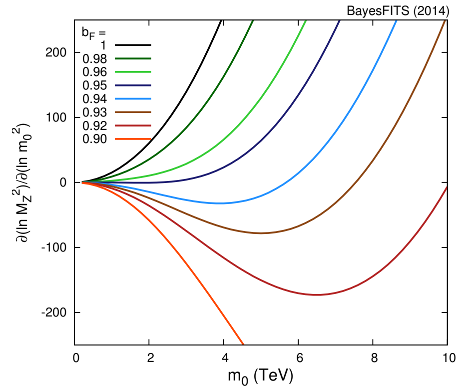
CMSSM: simplest boudary conditions at GUT give enormous FT

High scale relations to reduce FT in ~1 TeV higgsino region

$$m_{H_u}^2(M_{\rm SUSY}) = 0.074 m_0^2 - 1.008 m_{1/2}^2 - 0.080 A_0^2 + 0.406 m_{1/2} A_0$$

- **Higgs non-unification** $m_{H_u}^2 = b_F^2 m_0^2$

optimal when $b_F = 0.92 - 0.94$

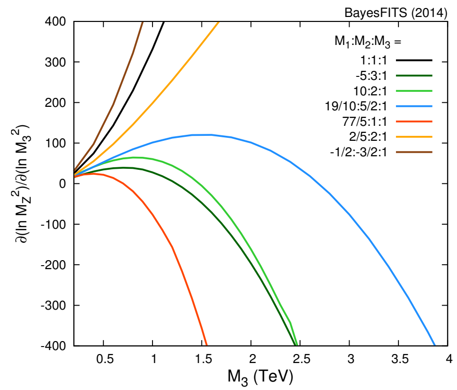


- **Gaugino non-unification** $M_1 : M_2 : M_3$

1402.1328

optimal when SU(5): $(-5:3:1)$, $(10:2:1)$

SO(10): $(19/10:5/2:1)$



- **Relate mu to scalars** $\mu = c_H m_0$

e.g, Giudice-Masiero

otherwise $\Delta_\mu \simeq 250$ since $\mu \simeq 1\,\mathrm{TeV}$

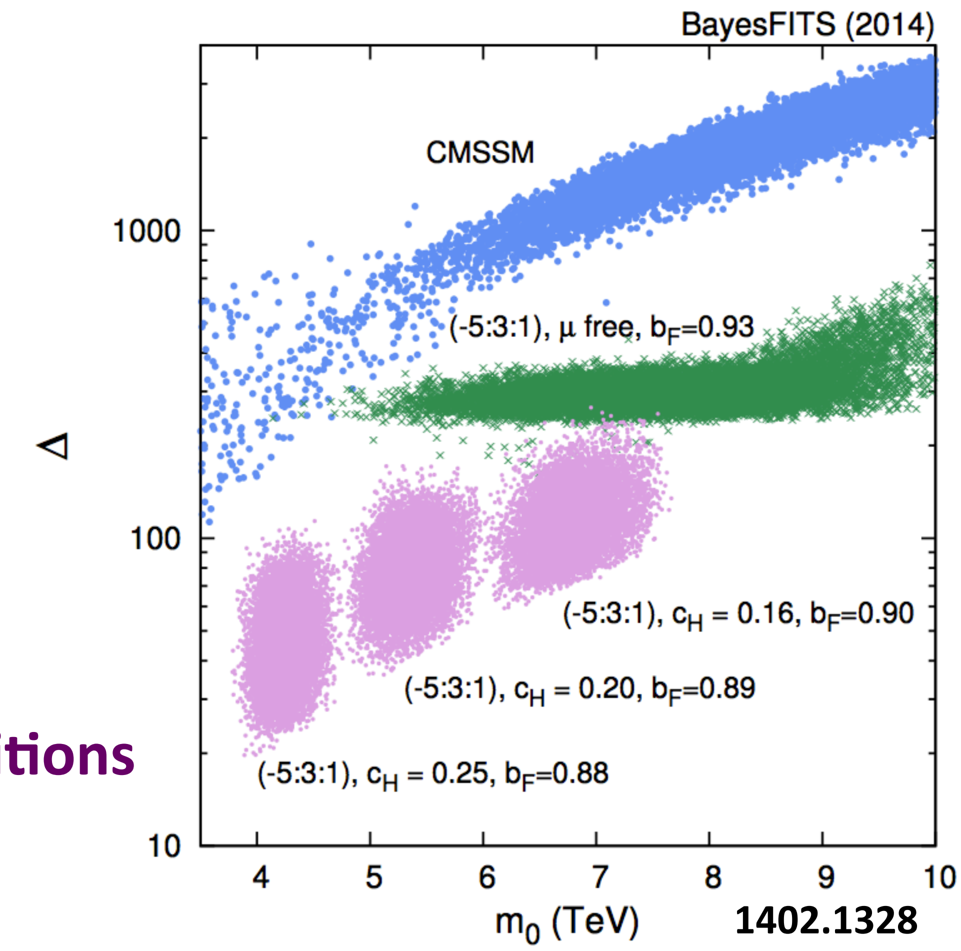
Reduce FT in ~1 TeV higgsino region

Altogether, for some BCs at unification scale

FT can be reduced as far down as ~20

Need to relax strict:

- **gauge coupling and**
- **mass unification conditions**
- **link mu to soft masses**



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All experimental constraints satisfied

…except $(g-2)_{mu}$