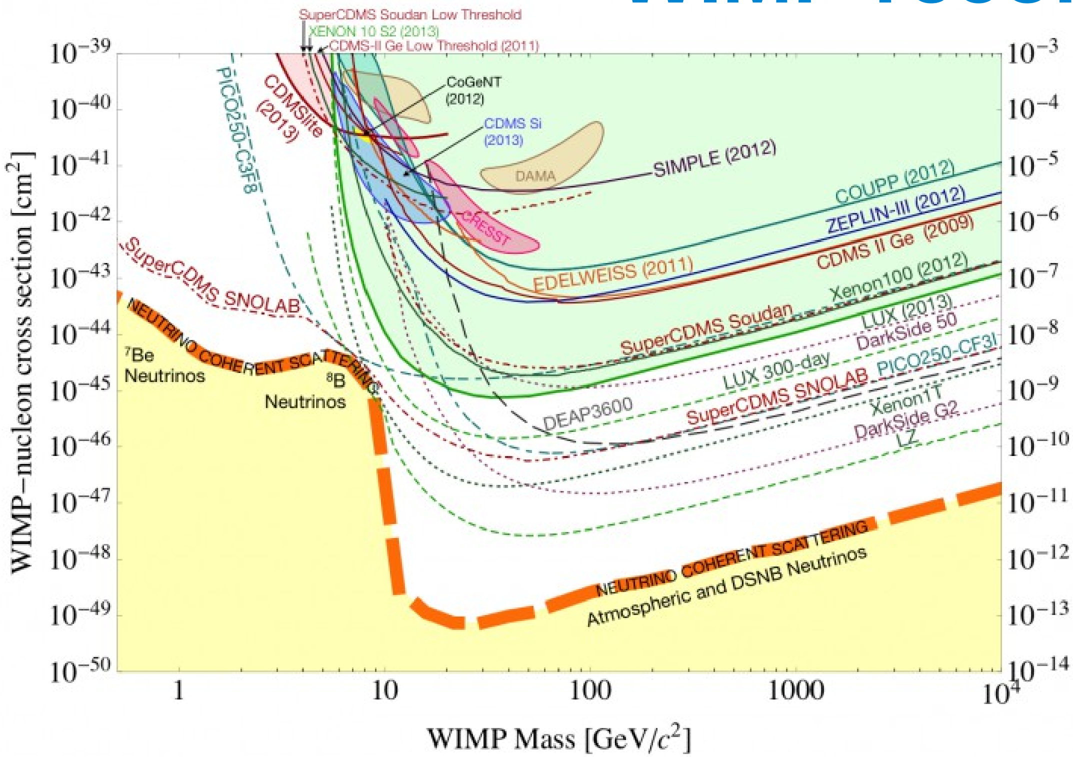
Reconstructing WIMP properties through signal measurements in direct detection, Fermi-LAT, and CTA

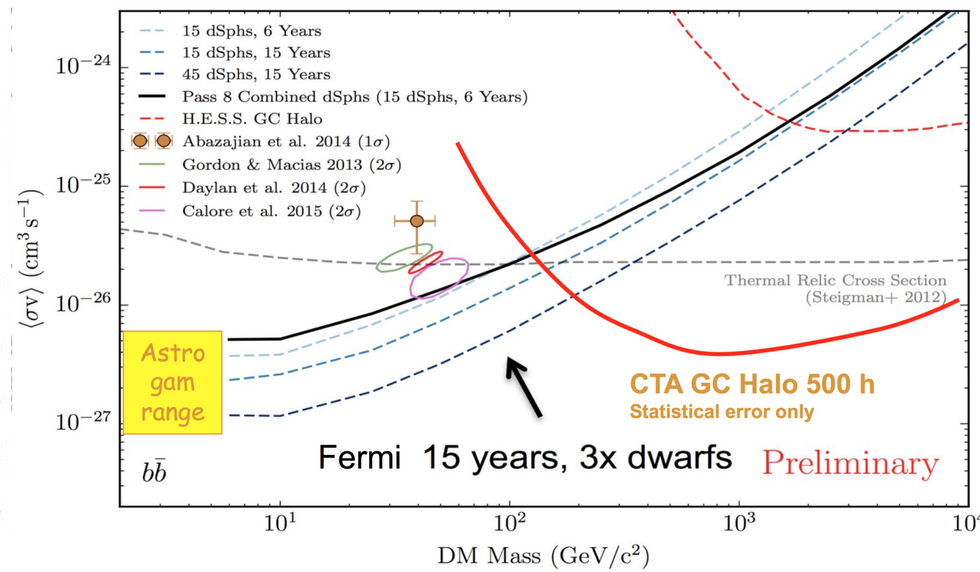
Enrico Maria Sessolo
National Centre for Nuclear Research (NCBJ)
Warsaw, Poland

RICAP 2016
Frascati, Italy
June 22, 2016

WIMP reconstruction



A. Morselli, Volcano Workshop 2016



If an unmistakeable detection is made in direct **and/or** indirect detection, how well can one reconstruct simple WIMP properties?

$$m_\chi,\ \ \sigma_p^{\rm SI},\ \ \sigma v,\ \ \text{final state}$$

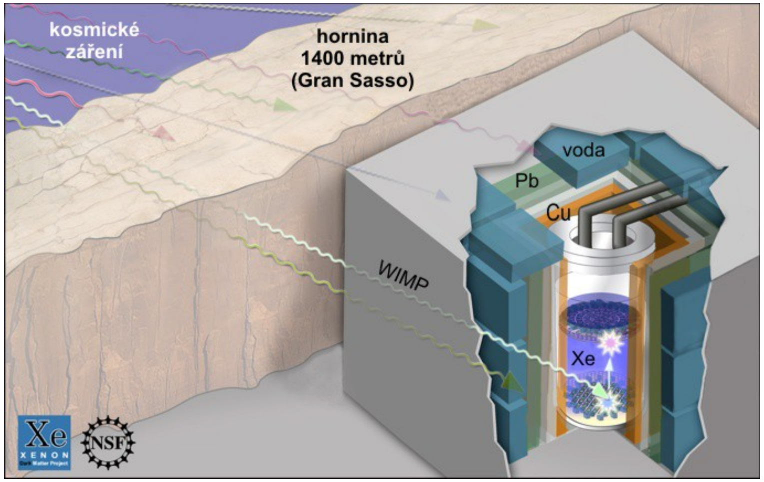
Roszkowski, EMS, Trojanowski, Williams, 1603.06519
A. Green, 0805.1704 (JCAP 2008)
Bernal, Goudelis, Mambrini, Munoz, 0804.1976 (JCAP 2009)
Arina, Bertone, Silverwood, 1304.5119 (PRD 2013)
Newstead, Jacques, Krauss, Dent, Ferrer, 1306.3244 (PRD 2013)...

Addressing...

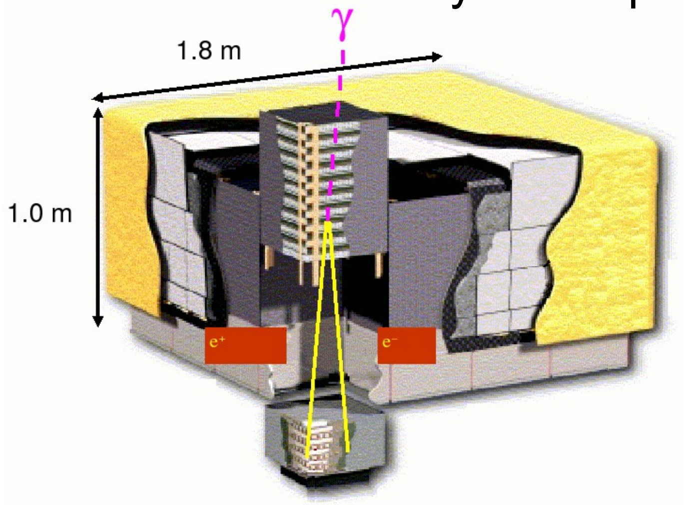
1. Complementarity of direct detection + gamma rays

(low WIMP mass values ~25-250 GeV)

XENON 1-T (Xe)
SCDMS-Snolab (Ge)
DarkSide-G2 (Ar)



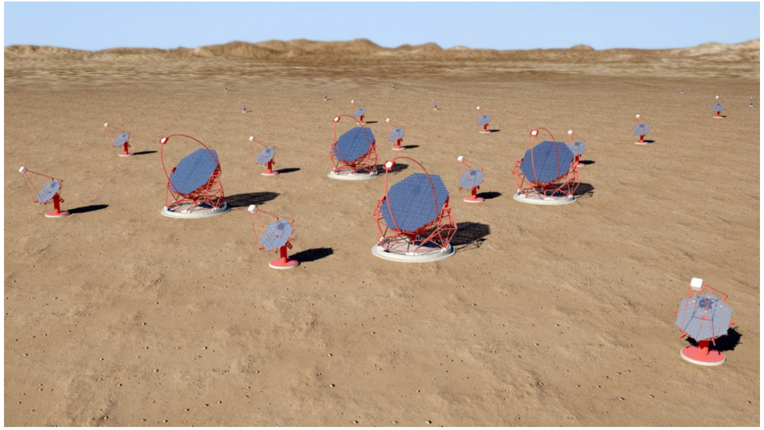
Fermi-LAT 15 yr 46 dSphs

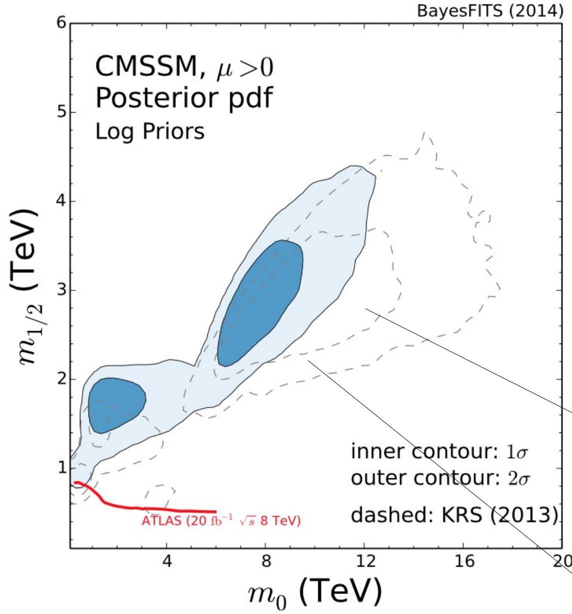


2. Reconstruction properties of CTA

(large WIMP mass ~ TeV)

CTA 500h

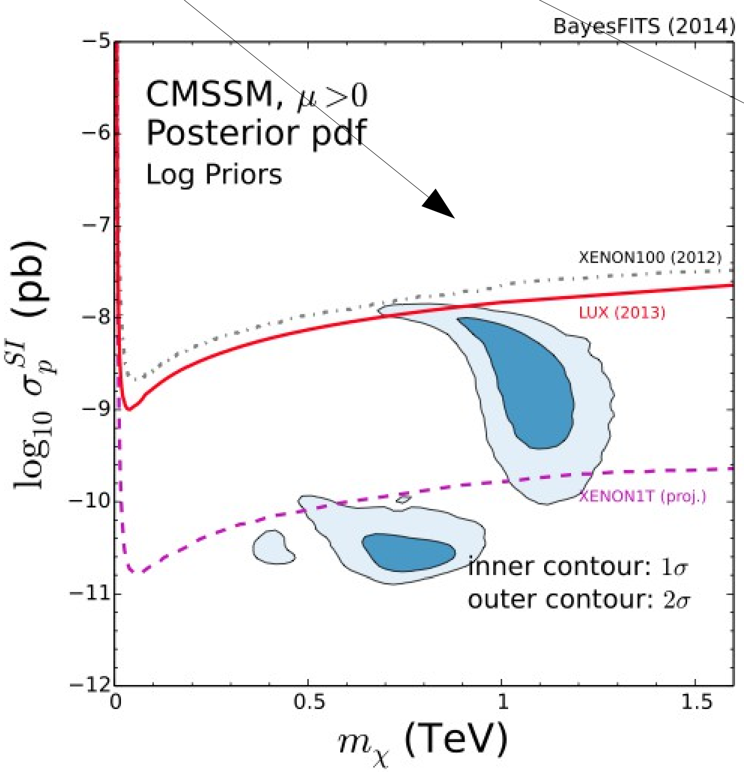


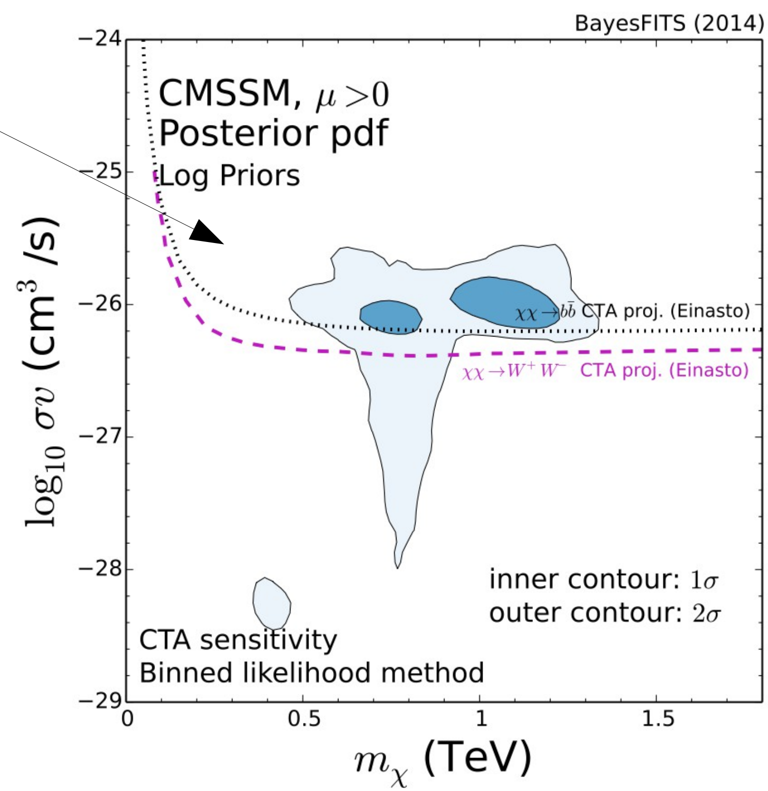


Motivation: dark matter signals (SUSY case)

Kowalska, Roszkowski, EMS, 1302.5956 (JHEP 2013)
Roszkowski, EMS, Williams, 1405.4289 (JHEP 2014)
Roszkowski, EMS, Williams, 1411.5214 (JHEP 2015)

Signals are expected soon in direct detection and gamma rays (CTA)



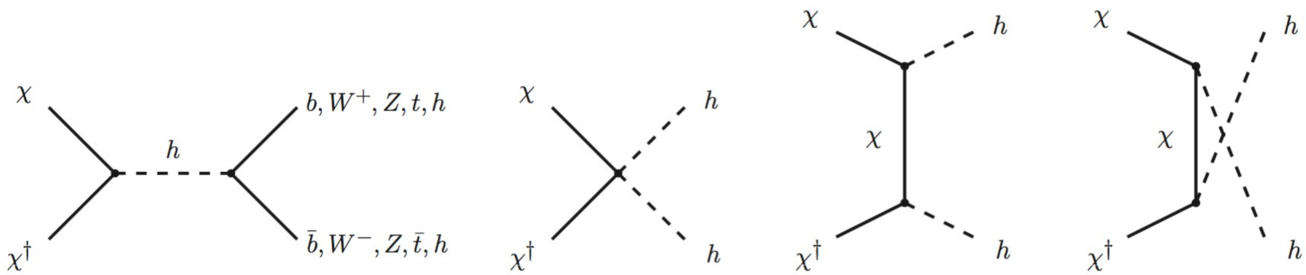


Motivation: WIMPs beyond SUSY

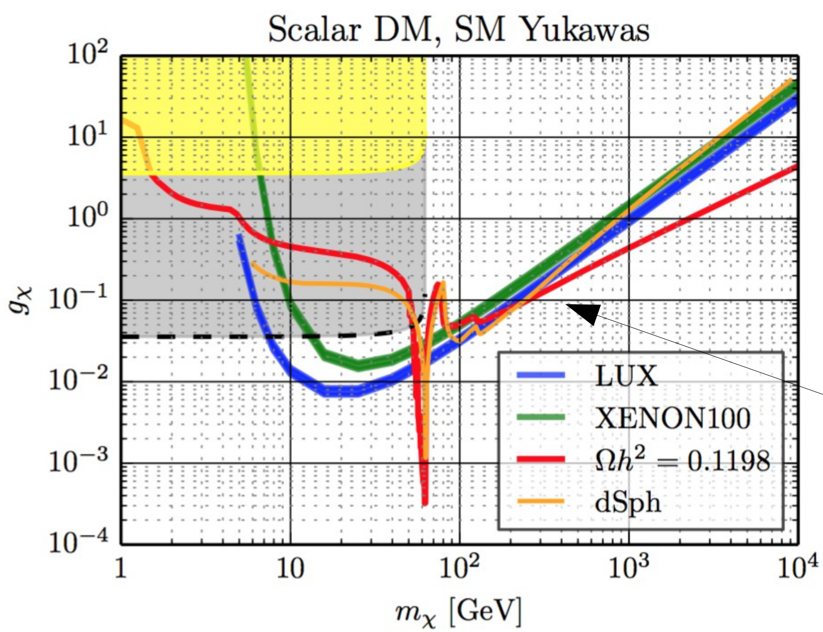
Signals in direct detection and/or gamma rays are not limited to SUSY models

Example: Higgs portal

$$\mathcal{L}_\chi = g_\chi \chi^\dagger \chi H^\dagger H$$



e.g. Bishara, Brod, Uttayarat, Zupan 1504.04022



Parameter space relic density:
<u>signals expected DD + dSphs!</u>

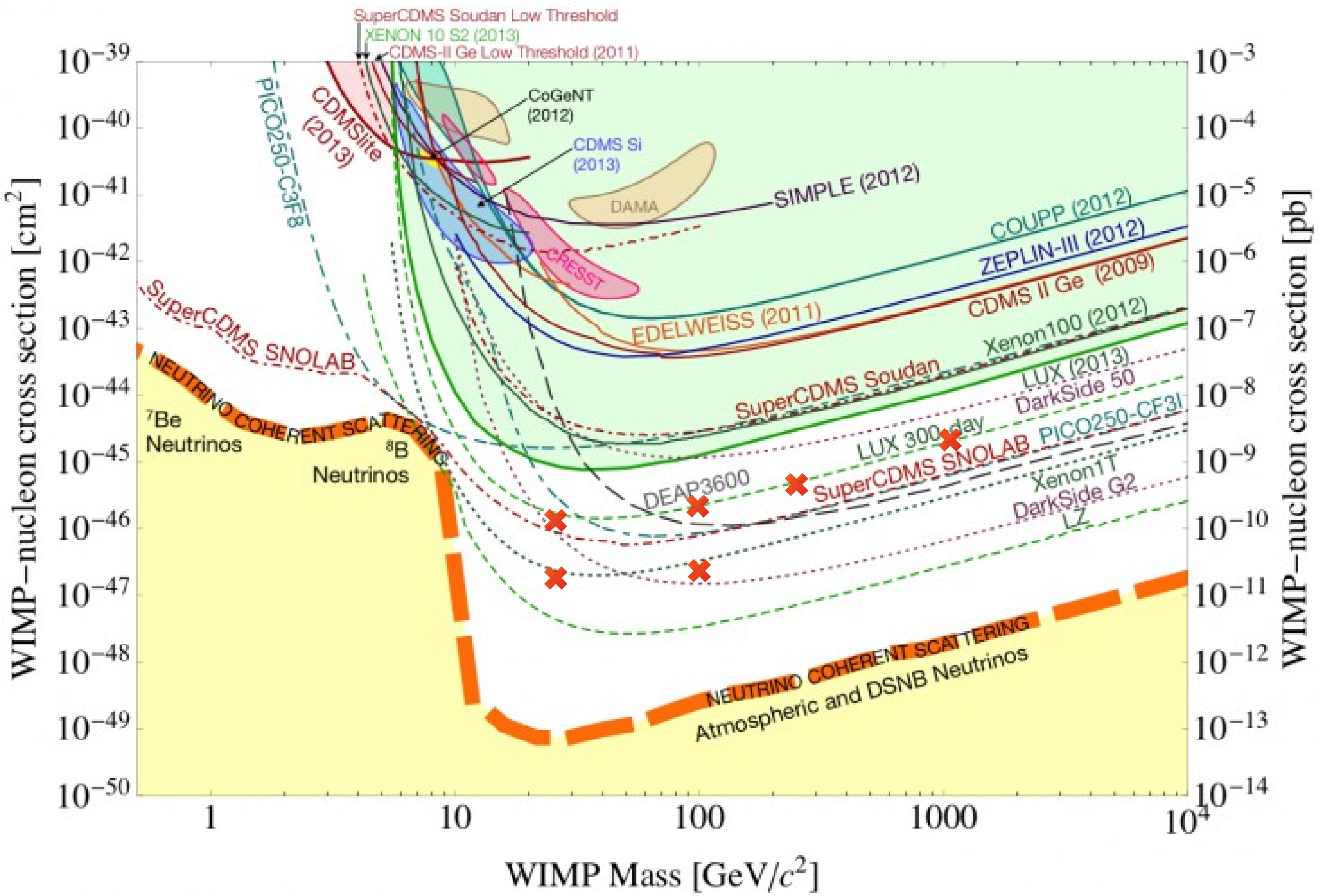
mχ ~ 100 – 500 GeV

Benchmark pts (mock signals)

	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) $\mu^+\mu^-$	

Consider different targets

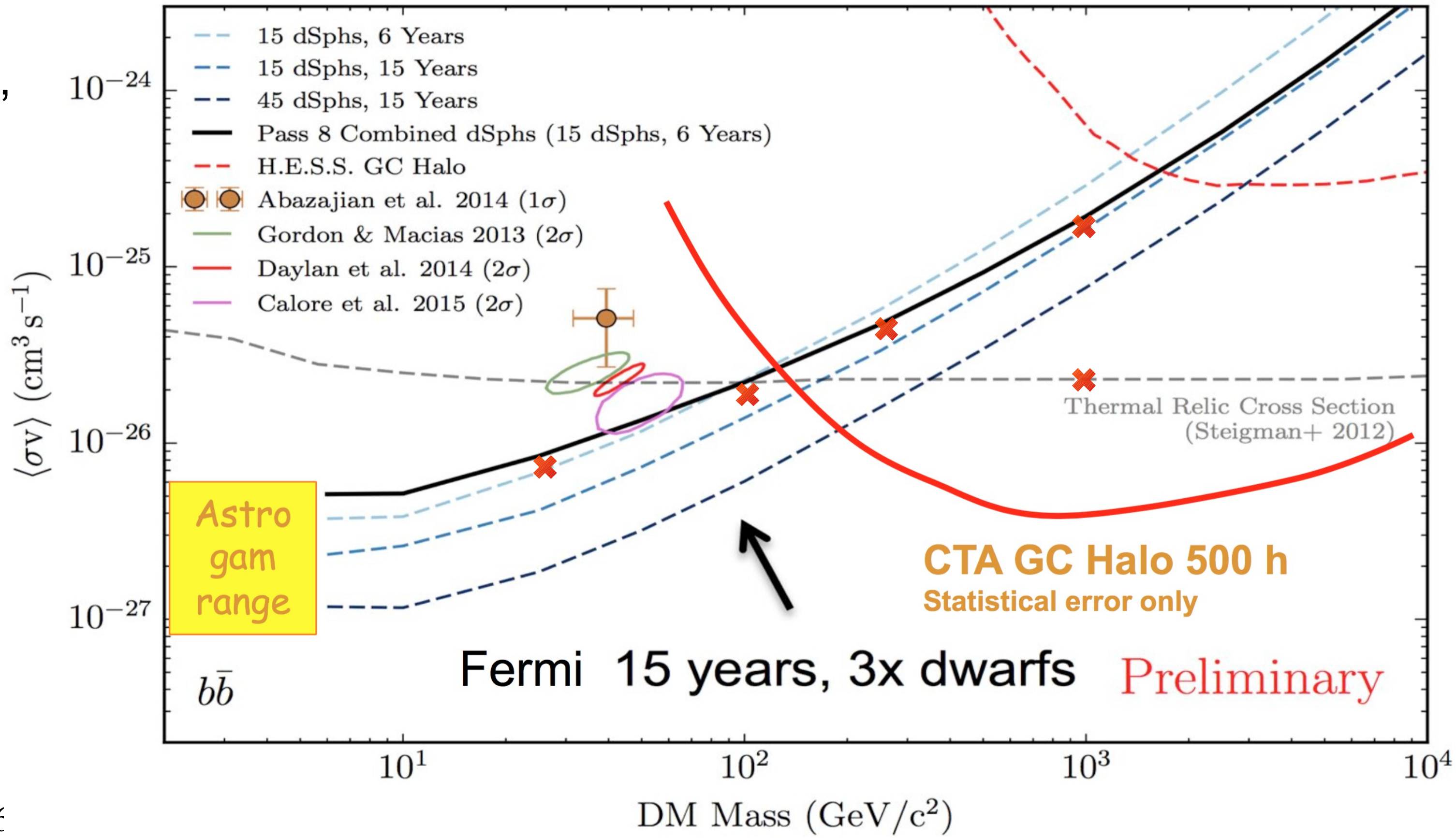
Xenon
Germanium
Argon



Benchmark pts (mock signals)

	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) $\mu^+\mu^-$	

Consider Fermi-LAT, CTA



Fit parameters through scan

Profile likelihood:

d **mock data**

m **scanned parameters** →

ξ observables

$$\mathcal{L}(m) \equiv p(d|\xi(m))$$

$$\delta\chi^2 \equiv -2\ln(\mathcal{L}/\mathcal{L}_{\max})$$

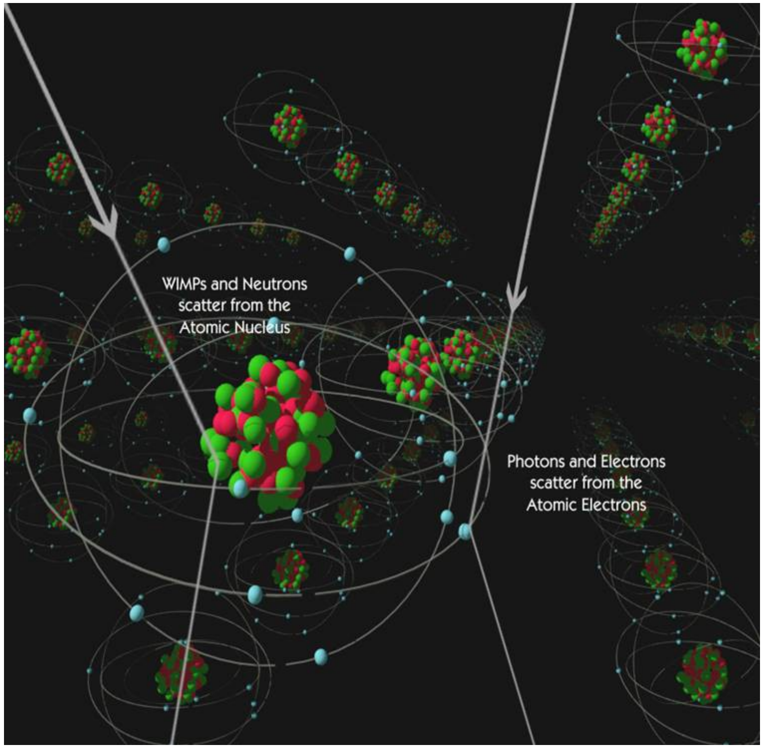
$$\mathcal{L}(\psi_{i=1,..,r}) = \max_{m\in\mathbb{R}^{n-r}} \mathcal{L}(m)$$

Symbol	Parameter	Scan range	Prior distribution
m_χ	WIMP mass	$10 - 10000\,\mathrm{GeV}$	log
σv	Annihilation cross section	$10^{-30} - 10^{-21}\ \mathrm{cm^3/s}$	log
σ_p^{SI}	Spin-independent cross section	$10^{-48} - 10^{-42}\ \mathrm{cm^2}$	log
	Hadronic benchmark points		
$f_{b\bar{b}}$	Branching ratio $b\bar{b}$ final state	$0 - 1^*$	See text
f_{WW}	Branching ratio WW final state	$0 - 1$	See text
f_{hh}	Branching ratio hh final state	$0 - 1$	See text
$f_{\tau\tau}$	Branching ratio $\tau\tau$ final state	$0 - 1$	See text
	Leptonic benchmark point –BP4(d)		
f_{lep}	Branching ratio leptons	$0 - 1^*$	See text
f_{had}	Branching ratio hadrons	$0 - 1$	See text
$f_{\tau\tau}$	Branching ratio $\tau\tau$ final state	$0 - 1$	See text
	Nuisance parameters		
v_0	Circular velocity	220 ± 20 km/s	Gaussian
v_{esc}	Escape velocity	544 ± 40 km/s	Gaussian
ρ_0	Local DM density	$0.3 \pm 0.1\,\mathrm{GeV/cm^3}$	Gaussian
γ_{NFW}	NFW slope parameter	1.20 ± 0.15	Gaussian

*The sum of the branching ratios is 1 and the prior is a modified Dirichlet distribution (see text).

Direct detection likelihood (signal and uncertainties)

See also A. Green, 0805.1704 (JCAP 2008)
Newstead, Jacques, Krauss, Dent, Ferrer, 1306.3244 (PRD 2013)
and more...



Measure the differential rate of struck nucleon:

$$\frac{dR}{dE_R} = \frac{\sigma_p^{\rm SI}}{2m_\chi\mu_{\chi p}^2} A^2 F_N^2(E_R)\mathcal{G}(v_{\rm min}, v_{\rm esc})$$

Uncertainties encoded in nuisance parameters:

$$\mathcal{G}(v_{\rm min}, v_{\rm esc}) = \rho_0 \int_{v_{\rm min}<|\mathbf{v}|<v_{\rm esc}} \frac{f(\mathbf{v}, v_0)}{|\mathbf{v}|} d^3v$$

(We don't consider isospin violation, velocity distribution and inelasticity uncertainties...)

Binned signal:

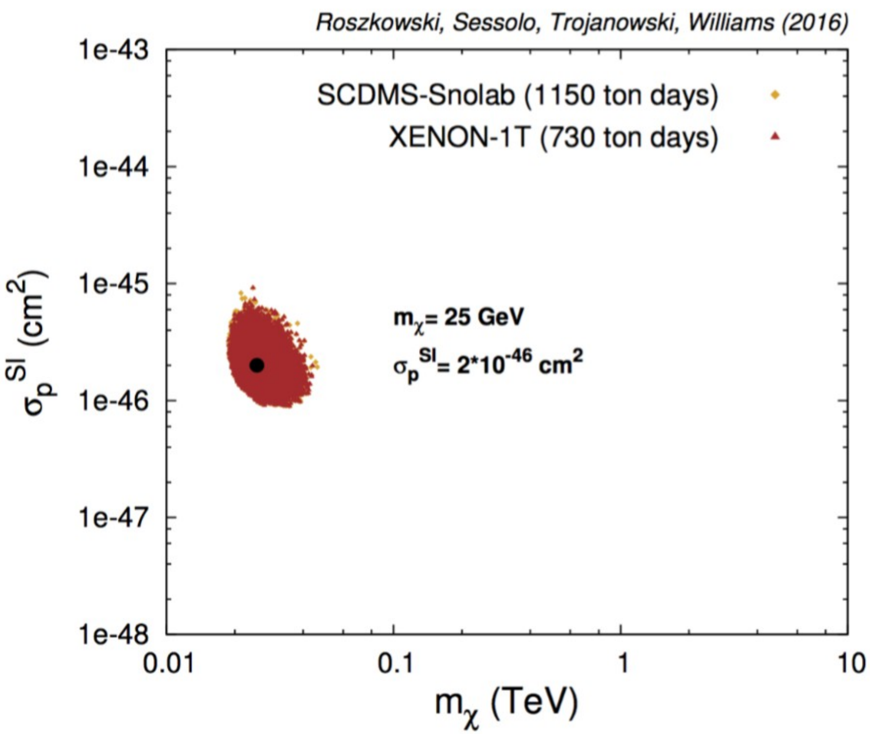
$$\mu_i = \text{exposure} \times \int_{E_{R,i-1}}^{E_{R,i}} \frac{dR}{dE_R} dE_R$$

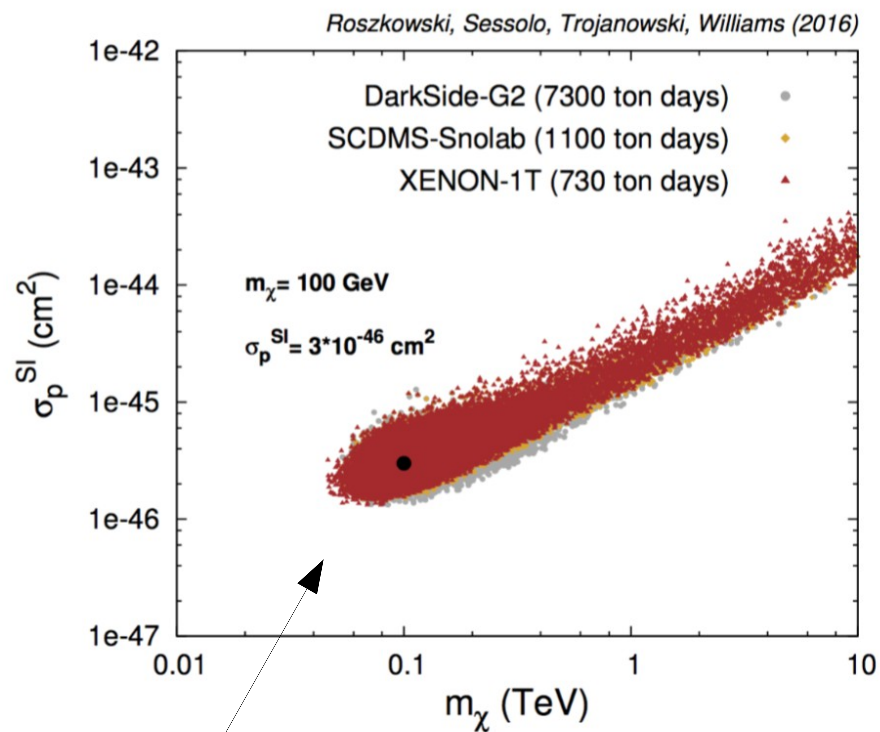
Likelihood function:

$$\mathcal{L}_{\rm DD} = \prod_{i=1}^{N_{\rm DD}} \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!}$$

Direct detection reconstruction (Xe, Ge, Ar)

95% C.L. regions:

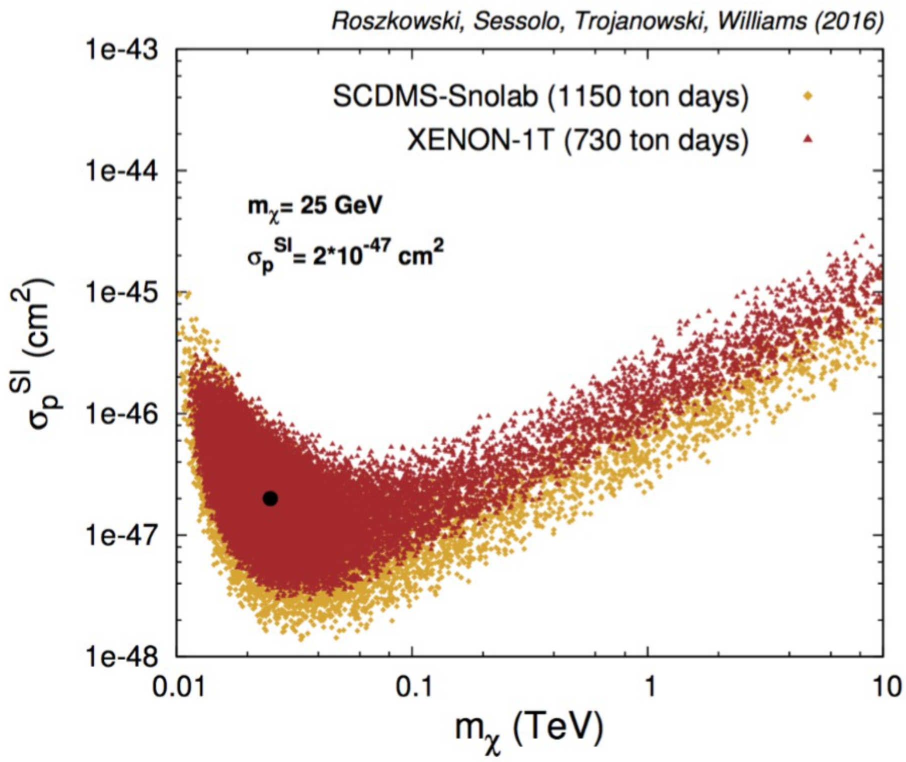


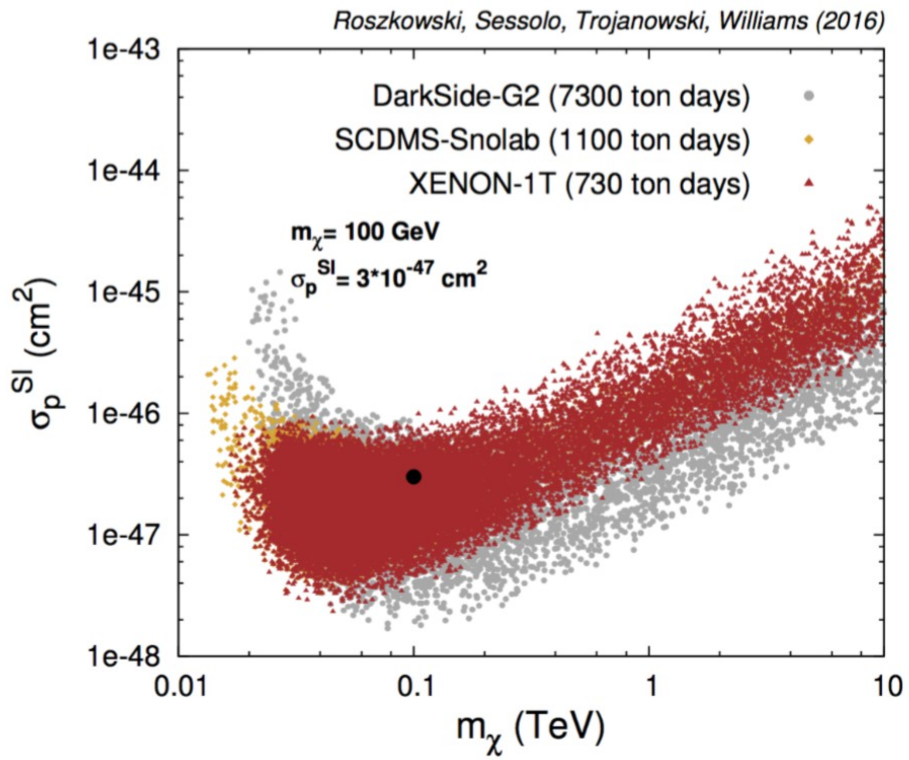


- Mχ = 25 GeV good!
- The spectrum of nuclear recoils is insensitive to the WIMP mass when this is greater than that of the target nucleus.
- Larger masses are up the degeneracy band (fig looks the same)

Direct detection reconstruction (Xe, Ge, Ar)

95% C.L. regions:





- Reconstruction lost if σ_{SI} down by 1 order of magnitude
- Exposure plays fundamental role (negligible BG)

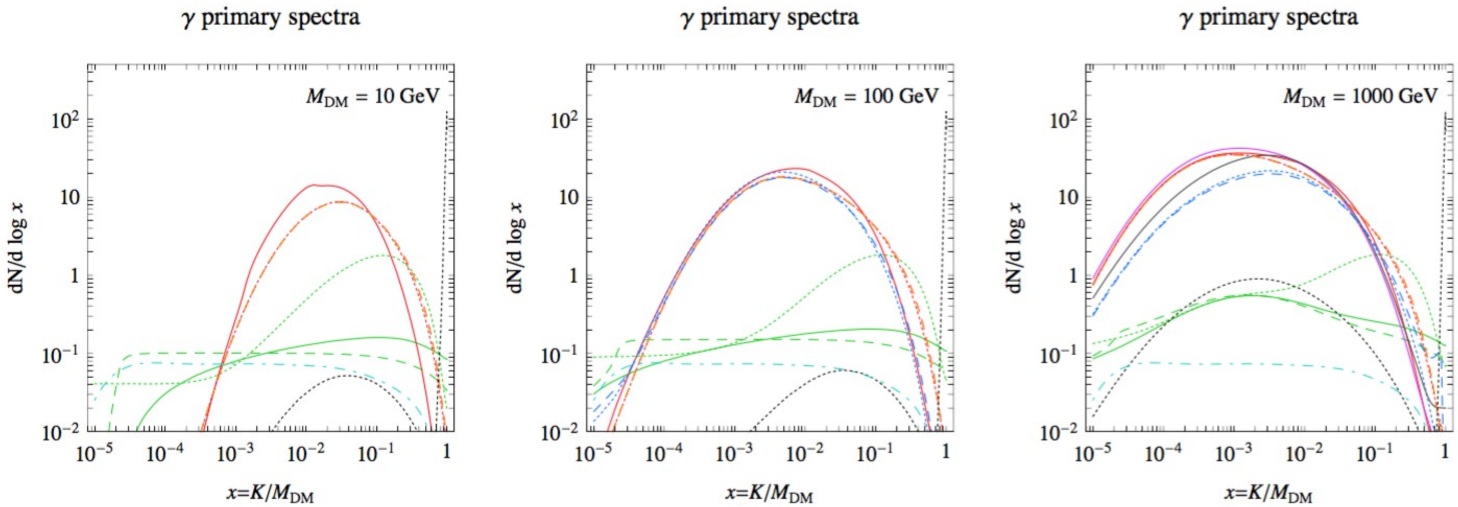
Gamma-ray dSphs likelihood

Measure the γ-ray flux:

$$\left(\frac{d\Phi}{dE}\right)_{\rm dSphs} = \frac{\sigma v}{8\pi m_\chi^2} J \frac{dN_\gamma}{dE}$$

Flux uncertainties:

- *J*-factor (take Fermi-LAT 1310.0828)
- Annihilation final state



$$\mathcal{L}_{\rm dSphs} = \prod_{j=1}^{46} \left\{ \int \frac{dJ_j}{\log(10)\bar{J}_j\sqrt{2\pi}\sigma_j} \exp\left[-\frac{(\log_{10} J_j - \log_{10}\bar{J}_j)^2}{2\sigma_j^2}\right] \times \right.$$

Energy bins →

$$\left. \prod_{i=1}^{N_{\rm Fermi}} \frac{1}{\sqrt{2\pi}\bar{\sigma}_{ij}} \exp\left[-\frac{\left(\frac{d\Phi_j}{dE_i} - \frac{d\bar{\Phi}_j}{dE_i}\right)^2}{2\bar{\sigma}_{ij}^2}\right] \right\}$$

Gamma-ray GC signal

Measure the γ-ray flux:

$$\left(\frac{d\Phi}{dE}\right)_{\rm GC} = \frac{\sigma v}{8\pi m_\chi^2}\left(J_{\Delta\Omega}\frac{dN_\gamma}{dE} + \frac{1}{E^2}\int_{m_e}^{m_\chi} dE_s \bar{I}_{{\rm IC},\Delta\Omega}(E,E_s)\frac{dN_{e^\pm}}{dE_s}\right)$$

Inverse Compton
Modifies prompt spectrum

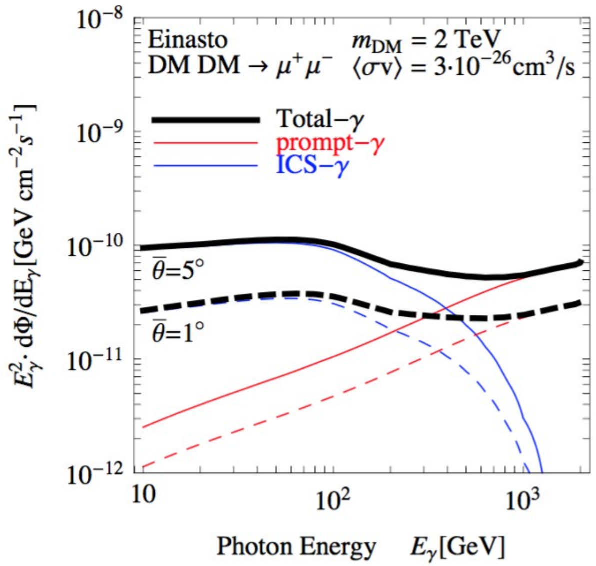
Uncertainties halo profile:

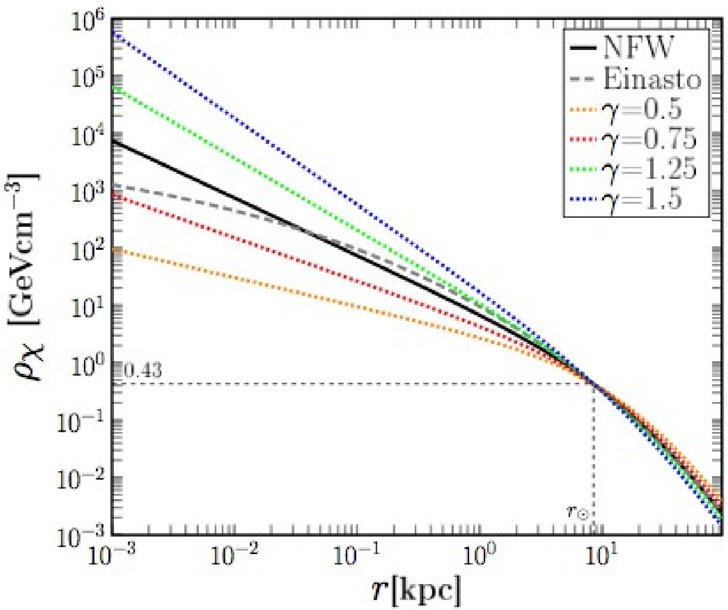
$$J_{\Delta\Omega} = \int_{\Delta\Omega}\int_{\rm l.o.s.} \rho^2[r(\theta)]dr(\theta)d\Omega$$

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

Parametrize by $\gamma_{\rm NFW}$, ρ_0

(e.g. Lefranc *et al.* 1502.05064)





γ-ray background uncertainties GC

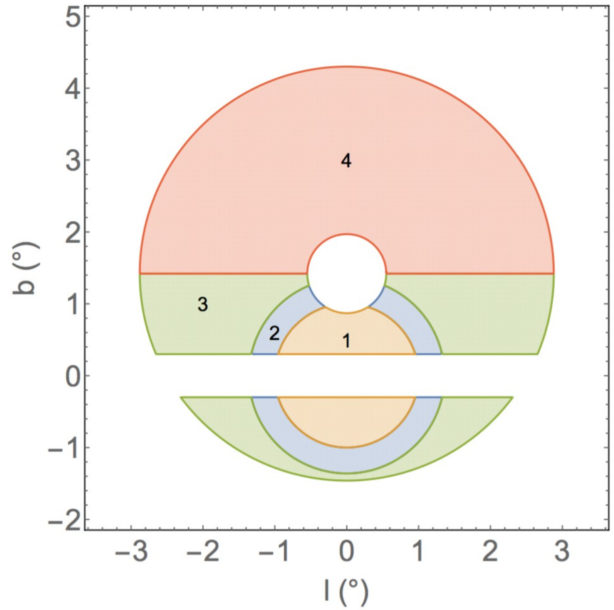
In each energy bin *i* the observed signal has 3 indep. components:

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

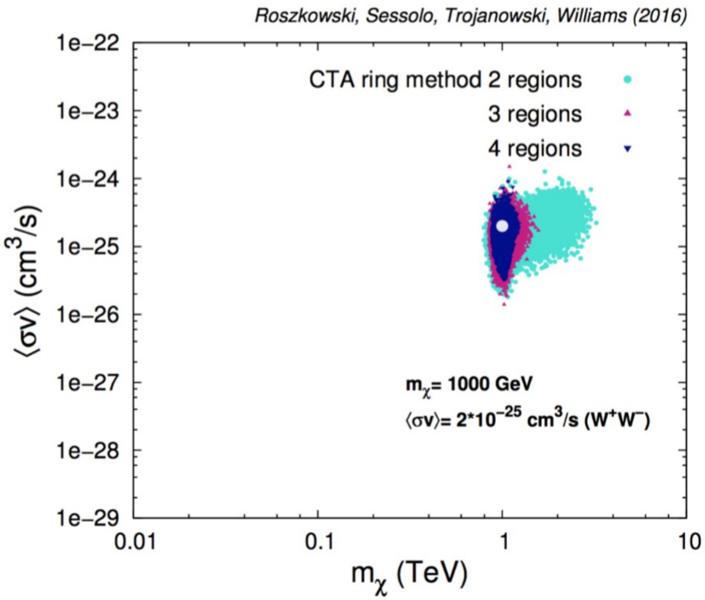
Solution: Fit DM signal and bg independently in different regions of the sky:

$$\mathcal{L}_{\rm CTA} = \prod_{i=1}^{N_{\rm CTA}} \left\{ \int dR_i^{\rm CR} e^{-\frac{\left(1-R_i^{\rm CR}\right)^2}{2\sigma_{\rm CR}^2}} \int dR_i^{\rm GDE} e^{-\frac{\left(1-R_i^{\rm GDE}\right)^2}{2\sigma_{\rm GDE}^2}} \left[\prod_{j=1}^{4} \frac{\mu_{ij}\left(R_i^{\rm CR}, R_i^{\rm GDE}\right)^{n_{ij}}}{n_{ij}!} e^{-\mu_{ij}\left(R_i^{\rm CR}, R_i^{\rm GDE}\right)} \right] \right\}$$

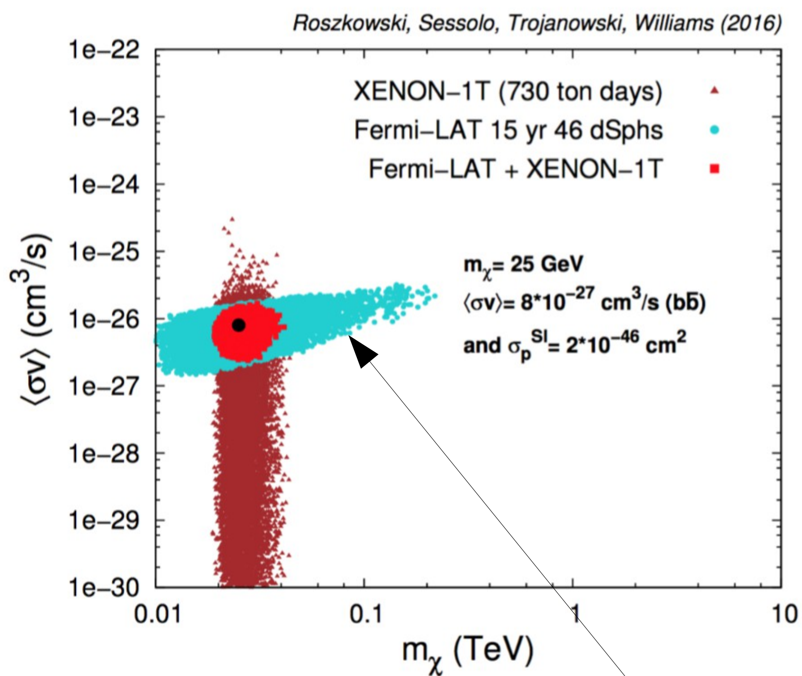
Example: split sky in 4 regions:

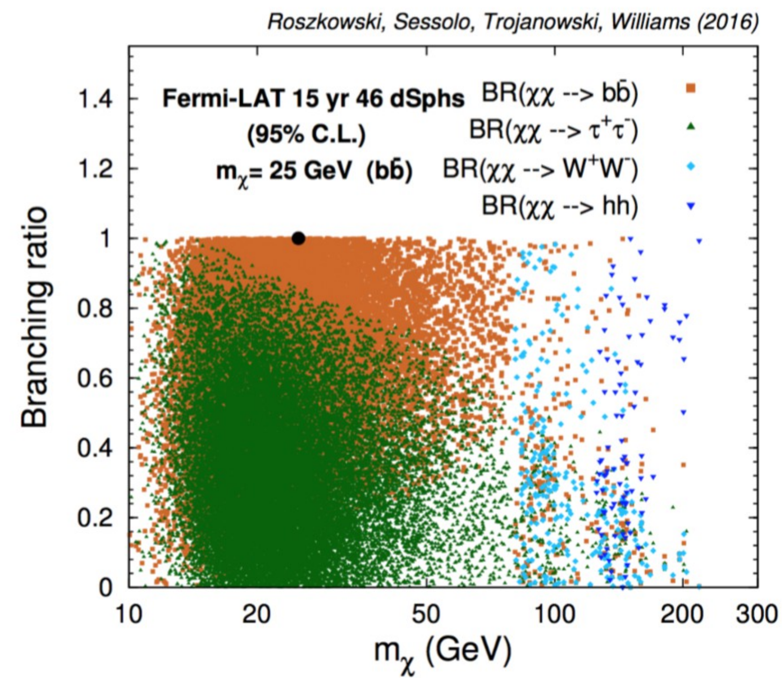


"3" does the trick:



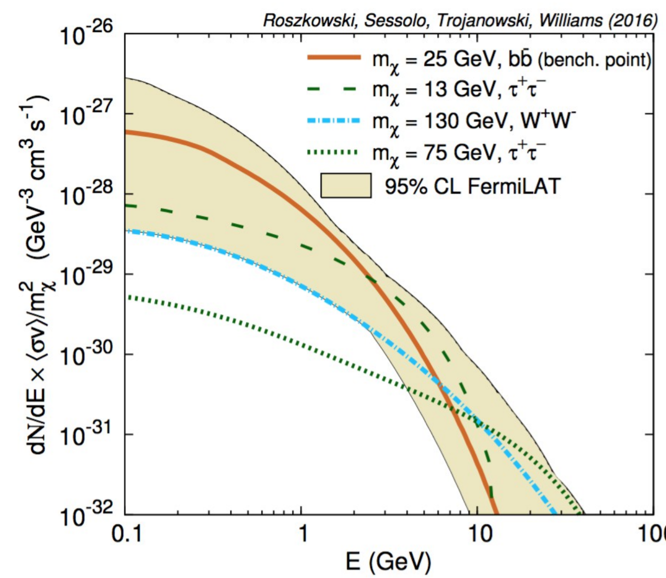
Fermi-LAT + Xenon-1T (mχ = 25 GeV)



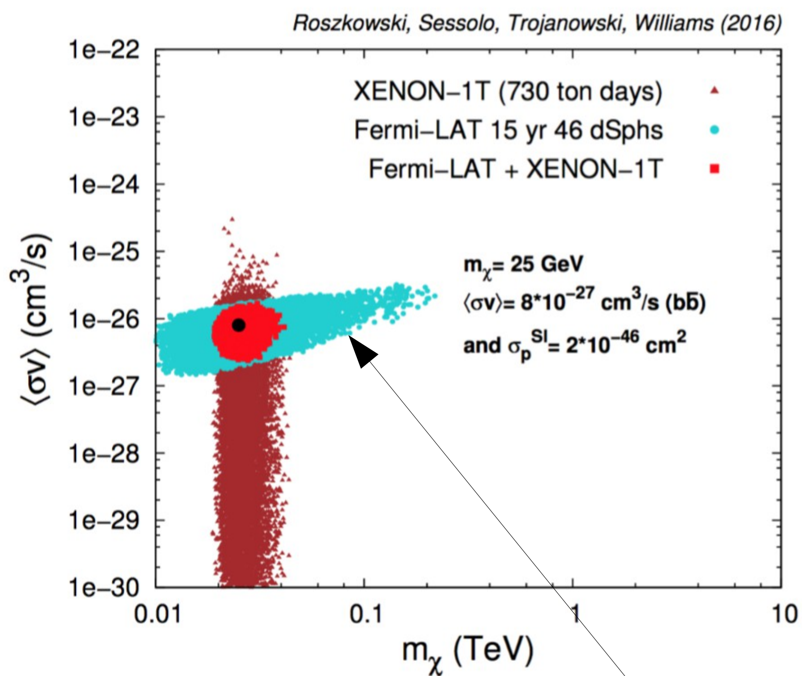


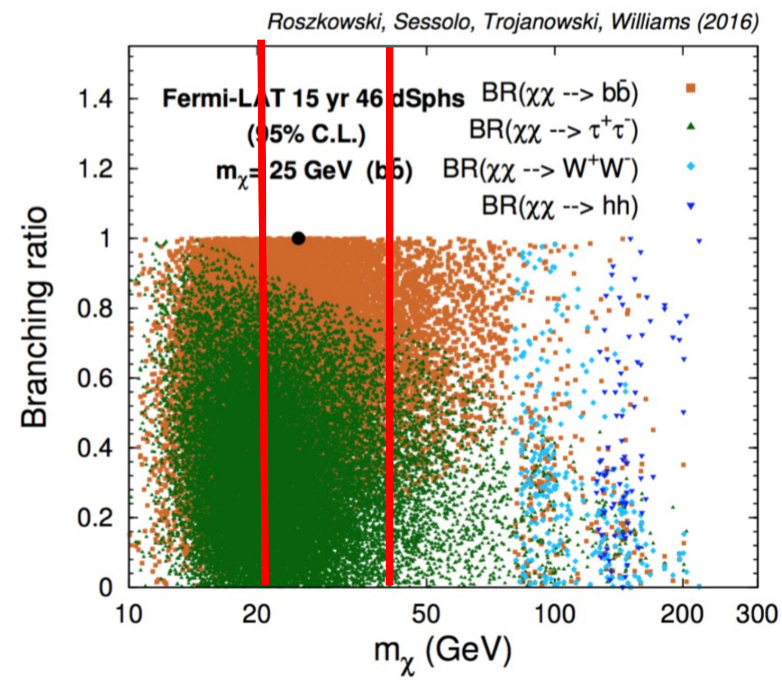
Fermi-LAT poor mass reconstruction

Info from both experiments improves mass and final state reconstruction



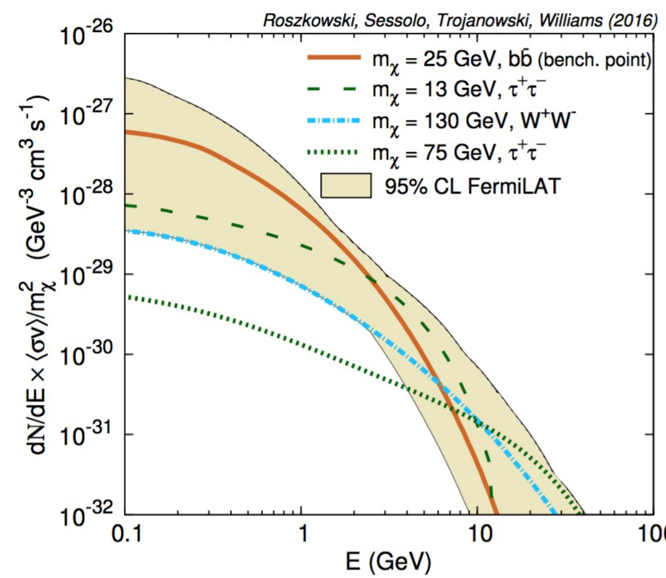
Fermi-LAT + Xenon-1T (mχ = 25 GeV)



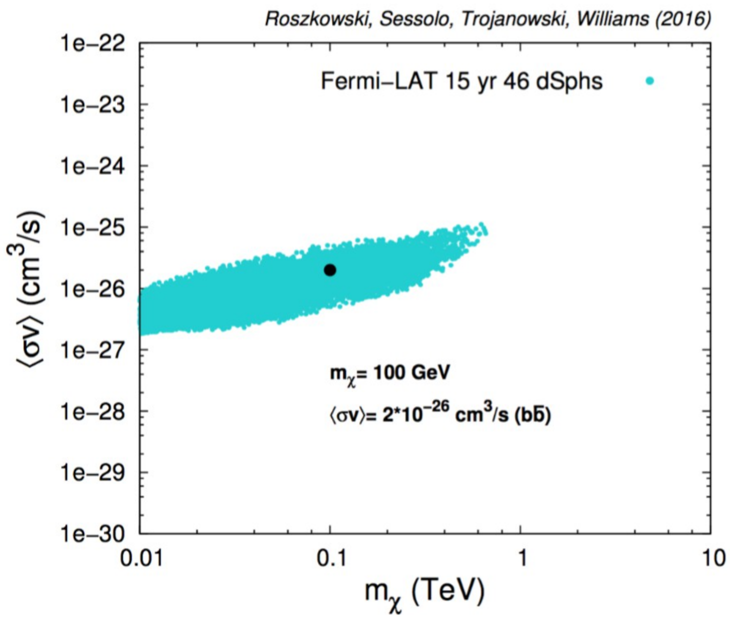


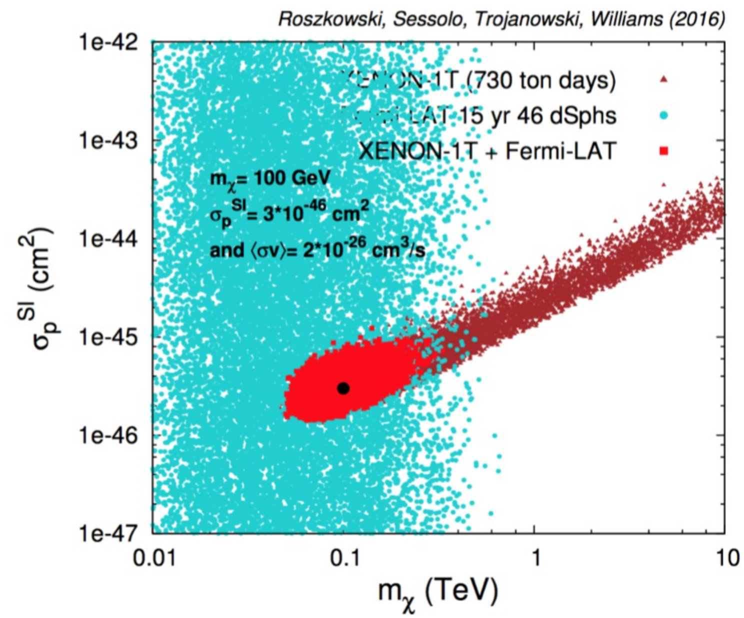
Fermi-LAT poor mass reconstruction

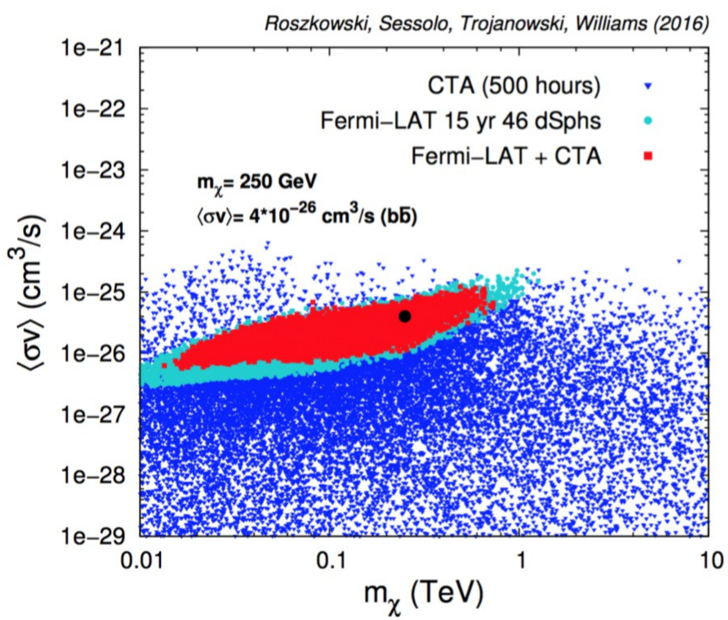
Info from both experiments improves mass and final state reconstruction

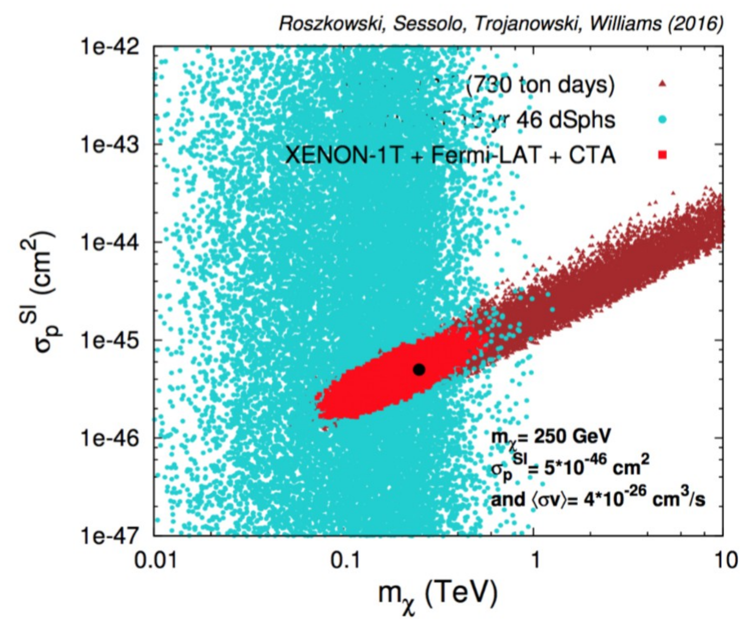


More complementarity (mχ = 100-250 GeV)

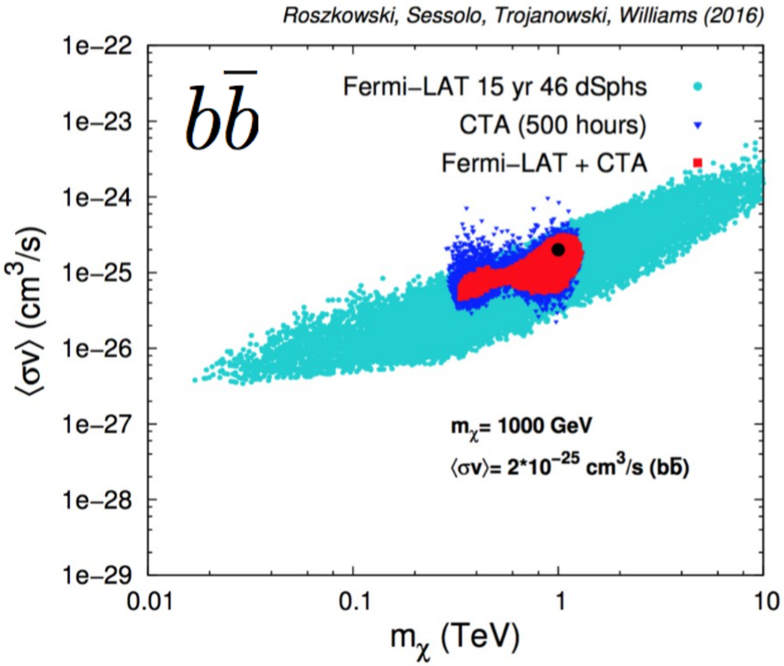


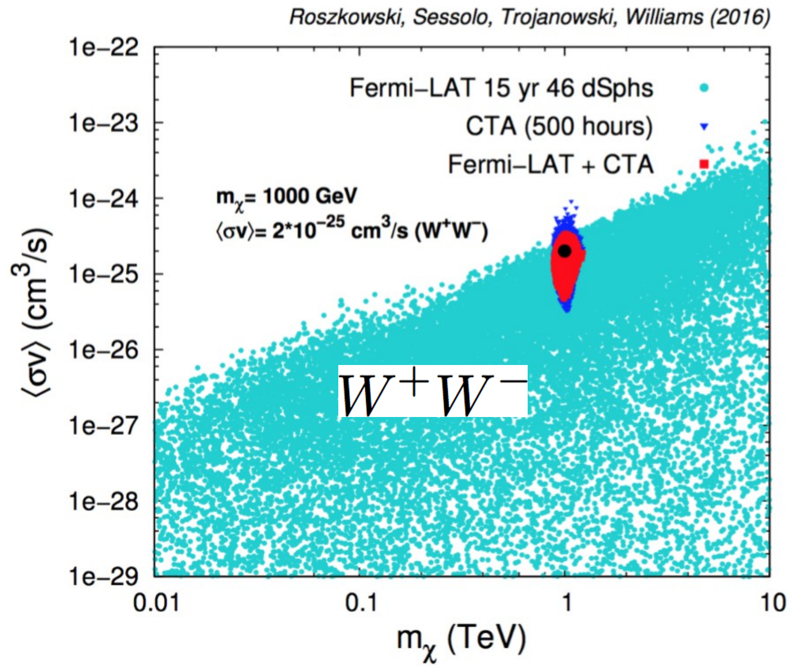




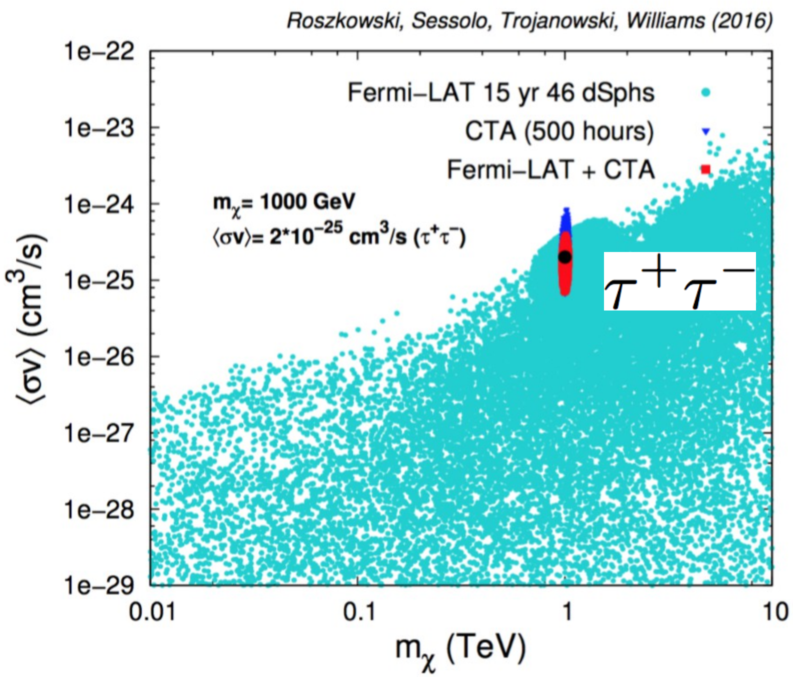


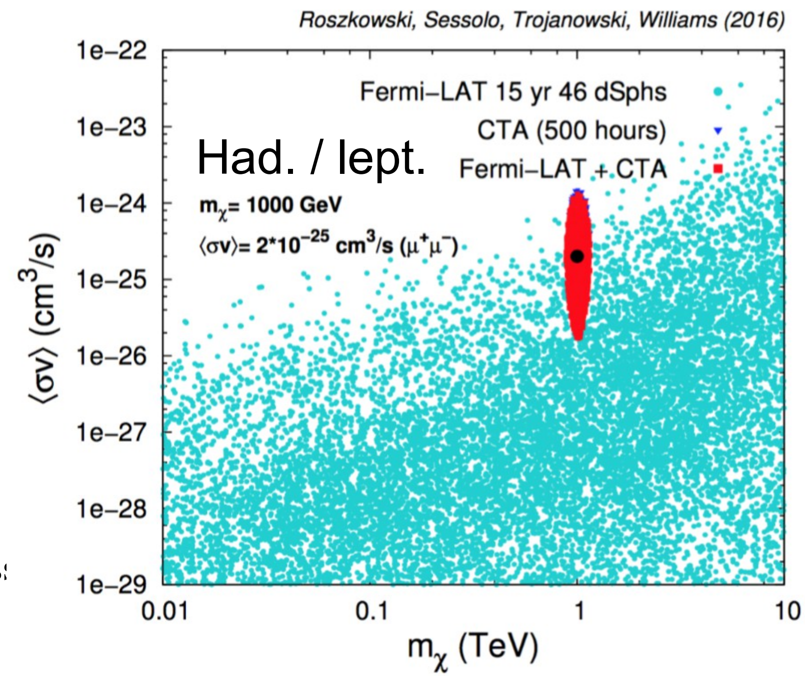
Fermi-LAT + CTA (mχ = 1000 GeV)



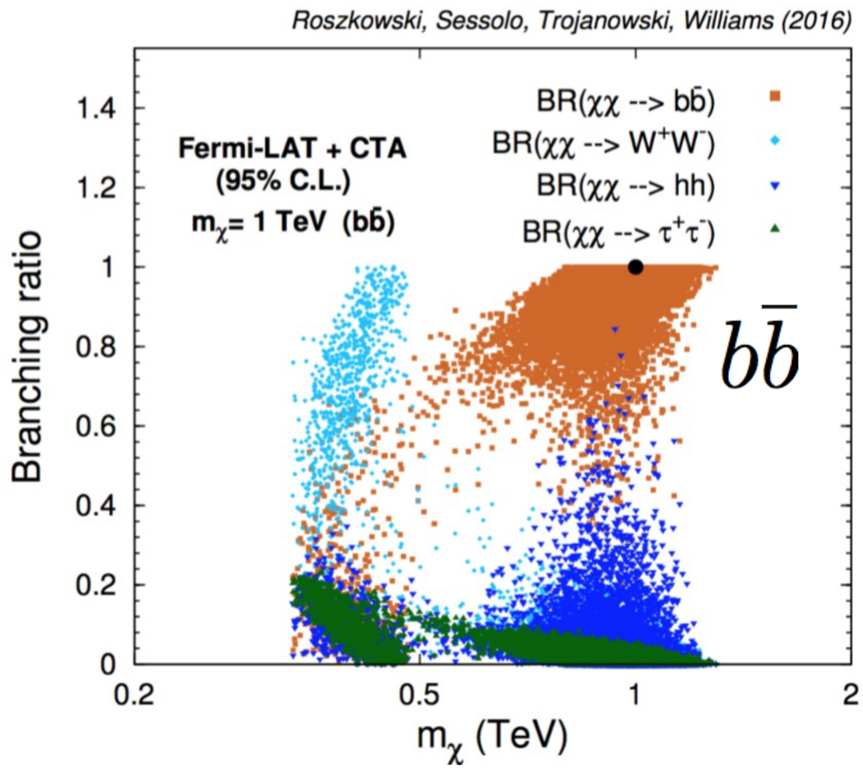


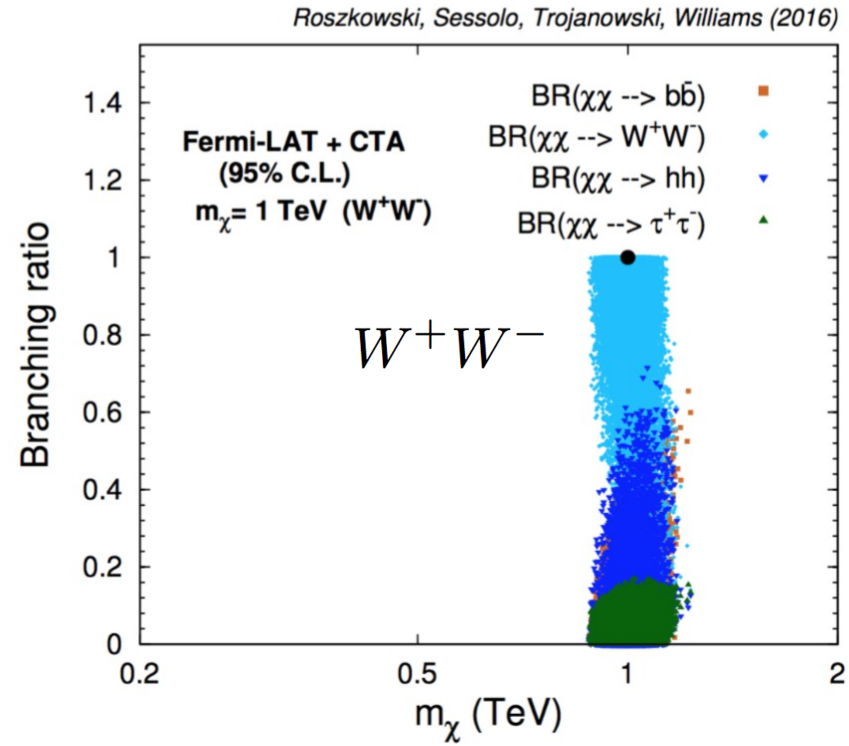
Quality of reconstruction strongly depends on final state of real signal...





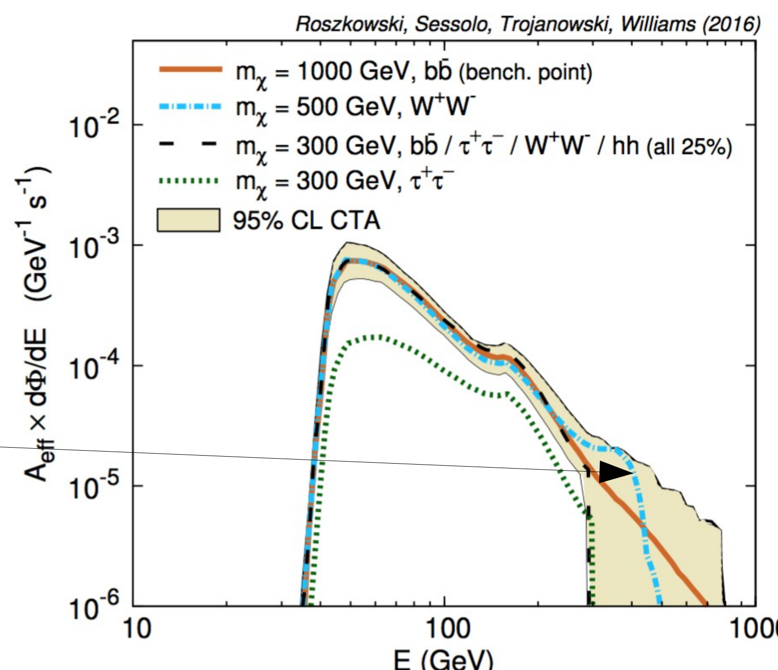
Final state reconstruction



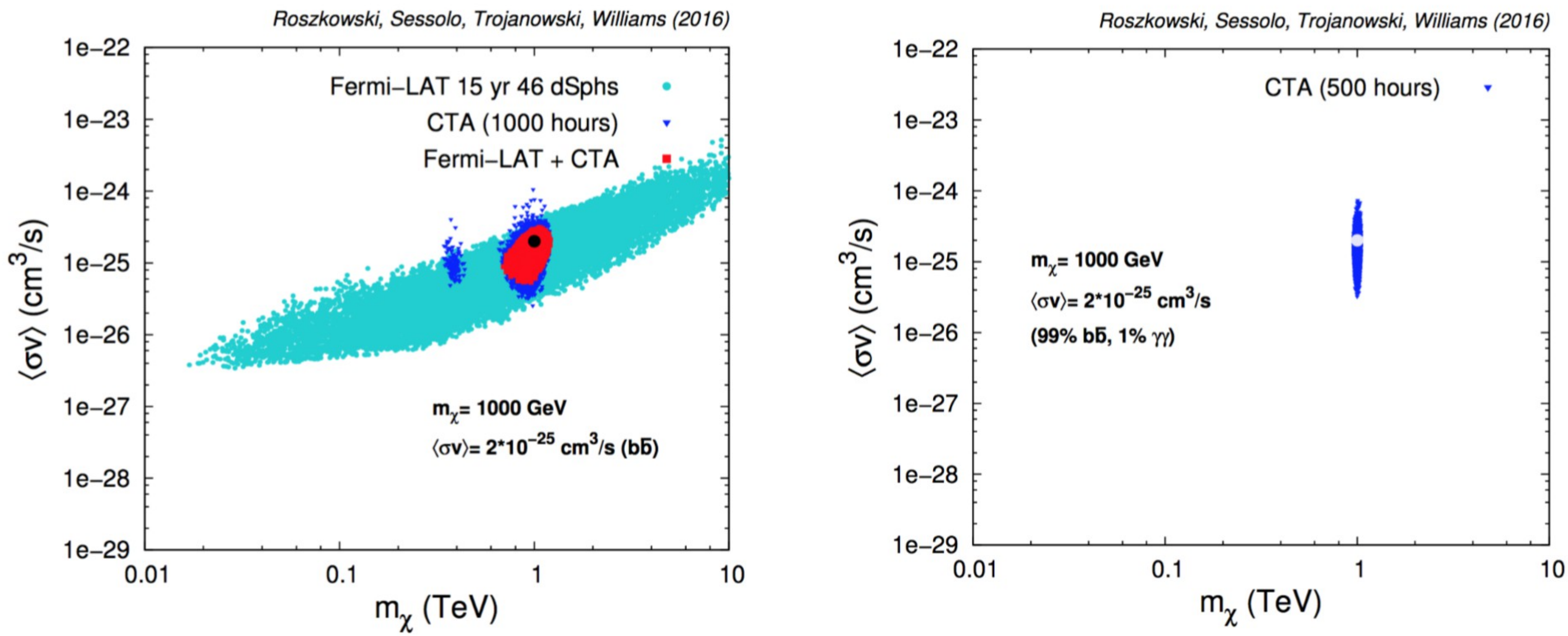


Some final states present specific features that make them very recognizable...

$$W^\pm \to W^\pm\gamma$$



How to improve $b\bar{b}$ CTA reconstruction?



> exposure...

1% γγ line...

… Significant improvement in mass reconstruction!

BACKUP

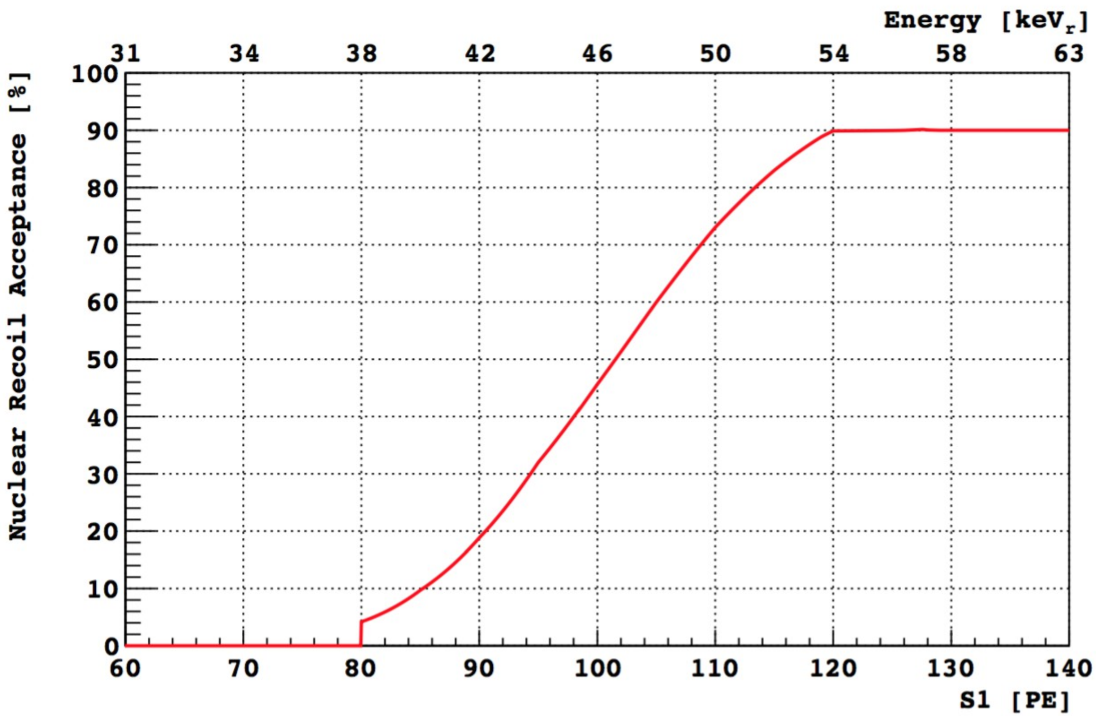
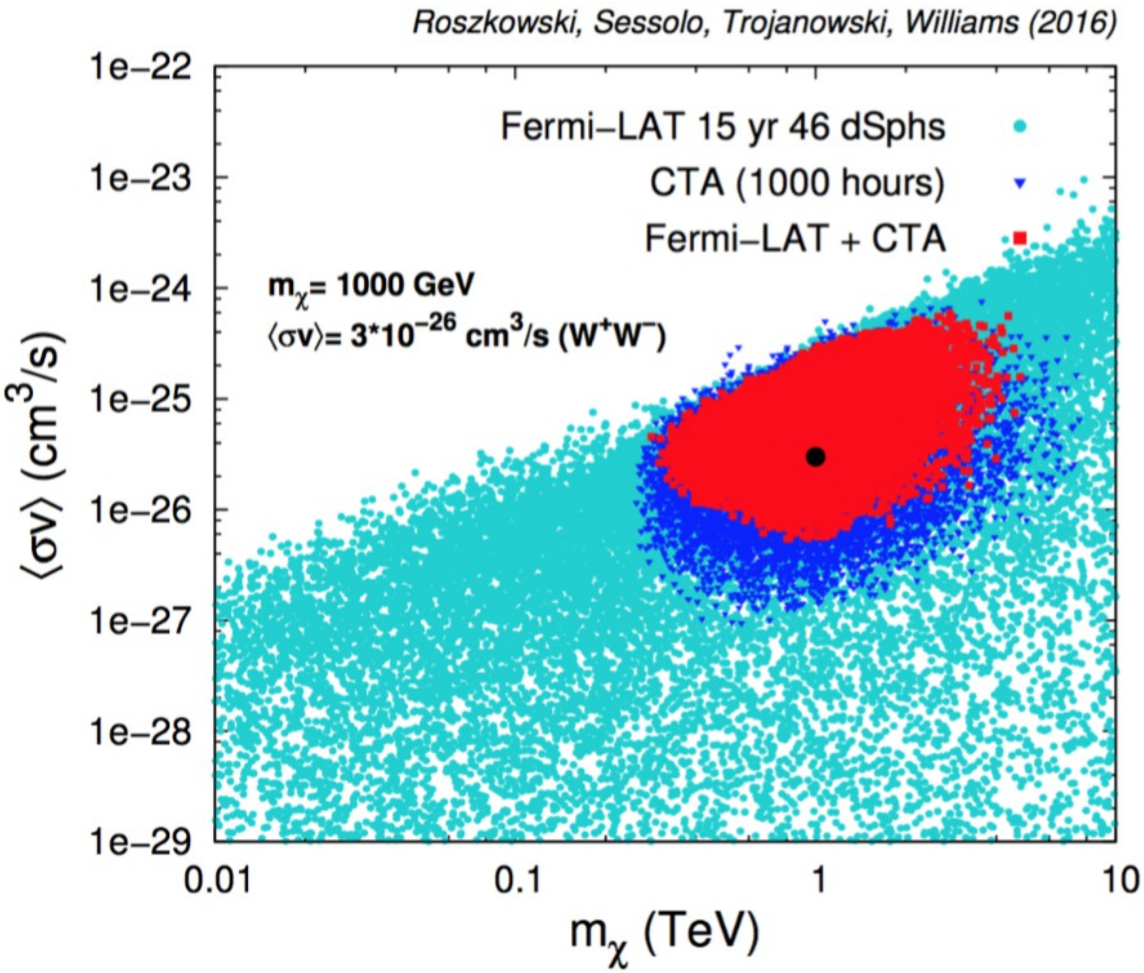


Figure 6: Nuclear recoil acceptance of the dark matter search box. Acceptance is fixed at 90% between 120 and 460 PE (54 and 206 keV$_r$).


Roszkowski, Sessolo, Trojanowski, Williams (2016)
Fermi–LAT 15 yr 46 dSphs
CTA (1000 hours)
Fermi–LAT + CTA
m_χ= 1000 GeV
$\langle\sigma v\rangle$= 3*10^{-26} cm^3/s (W^+W^-)
$\langle\sigma v\rangle$ (cm^3/s)
1e−22
1e−23
1e−24
1e−25
1e−26
1e−27
1e−28
1e−29
0.01
0.1
1
10
m_χ (TeV)