UNIVERSITEIT VAN AMSTERDAM

Complementarity between direct detection and neutrino signals

In collaboration with
G. Bertone and H. Silverwood
arXiv:1304.5119

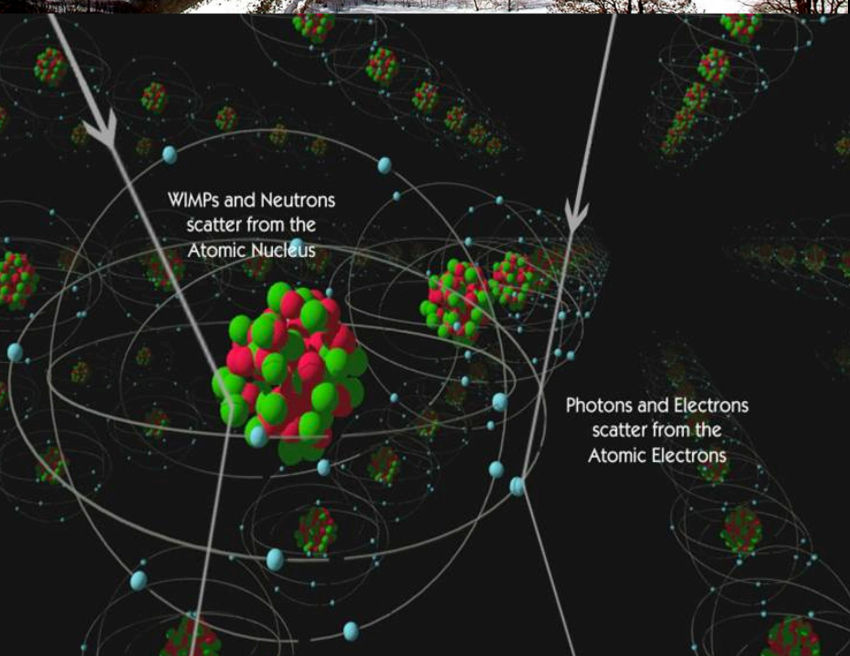
Bolshoi simulation, NASA

KITP, Dark Matter workshop, UCSB

May 28th 2013

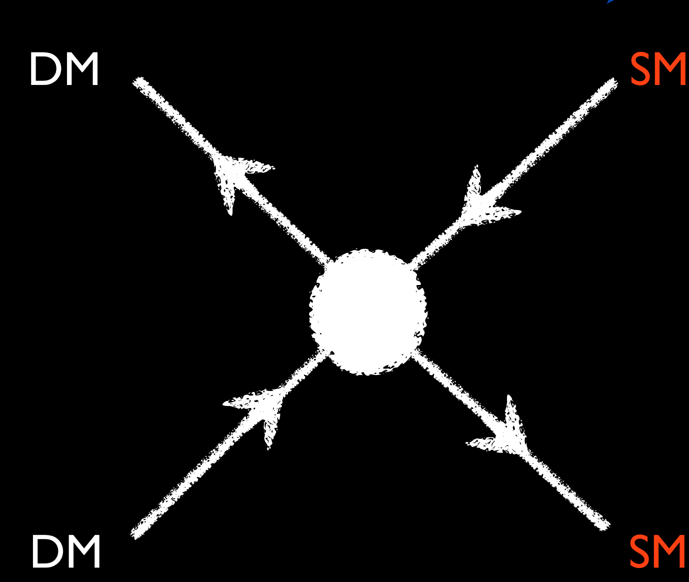
Chiara Arina

Dark Matter (WIMPs) detection



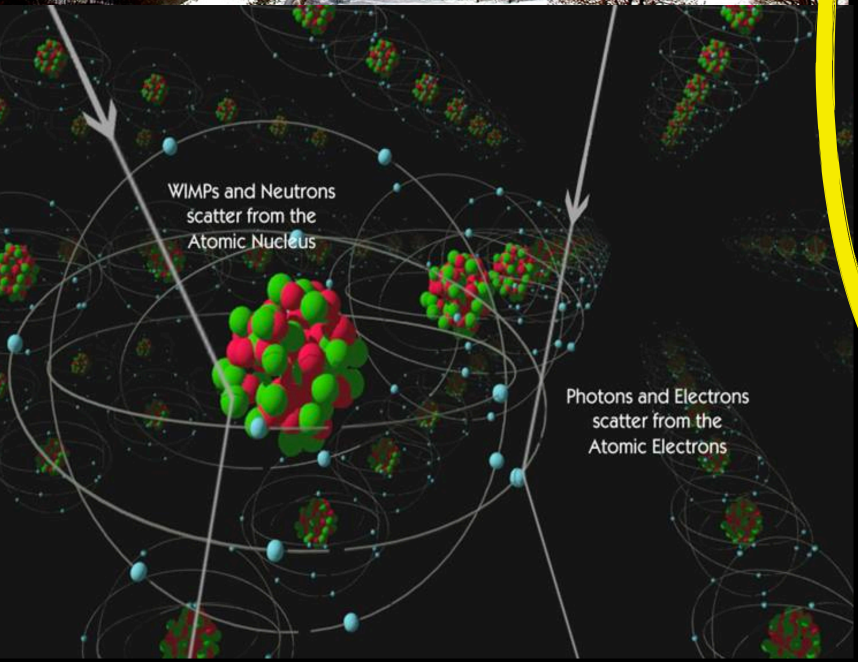
Indirect detection
(Freeze-out in the early Universe)

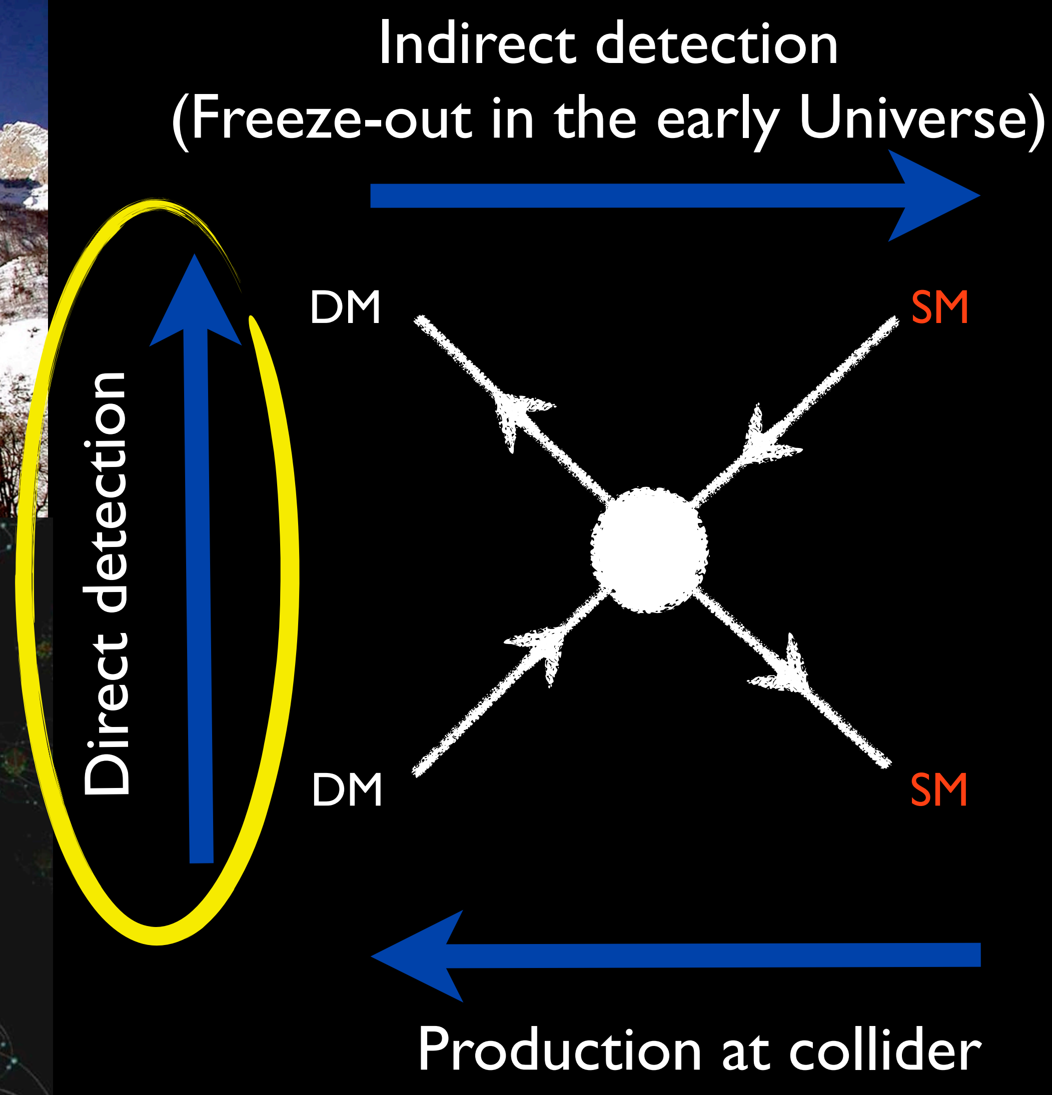
Direct detection



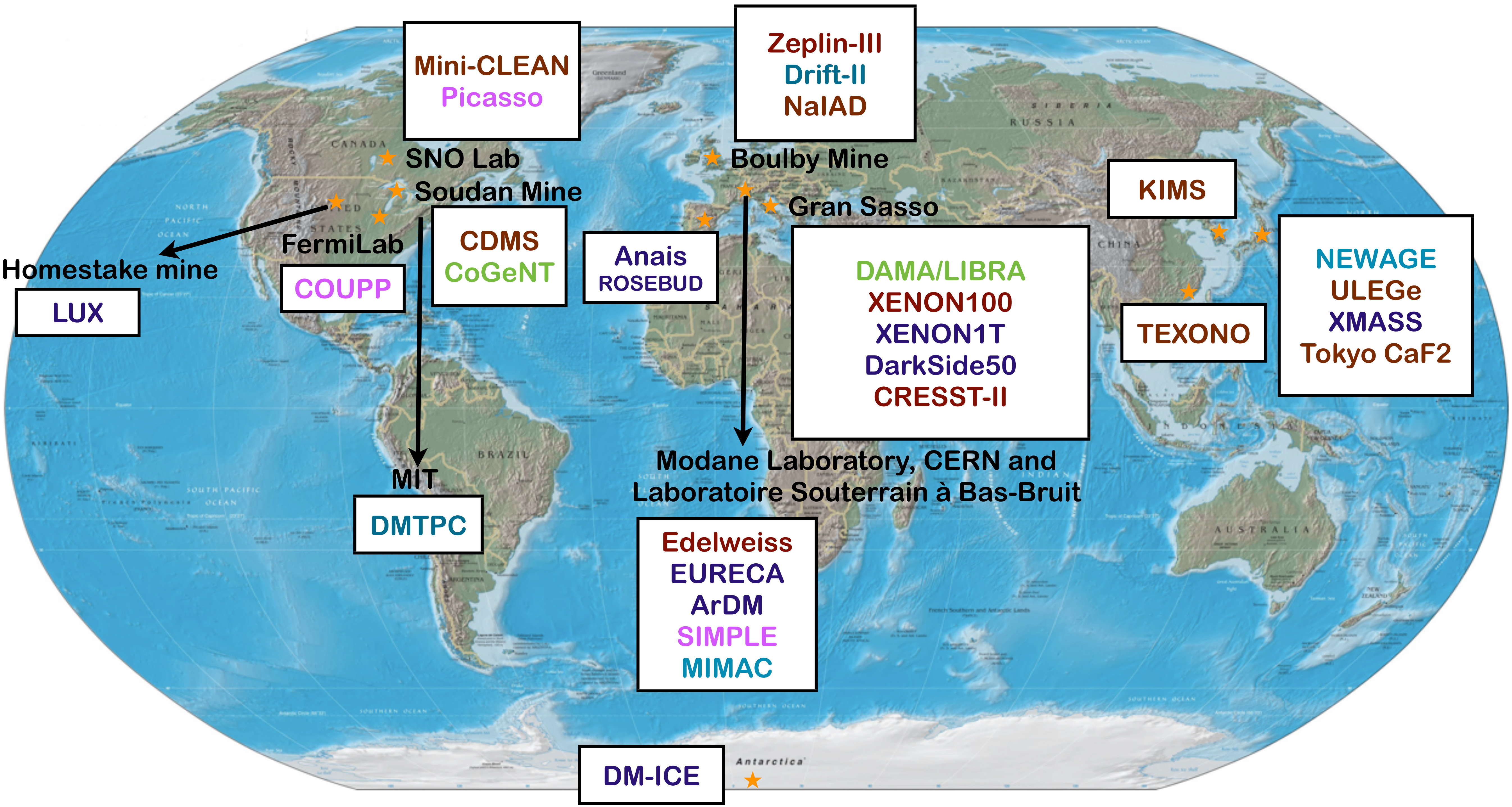
Production at collider

Dark Matter (WIMPs) detection





Direct Detection Experiment Map

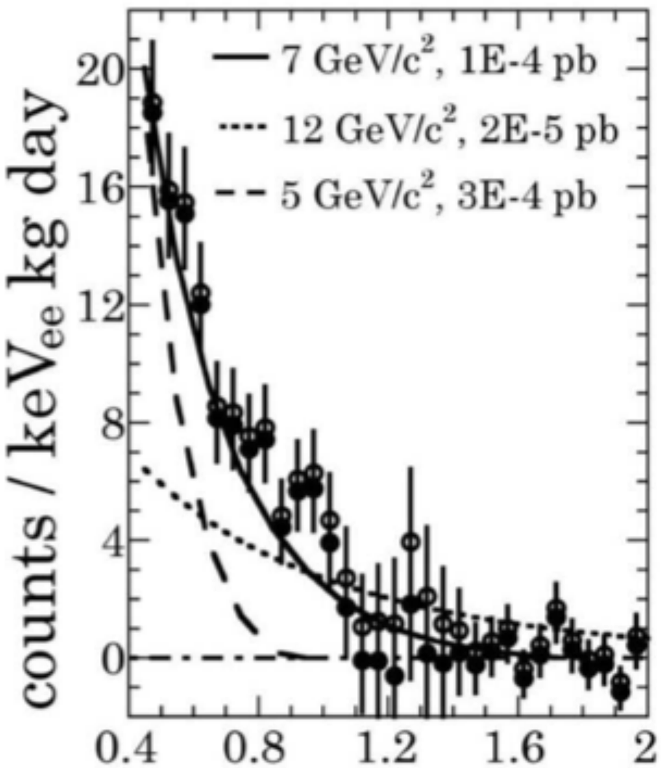


- background rejection technique
- directional signature
- annual modulation signature
- bubble chamber
- planned or under construction

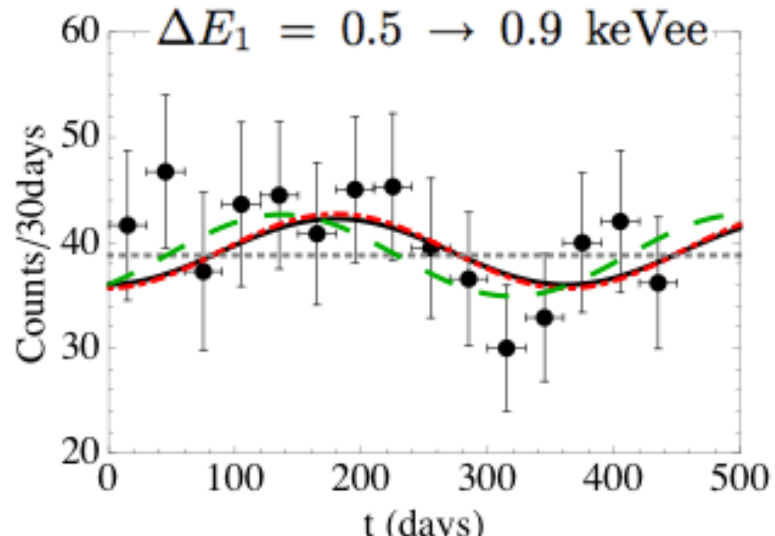
Puzzling status of DM direct detection

1) Claims of hints of Dark Matter at low mass (~ 10 GeV) by 4 experiments

CoGeNT



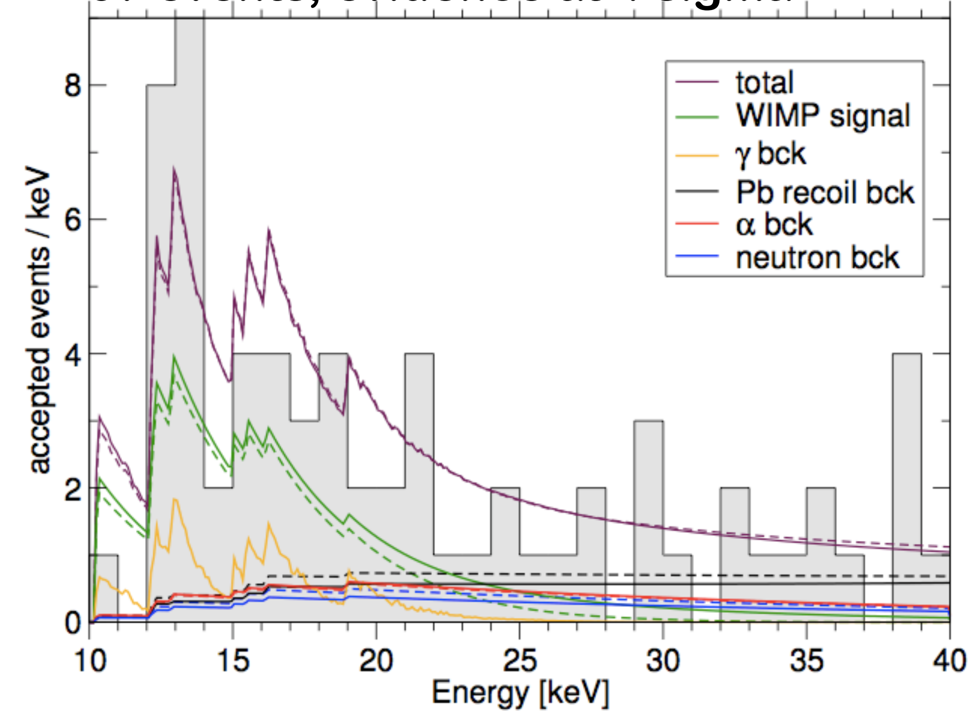
Aalseth et al. arXiv:1106.0650
annual modulation claim



CA, J.Hamann, R.Trotta and Y.Wong, JCAP1203 (2012),arXiv:11113238

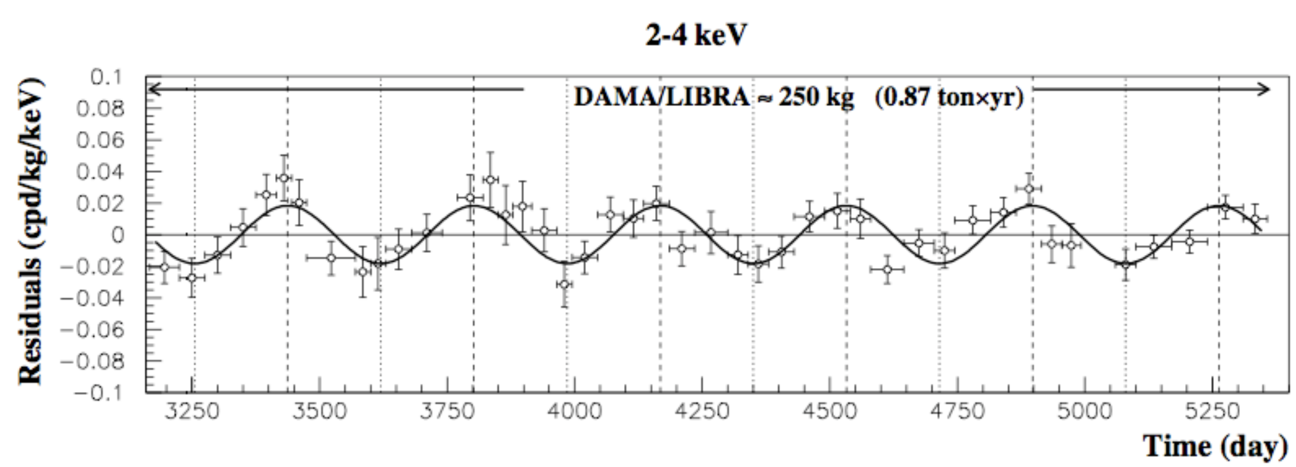
CRESST-II

Angloher et al., arXiv:1109.0702
67 events, evidence at 4 sigma



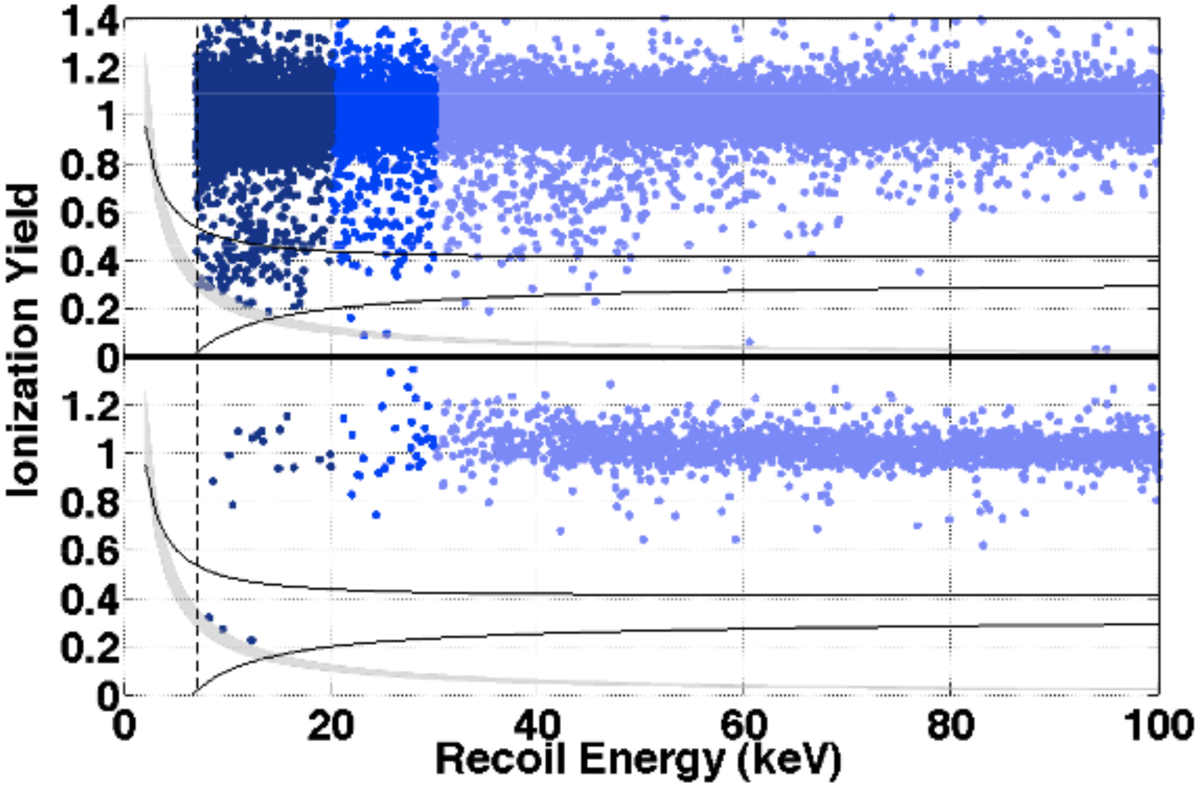
DAMA/LIBRA

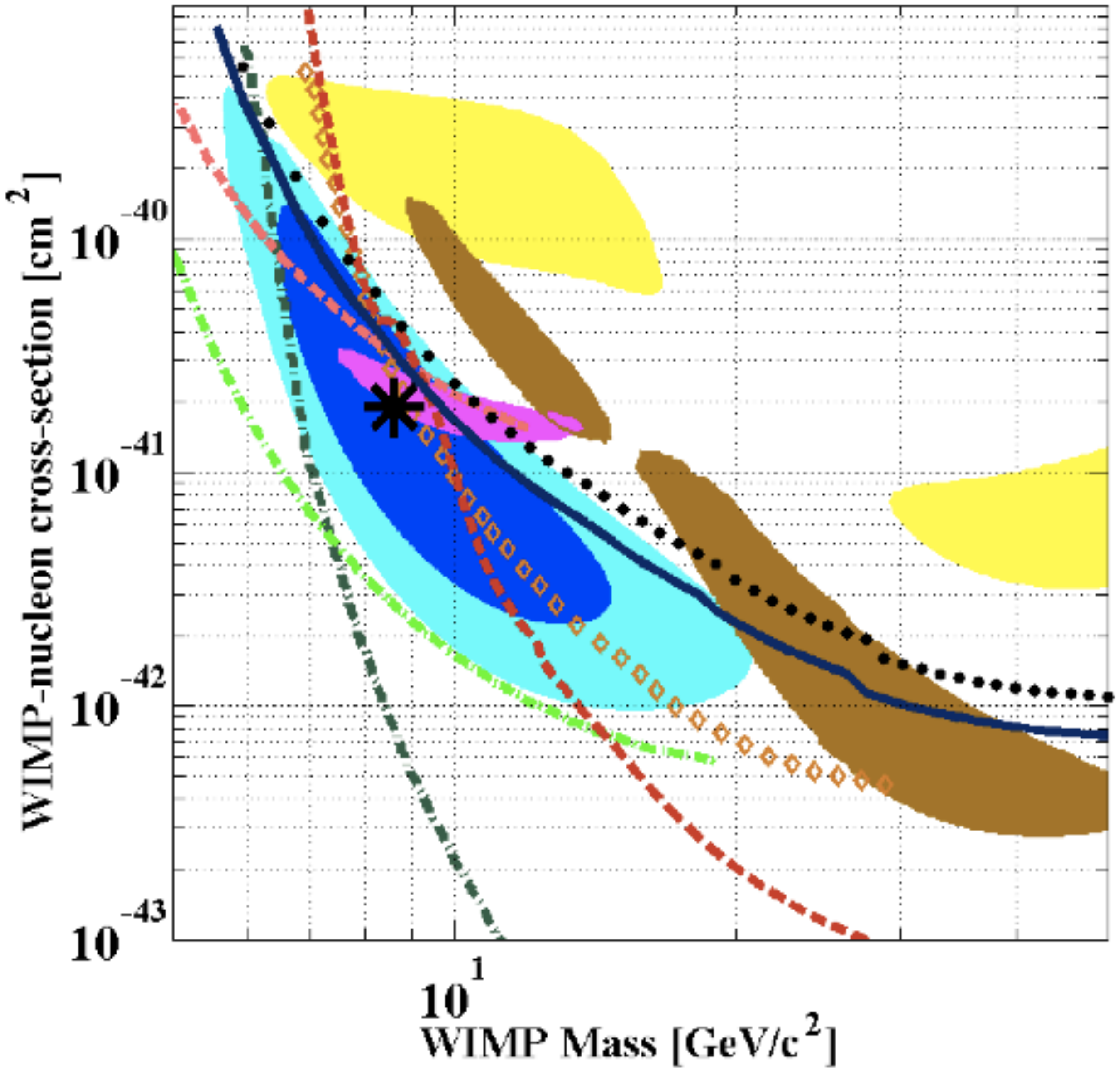
Bernabei et al. arXiv:1002.1028
annual modulation, 8.9 sigma significance,
13 annual cycles, 1.17 tonxyr



Puzzling status of DM direct detection

CDMS Si
arXiv:1304.4279





2) Several exclusion limits in contrast with the 'excesses' (XENON100, CDMS ...)

See recent works:
Frandsen et al. 1304.6066,
Mao et al.1304.6401,
Del Nobile et al. 1304.6183

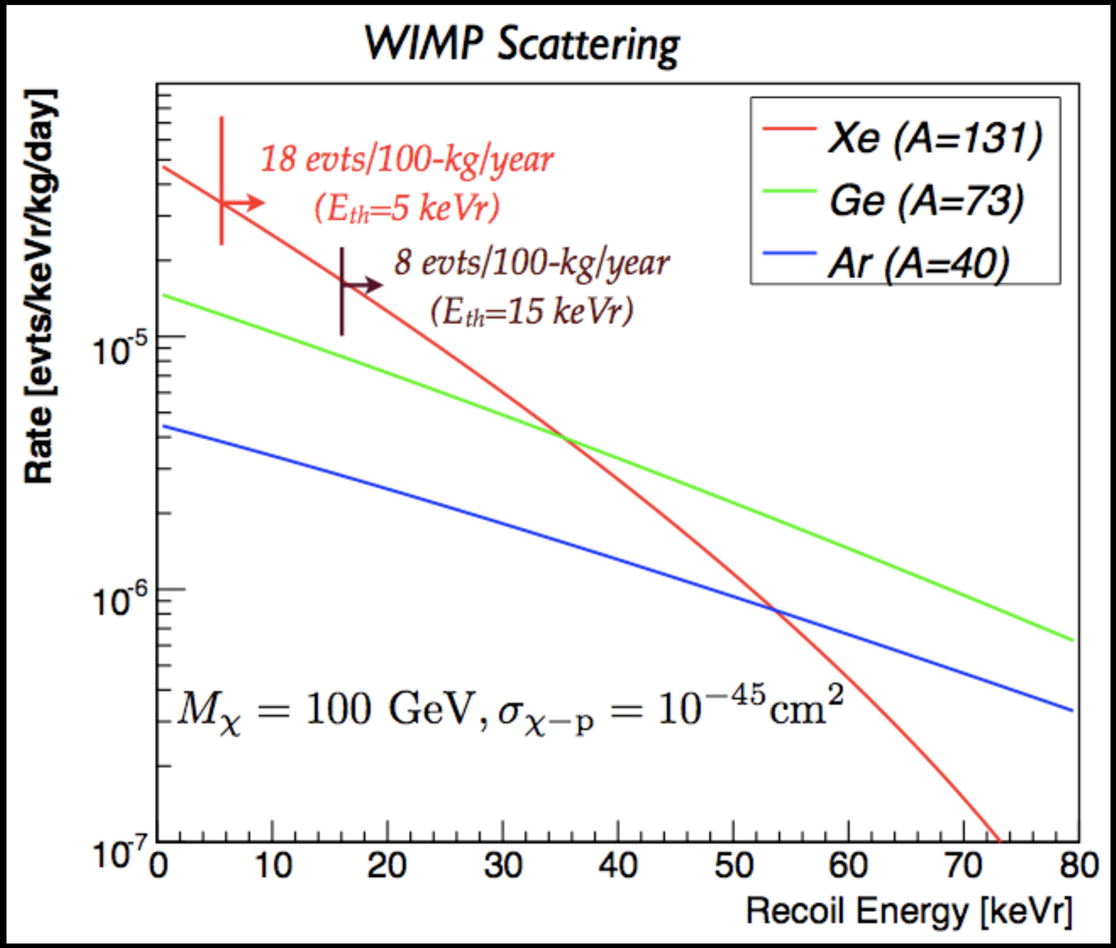
Experimental Issues

1. A detector should be the largest possible and have long exposure time because of the small event rate

2. A detector needs to have the lowest threshold possible because the signal has no particular features and is characterized by small recoil energies

$$\langle E_R \rangle \sim \text{keV}\left(\frac{m_\mathcal{N}}{\text{GeV}}\right)\left(\frac{m_{DM}}{m_{DM}+m_\mathcal{N}}\right)^2$$

↓



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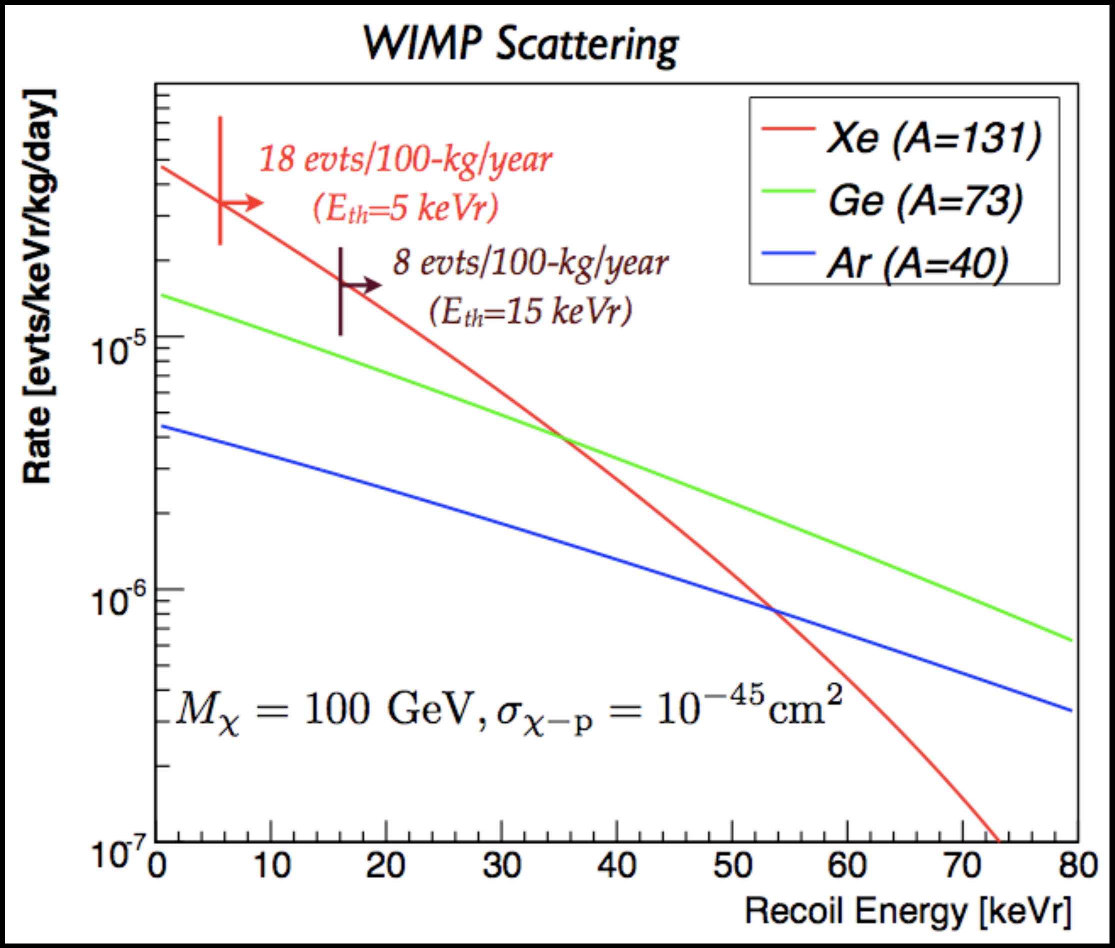


- Background discrimination = source of SYSTEMATICS !!

  - misidentified electrons (surface events)
  - neutrons in the recoil band
  - use of multiple detection techniques (ionization, heat, scintillation)
  - use of signature proper of the a WIMP such as the annual modulation due to the Earth motion around the Sun

Theoretical Issues

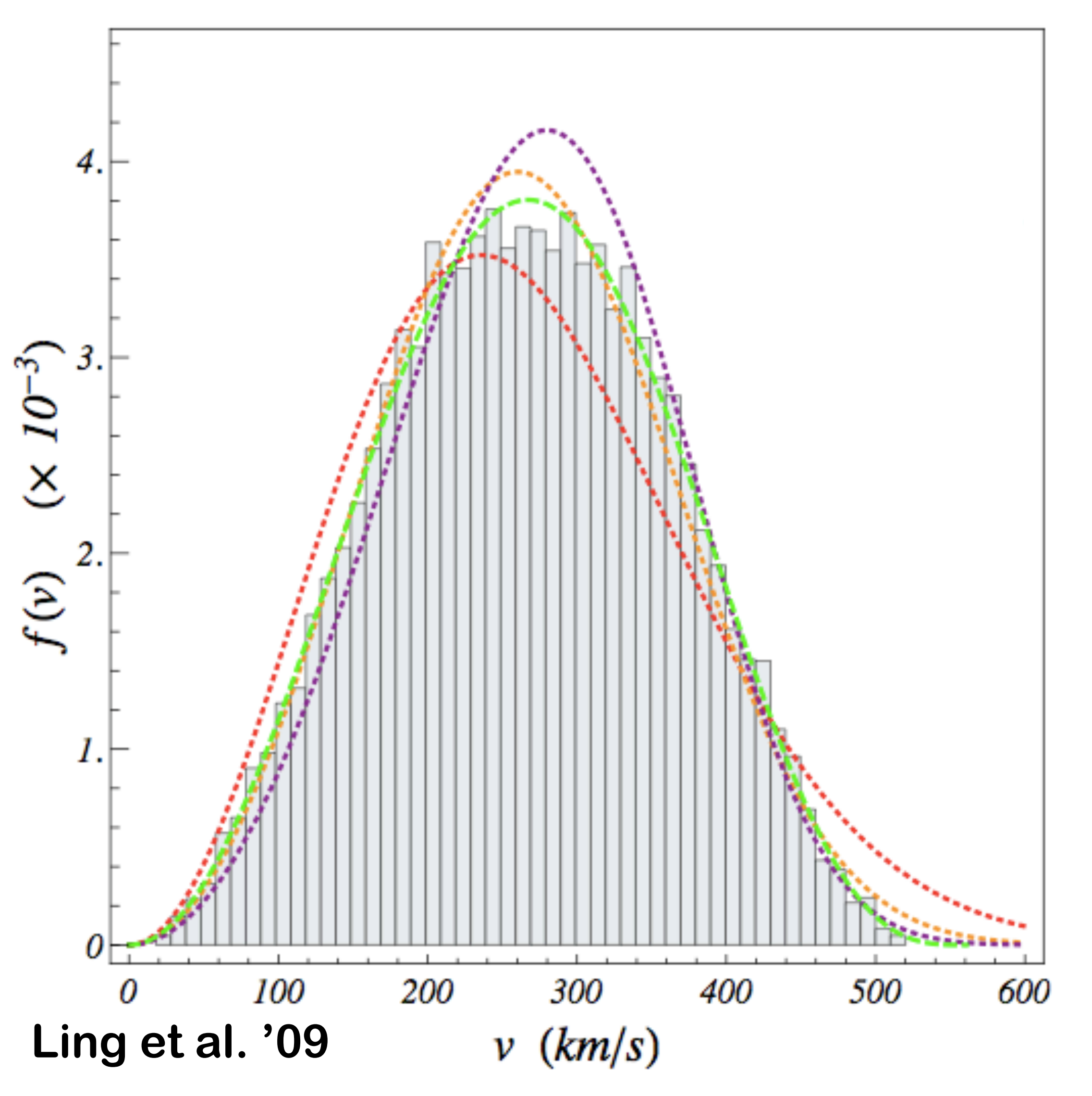
1. Theoretical model parameters (m_{DM}, σ) span several orders of magnitude

2. DM velocity distribution

   - depends on the solar neighborhood quantities and properties
   - approximated with Standard Model Halo (SMH), that is a spherically symmetric and isotropic Maxwellian distribution

- Consider a Milky Way-like galaxy simulated with the code RAMSES (DM + baryons) and the velocity distribution in a shell 7 < R < 9 kpc (sun position)

- Maxwellian distribution does not describe well DM velocity distribution



Ling et al. '09

3. Astrophysical parameters in the solar neighborhood are uncertain by a factor 2 or 10%

$$v_0^{obs} = 230 \pm 24.4 \text{ km s}^{-1}$$
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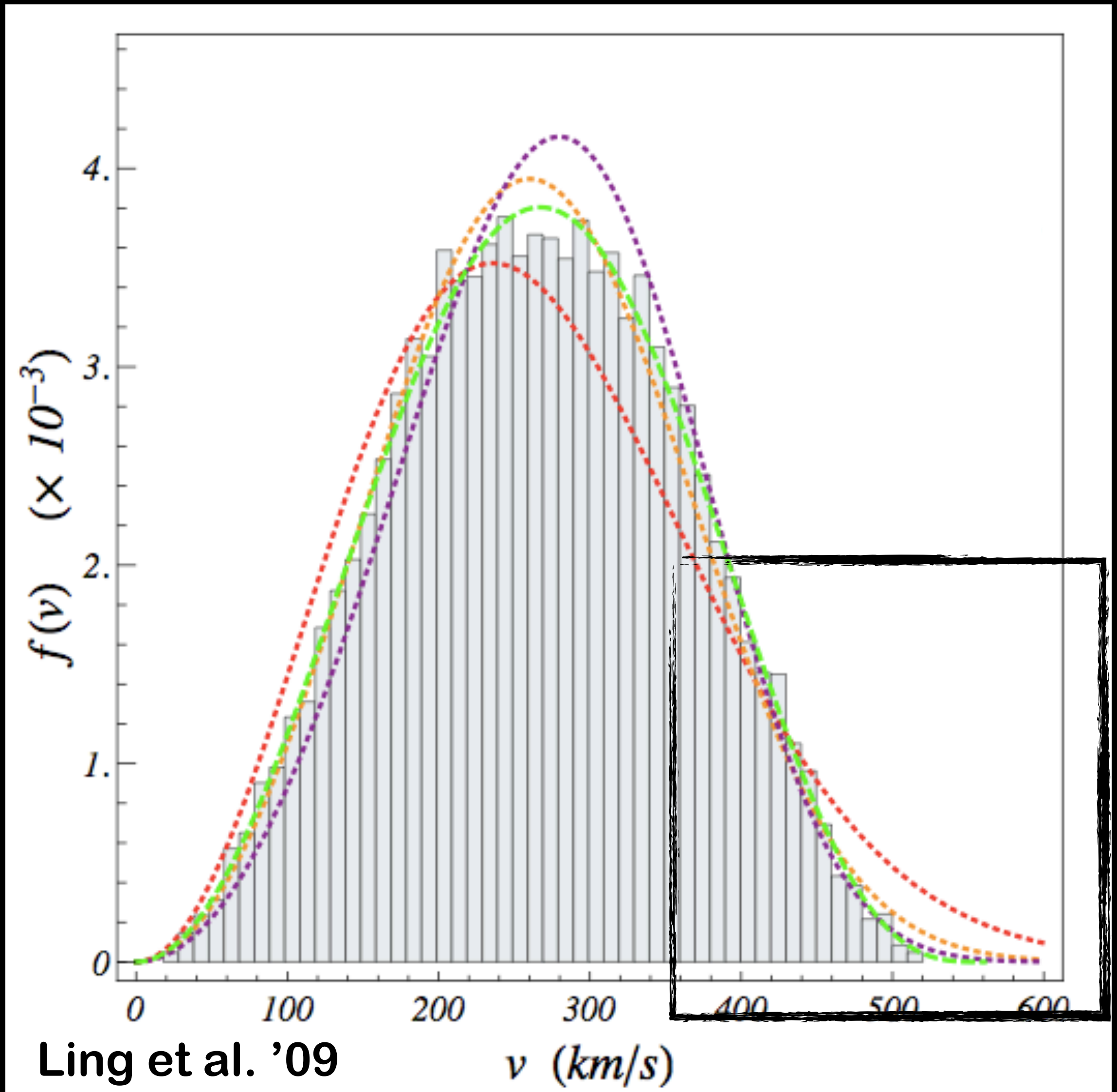

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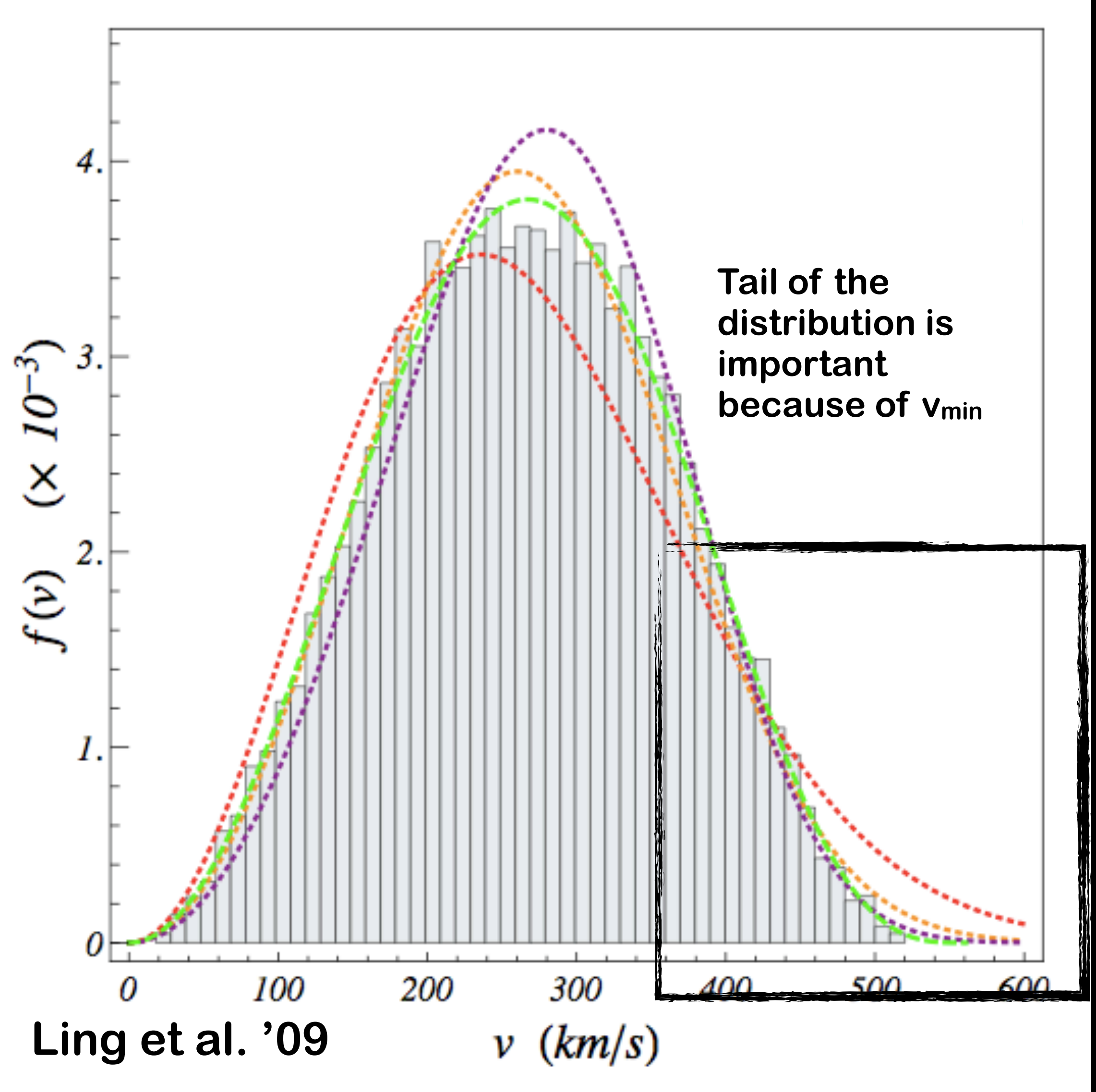

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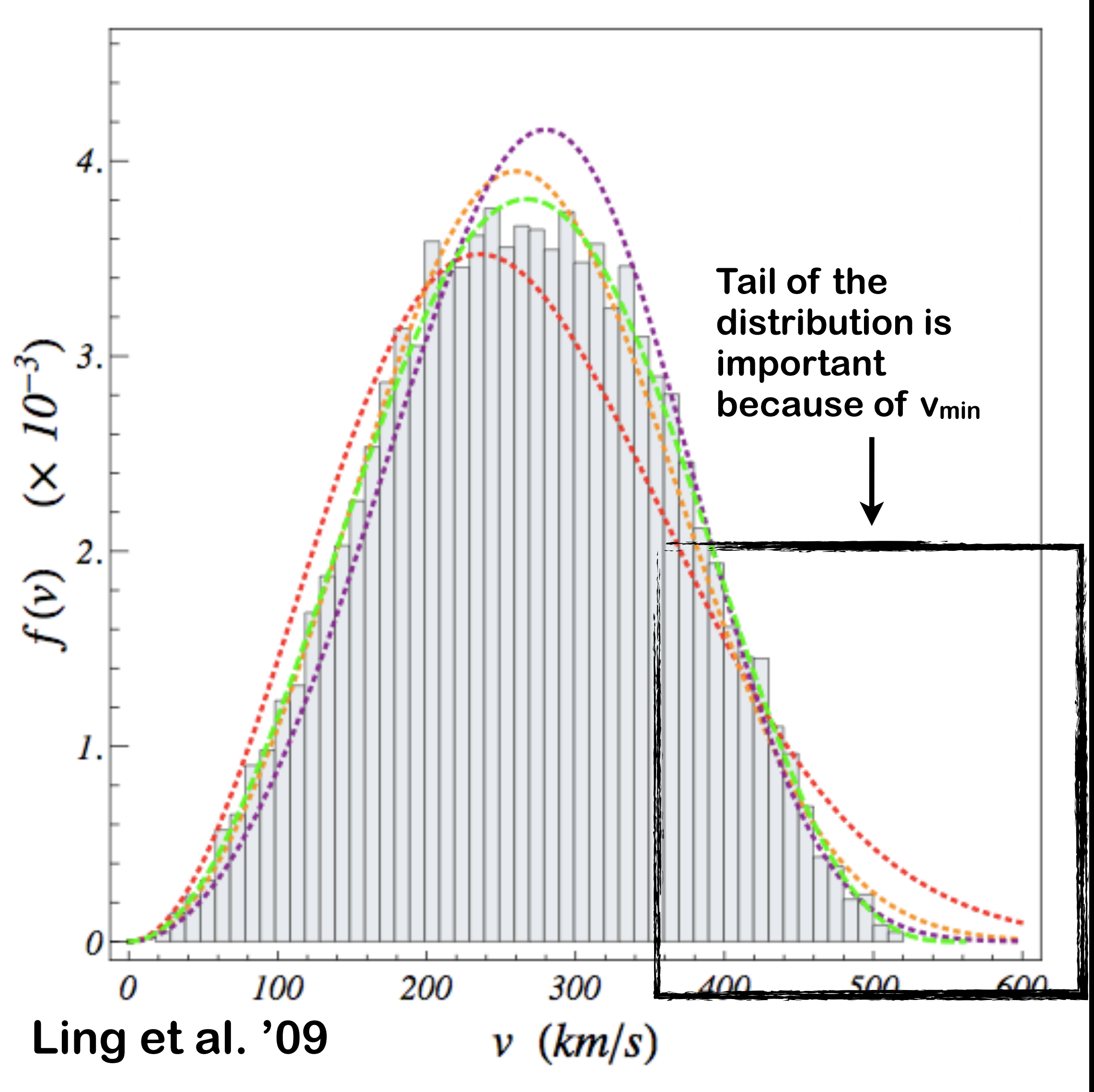

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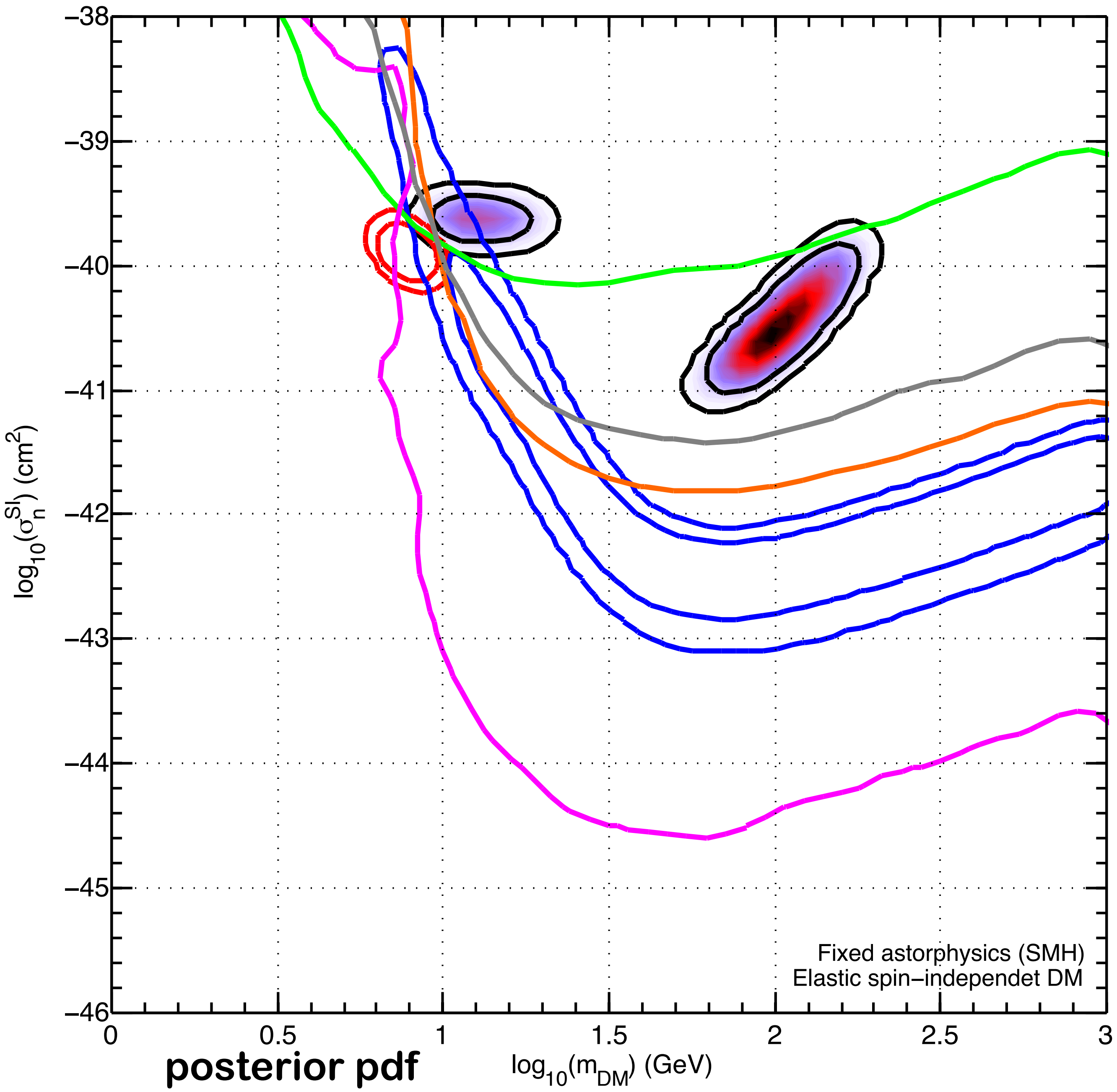
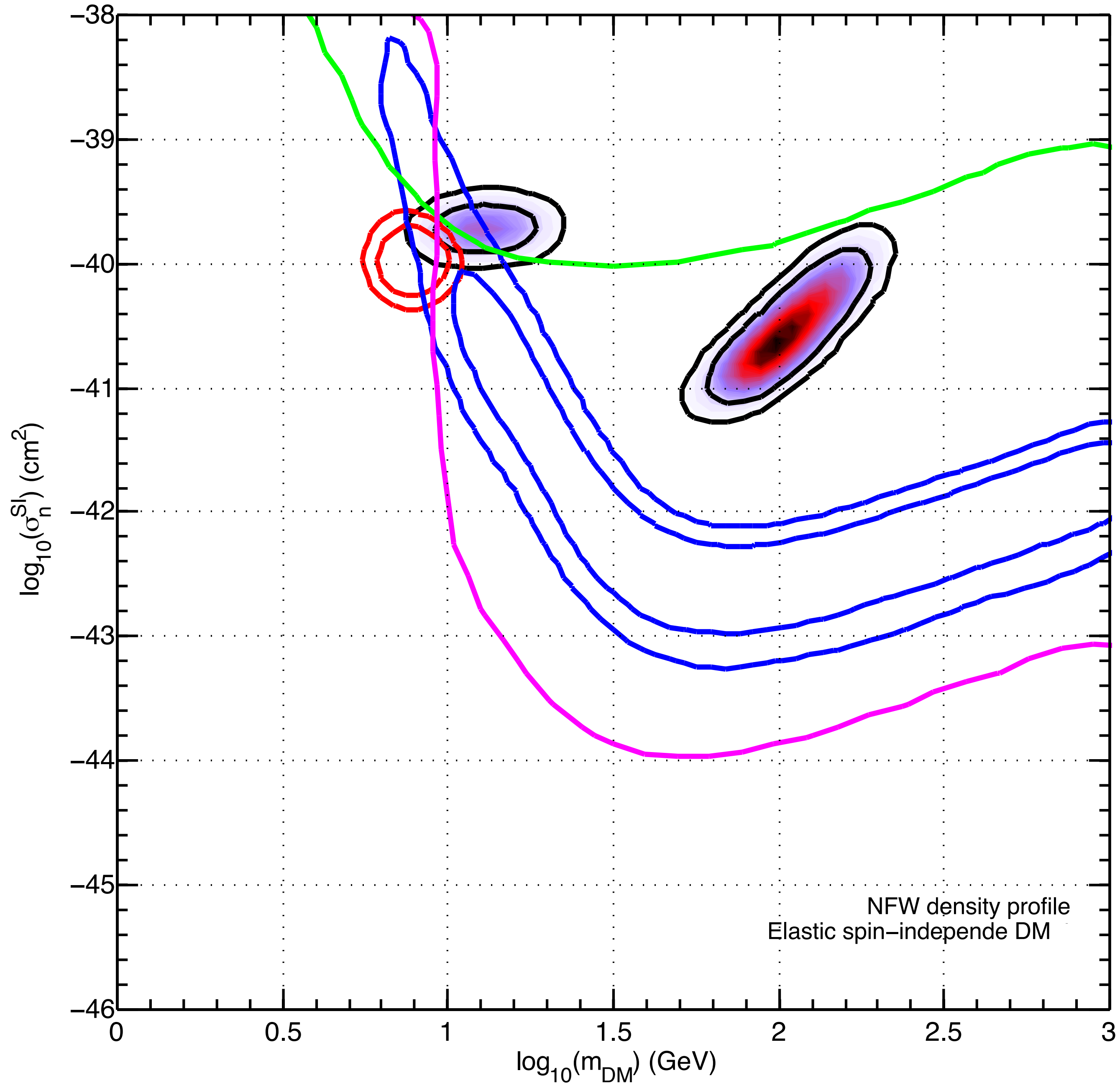
ASTROPHYSICAL uncertainties + exp. SYSTEMATICS

Bayesian procedure of marginalizing over all nuisance parameters

CA, J.Hamann and Y.Wong, JCAP 1109 (2011), arXiv:1105.5121
CA, arXiv:1211.0435, Phys.Rev.D86 (2012)



posterior pdf



(i) Upper bounds become less constraining however they are still in tension;
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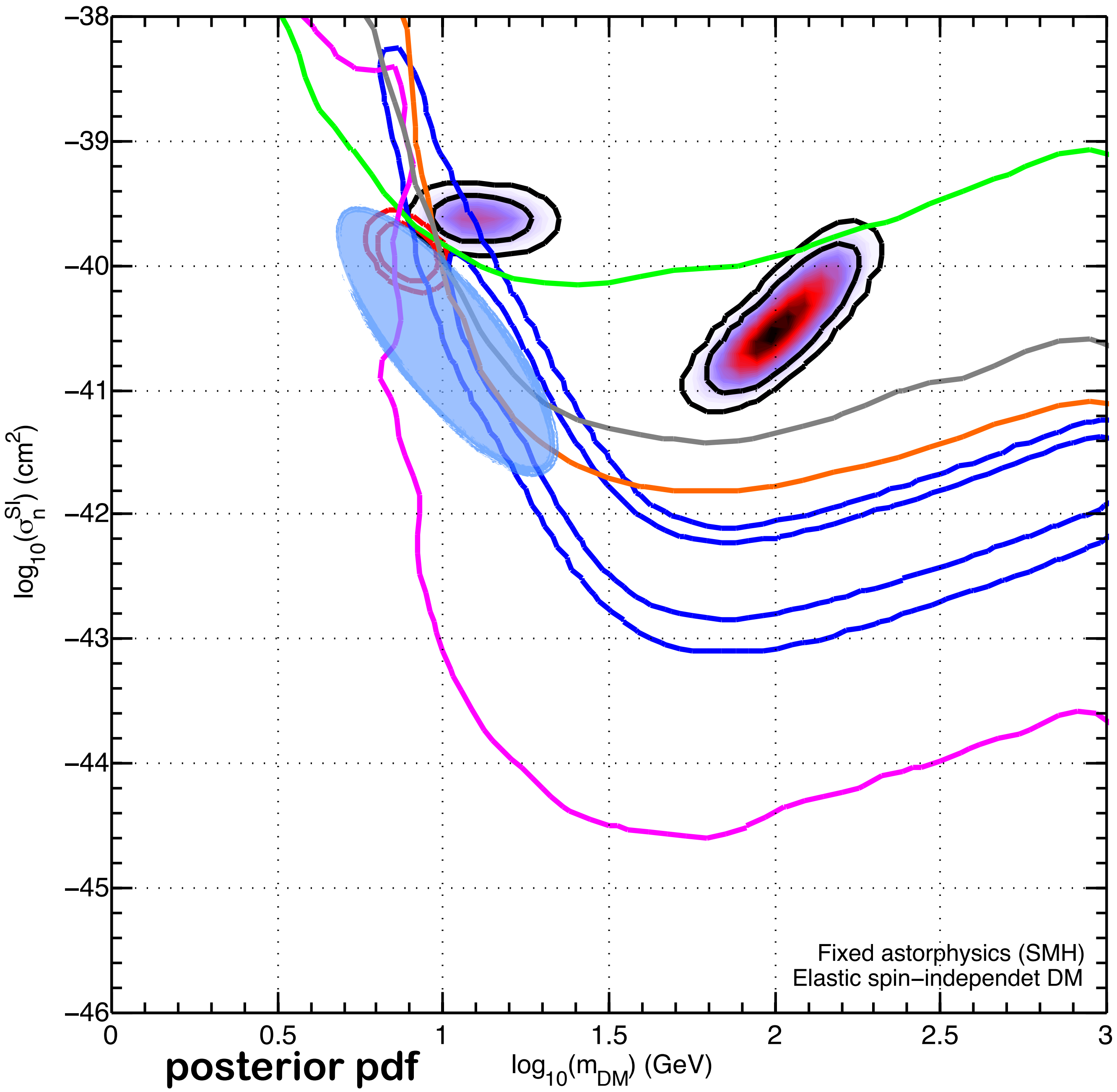

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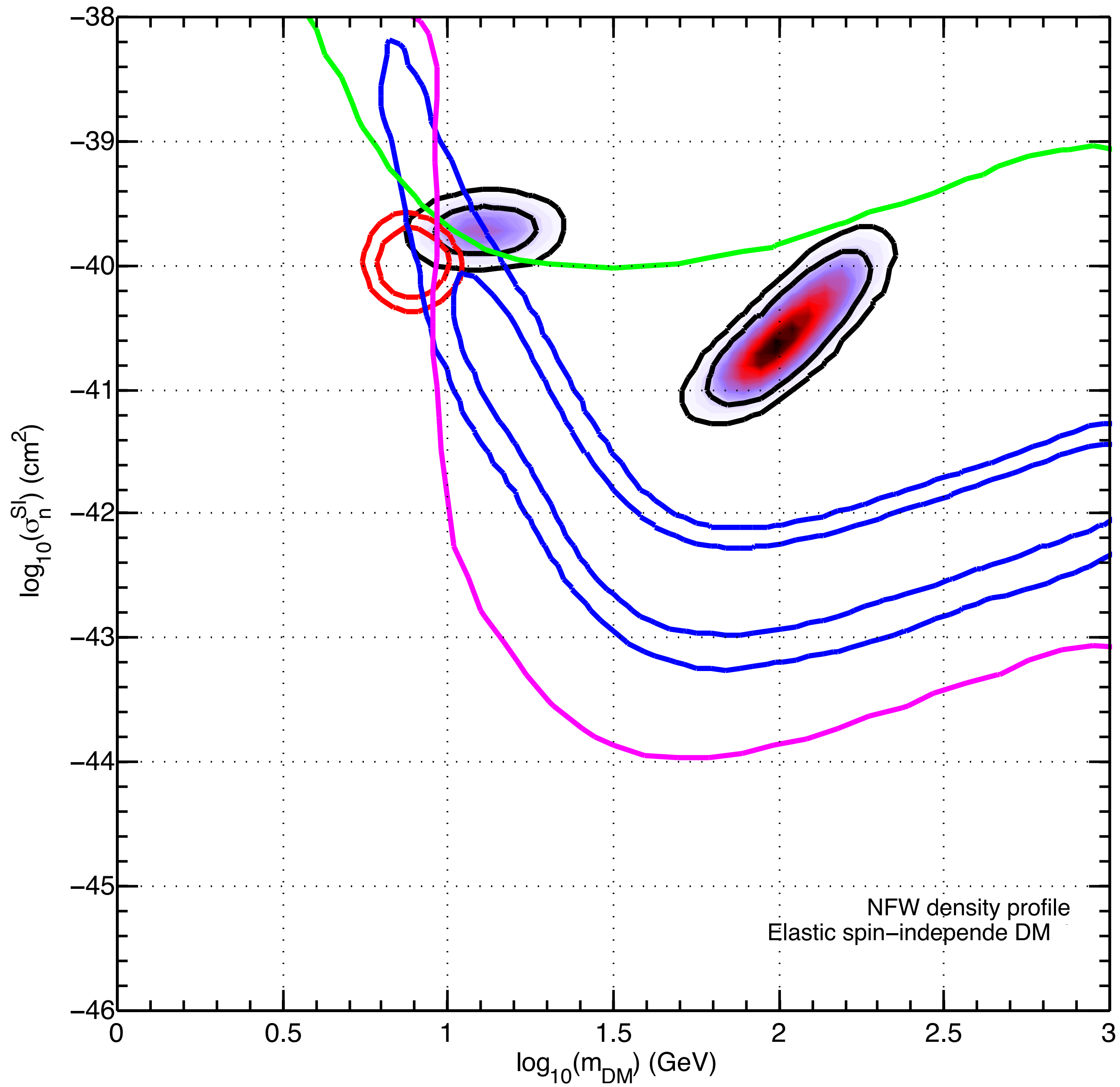

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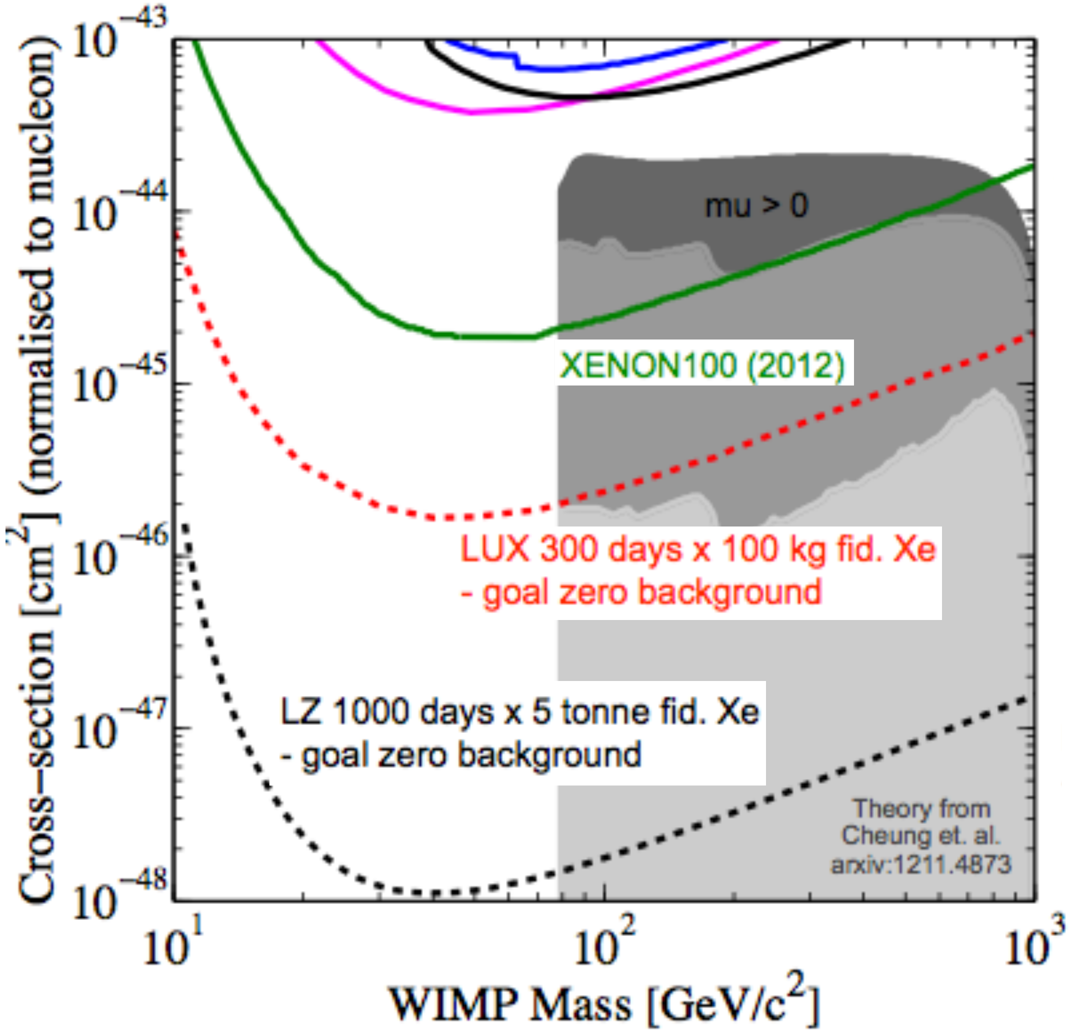
Expected soon (~ 2013)

Updates from Aspen 2013 conference

(1) LUX (LXe) is running and will soon release data from 2 month running, ultimate goal is 300 day of science run

(2) DarkSide-50 (Ar) running:

- not yet competitive but prototype for DarkSide5000
- light element, complementary to Xe



(3) Super-CDMS Soudan (10 Kg Ge) is running and results are promising for:

- Spin-independent WIMP sensitivity comparable to XENON100 with a different nuclear target (2015)
- Special strategy for low thresholds to study dark matter with masses <10 GeV

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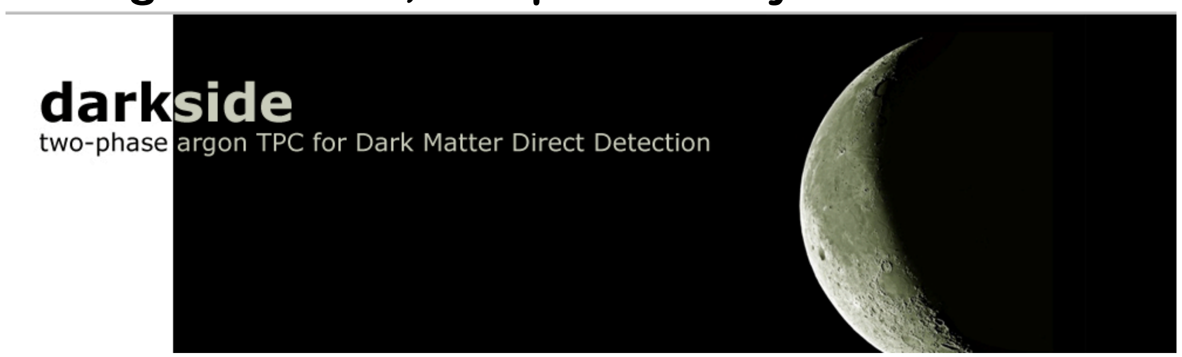

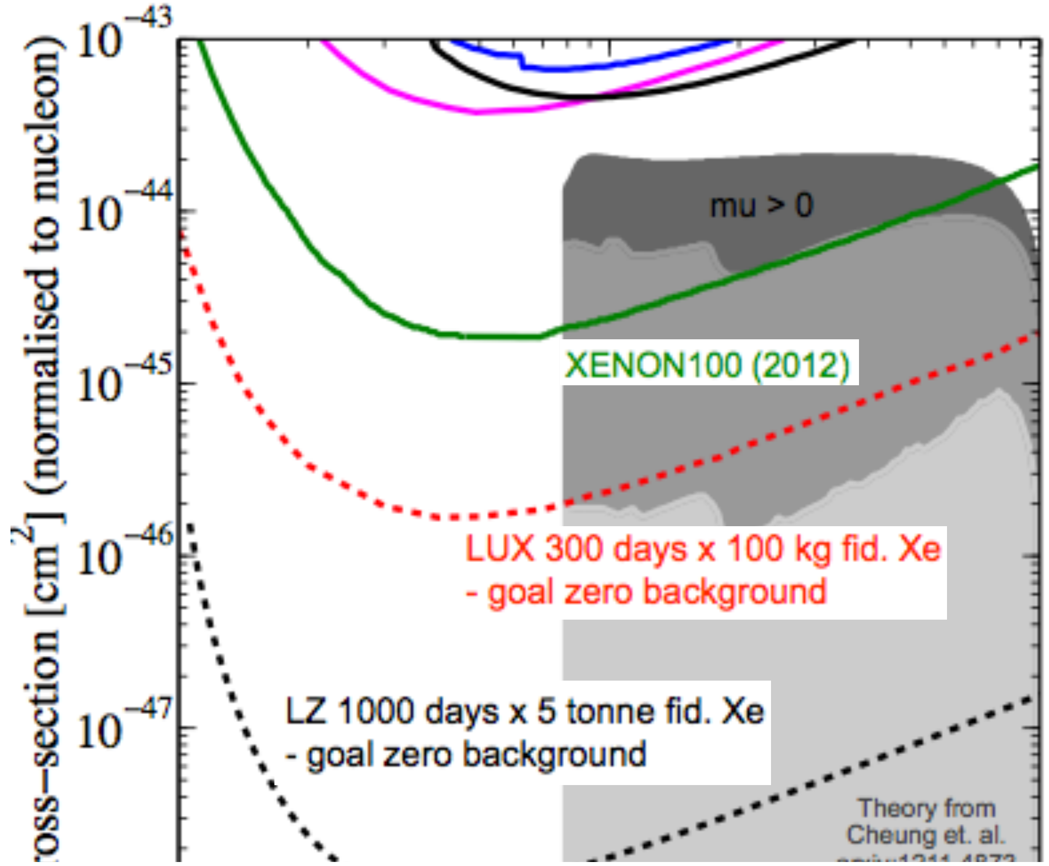

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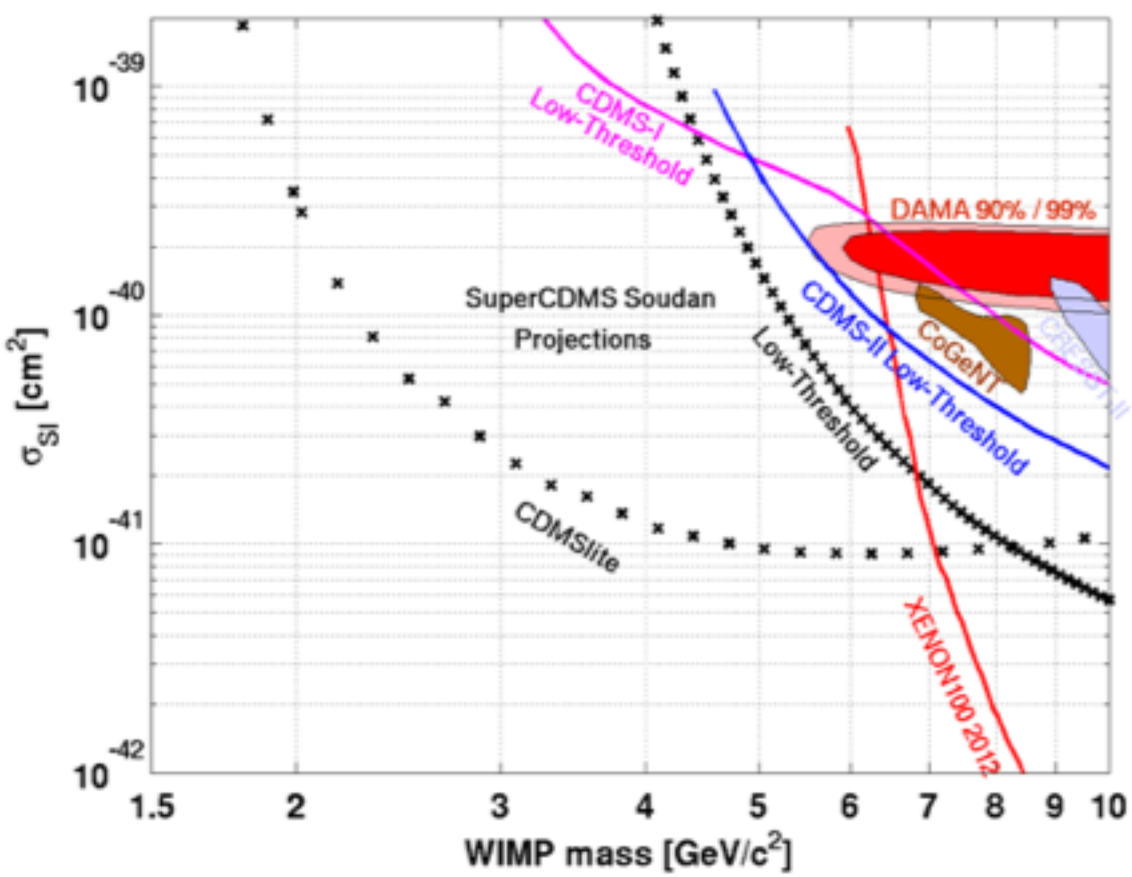


Moving to Ton scale detectors

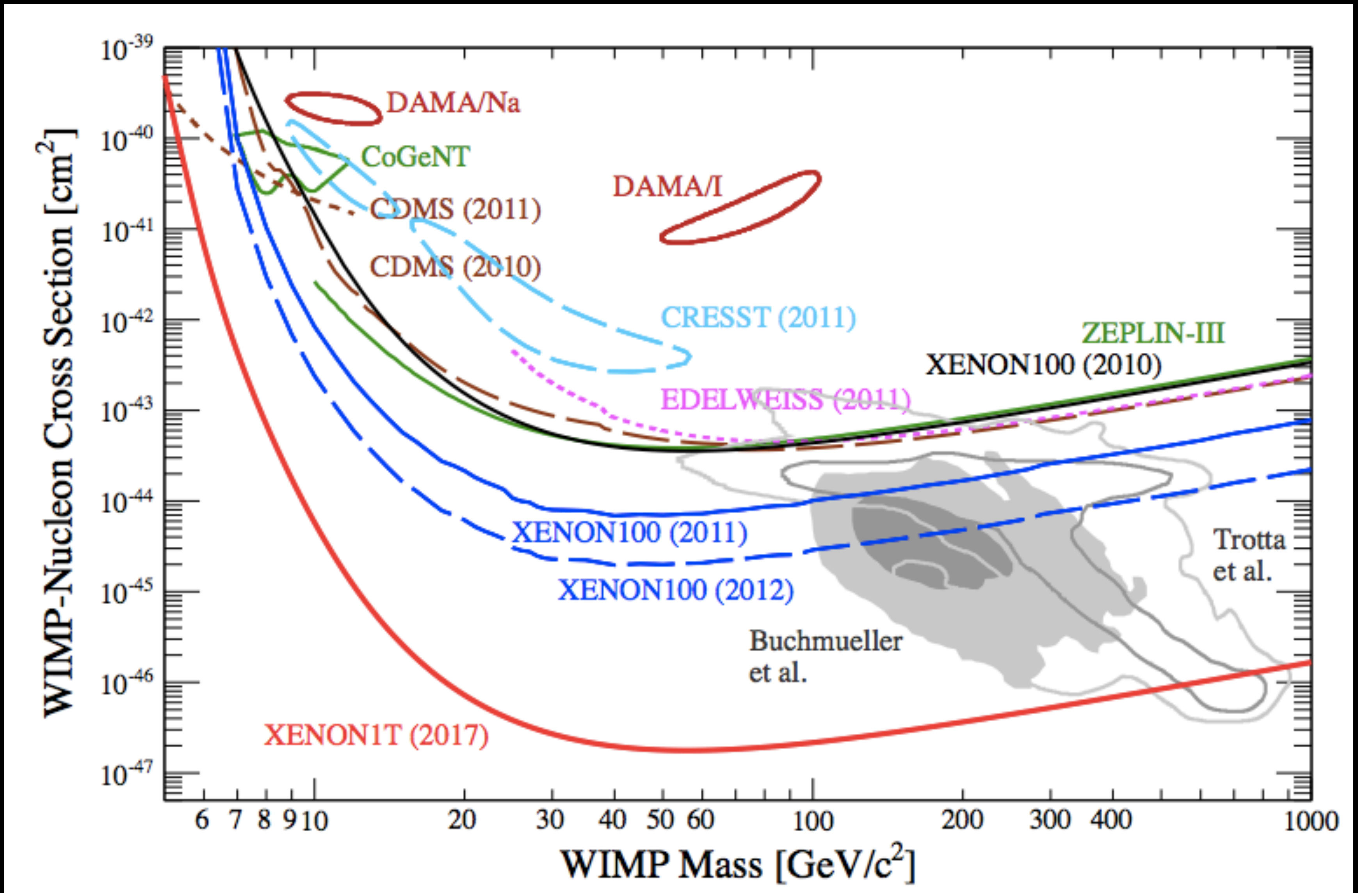
Updates from Aspen 2013 conference

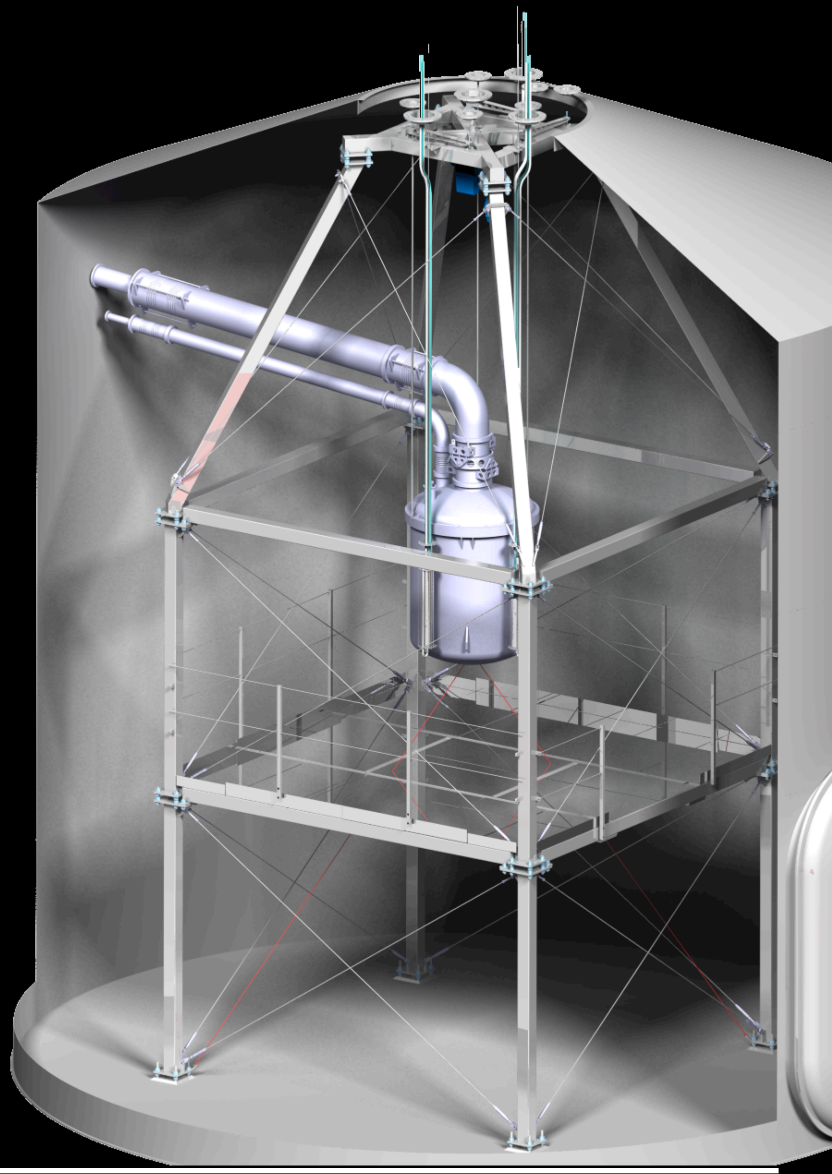
Lot of effort: XMASS, DEAPClean, SuperCDMS Soudan... Among others:

XENON1T:

- start construction ~ 2013
- science run expected to start 2015

Elena Aprile, arXiv:1206.6288





Outline of the rest of the talk

(A) Identification of a generic WIMP candidate

- Suppose there is a 'convincing' dark matter (DM) detection in a direct search experiment
- Next step: reconstruction of the theoretical physical parameters describing the dark matter (i.e. mass, cross-section on nucleus)
- Direct detection experiments have known limitation in reconstruction of dark matter parameters

(B) Complementarity to resolve the theoretical DM parameters

- Exploit complementarity of DM searches to improve the reconstruction of these parameters
- In particular consider neutrino telescopes, sensitive as well to the cross-section dark matter-nucleus.

(C) Discussion about astrophysical issues

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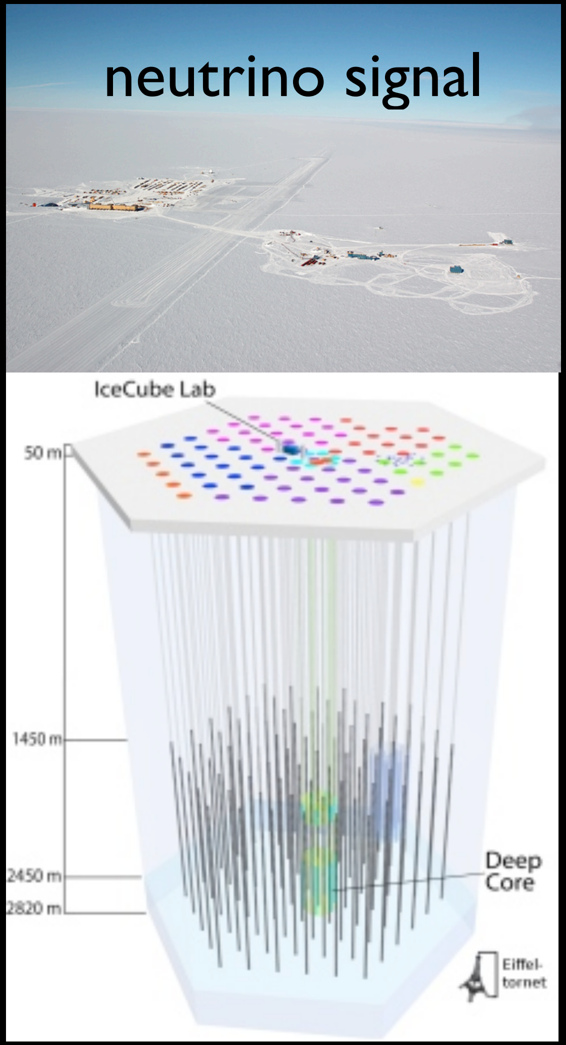

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Future XENON1T experiment (2017)

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Particle and nuclear physics

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E} = \frac{\mathrm{d}\sigma}{\mathrm{d}E}\Big|_{SI} + \frac{\mathrm{d}\sigma}{\mathrm{d}E}\Big|_{SD} \quad \begin{cases} \frac{\mathrm{d}\sigma}{\mathrm{d}E}\Big|_{\mathrm{SI}} = \frac{M_{\mathcal{N}}\sigma^{\mathrm{SI}}}{2\mu_n^2 v^2} \frac{\left(f_p Z + (A-Z) f_n\right)^2}{f_n^2} \mathcal{F}_{\mathrm{SI}}^2(E) \\ \frac{\mathrm{d}\sigma}{\mathrm{d}E}\Big|_{\mathrm{SD}} = \frac{4 M_{\mathcal{N}}\sigma^{\mathrm{SD}}}{3\mu_n^2\, v^2} \frac{J+1}{J} \left(\langle S_p\rangle + a_n/a_p \langle S_n\rangle\right)^2 \mathcal{F}_{\mathrm{SD}}^2(E) \end{cases}$$

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Particle and nuclear physics

DM parameters

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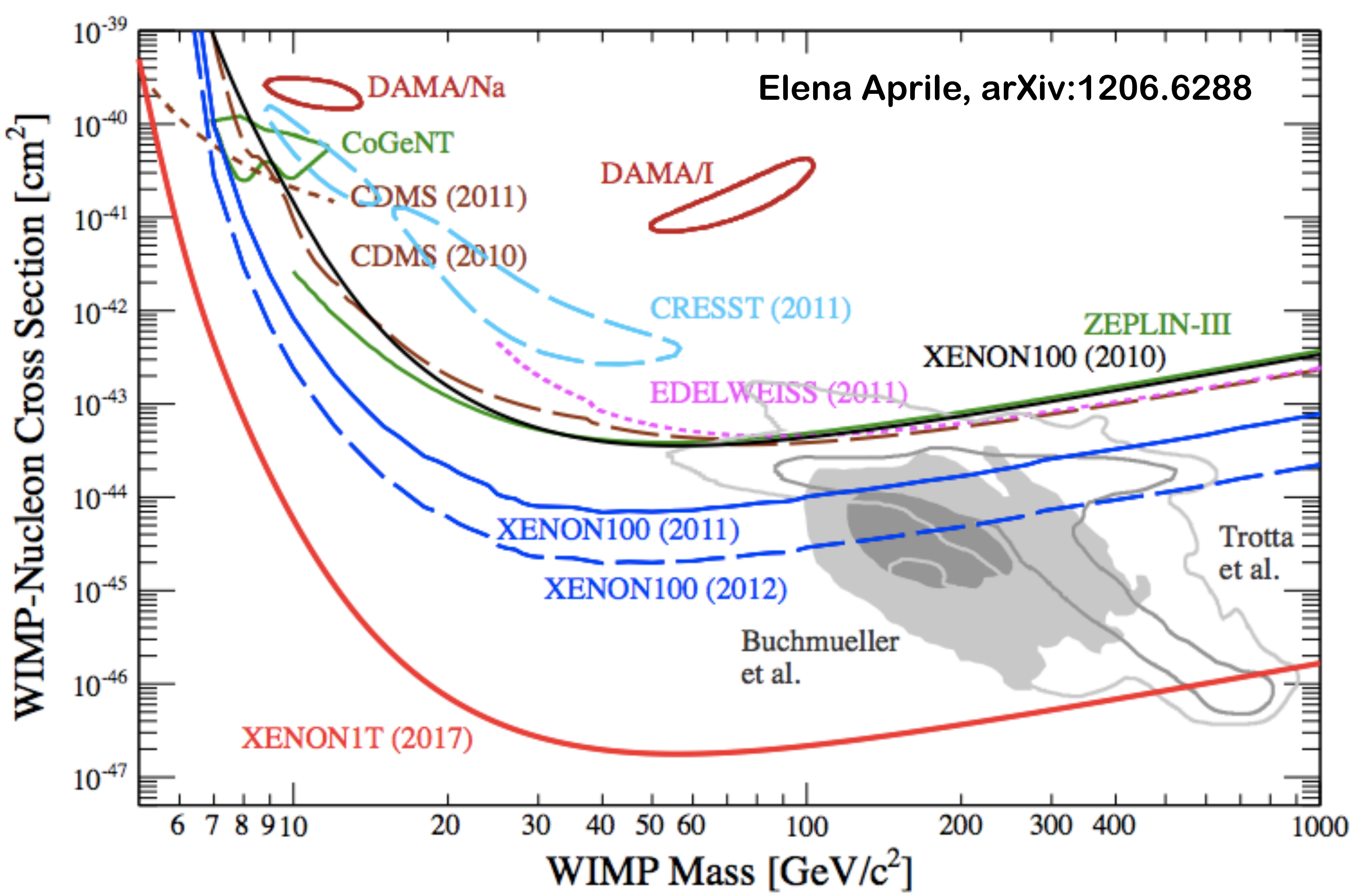

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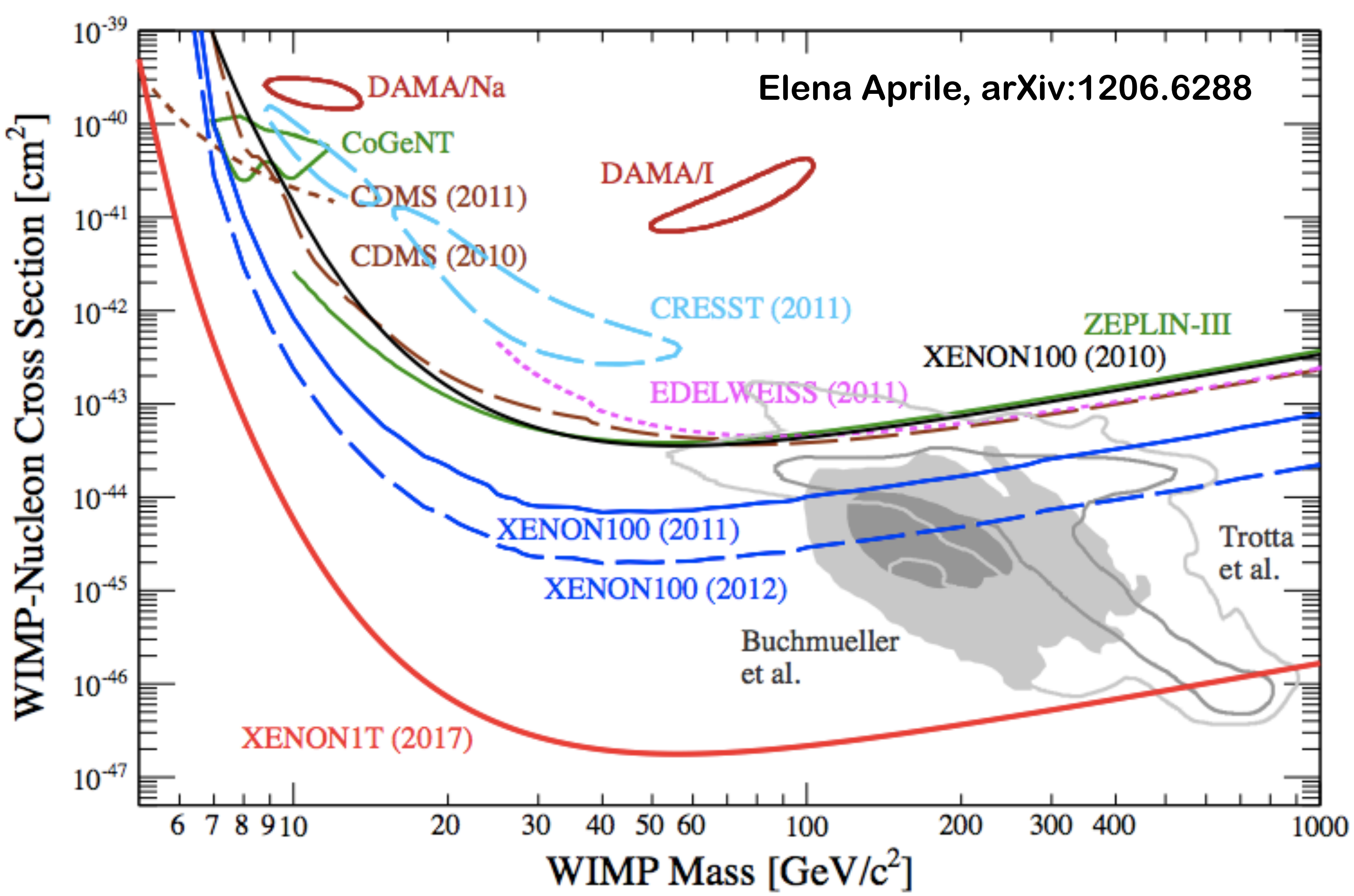

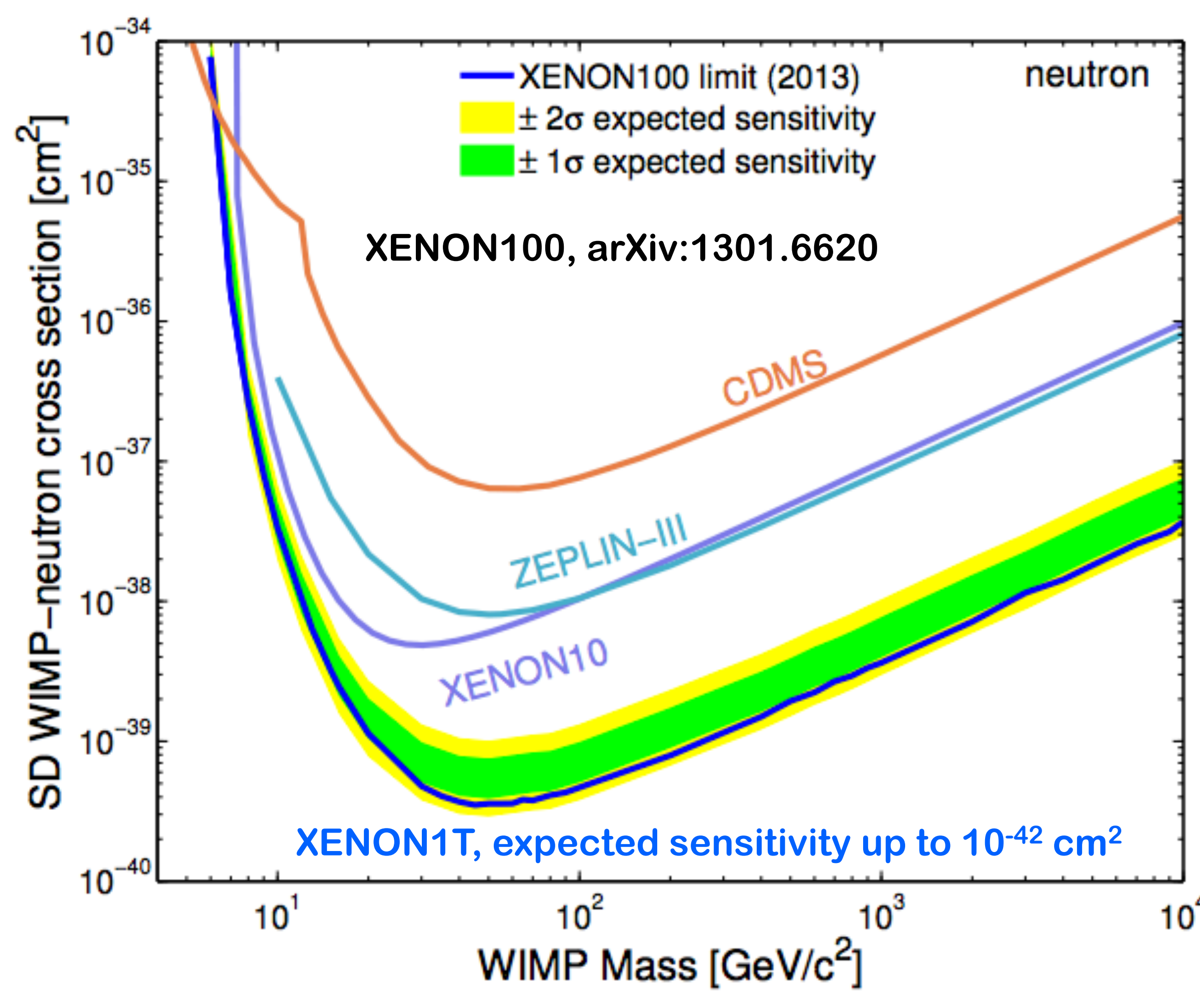

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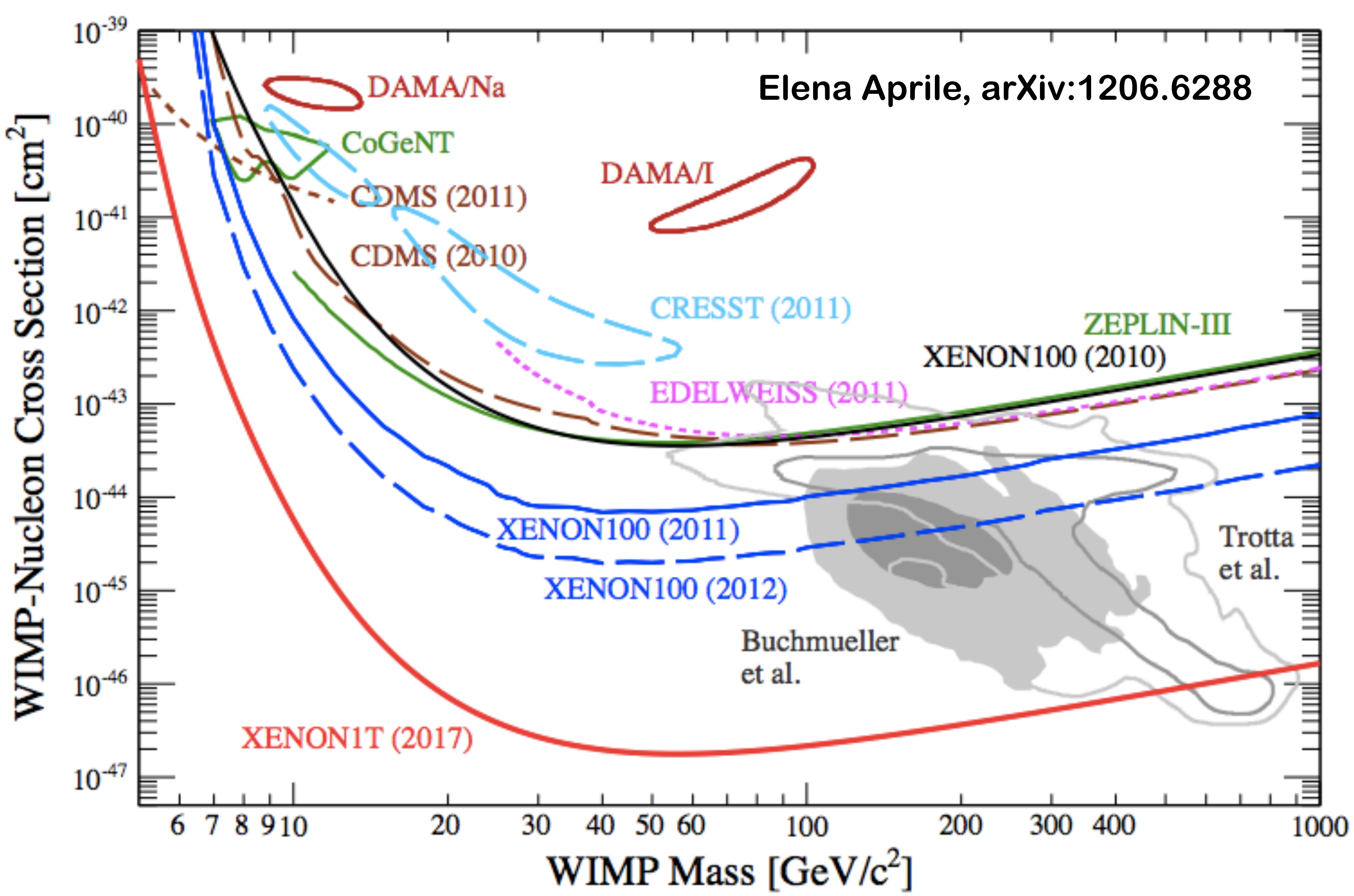
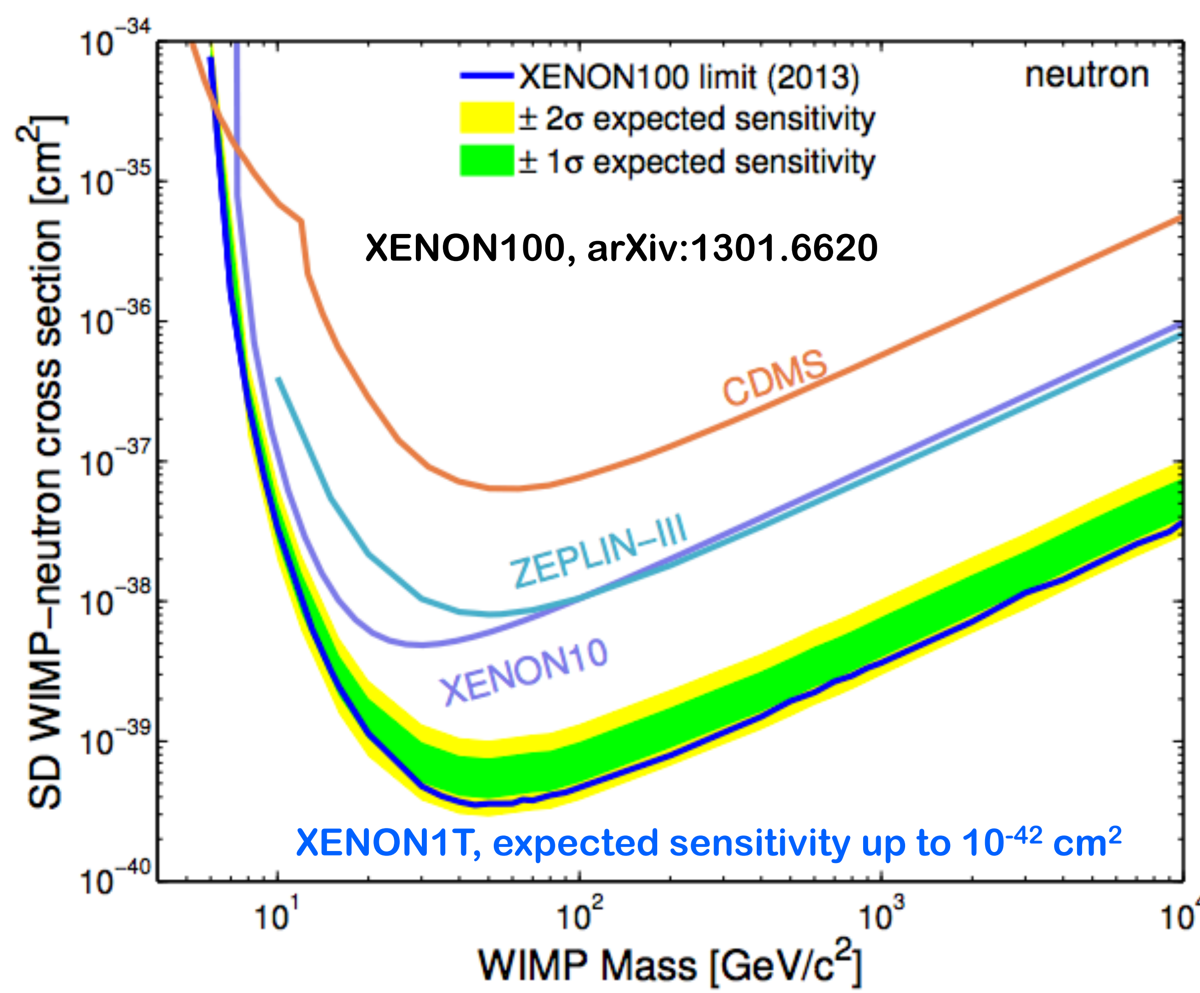
structure functions, huge nuclear uncertainties





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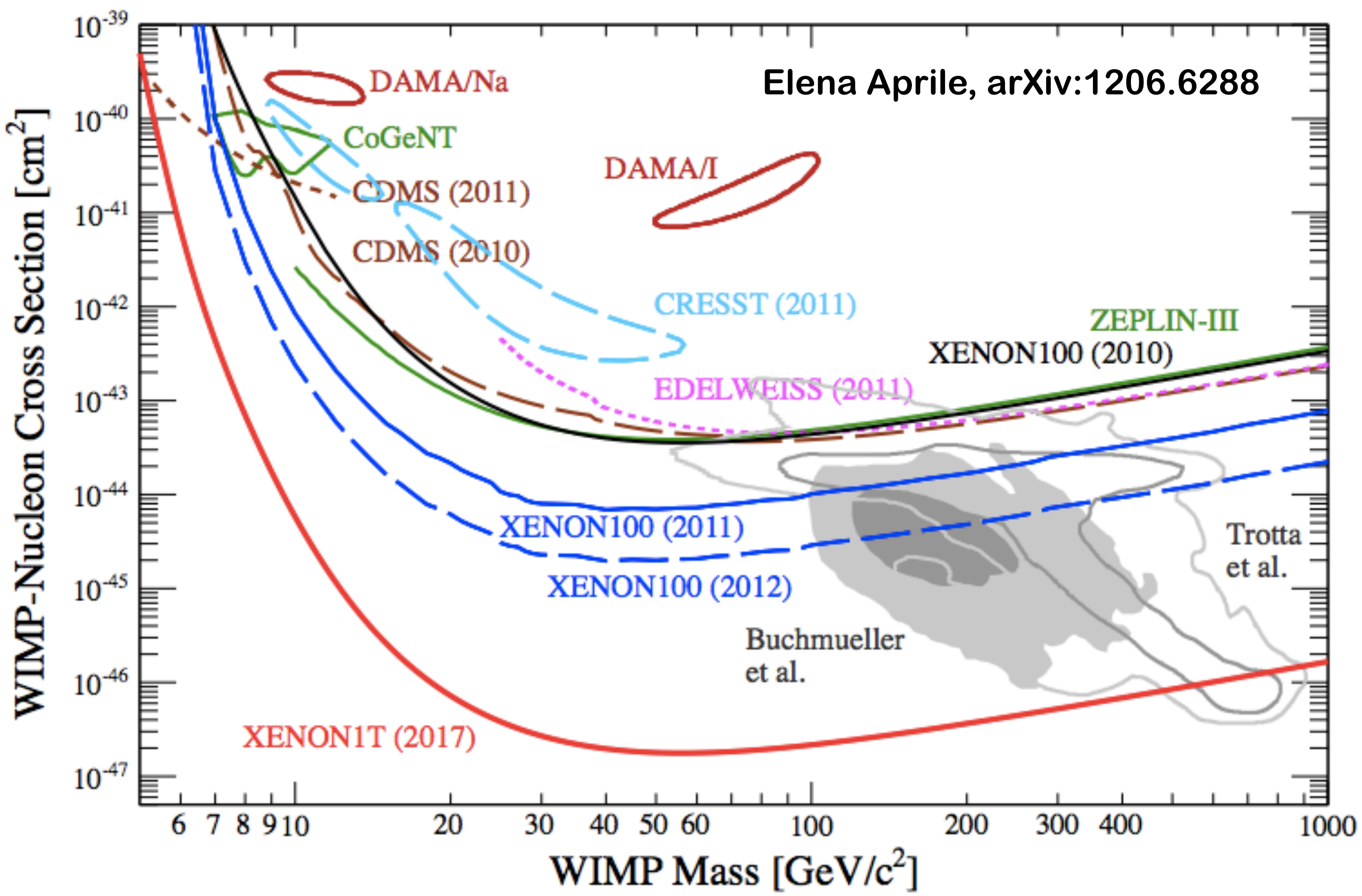
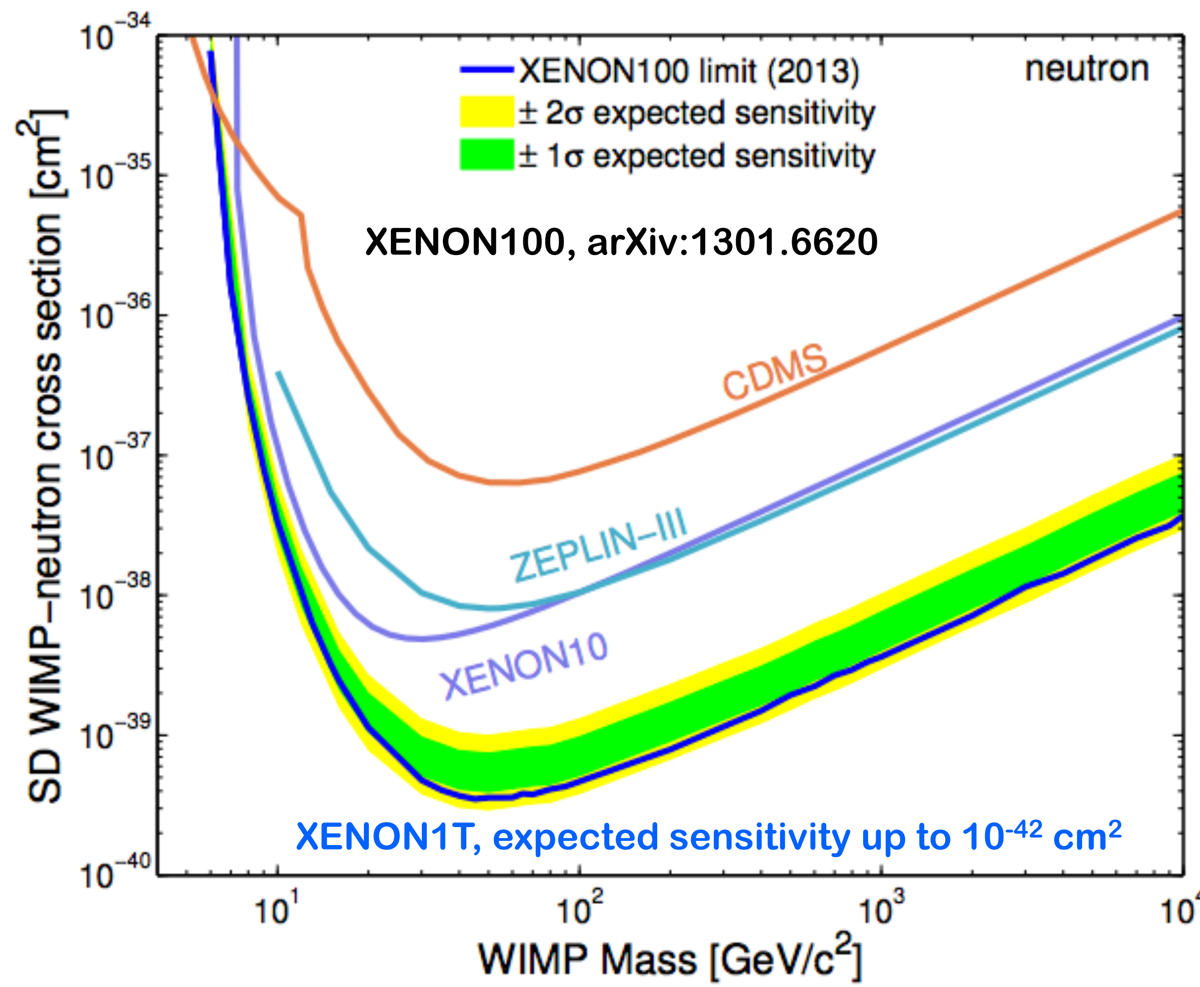
structure functions, huge nuclear uncertainties





Bayesian Inference framework

X = Mock data (1 realization) from phenomenological models arising from MSSM25

	$m_{\rm DM}$ [GeV]	σ_n^{SI} [cm^2]	σ_n^{SD} [cm^2]
A	60	3.7×10^{-49}	2.0×10^{-40}
B	100	8.8×10^{-46}	2.0×10^{-40}
C	500	1.1×10^{-45}	9.6×10^{-45}

X data

$$\theta = \{\theta_1, ..., \theta_n, \psi_a, ..., \psi_z\}$$

θ_i theoretical model parameters

ψ_k nuisance parameters = astrophysics, nuclear and systematics

$$\mathcal{P}(\theta|X)\mathrm{d}\theta \propto \mathcal{L}(X|\theta) \cdot \pi(\theta)\mathrm{d}\theta$$

Posterior probability function (PDF)

Likelihood (proper of each EXP)

Prior

Common prior choices that do not favour any parameter region

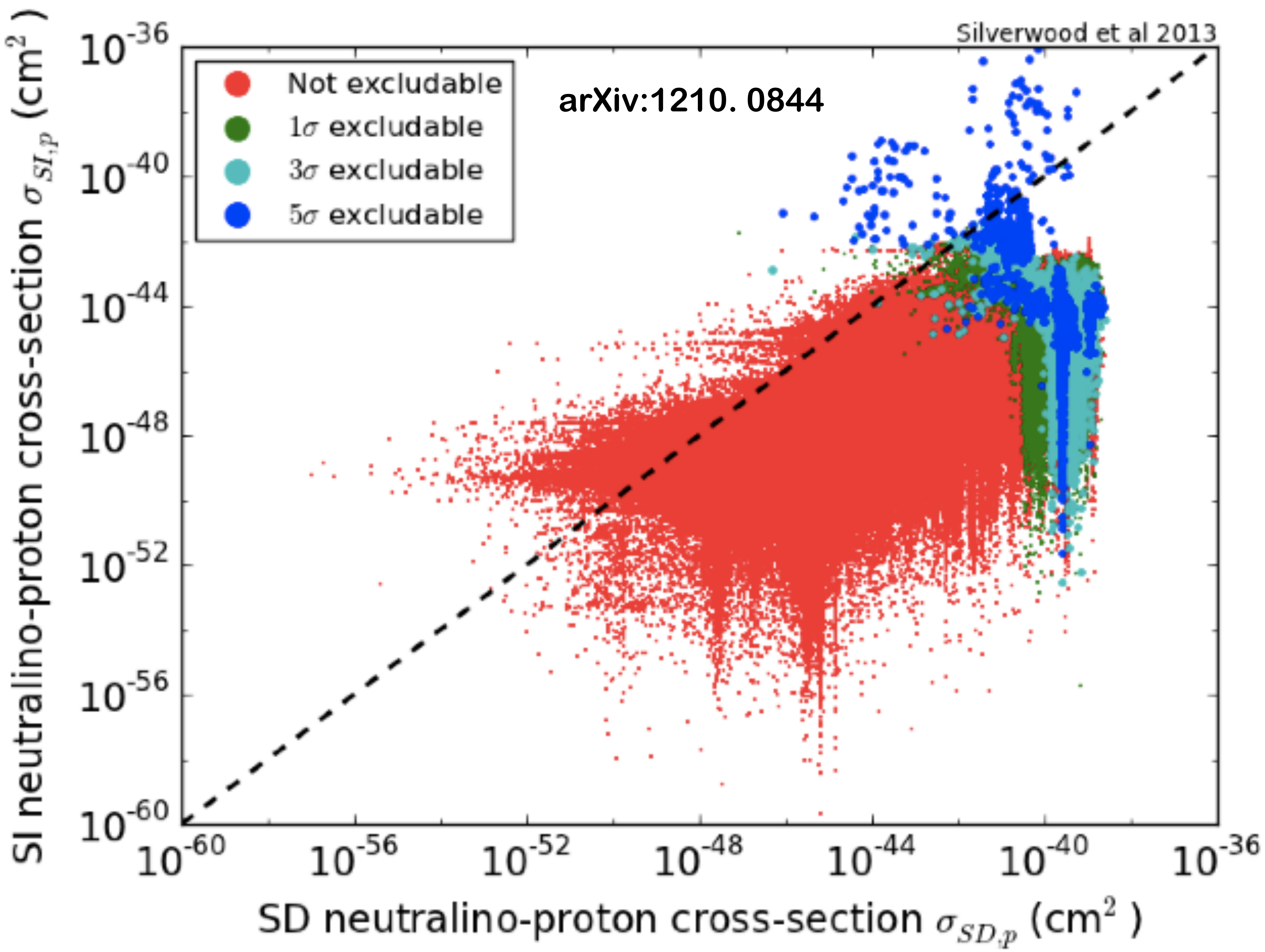
WIMP Parameters	Prior
$\log_{10}(m_{\rm DM}/\mathrm{GeV})$	$1 \to 3$
$\log_{10}(\sigma_p^{\rm SI}/\mathrm{cm}^2)$	$-60 \to -43$
$\log_{10}(\sigma_p^{\rm SD}/\mathrm{cm}^2)$	$-55 \to -38$

2D (1D) Posterior pdf sampled with MultiNest and marginalized over nuisance/other physical parameters

$$\mathcal{P}_{\rm mar}(\theta_1, ..., \theta_n|X) \propto \int \mathrm{d}\psi_1 ... \mathrm{d}\psi_m \; \mathcal{P}(\theta_1, ..., \theta_n, \psi_1 ..., \psi_m|X)$$

Particle physics models

- **Several models predict both a SI and SD contribution to the direct detection events**



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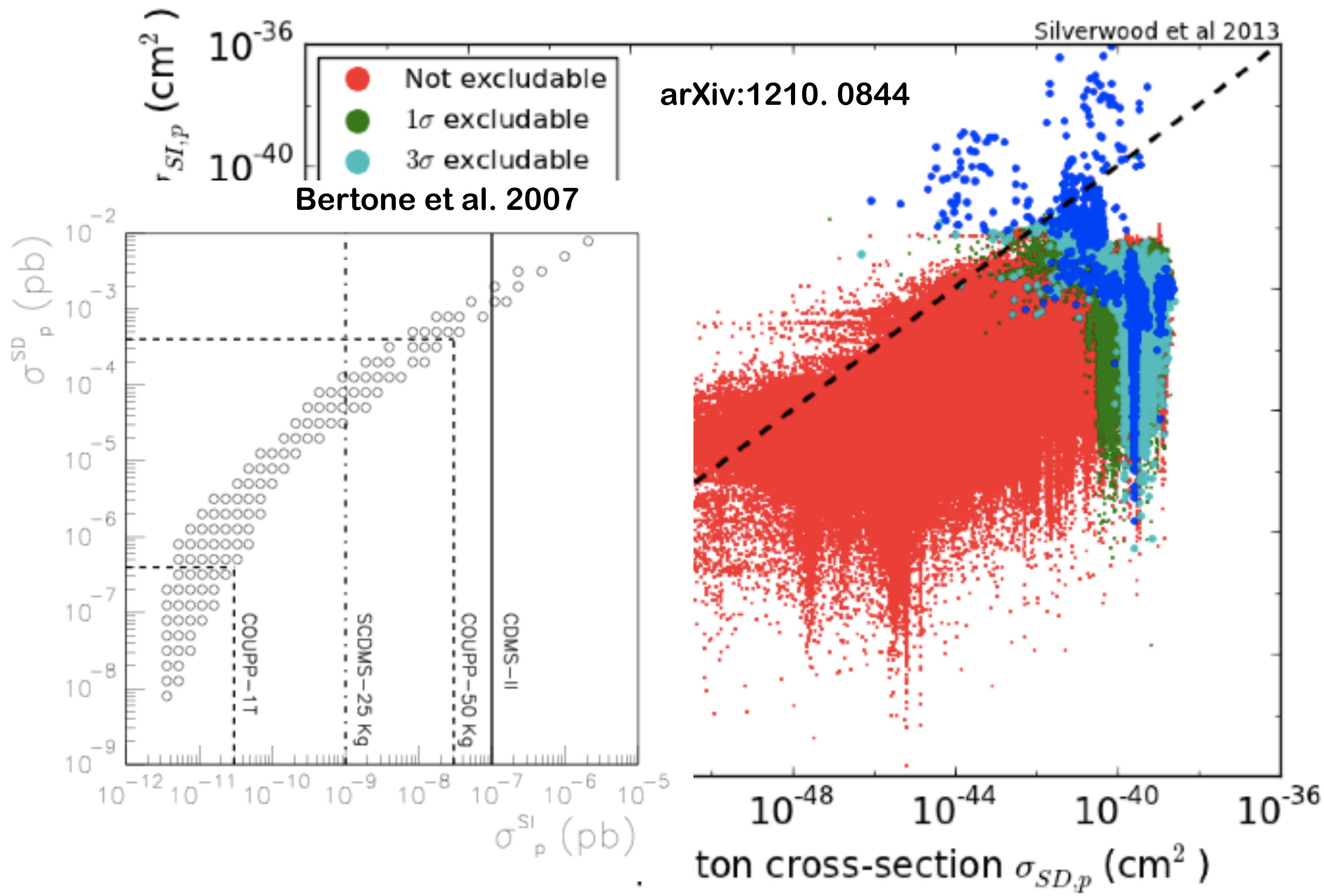

Particle physics models

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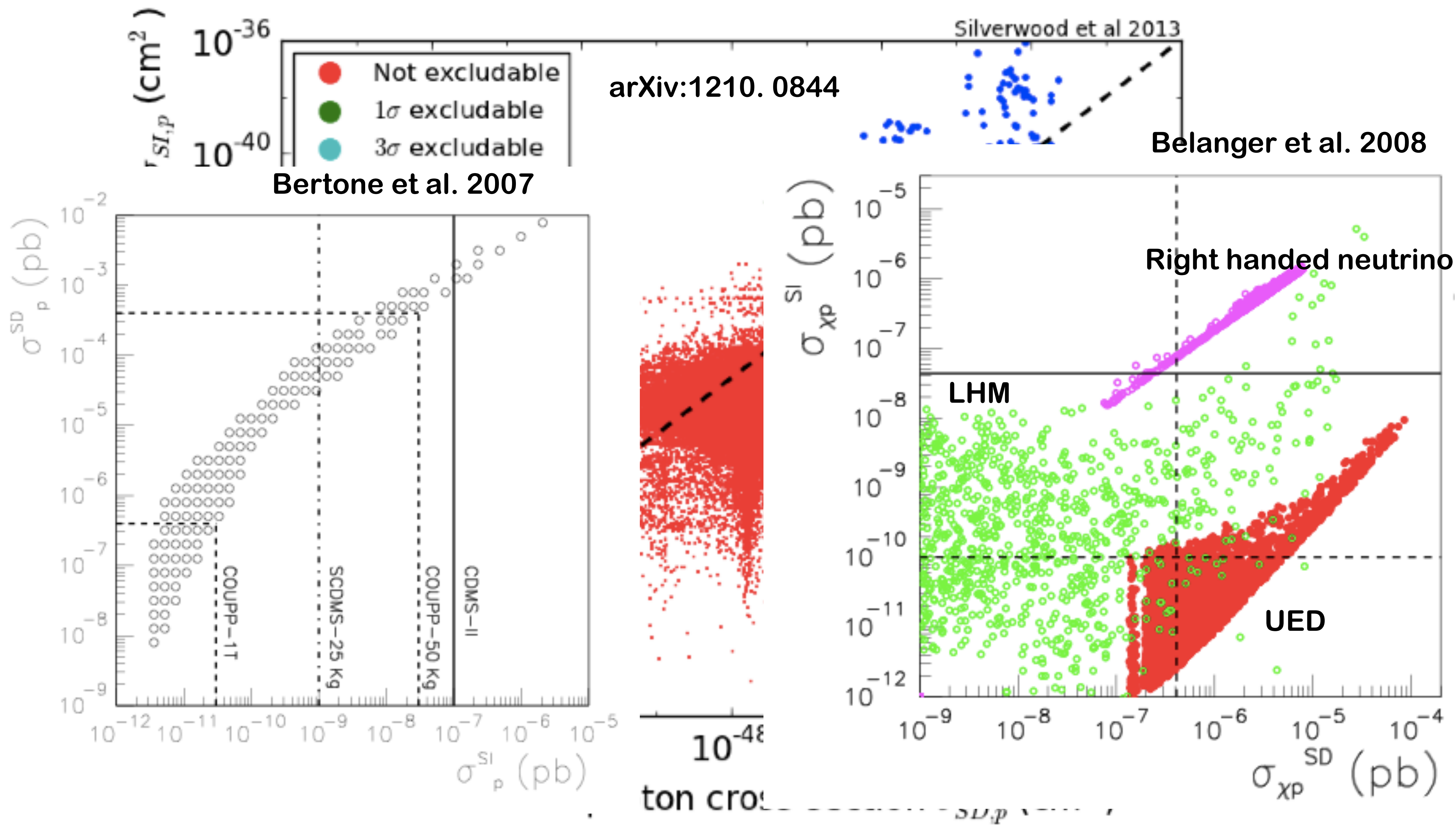
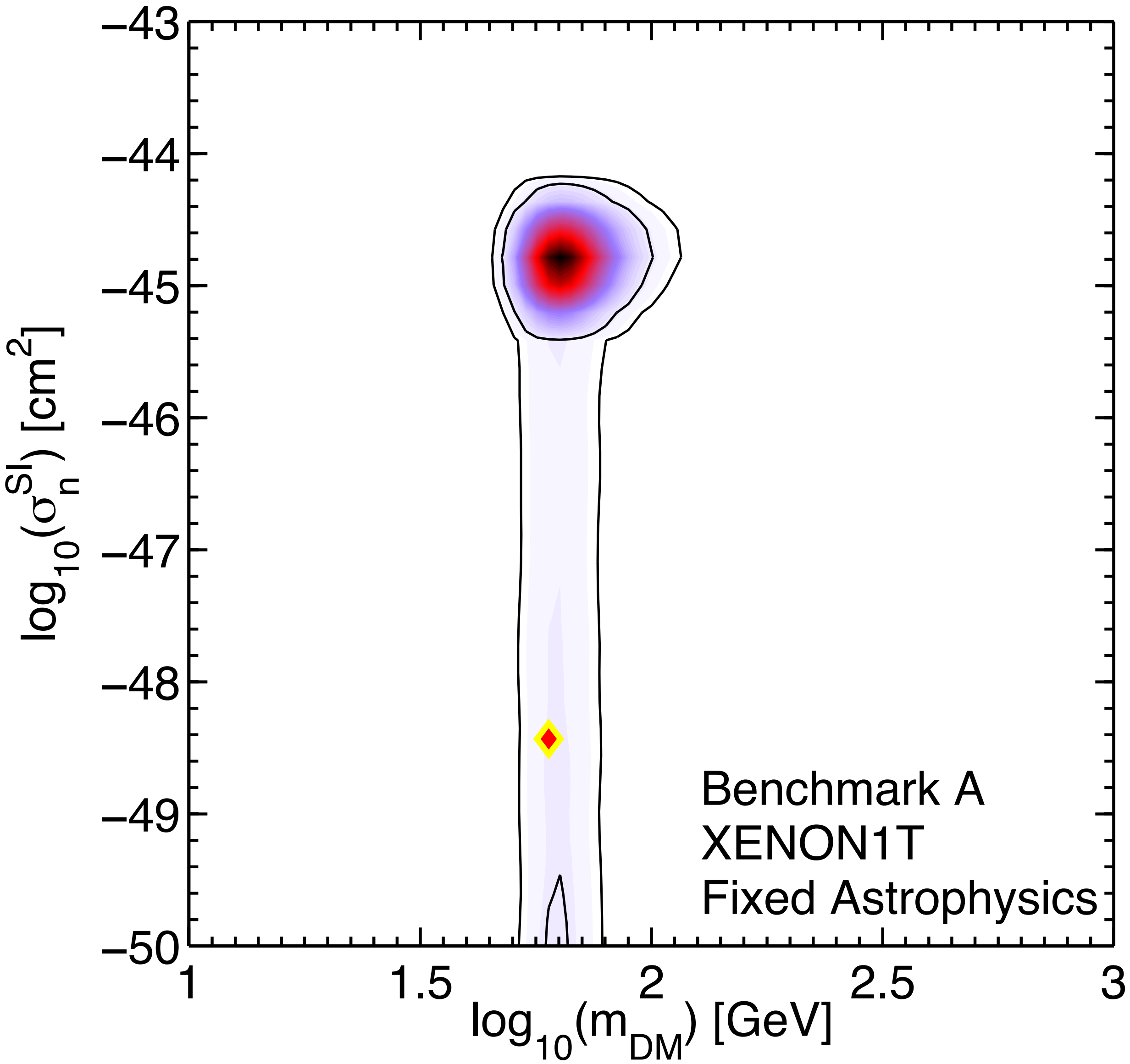
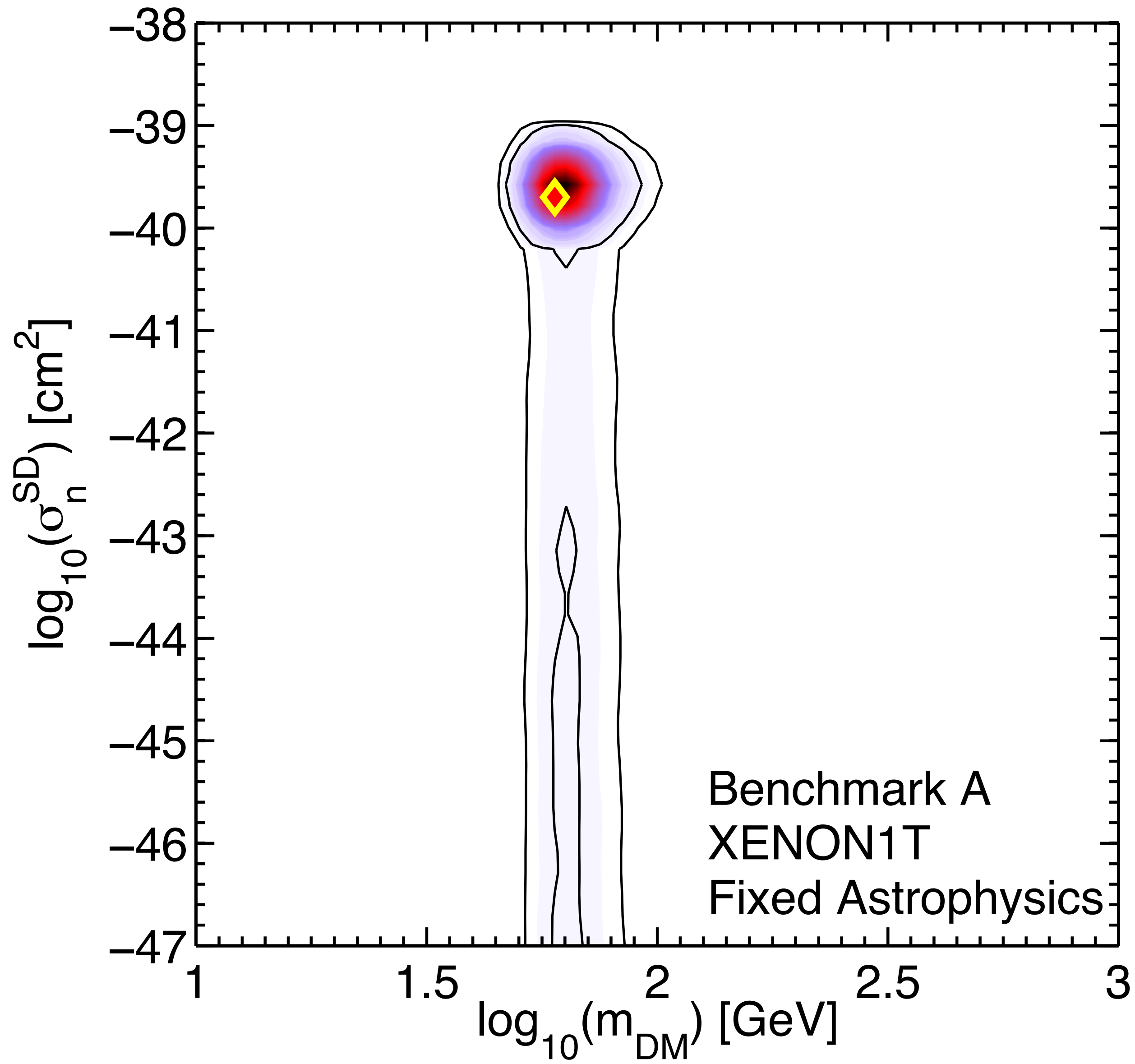


Inference for XENON1T

- Degeneracy between SI and SD contributions to the number of observed events

$S^{\rm SI}_{\rm Xe}(\Theta)$	$S^{SD}_{\rm Xe}(\Theta)$ (CEFT)
1.1	422.8
252.8	356.1
74.4	4.4×10^{-3}



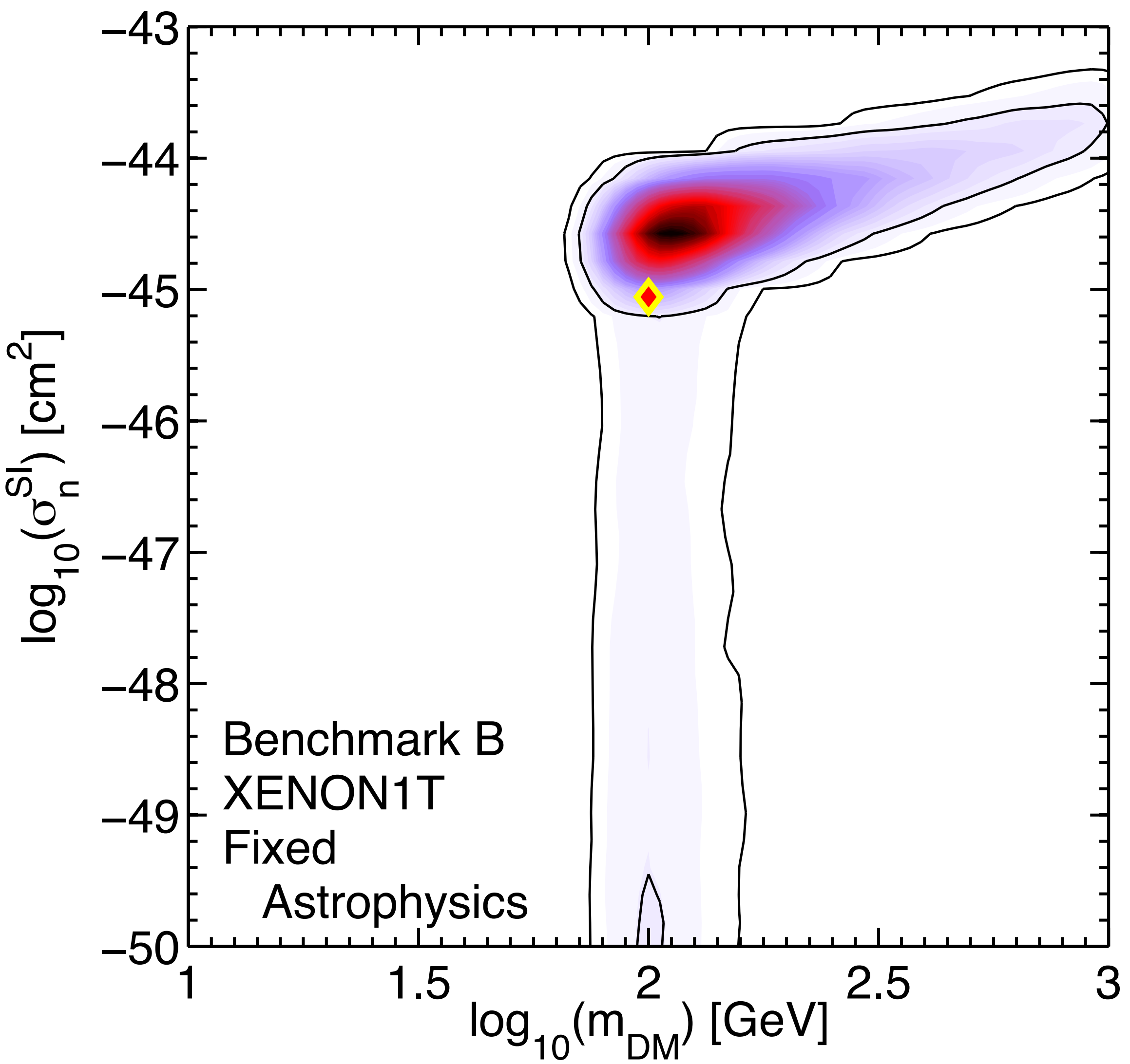


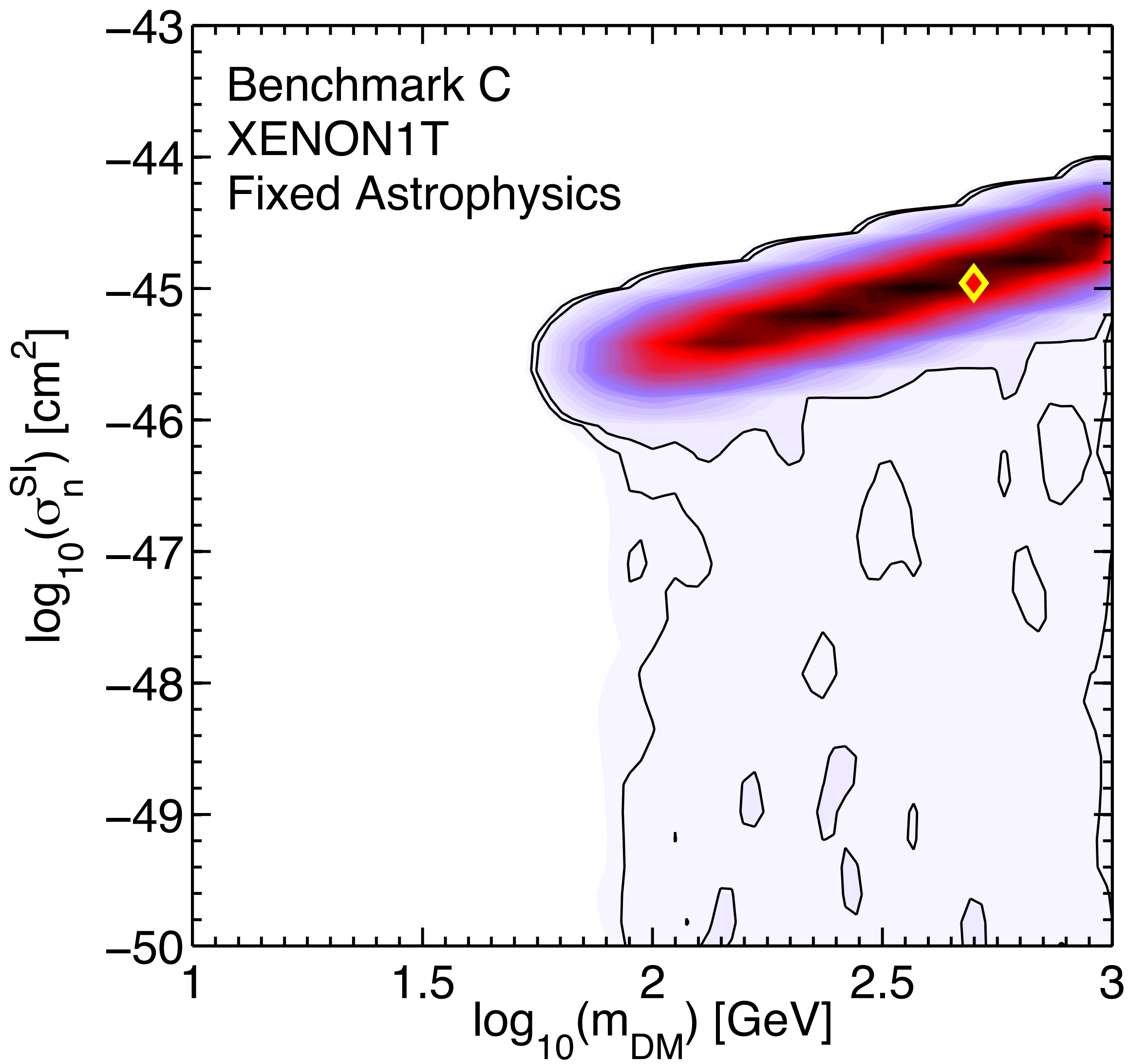
2D marginalized posterior pdf for 68% and 95% C.L.

No nuisance parameters

Inference for XENON1T

- Usual limitation of direct detection experiments: for $m_{DM} > m_{nucleus}$ the rate goes as $1/m_{DM}$ and the reconstruction becomes affected by the diminished sensitivity;
- The features are unphysical and are due to difficulties in sampling a flat likelihood.



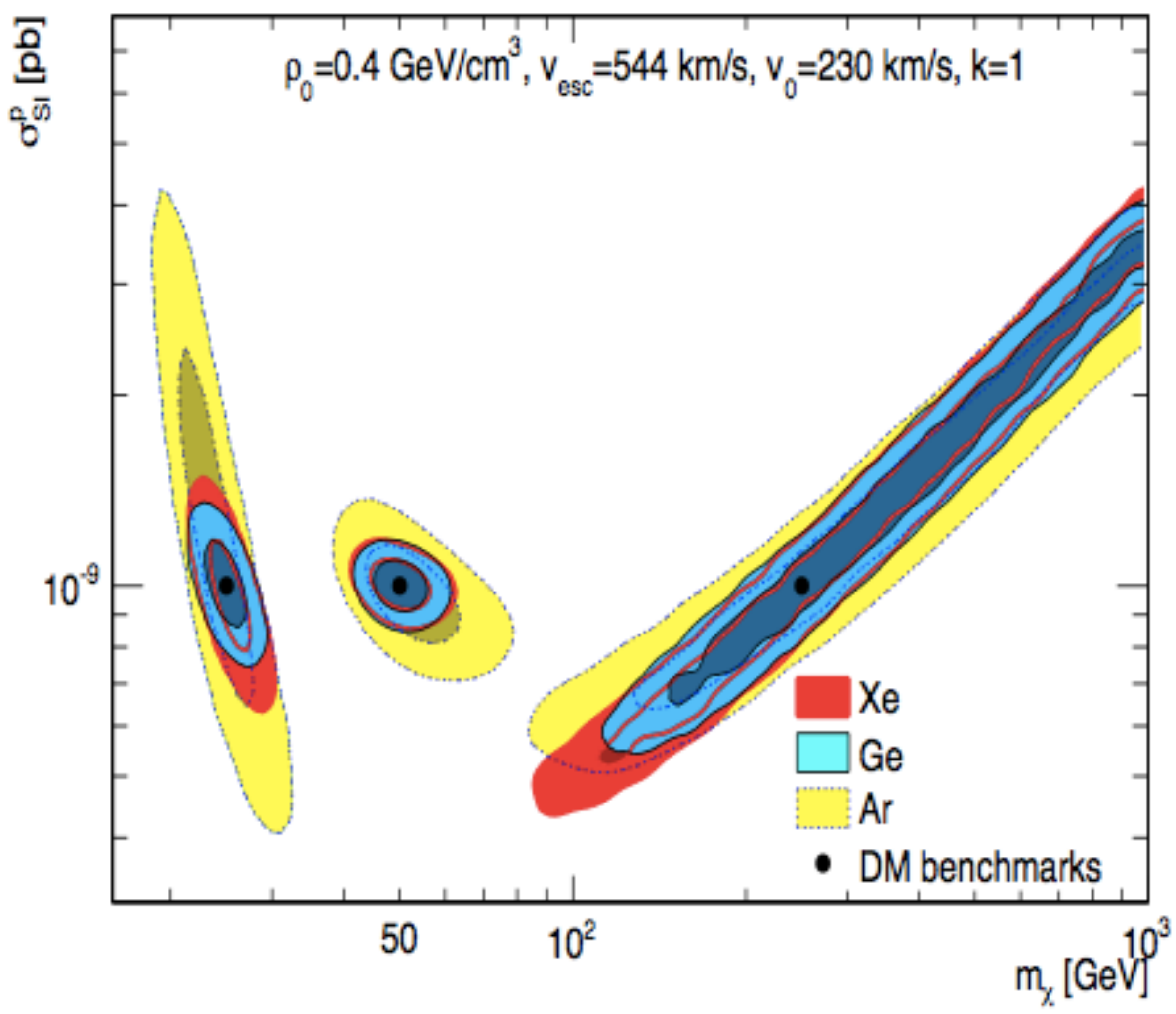


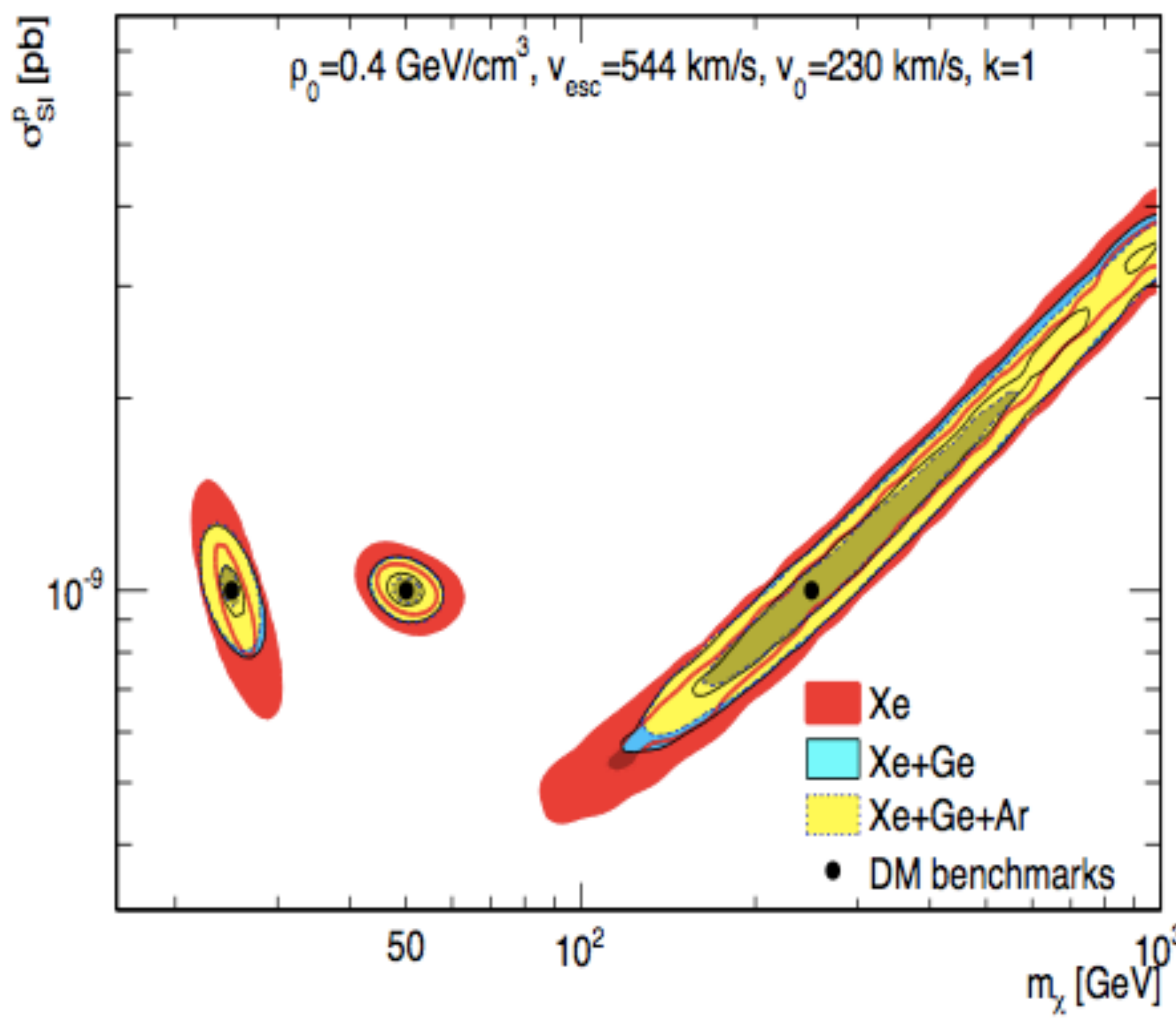
2D marginalized posterior pdf for 68% and 95% C.L.

No nuisance parameters

Mass degeneracy

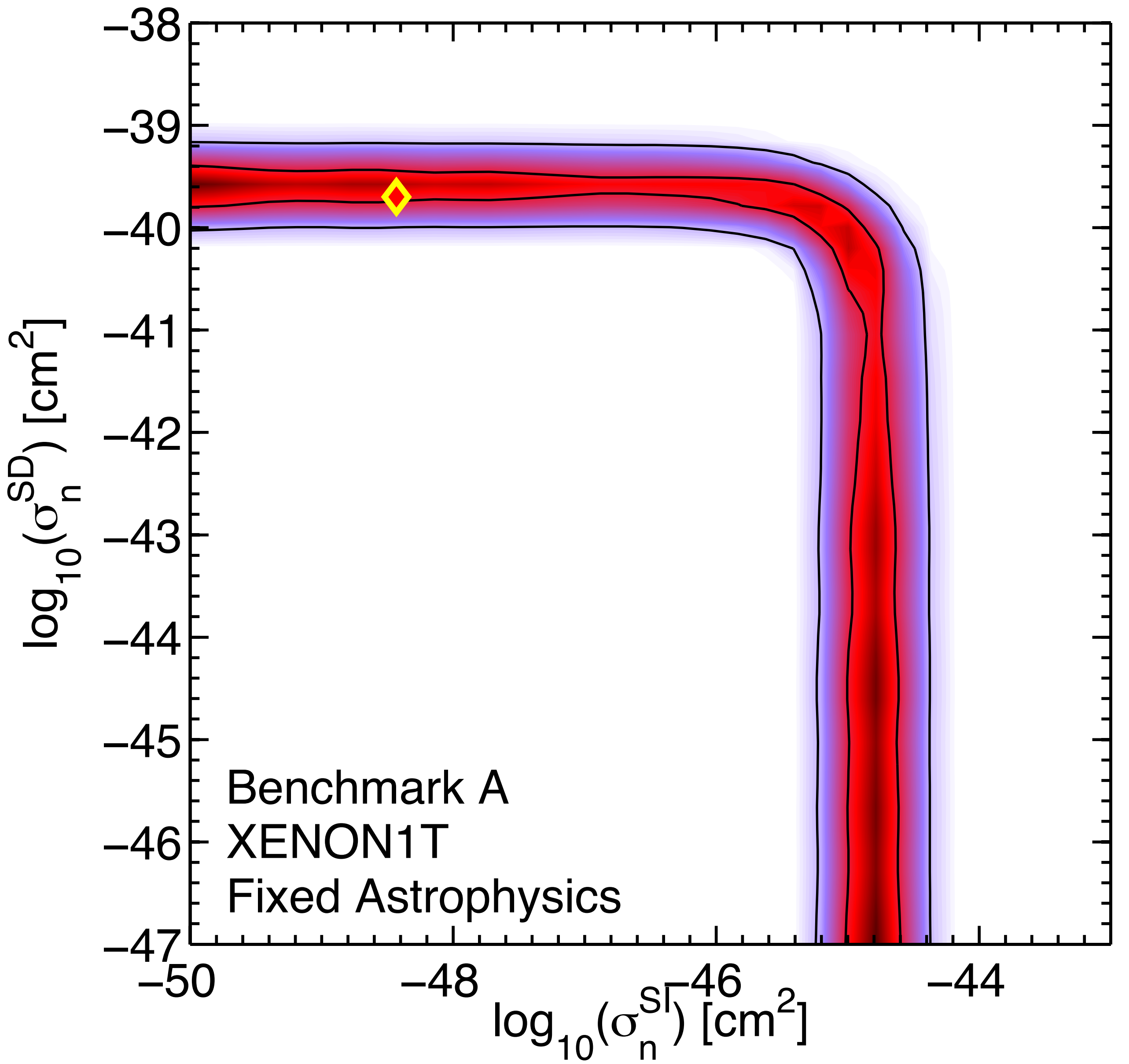
• **A possible way to reduce uncertainties in the mass reconstruction is the combination of several target materials (Pato et al. arXiv:1012.3458)**

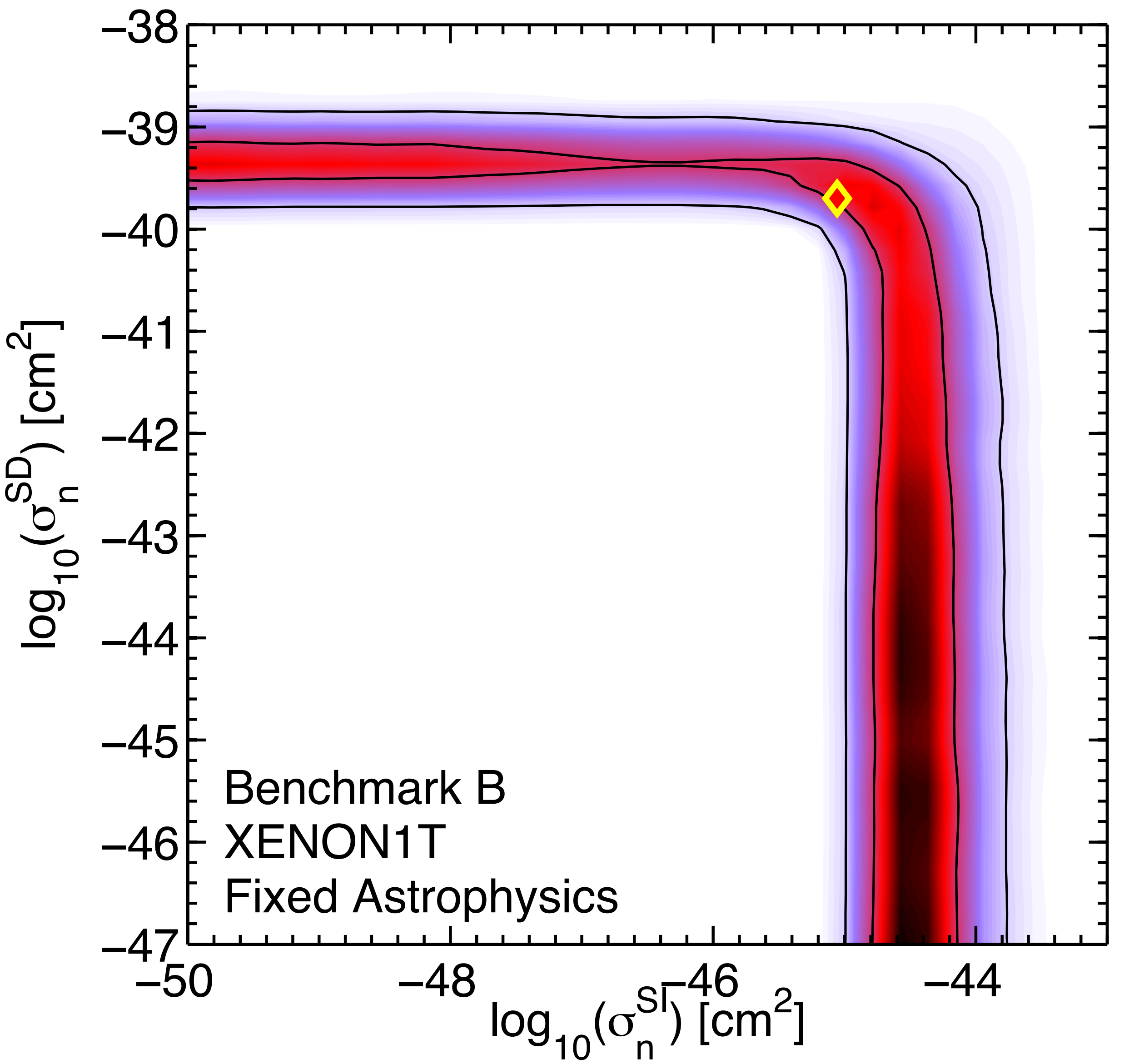




Inference for XENON1T

- **The degeneracy can be seen as well in the plane SI and SD**





2D marginalized posterior pdf for 68% and 95% C.L.

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Inference for XENON1T

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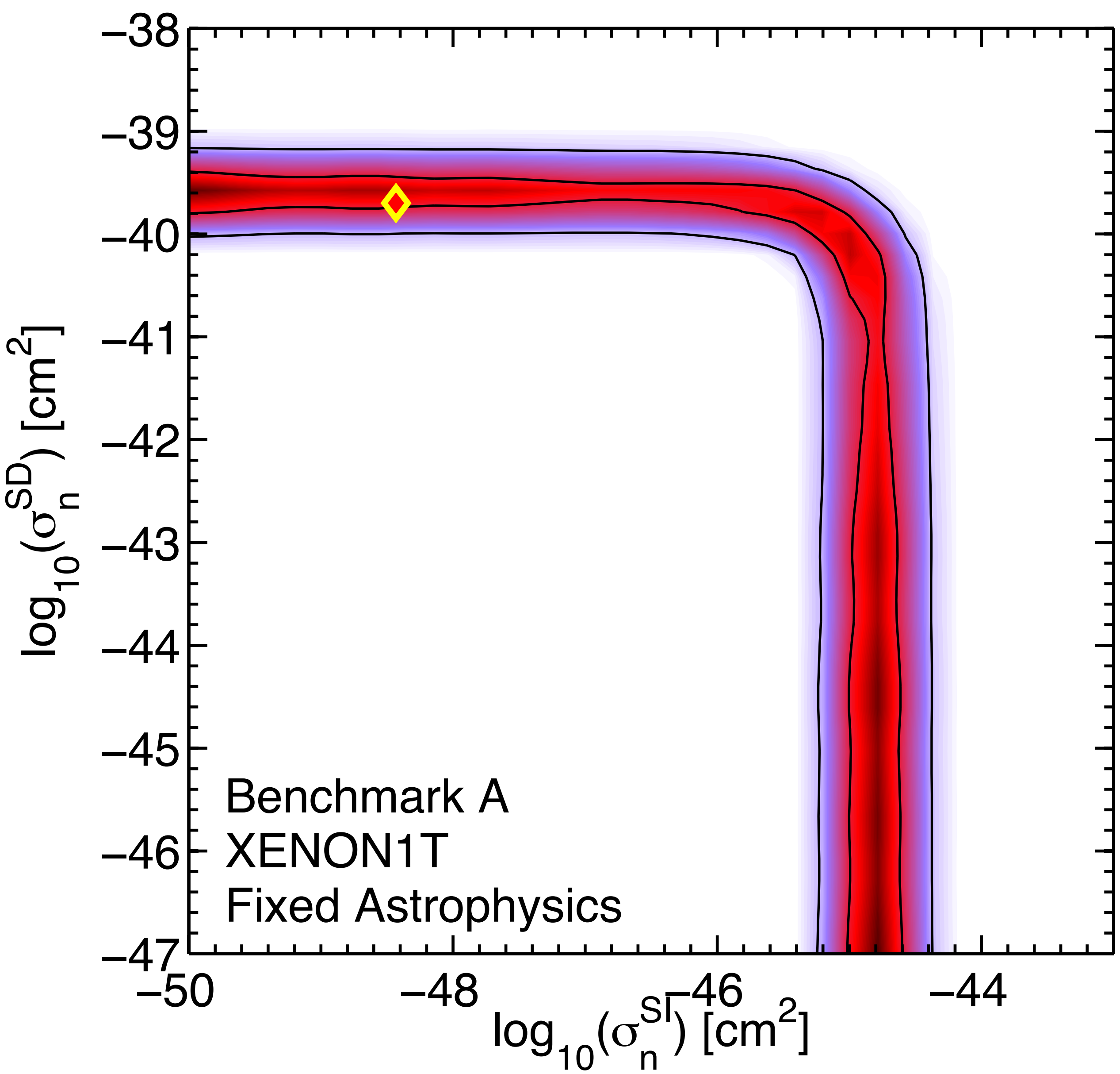
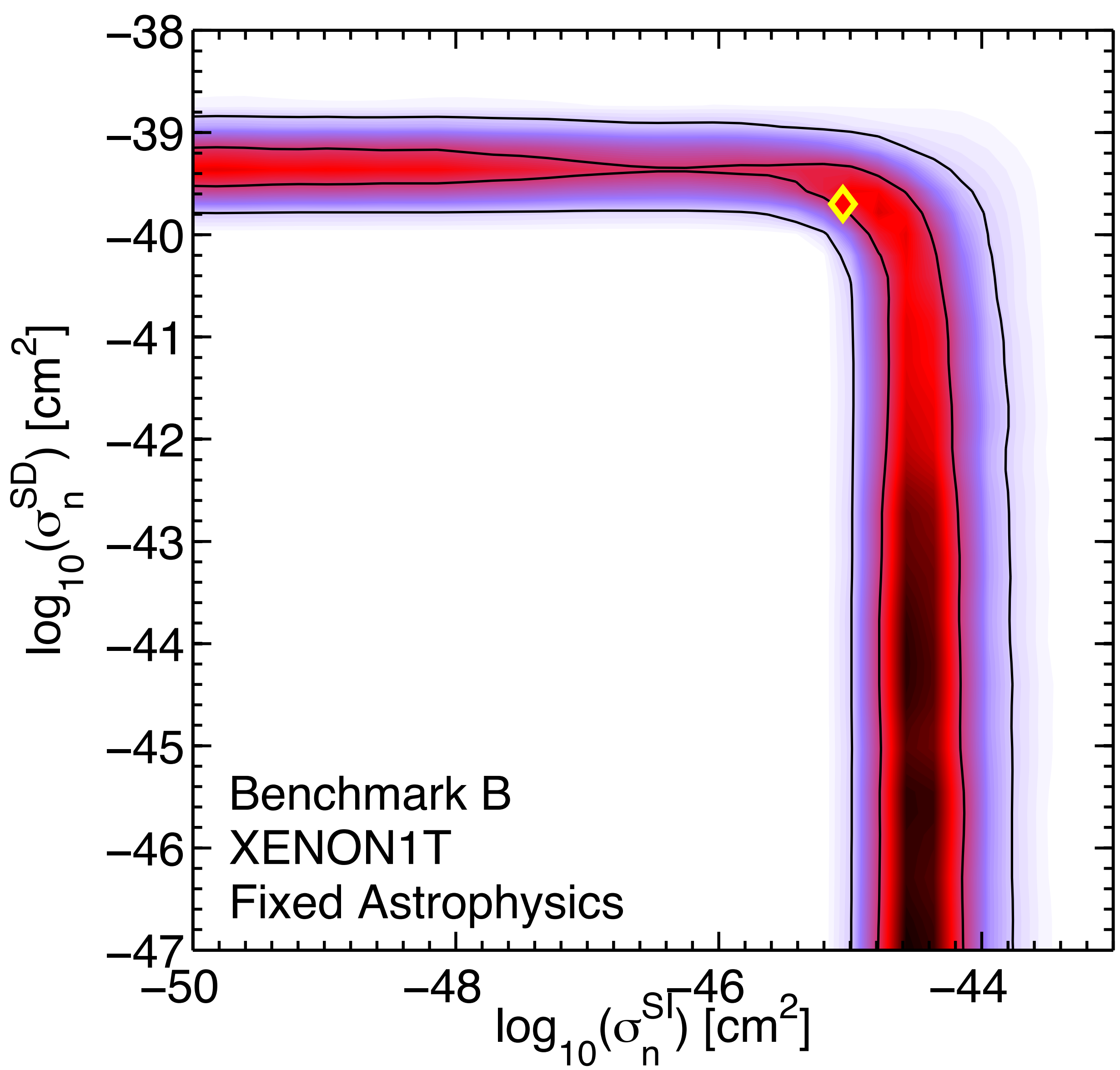
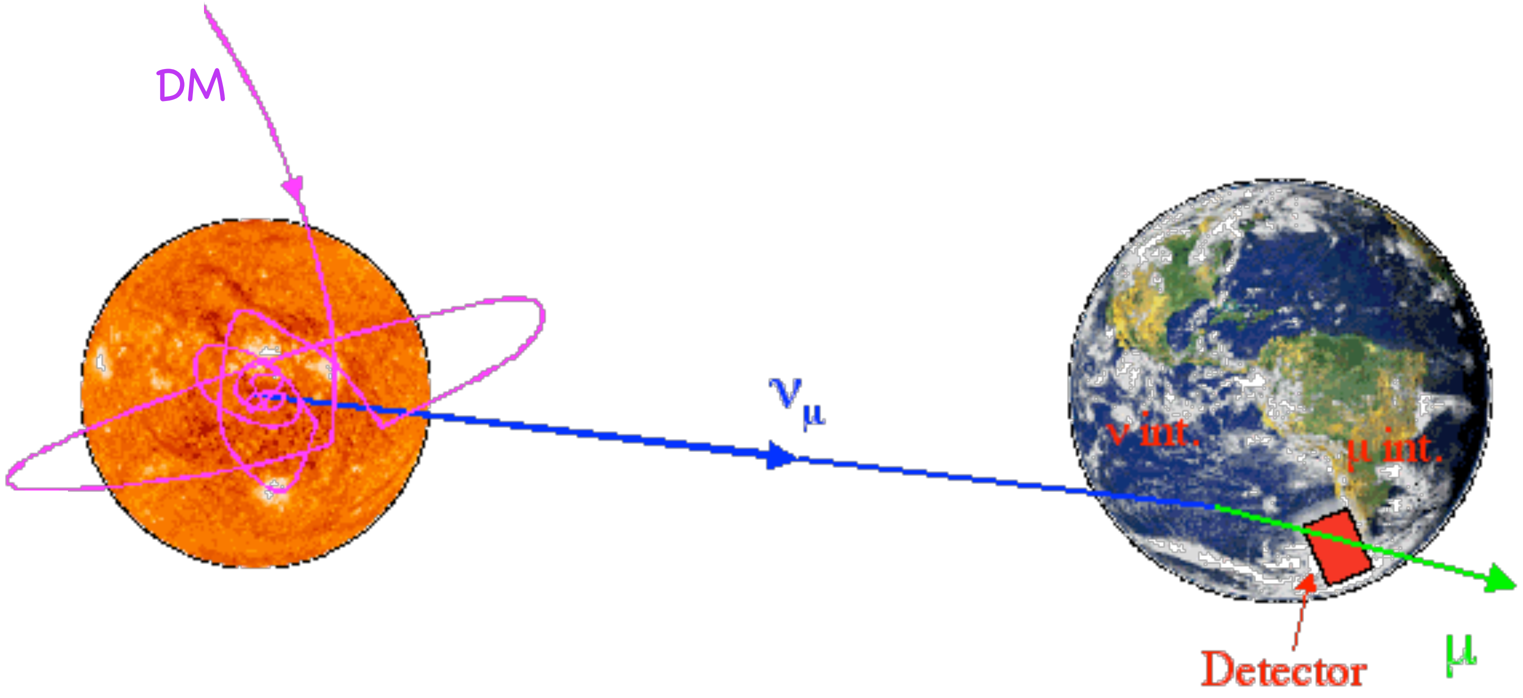




2D marginalized posterior pdf for 68% and 95% C.L.

No nuisance parameters

IceCube 86 including Deepcore



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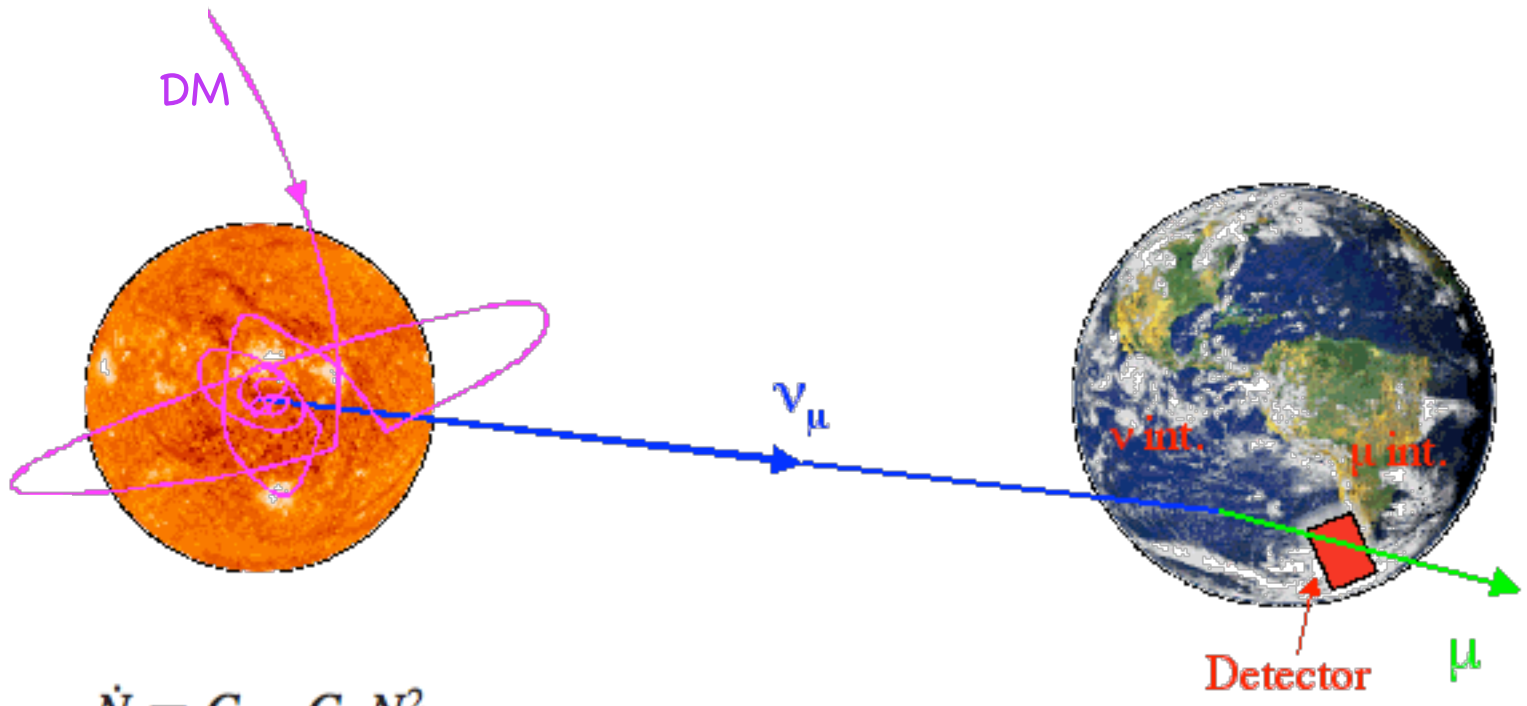
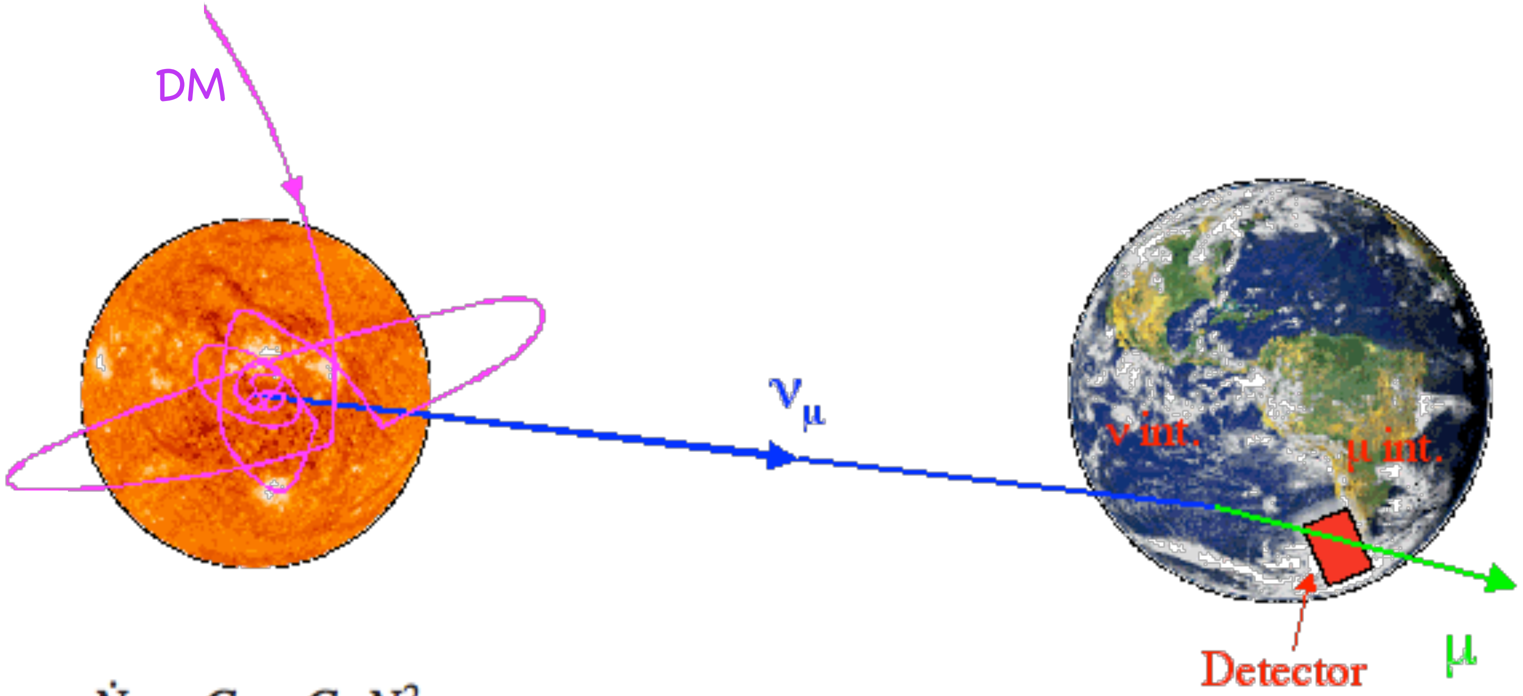


$$\dot{N} = C - C_A N^2$$

IceCube 86 including Deepcore



$$\dot{N} = C - C_A N^2$$

$$\Gamma_A = \frac{C_A}{2} N_{\rm eq}^2 = \frac{C}{2}$$

steady state approximation

(allows to get rid of $\langle \sigma_a v \rangle$)

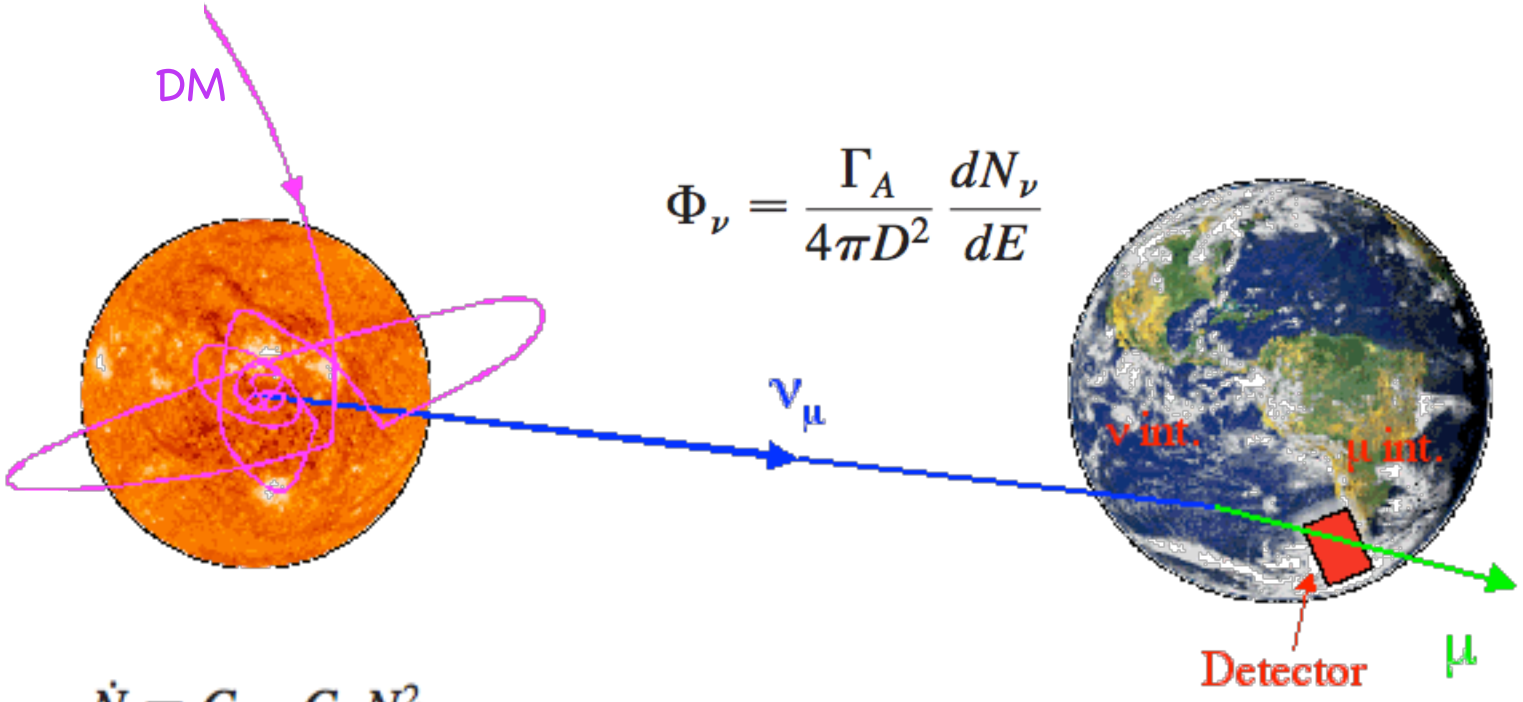
$$C_c = \frac{\rho_\odot}{m_{\rm DM}} \int_0^R {\rm d}r \sum_i \frac{{\rm d}C_i}{{\rm d}V} 4\pi r^2$$

$$\frac{{\rm d}C_i}{{\rm d}V} = \int_0^{u_{\rm max}} {\rm d}u \frac{\hat{f}(u)}{u} w \Omega_{v,i}^-(w)$$

↓

$$\sigma_i = \begin{cases} \sigma^{\rm SI} + \sigma^{\rm SD} & \text{for } i = 1, \\ \beta^2 \sigma^{\rm SI} A_i^2 & \text{for } i \geq 2. \end{cases}$$

IceCube 86 including Deepcore



$$\Phi_\nu = \frac{\Gamma_A}{4\pi D^2}\frac{dN_\nu}{dE}$$

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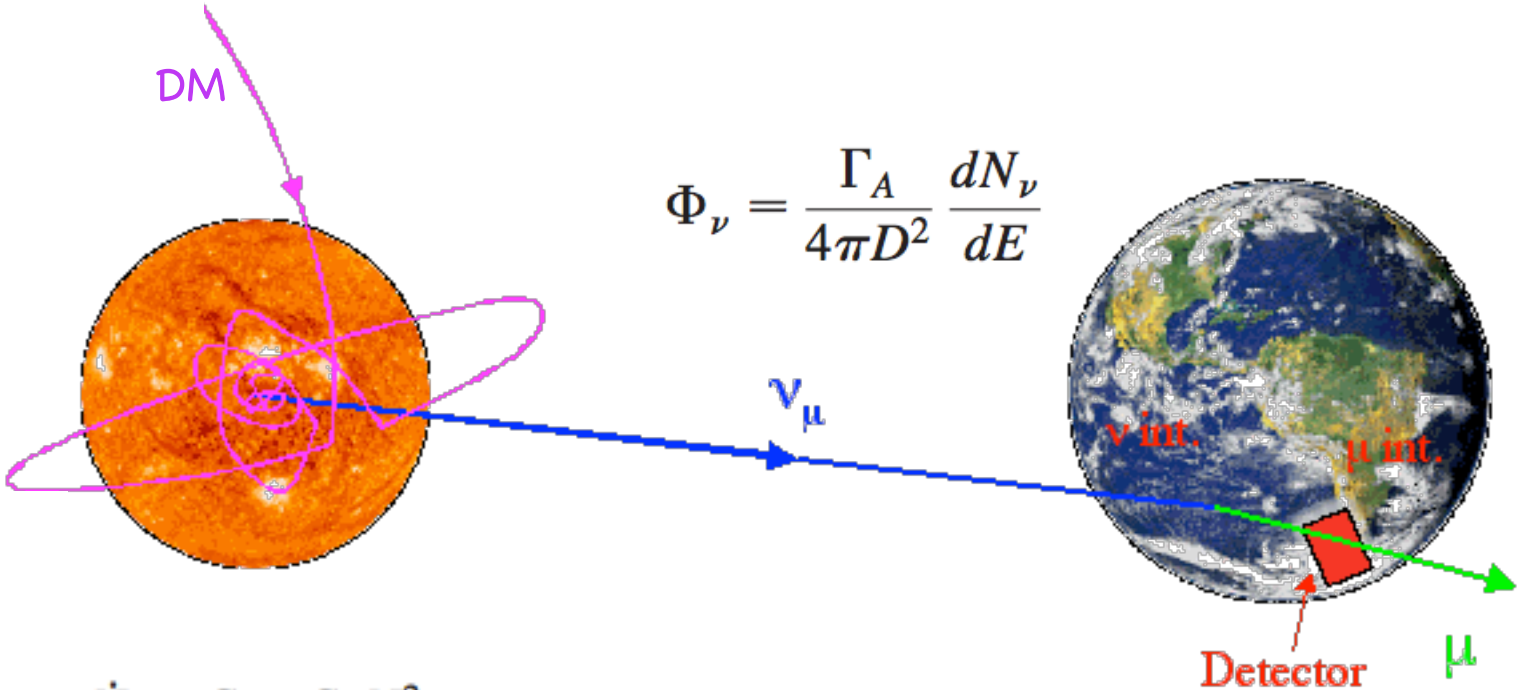

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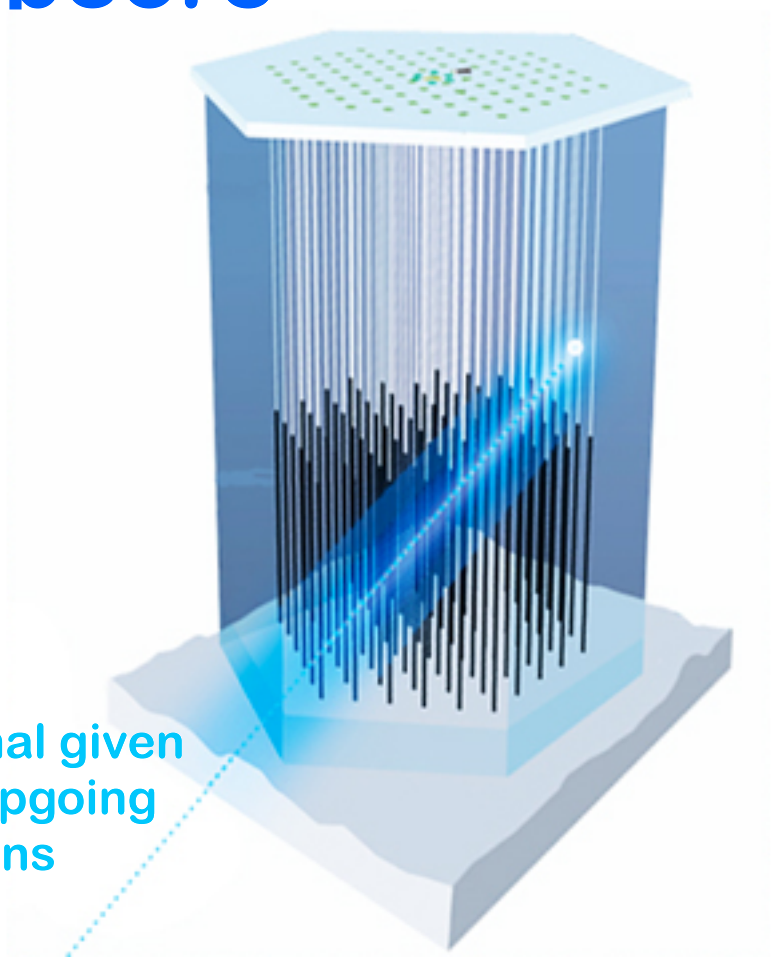

Signal given by upgoing muons

$$\dot{N} = C - C_A N^2$$

$$\Gamma_A = \frac{C_A}{2}N_{\rm eq}^2 = \frac{C}{2}$$

steady state approximation

(allows to get rid of $\langle\sigma_a v\rangle$)

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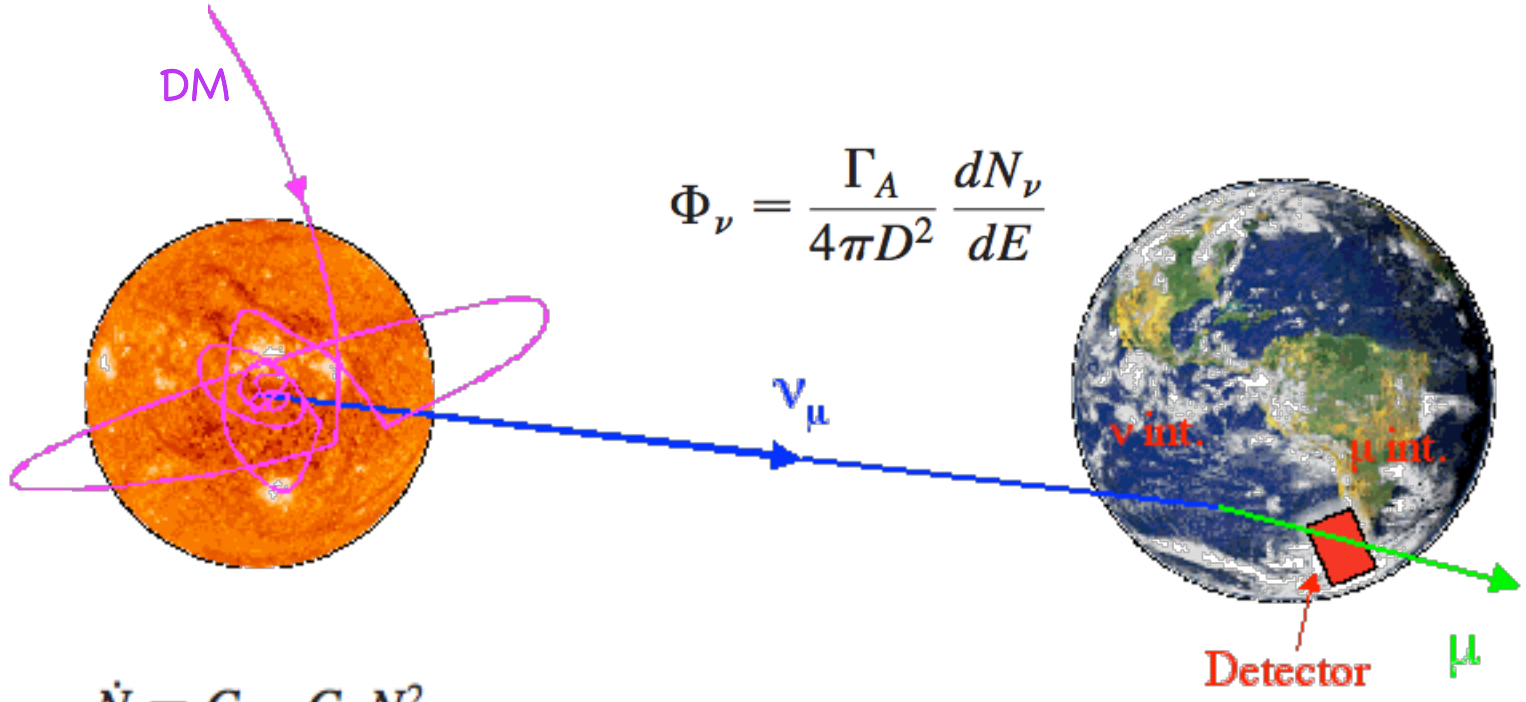

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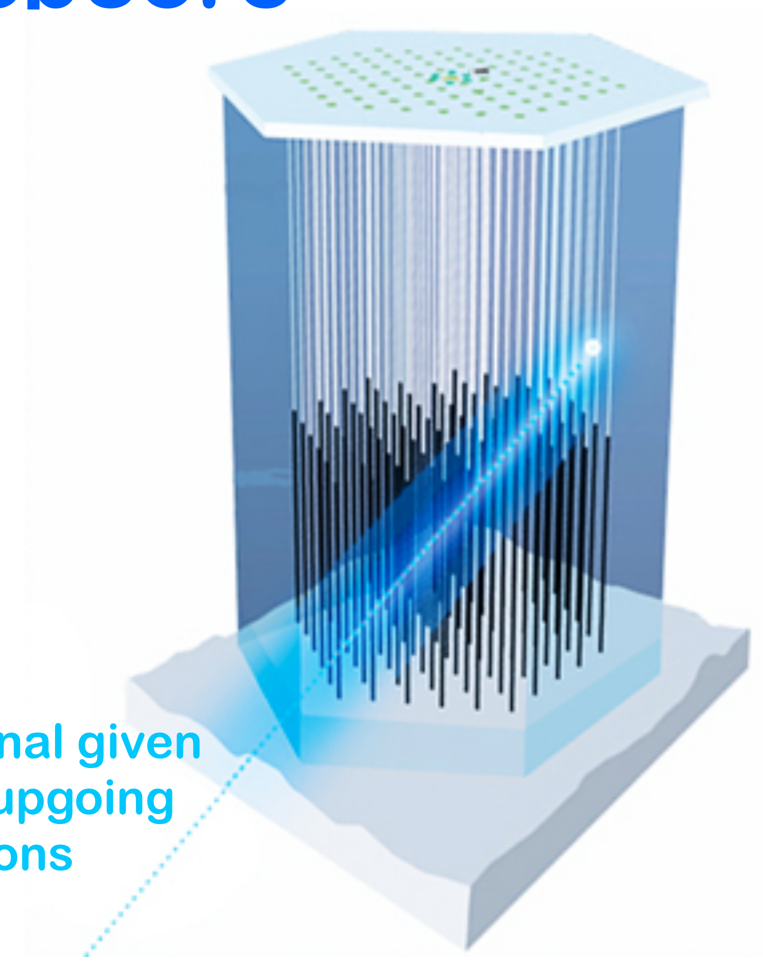

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(allows to get rid of $\langle \sigma_a v \rangle$)

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DM parameters

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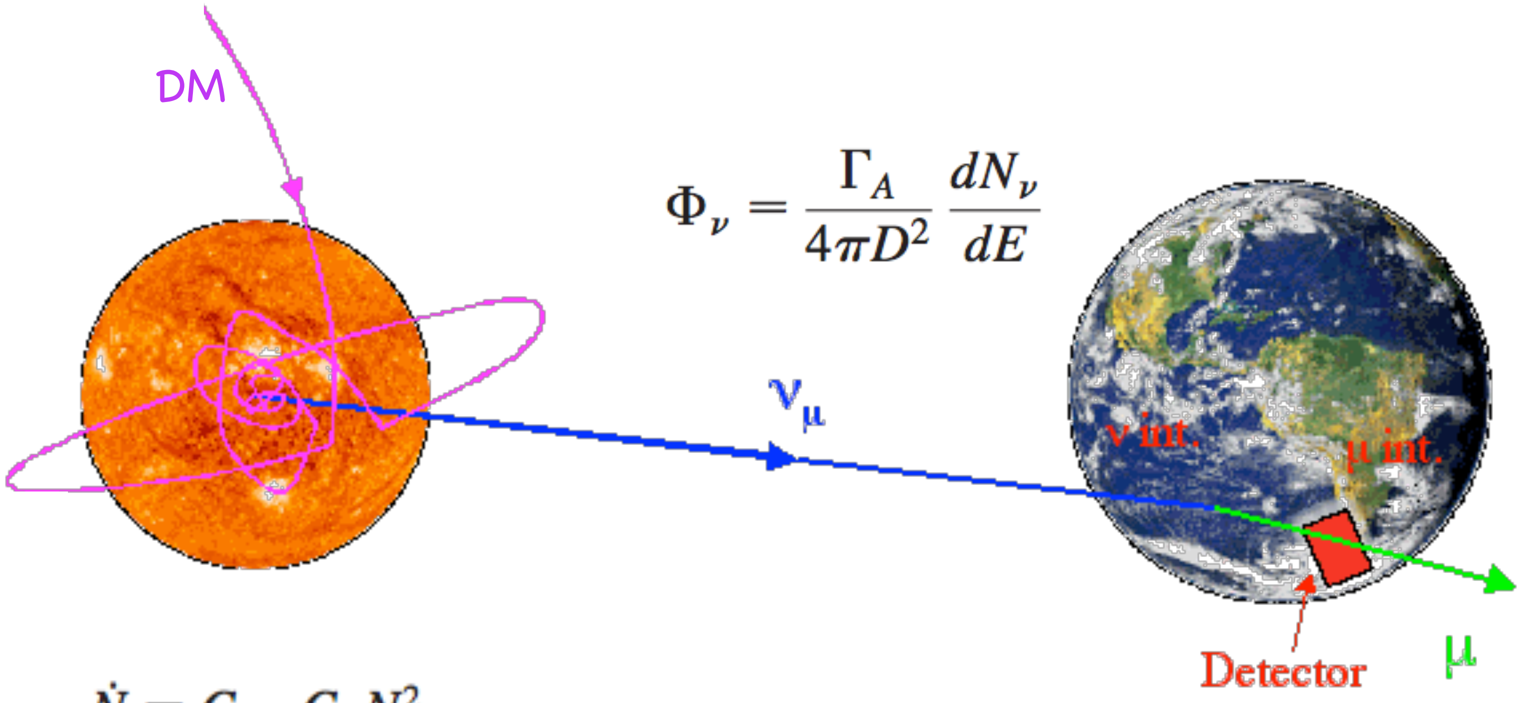
IceCube 86 including Deepcore



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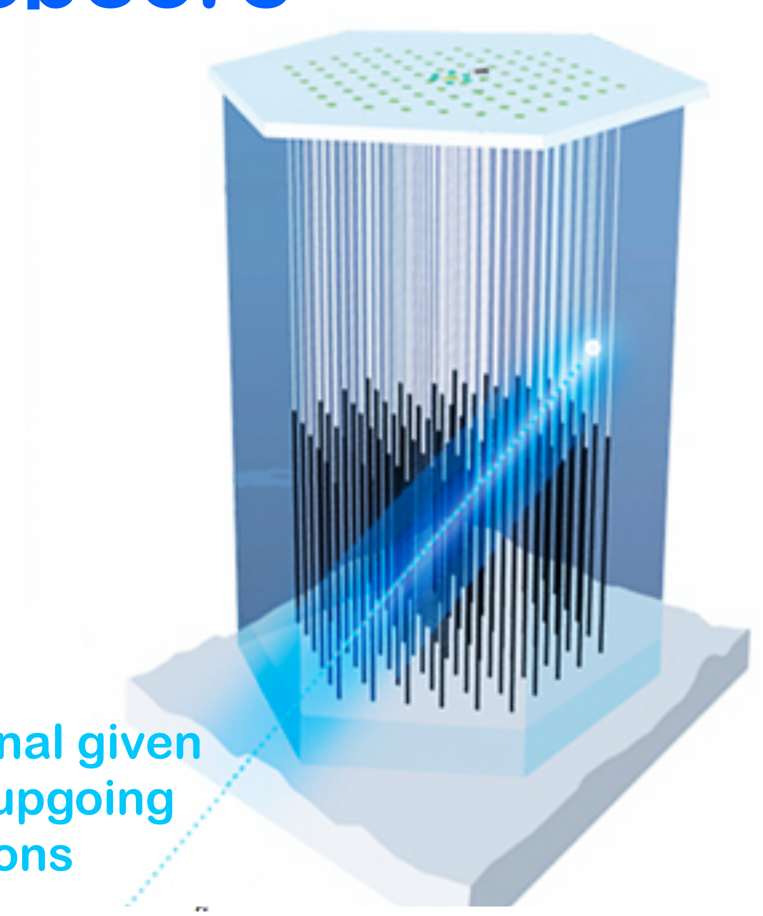

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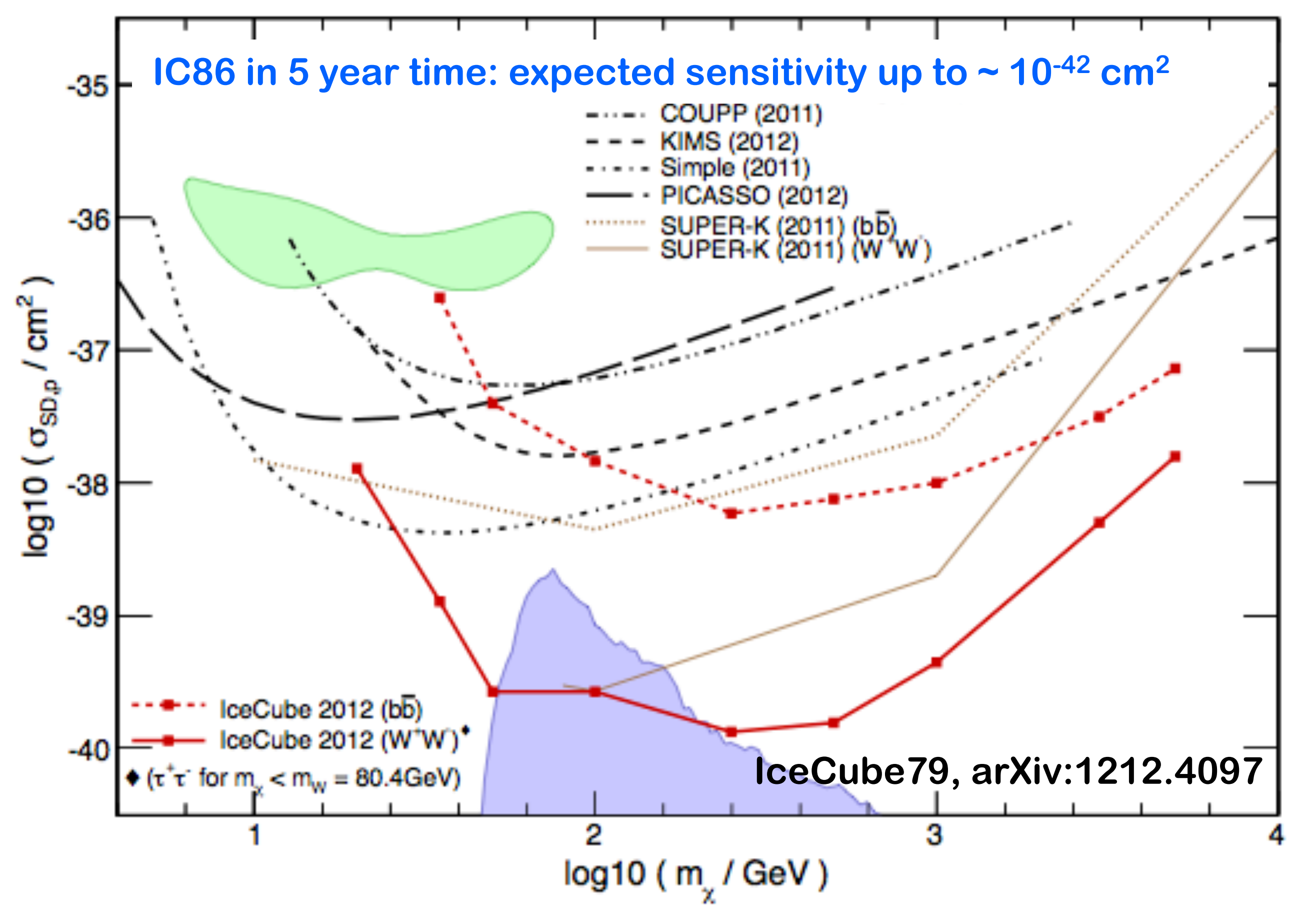
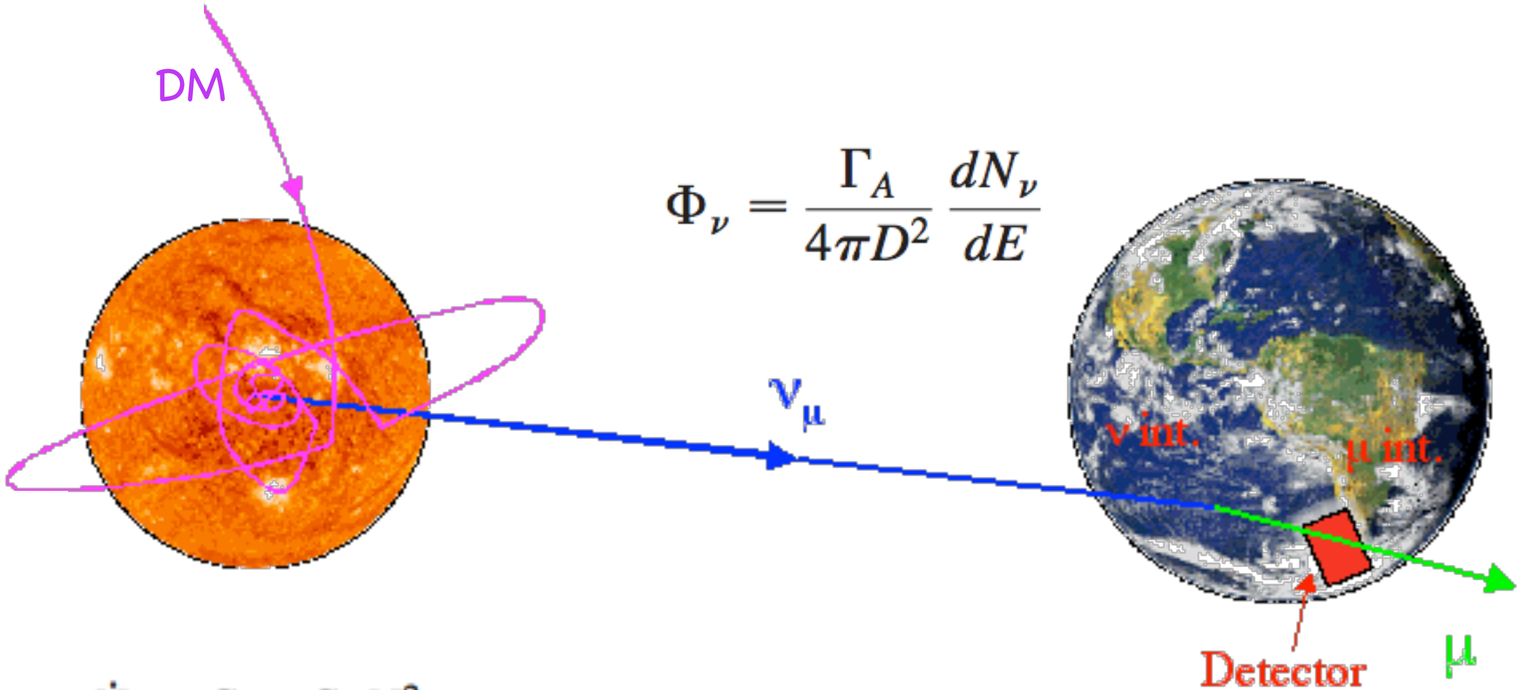
DM parameters

IC86 in 5 year time: expected sensitivity up to ~ 10^{-42} cm^2



IceCube79, arXiv:1212.4097

IceCube 86 including Deepcore



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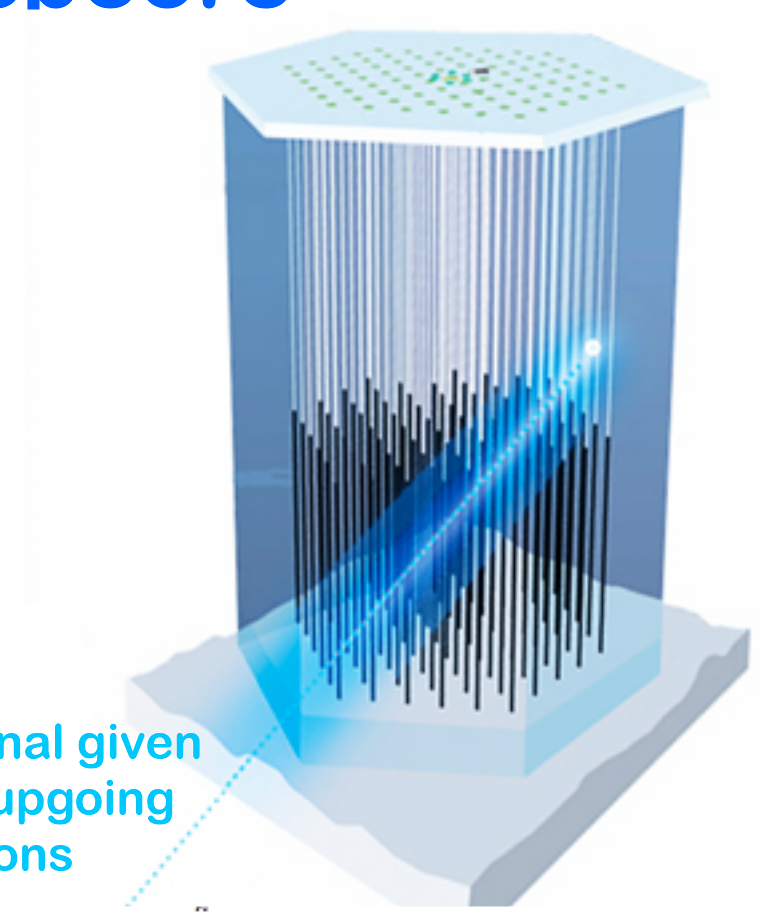

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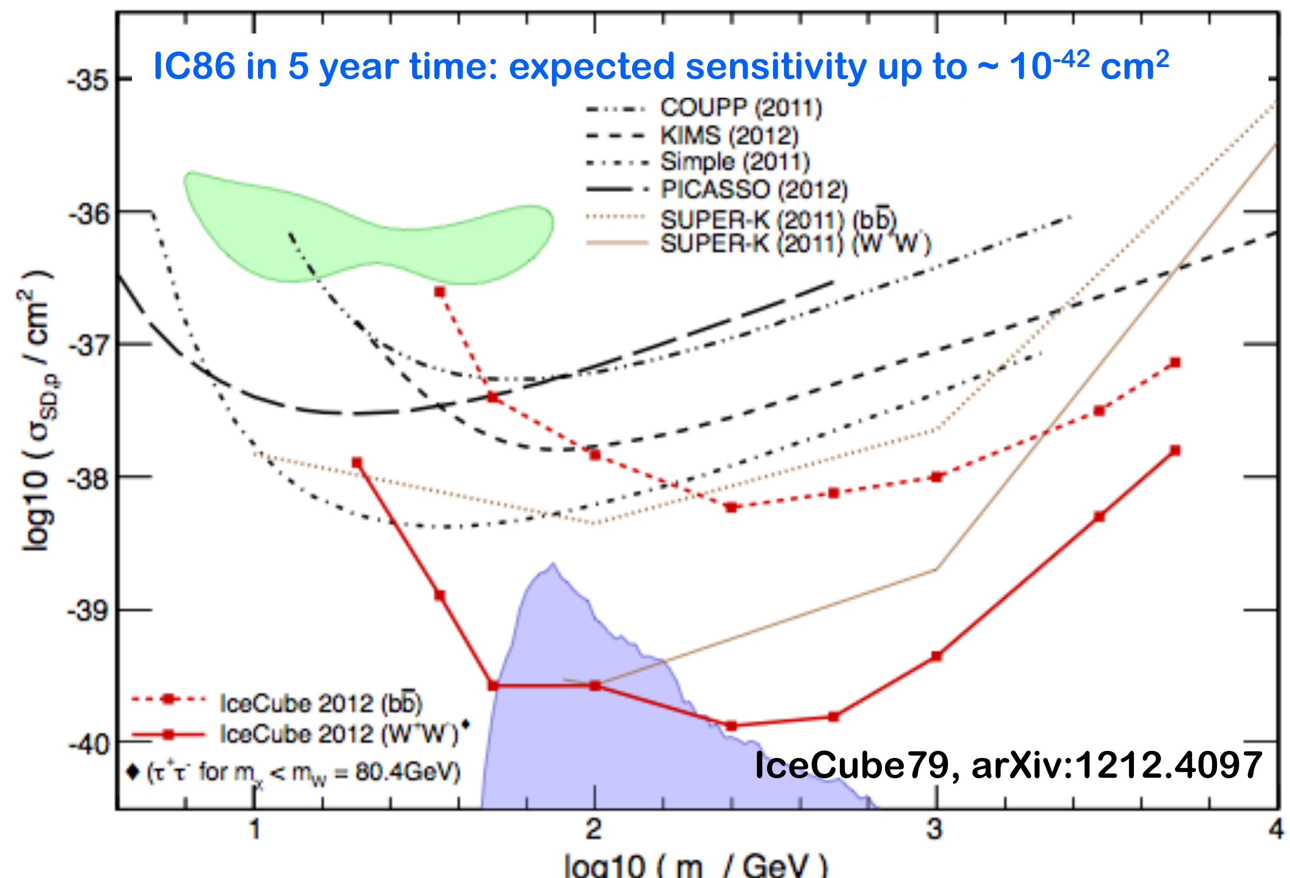
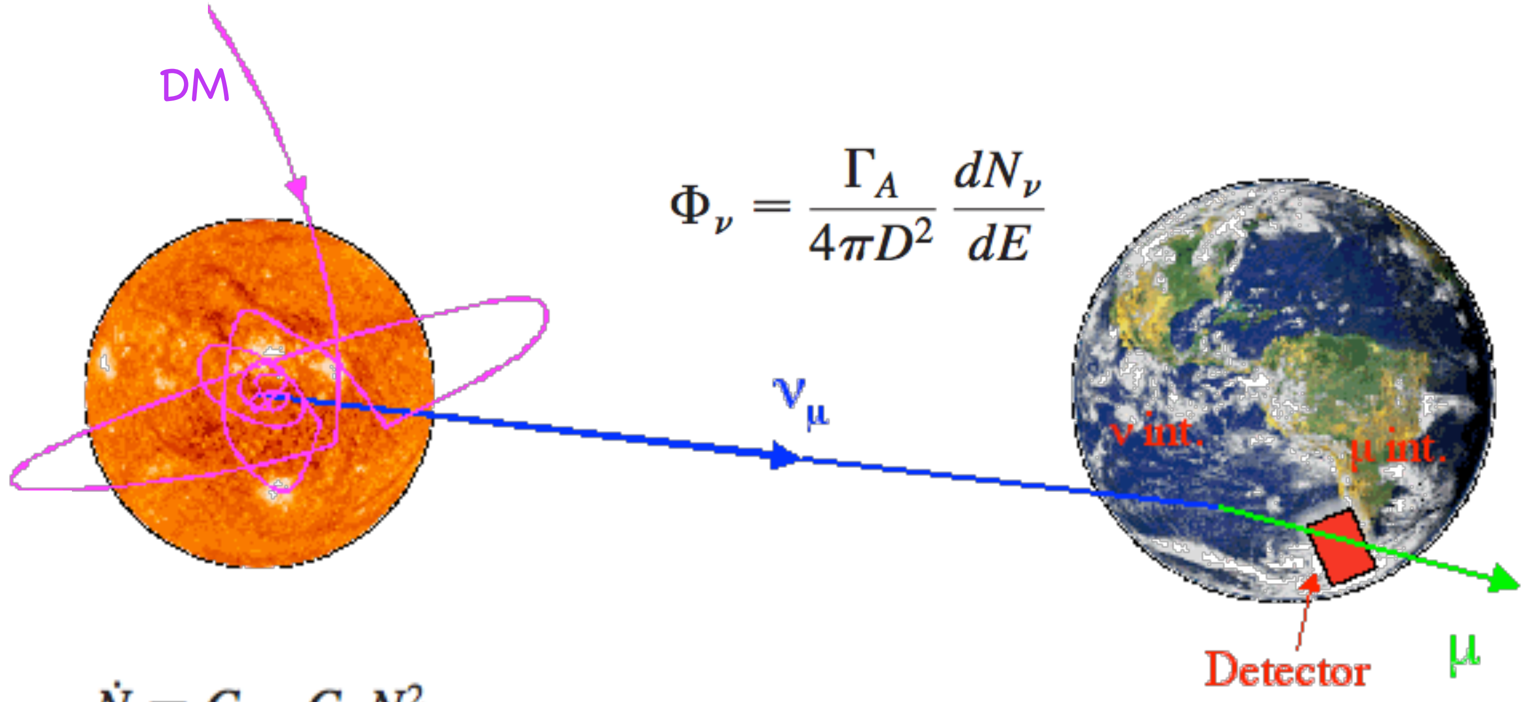


The signal is not affect by nuclear uncertainties because scattering occurs on protons

IceCube 86 including Deepcore



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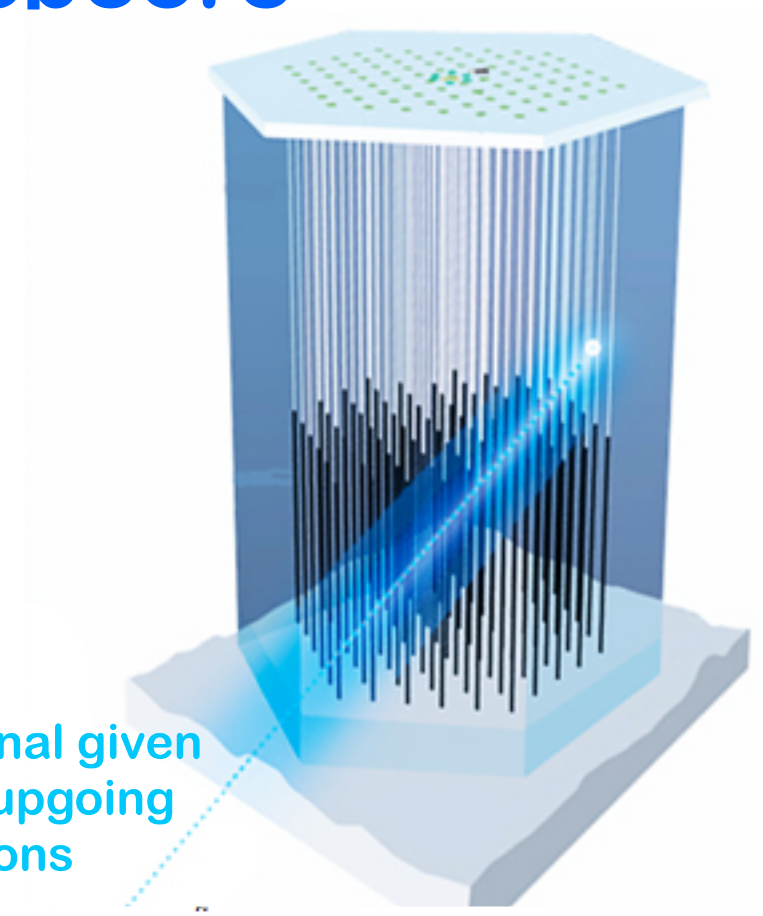

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astrophysical uncertainties

DM parameters

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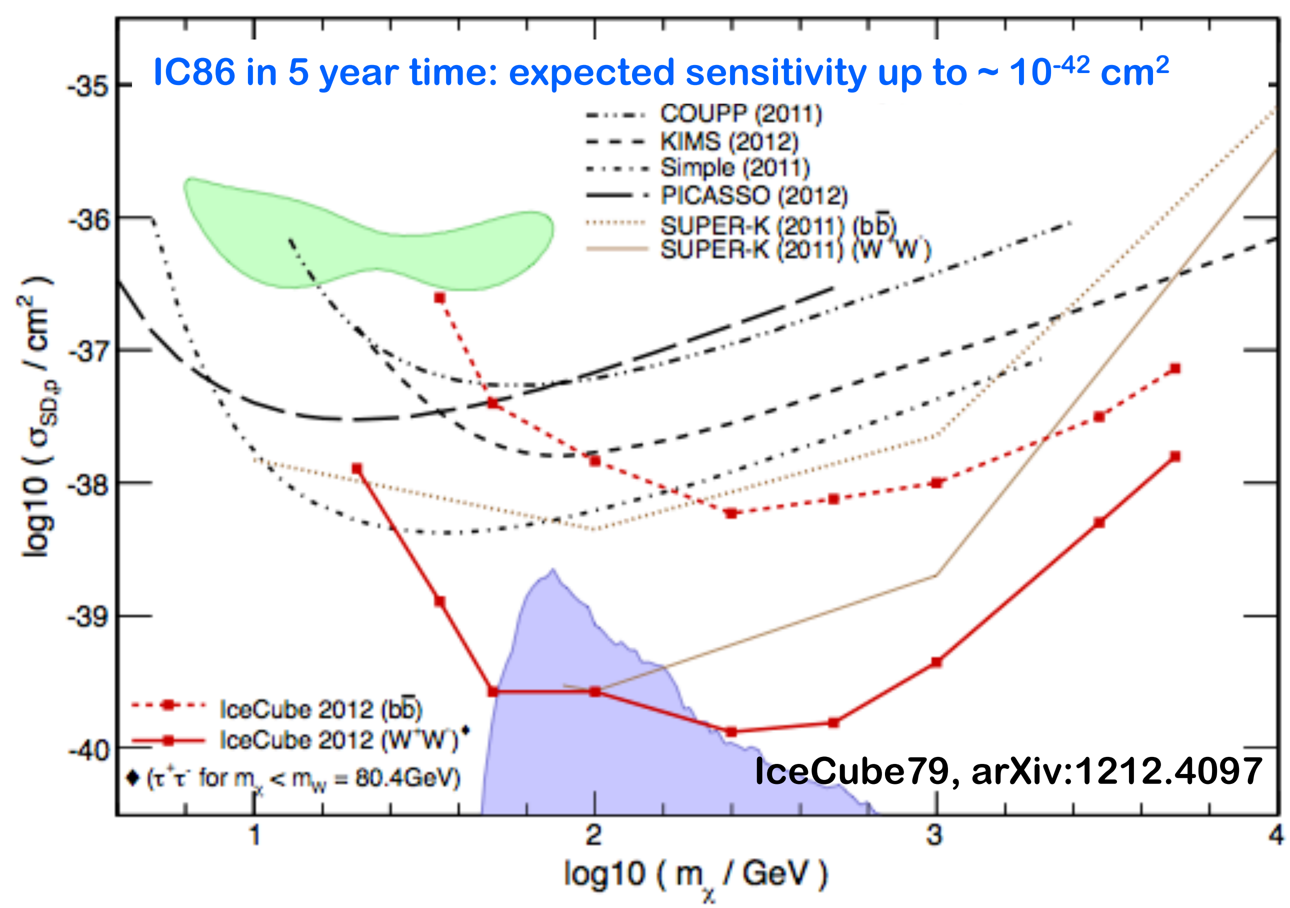


The signal is not affect by nuclear uncertainties because scattering occurs on protons

Inference for IceCube alone

	$m_{\rm DM}$ [GeV]	σ_n^{SI} [cm^2]	σ_n^{SD} [cm^2]
A	60	3.7×10^{-49}	2.0×10^{-40}
B	100	8.8×10^{-46}	2.0×10^{-40}
C	500	1.1×10^{-45}	9.6×10^{-45}

$S_\mu(\Theta)$
24.9 $(\tau^+\tau^-)$
66.0 (W^+W^-)
7.8 $(\nu_\mu\bar{\nu}_\mu)$

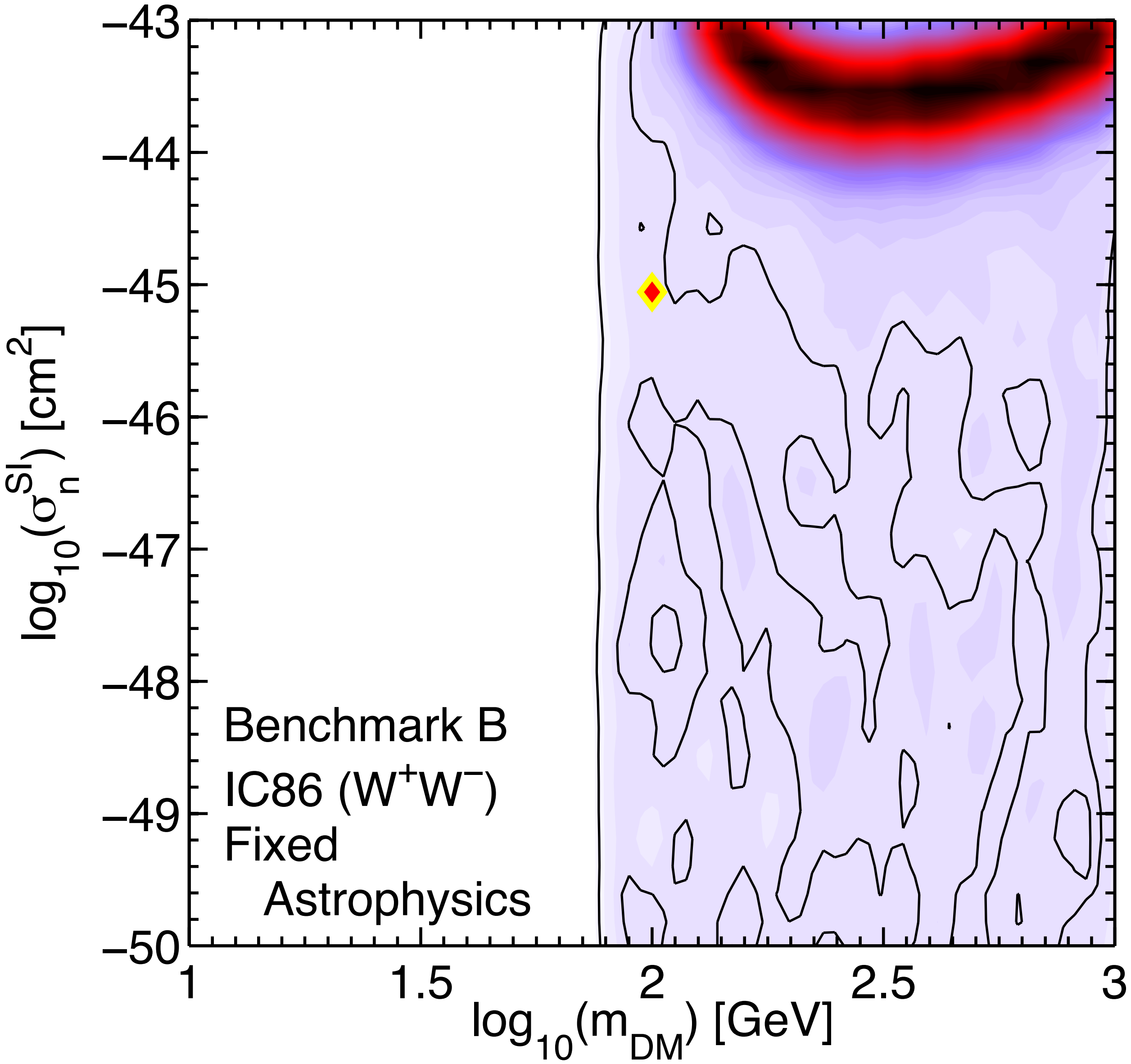
- **Likelihood of IceCube: the public likelihood released with DarkSUSY**
- **Considered only the winter season for data taking**
- **Expected background in 5 years is 205 events**
- **Only one energy bin, we use the event number likelihood (not possible a spectral analysis)**
- **Poor energy resolution: for muons with energy less than 10^8 GeV, it can be affected by a factor of 2**

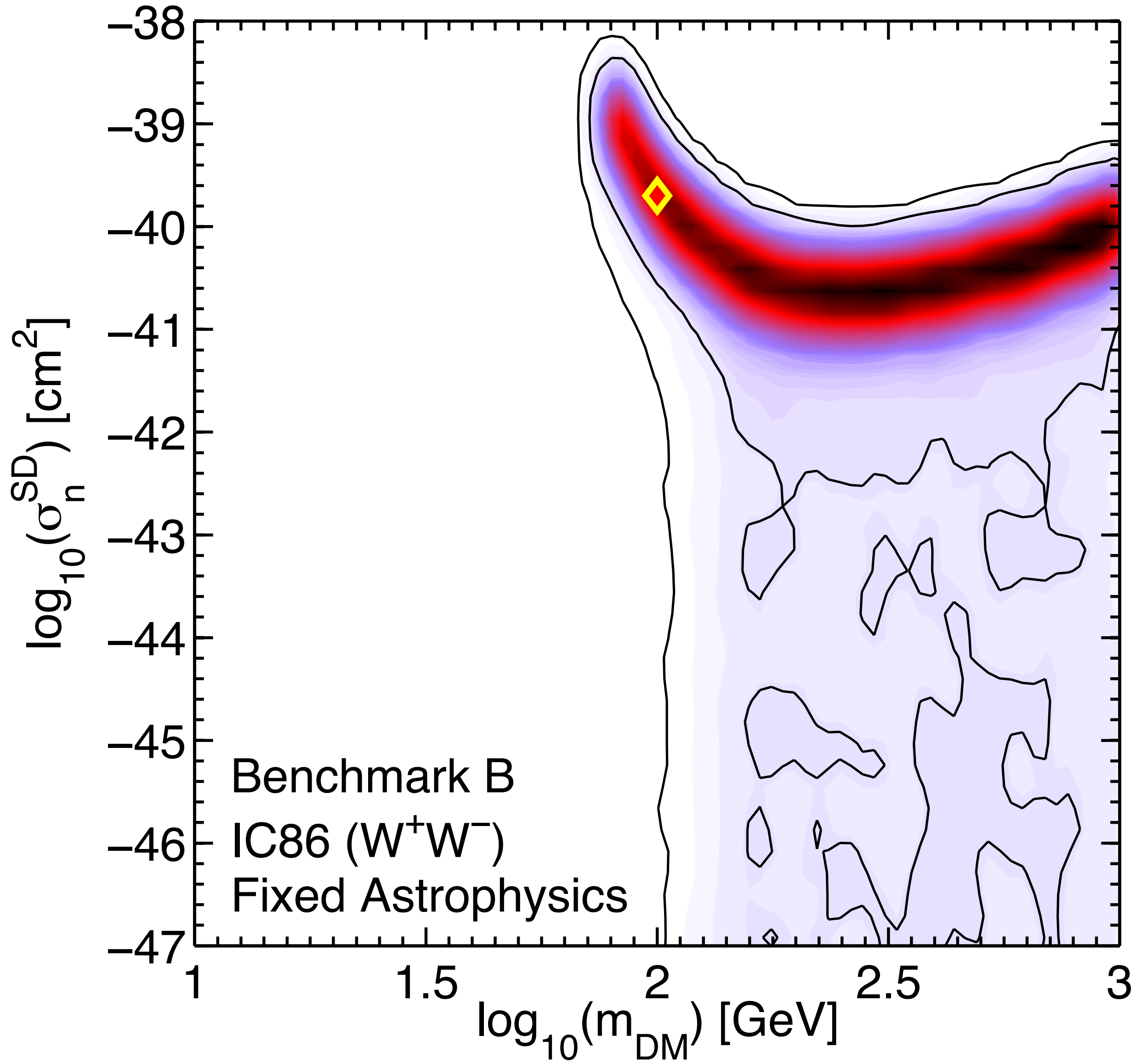
Inference benchmark A and C: the posterior pdf is flat in all the priors range, meaning no detection hence providing only an upper-bound on the DM parameters

Inference for IceCube

2D marginalized posterior pdf for 68% and 95% C.L.

- **Almost independent on SI**
- **Sensitive to SD**
- **Again the features have no physical meaning**

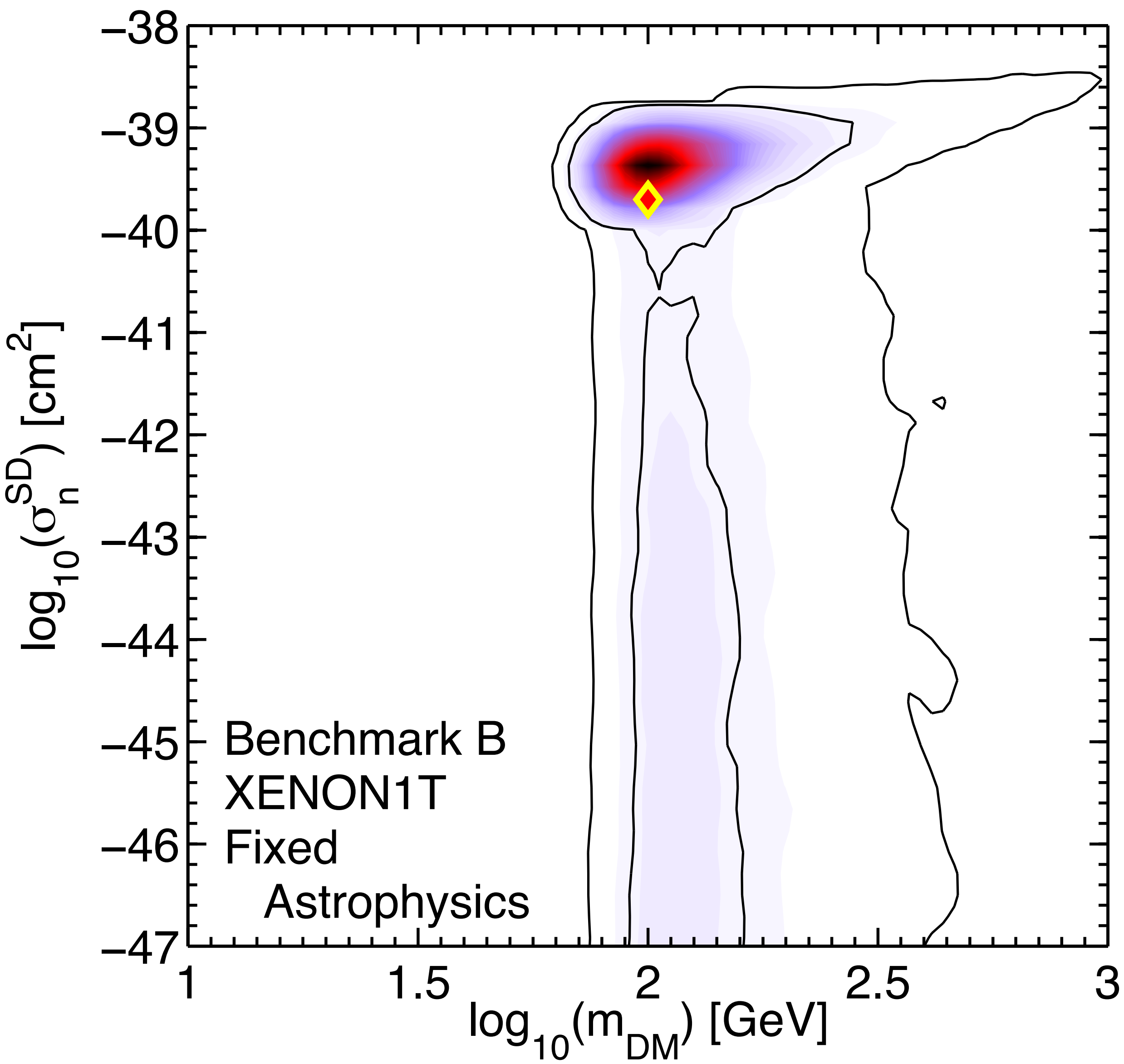


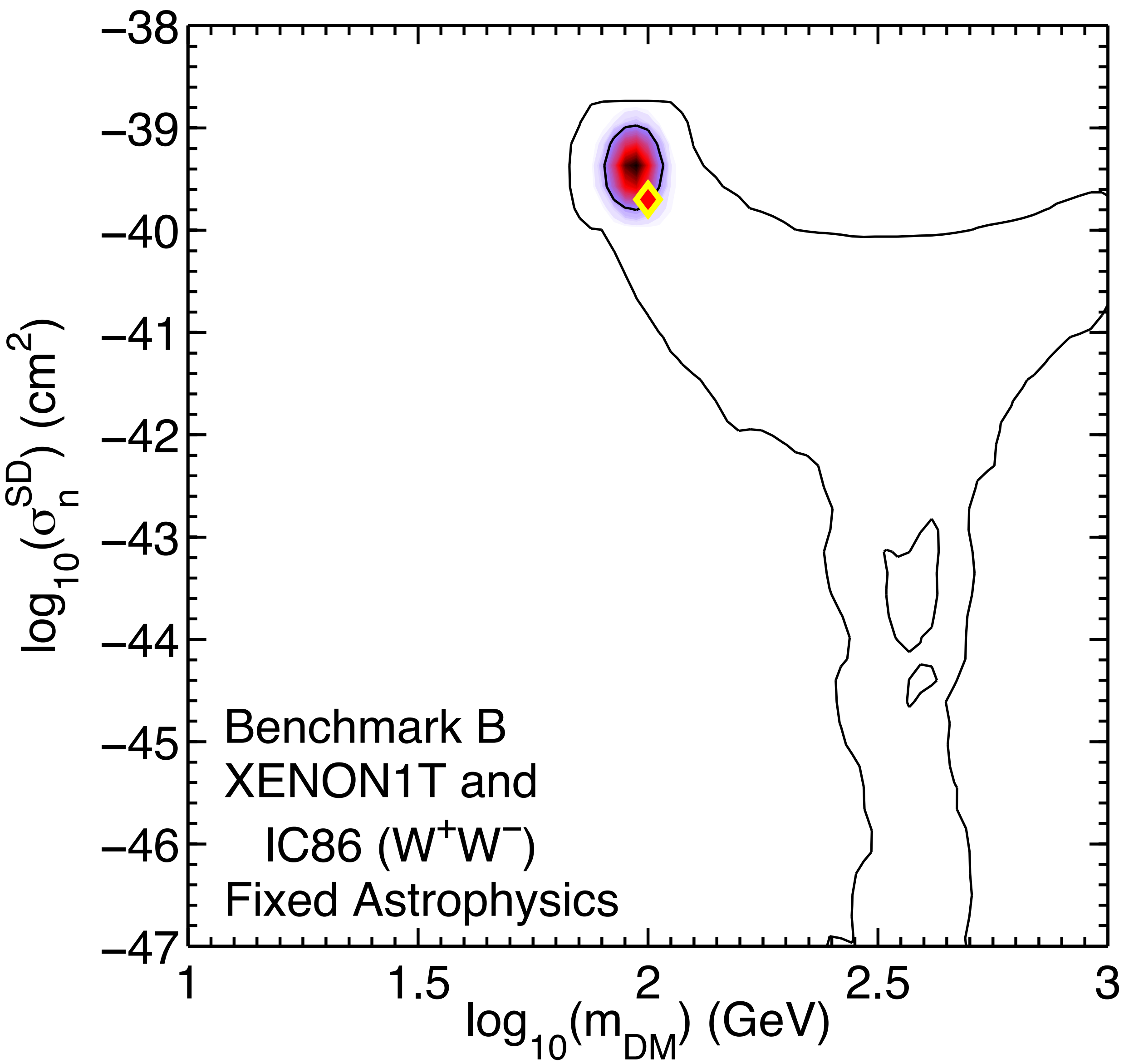


Inference for XENON1T and IceCube combined

2D marginalized posterior pdf for 68% and 95% C.L.

- Detection in both experiments
- Determination of SD contribution and of the mass

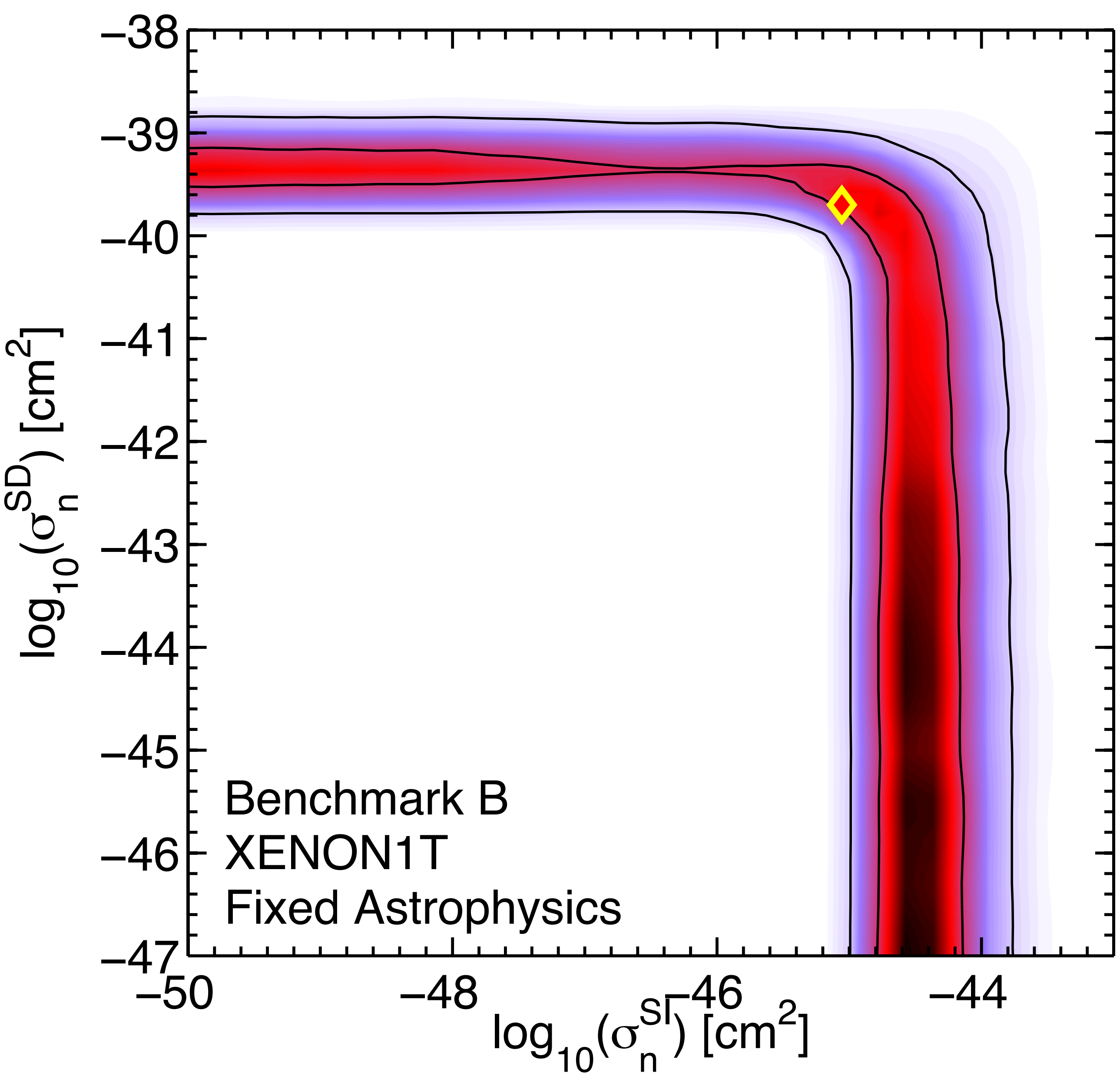


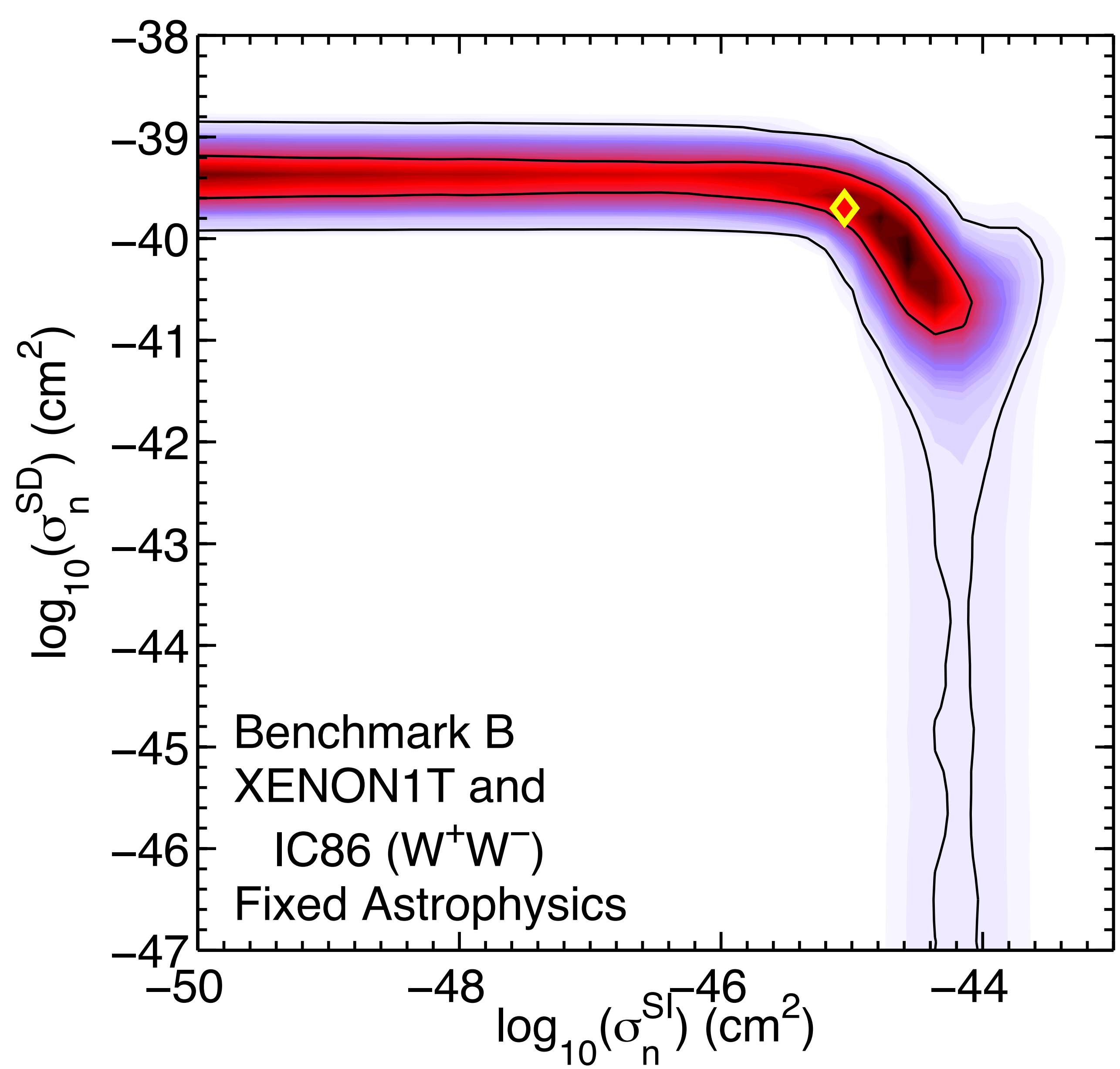


Combined XENON1T and IceCube

2D marginalized posterior pdf for 68% and 95% C.L.

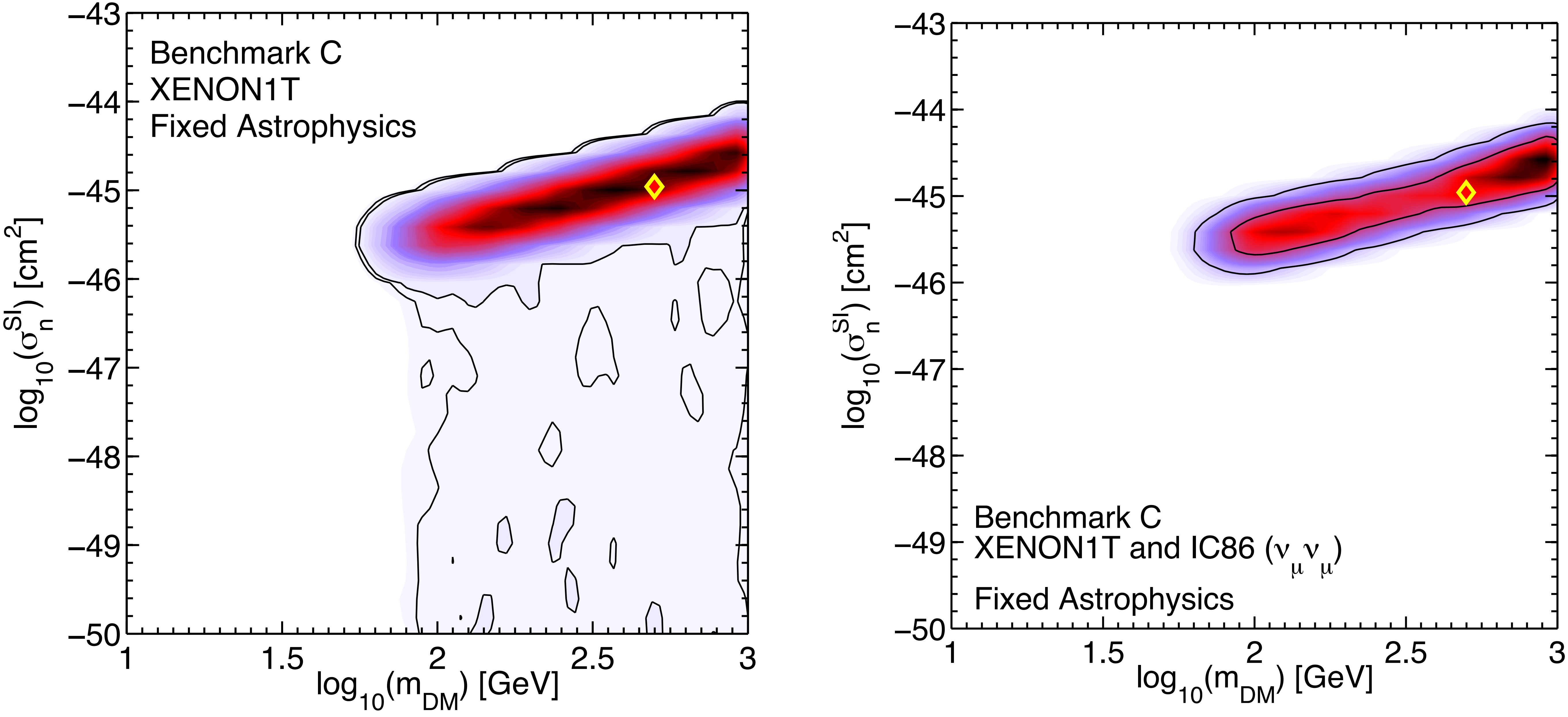
- **Only upper bound for the SI cross-section**





Combined XENON1T and IceCube

Even if there is no detection in IceCube: tightening of the confidence level (similar for case B)

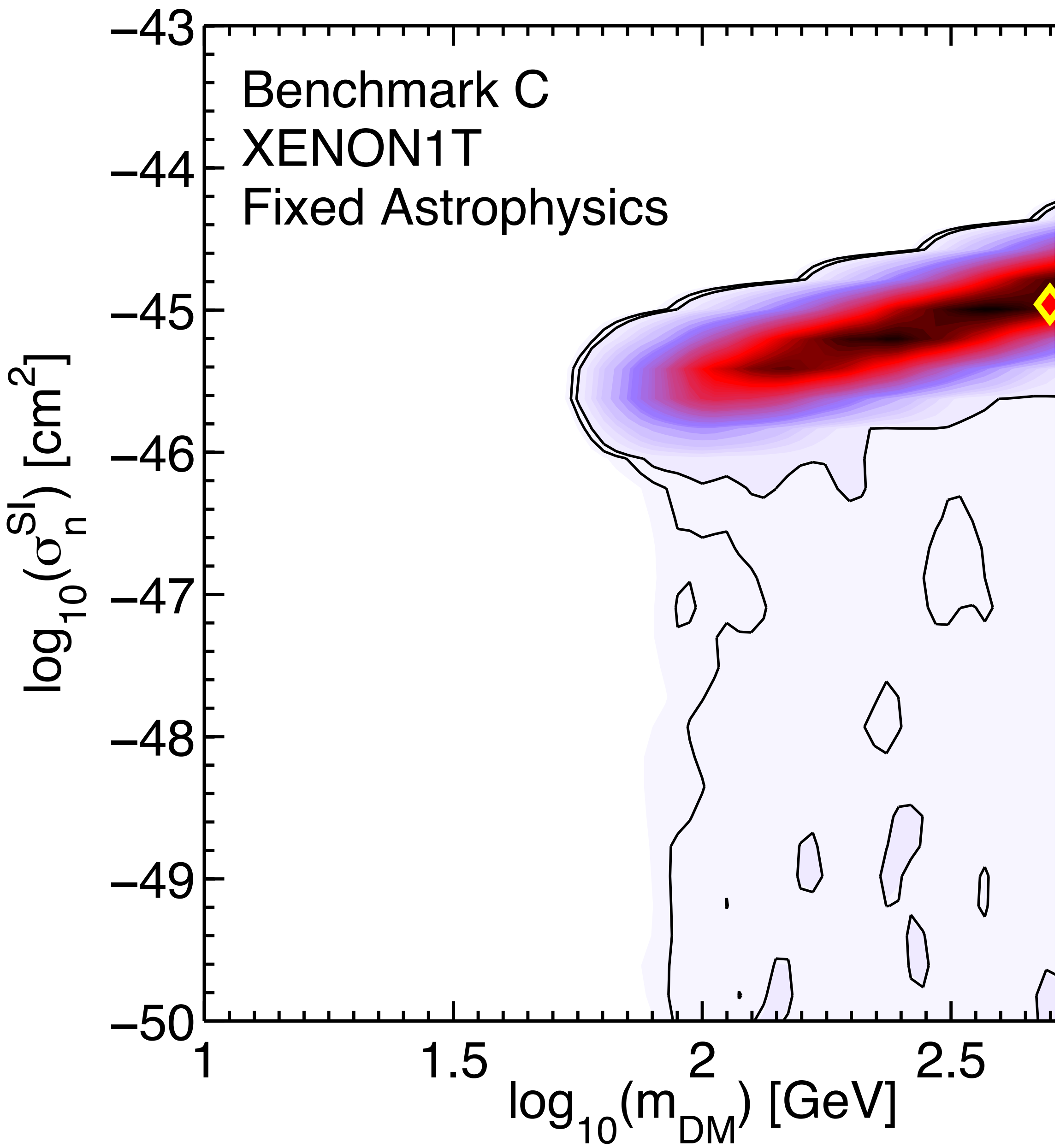


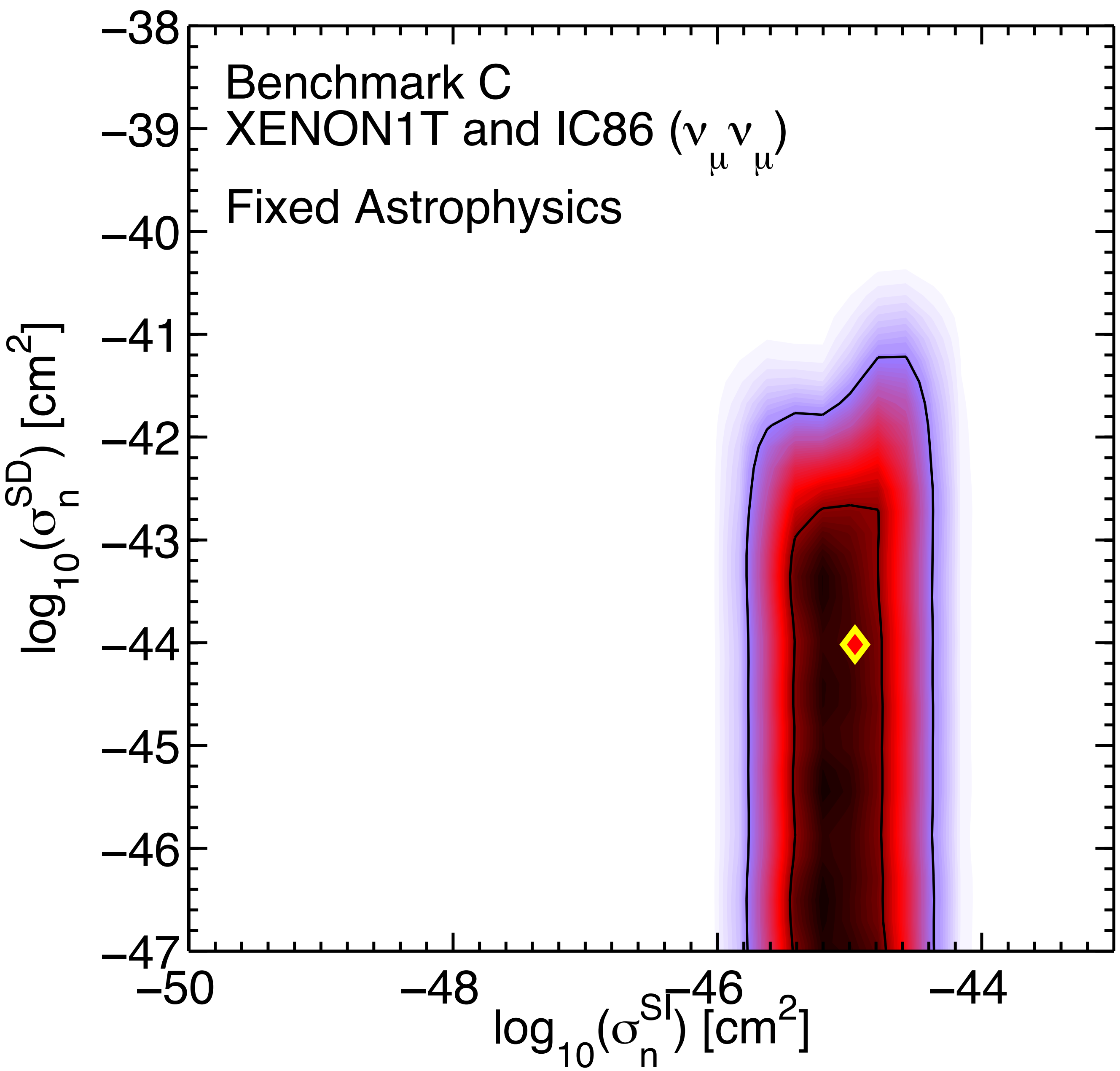
- Tightening of the credible regions
- SI gets a lower bound as well
- Mass degeneracy is not uplifted

2D marginalized posterior pdf for 68% and 95% C.L.

Combined XENON1T and IceCube

Even if there is no detection in IceCube:





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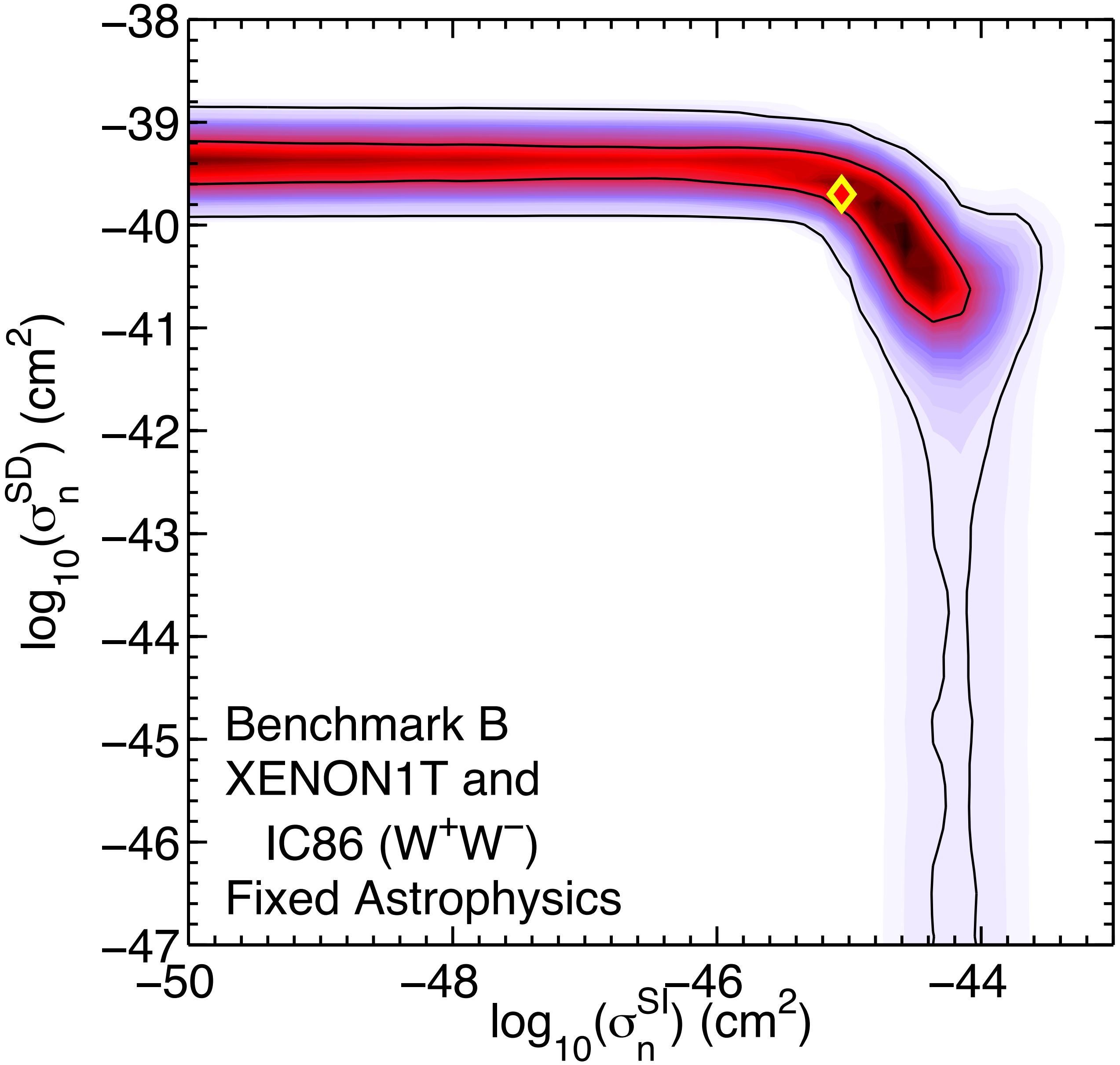
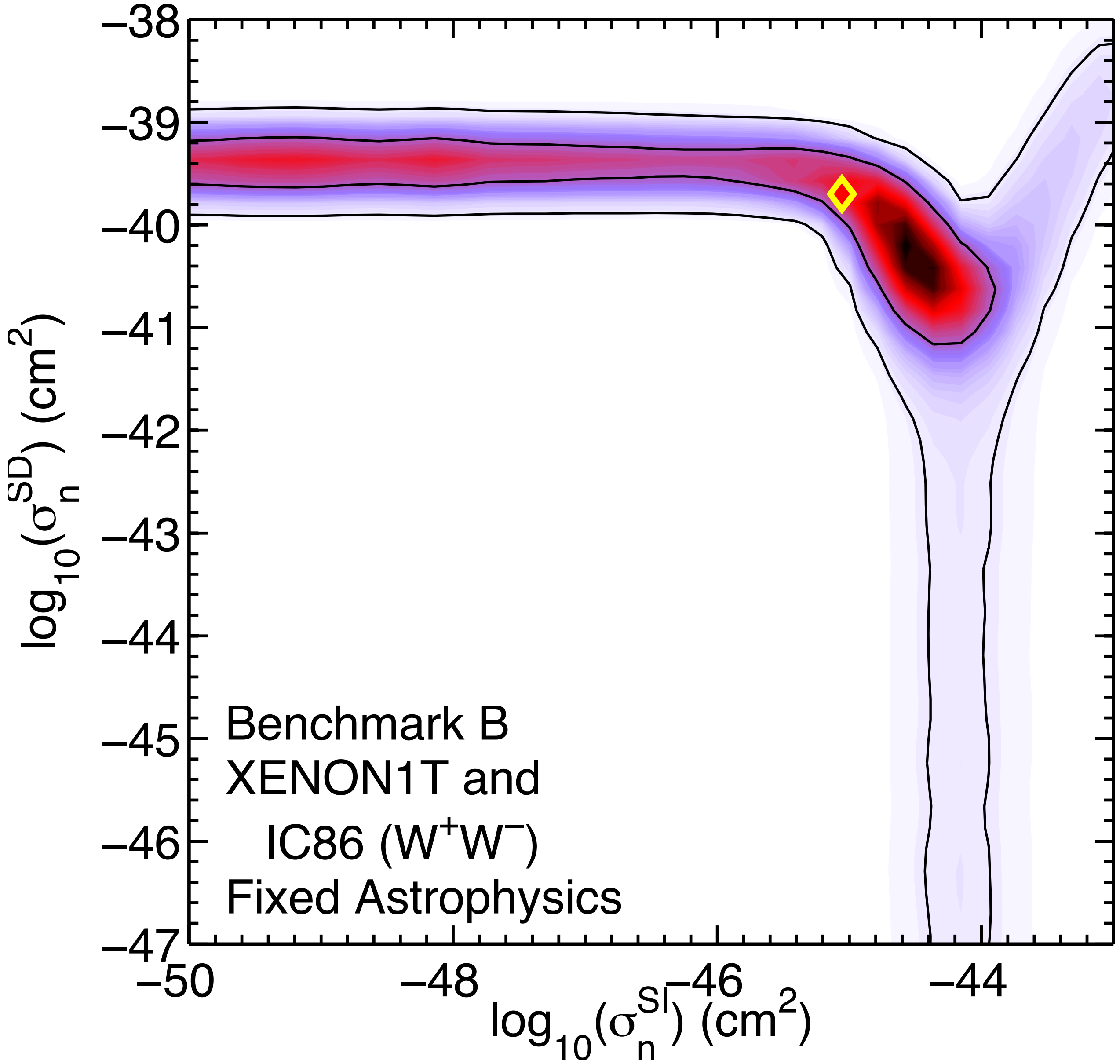
2D marginalized posterior pdf for 68% and 95% C.L.

Discussion of the prior dependence

- **Prior on the mass: 10 GeV to 1 TeV (as it is natural for WIMP definition) compared to 10 GeV to 10 TeV**





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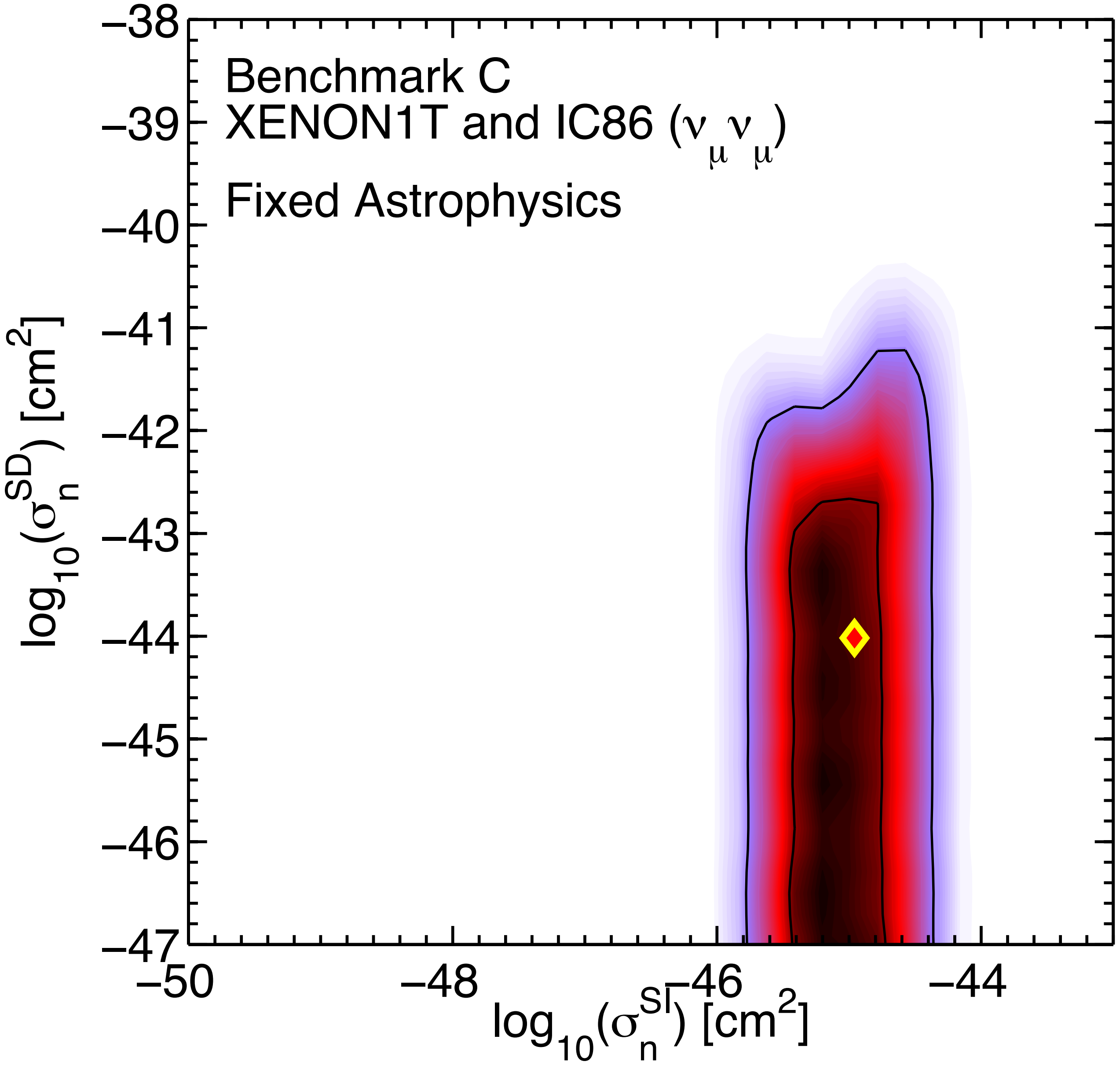

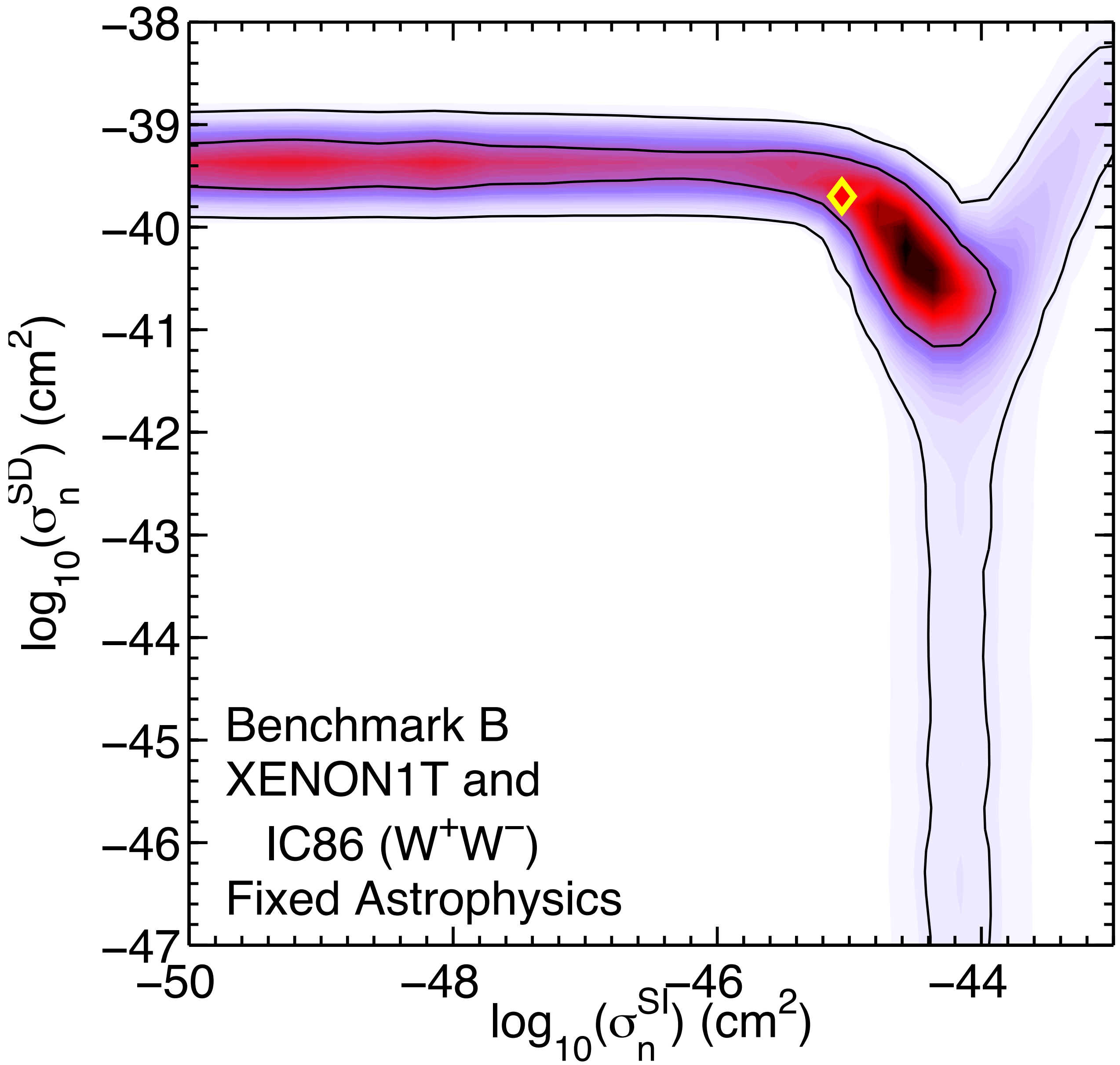

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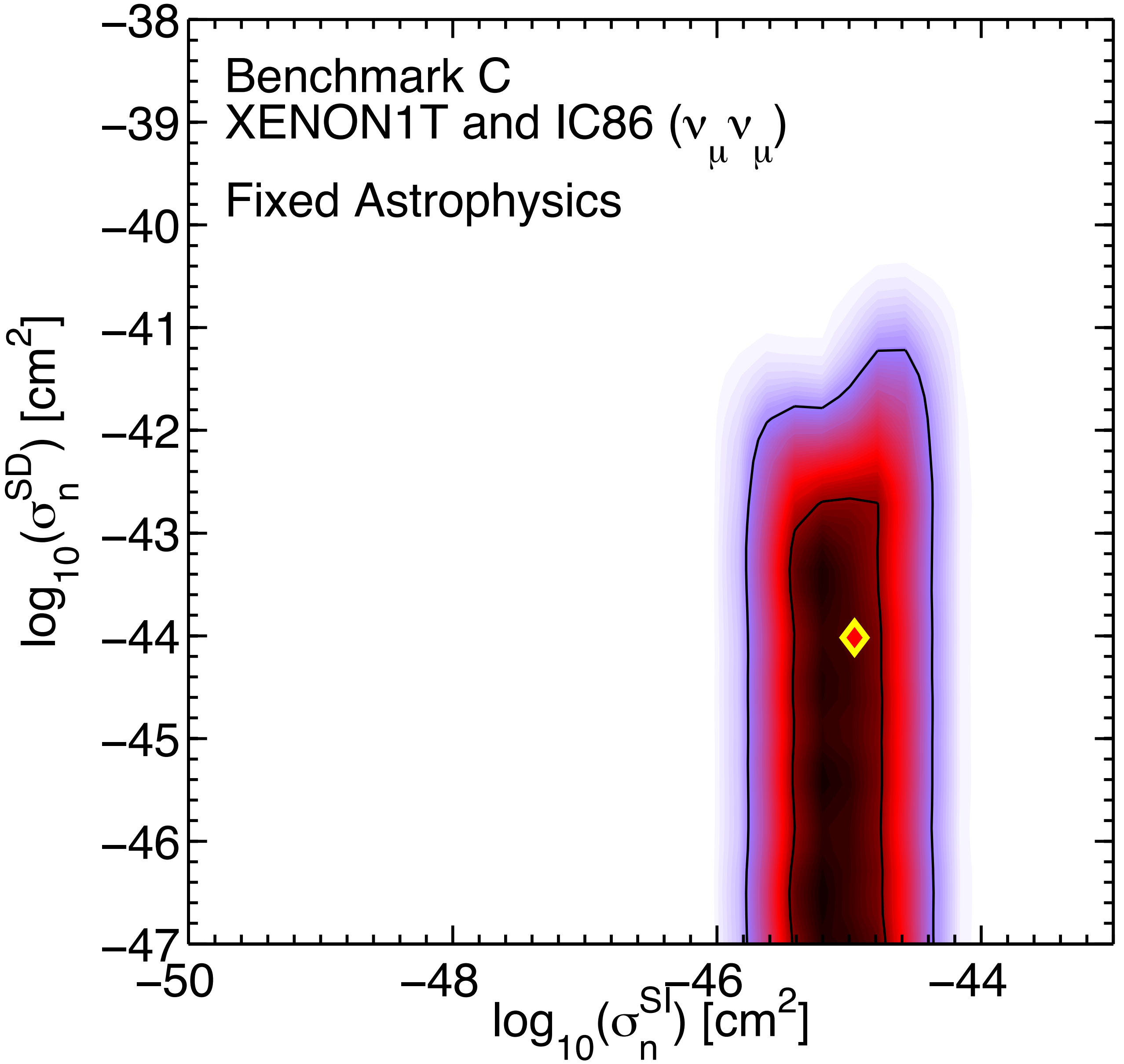
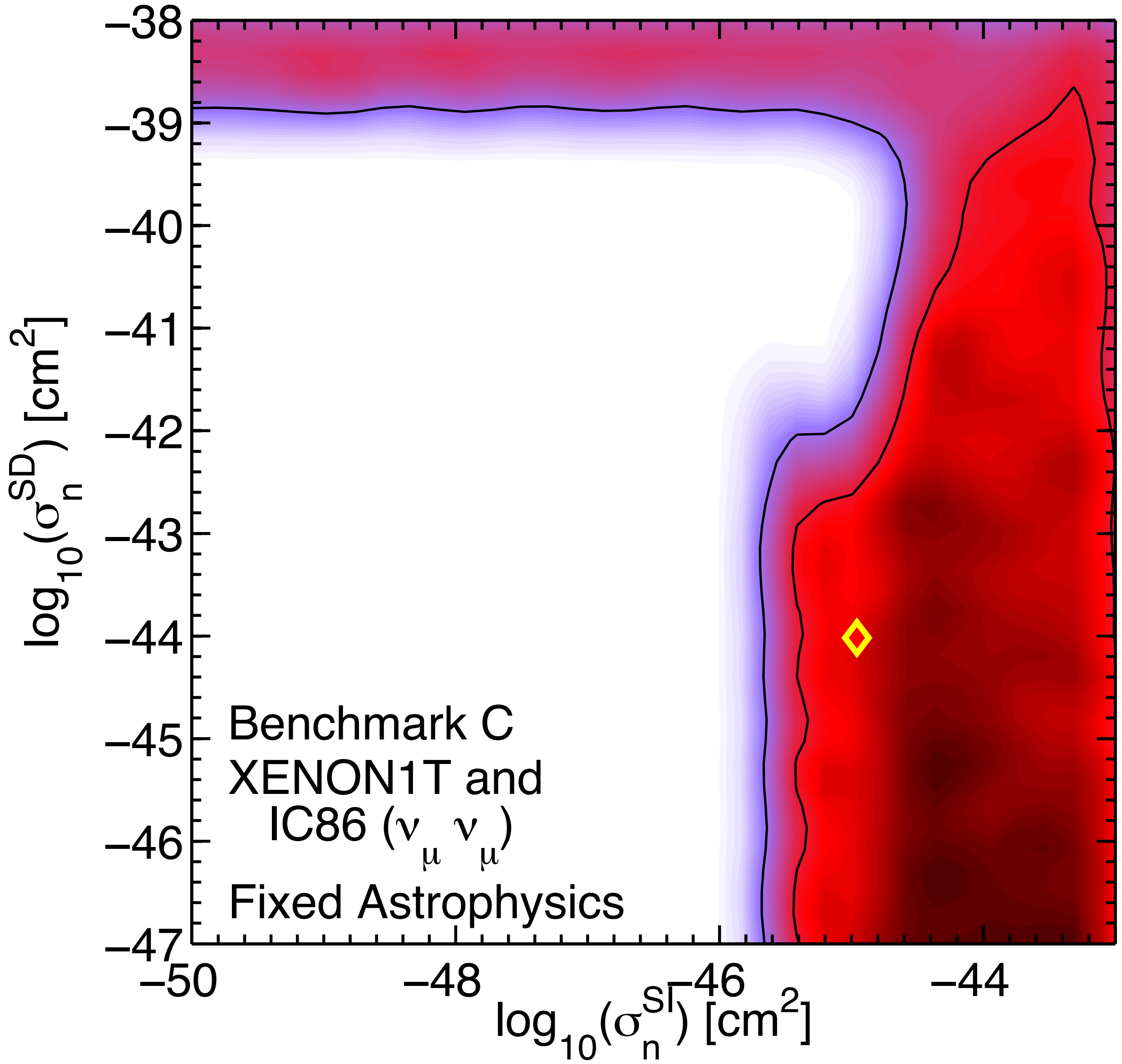
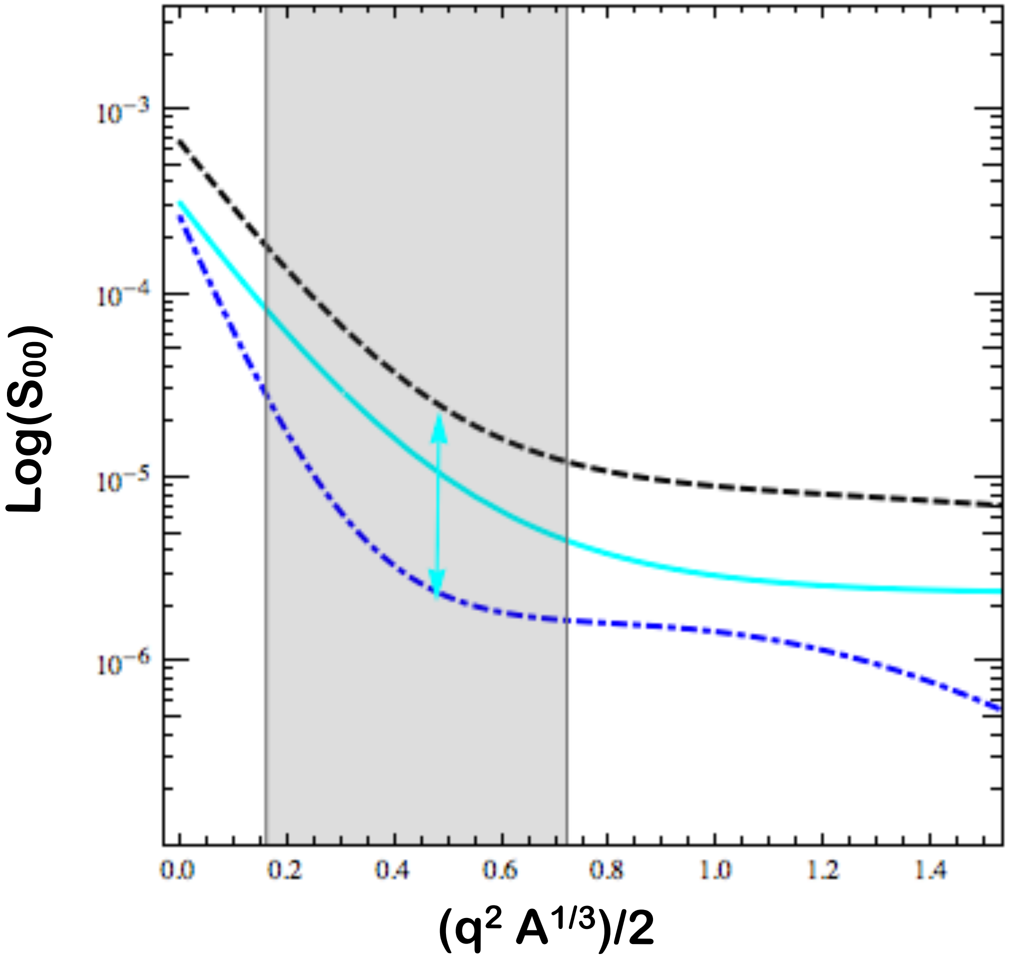




Inclusion of uncertainties

(A) Nuclear structure functions (S_{00}) for SD interaction



	m_{DM} [GeV]	S^{SD}_{pred} (CEFT)	S^{SD}_{pred} (NijmegenII)
A	60	422.8	170.9
B	100	356.09	122.3
C	500	4.42×10^{-3}	1.48×10^{-3}

(i) Number of events affected by a factor of 3
(ii) Systematic offset and bias if the reconstruction does not reproduce the true structure function

Likelihood for nuisance parameters is an interpolating function for the structure function with flat prior on the 3 free parameters

Inclusion of uncertainties

(B) Galactic DM parameters measured up to a different degree of precision

Observable	Constraint
Local standard of rest	$v_0^{\mathrm{obs}} = 230 \pm 24.4$ km s^{-1}
Escape velocity	$v_{\mathrm{esc}}^{\mathrm{obs}} = 544 \pm 39$ km s^{-1}
Local DM density	$\rho_\odot^{\mathrm{obs}} = 0.4 \pm 0.2$ GeV cm^{-3}

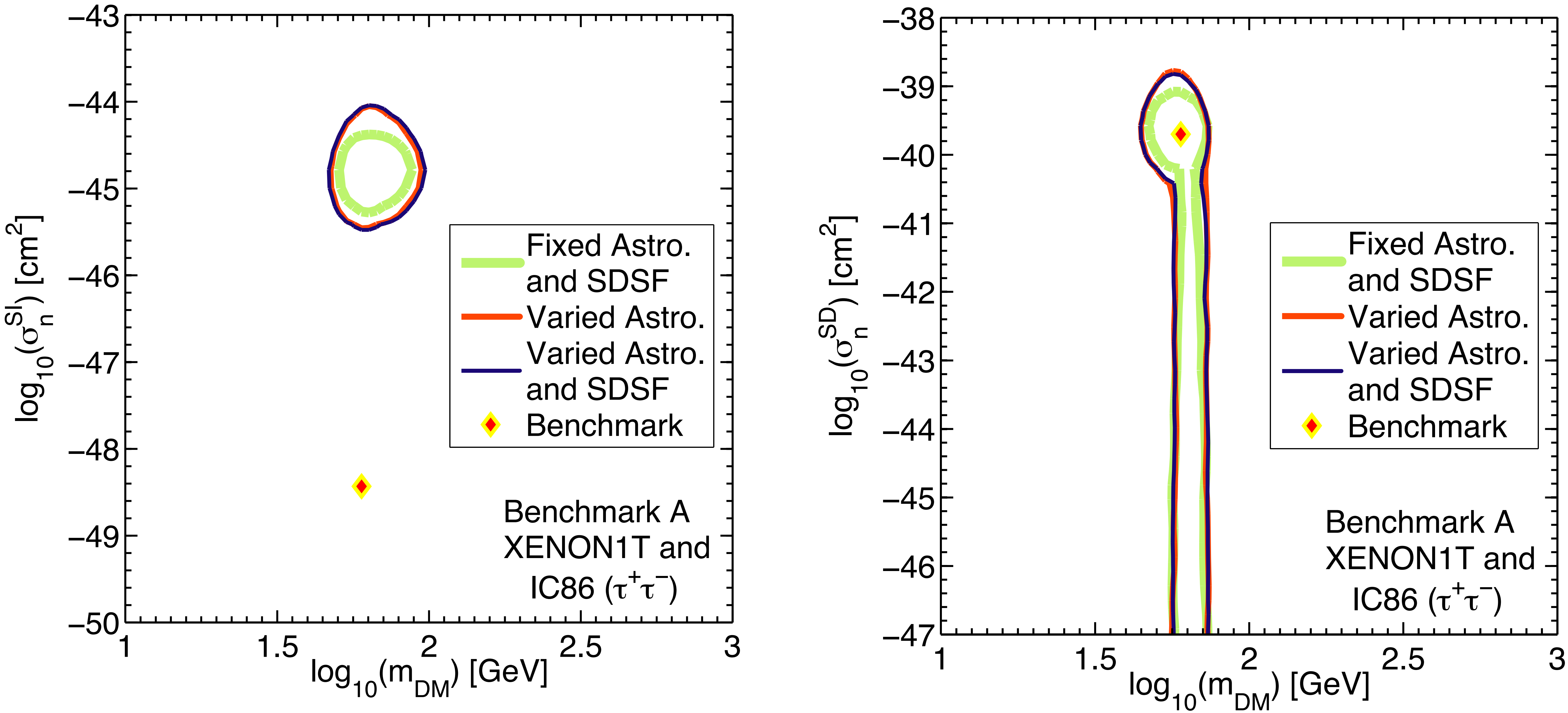
Include a likelihood for nuisance parameters:

- **gaussian likelihood for astrophysics**
- **the shape of the velocity distribution is not varied, assumed to be the standard Maxwellian distribution as in the case of 'fixed astrophysics'**

$$\ln \mathcal{L}_{\mathrm{Astro}} = -\frac{(v_0 - \bar{v}_0^{\mathrm{obs}})^2}{2\sigma_{v_0}^2} - \frac{(v_{\mathrm{esc}} - \bar{v}_{\mathrm{esc}}^{\mathrm{obs}})^2}{2\sigma_{v_{\mathrm{esc}}}^2} - \frac{(\rho_\odot - \bar{\rho}_\odot^{\mathrm{obs}})^2}{2\sigma_{\rho_\odot}^2}$$

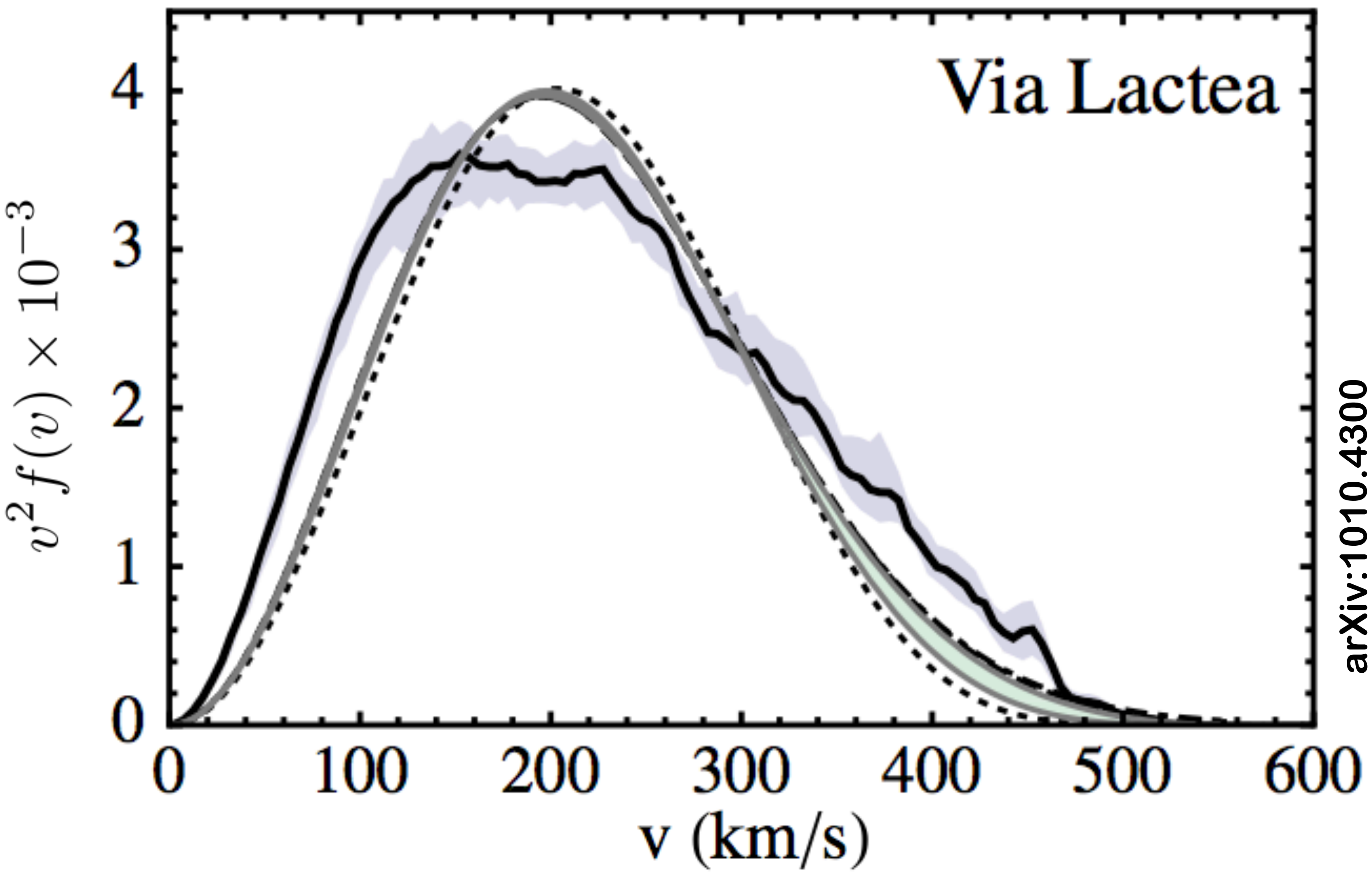
Results marginalized over all nuisance parameters

2D marginalized posterior pdf and 68% C.L.



Shape of the velocity distribution

- **XENON1T and IceCube are both affect by the DM velocity distribution function**
- **However the dependence on it is different in the two experiments**



arXiv:1010.4300

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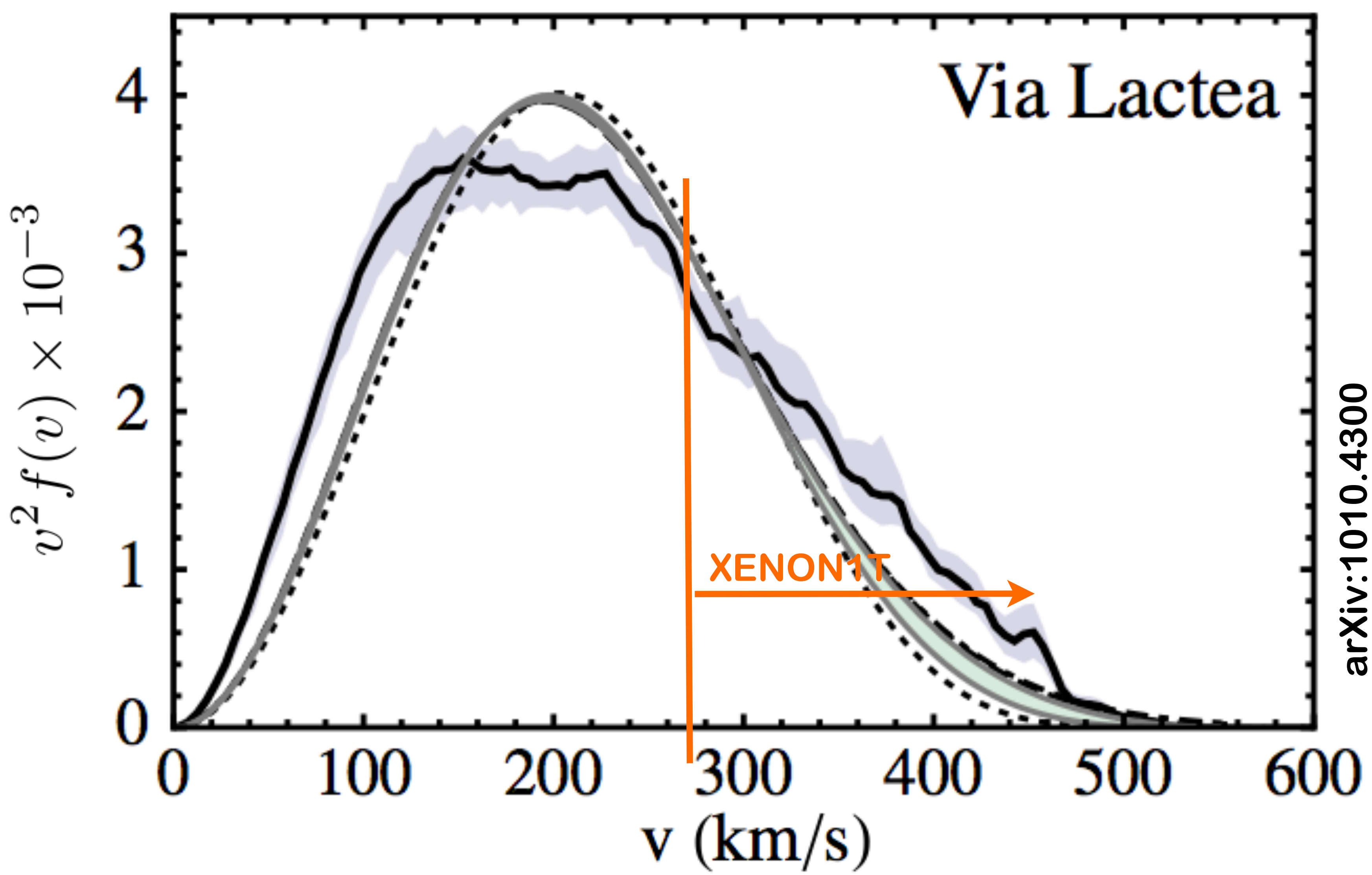

only high velocity particle can produce a nuclear recoil with energy E above threshold ~10 keV

$$v_{\rm min} = \sqrt{M_{\mathcal{N}} E / 2\mu}$$

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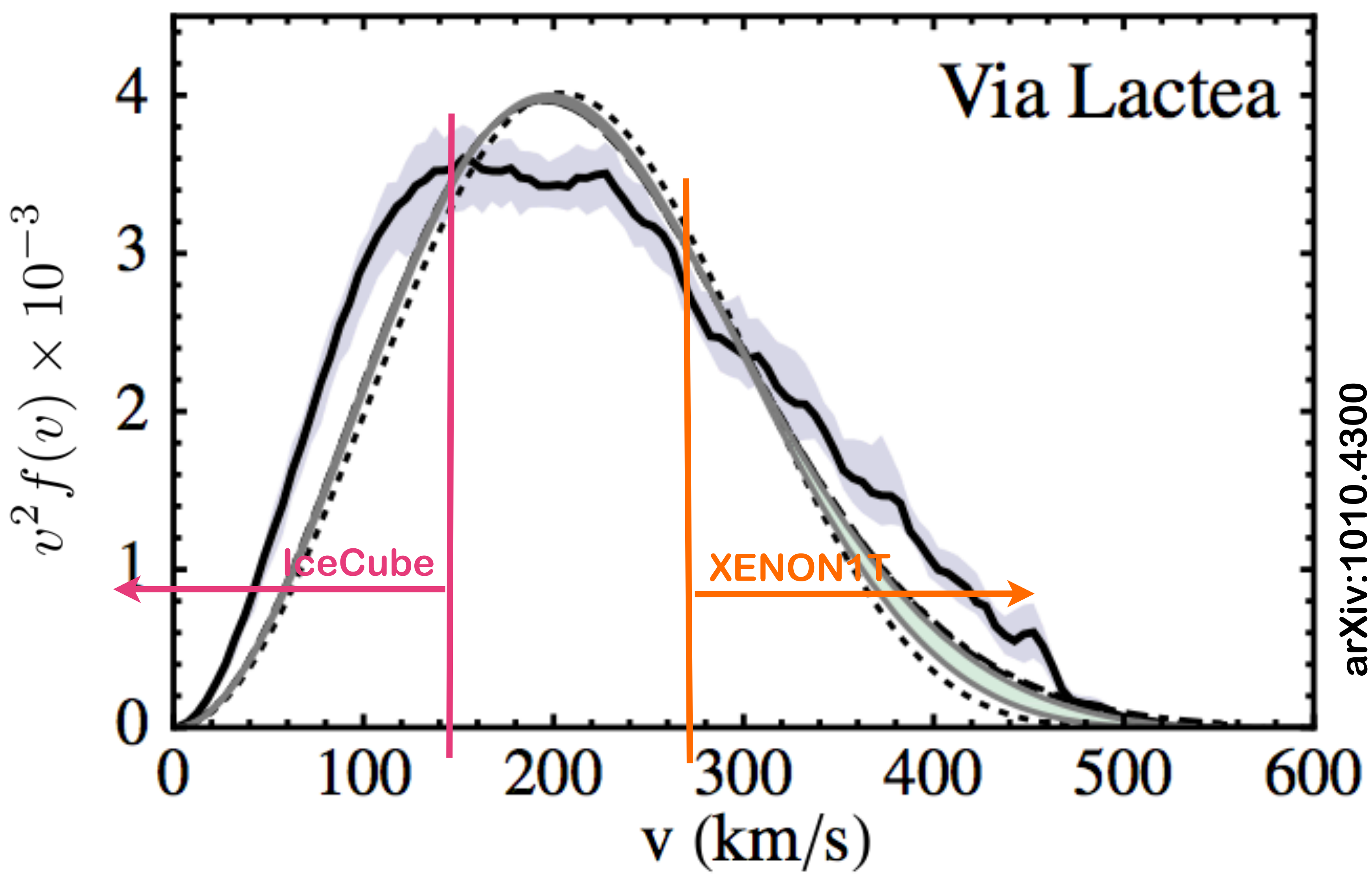

only low velocity WIMPs get captured

$$u_{\rm max} = \frac{\sqrt{4 m_{\rm DM} M_{\mathcal{N}}}}{m_{\rm DM} - M_{\mathcal{N}}} v$$

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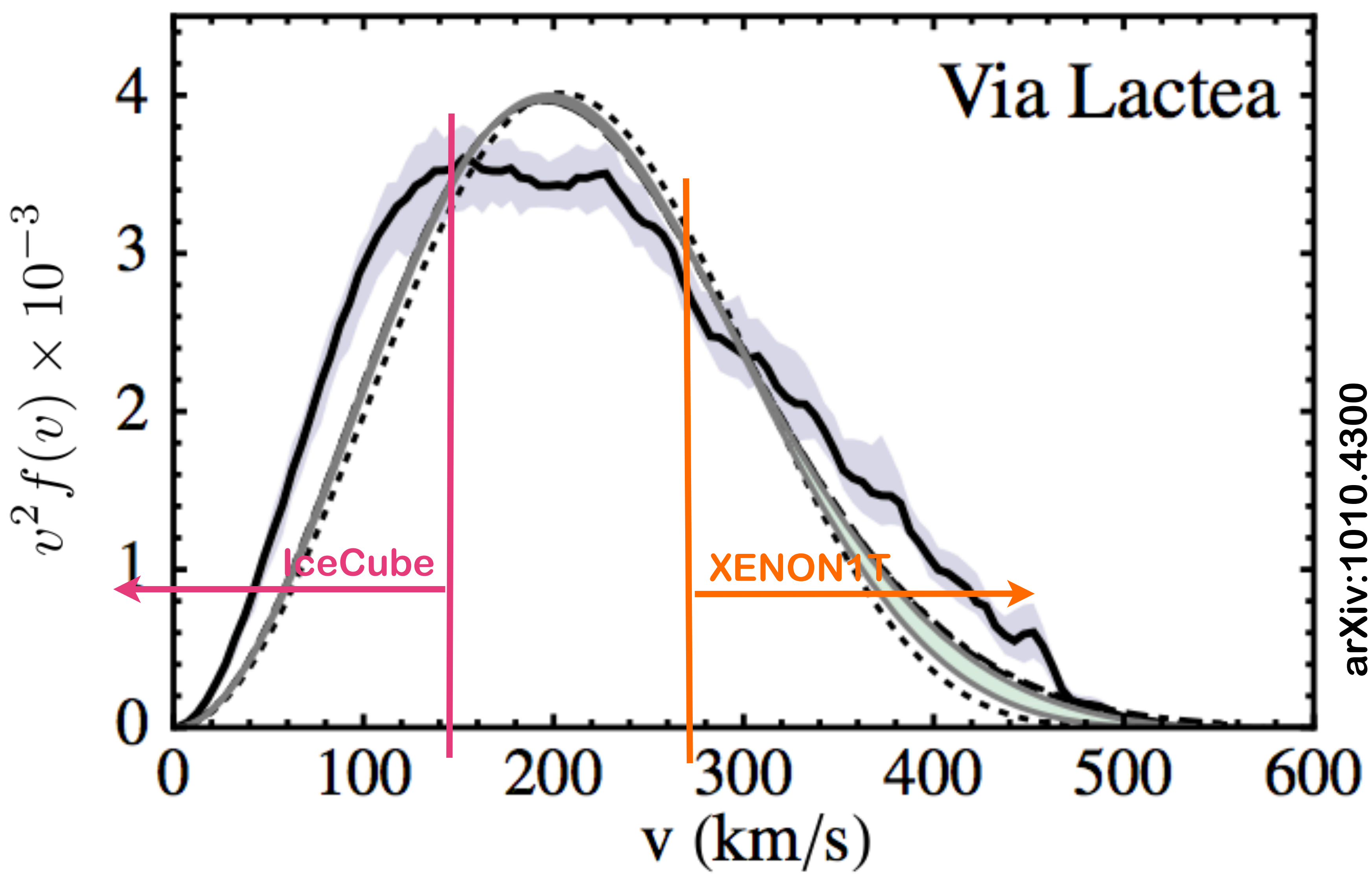

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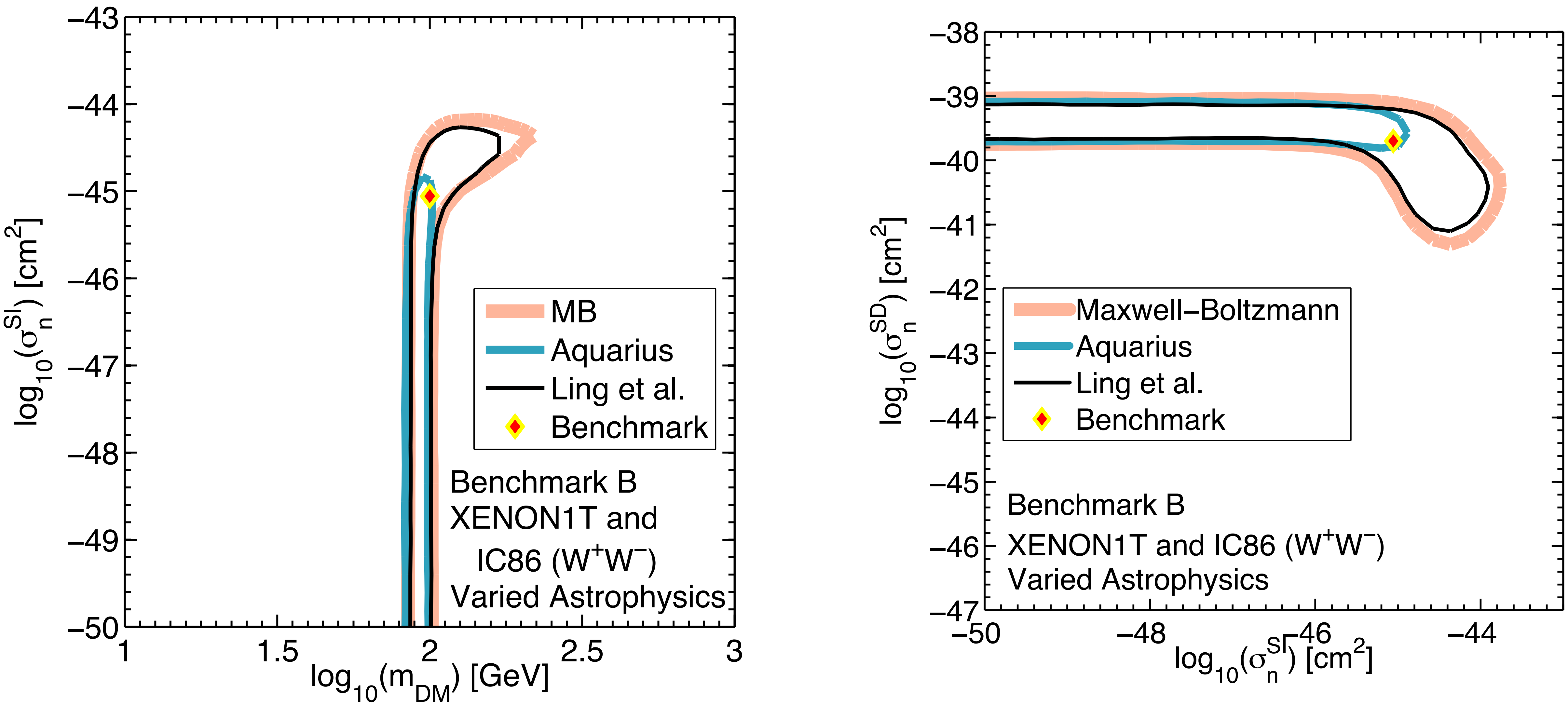
Maxwellian parametrization underestimates both tails of N-body velocity distributions

N-body simulation versus Maxwellian distribution

For a 100 GeV particle the difference in the event number is for Aquarius 15% for the low tail and 17% in the high tail (u_{max} ~ 200 km/s while v_{min} ~ 300 km/s)
Ramses simulation with baryons very close to MB (~4% variation)

Estimation of the bias in the reconstruction if it is assumed a standard halo model but the true velocity distribution is taken to be given by the N-body simulation: the reconstruction is robust against variation of the shape of the velocity distribution



2D marginalized posterior pdf and 68% C.L.

Conclusions

1) A detection in both experiments can help in reconstructing the degenerate parameters and overcome the limitation of pure direct detection experiments (other way: combine different target materials)
2) Even a non detection in IceCube86 improuves the reconstruction
3) In 5 year-time hopefully astro/nuclear parameters will be more constrained and the optimistic picture will hold (see GAIA satellite and experimental dd effort)

IceCube likelihood:

- Publicly available number likelihood without spectral information;
- Spectral information should improuve the reconstruction of all physical parameters even if the energy resolution is still a factor of 2;
- Now that IceCube79 have published the ana;ysis could bepossible to use their energy dependence as guideline for forecasts
- Spectral information might be relevant for resolving the DM mass reconstruction in combination with direct detection experiments!

Systematics due to different dependence of astrophysical parameters in the rates

- the capture rate is sensitive to the averaged DM density (averaged over one Sun period around the galactic center ~ 2 10^8 years);
- the direct detection rate depends only on the DM density at the Sun position;
- the equilibration time of our benchmarks is ~ solar orbit, hence number of events can be affected by this difference.