From EFT to Superradiance, Dark Matter Searches with XENON

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Neutrino seminar series, Fermilab

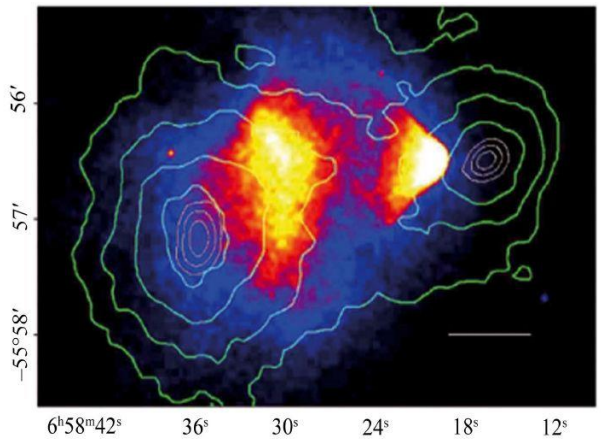
October 2017

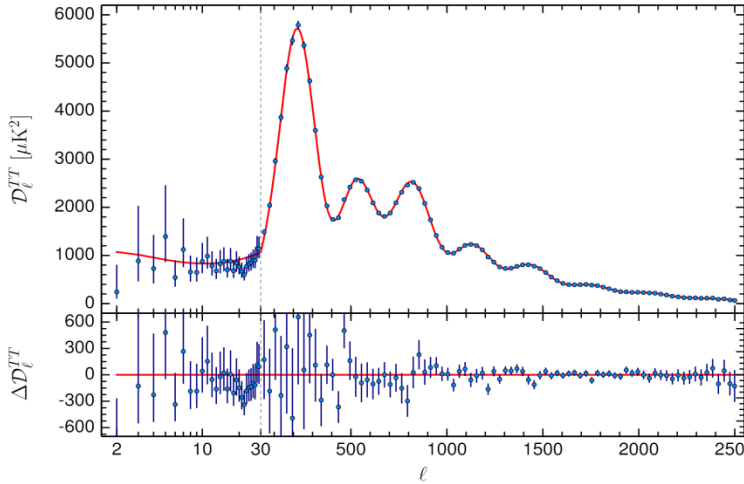
Introduction
EFT
XENON1T
Superradiance
Summary

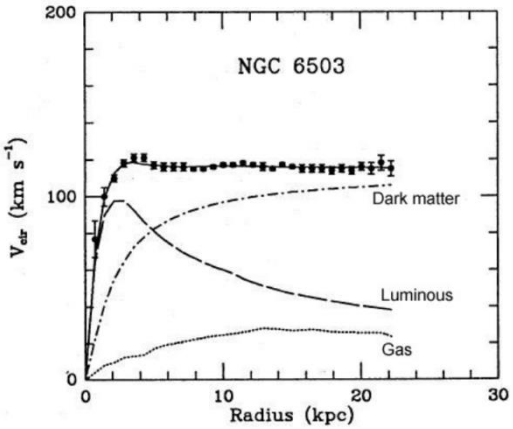
Outline

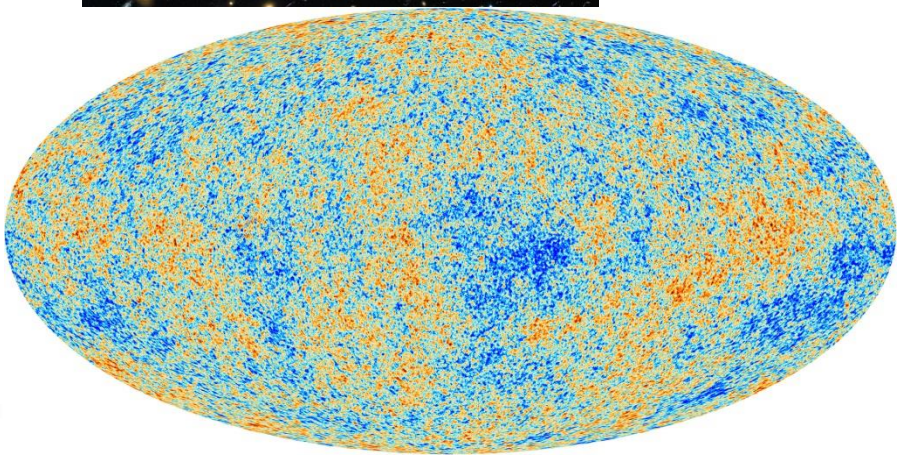
- Introduction.
- EFT analysis in XENON100 – Increasing energy range.
- XENON1T first results – Increasing detector volume.
- Superradiance in LXe – Decreasing background.

Evidence for DM









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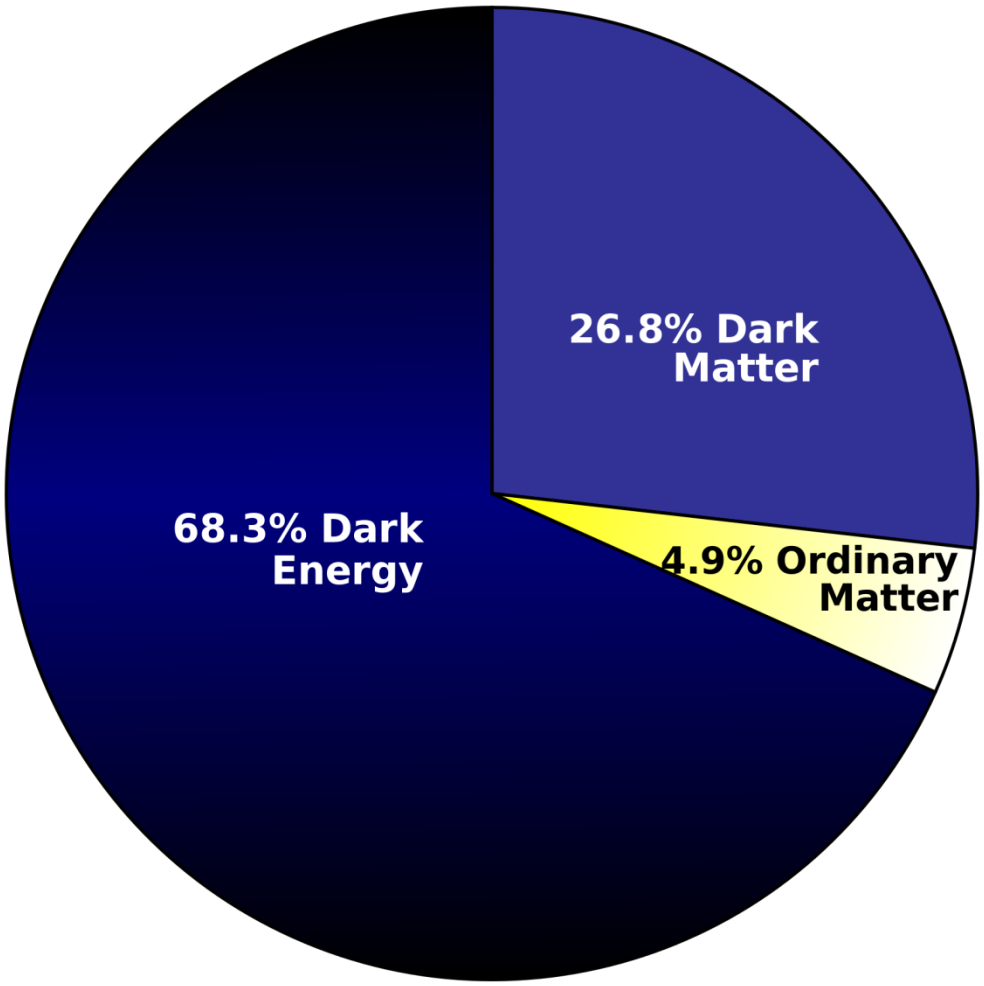
DM Evidence



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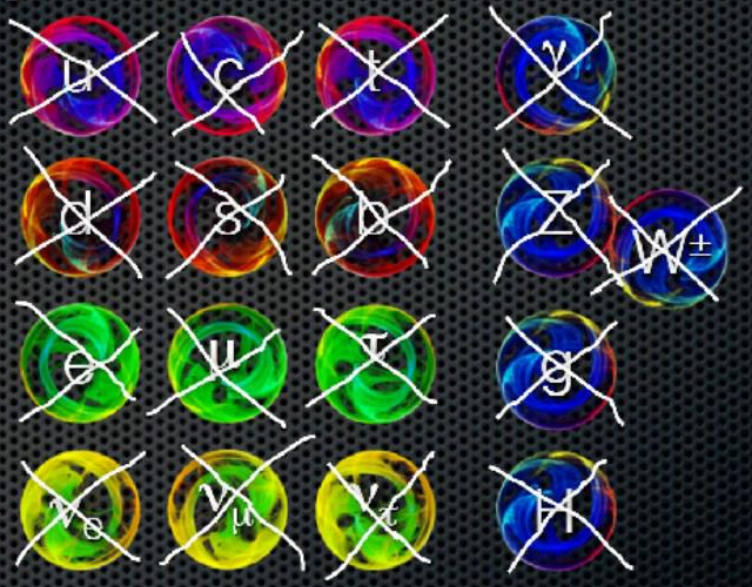
The DM Problem

We know Dark Matter has to be

- neutral
- cold
- stable
- no EM interaction
- non-baryonic
- correct density

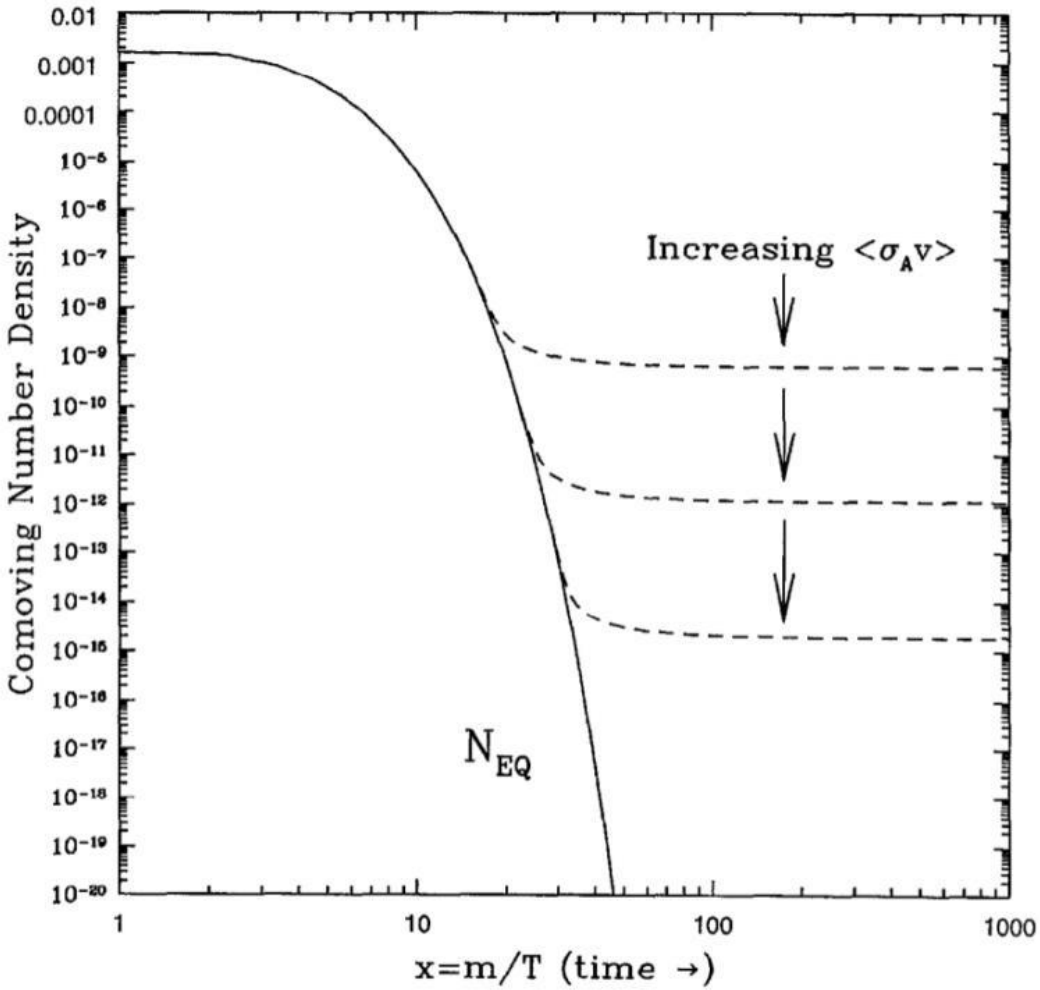


-> No Standard Model Candidate

WIMP Miracle

Weakly Interacting Massive Particles

- Correct relic abundance ↔ σ_{weak}.
- Expected by many extension of SM.
- Z exchange excluded, still most favorable candidate.



Direct Detection

Typical assumptions:

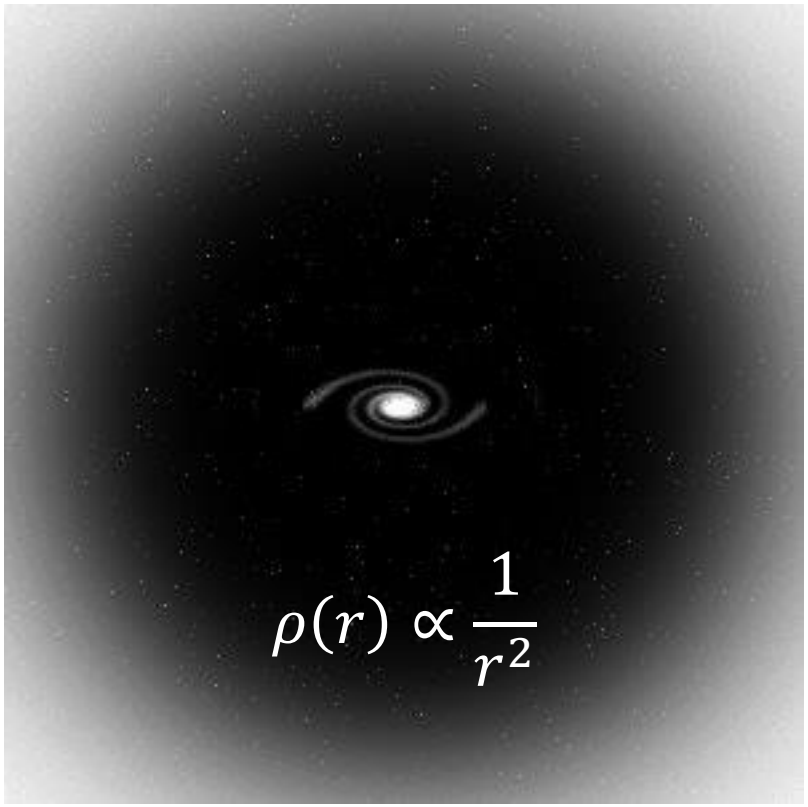
- Local density ~ 0.3 GeV/cm^3
- Average Velocity ~ 220 km/s

WIMP Interaction:

- Very small rate – O(1) event/ton/year ? .
- Low energy - O(10-100keV)

Direct detection requirement:

- Large detector mass.
- Ultra low background.



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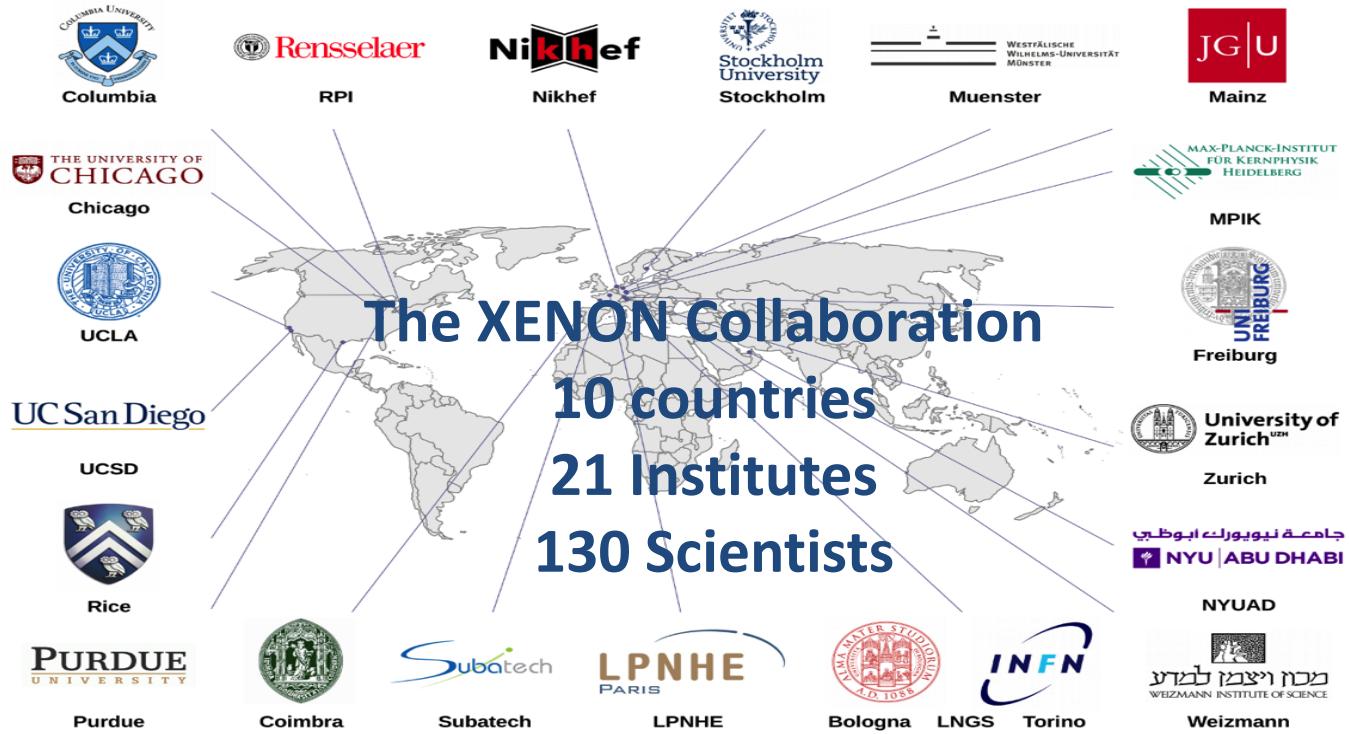
XENON Dark Matter Project



The XENON Collaboration
10 countries
21 Institutes
130 Scientists

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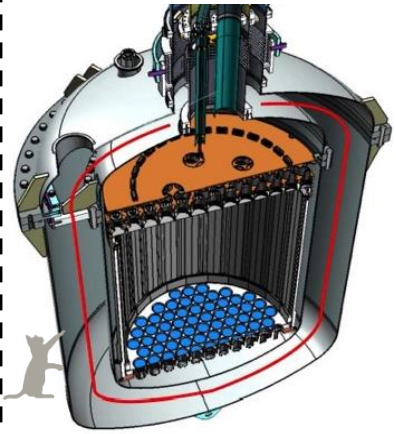
Timeline of the Xenon Program

	XENON10	XENON100	XENON1T	XENONnT
				
Era	2005-2007	2008-2016	2012-2018	2019-2023
Mass	25 kg	161 kg	3200 kg	~8000 kg
Drift	15 cm	30 cm	100 cm	144 cm
Status	Achieved (2007)	Achieved (2016)	Projected (2018)	Projected (2023)
σ_{SI} Limit (@50 GeV/c²)	8.8×10^{-44} cm²	1.1×10^{-45} cm²	1.6×10^{-47} cm²	1.6×10^{-48} cm²

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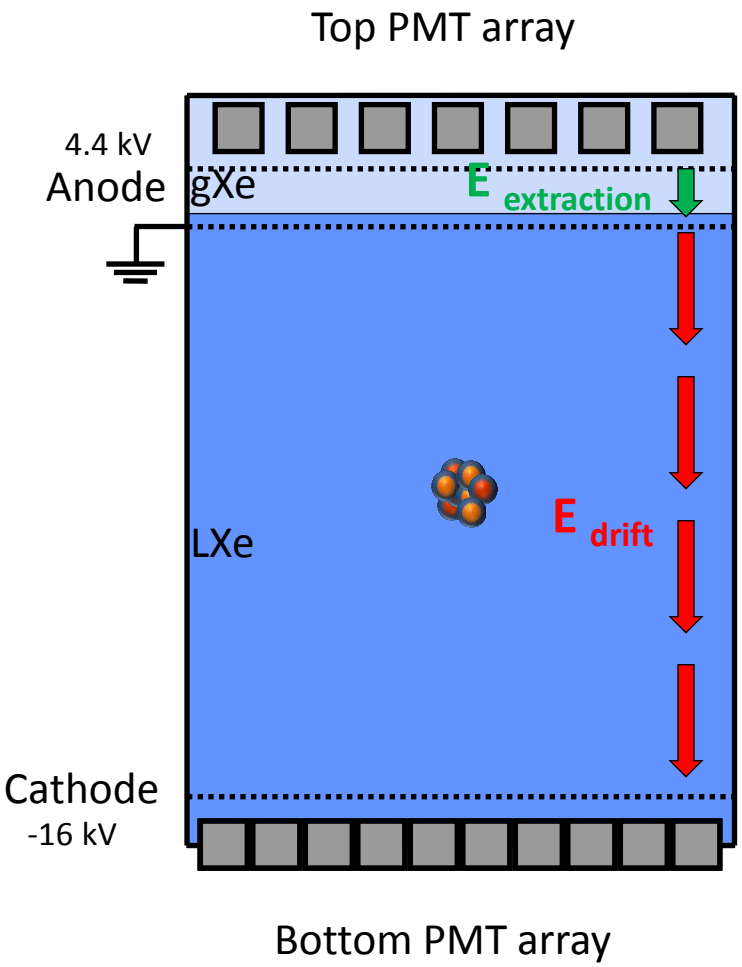
Detection Principle



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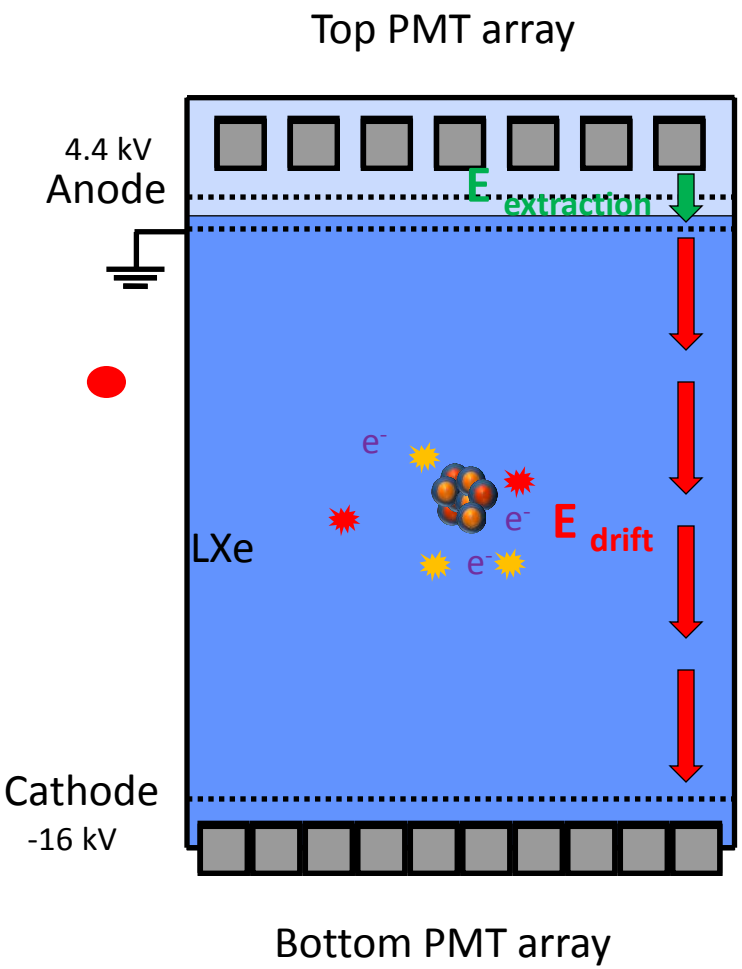

$$Xe^* + Xe + Xe \rightarrow Xe_2^*$$

$$\boxed{Xe_2^* \rightarrow 2Xe + h\nu}$$

$$Xe^+ + Xe \rightarrow 2Xe_2^+$$

$$2Xe_2^+ + e^- \rightarrow Xe^{**} + Xe$$

$$\mathrm{Xe}^{**} \rightarrow Xe^* + \mathrm{heat}$$

$$Xe^* + Xe + Xe \rightarrow Xe_2^* + Xe$$

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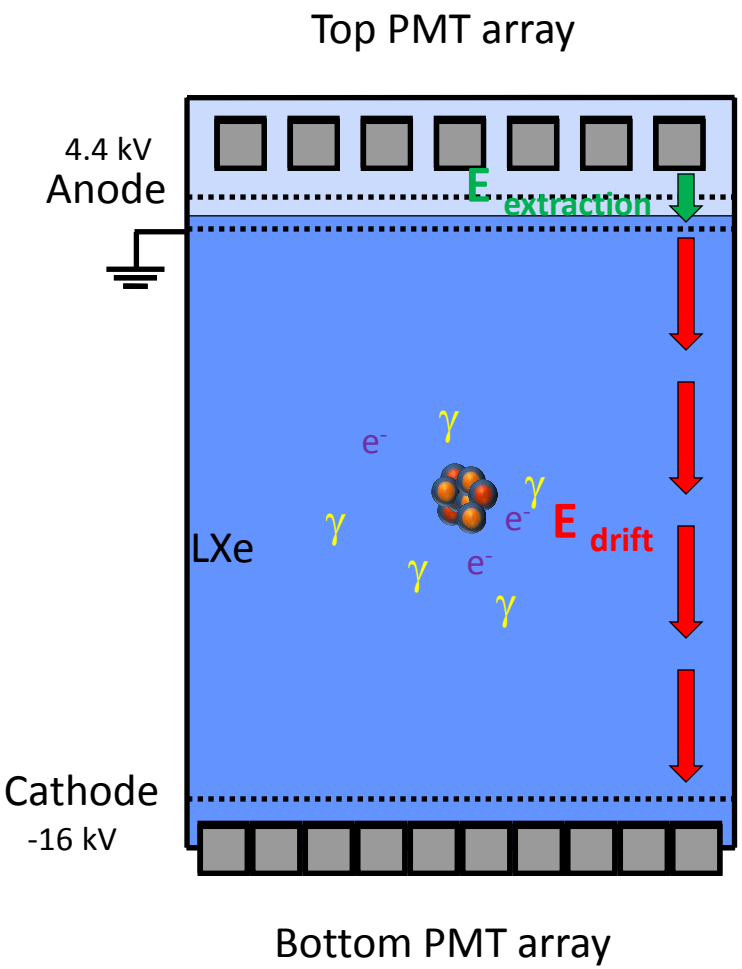
Detection Principle



$$Xe^* + Xe + Xe \rightarrow Xe_2^*$$

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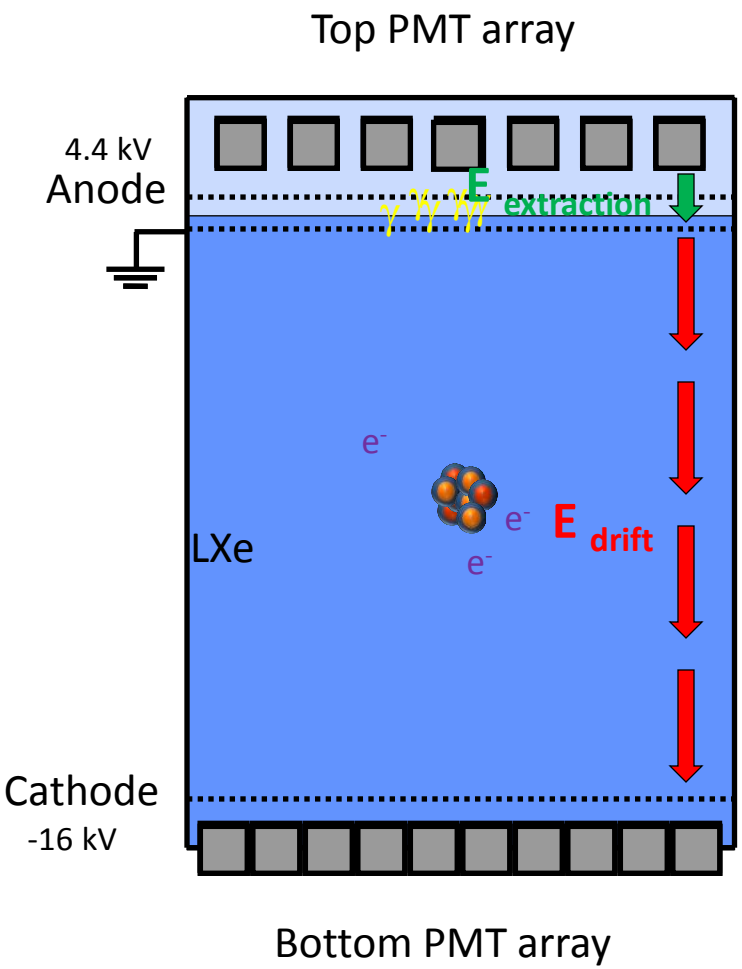
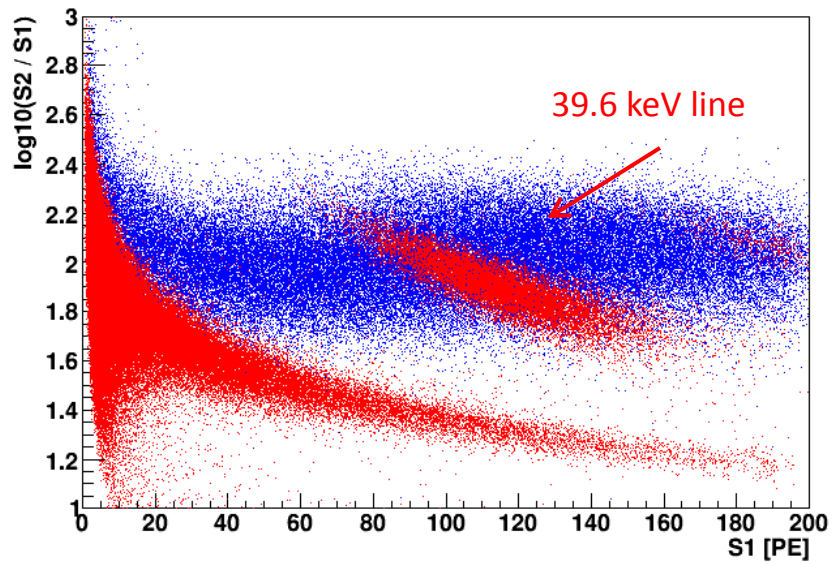


- e , γ – background
- WIMP, N – signal



1. EFT SEARCH FOR HIGH ENERGY RECOILS

Increasing Energy Range

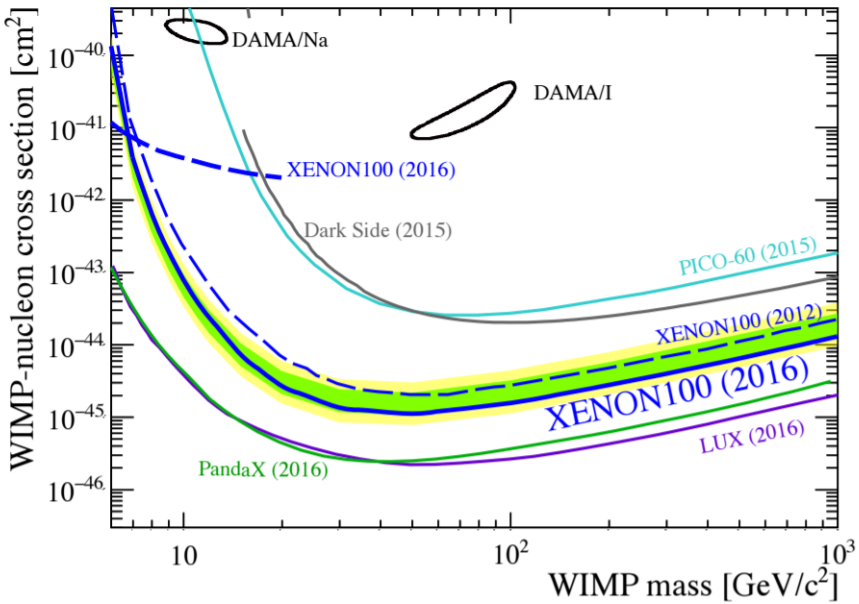
Increasing Detector Volume

Decreasing Background

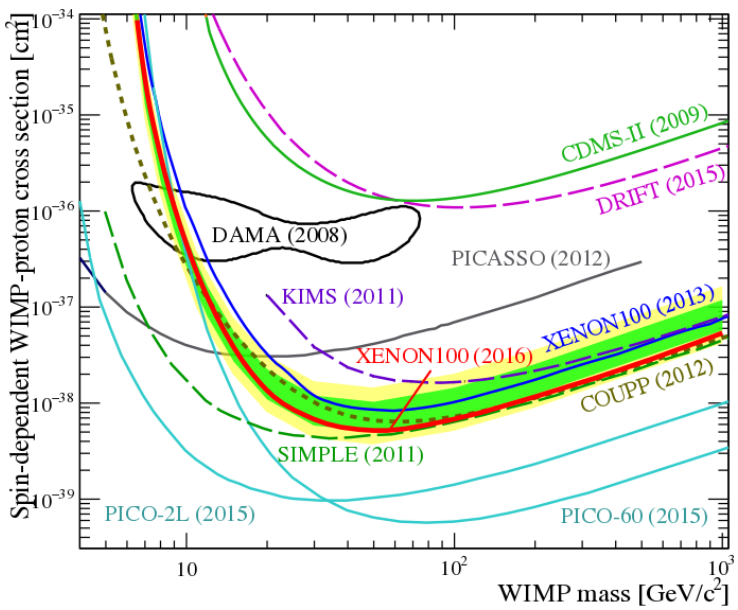
Effective field theory search for high-energy nuclear recoils using the XENON100 dark matter detector
PhysRevD: 96.042004

Standard Interactions

Spin Independent



Spin Dependent



arXiv: 1301.6620

EFT Interactions

- Direct detection interactions are non relativistic.
- $q(i) \cdot x(i)$ *small* - new operators which are momentum dependent.
- Non relativistic EFT -> a model independent approach
- 4 linearly independent quantities $S_N, S_\chi, \vec{q}, v^\perp$

$$\vec{v} = v_{\chi,in} - v_{N,out}$$
$$v^\perp = \vec{v} + \frac{q}{2\mu_N}$$

EFT Interactions

$$L_{int} = c\,\Psi_\chi^* \hat{O}_\chi \psi_\chi \psi_N^* \hat{O}_N \psi_N = \sum_{\alpha=p,n} \sum_{i=1}^{15} c_i^\alpha \hat{O}_i^\alpha$$

SI

$$O_1 = 1_\chi 1_N$$

$$\cancel{O_2 = (v^\perp)^2}$$

Cannot be obtained at leading order from relativistic

$$O_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$$

SD

$$O_4 = \vec{S}_\chi \cdot \vec{S}_N$$

$$O_5 = i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$$

$$O_6 = (\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$$

$$O_7 = \vec{S}_N \cdot \vec{v}^\perp$$

$$O_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$O_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$$

$$O_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$

$$O_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

$$O_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$$

$$O_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \times \frac{\vec{q}}{m_N})$$

$$O_{14} = i(\vec{S}_\chi \times \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \vec{v}^\perp)$$

$$O_{15} = -(\vec{S}_\chi \times \frac{\vec{q}}{m_N})[(\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}]$$

Exotic, don't arise from spin 0/1 mediators

Fitzpatrick et al. arXiv:1203.3542
Anand et al. arXiv: 1308.6288

EFT Interactions

Nuclear Response

M	Σ''	Σ'	Δ	Φ''	$\tilde{\Phi}'$
SI	SD	SD	LD	LSD	Tensor-LSD
	(longitudinal)	(transverse)	(ang-mom)	(spin-orbit)	

M

$$O_1 = 1_\chi 1_N$$

$$\cancel{O_2 = (v^\perp)^2}$$

Cannot be obtained at leading order from relativistic

$$O_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$$

$\Sigma' + \Sigma''$

$$O_4 = \vec{S}_\chi \cdot \vec{S}_N$$

$$O_5 = i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$$

$$O_6 = (\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$$

$$O_7 = \vec{S}_N \cdot \vec{v}^\perp$$

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$$O_{14} = i(\vec{S}_\chi \times \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \vec{v}^\perp)$$

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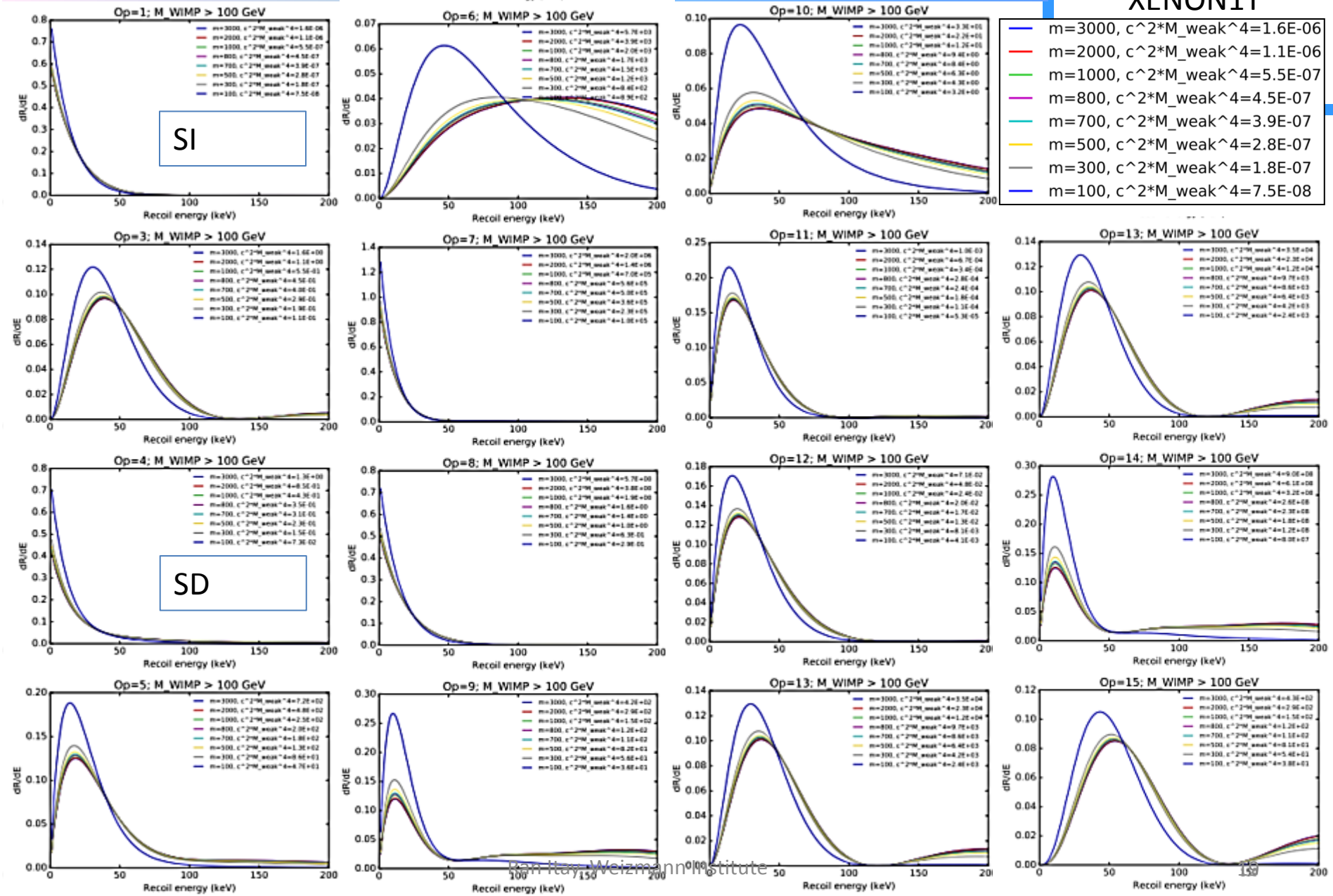
From EFT to Superradiance, DM searches with XENON

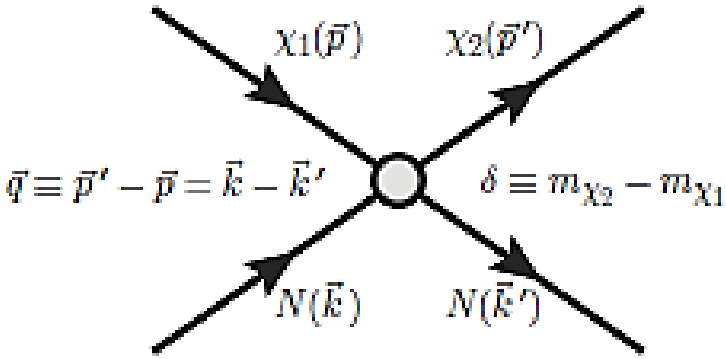


Inelastic WIMP

Same operators, small modification.

$$v^{\perp}_{inelastic} = v^{\perp}_{elastic} + \frac{\boldsymbol{\delta_m}}{|\vec{q}|^2}\,\vec{q}$$

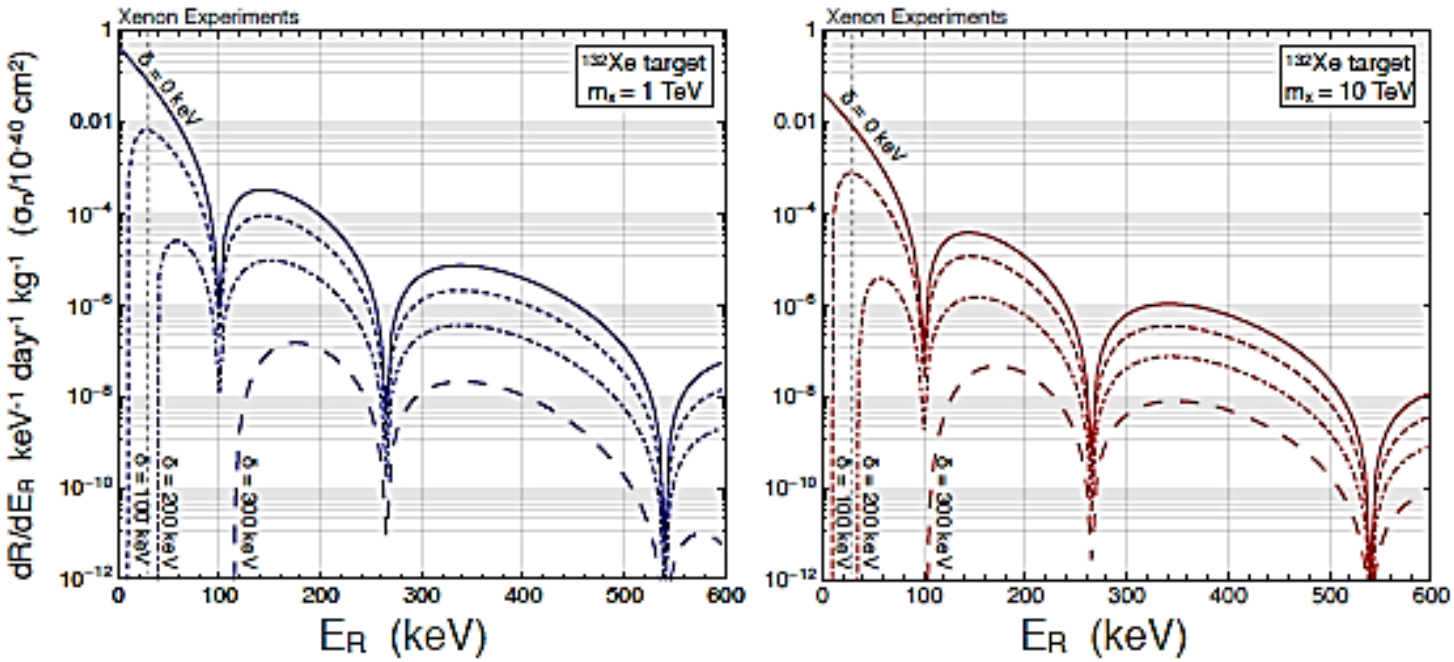
$$v_{min} = \sqrt{\frac{1}{(2m_N E_R)}}\left|\frac{m_N E_R}{\mu_N} + \boldsymbol{\delta_m}\right|$$



G. Barello et al. arXiv: 1409.0536

Inelastic WIMP

Interactions suppressed at low momentum transfer.



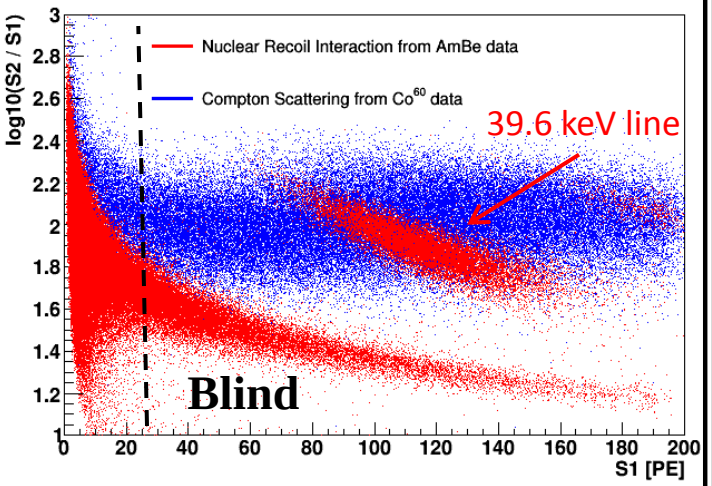
Bramante et al. arXiv 1608.02662

Strategy

- Blind analysis, data of Run 2, 28.2.11 – 31.3.12 (34*225.6 kg*day)
- Treat each operator separately
- Signal region divided into 2 energy regimes.

Low Energy (3-30PE),
"standard" analysis.

- Signal Model – MC based
- Detector acceptance
- Background Model (fit)
- Profile Likelihood(pdf in S1)

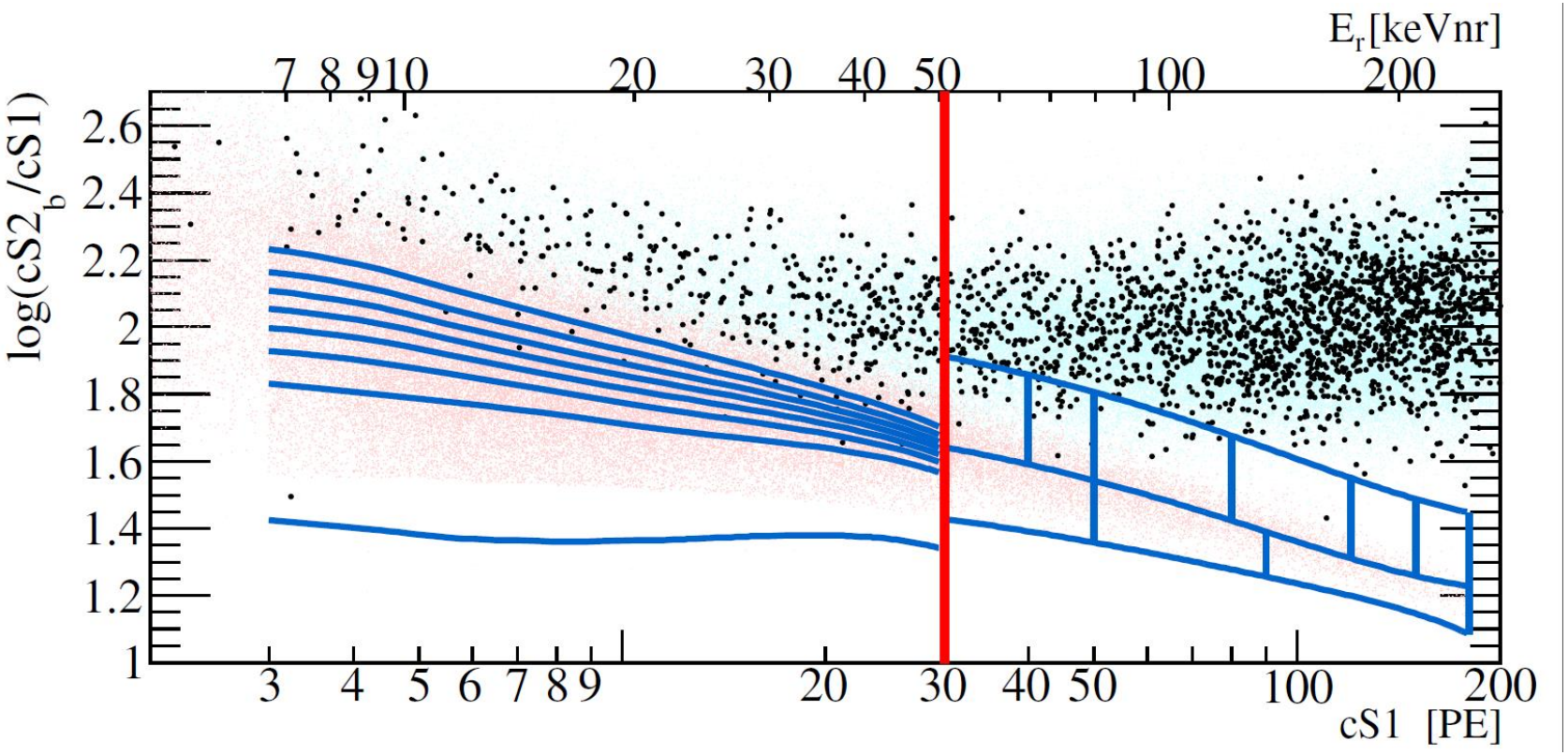


High Energy (30-180PE),
This work.

- Signal Model – calibration based
- Detector acceptance
- Background Model (calibration data)
- Profile Likelihood (binned S1)

Likelihood combination

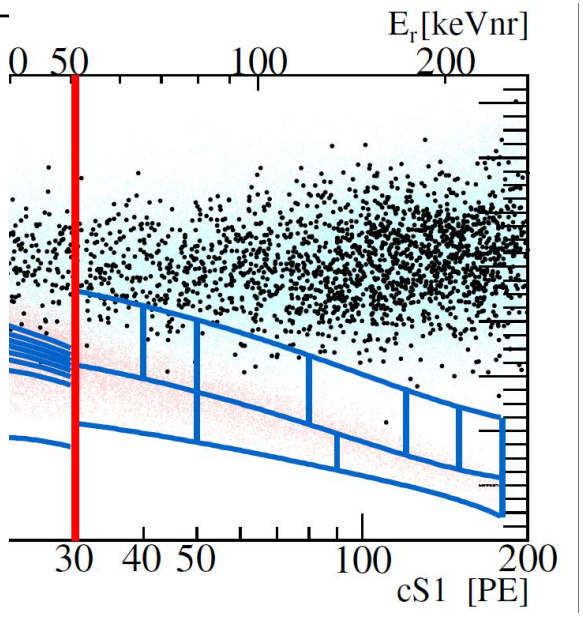
Background Model



Background Model

High Energy (30-180PE)

#	Band	Energy Range (cS1)	# Background Events
1	upper	30 - 40	24±5
2	upper	40 - 50	16±3
3	upper	50 - 80	12±3
4	upper	80 - 120	1.1 ± 0.3
5	upper	120 - 150	$(1.0 \pm 0.5) \times 10^{-1}$
6	upper	150 - 180	$(0.8 \pm 0.4) \times 10^{-1}$
7	lower	30 - 50	0.9 ± 0.3
8	lower	50 - 90	$(3.5 \pm 1.2) \times 10^{-1}$
9	lower	90 - 180	$(1.8 \pm 0.7) \times 10^{-1}$

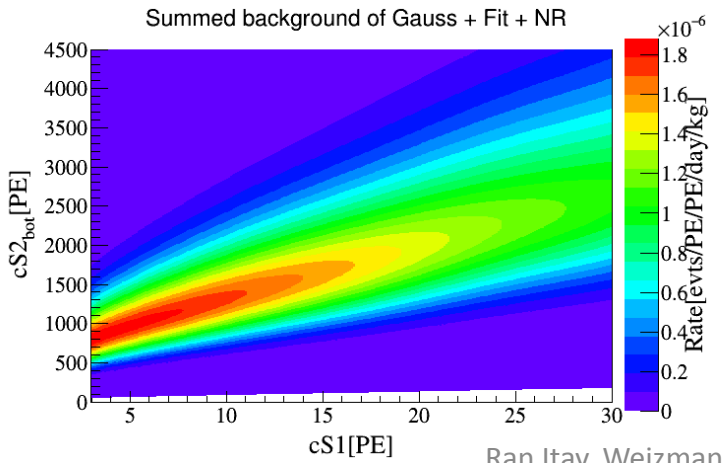


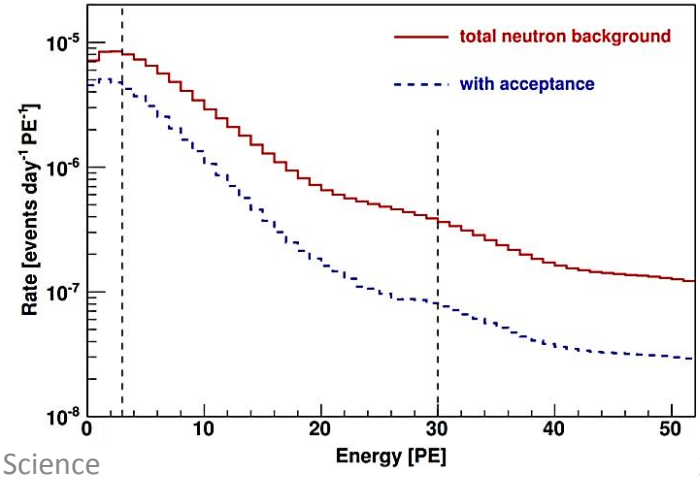
Background Model

Low Energy (3-30PE)

Science Run – II

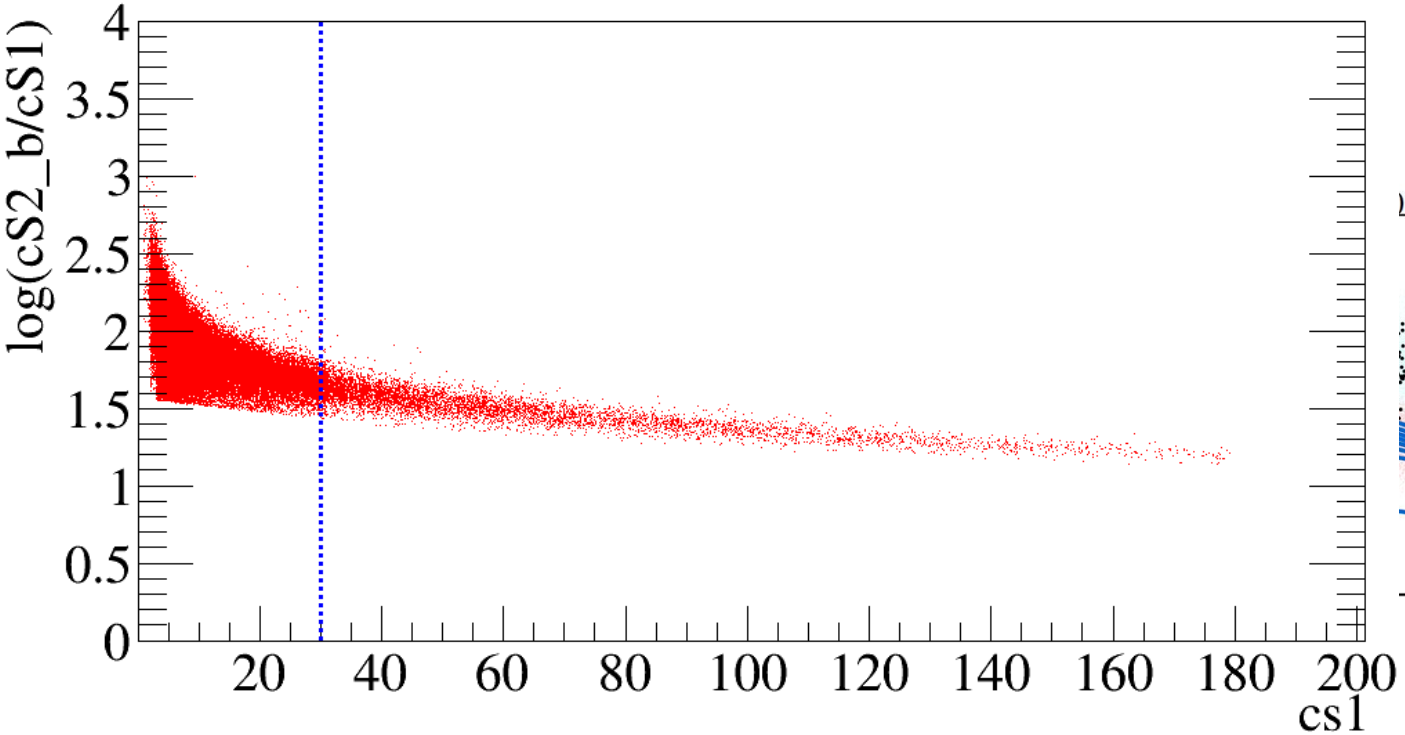
- Gaussian Component
- Fit to anomalous leakage
- Radiogenic and Cosmogenic neutrons

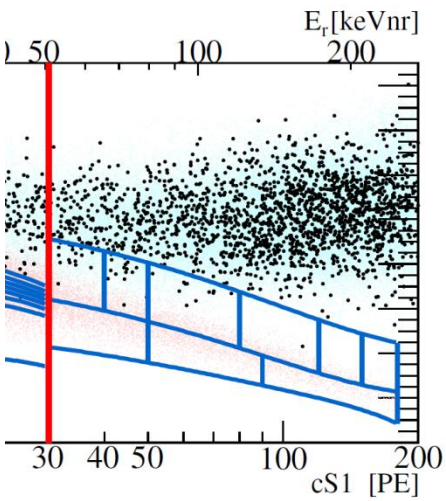




Signal Model

High Energy (30-180PE)





Signal Model

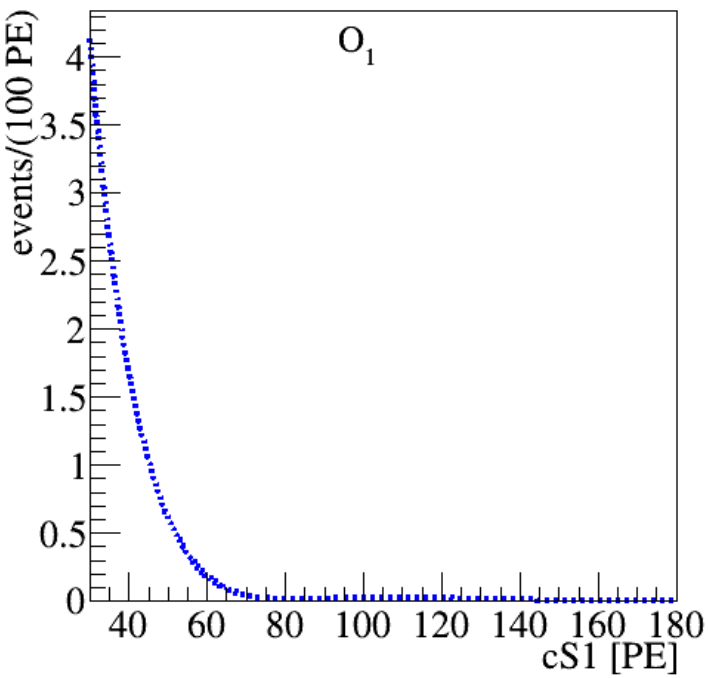
High Energy (30-180PE)

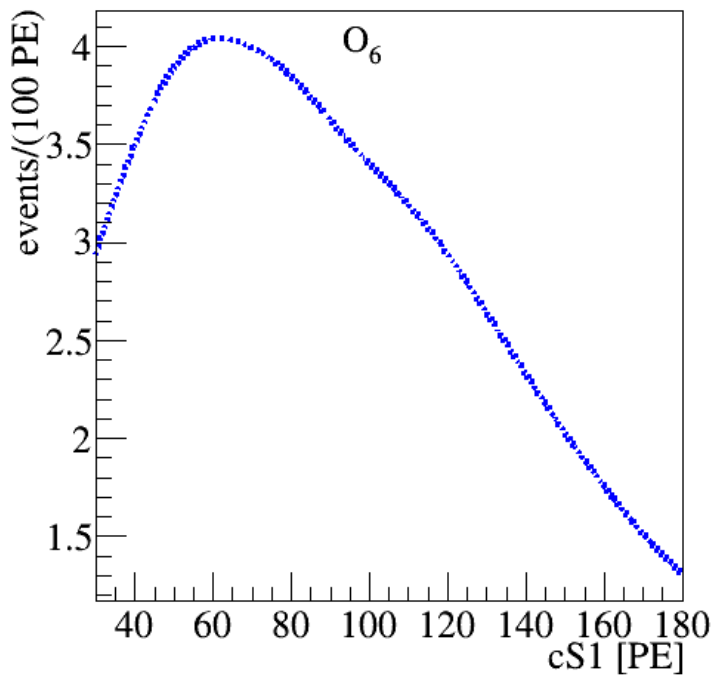
SI.

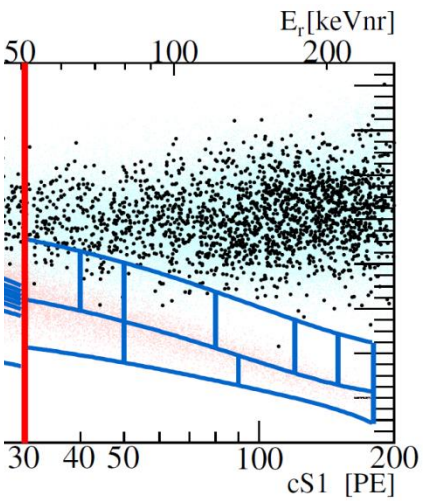
$\hat{O}_1 = 1_\chi \cdot 1_N$

SD (longitudinal only).

$\hat{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q})$

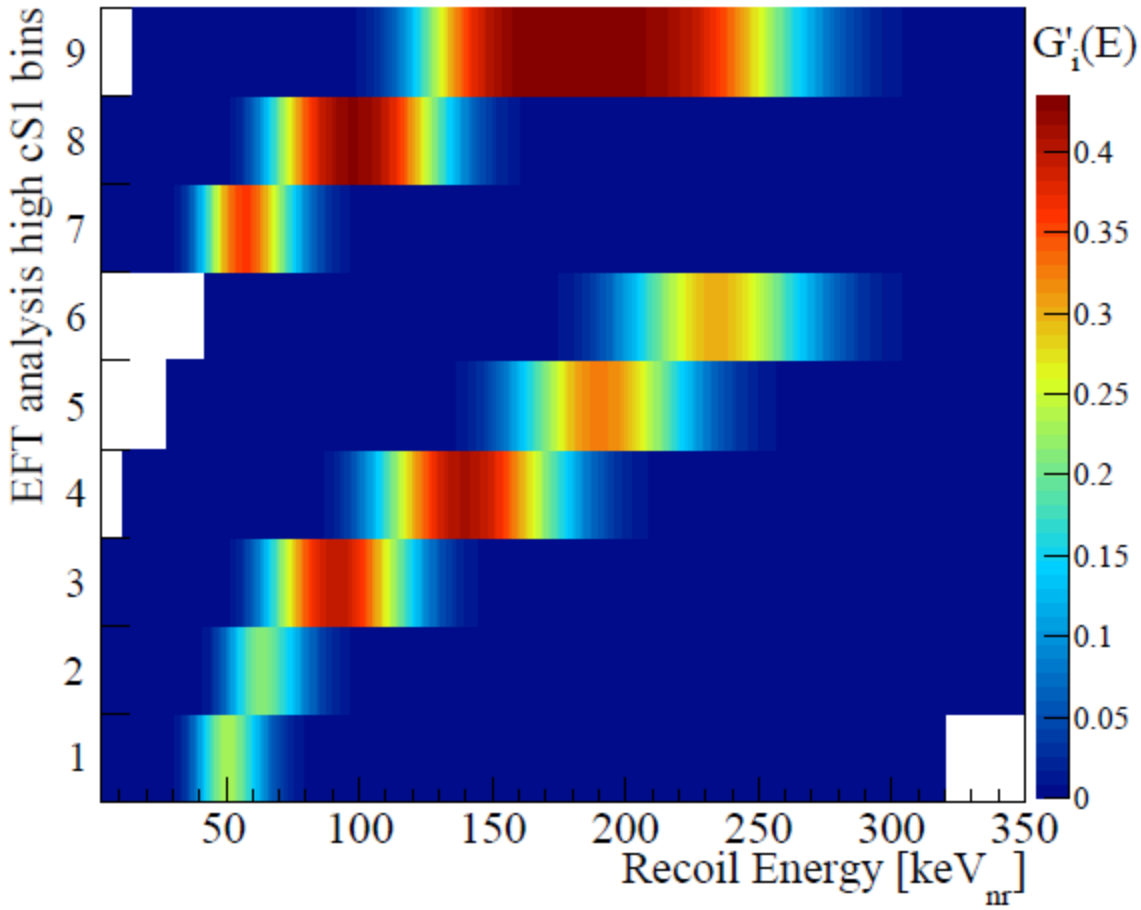






Signal Model

High Energy (30-180PE)



Signal Model

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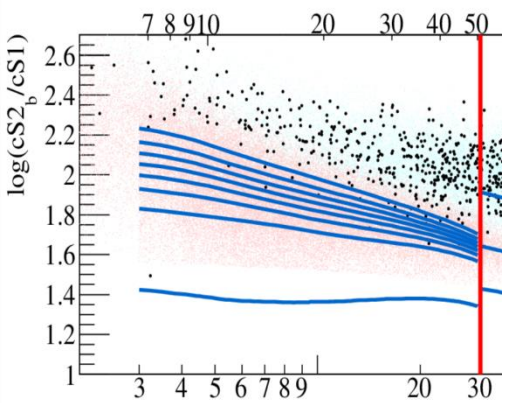
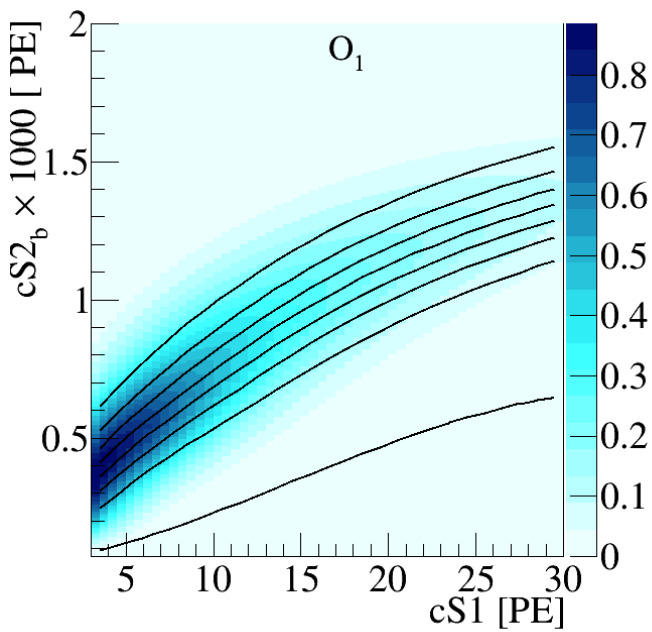
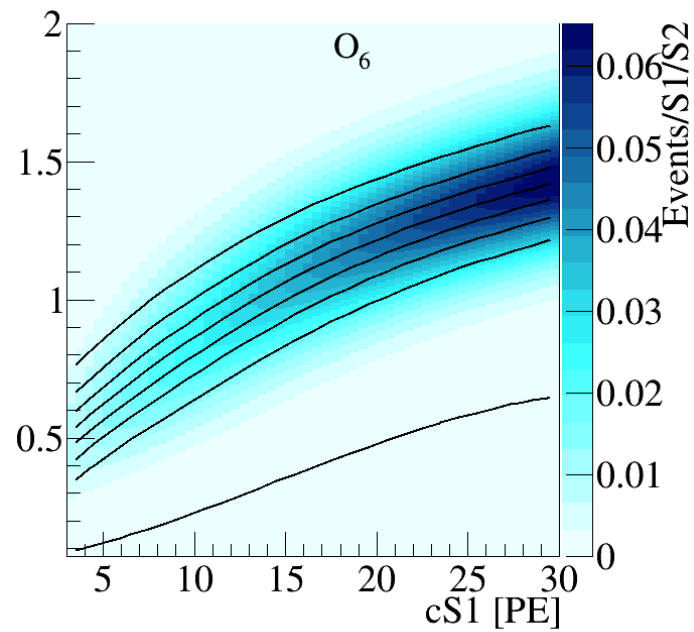


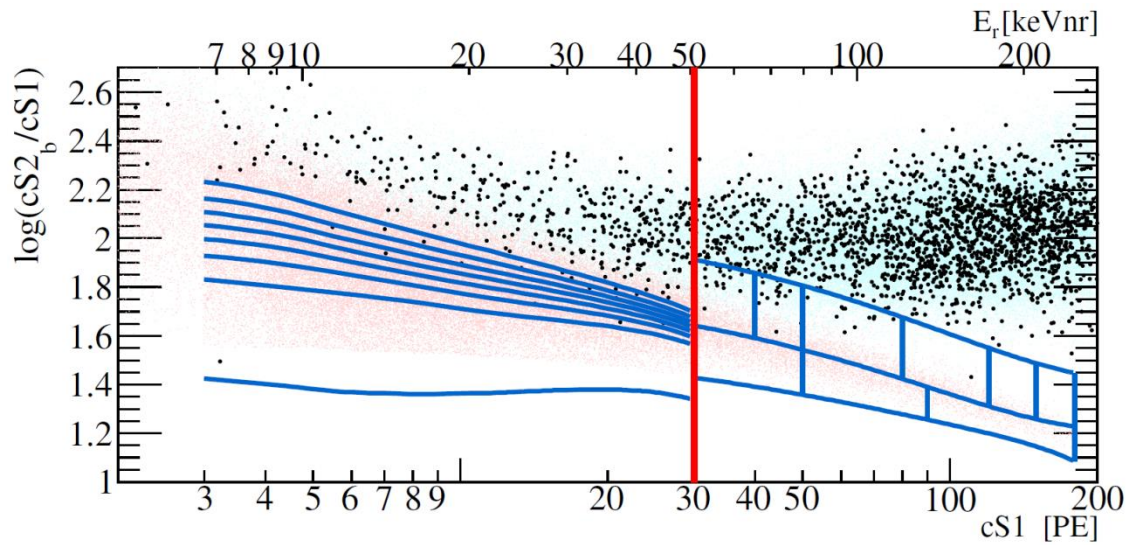




Benchmark Result

Benchmark Definition

AmBe mean – above
3σ quantile – below



HighE

Expected number of events – $1.4 \pm 0.3_{stat}$
Observed number of events – 0

LowE

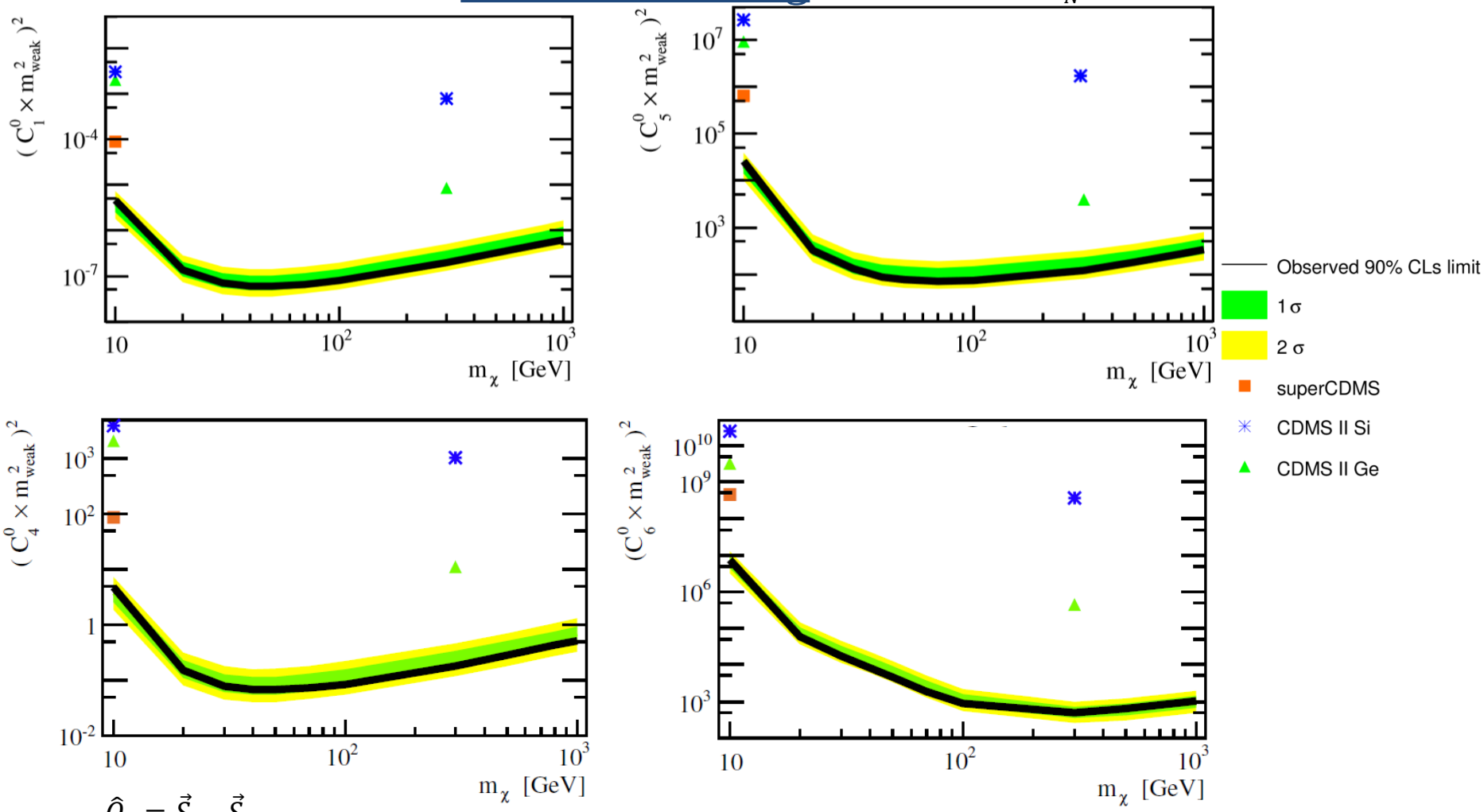
Expected number of events – $3 \pm 0.5_{stat}$
Observed number of events - 3

Exclusion Limits

Elastic scattering

$\hat{O}_1 = 1_\chi \cdot 1_N$

$\hat{O}_5 = i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perperp)$



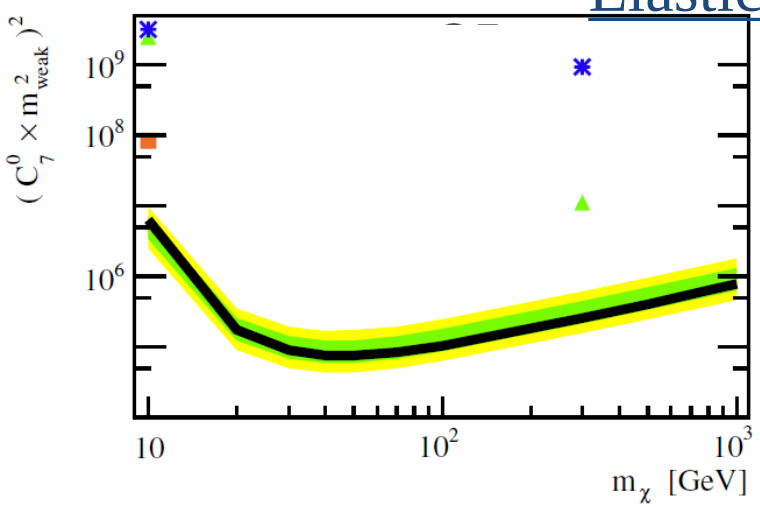
$\hat{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$

$\hat{O}_6 = (\vec{S}_\chi \cdot \vec{q}) \cdot (\vec{S}_N \cdot \vec{q})$

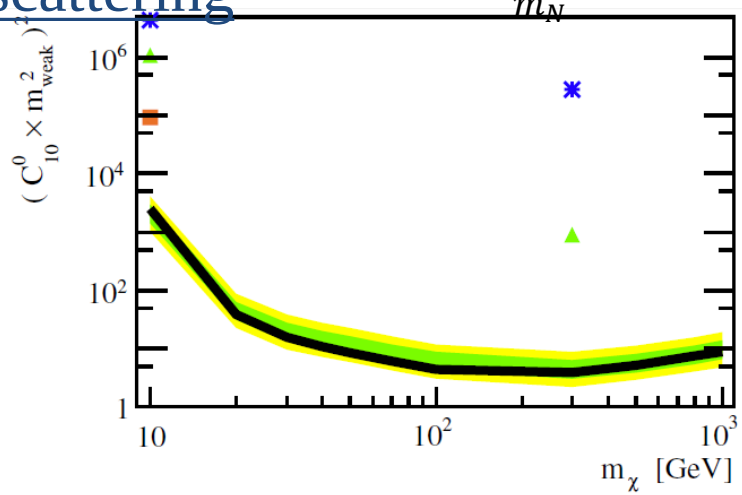
Exclusion Limits

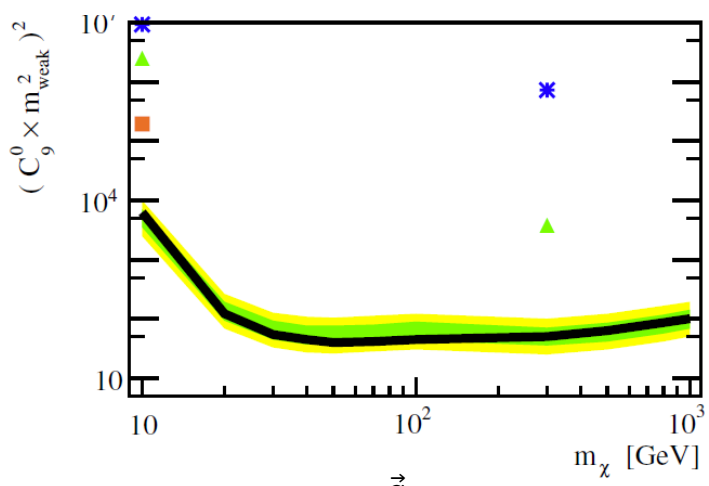
Elastic scattering

$\hat{O}_7 = \vec{S}_N \cdot \vec{v}^{\perp}$

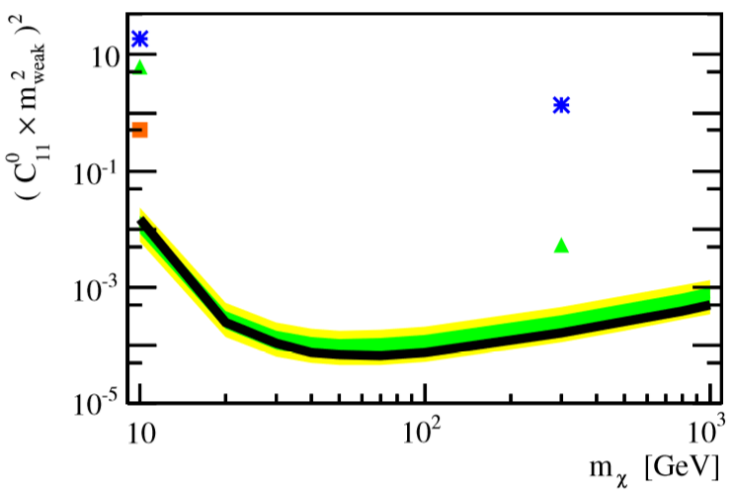


$\hat{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$





$\hat{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$



$\hat{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$

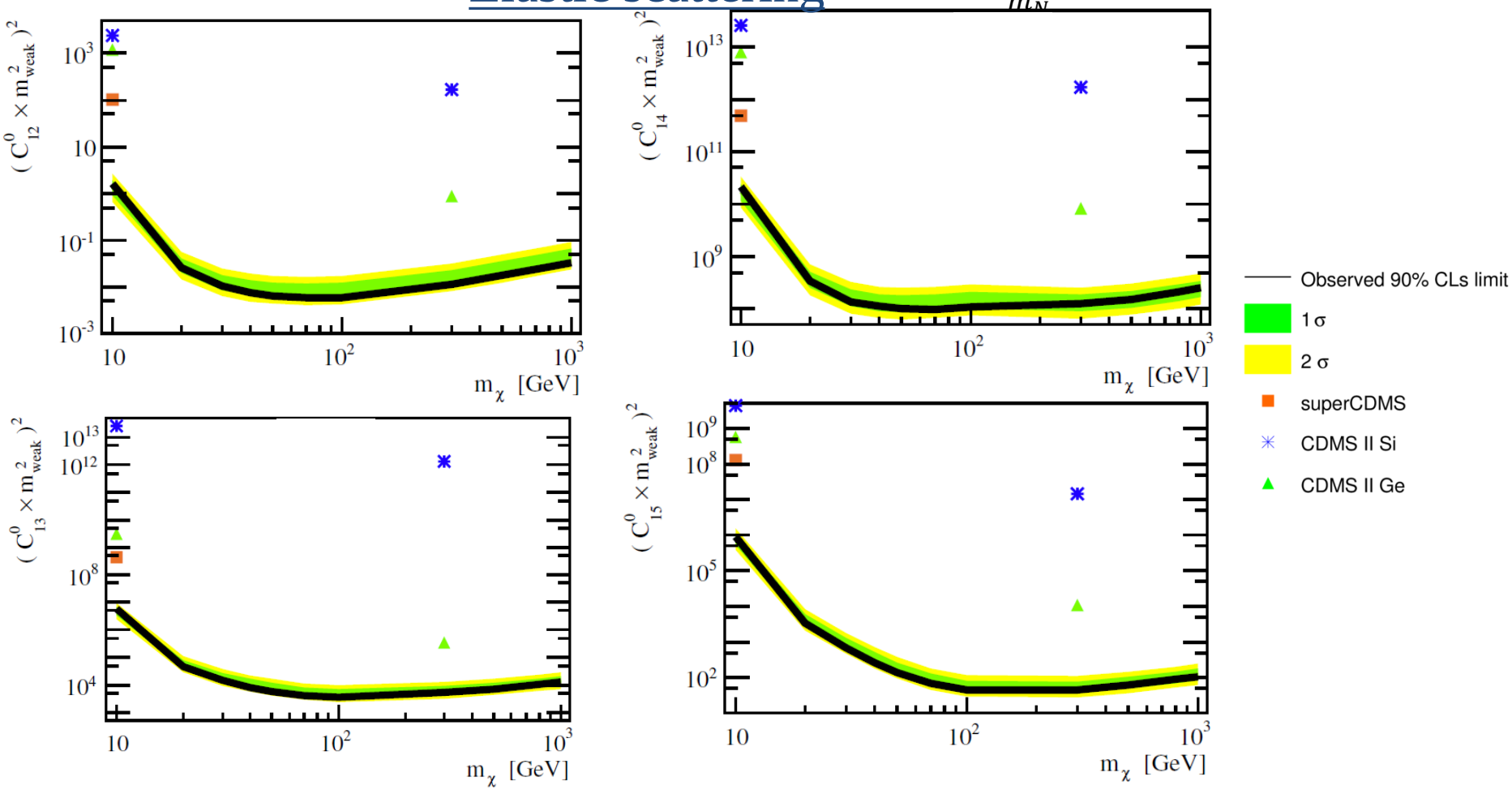
Observed 90% CLs limit
1 σ
2 σ
superCDMS
CDMS II Si
CDMS II Ge

Exclusion Limits

Elastic scattering

$\hat{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$

$\hat{O}_{14} = i(\vec{S}_\chi \times \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \vec{v}^\perp)$



$\hat{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \times \frac{\vec{q}}{m_N})$

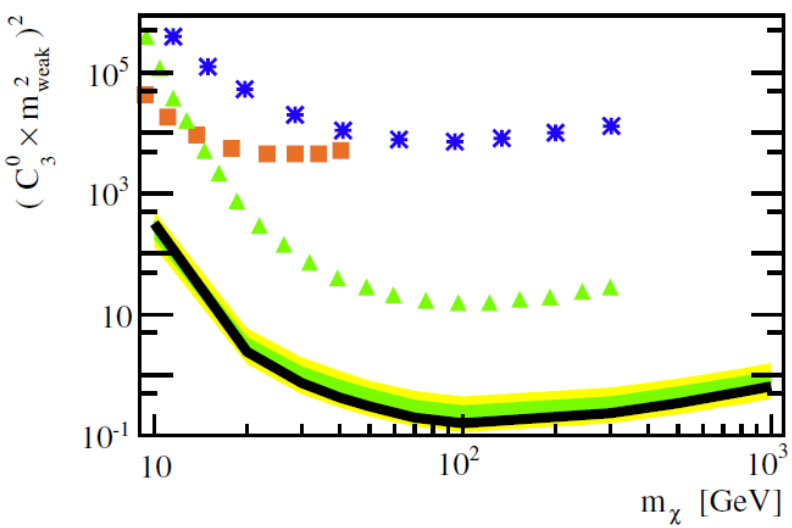
$\hat{O}_{15} = -(\vec{S}_\chi \times \frac{\vec{q}}{m_N})[(\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}]$

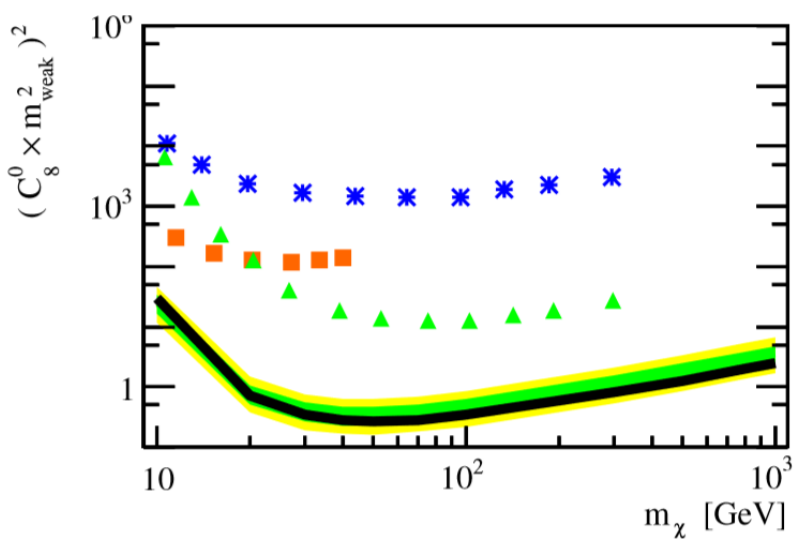
Exclusion Limits

Elastic scattering

$$O_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^{\perp})$$

$$\hat{O}_8 = \vec{S}_\chi \cdot \vec{v}^{\perp}$$



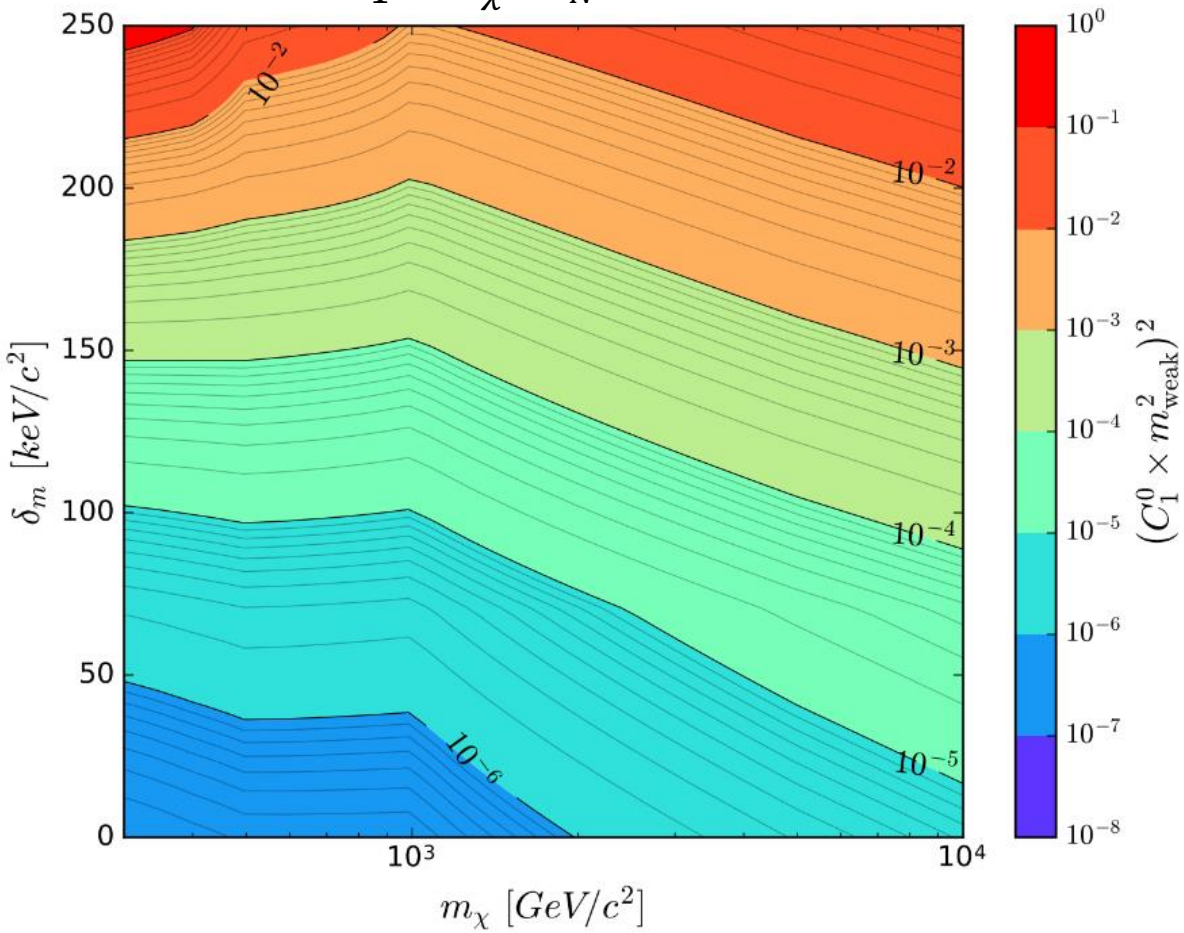


- Observed 90% CLs limit
- 1 σ
- 2 σ
- superCDMS
- CDMS II Si
- CDMS II Ge

Exclusion Limits

Inelastic WIMP

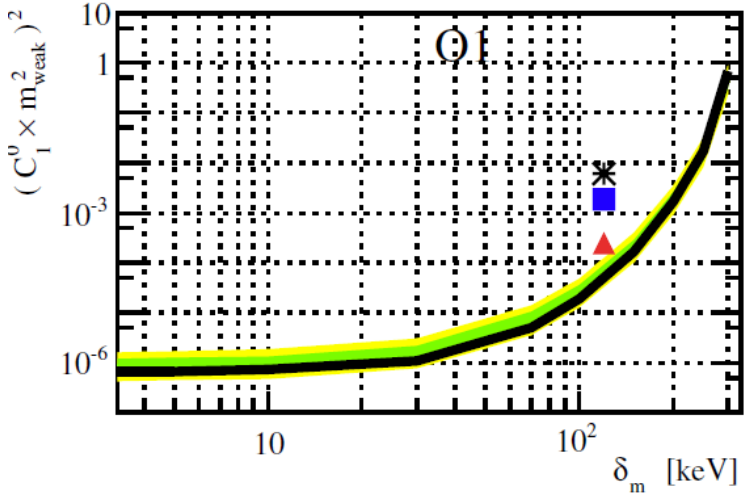
$\hat{O}_1 = 1_\chi \cdot 1_N$



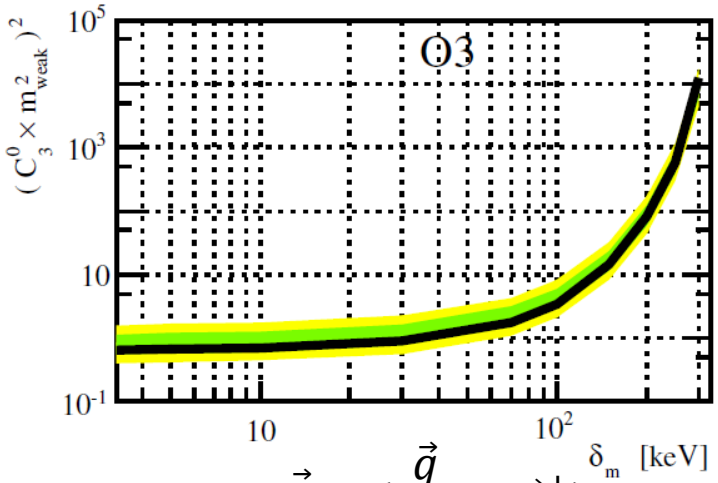
Exclusion Limits

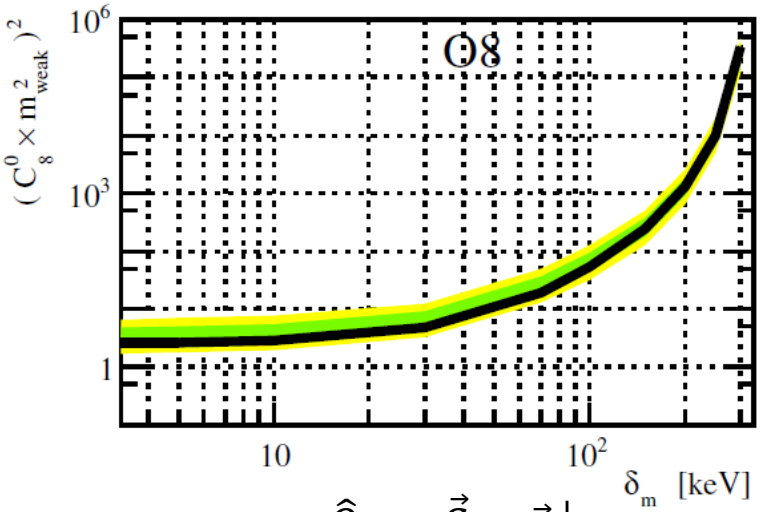
Inelastic WIMP

$\hat{O}_1 = 1_\chi \cdot 1_N$



XENON 2011
CDMS-II
ZEPLIN-III





$O_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$

$\hat{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$

XENON1T FIRST RESULTS

Increasing Energy Range

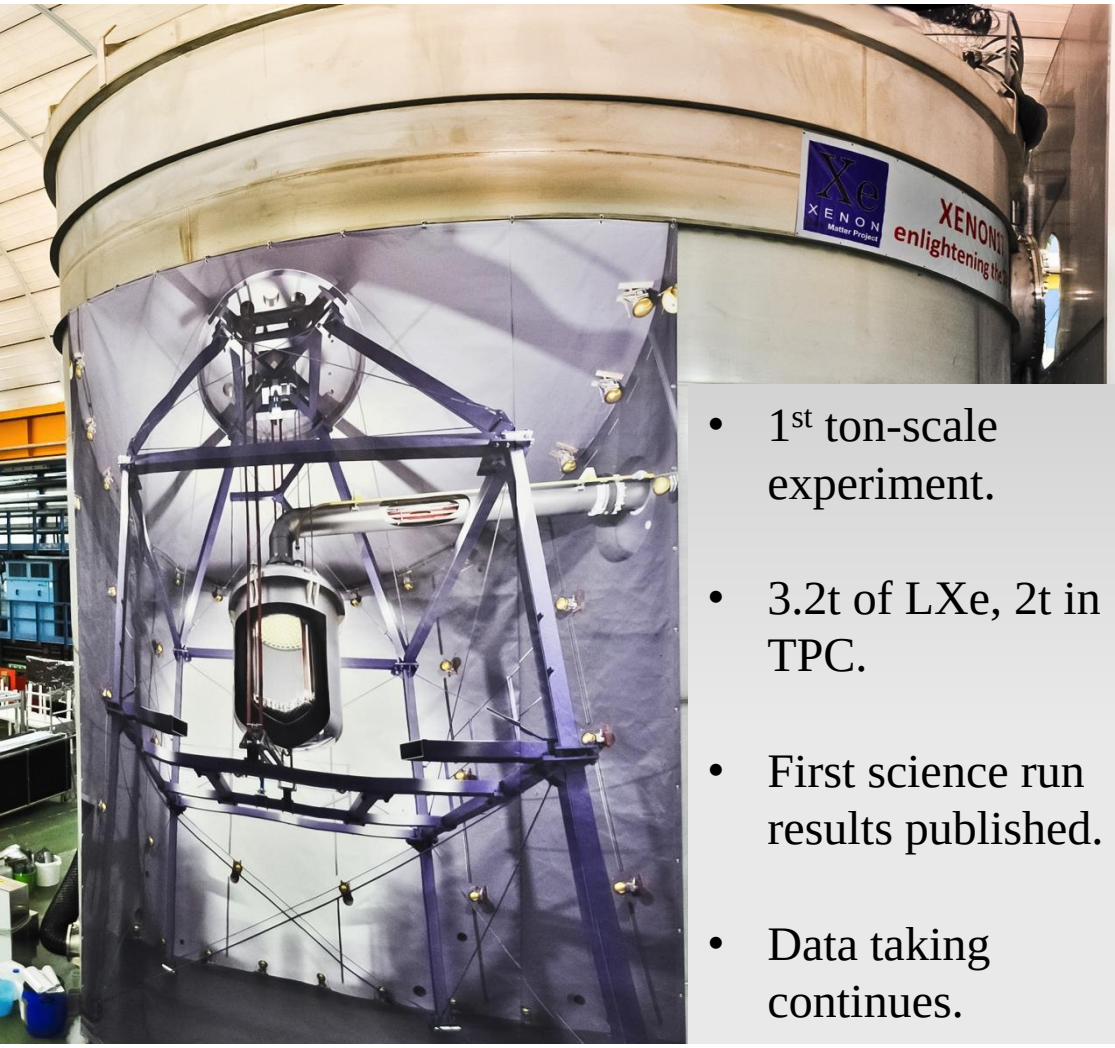
Increasing Detector Volume

Decreasing Background

First Dark Matter Search Results from the XENON1T Experiment
arXiv: 1705.06655

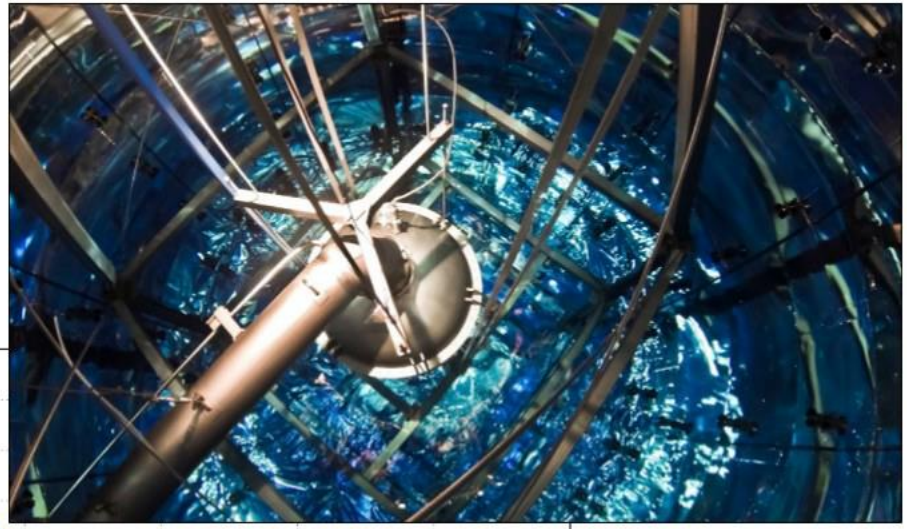
XENON1T First Results

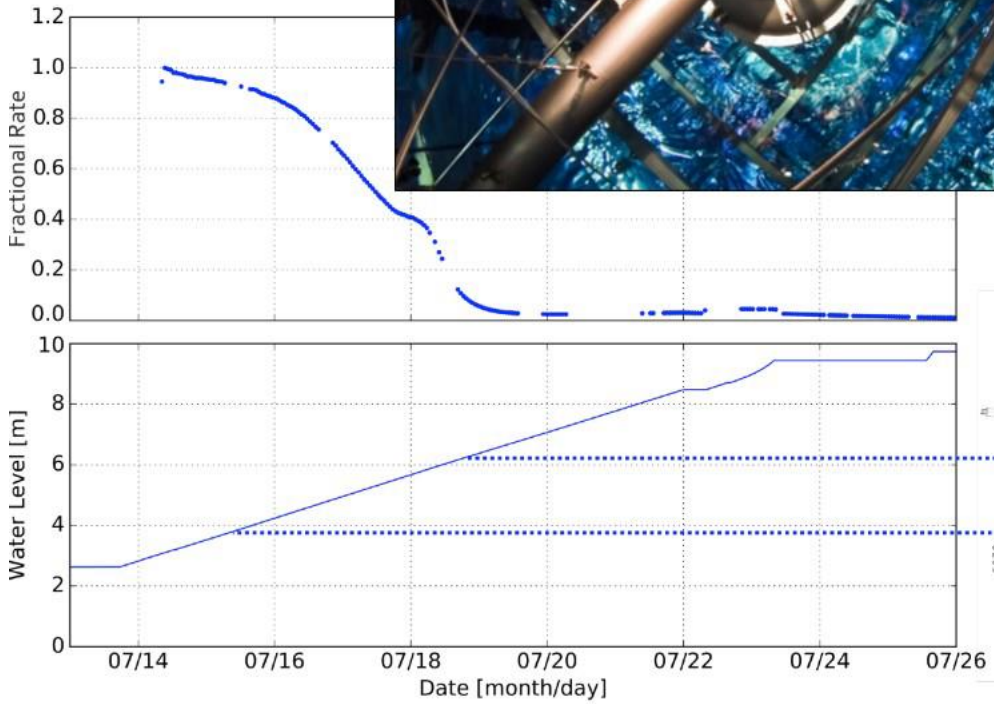
XENON1T First Results

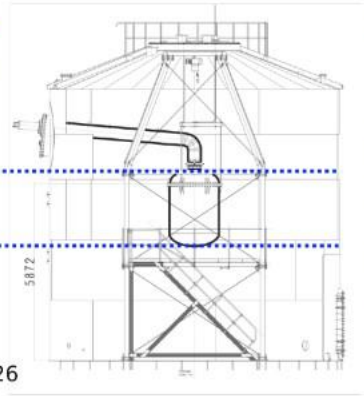


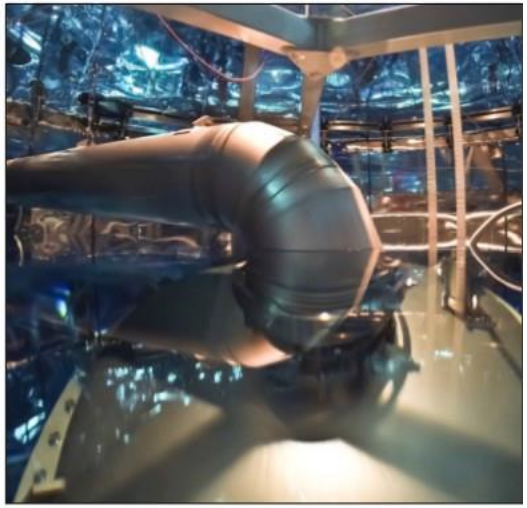
- 1st ton-scale experiment.
- 3.2t of LXe, 2t in TPC.
- First science run results published.
- Data taking continues.

Water Tank



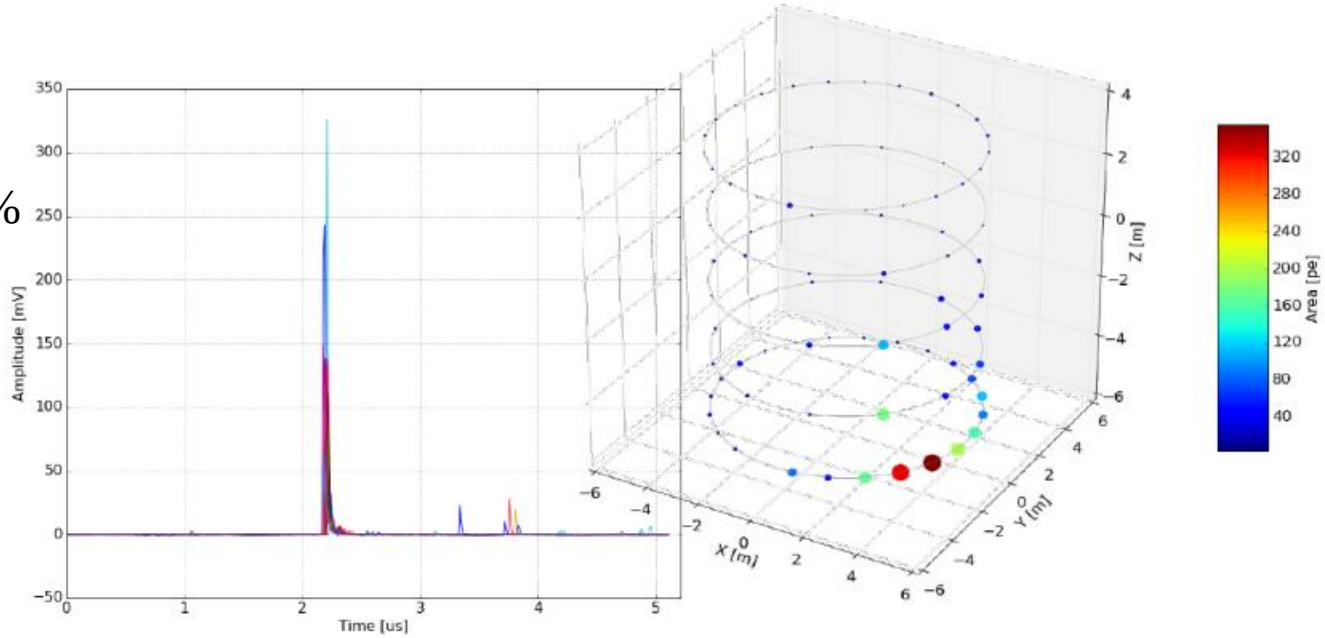

Fractional Rate
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Water Level [m]
10
8
6
4
2
0
07/14
07/16
07/18
07/20
07/22
07/24
07/26
Date [month/day]





Water Tank

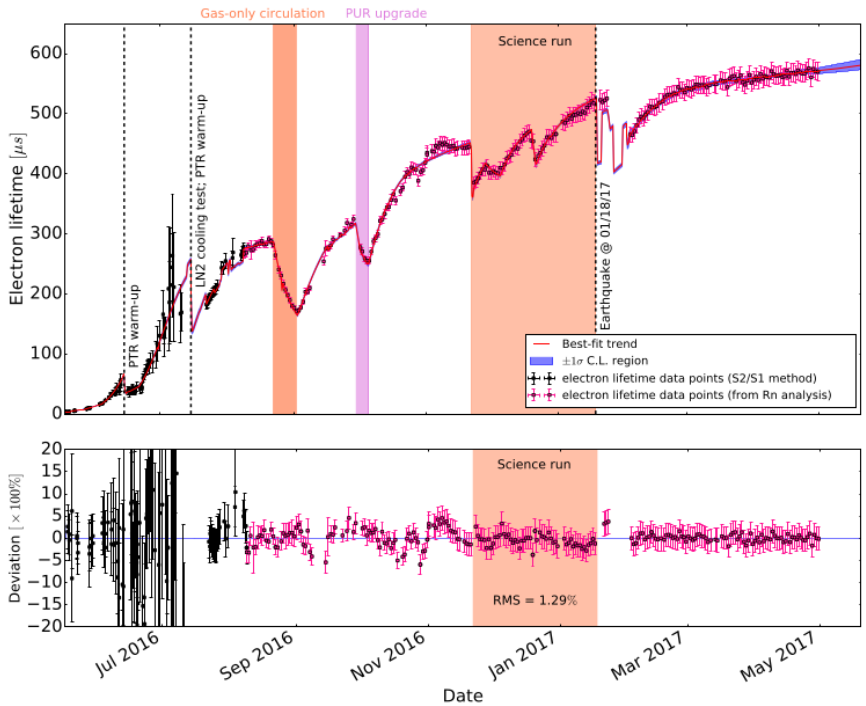
- Active against Muons.
- 84 hige QE 8” Hamamtsu PMTs
- Trigger efficiency > 99.5%
- Cosmogenic neutrons suprresed <0.01 events/ton/year.
- No coincidence with TPC found in this run.

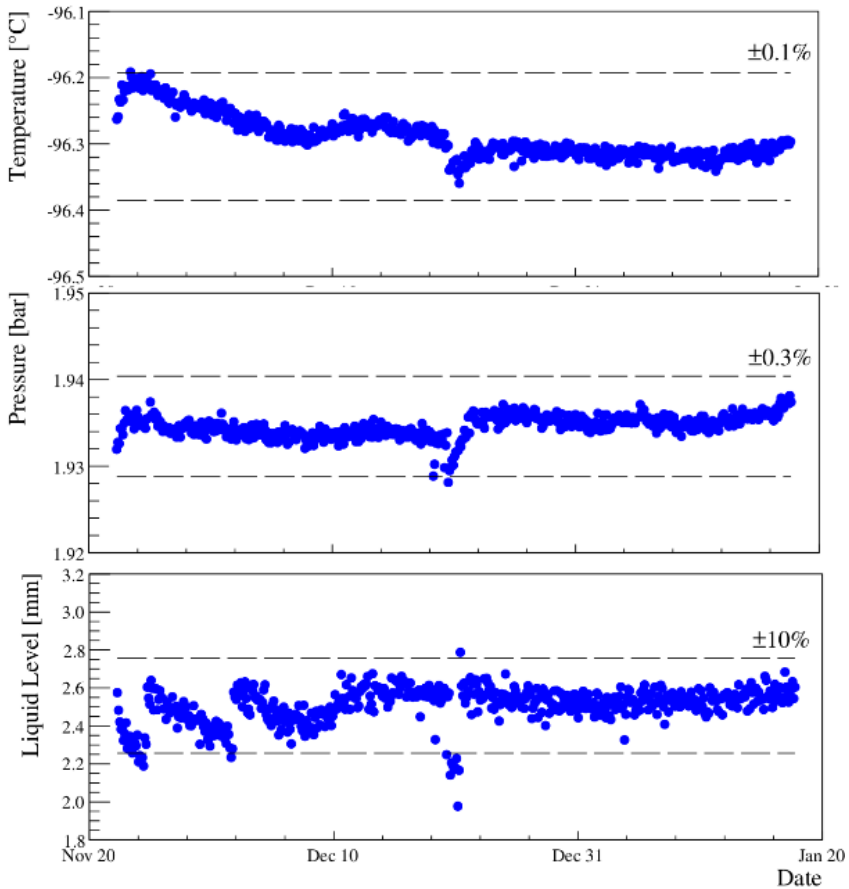


JINST 9, 11007 (2014)

Stability and Purification

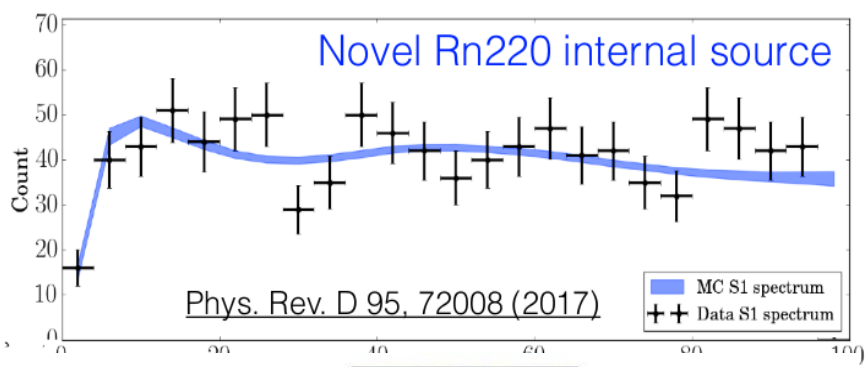
- Critical parameters stable .
- Good electron lifetime evaluation.

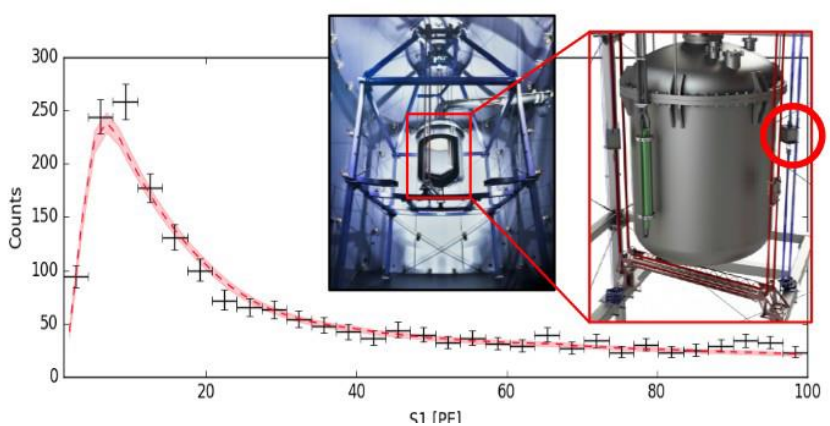


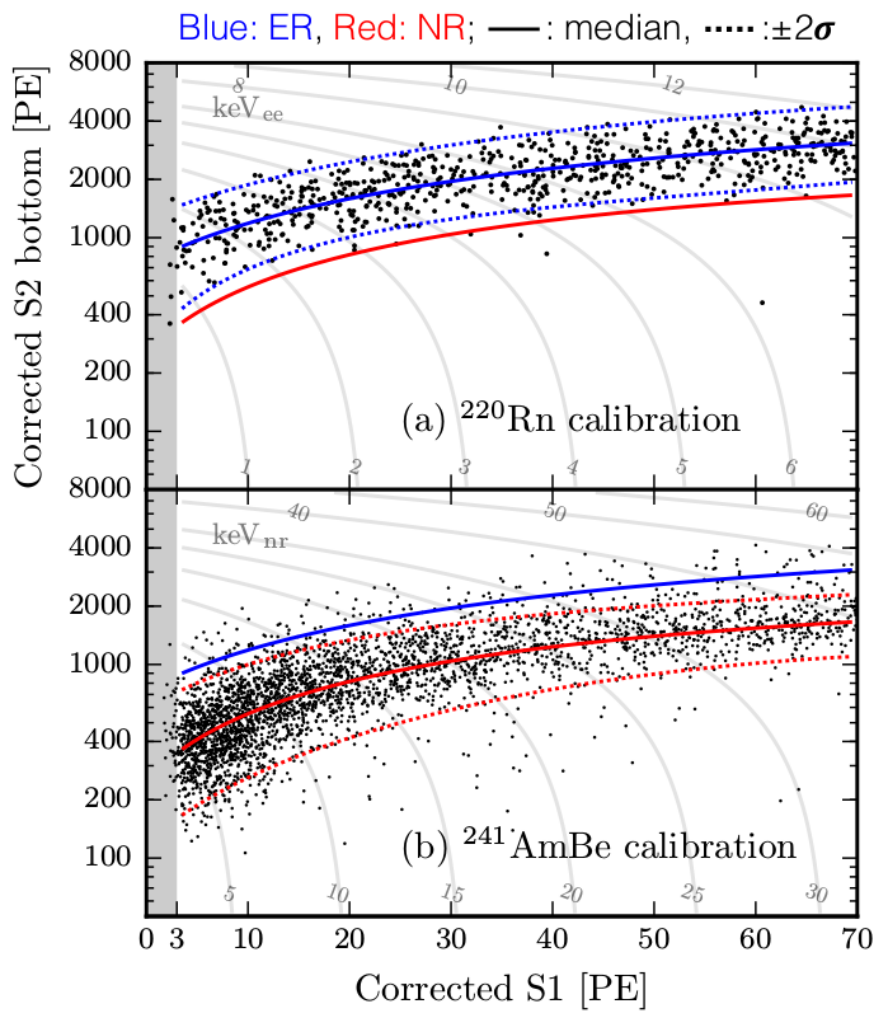


Calibration

- ER calibration using ^{220}Rn and ^{83m}kr.
- NR calibration using ^{241}AmBe .
- All parameters fit to model with no significant deviation.

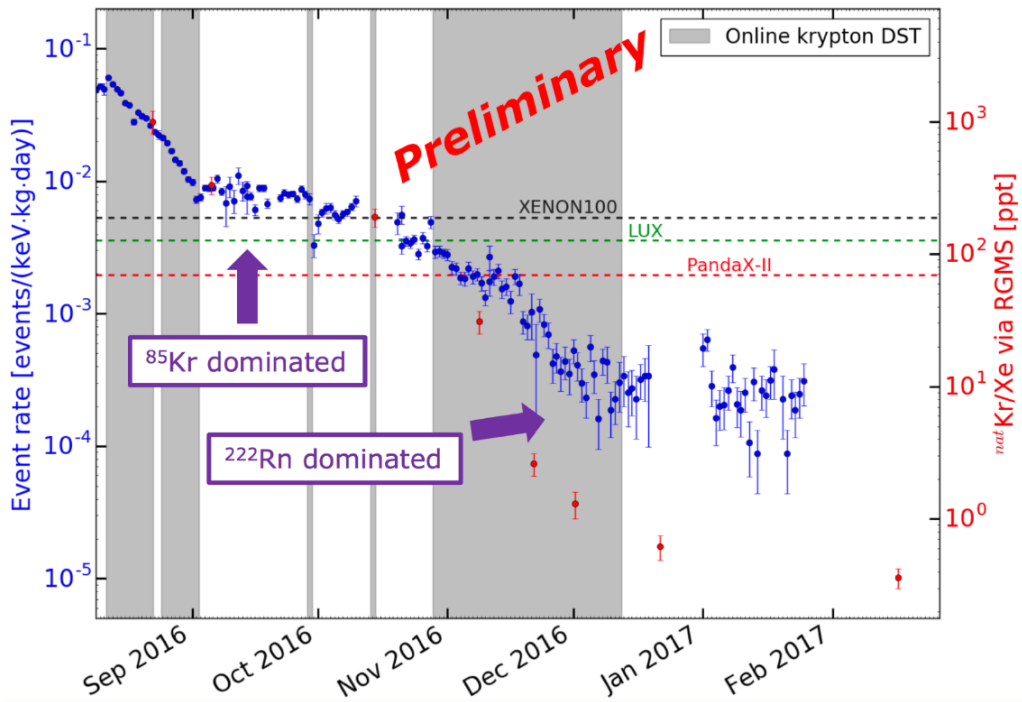






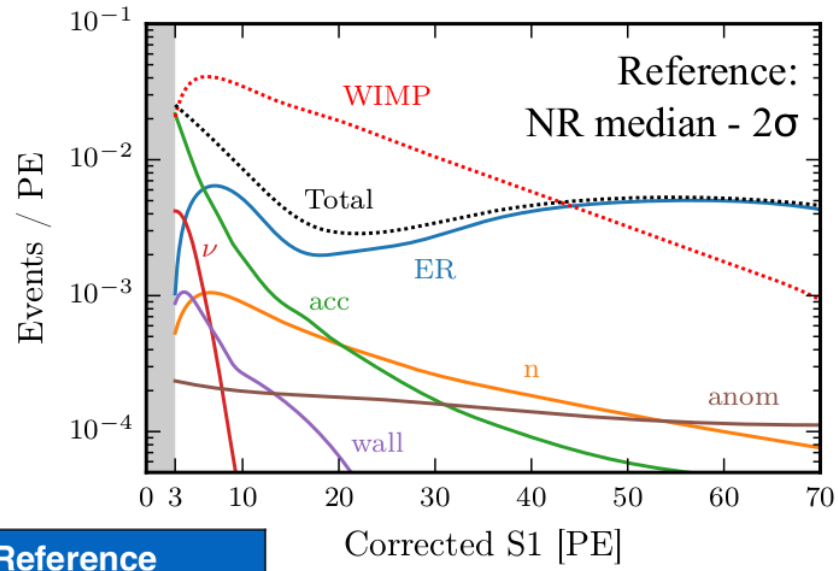
Background

Lowest Background level achieved in direct detection experiment



Background

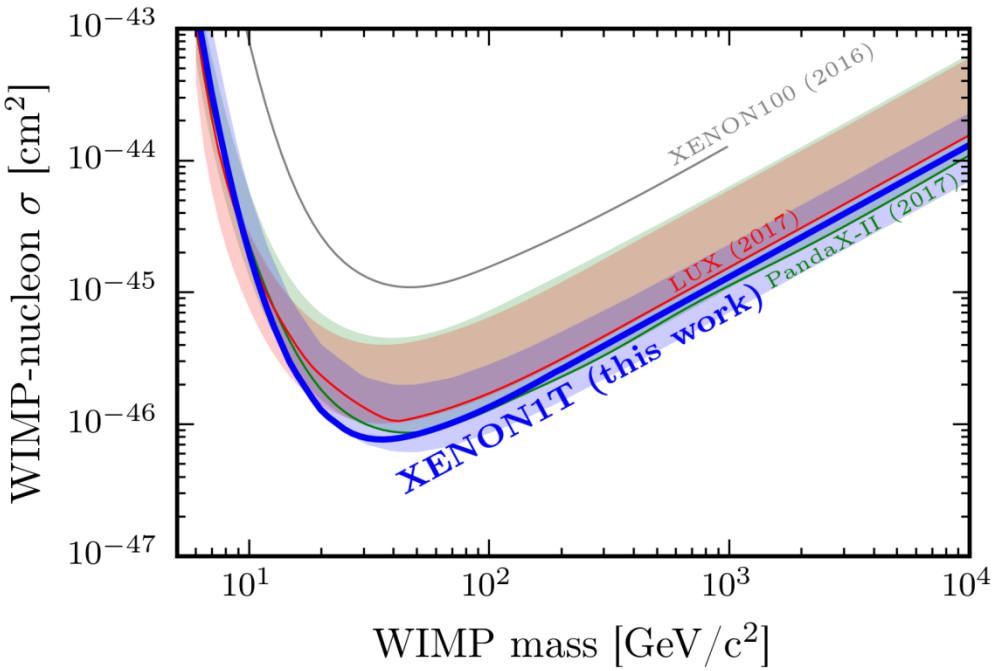
- ER and NR spectral shapes derived from models fitted to calibration data.
- Other background expectations are data driven, derived from a control sample.

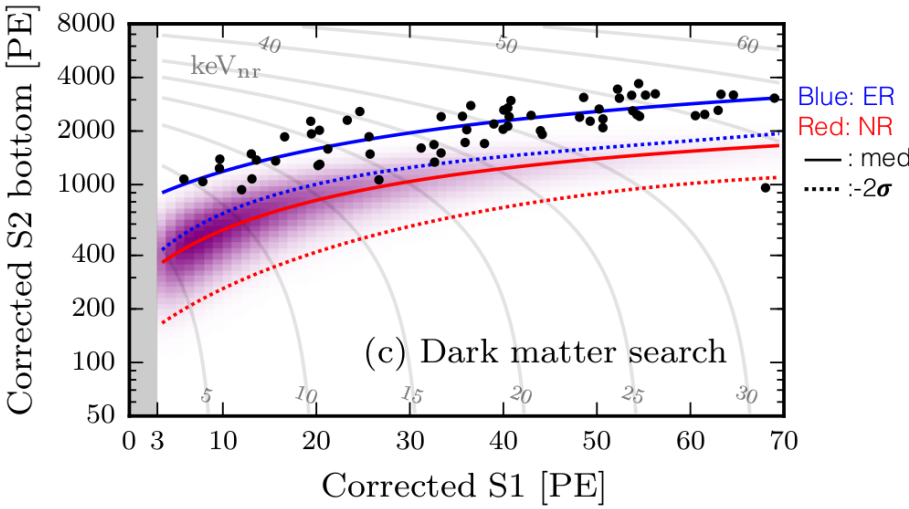


Background & Signal Rates	Total	Reference
Electronic recoils *(ER)*	62 ± 8	0.26 (+0.11)(-0.07)
Radiogenic neutrons *(n)*	0.05 ± 0.01	0.02
CNNS (ν)	0.02	0.01
Accidental coincidences (*acc*)	0.22 ± 0.01	0.06
Wall leakage (*wall*)	0.52 ± 0.32	0.01
Anomalous (*anom*)	0.09 (+0.12)(-0.06)	0.01 ± 0.01
Total background	**63 ± 8**	**0.36 (+0.11)(-0.07)**
50 GeV/c^2, 10^{-46} cm^2 WIMP *(NR)*	1.66 ± 0.01	0.82 ± 0.06

Results

- 34.2 days with 1 ton fiducial volume.
- Data is compatible with background (0 event in signal region).





- Best limit on SI interactions up to ~100GeV.
- Lowest background experiment.
- Data taking continues.

SUPERRADIANCE IN XENON

DIREXENO

Increasing energy range
Increasing Detector Volume
Decreasing Background

Background Sources

- ER rejection improves sensitivity.
- Directionality.

Background & Signal Rates	Total	Reference
Electronic recoils *(ER)*	62 ± 8	0.26 (+0.11)(-0.07)
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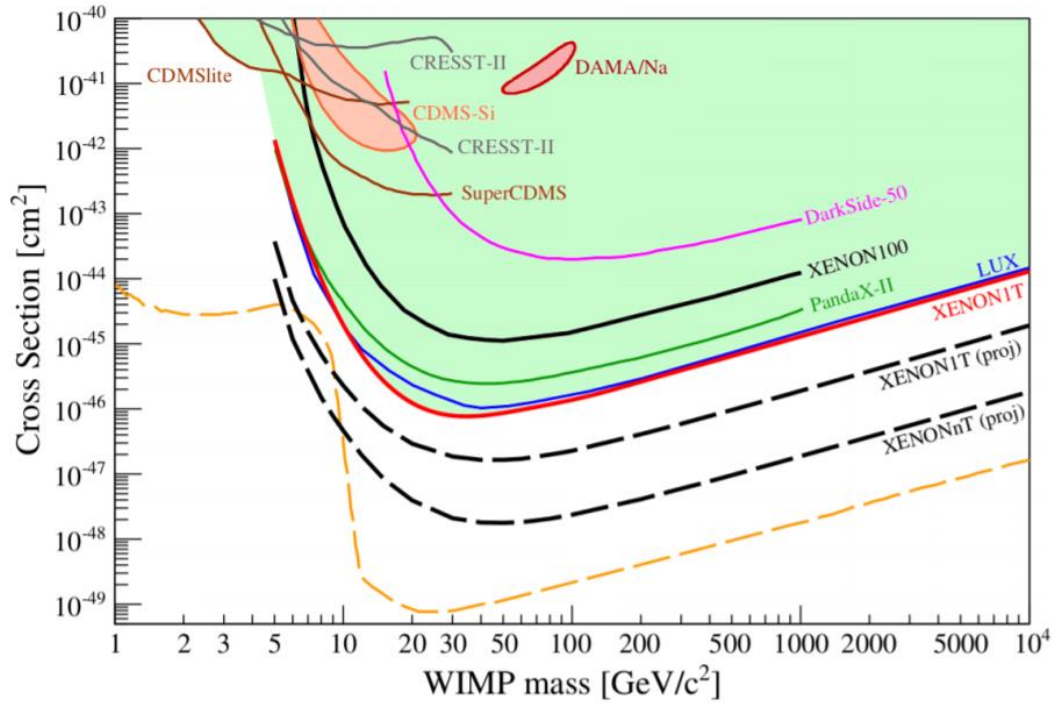
50 GeV/c^2, 10^{-46} cm^2 WIMP *(NR)*	1.66 ± 0.01	0.82 ± 0.06

Background Source	Type	Rate $[(t \times y)^{-1}]$
^{222}Rn (10 μBq/kg)	ER	620
solar pp- and ^{7}Be-neutrinos	ER	36
^{85}Kr (0.2 ppt of ^{nat}Kr)	ER	31
$2\nu\beta\beta$ of ^{136}Xe	ER	9
Material radioactivity	ER	30
Radiogenic neutrons	NR	0.55
CNNS (mainly solar ^{8}B-neutrinos)	NR	0.6
Muon-induced neutrons	NR	<0.01

726 event/ton/year

Background Sources

- ER rejection improves sensitivity.
- Directionality.



Background Source	T	
^{222}Rn (10 μBq/kg)	I	
solar pp- and ^{7}Be-neutrinos	I	
^{85}Kr (0.2 ppt of ^{nat}Kr)	I	
$2\nu\beta\beta$ of ^{136}Xe	ER	9
Material radioactivity	ER	30
Radiogenic neutrons	NR	0.55
CNNS (mainly solar ^{8}B-neutrinos)	NR	0.6
Muon-induced neutrons	NR	<0.01

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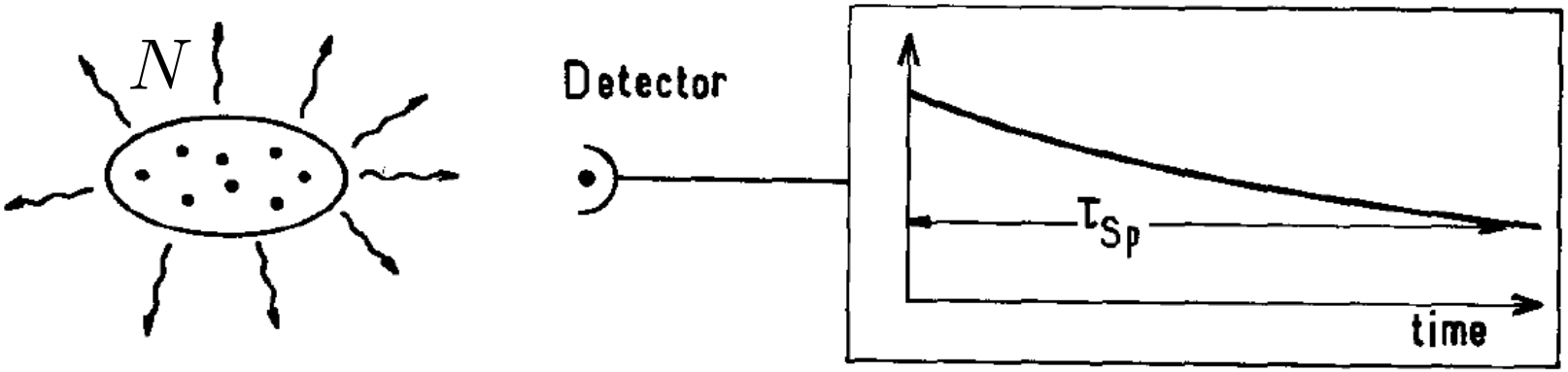
Spontaneous Emission

In ordinary spontaneous emission:



Dicke. 1954
Gross, Haroche 1982.

$$I \propto N \qquad \frac{dI}{d\Omega} = const.$$

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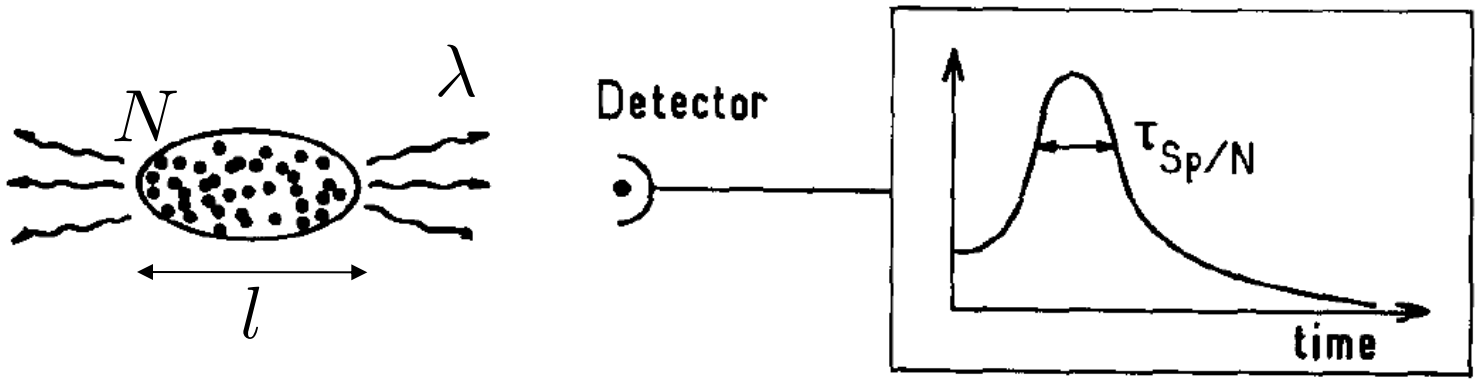

Dicke. 1954
Gross, Haroche 1982.

If $l \lesssim \lambda$ $\quad I \propto N^2 \quad \frac{dI}{d\Omega} \neq const.$

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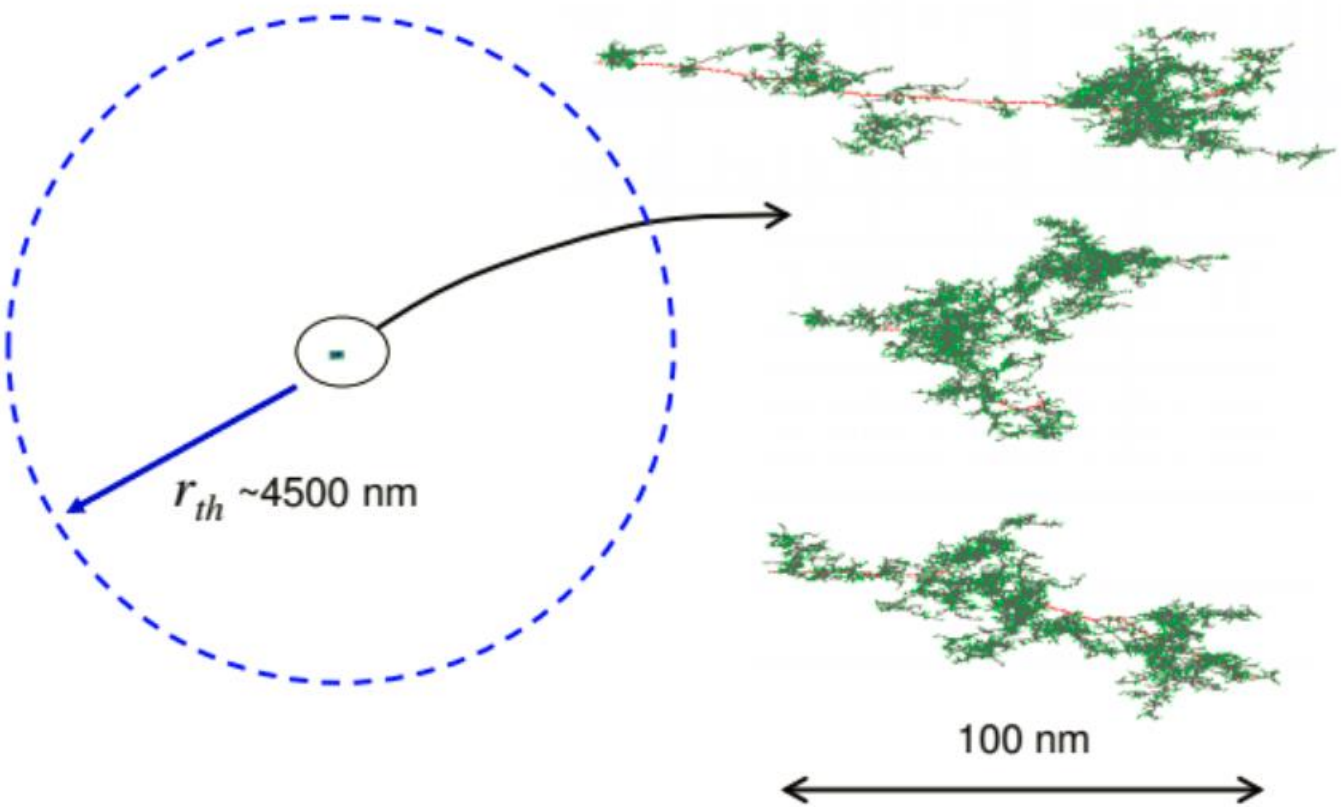


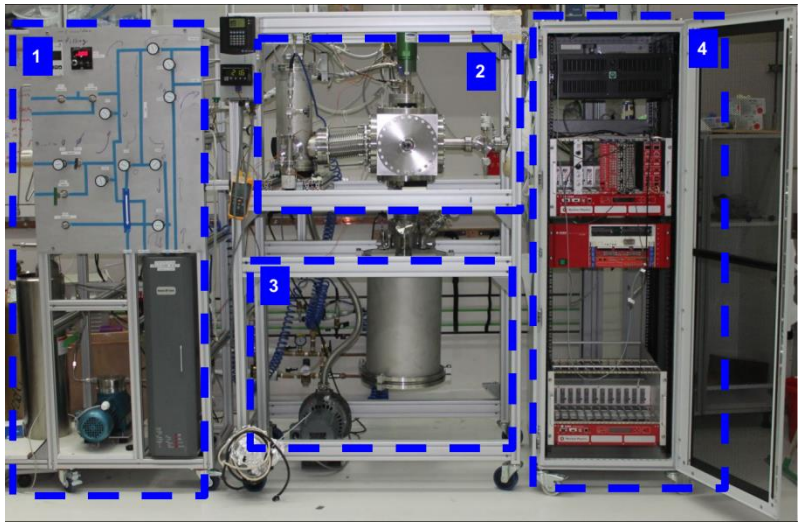
NR in liquid xenon:

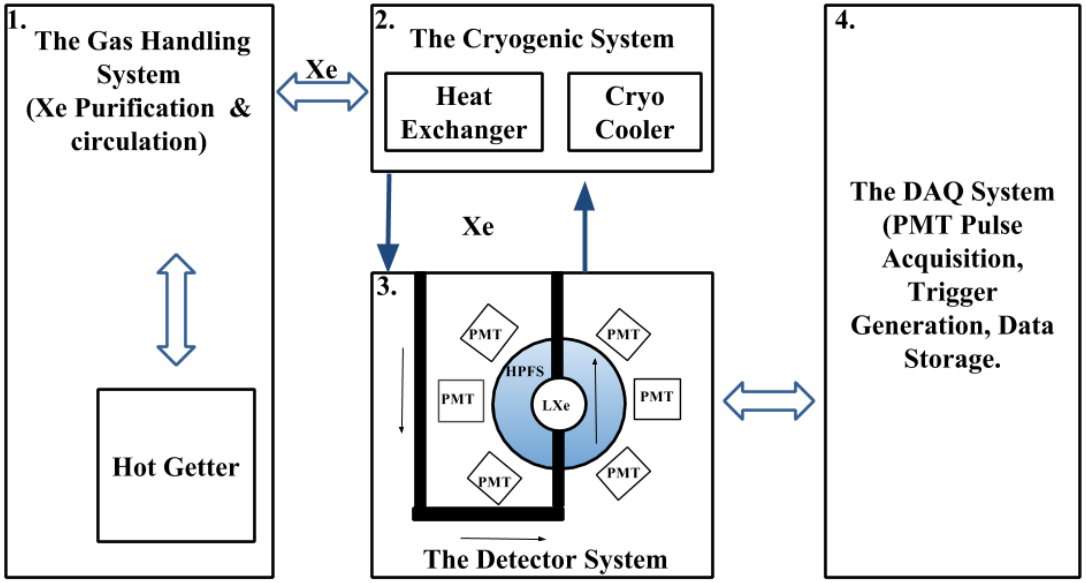
$$\lambda = 178 \text{ nm}$$
$$l \sim 100 \text{ nm}$$

Chapel et al. arXiv:1207.2292

DireXeno

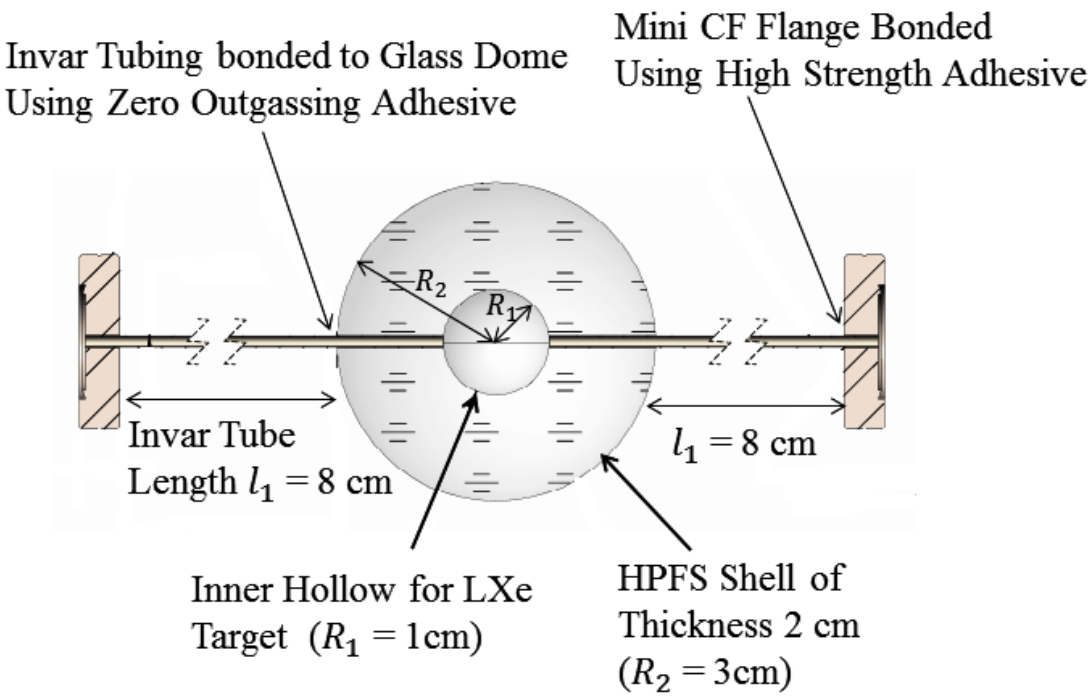
DireXeno: Directional Xenon. Apparatus for measuring spatial and temporal scintillation properties of LXe.

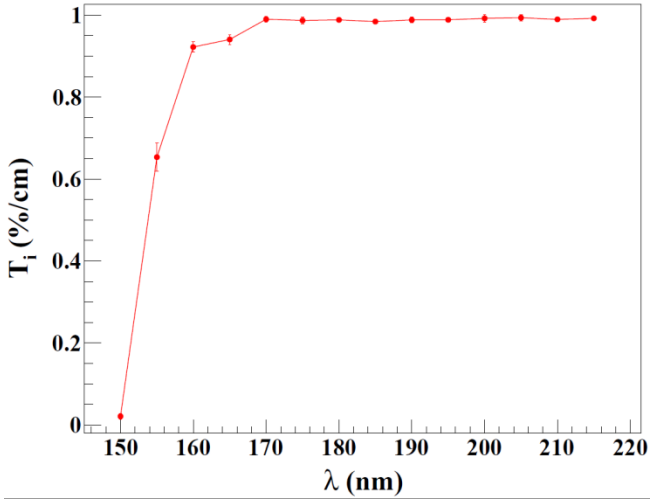




Optical Properties

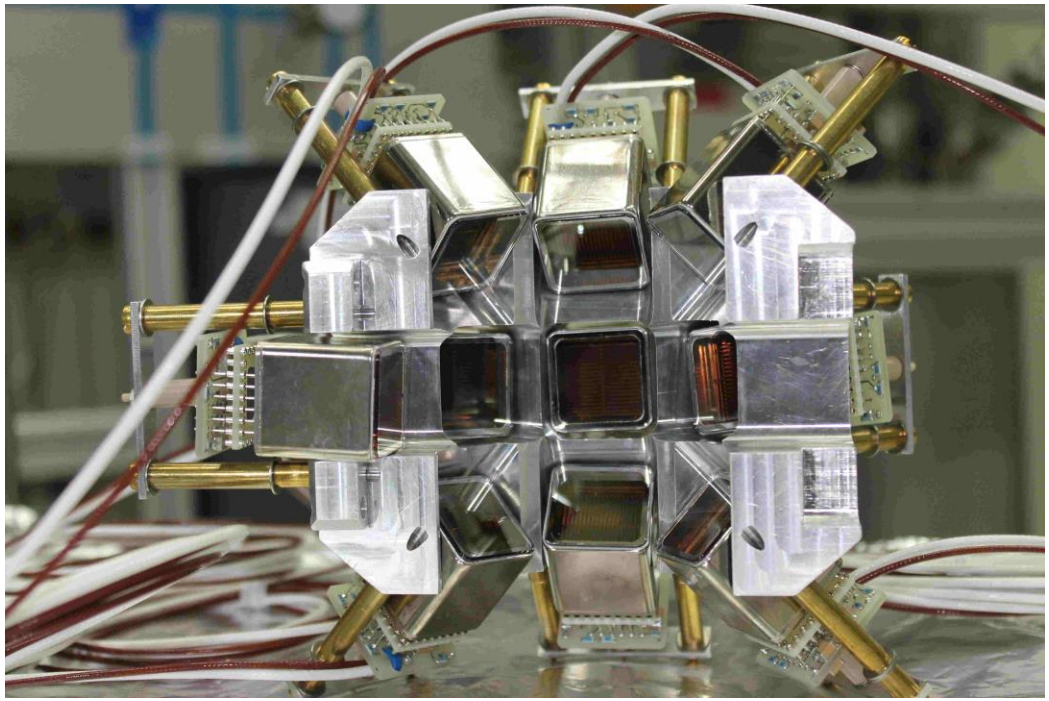
- Sphere should be VUV transparent
- $N_{HPFS} = 1.58 \sim N_{LXe}$ –> No diffraction in LXe-HPFS
- R2 >> R1 –> No diffraction in HPFS-Vacuum

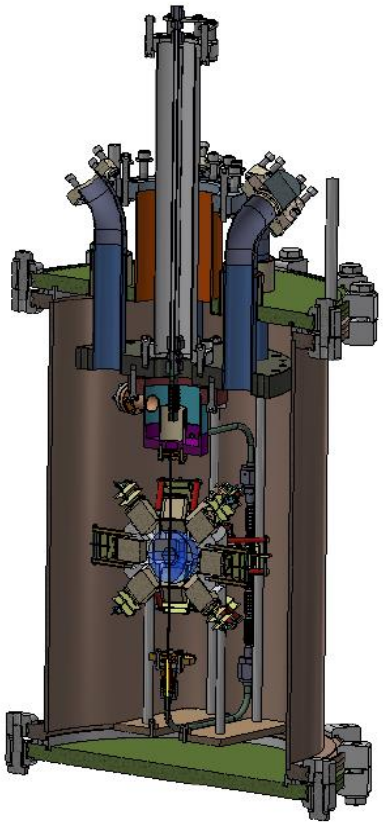




Optical Coverage

- 20 square 1” PMT with 4π coverage.
- Time resolution of O(ns)

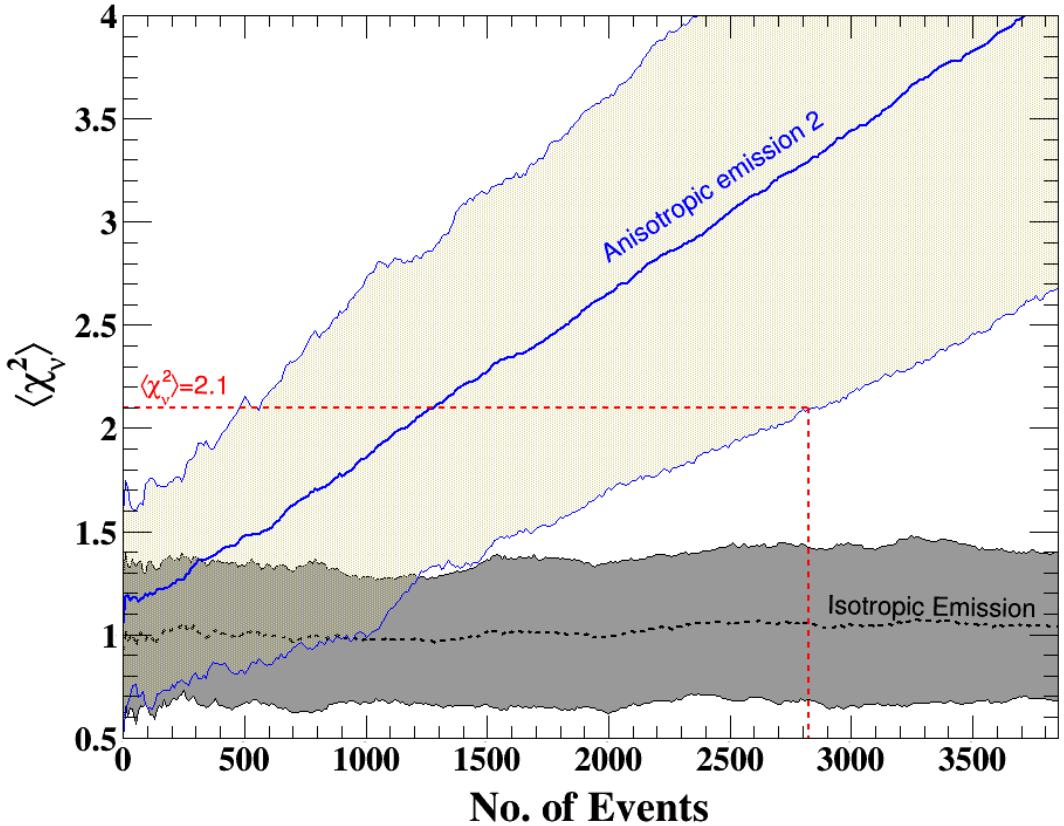




Projected Sensitivity

χ^2 – Angle correlation

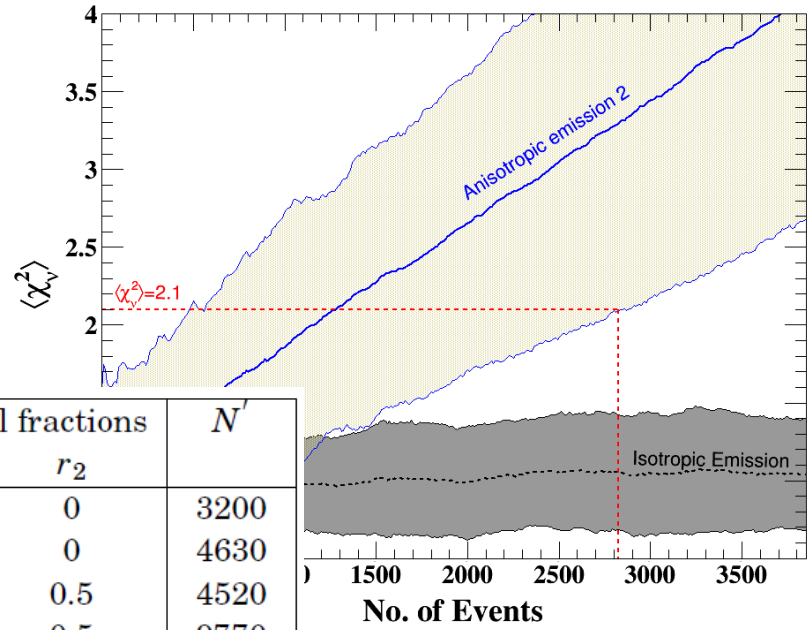
$$\chi^2_\nu = \frac{1}{\nu}\sum_{i=1}^{\nu}\frac{(O_i - E_i)^2}{E_i}$$



Pattern no.	No. of beams	type	Beam half widths σ_1	σ_2			
1	1	single beam	5^0	-			
2	1	single beam	15^0	-			
3	2	correlated	5^0	5^0			
4	2	correlated	15^0	15^0			
5	2	uncorrelated	5^0	5^0			
6	2	uncorrelated	5^0	10^0			
7	2	uncorrelated	15^0	15^0			
8	2	uncorrelated	10^0	30^0			
9	2	uncorrelated	10^0	30^0	0.2	0.8	56000
10	2	uncorrelated	30^0	10^0	0.2	0.8	43000

Projected Sensitivity

Estimated time for standard sources - O(weeks)



Pattern no.	No. of beams	type	Beam half widths		Signal fractions		N'
			σ_1	σ_2	r_1	r_2	
1	1	single beam	5^0	-	1	0	3200
2	1	single beam	15^0	-	1	0	4630
3	2	correlated	5^0	5^0	0.5	0.5	4520
4	2	correlated	15^0	15^0	0.5	0.5	9770
5	2	uncorrelated	5^0	5^0	0.5	0.5	9370
6	2	uncorrelated	5^0	10^0	0.5	0.5	19500
7	2	uncorrelated	15^0	15^0	0.5	0.5	28200
8	2	uncorrelated	10^0	30^0	0.5	0.5	49900
9	2	uncorrelated	10^0	30^0	0.2	0.8	56000
10	2	uncorrelated	30^0	10^0	0.2	0.8	43000

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Summary

1. **EFT approach for WIMP scattering in XENON100 detector.**

   - EFT analysis for elastic scattering , and Inelastic WIMP models
   - Energy range extended to 180PE (240 keVnr), previously up to 30PE (43 keVnr)
   - Data compatible with background -> Exclusion limits.
   - Tables for detector response online.

2. **XENON1T First Results**

   - First ton-scale LXe detector.
   - Lowest background experiment
   - Data taking continues, stay tuned.

3. **Superradiance in LXe.**

   - DireXeno.
   - ER background discrimination.
   - Directionality (neutrino rejection).

Questions

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Backup Slides

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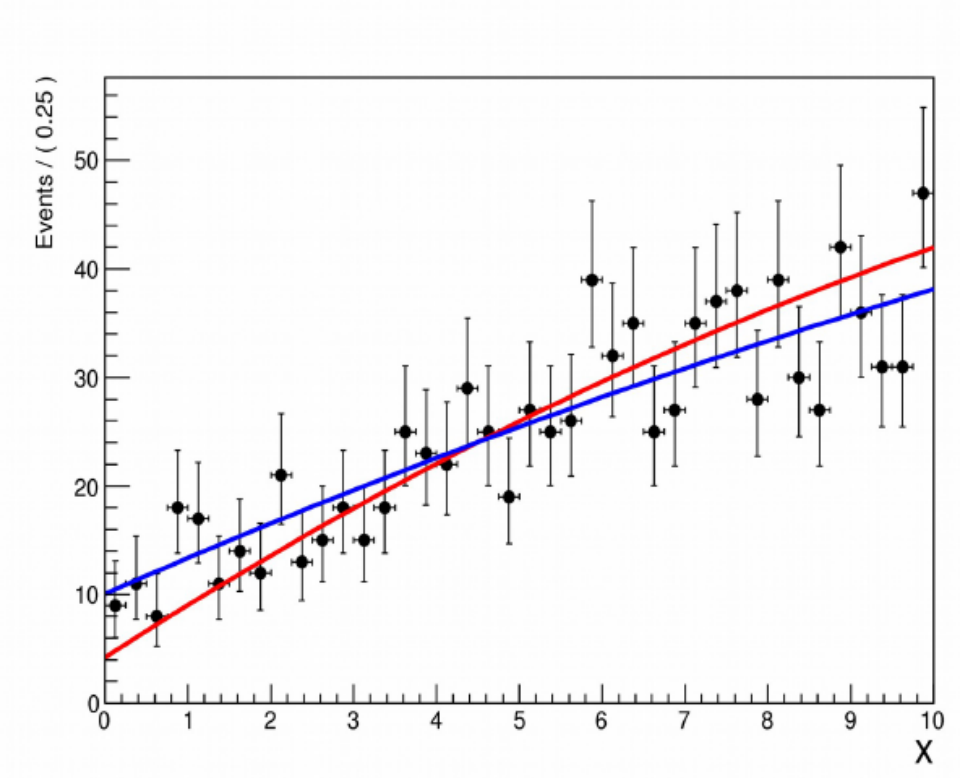
Motivation

- Too many parameters
- Hidden parameters
- No underlying model
- Error propagation
- Unbinned profile likelihood analysis



Priel et al., JCAP, 1705(05), 2017

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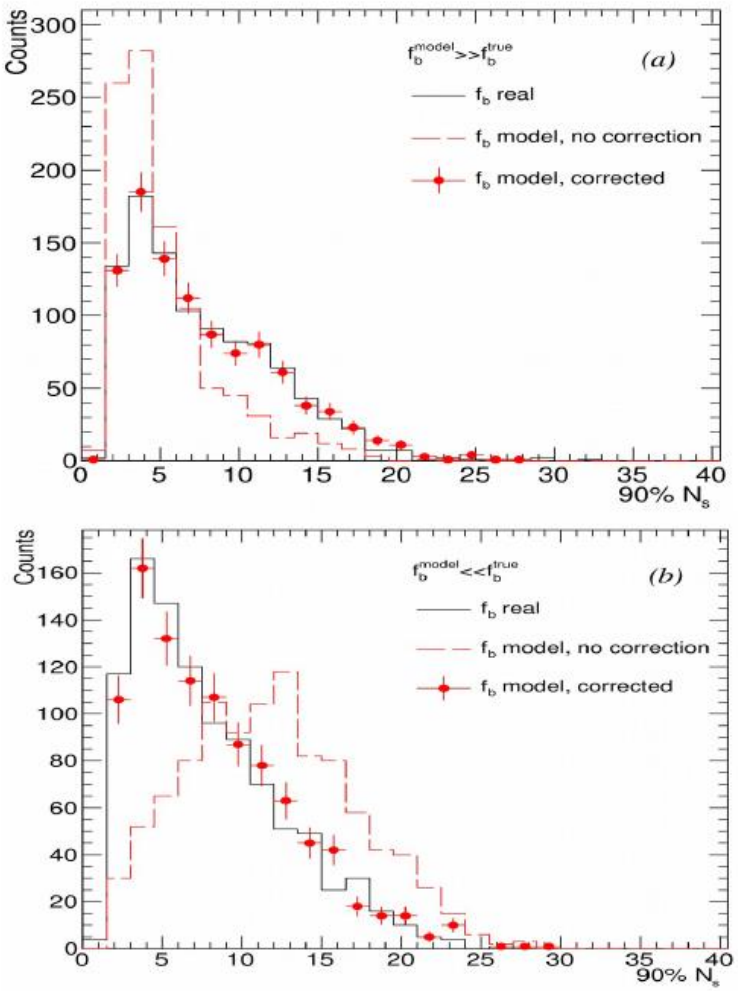
Superradiance
Summary

- Use benchmark model.
- Add signal like component to the background model.
- Comes alongside the standard construction of uncertainties.
- Universal solution, and not model dependent.