Low energy signals in xenon detectors

from supernova neutrinos to light dark matter

Christopher M^{c}Cabe

arXiv:1606.09243 (PRD) & arXiv:1702.04730

UCL - 5th May 2017

Science & Technology Facilities Council

KING'S College LONDON

~~GRAPPA GRavitation AstroParticle Physics Amsterdam~~

~~UNIVERSITY OF AMSTERDAM~~

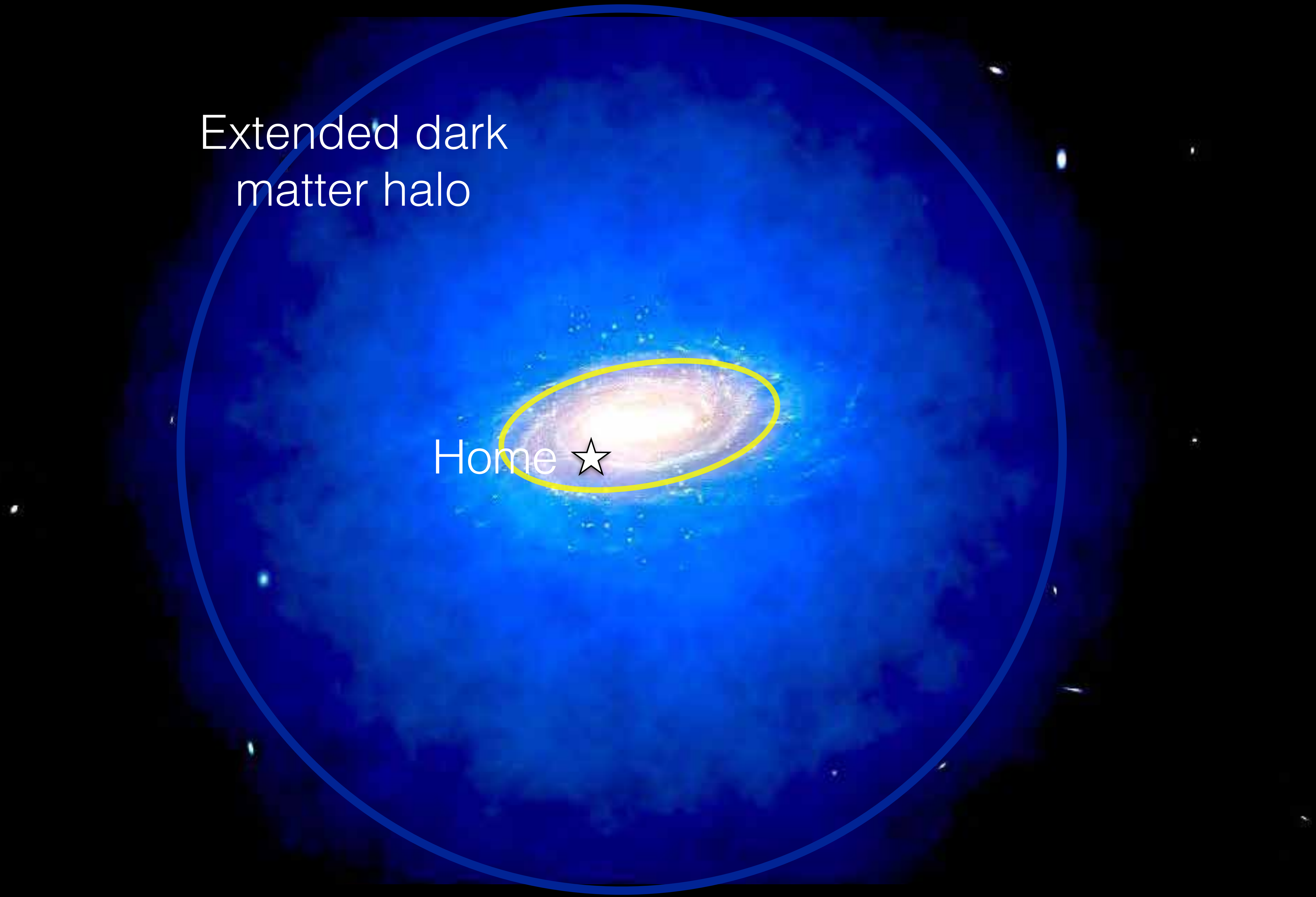
Outline

- Motivation: Dark matter
- Direct detection experiments & recent progress

- New low-energy signals in xenon detectors:
  1. Nuclear recoils: supernova neutrinos
  2. Electronic recoils: sub-GeV dark matter

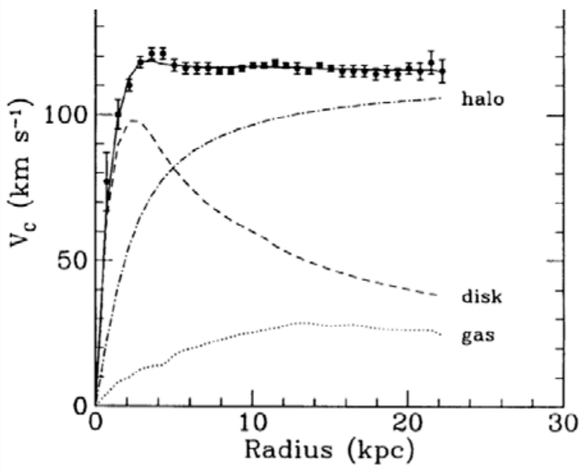
Motivation:
Dark matter

Dark Matter

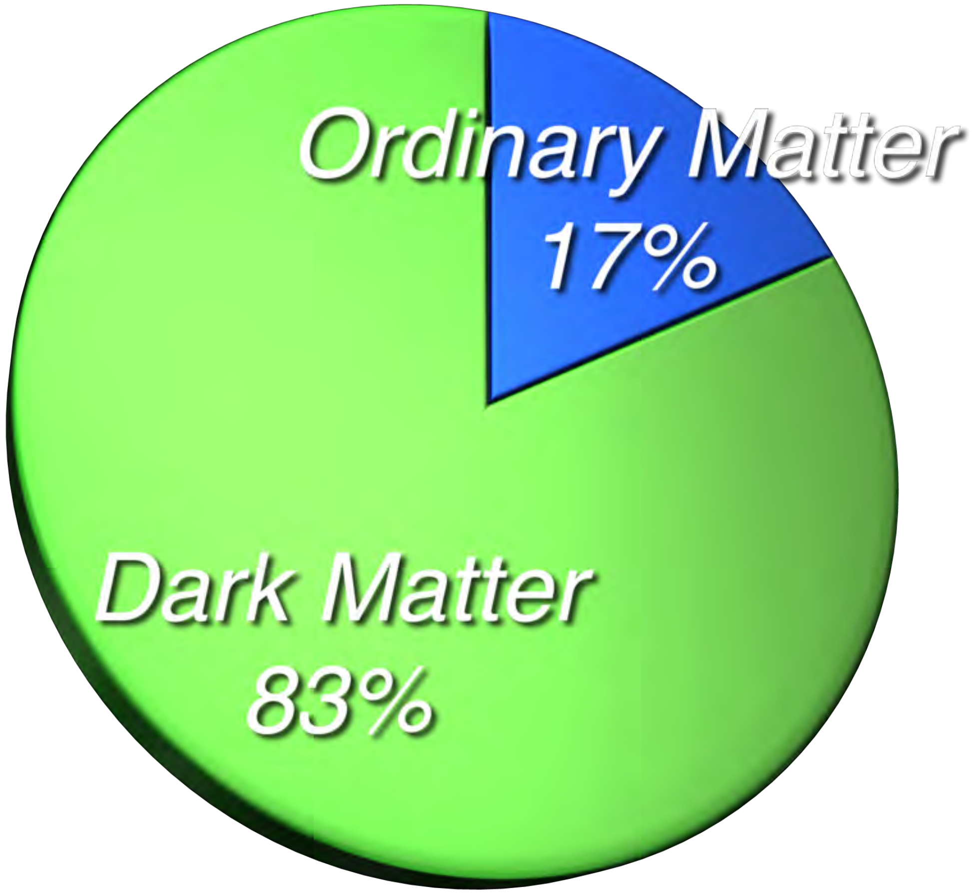


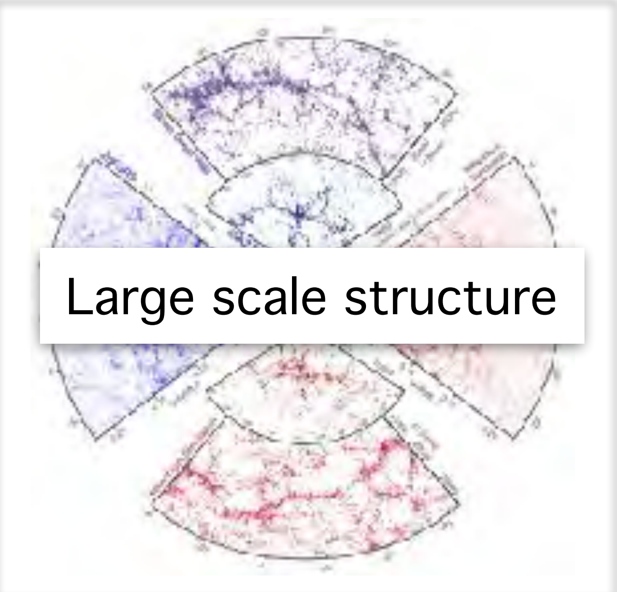
Evidence for dark matter

Galaxy rotation curves



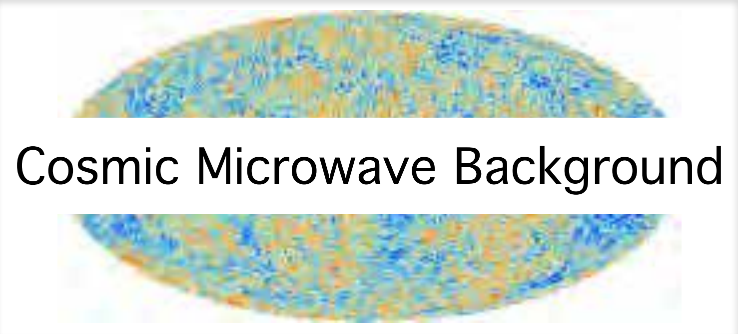
Matter in the Universe





Large scale structure

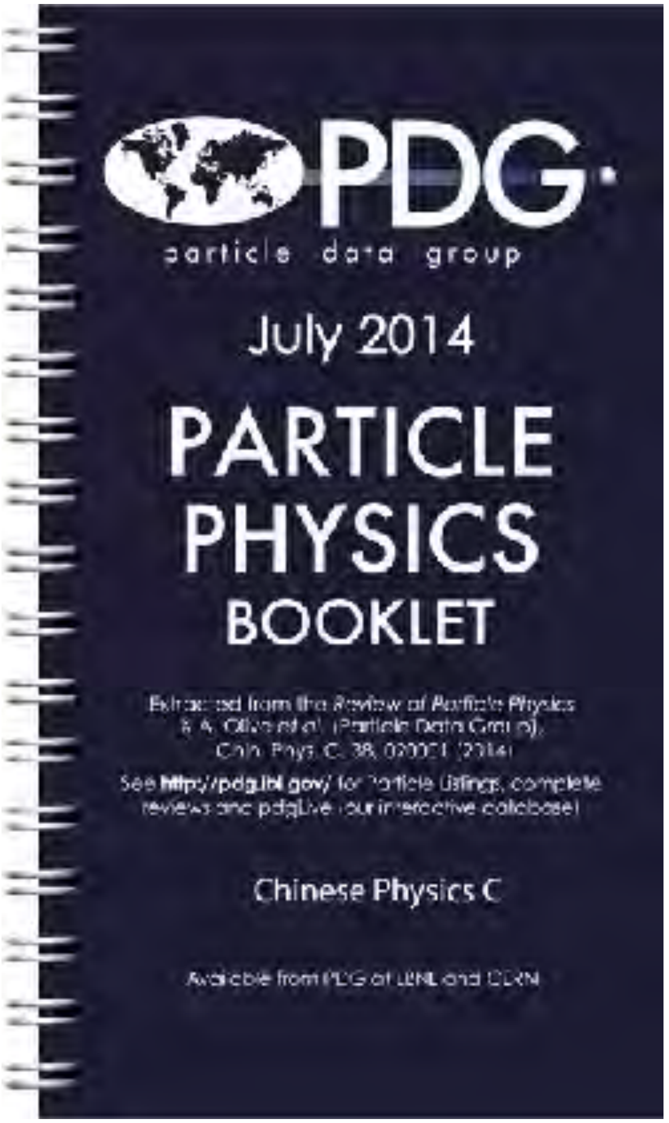
'The Bullet Cluster'



Cosmic Microwave Background

Evidence from gravitational interactions over many distance scales

What would we like to know?



PDG
particle data group
July 2014
PARTICLE PHYSICS BOOKLET
Extracted from the Review of Particle Physics
K.A. Olive et al. (Particle Data Group),
Chin. Phys. C, 38, 090001 (2014)
See http://pdg.lbl.gov/ for Particle Listings, complete reviews and pdgLive (our interactive database)
Chinese Physics C
Available from PDG at LBNL and CERN

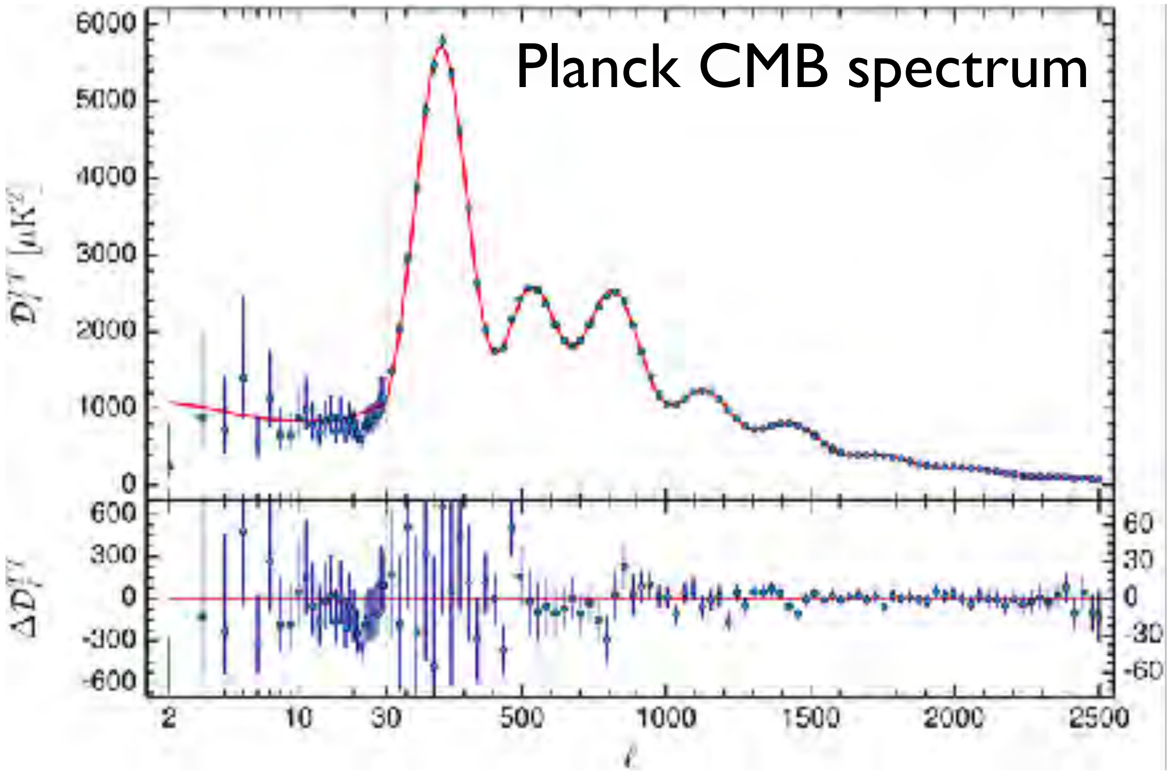
Dark Matter Particle (X^0)

X^0 mass: $m = ?$
X^0 spin: $J = ?$
X^0 parity: $P = ?$
X^0 lifetime: $\tau = ?$
X^0 scattering cross-section on nucleons: $?$
X^0 production cross-section in hadron colliders: $?$
X^0 self-annihilation cross-section: $?$

Interactions with matter are generic

Precise determination of DM density:

$$\Omega_{\rm DM}h^2 = 0.1198 \pm 0.0015$$



Explaining $\Omega_{\rm DM}h^2$

interactions with matter

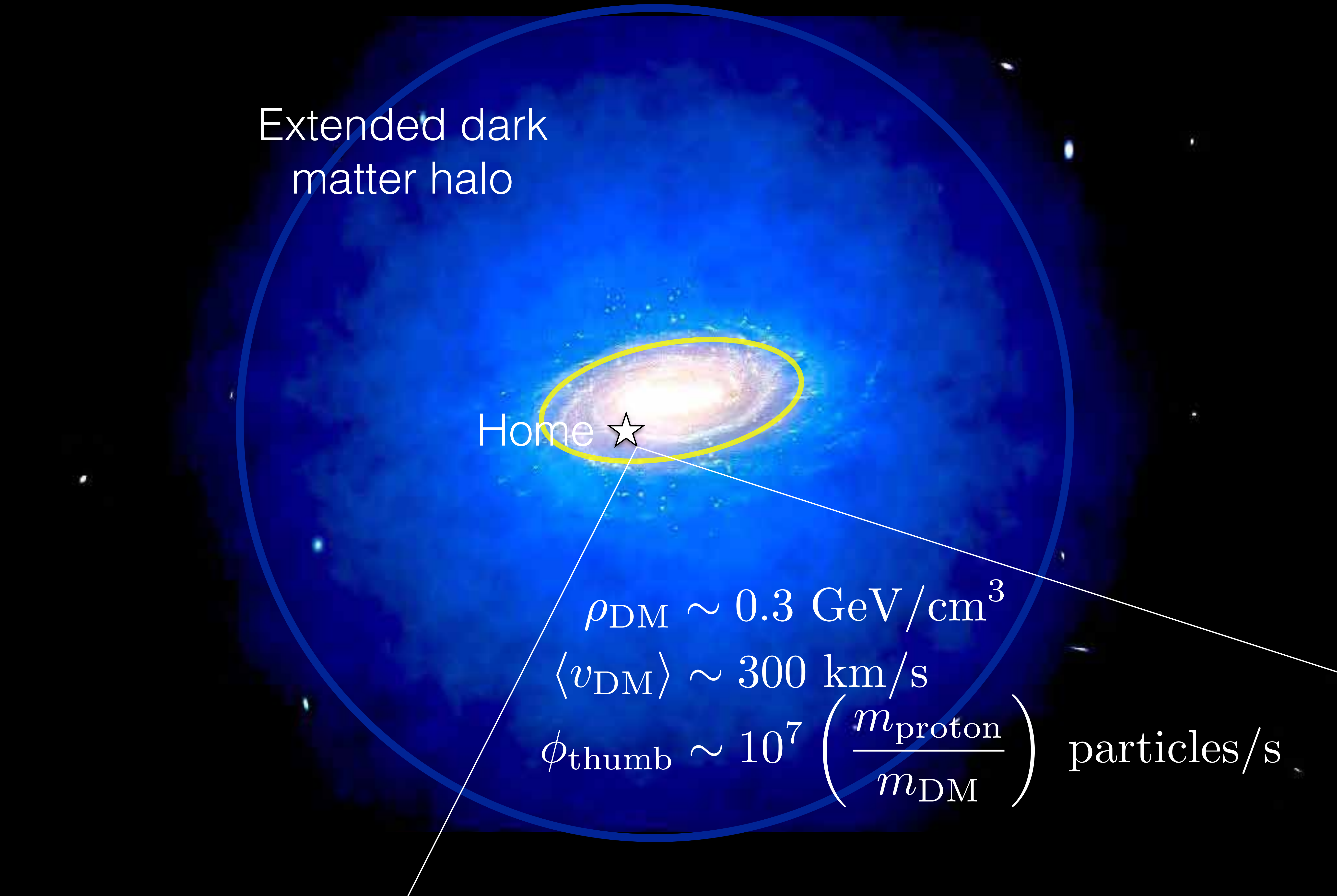
interaction strength

Thermal candidates:
WIMPs
SIMPs
Asymmetric DM
. . .

Non-thermal candidates:
axions
FIMPs

gravitinos
primordial black holes
. . .

Dark Matter



$$\rho_{\mathrm{DM}} \sim 0.3\ \mathrm{GeV}/\mathrm{cm}^3$$

$$\langle v_{\mathrm{DM}} \rangle \sim 300\ \mathrm{km/s}$$

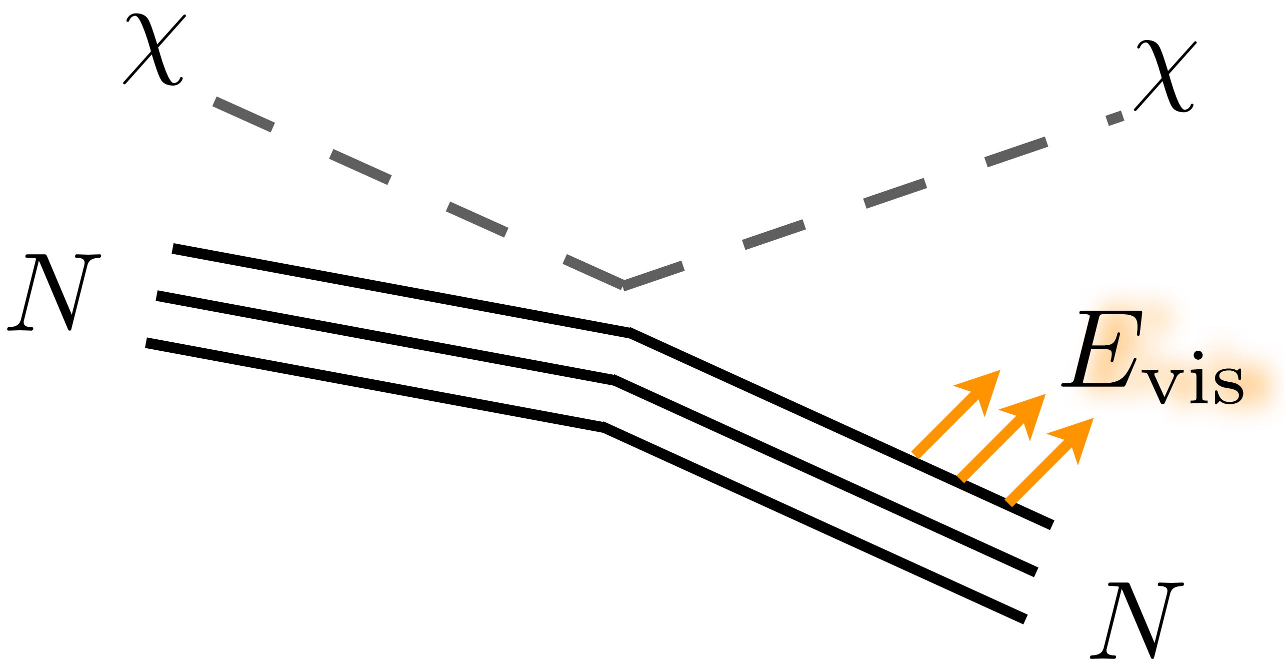
$$\phi_{\mathrm{thumb}} \sim 10^7 \left(\frac{m_{\mathrm{proton}}}{m_{\mathrm{DM}}} \right)\ \mathrm{particles/s}$$

Direct detection experiments
&
Recent progress

Direct detection experiments

Aim: detect collisions of dark matter with an atom/nucleus

Goodman & Witten (1985)



$$E_{\text{vis}} \approx 1 - 100\ \text{keV}$$

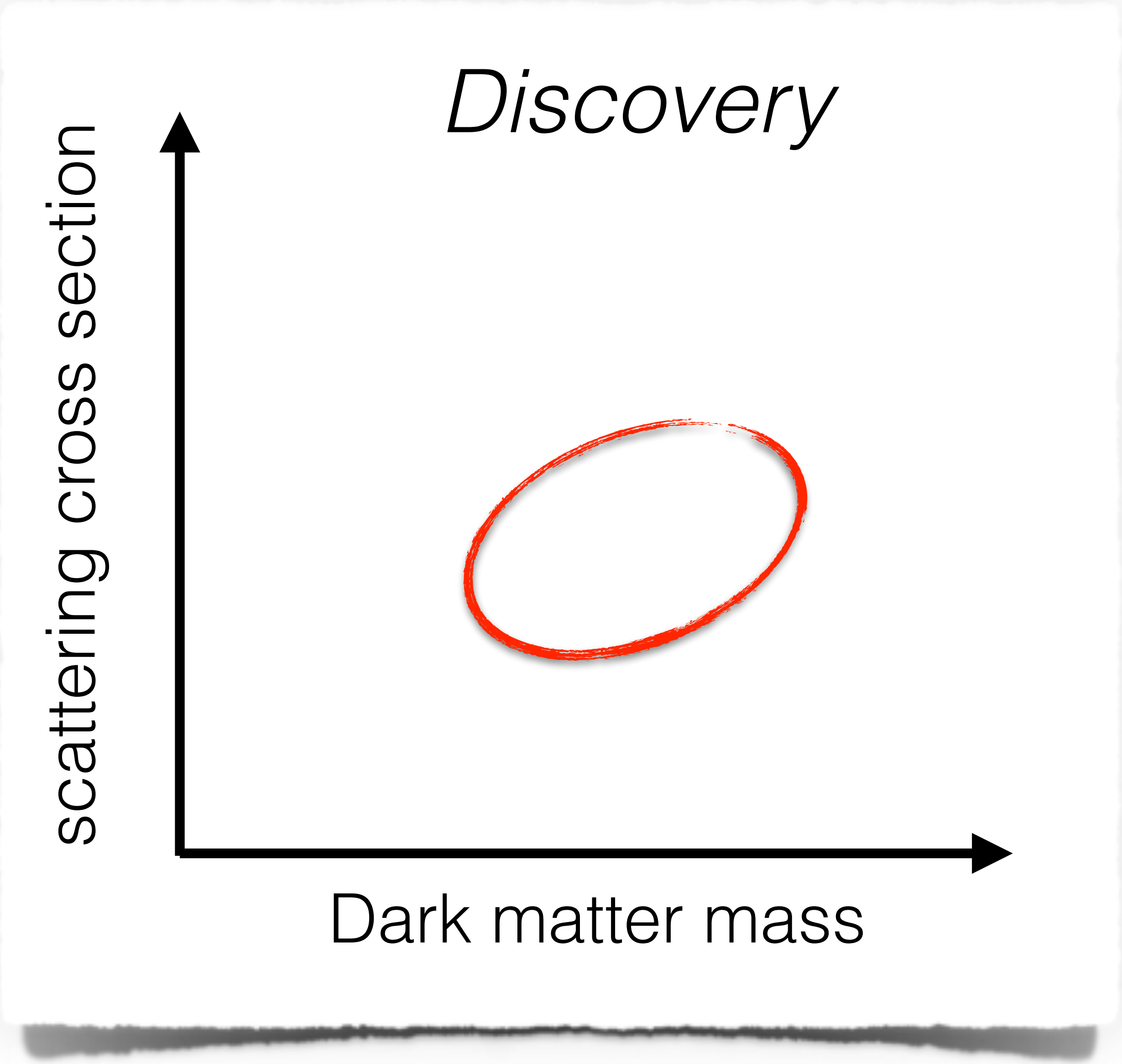
Event rate: few events / year

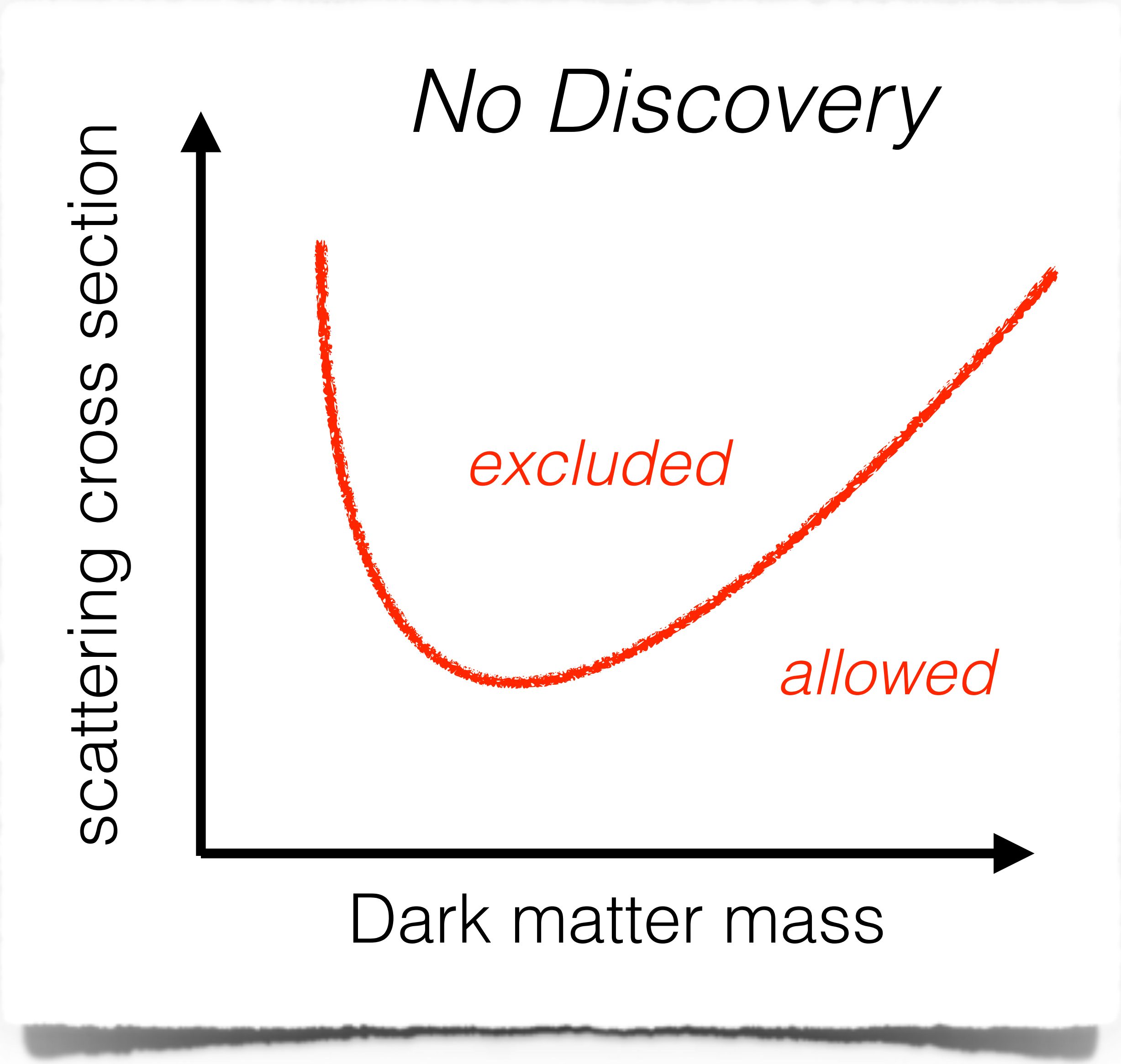
Ultra-sensitive keV energy detectors

Direct detection signals

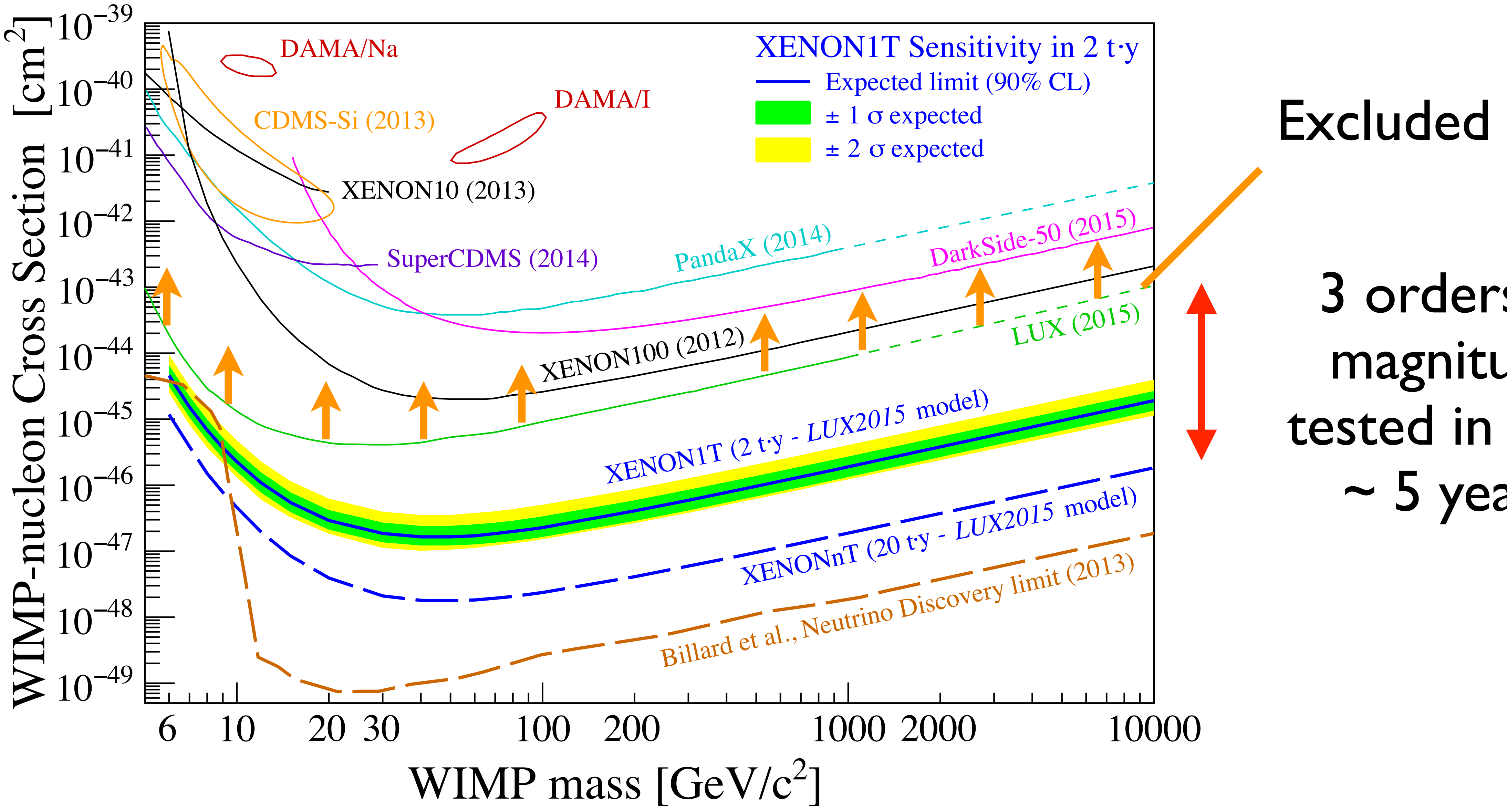
Measurement/constraints on

1. *Dark matter mass*
2. *Scattering cross section with nucleons*





Direct detection limits

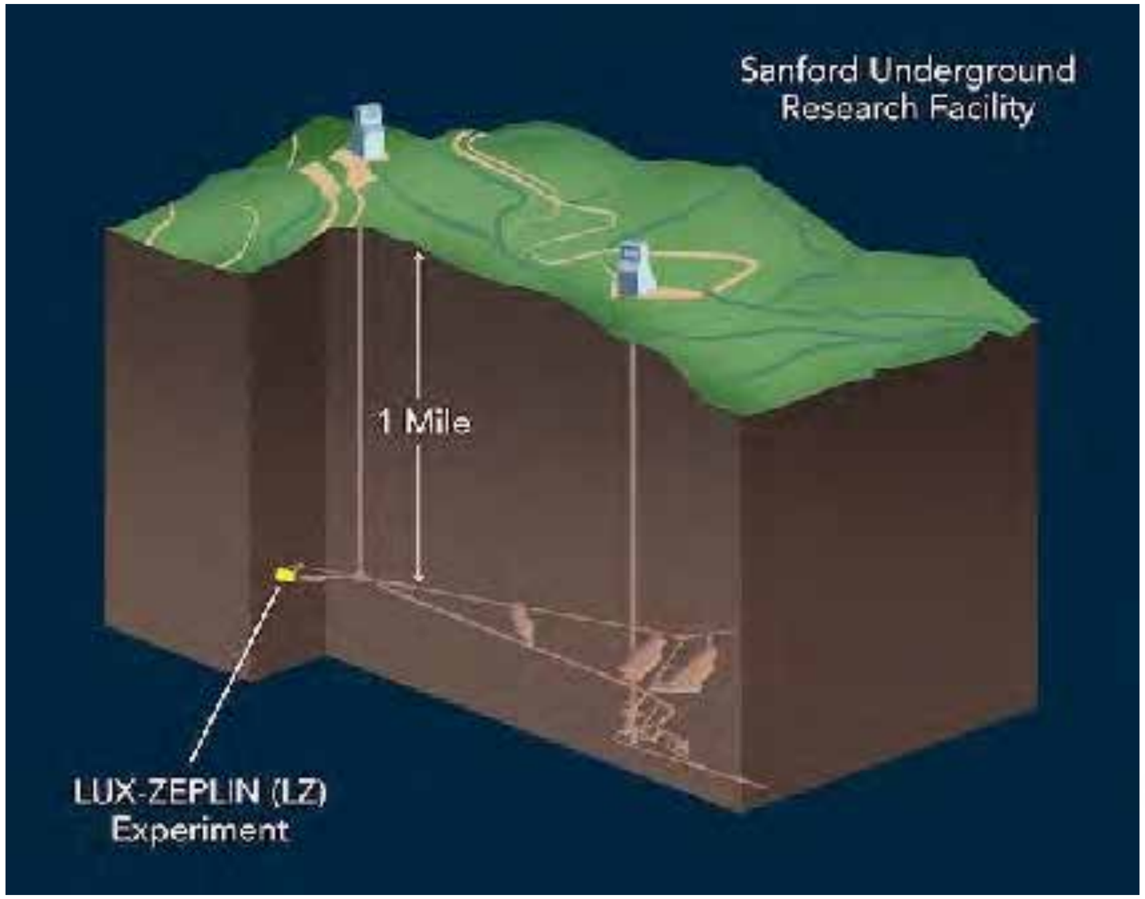


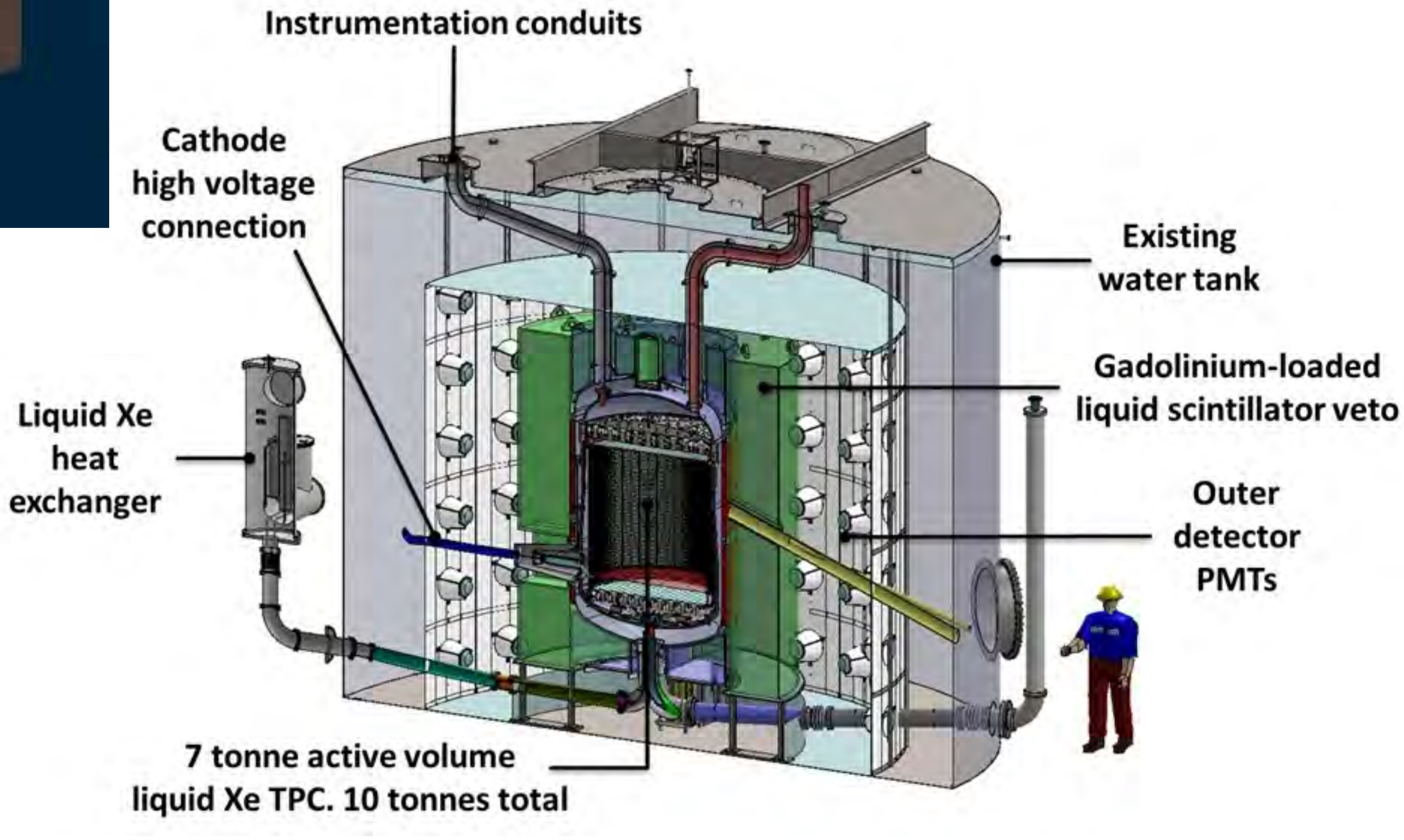
Excluded

3 orders of magnitude tested in next ~ 5 years

Experiments with xenon (LUX & XENON) are the most sensitive

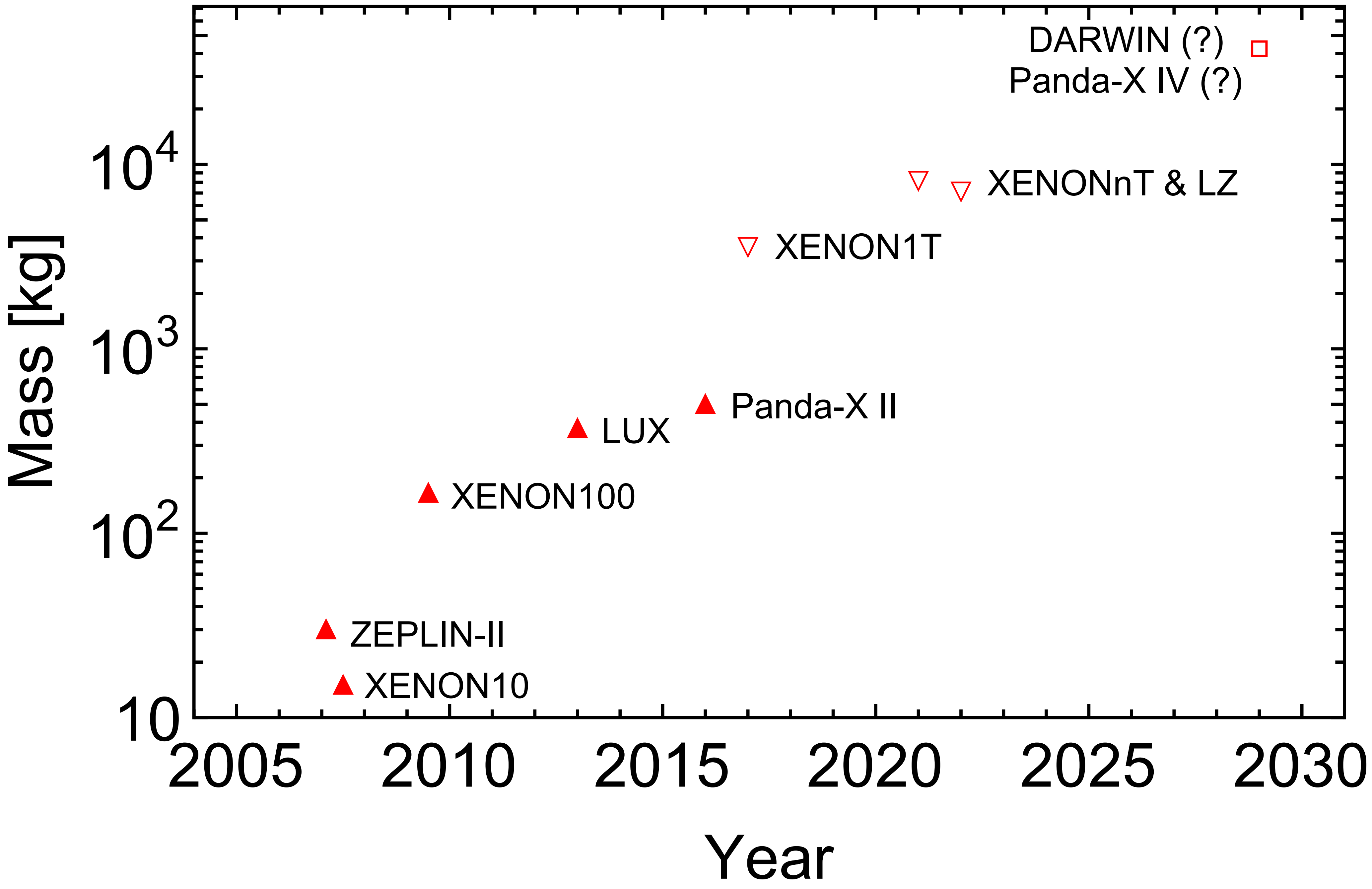
Xenon dark matter detectors





Xenon detectors: Recent progress 1

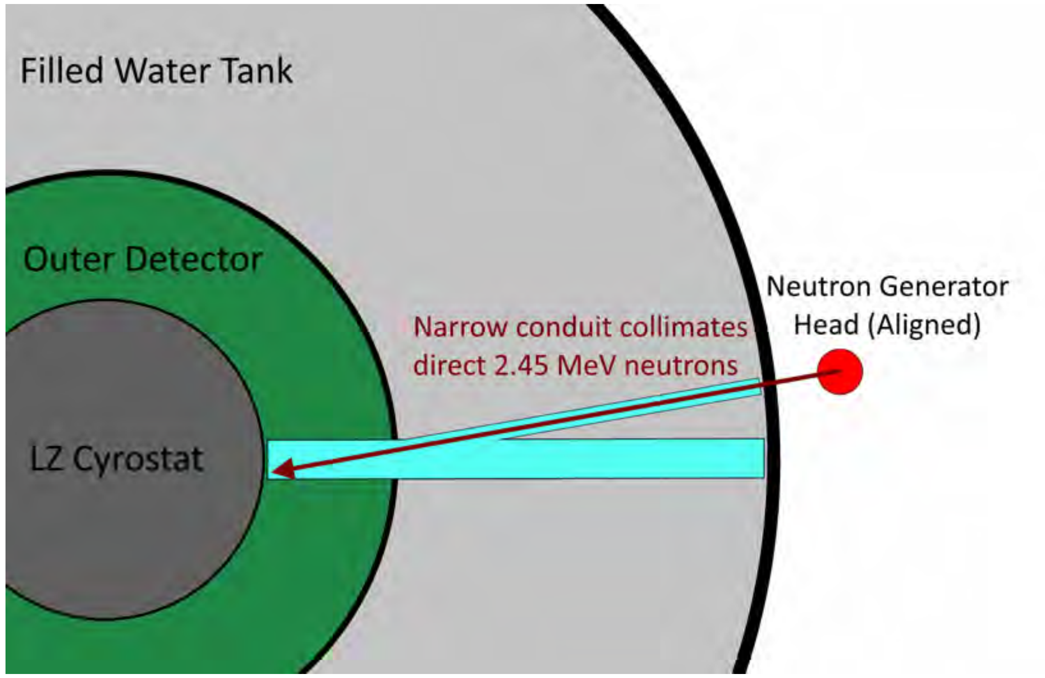
Xenon detectors have been getting (much) bigger



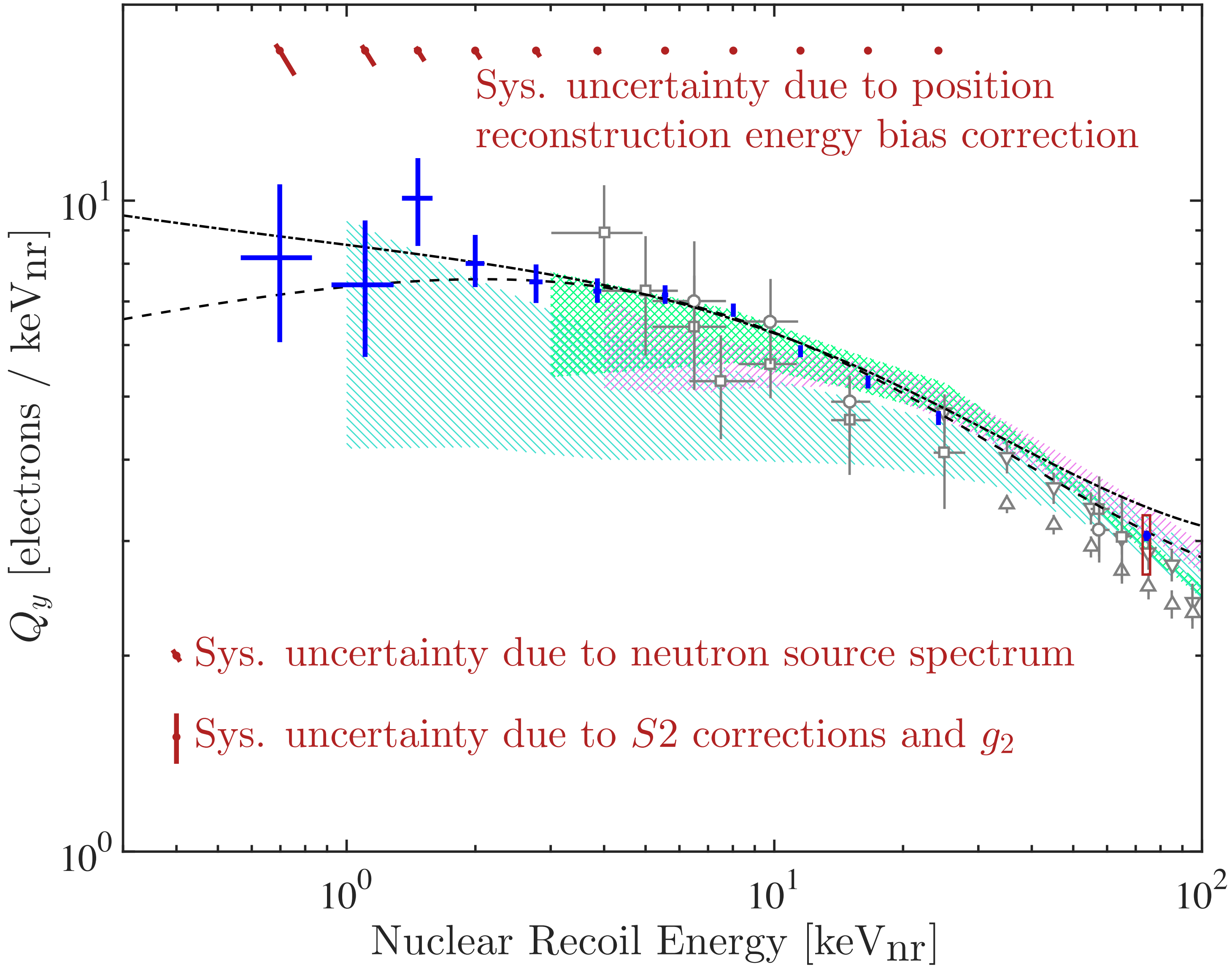
Recent progress 2: Much better calibration

LUX leads the way in sensitivity… and in calibrating their detector

Nuclear recoil calibration to 0.7 keV



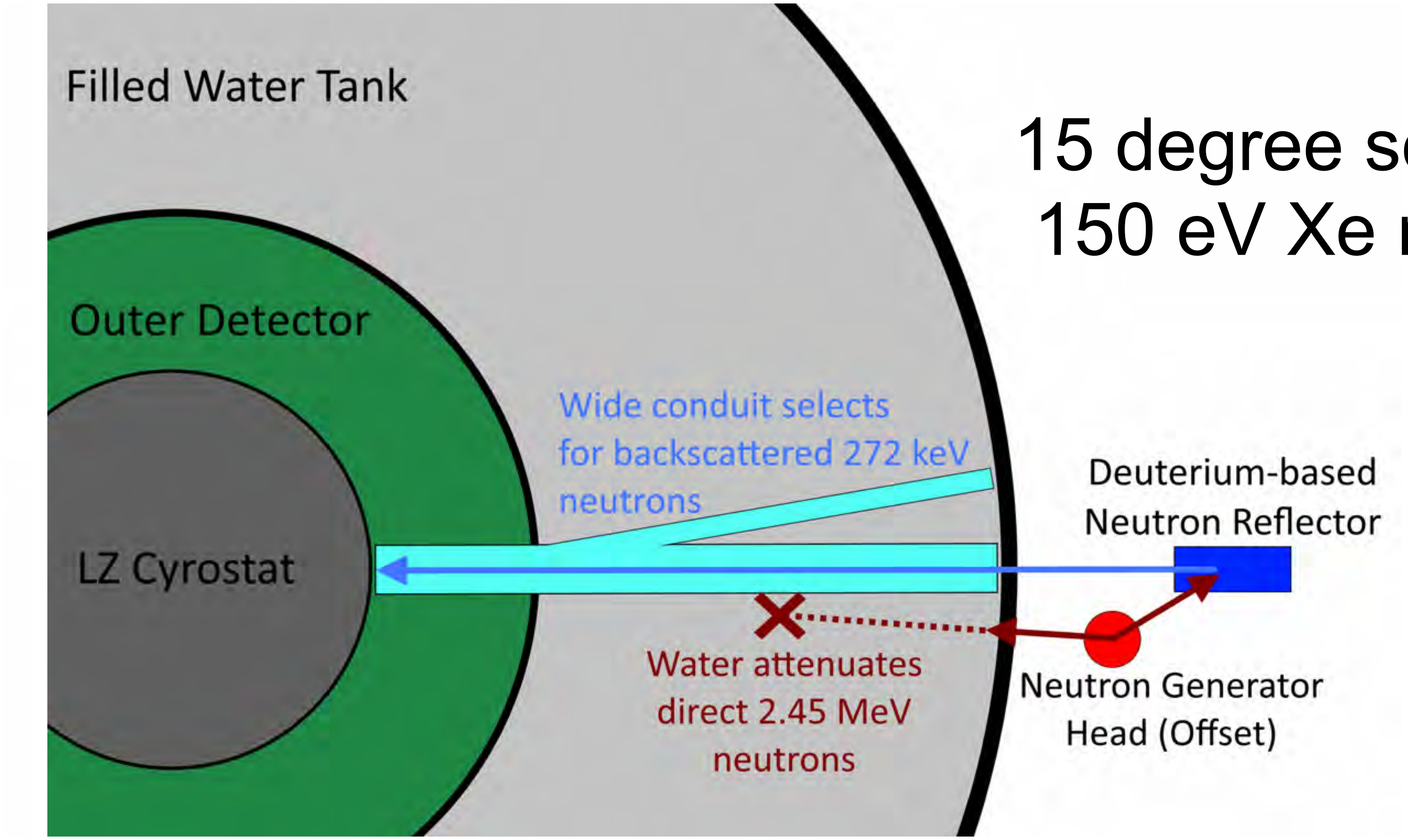
D-D generator: arXiv:1608.05381



Recent progress 2: Much better calibration

LUX leads the way in sensitivity… and in calibrating their detector

Nuclear recoil calibration to 0.7 keV… and plans to go lower (150 eV?)



15 degree scatter:
150 eV Xe recoil possible

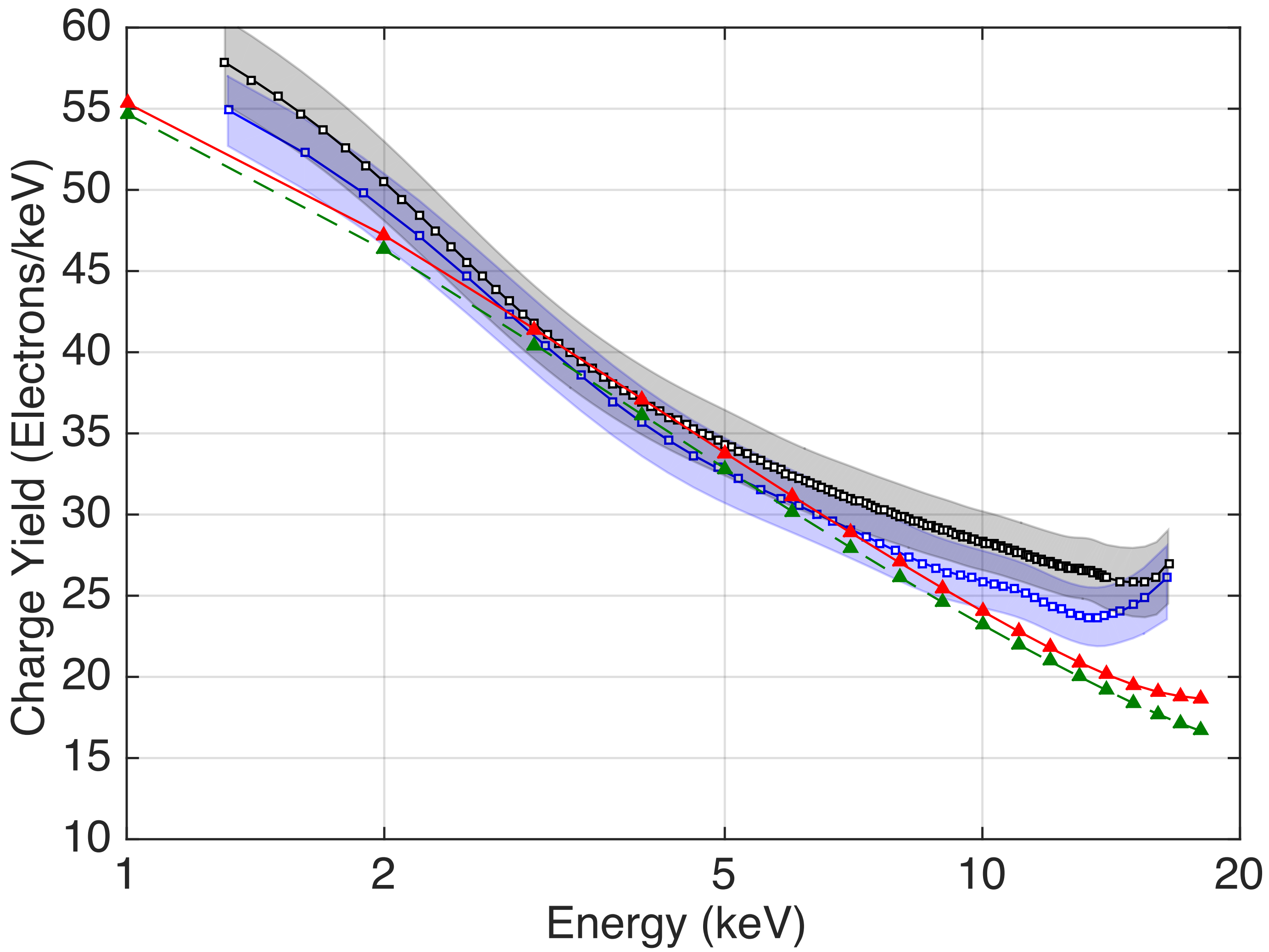
LZ TDR
arXiv:1703.09144

Recent progress 2: Much better calibration

LUX leads the way in sensitivity… and in calibrating their detector

Electronic recoil calibration to 1.3 keV (tritium)

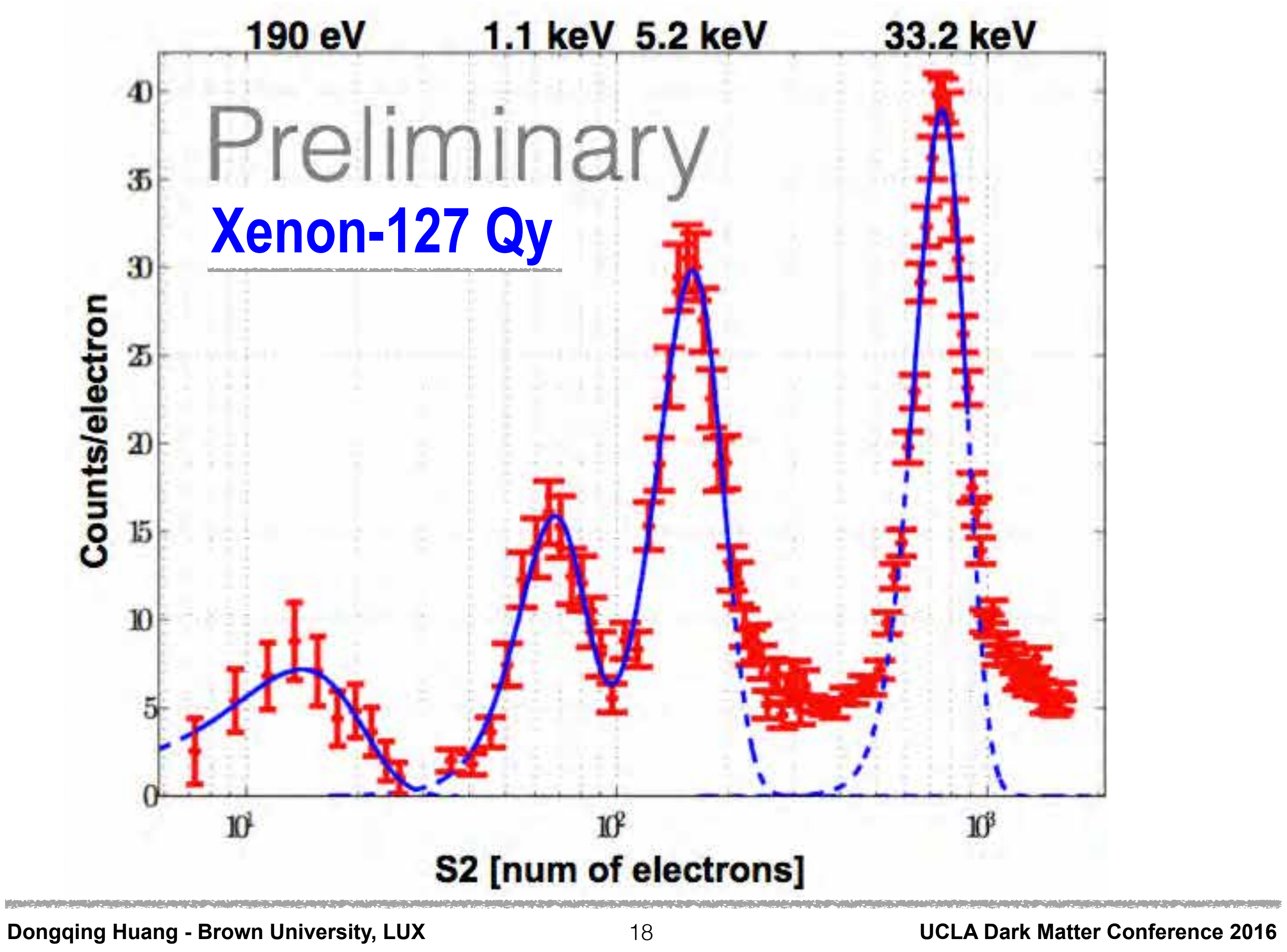
tritium, arXiv:1512.03133



Recent progress 2: Much better calibration

LUX leads the way in sensitivity… and in calibrating their detector

Electronic recoil calibration to 1.3 keV (tritium)
0.19 keV (127-Xe)

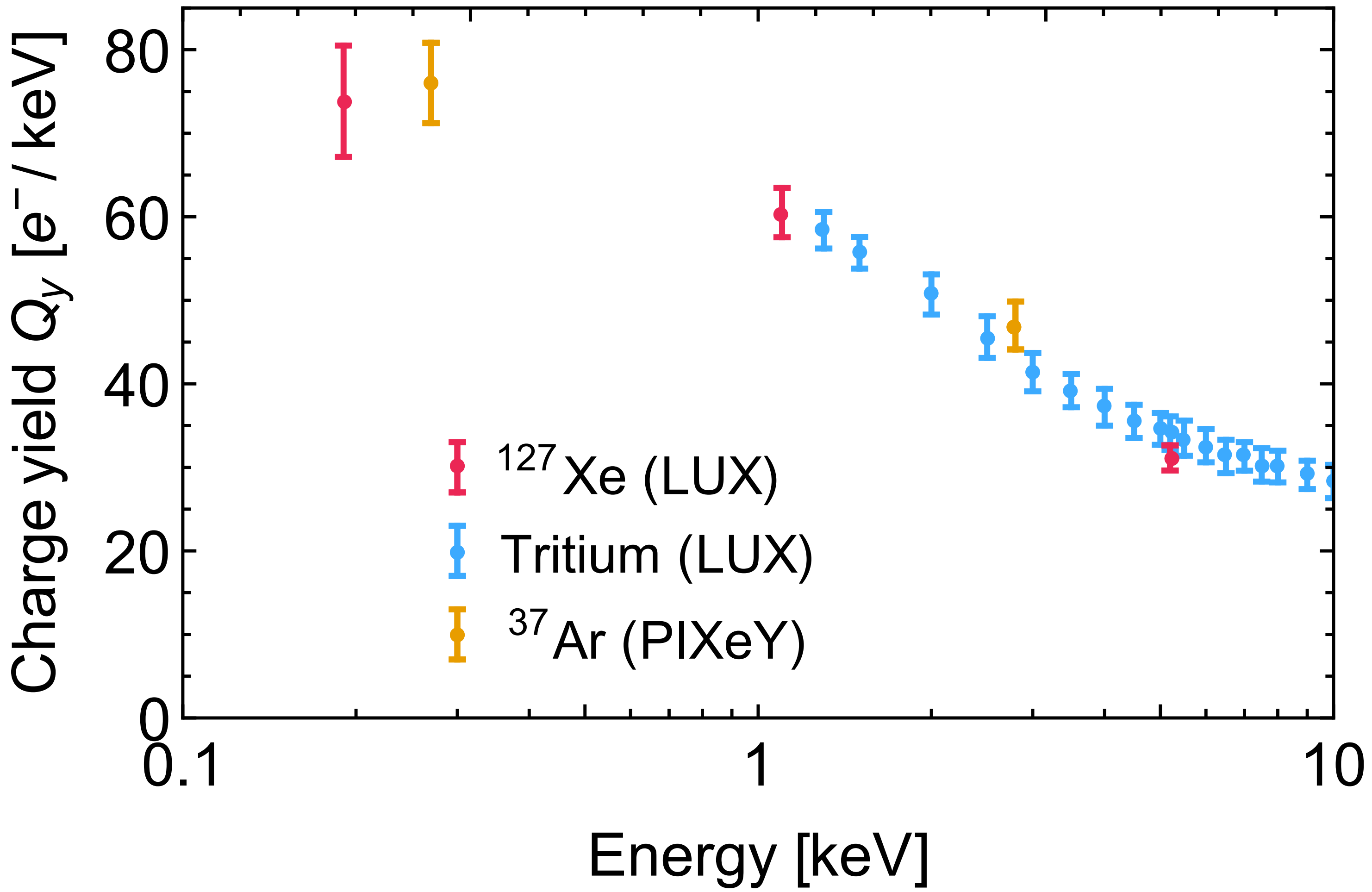


Dongqing Huang - Brown University, LUX 18 UCLA Dark Matter Conference 2016

Recent progress 2: Much better calibration

LUX leads the way in sensitivity… and in calibrating their detector

Electronic recoil calibration to 1.3 keV (tritium)
0.19 keV (127-Xe)
0.27 keV (37-Ar)



Calibration: summary

Pre-LUX: ~ 4 keV
Post-LUX: ~ 0.2 keV

Xenon direct detection experiments:

1. Becoming much bigger (x10-100)
2. Better calibration: now at sub-keV energies

So what?

New low-energy signals in xenon detectors:

1. Nuclear recoils: supernova neutrinos
2. Electronic recoils: sub-GeV dark matter

New low energy signals:
1. Supernova neutrinos

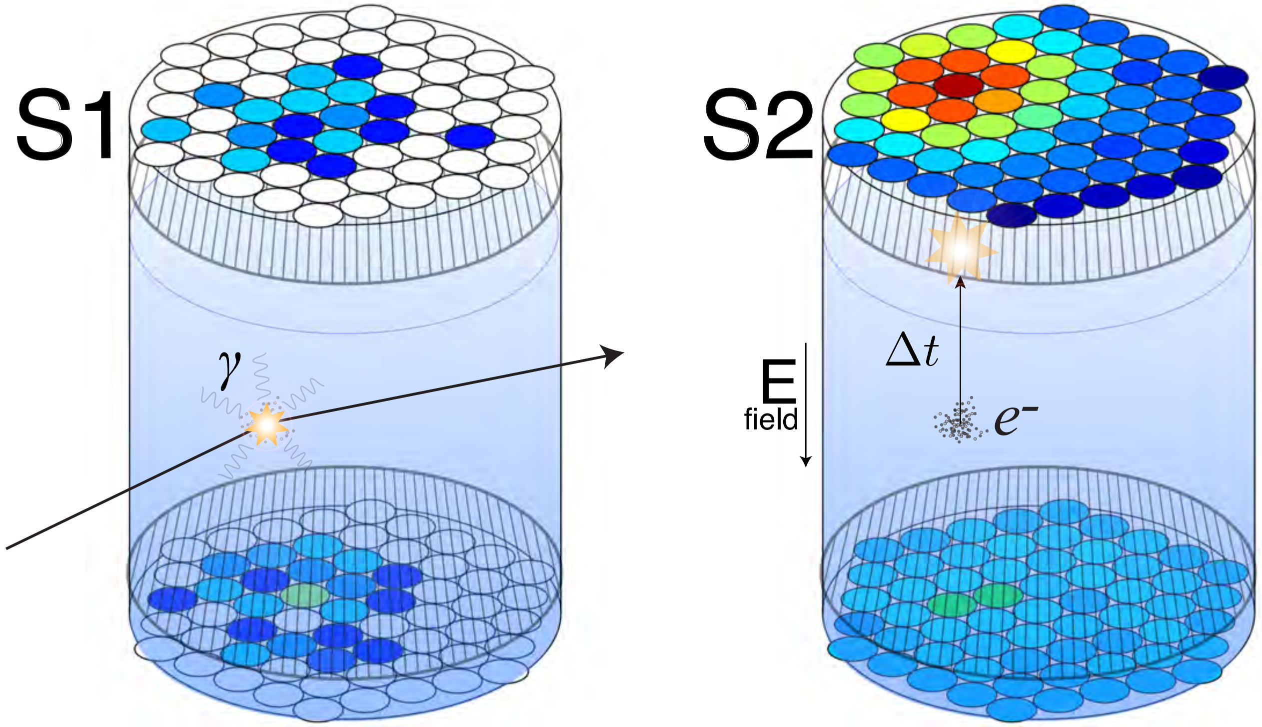
Dual-phase xenon detectors

- Dual-phase xenon as *neutrino* detectors

S1: proportional to # photons

S2: proportional to # electrons

S1+S2: 3D position reconstruction



From kinematics: $E_\mathrm{R} \sim 2.4\ \mathrm{keV} \left(\frac{E_\nu}{12\ \mathrm{MeV}}\right)^2$

(Neutrino signal similar to low-mass dark matter signal)

Supernova neutrinos

Supernovae: among the most energetic events in the Universe.
Originate from the core-collapse of very massive stars

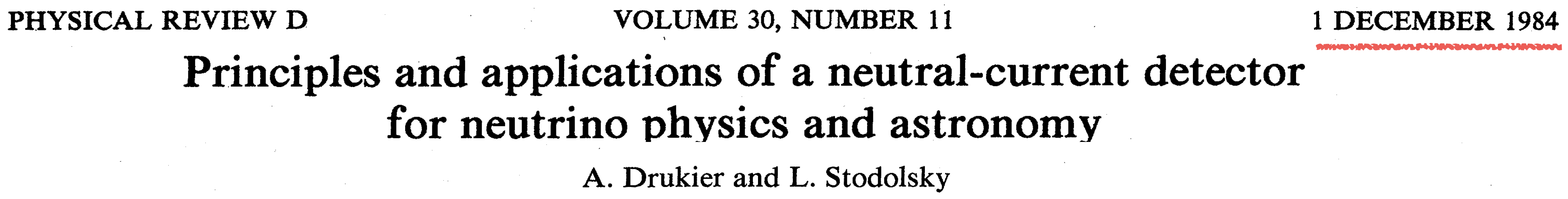
Energy:
~10^{53} erg released
~99% is emitted by all neutrino flavours
Neutrino energy ~ 15 MeV

Time:
Neutrino emission lasts ~10 s

When/where:
~1-3 SN/century in our galaxy
distance ~10 kpc

detection: will shed light on the properties of neutrinos and the explosion

DM detectors as neutrino detectors



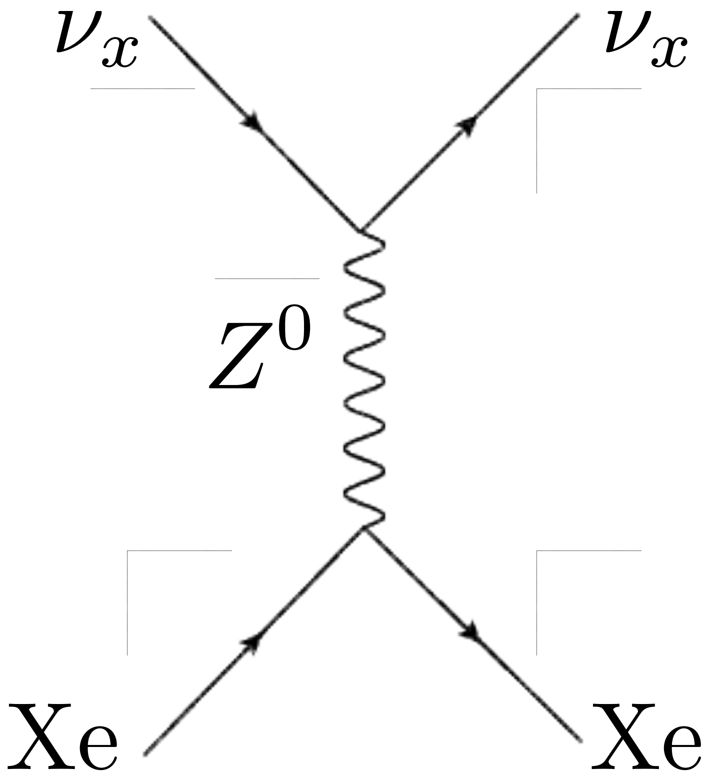
PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky

A neutral-current detector:

1. responds to all types of neutrinos equally
2. gains from a coherence factor:
   neutron-number^2
3. responds to neutrinos in a known way:
   can infer incoming neutrino spectrum



DM detectors as SN neutrino detectors

> “Elastic scattering detectors can have yields of a few or more neutrino events per tonne for a supernova at 10 kpc”
>
> Horowitz et al 2003

Why is it timely to think about this?

Tonne scale experiments are here:

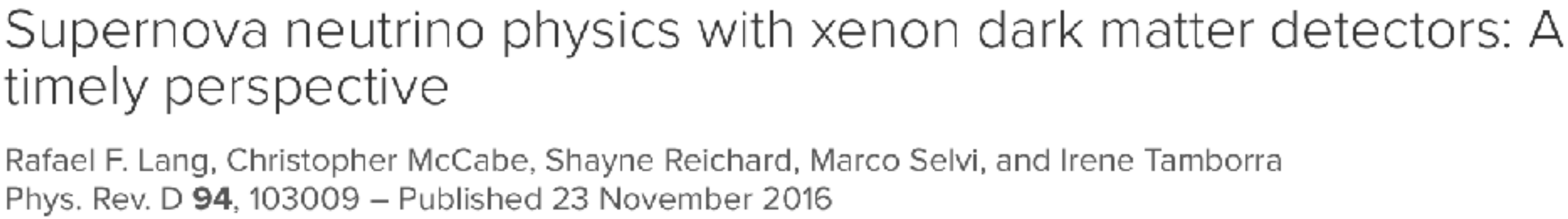
running: XENON1T (~ 2 t)

in design/construction: XENONnT & LZ (~ 7 t)

R&D: DARWIN (~ 40 t)

What physics can we do with these detectors?

DM detectors as SN neutrino detectors



Supernova neutrino physics with xenon dark matter detectors: A timely perspective

Rafael F. Lang, Christopher McCabe, Shayne Reichard, Marco Selvi, and Irene Tamborra

Phys. Rev. D **94**, 103009 – Published 23 November 2016

arXiv:1606.09243

1. *Simulate the SN neutrino signal in a dual-phase xenon detector*

Extracting physics from:

2. *the number of events*
3. *the shape of the spectrum*

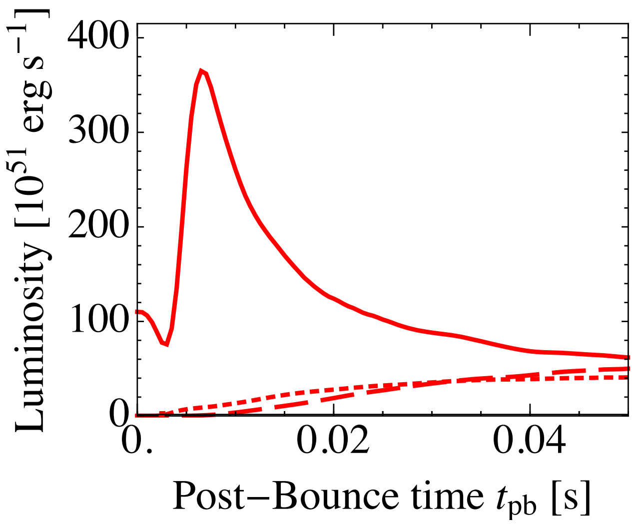
(first pass at this problem: everything could be improved)

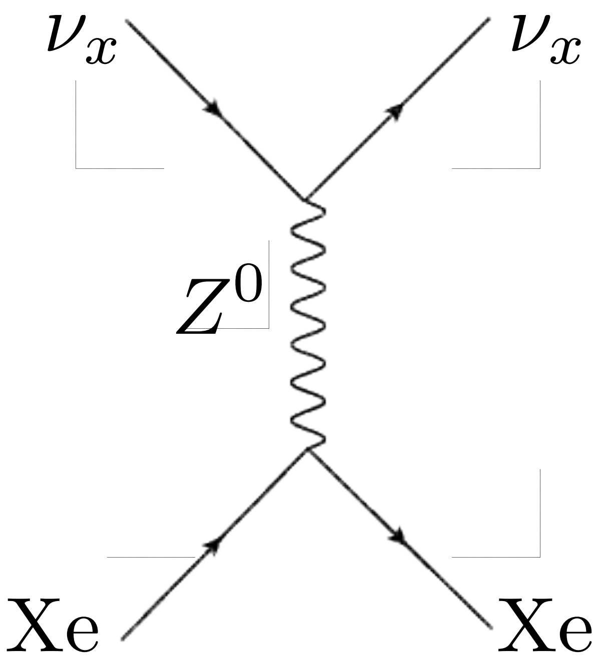
1. Simulating the supernova neutrino signal in a dual-phase xenon detector

Rate calculation: Ingredients

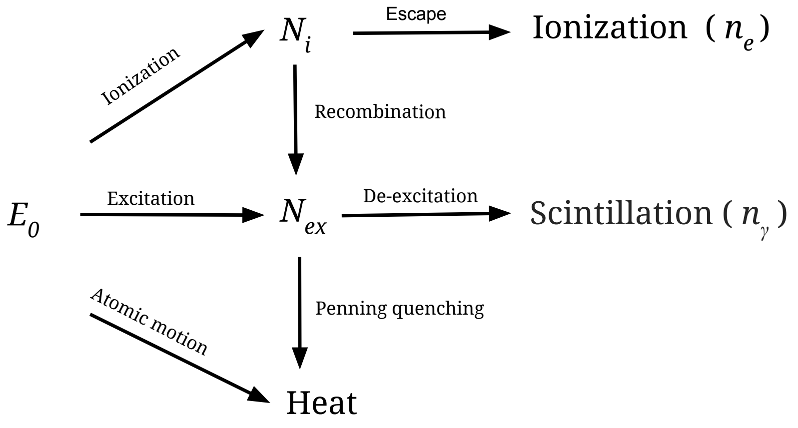
$$\boxed{\text{Rate} = \text{Flux} \times \text{cross section} \times \text{detector response}}$$

neutrino flux





Nuclear recoil energy transferred to photons, electrons or heat



E_0

Ionization

N_i

Escape

Ionization (n_e)

Recombination

Excitation

N_{ex}

De-excitation

Scintillation (n_γ)

Atomic motion

Penning quenching

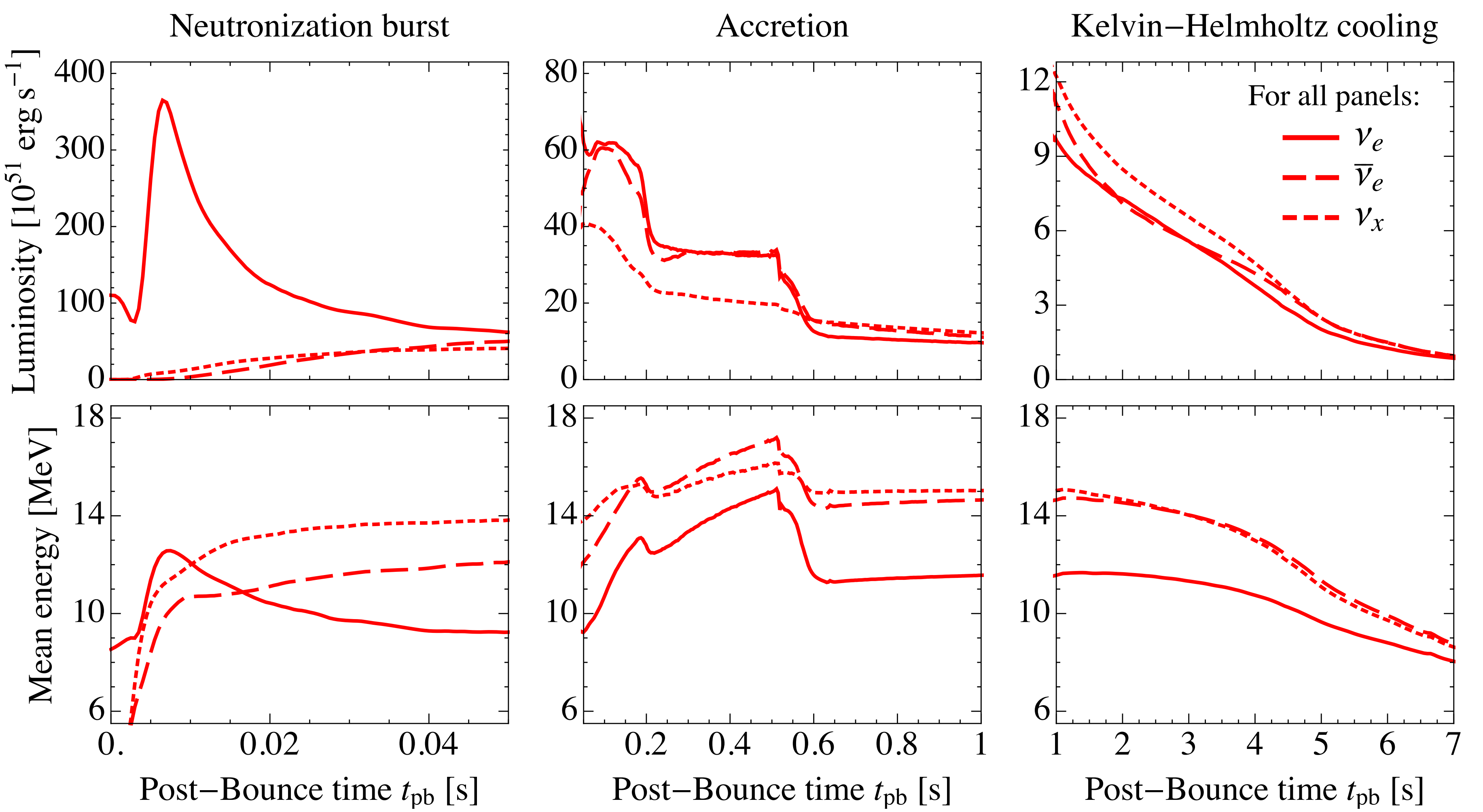
Heat

SN neutrino signal from simulations

Use results from four 1D simulations by the Garching group:

- Two progenitor masses (11 & 27 M_{Sun})
- Two equation of states (LS220 & Shen EoS)

27 M_{Sun} LS220; 27 M_{Sun} Shen; 11 M_{Sun} LS220; 11 M_{Sun} Shen



$$\nu_x = \begin{pmatrix} \nu_\mu \\ \bar{\nu}_\mu \\ \nu_\tau \\ \bar{\nu}_\tau \end{pmatrix}$$

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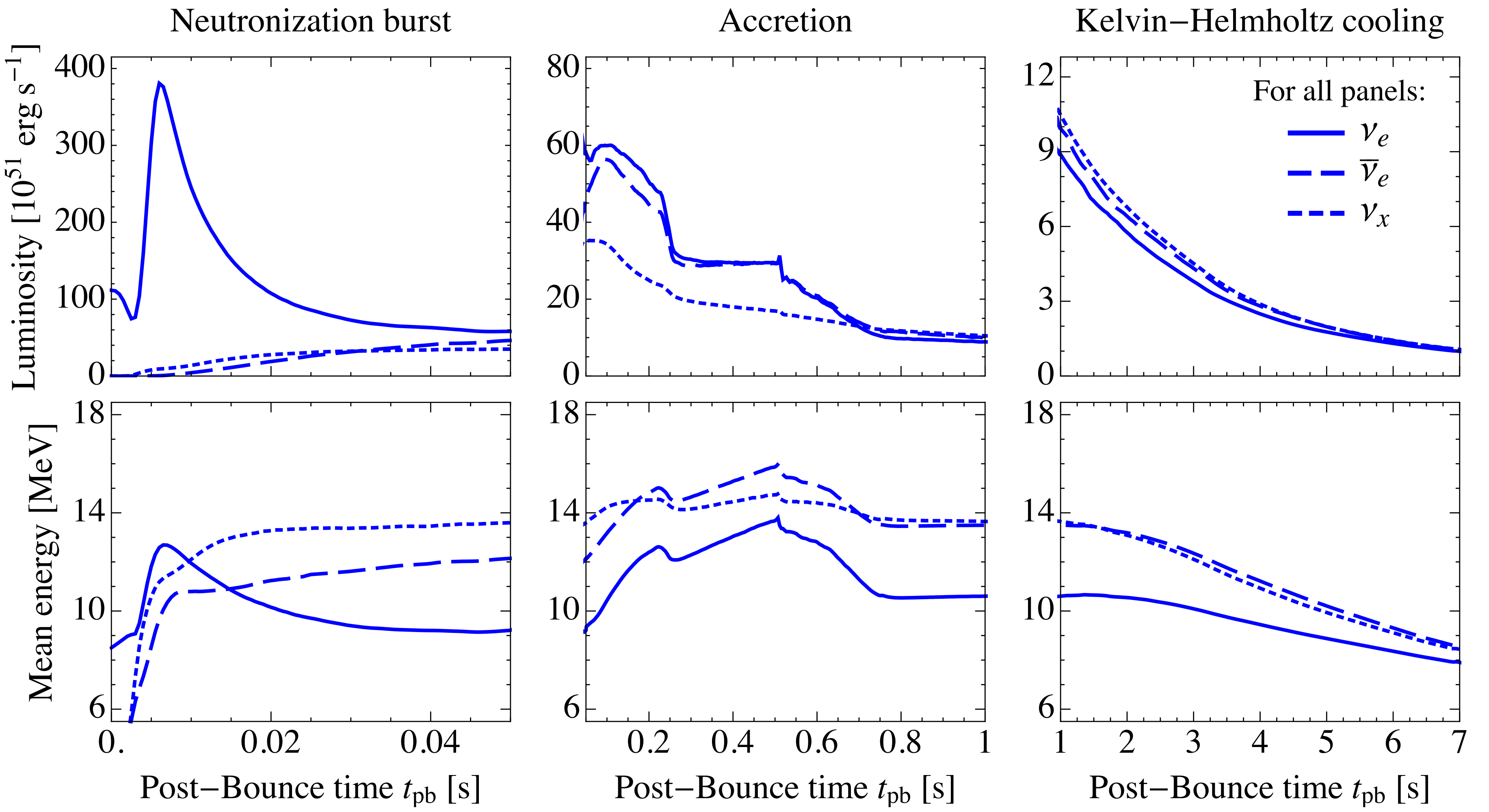

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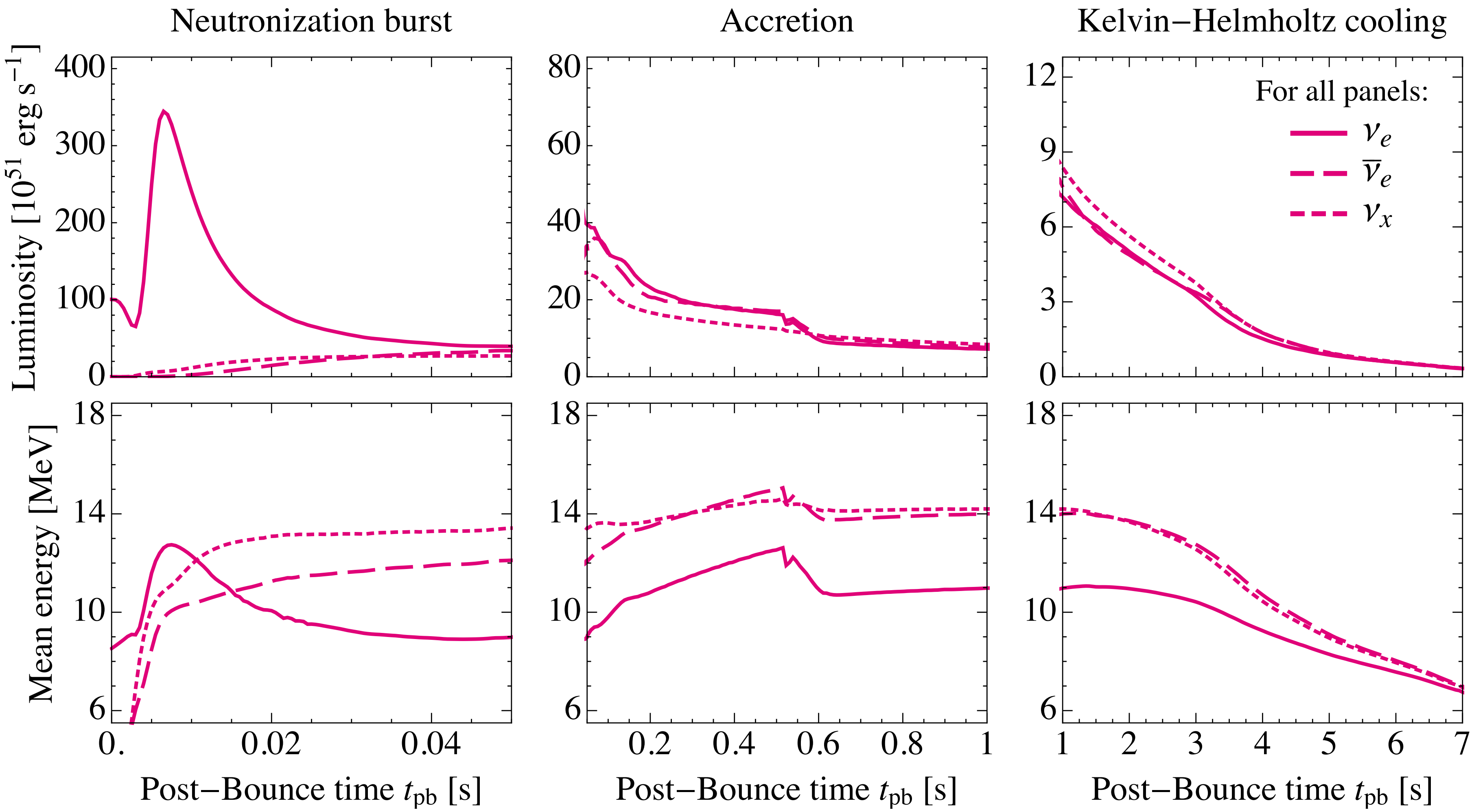

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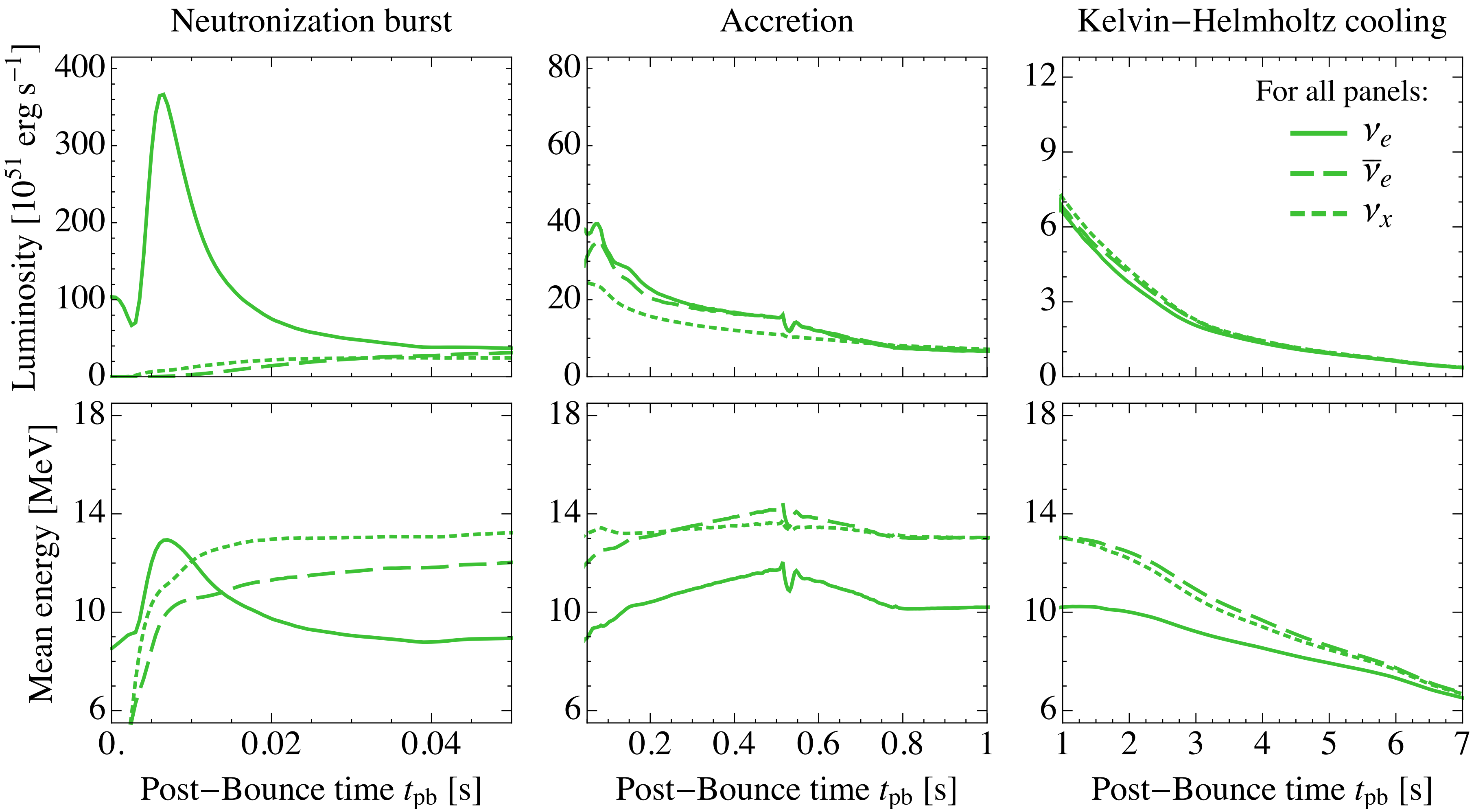
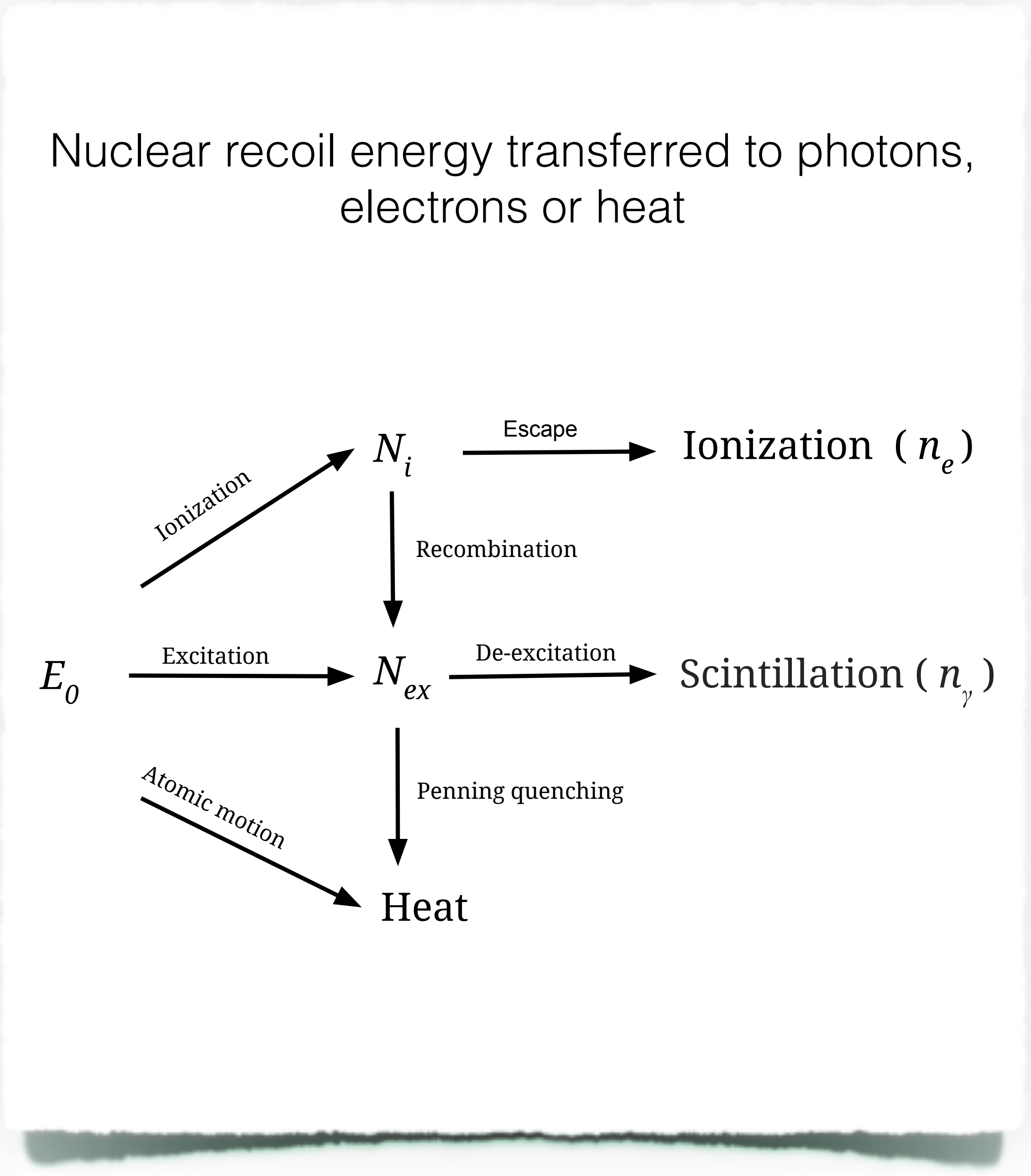


$$\nu_x = \begin{pmatrix} \nu_\mu \\ \bar{\nu}_\mu \\ \nu_\tau \\ \bar{\nu}_\tau \end{pmatrix}$$

Detector response

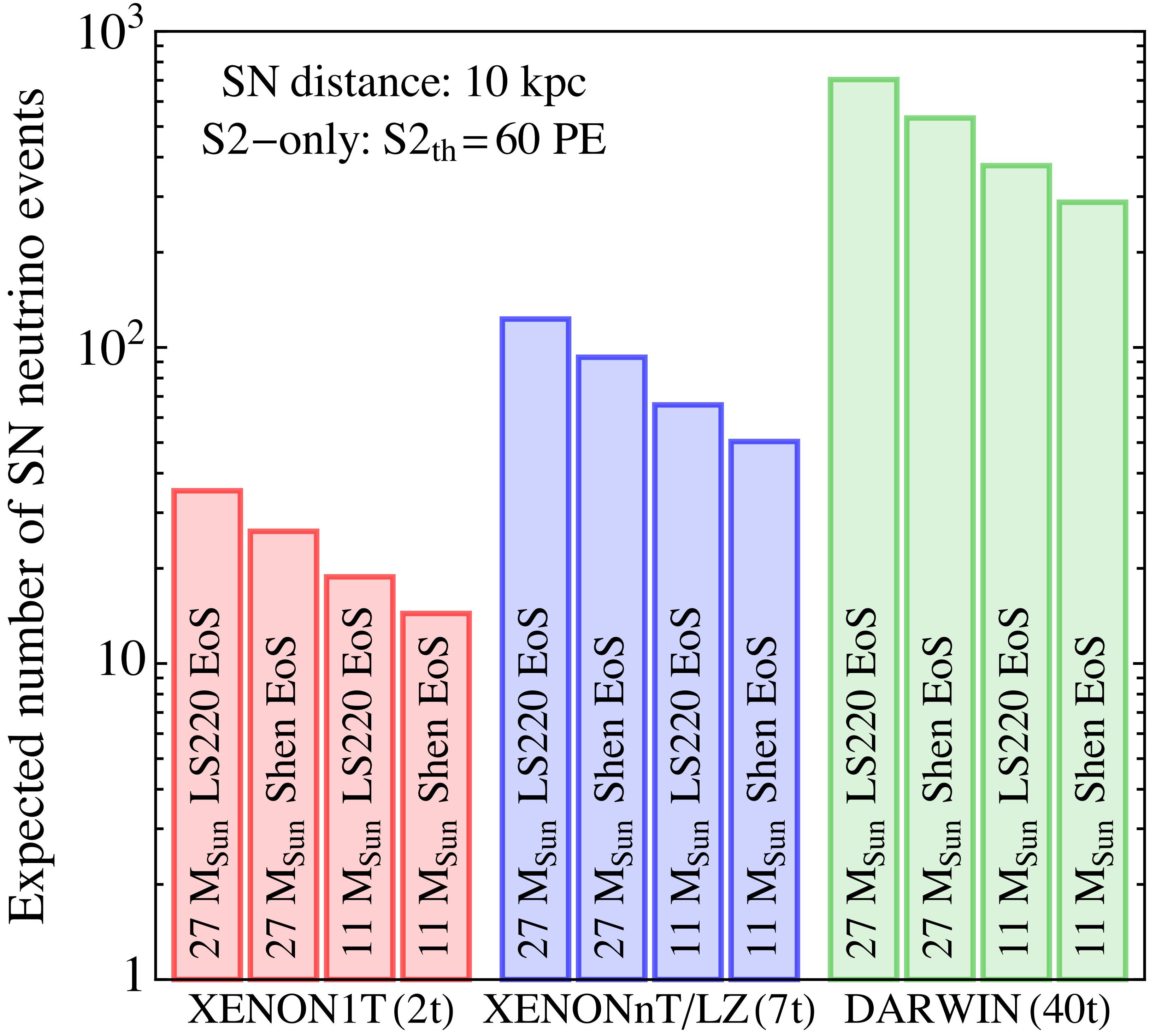
Ask me afterwards…



Nuclear recoil energy transferred to photons, electrons or heat

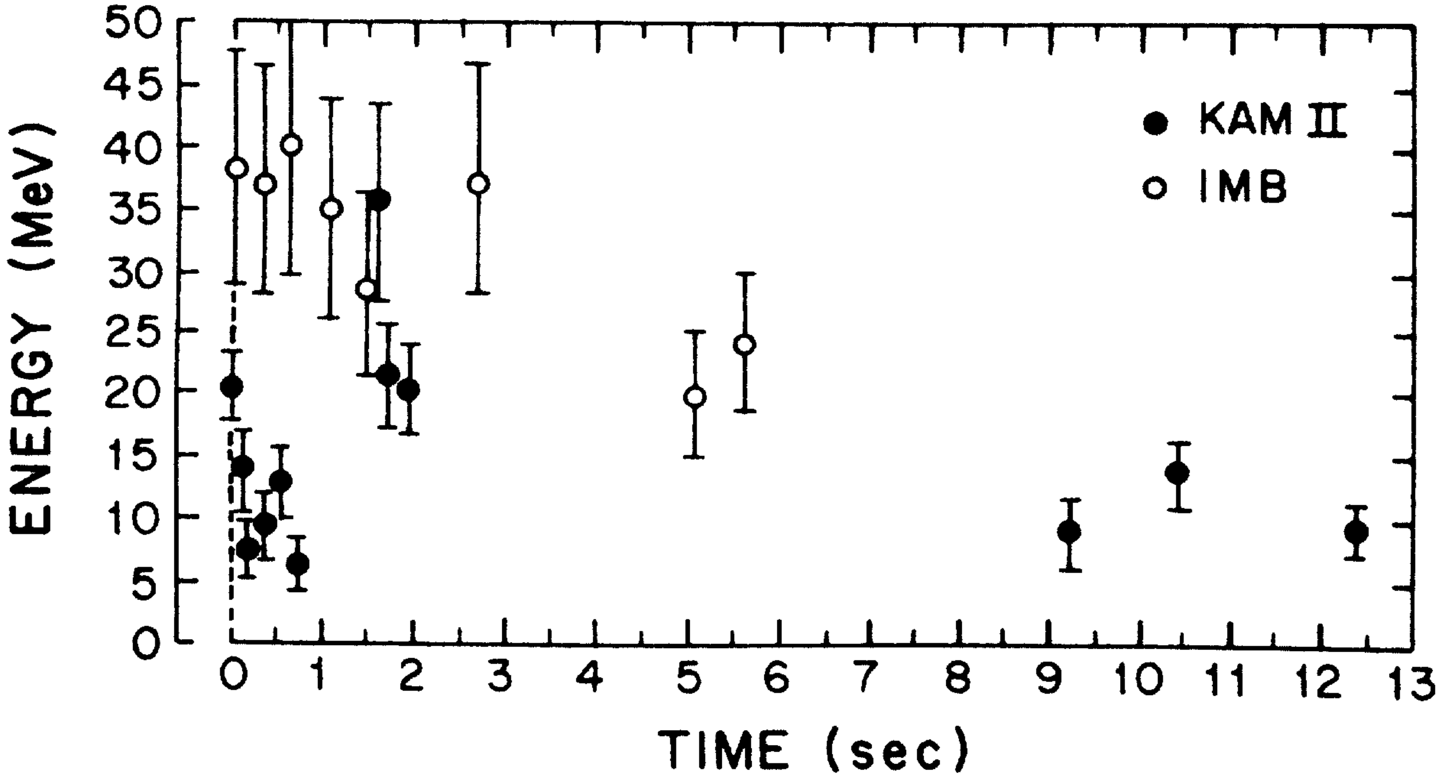
Extracting physics from:
2. the number of events

Expected number of events



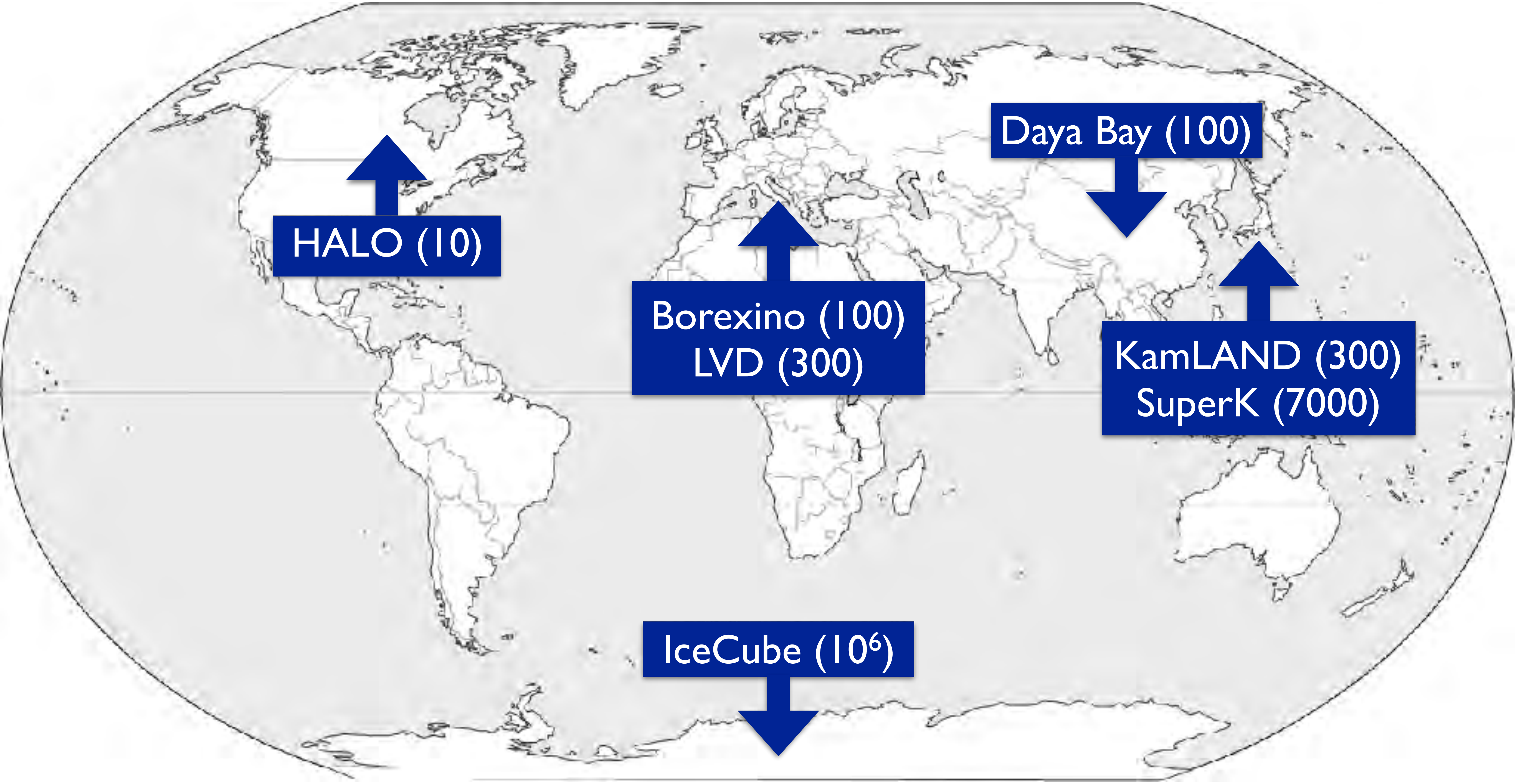
Past detection of supernova neutrinos

Neutrinos from SN1987A detected with
- Kamiokande-II (12 events)
- IMB (8 events)
- Baksan (5 events)



PRD 38 1988

Current detectors for supernova neutrinos



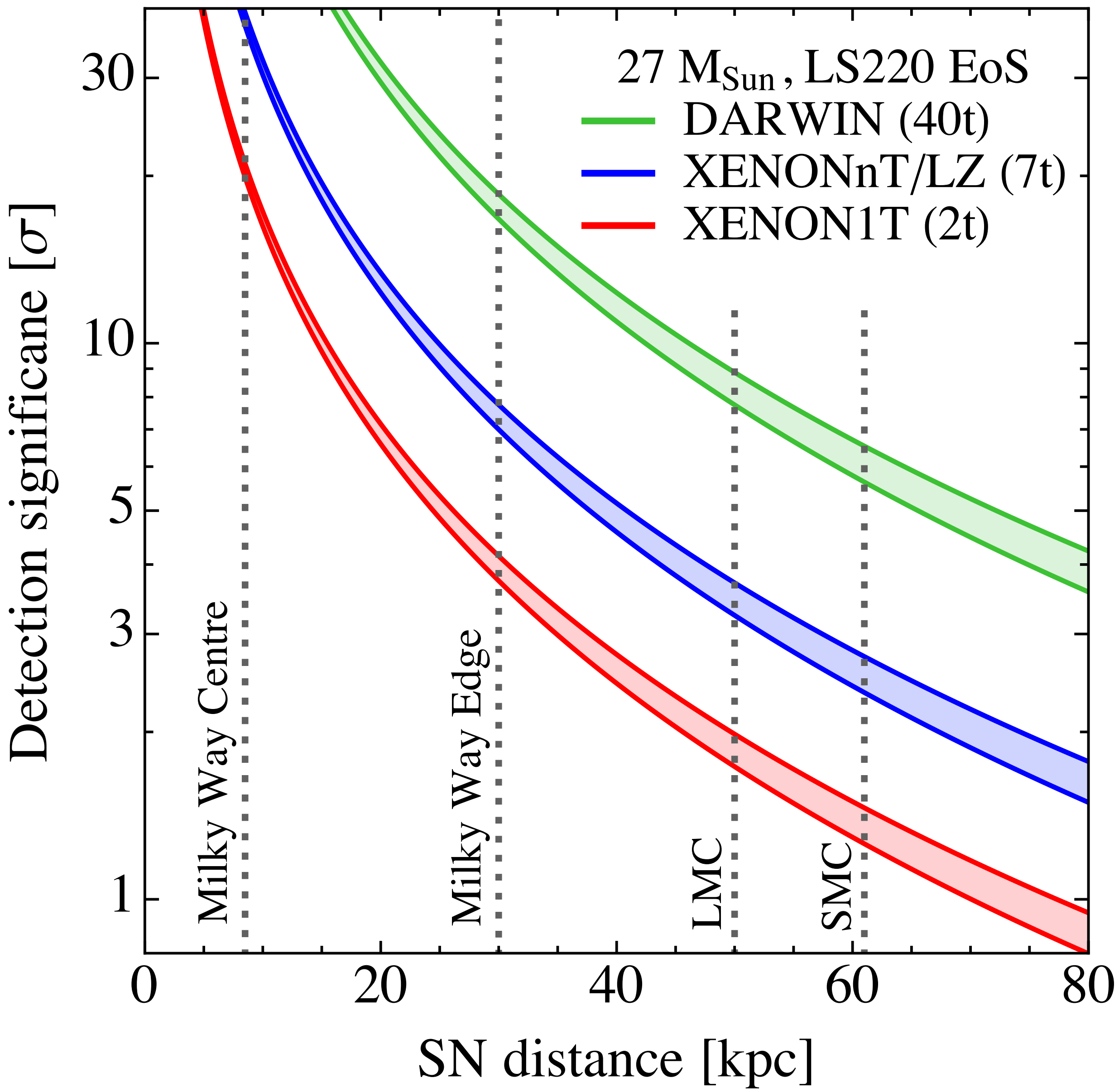
Events from a supernova burst at 10 kpc arXiv:1310.5783

Discovery significance

XENON1T: discovery to 20 kpc

XENONnT/LZ: discovery to Milky Way edge

DARWIN: discovery to Large/Small Magellanic Cloud



$$\mathrm{XENON1T} : 35.2 \left(\frac{10\ \mathrm{kpc}}{d}\right)^2 \mathrm{events}$$

$$\mathrm{XENONnT/LZ} : 123 \left(\frac{10\ \mathrm{kpc}}{d}\right)^2 \mathrm{events}$$

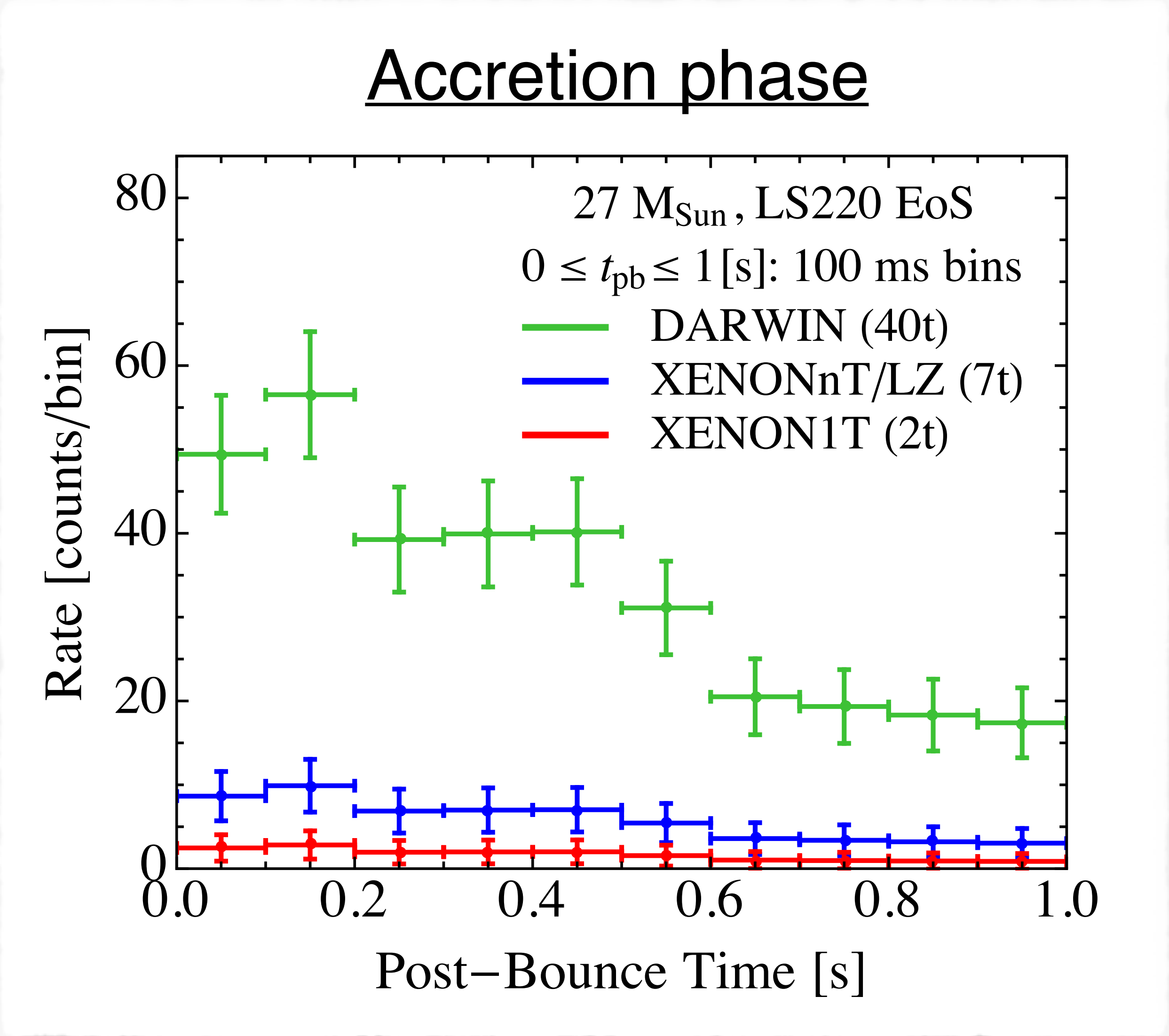
$$\mathrm{DARWIN} : 704 \left(\frac{10\ \mathrm{kpc}}{d}\right)^2 \mathrm{events}$$

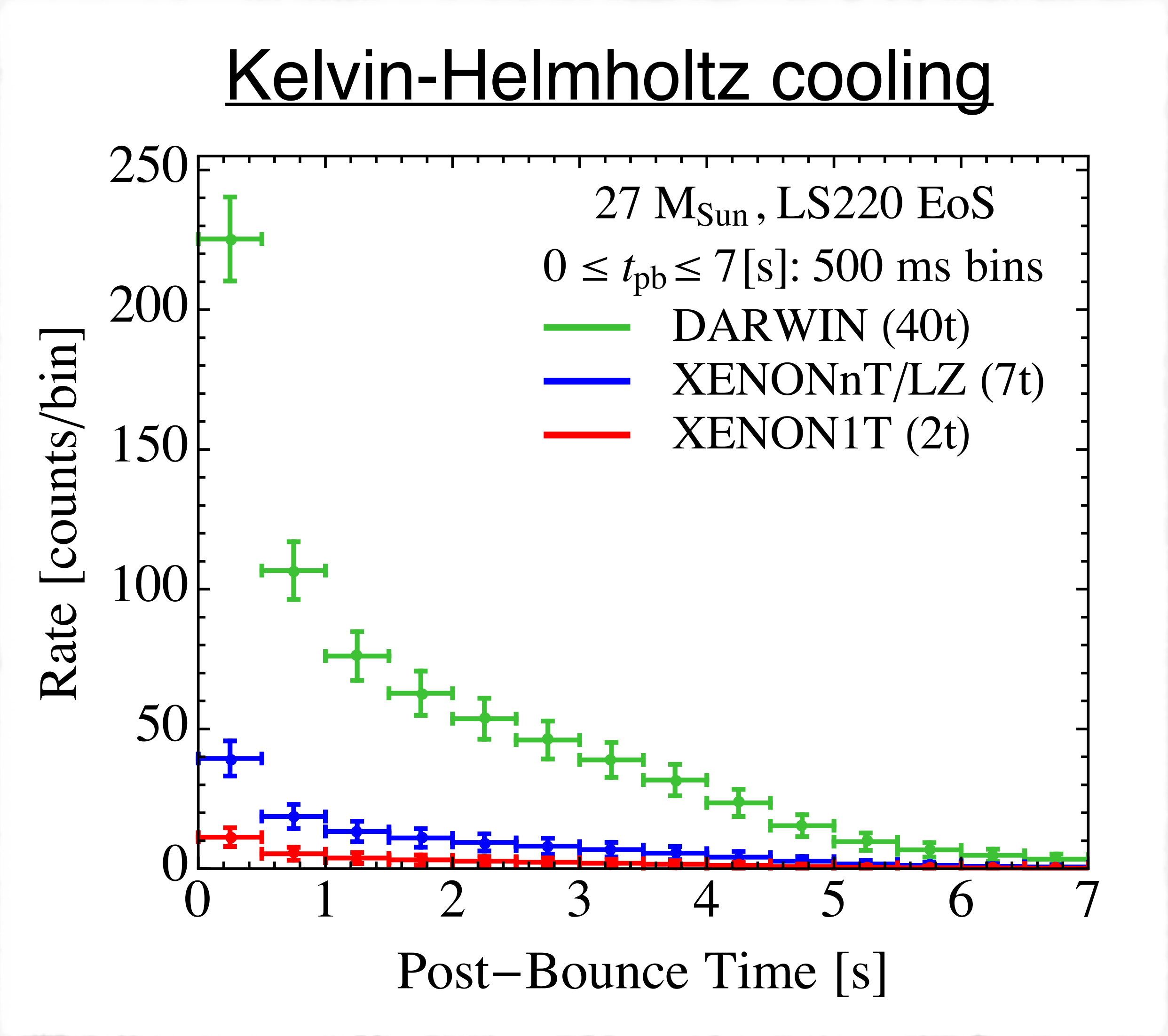
Background estimate (0.1 event/tonne) from XENON10 & XENON100

Neutrino light curve

See also:
Chakraborty et al
1309.4492

- Distinguishing the phases of the (10 kpc) supernova neutrino emission





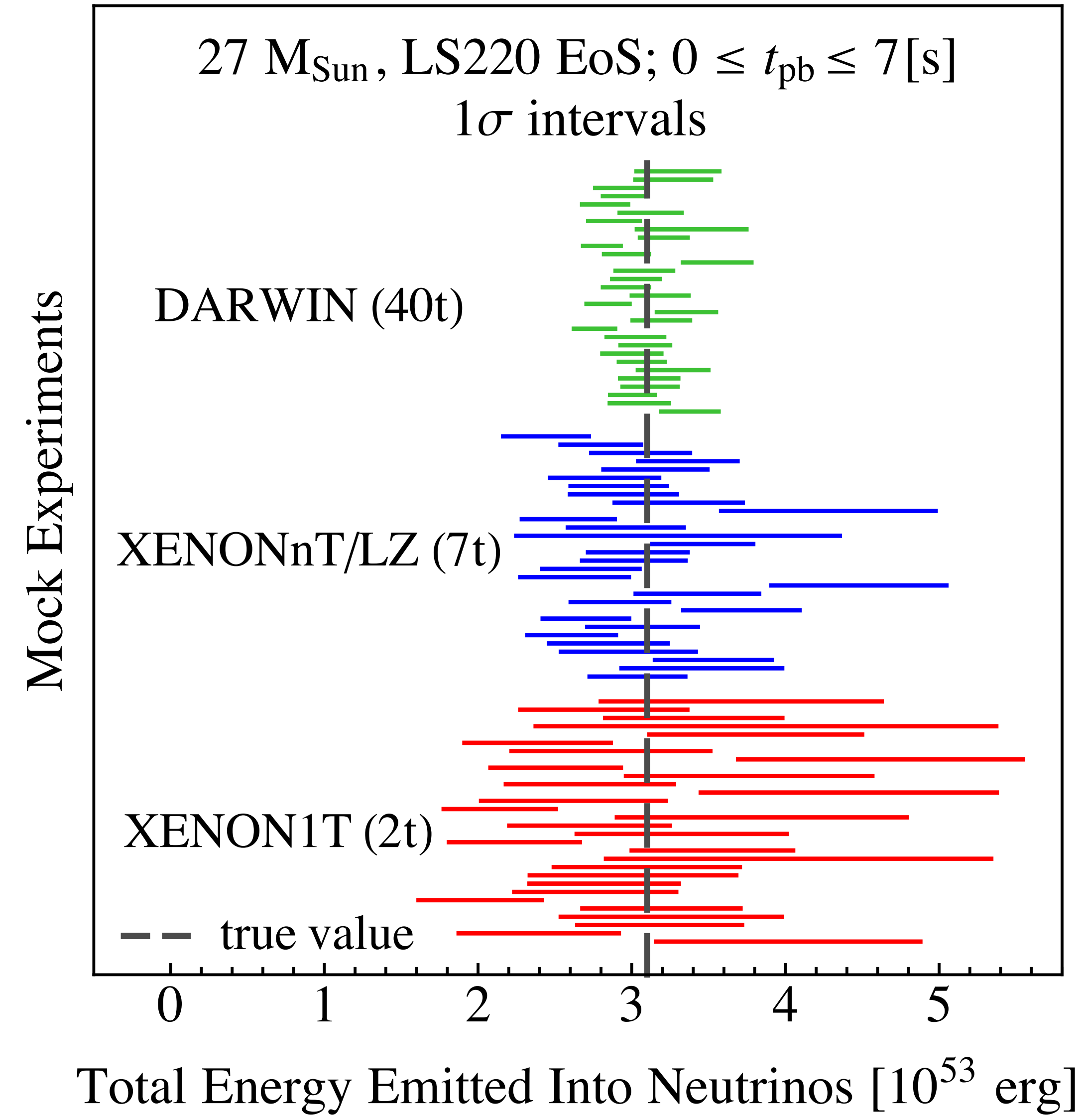
- Clear differentiation of phase with DARWIN
- Partial differential with XENONnT/LZ but none with XENON1T

Extracting physics from:

3. *the shape of the spectrum (measured S2 value)*

Energy released into neutrinos

- Excellent reconstruction with DARWIN
- XENON1T also good



precision

$\sim 5\%$

$\sim 10\%$

$\sim 20\%$

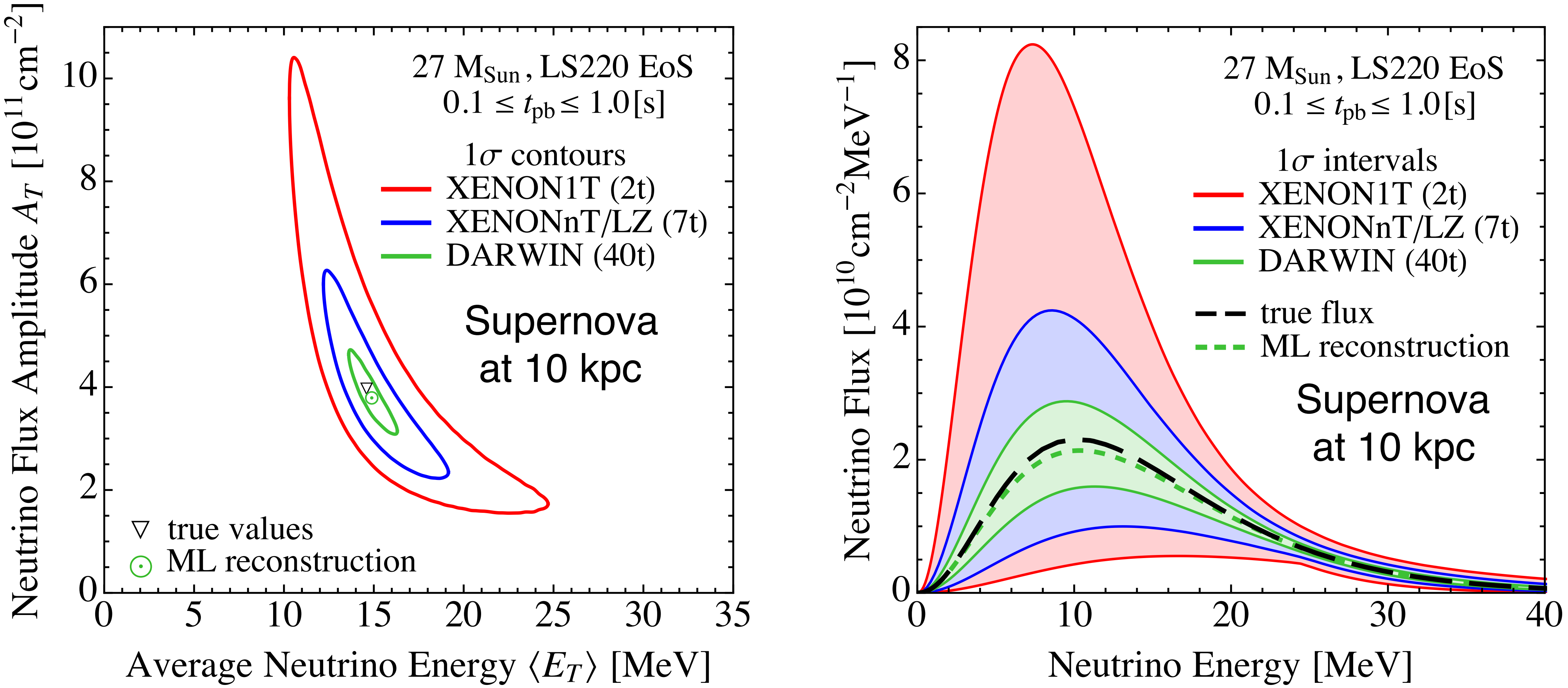
Supernova
at 10 kpc

SN neutrino flux

- Flux parameterisation ansatz (motivated from simulations):

Keil et al 0208035

$$A_T\,\xi_T\left(\frac{E_\nu}{\langle E_T\rangle}\right)^{\alpha_T}\exp\left(\frac{-(1+\alpha_T)E_\nu}{\langle E_T\rangle}\right)$$ with $\alpha_T = 2.3$, $\langle E_T\rangle$, A_T determined from fit



SN neutrino summary

A xenon direct detection experiment:

1. responds to all types of neutrinos equally
2. gains from a coherence factor (neutron-number^2)
3. responds to neutrinos in a known way (can infer incoming neutrino spectrum)

For a SN at 10 kpc from Earth:

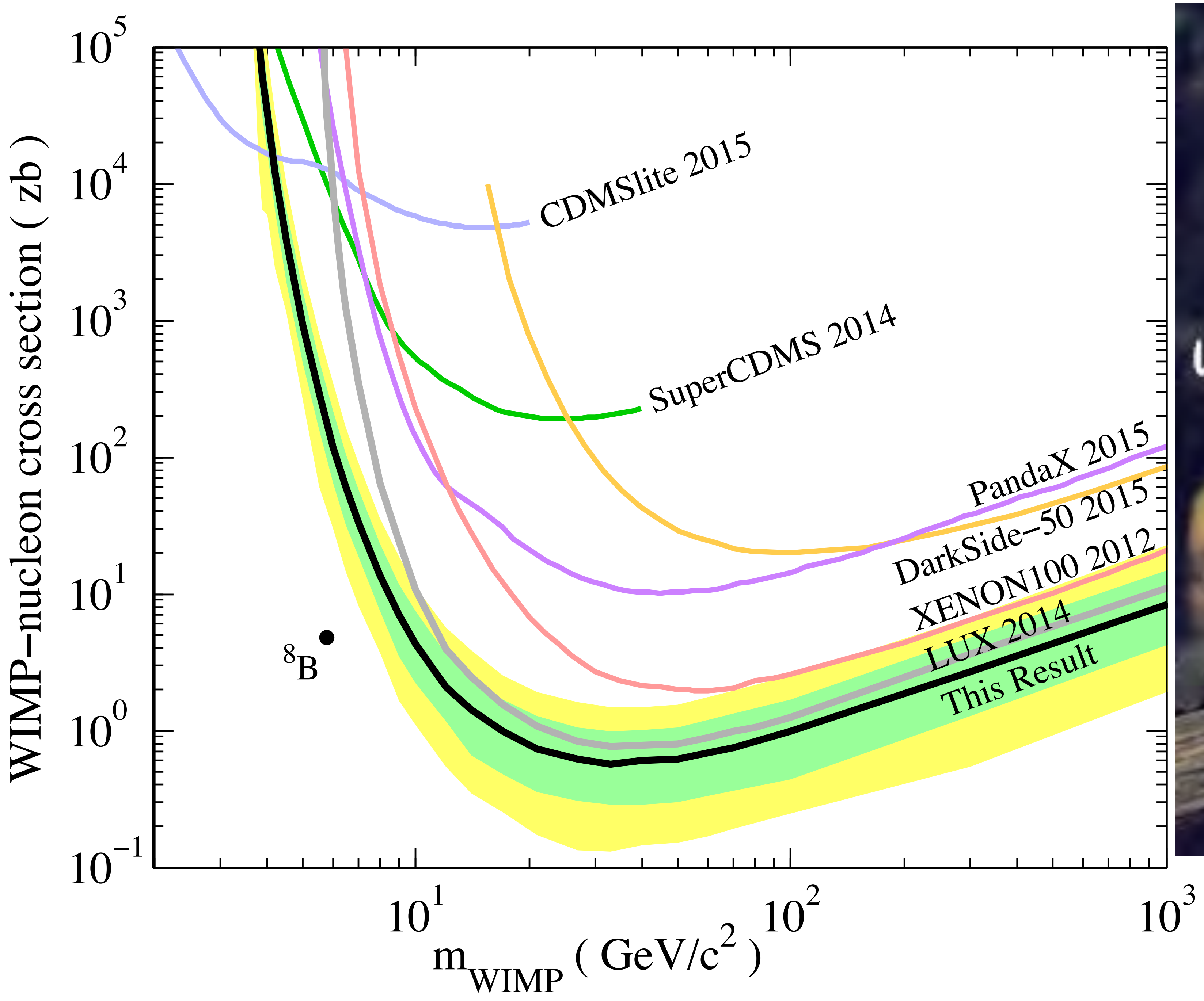
(SN at 2.2 kpc in XENON1T = SN at 10 kpc in DARWIN)

	High significance discovery	Light curve reconstruction	Total nu-energy reconstruction	nu-spectrum reconstruction
XENON1T (2t)	✔	✗	~	~
XENONnT/LZ (7t)	✔	~ ✗	✔	~ ✔
DARWIN (40t)	✔	✔	✔	✔

New low energy signals:
2. Sub-GeV dark matter

Motivation

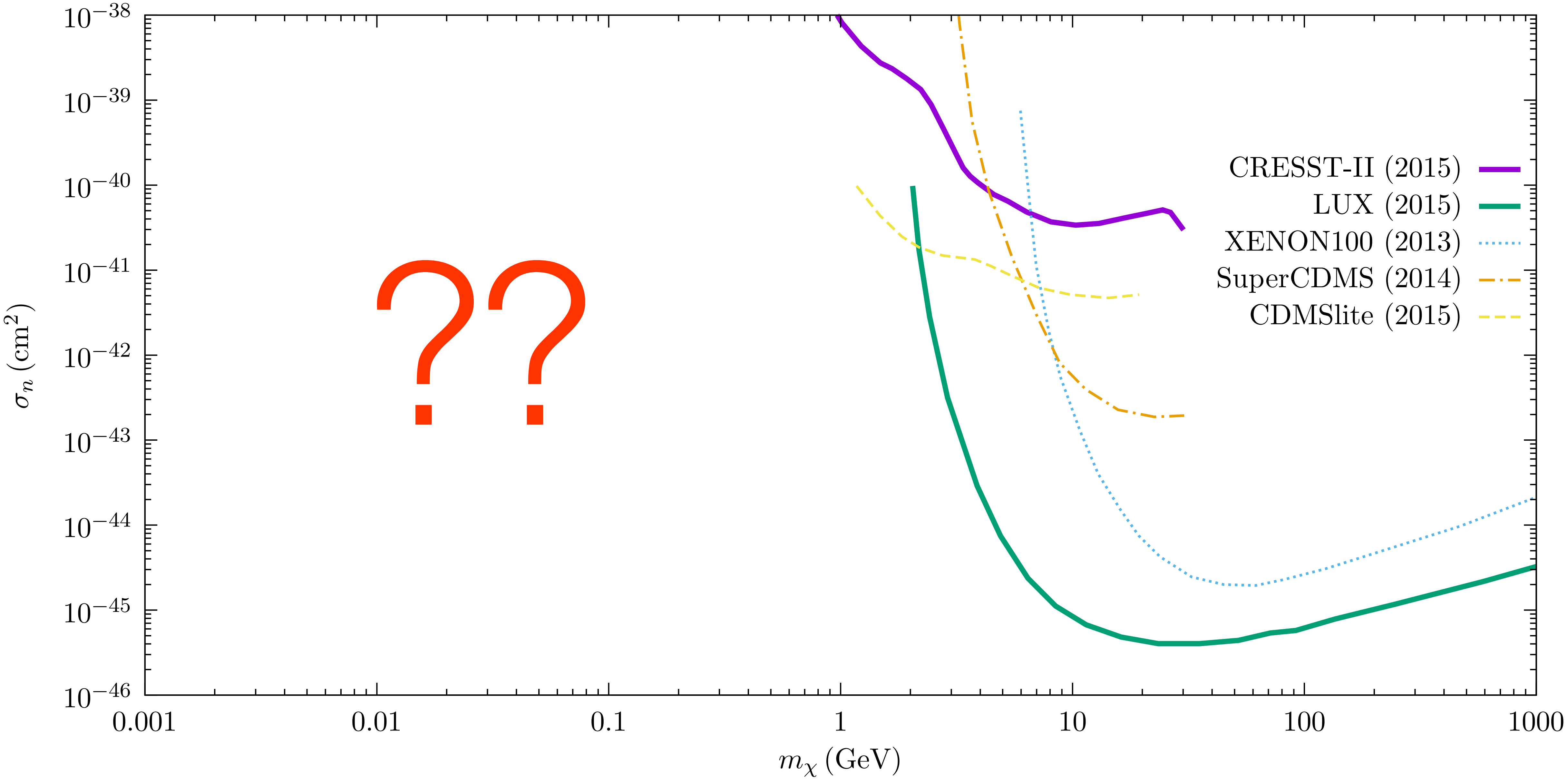
Detecting dark matter is hard



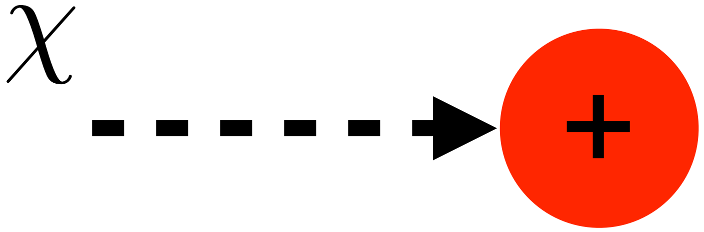
Motivation

Detecting dark matter is hard

Detecting sub-GeV dark matter is even harder

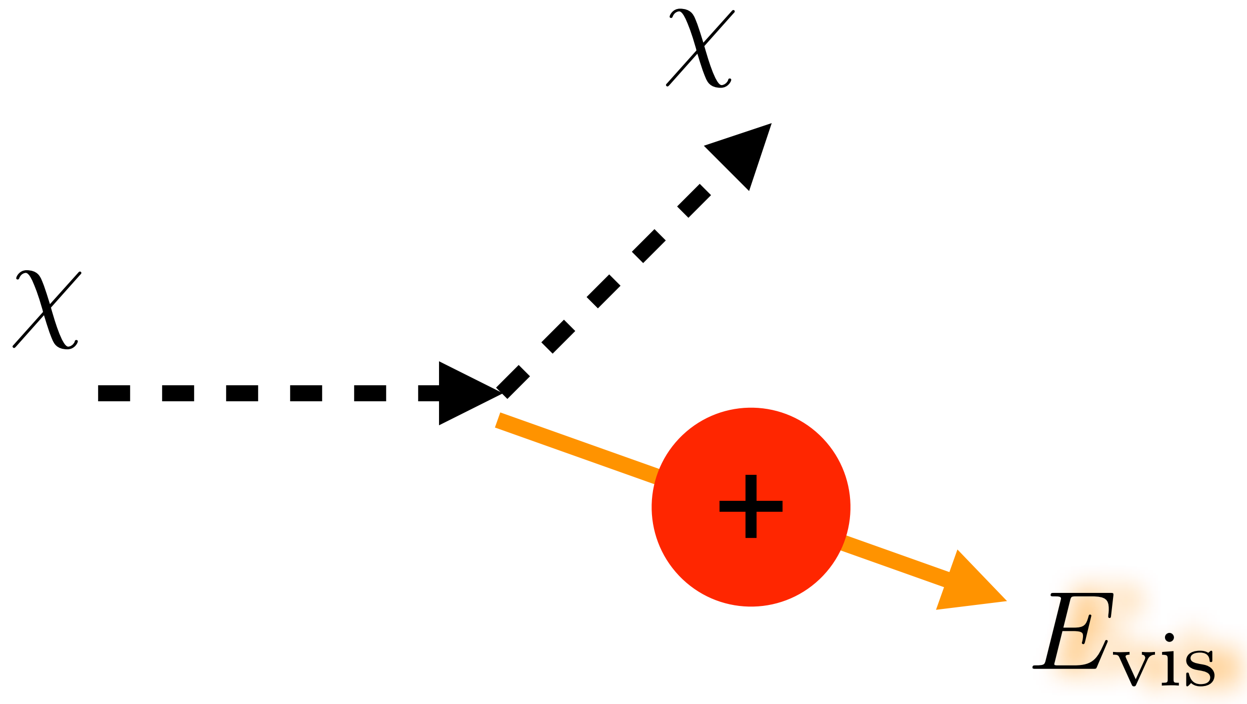


Normal signal



xenon nucleus

Normal signal

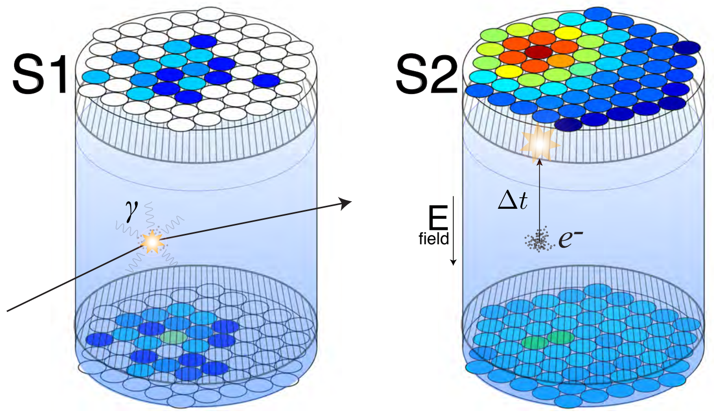


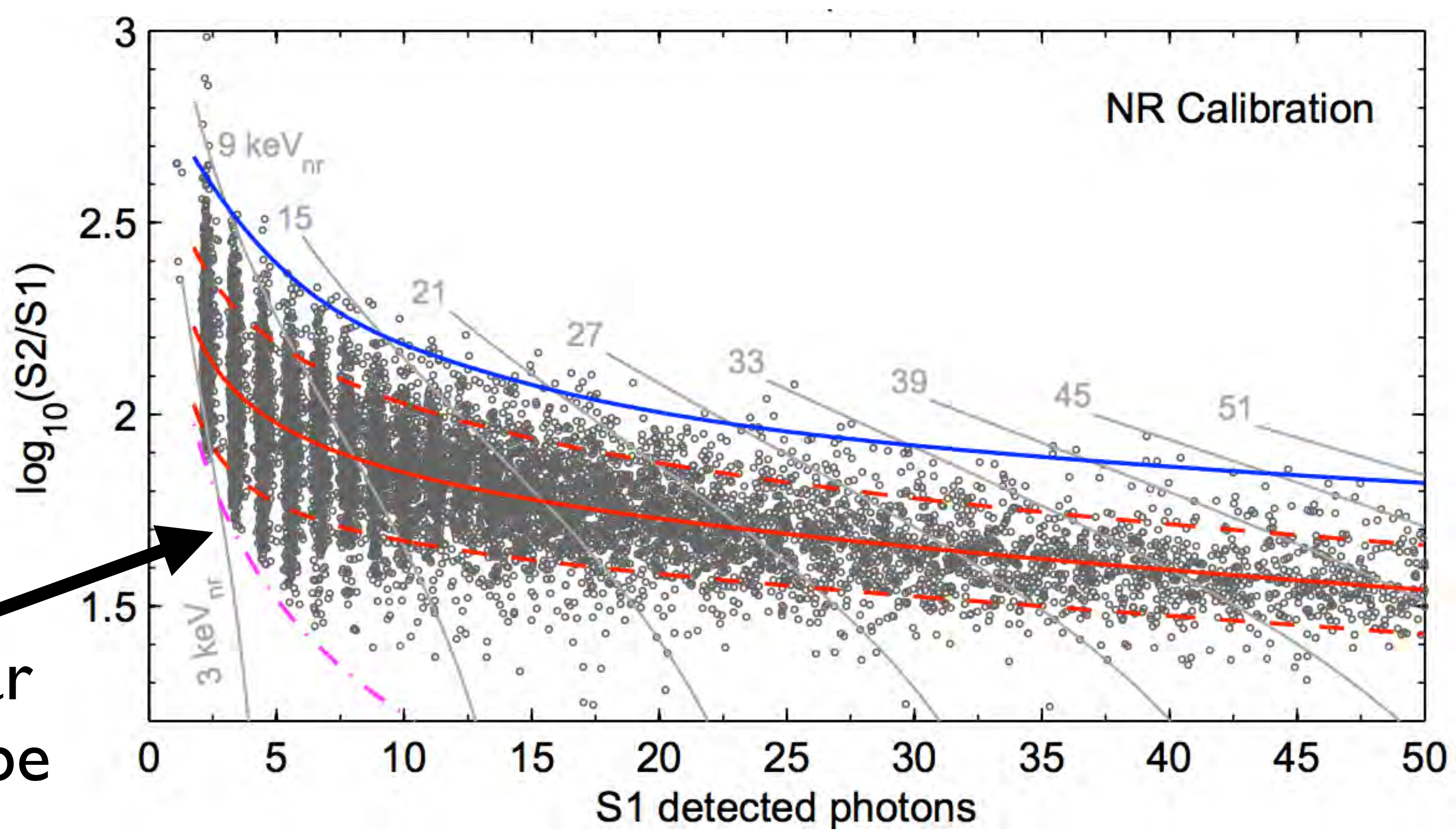
measure recoil energy
of the xenon nucleus

$$E_{\rm R}^{\rm max} \approx 0.1~\text{keV}$$
$$\times\,(131/A)\,(m_{\rm DM}/1~\text{GeV})^2$$

keV nuclear recoils in LUX

$$E_{\mathrm{R}}^{\mathrm{max}} \approx 0.1\ \mathrm{keV} \cdot (m_{\mathrm{DM}}/1\ \mathrm{GeV})^2$$



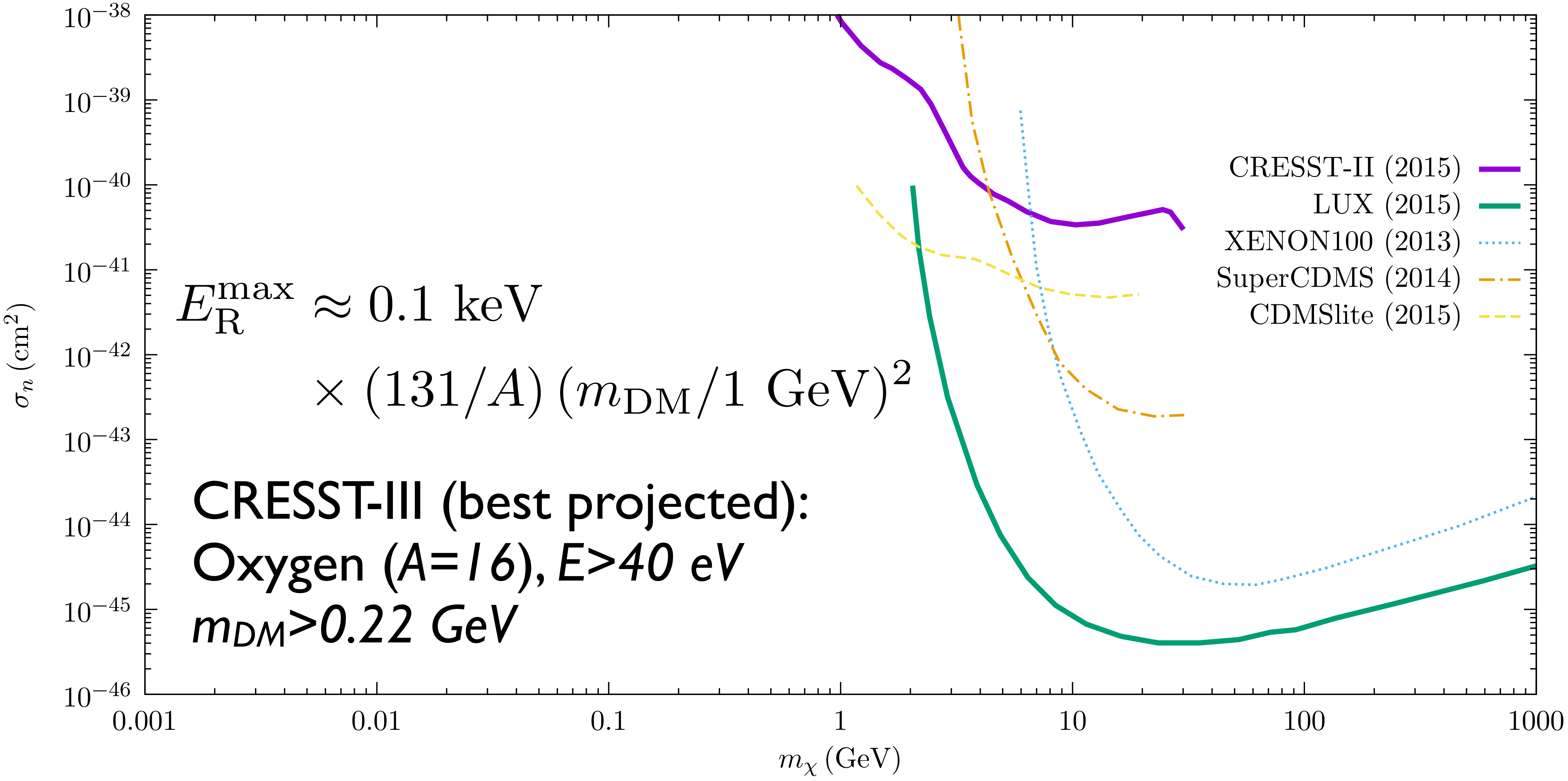


sub- keV nuclear recoils will not be detected

Not enough energy to produce a signal

Detecting dark matter is hard

Detecting sub-GeV dark matter is even harder

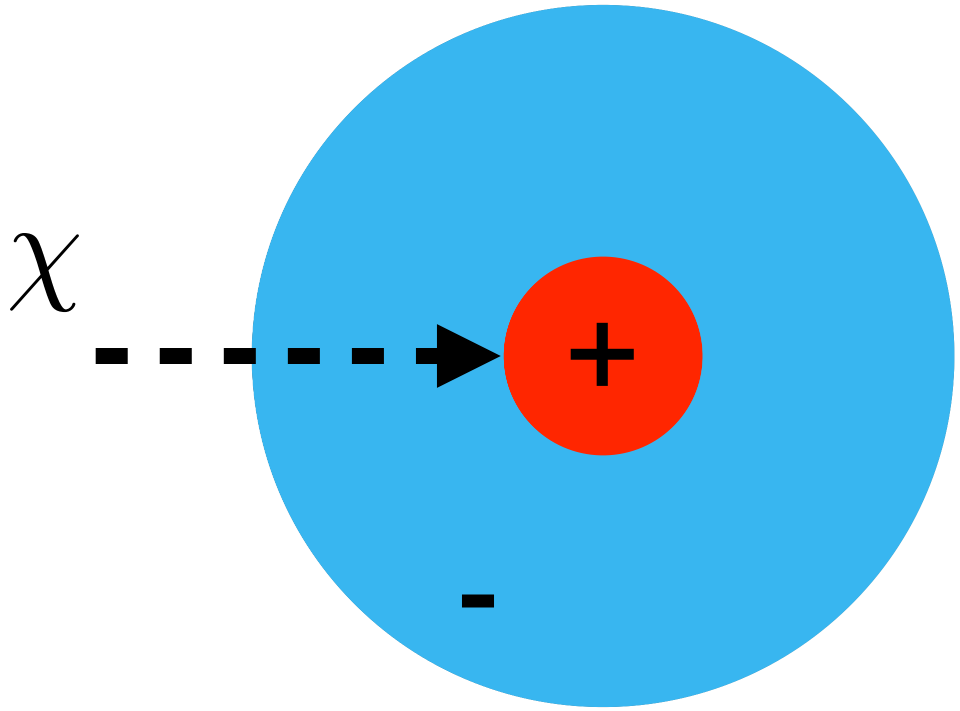


$$E_{\mathrm{R}}^{\mathrm{max}} \approx 0.1\ \mathrm{keV} \times (131/A)\,(m_{\mathrm{DM}}/1\ \mathrm{GeV})^2$$

CRESST-III (best projected):
Oxygen (*A*=16), *E*>40 eV
m_{DM}>0.22 GeV

A new idea

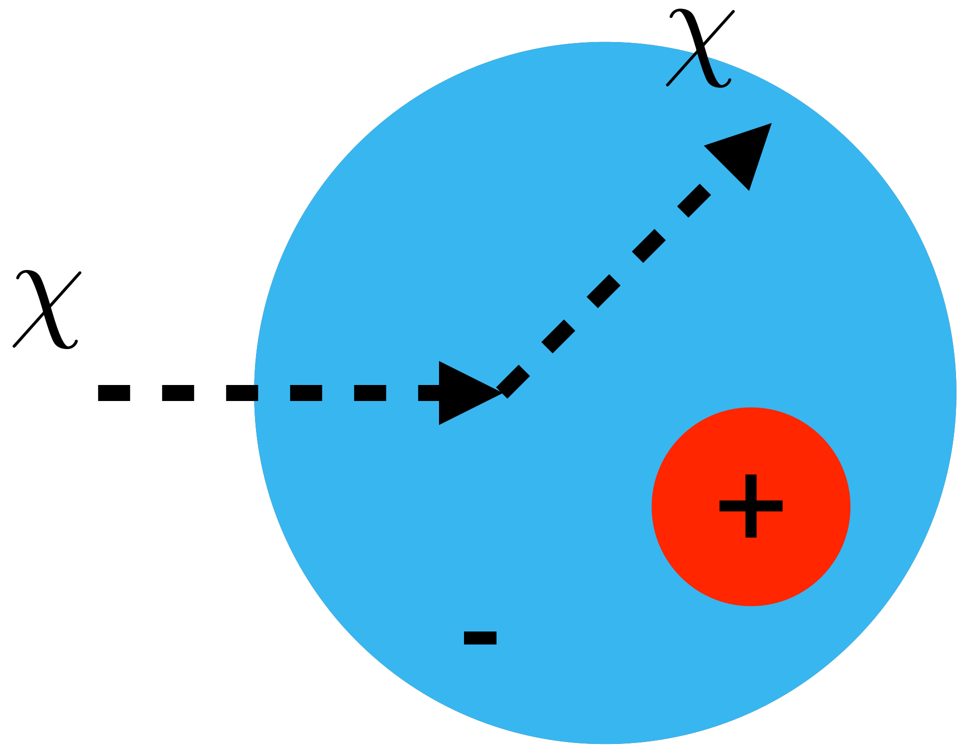
Kouvaris & Pradler: 1607.01789, PRL



xenon atom
(ground state)

A new idea

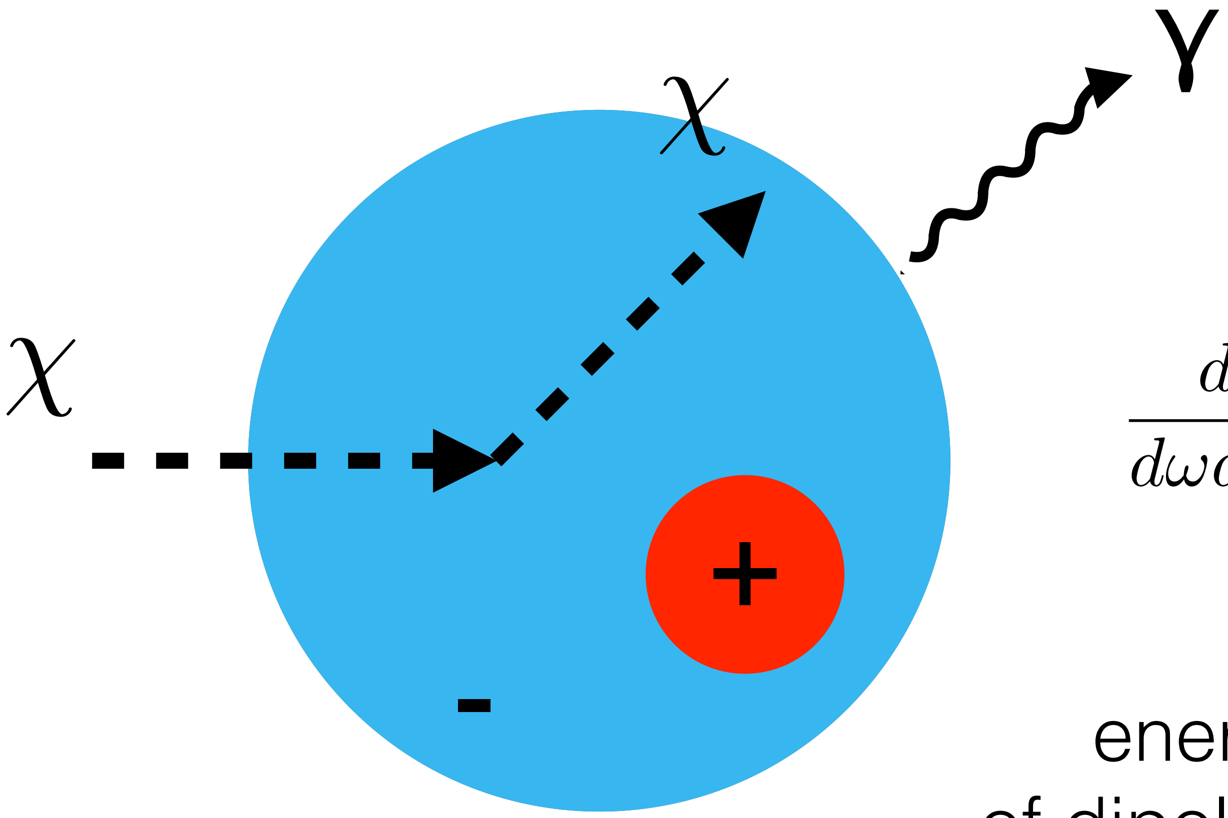
Kouvaris & Pradler: 1607.01789, PRL



xenon atom
(polarised)

A new idea

Kouvaris & Pradler: 1607.01789, PRL



Polarised atom
emits a photon

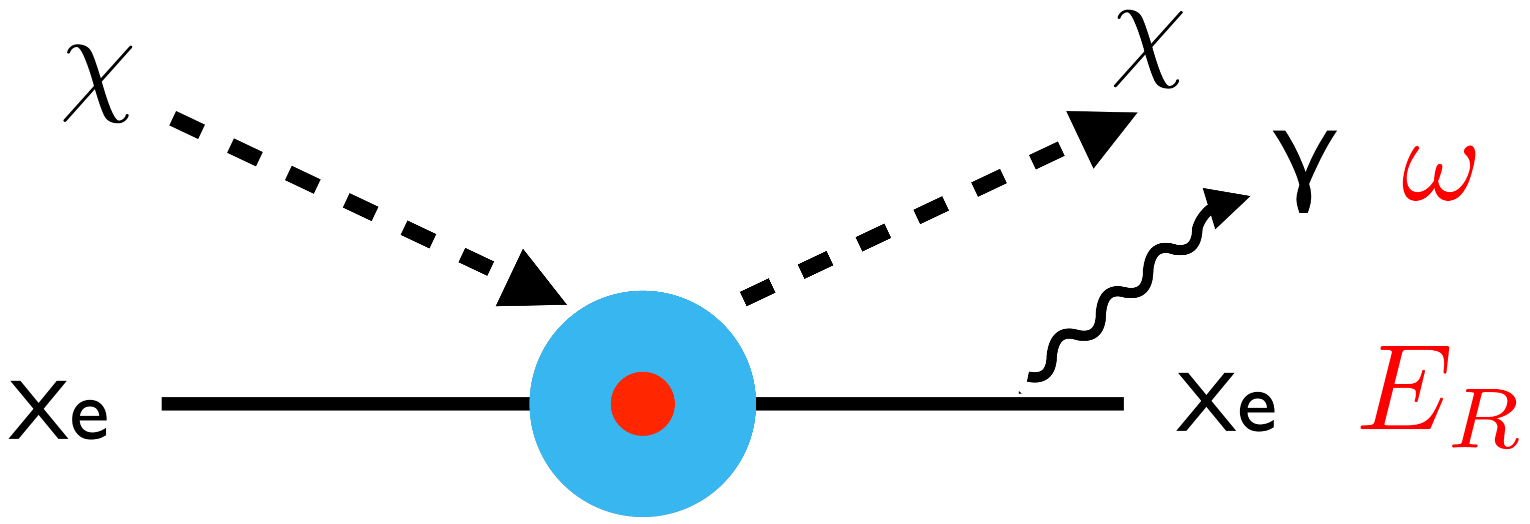
$$\frac{d\sigma}{d\omega dE_R} \propto \omega^3 \times |\alpha(\omega)|^2 \times \frac{E_R}{m_N} \times \frac{d\sigma}{dE_R}$$

energy scaling
of dipole emission

polarizability of the atom

A new idea: why is it interesting?

Kouvaris & Pradler: 1607.01789, PRL



Maximum photon energy:

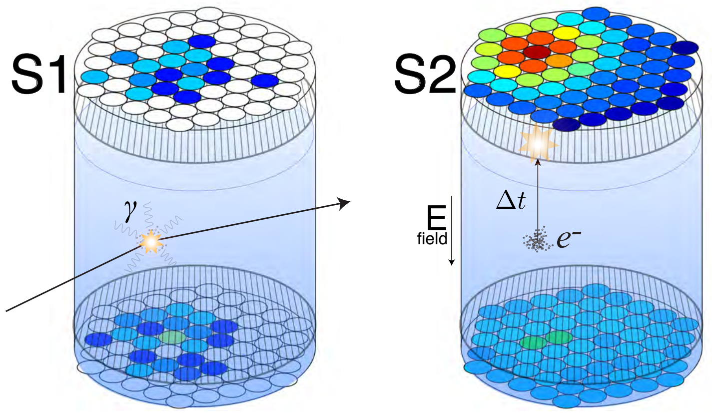
$$\omega^{\max} \approx 3~\mathrm{keV} \cdot (m_{\mathrm{DM}}/1~\mathrm{GeV})$$

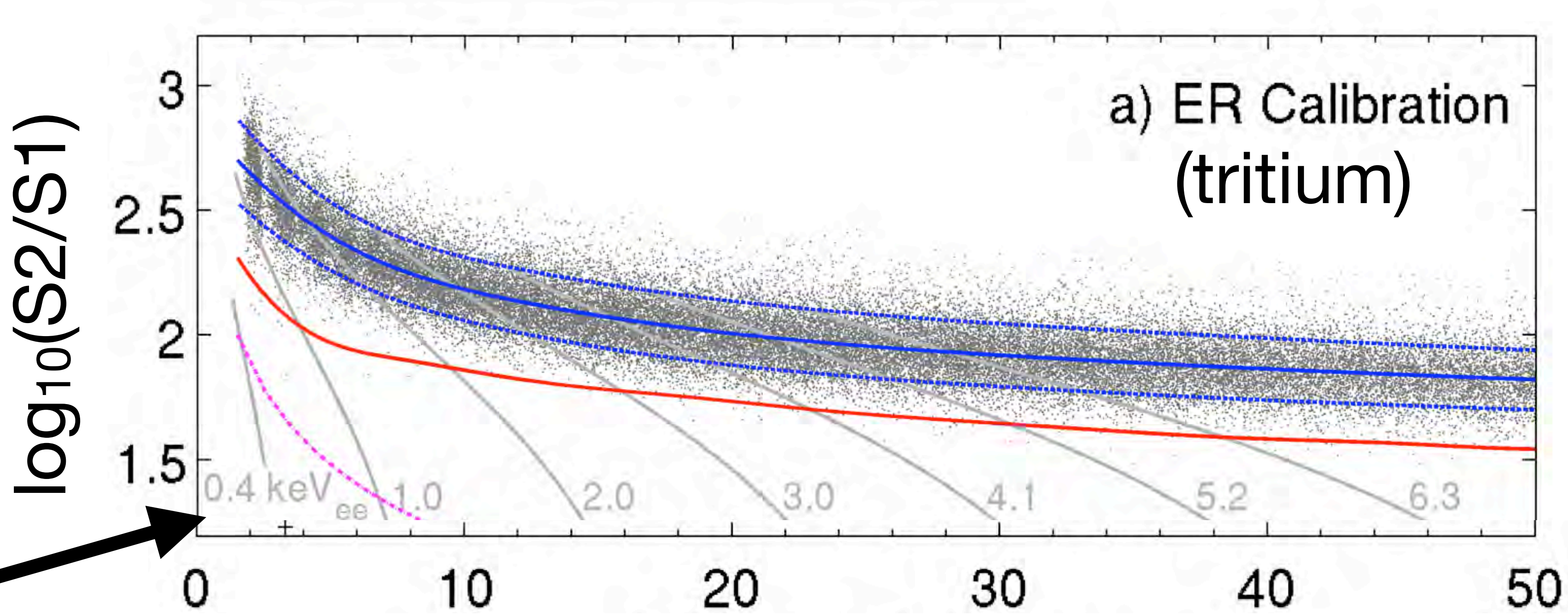
Maximum nuclear recoil energy: $E_{\mathrm{R}}^{\max} \approx 0.1~\mathrm{keV}$

$$\times\,(131/A)\,(m_{\mathrm{DM}}/1~\mathrm{GeV})^2$$

keV photons in LUX

$$\omega^{\max} \approx 3\,\mathrm{keV}\cdot(m_{\mathrm{DM}}/1\,\mathrm{GeV})$$

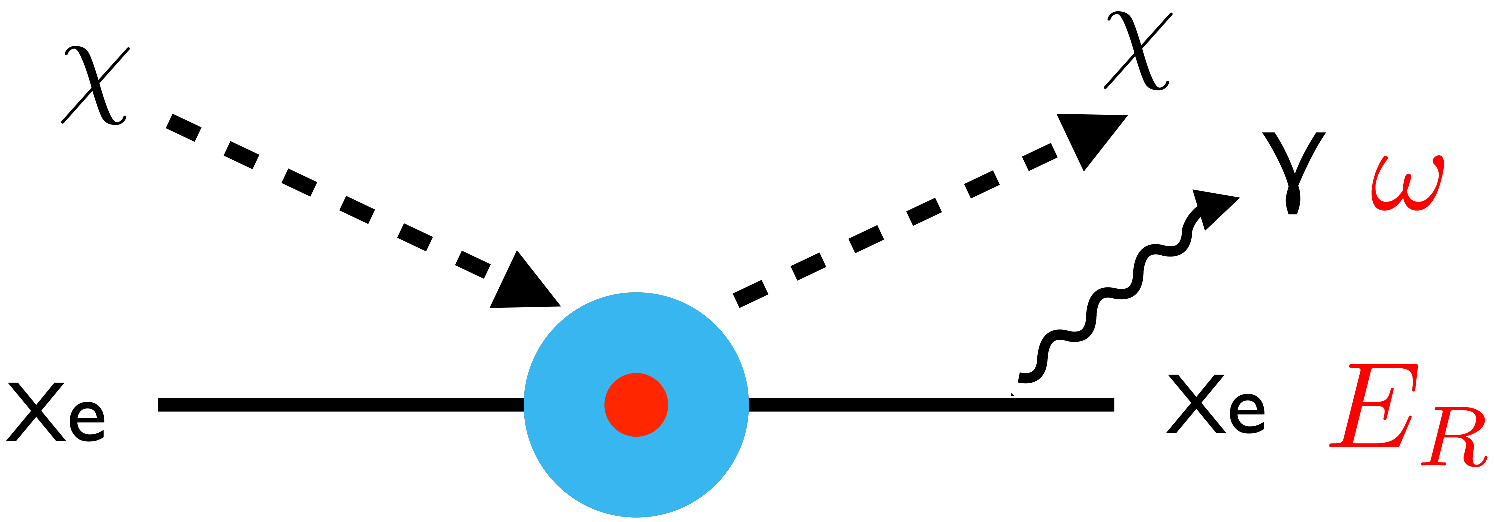




keV photons
will be detected

S1 (detected photons)

What’s the catch?

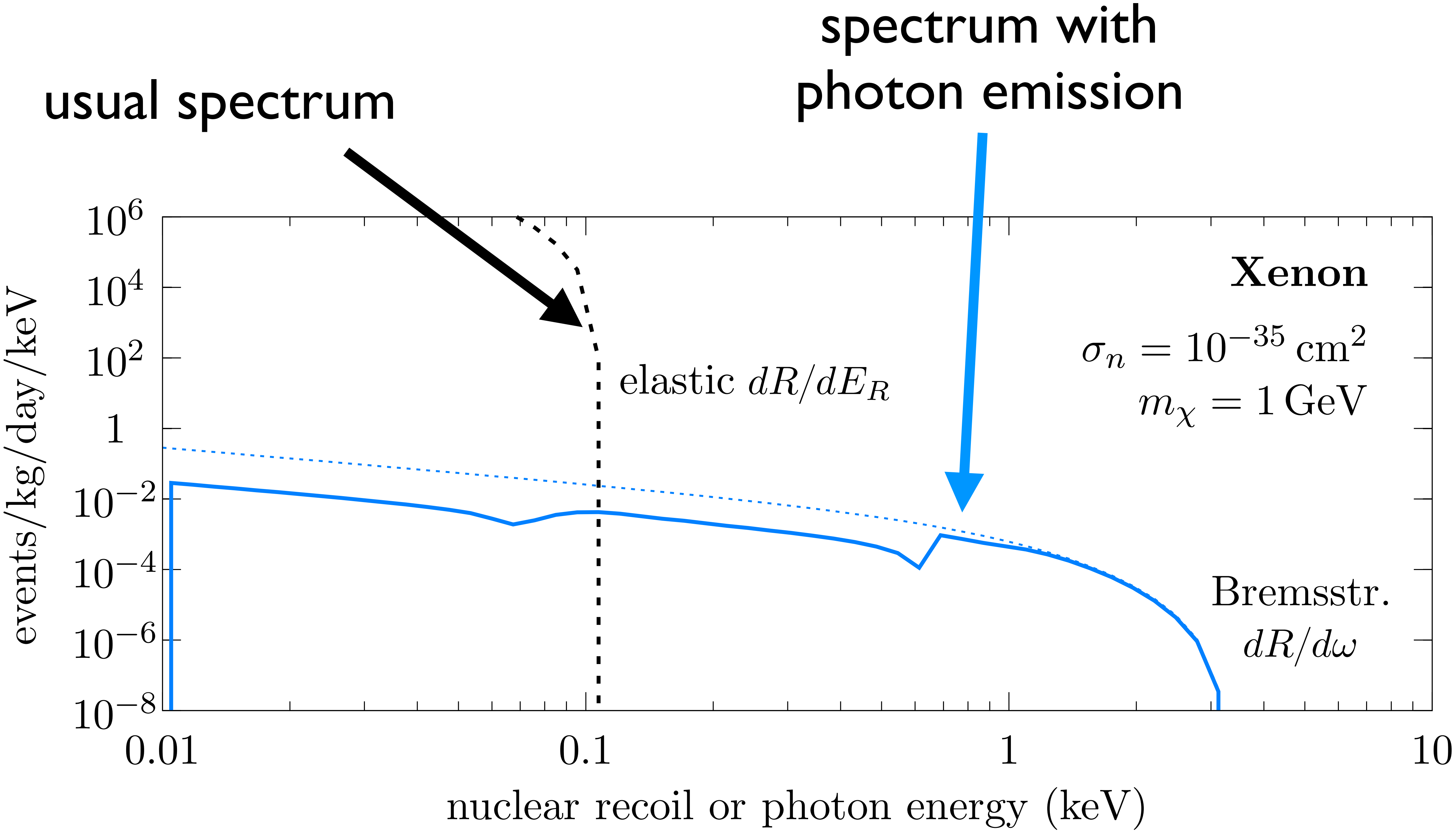


$$\frac{d\sigma}{dE_R d\omega} = \frac{4Z^2\alpha}{3\pi}\frac{1}{\omega}\frac{E_R}{m_N} \times \frac{d\sigma}{dE_R}\Theta(\omega - \omega_{\rm max})$$

Price to pay

$$\simeq \frac{7 \times 10^{-8}}{\omega}\left(\frac{E_R}{1\,\mathrm{keV}}\right) \times \frac{d\sigma}{dE_R} \quad \text{(Xenon)}$$

Energy spectrum


usual spectrum

spectrum with photon emission

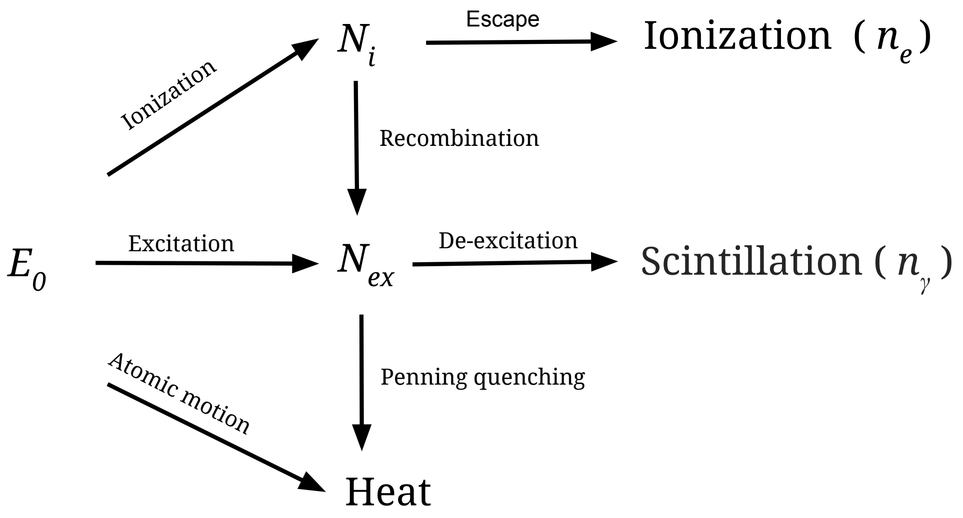
Setting limits with LUX

1. Calculate the number of expected events (the efficiency)
2. Calculate what they would observe in the S1-S2 plane

1. Expected number of events (efficiency)

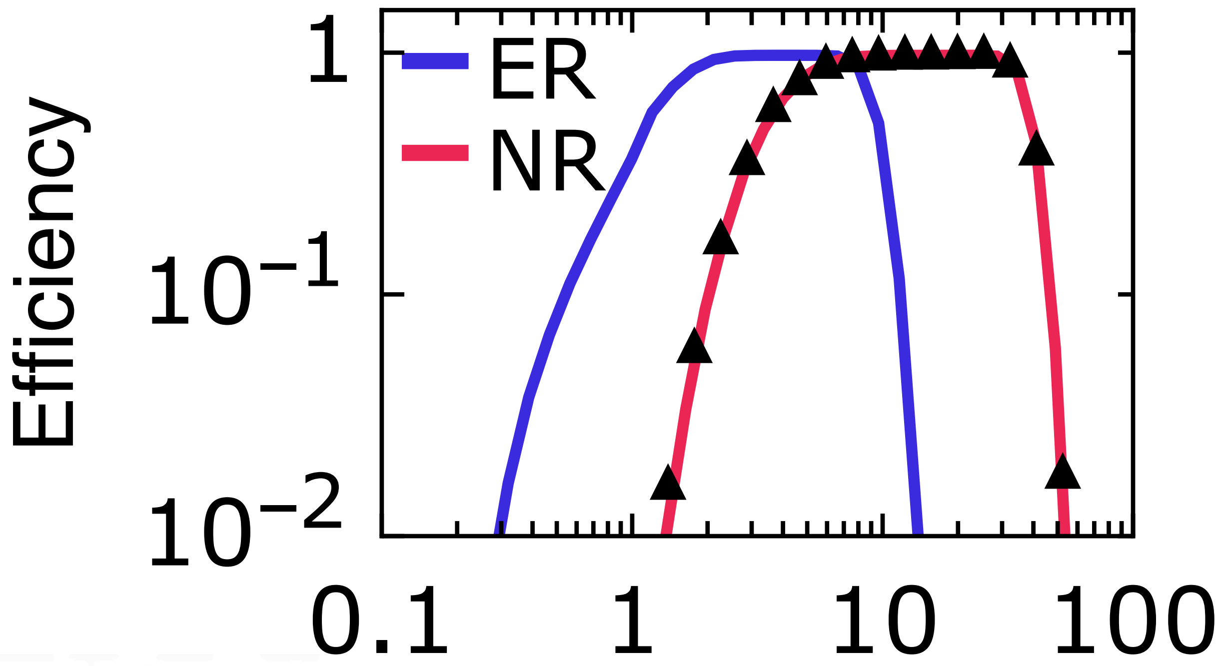
Detector response: Ask me afterwards…

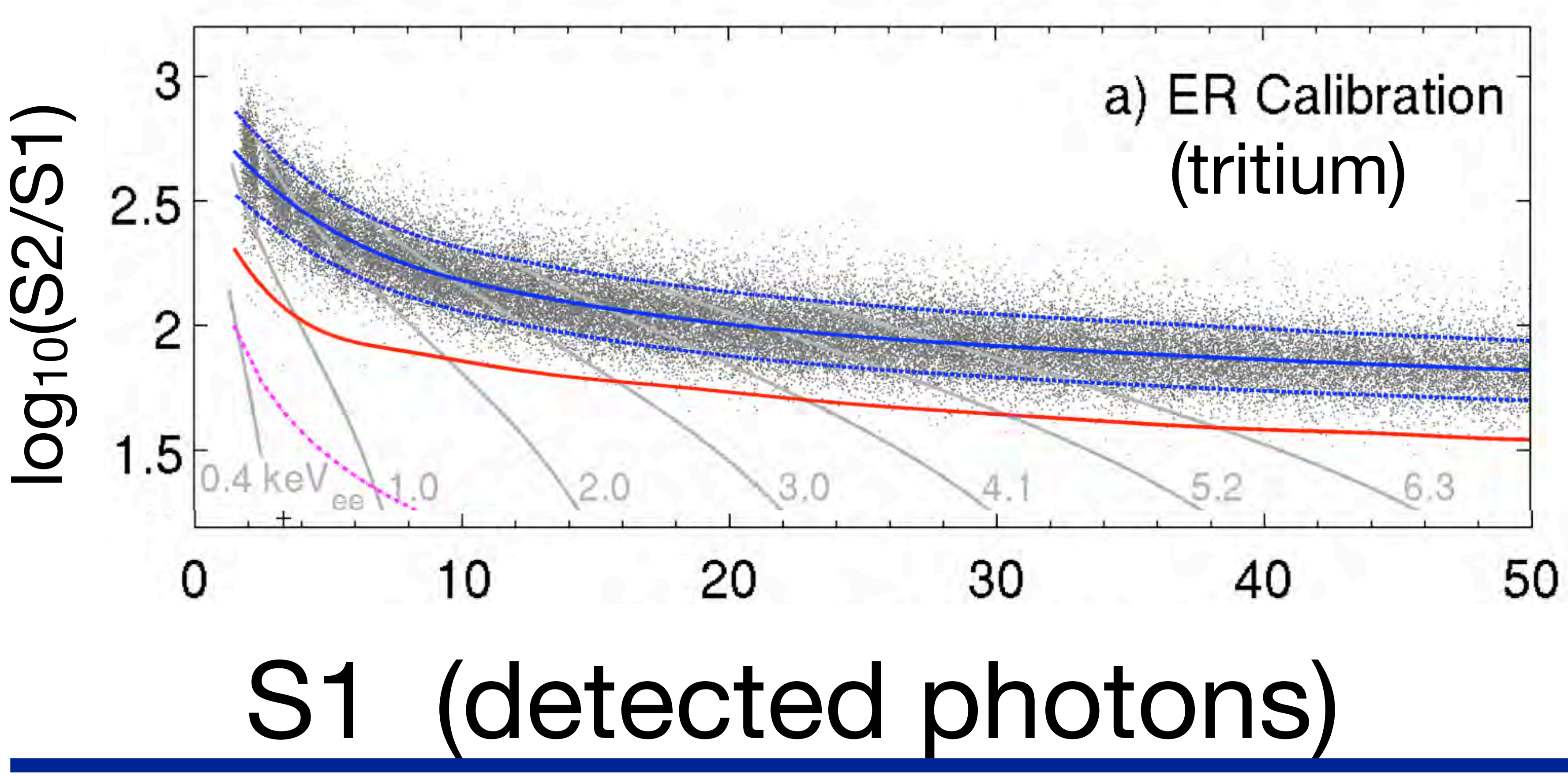
Nuclear recoil energy transferred to photons, electrons or heat



I. Expected number of events (efficiency)

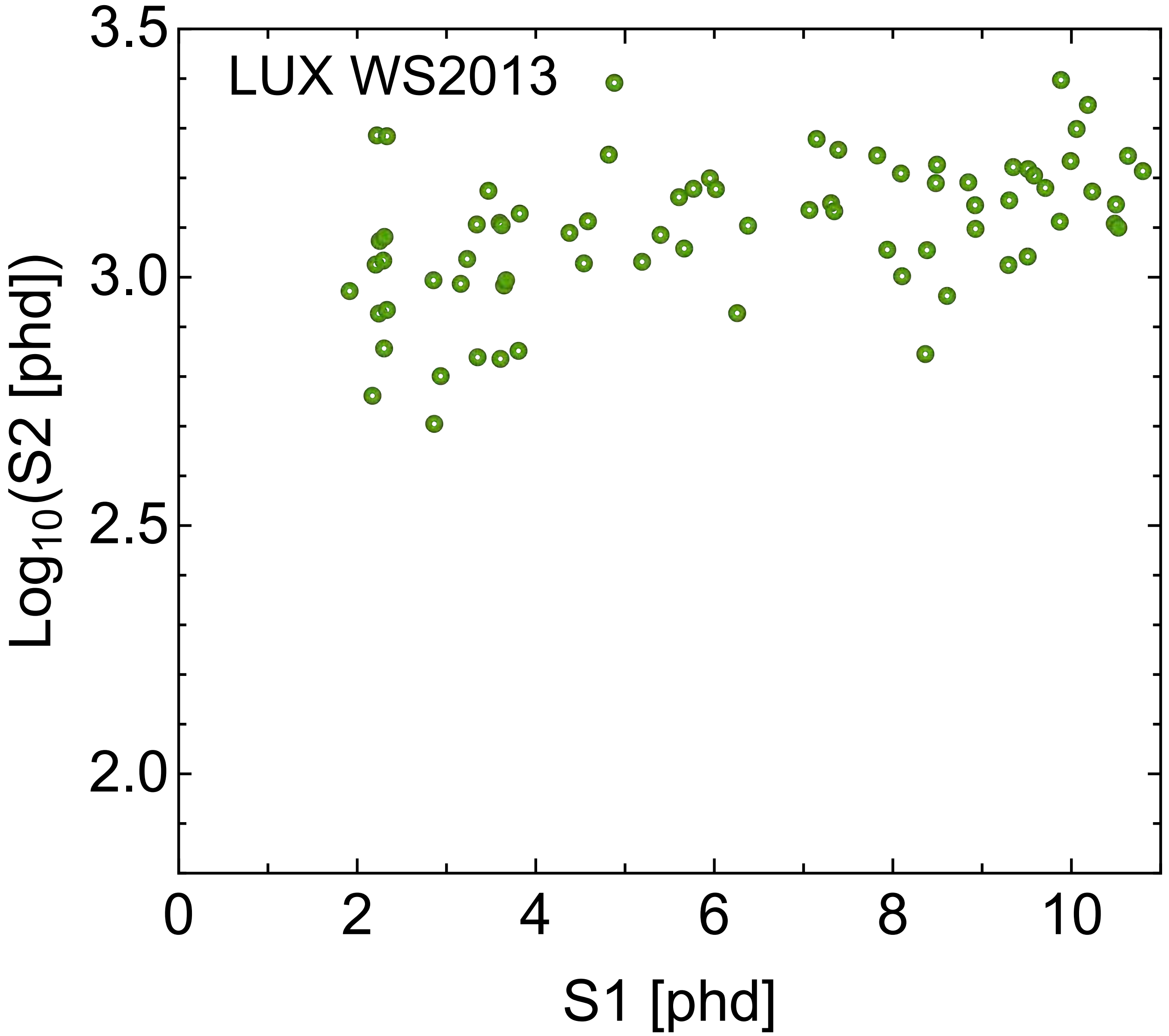
$$\omega^{\mathrm{max}} \approx 3\,\mathrm{keV}\cdot(m_{\mathrm{DM}}/1\ \mathrm{GeV})$$





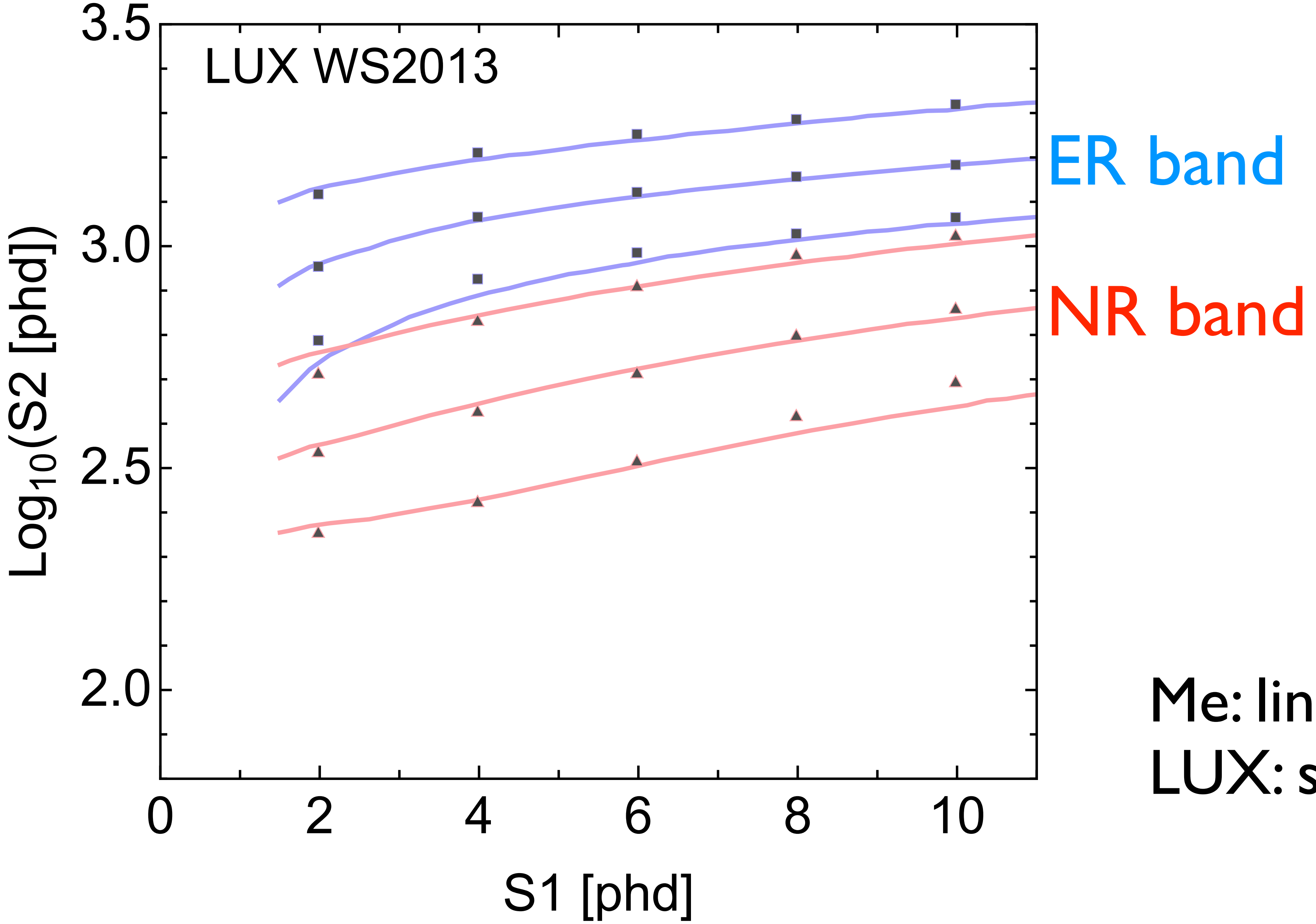
2. Signal in the S1-S2 plane

What LUX measured:



2. Calculate what they would observe in the S1-S2 plane

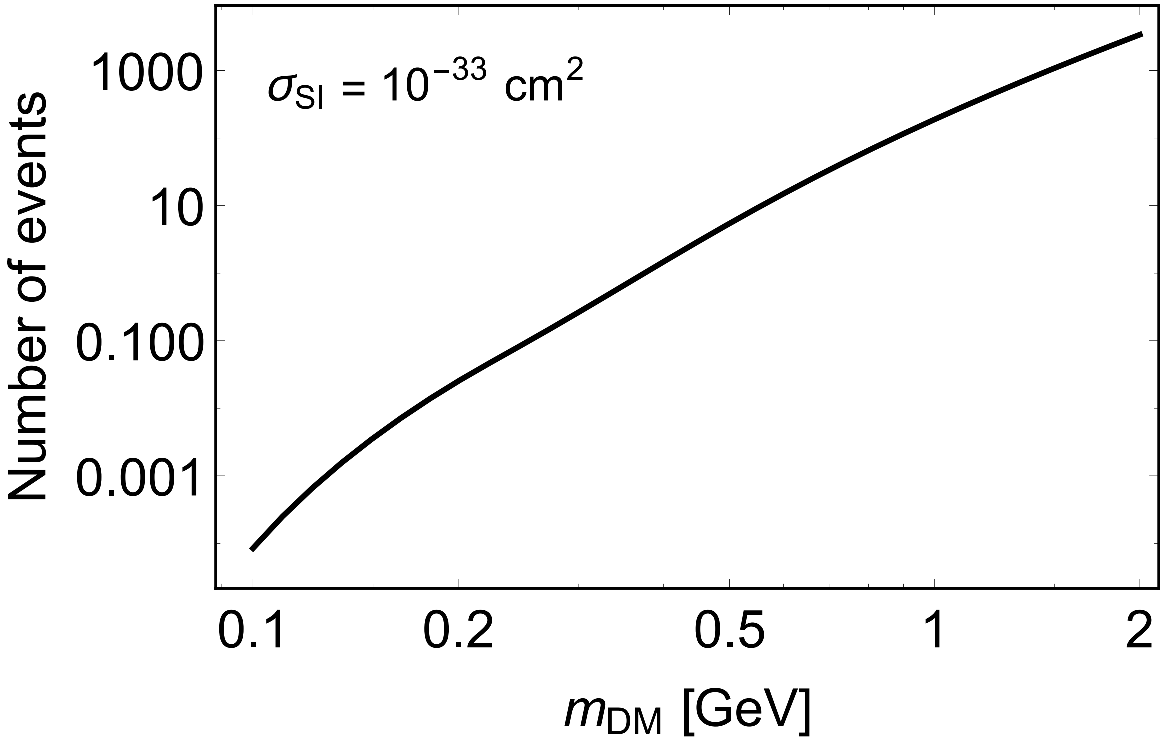
Reproduce ER and NR bands:

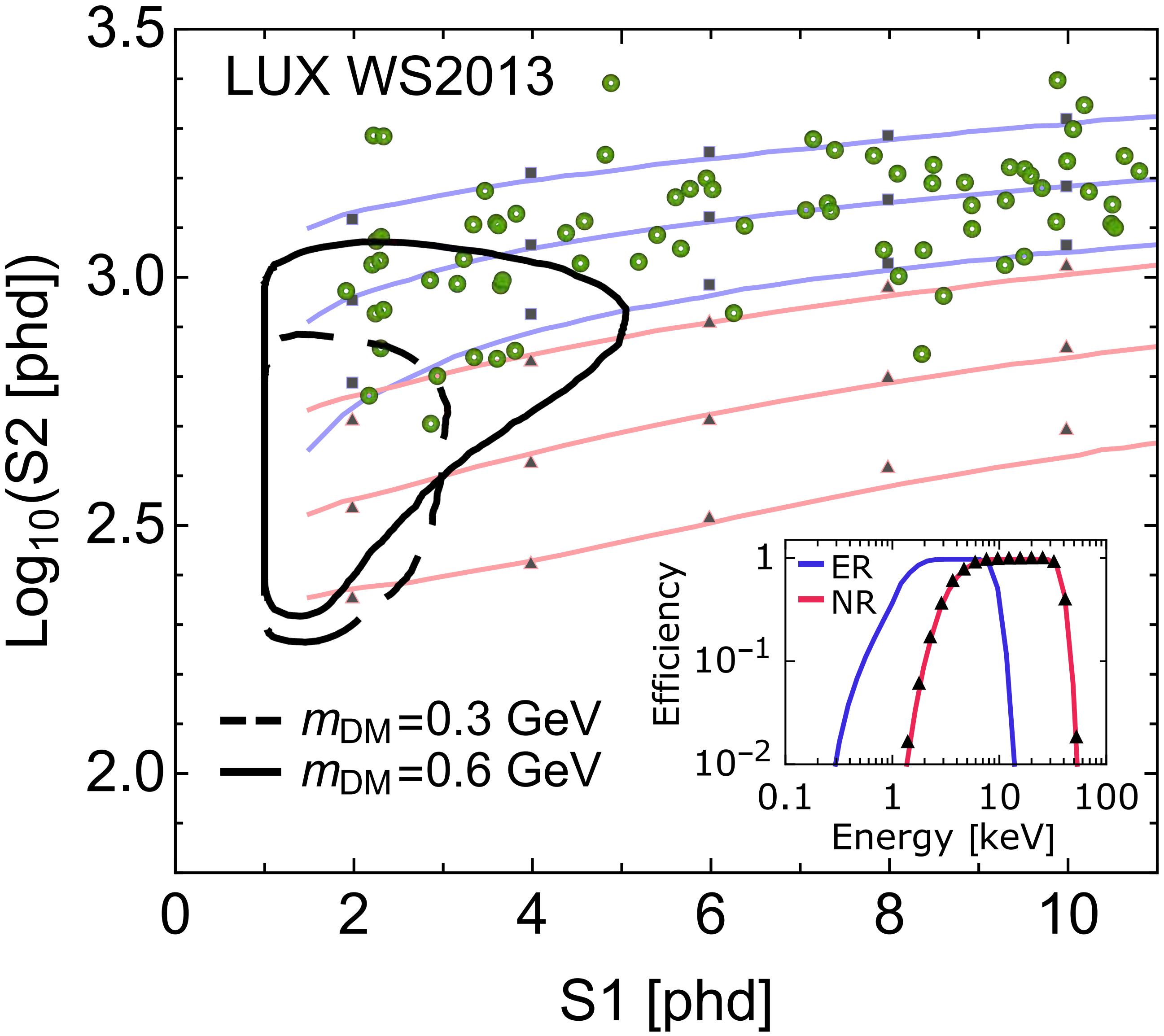


Me: lines
LUX: squares/triangles

2. Calculate what they would observe in the S1-S2 plane

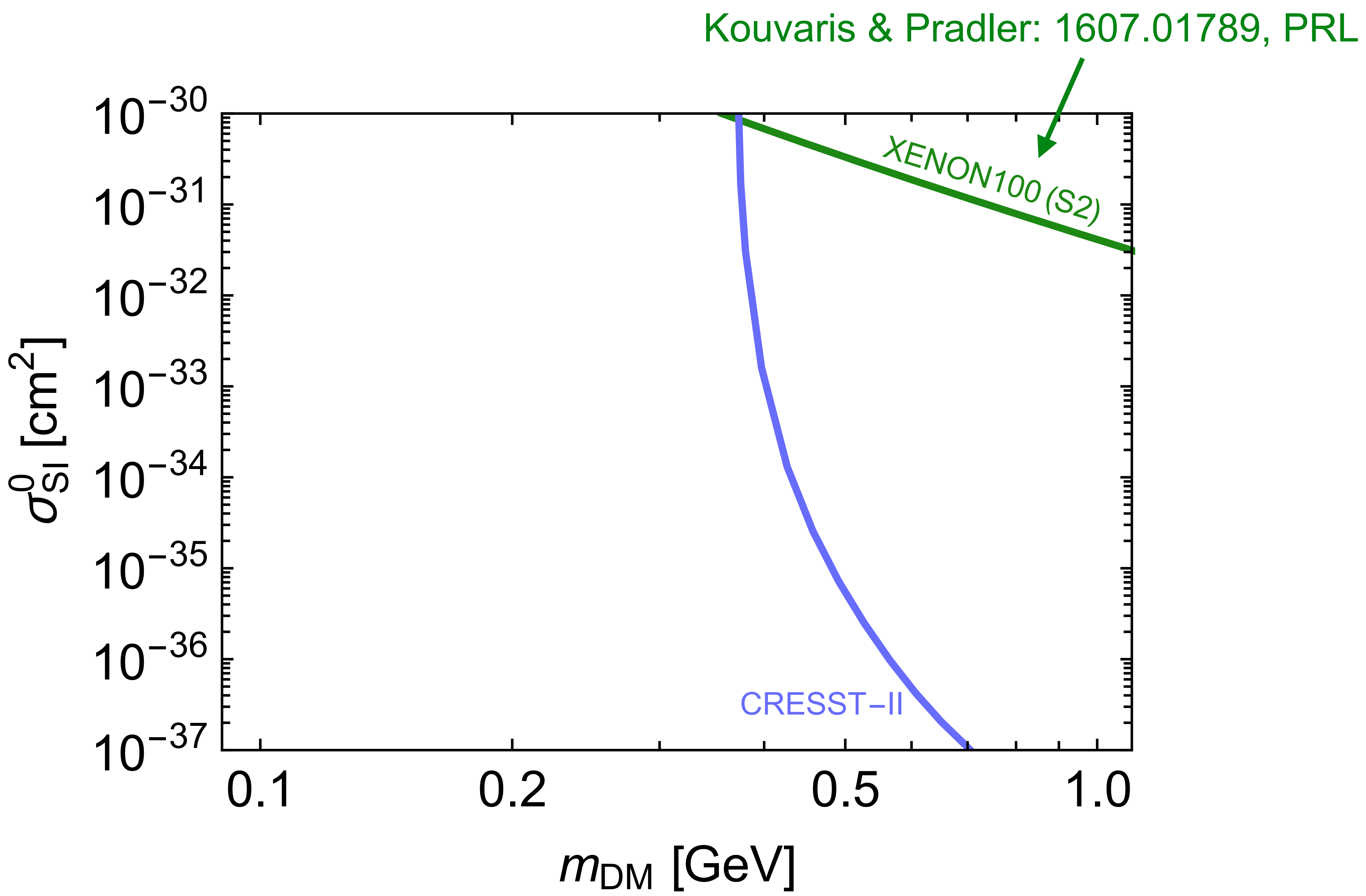
All together:



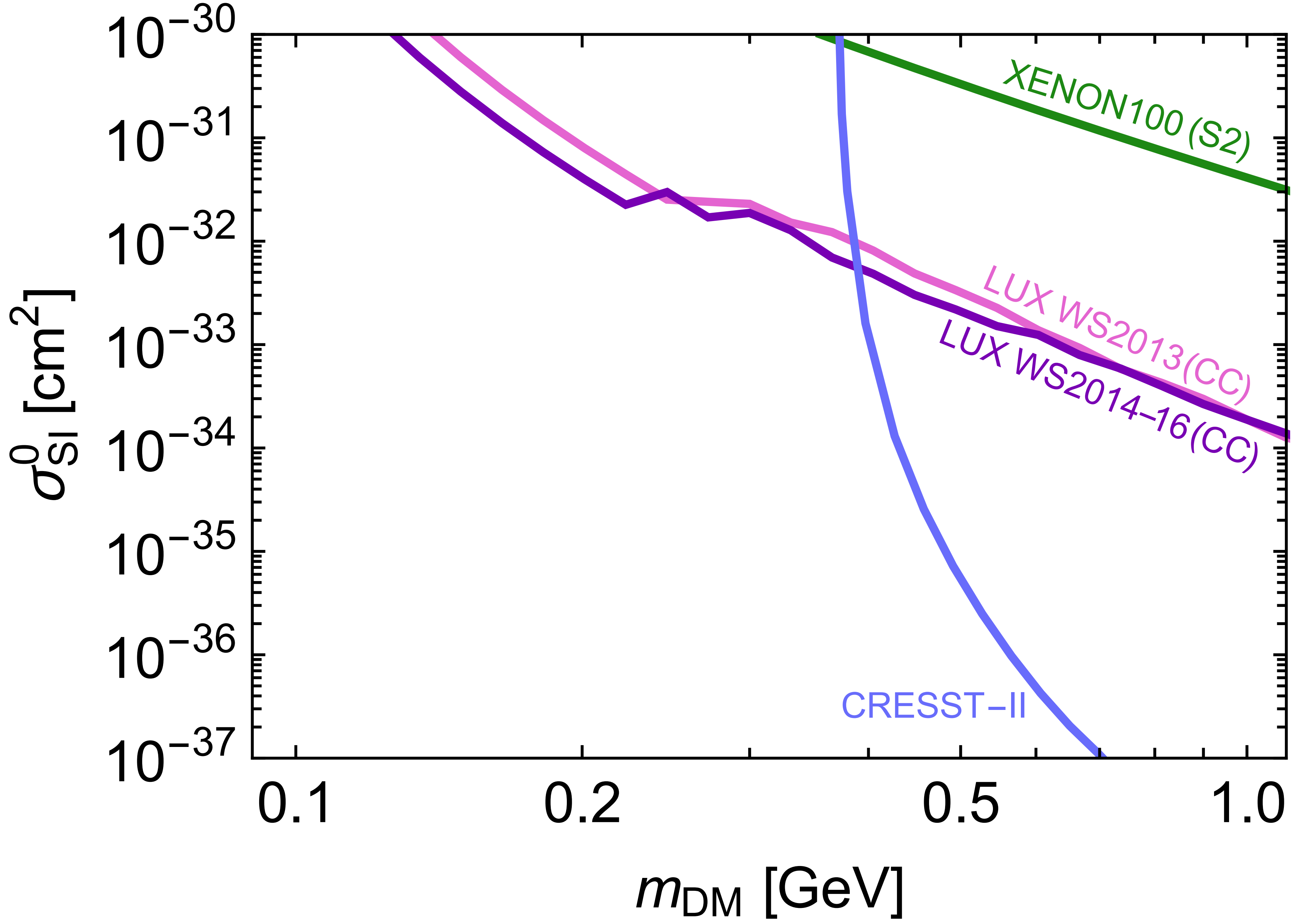


Constraints

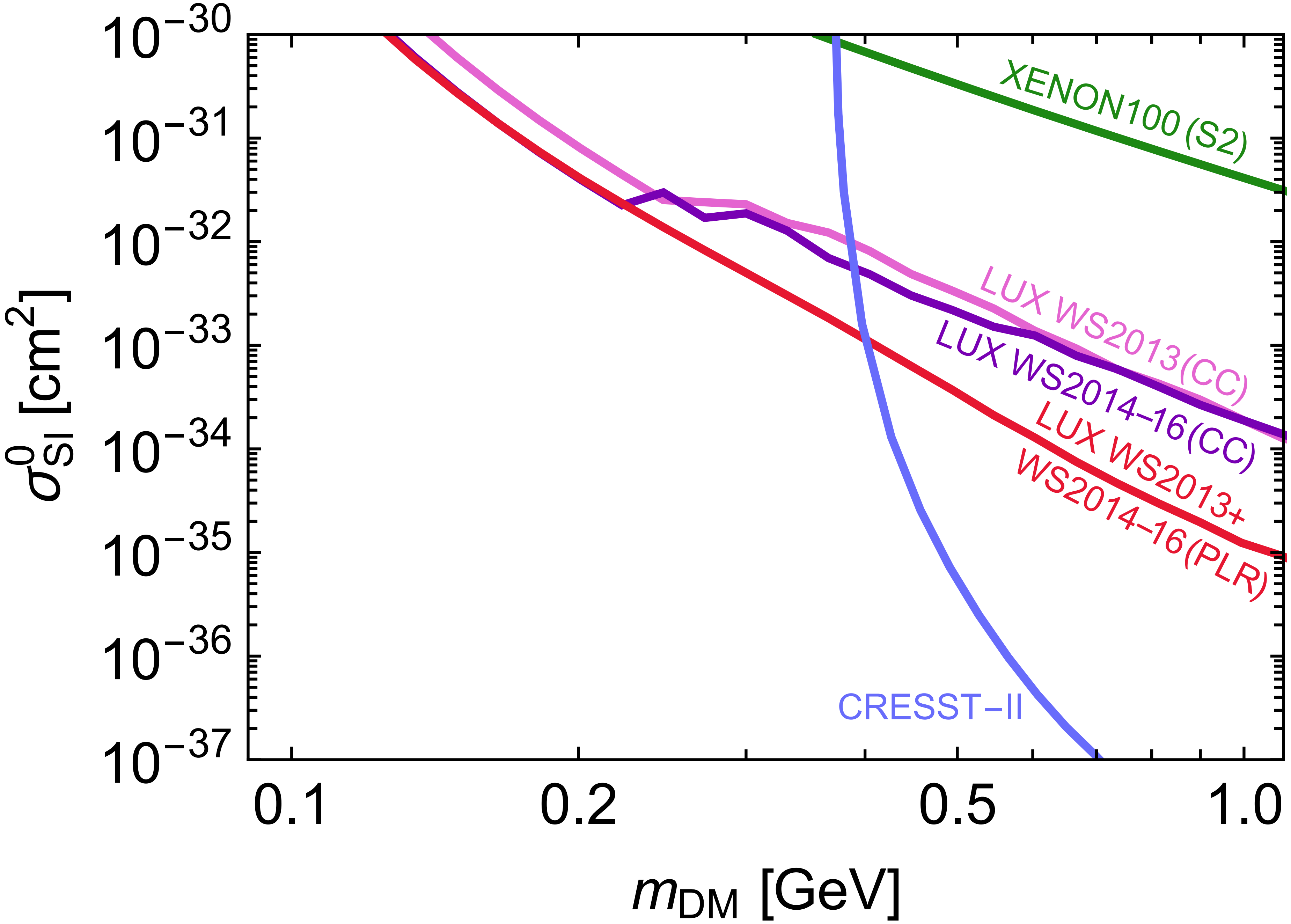
Kouvaris & Pradler: 1607.01789, PRL



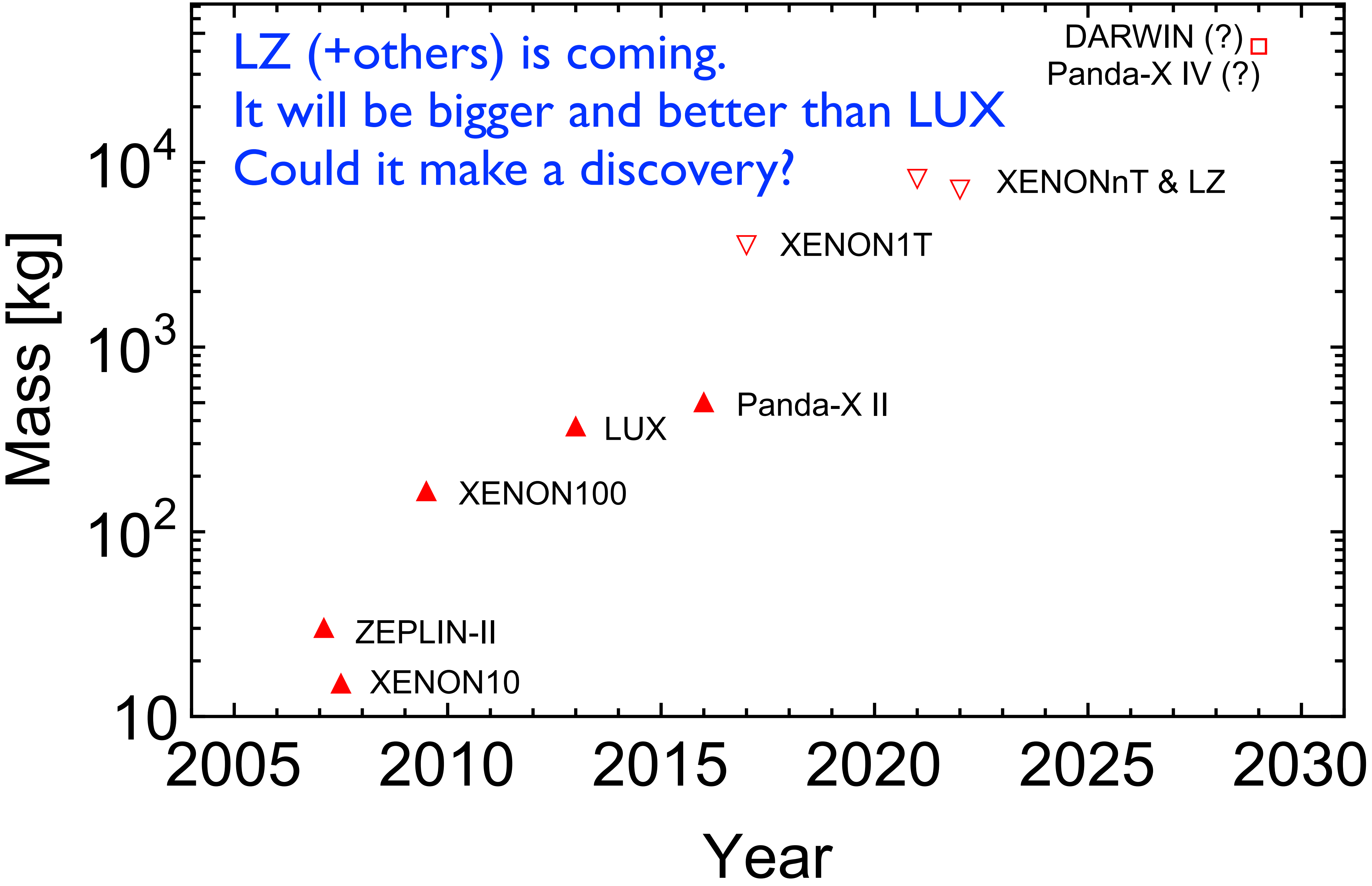
Constraints



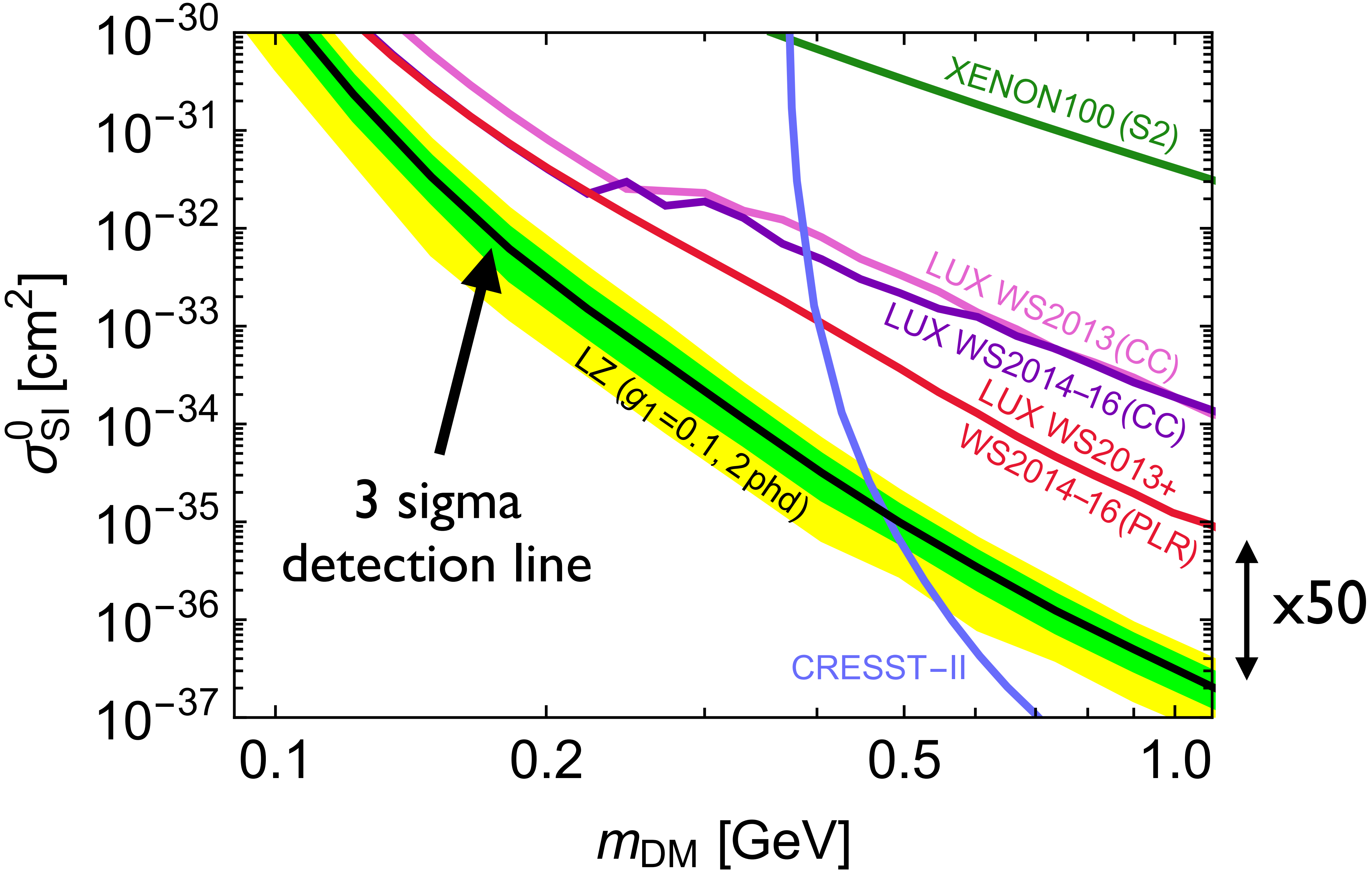
Constraints



Discovery potential


LZ (+others) is coming.
It will be bigger and better than LUX
Could it make a discovery?

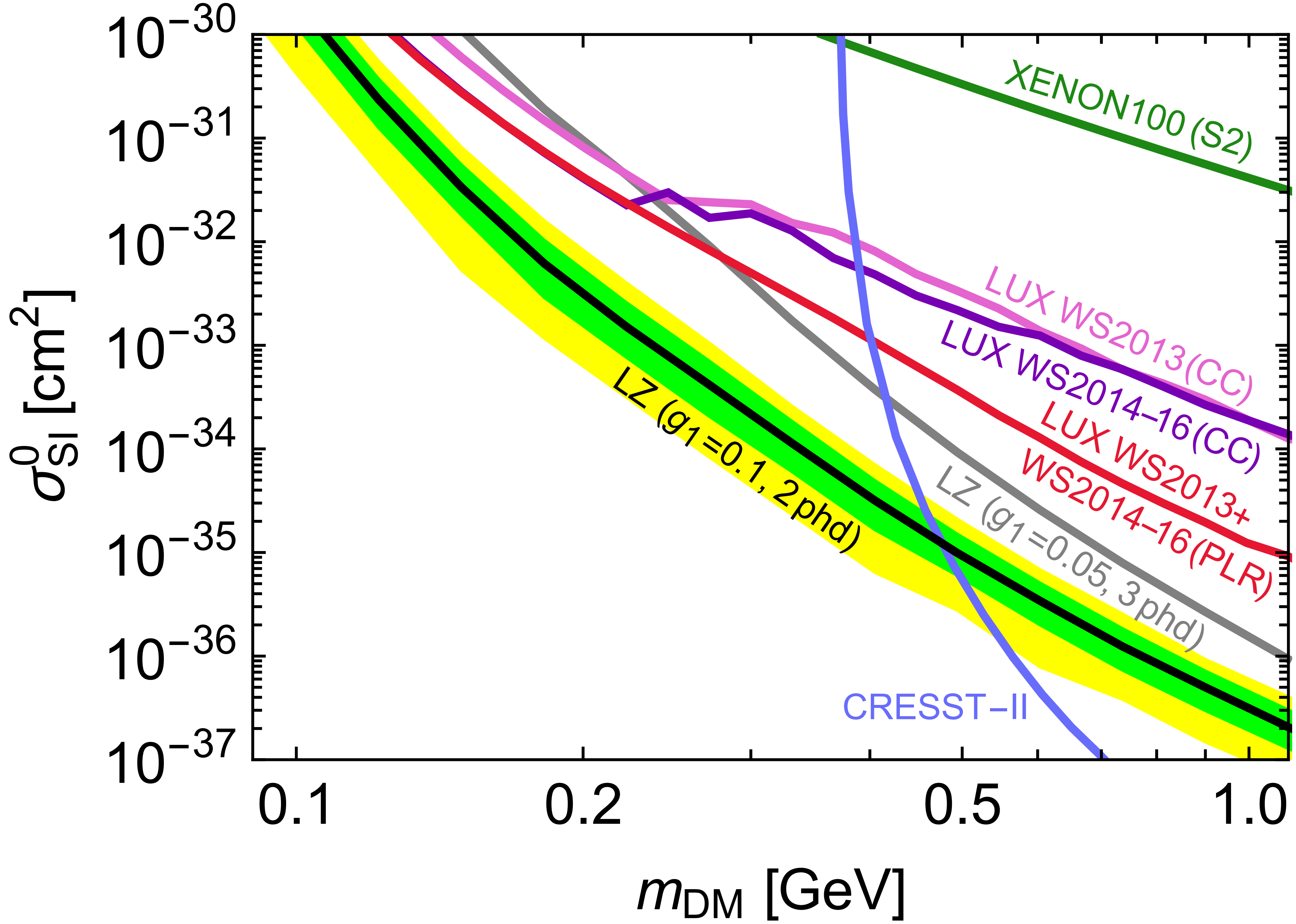
Discovery potential



3 sigma detection line

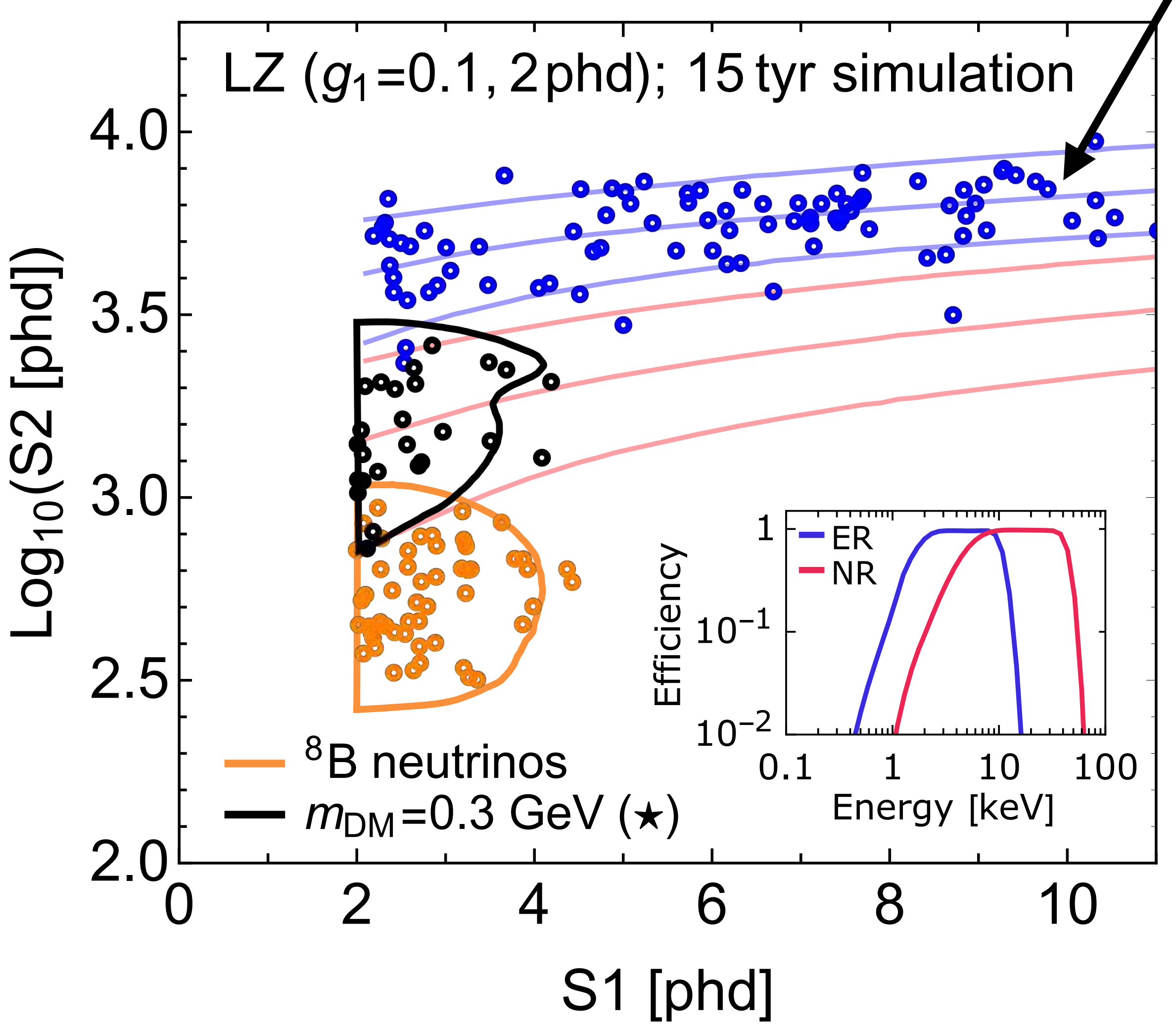
x50

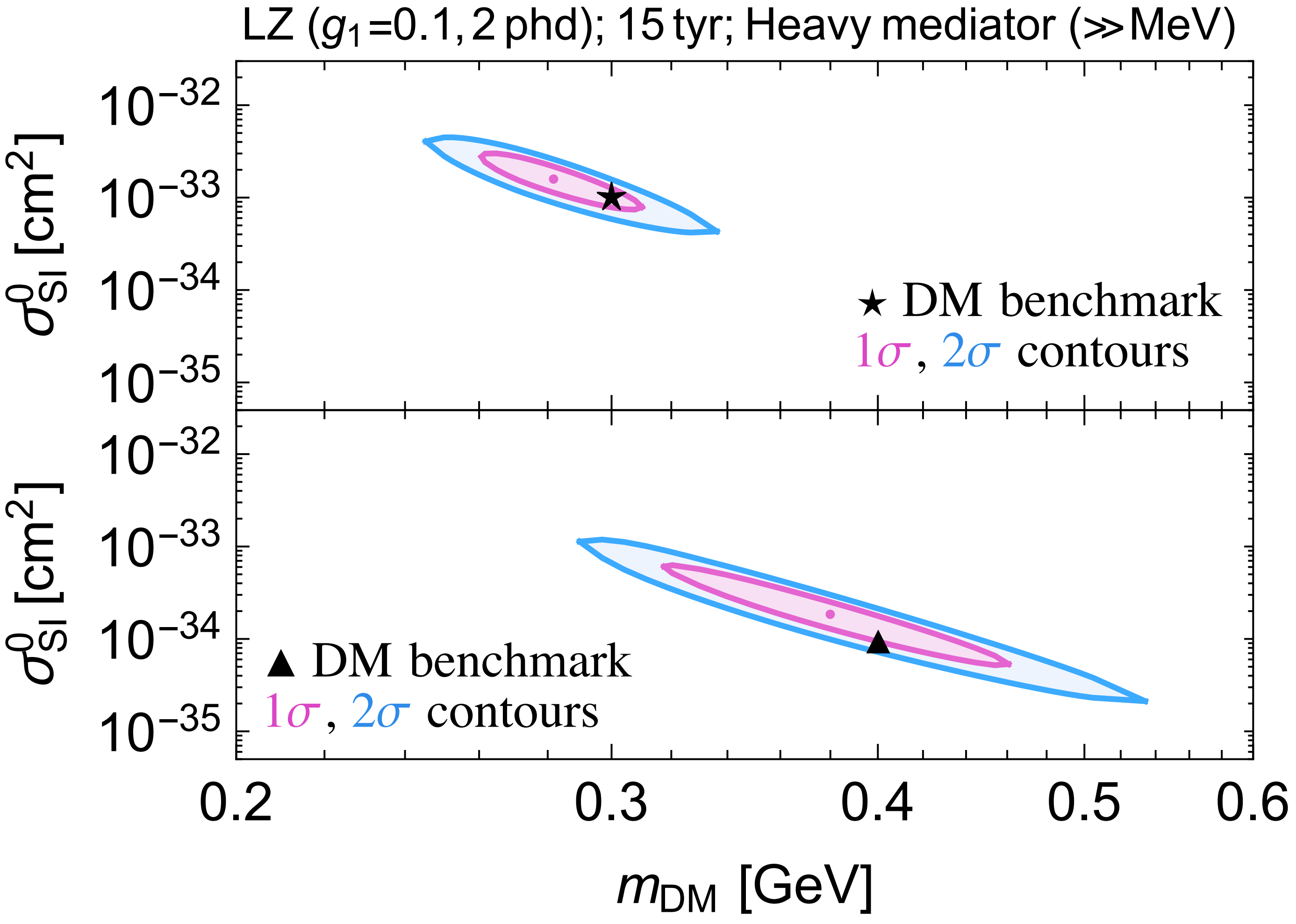
Discovery potential



Discovery potential

events from pp neutrinos





The parameters of sub-GeV DM can be reconstructed!

Summary

Xenon detectors are getting bigger
Our understanding of them is getting better

↓

Opportunities to search for (discover !) new signals

1. Nuclear recoils: supernova neutrinos
2. Electronic recoils: sub-GeV dark matter

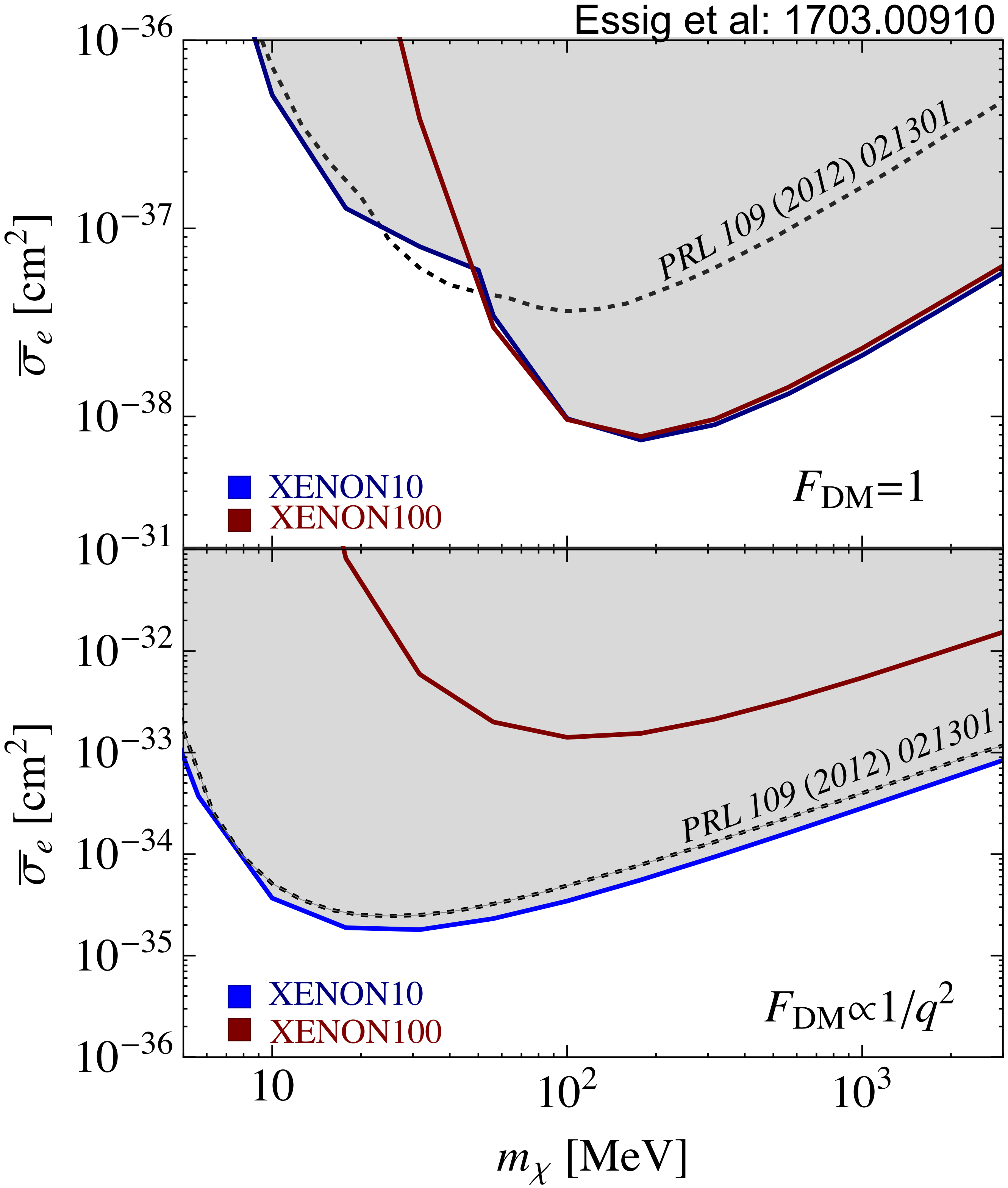
Are there others?

Thank you

Backup

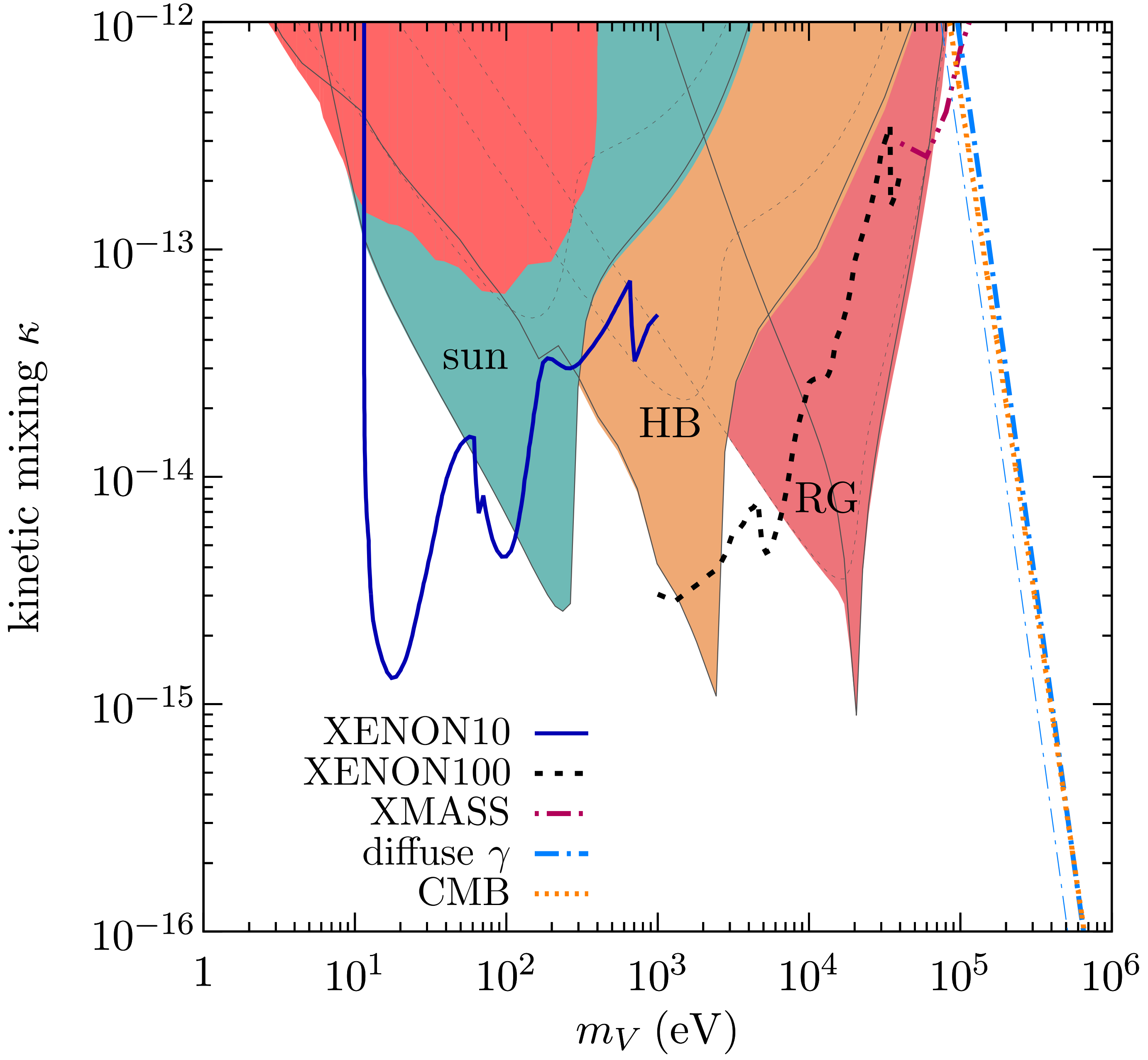
Backup: sub-GeV DM

Other ideas: electron scattering



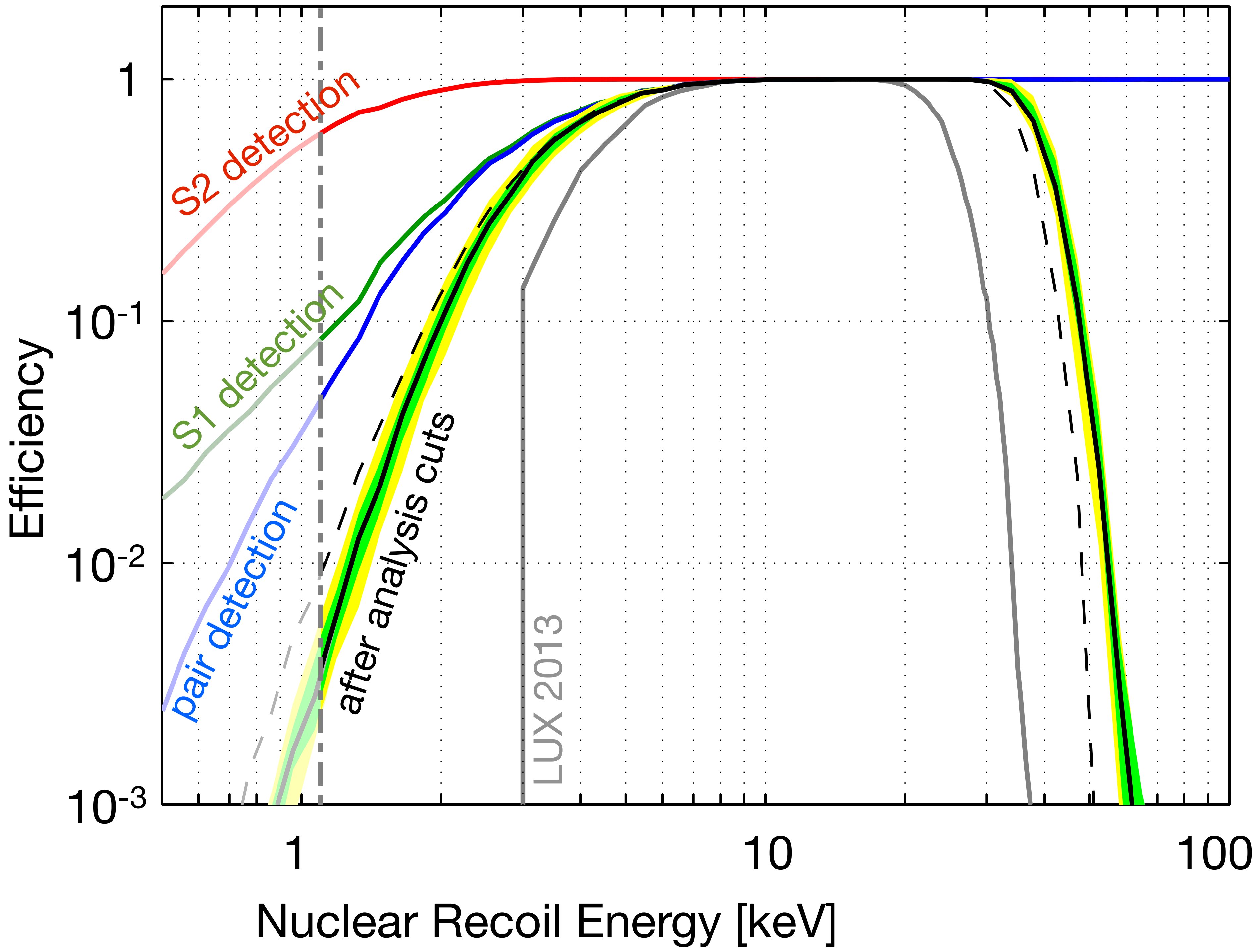
Other ideas: absorption

An et al: 1412.8378



S2 efficiency: order of magnitude higher

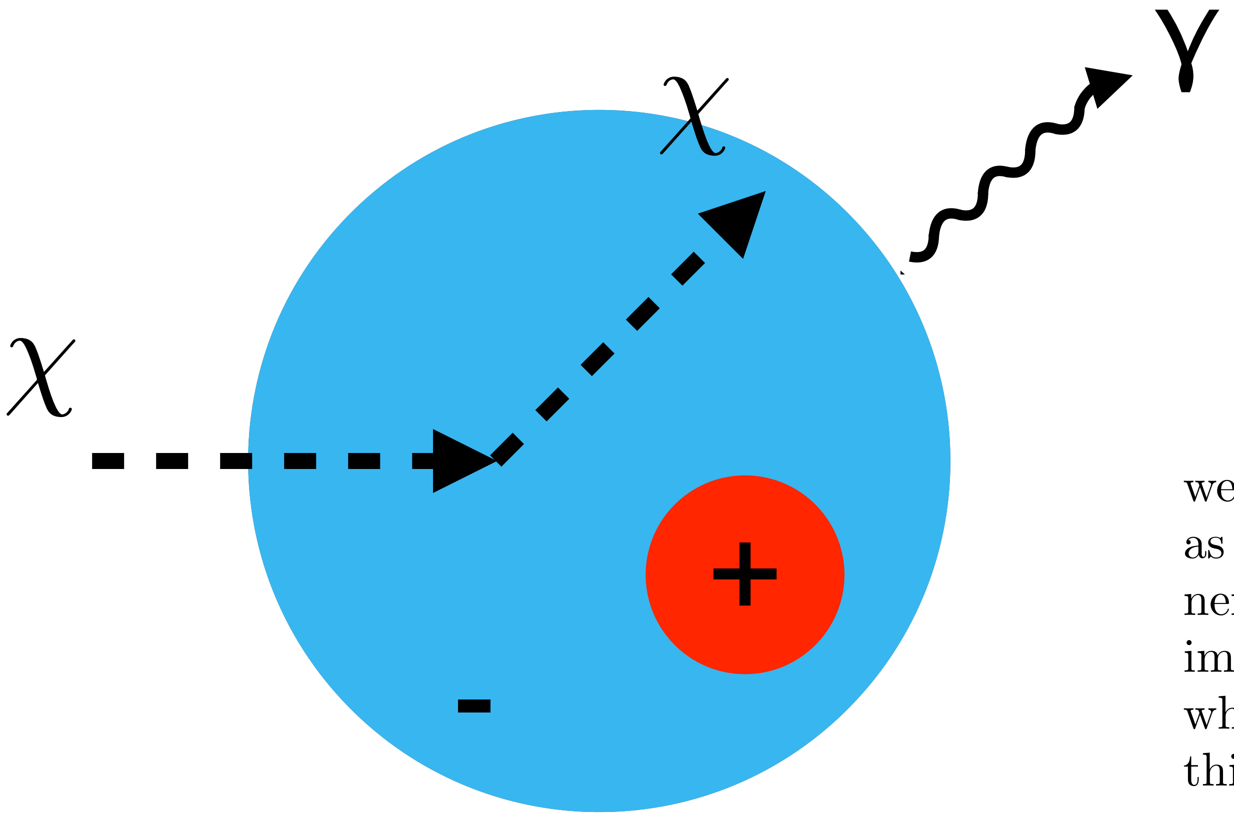
LUX 2013 reanalysis efficiencies



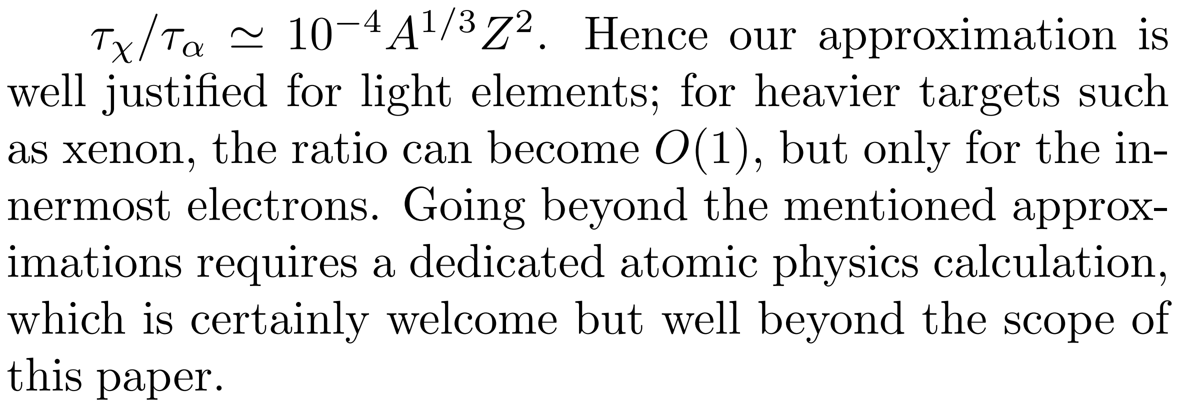
A new idea: assumptions

Kouvaris & Pradler: 1607.01789, PRL

- Nucleus kick instantaneous (on time scale for electrons in orbit to adjust to the perturbation τ_α)



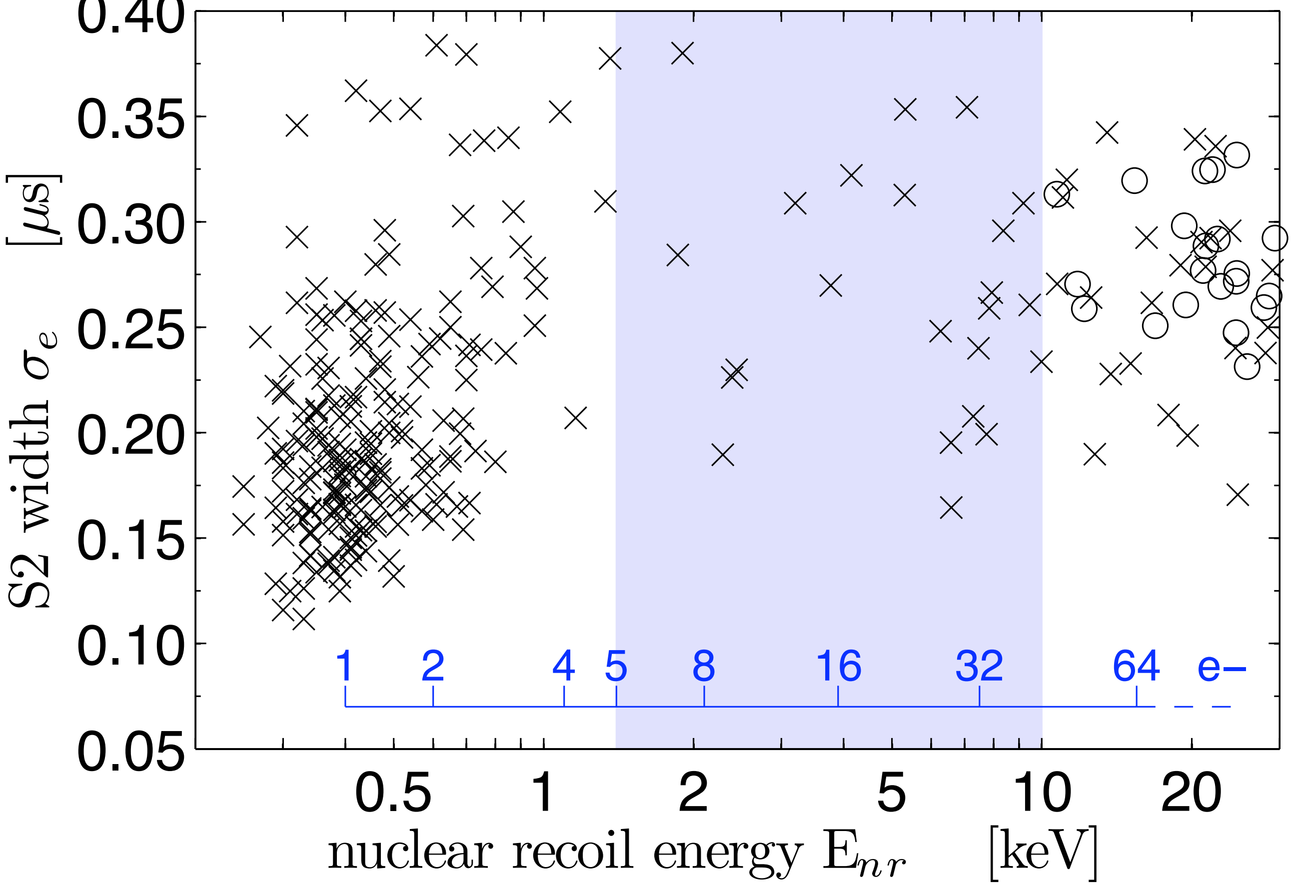
Polarised atom
emits a photon

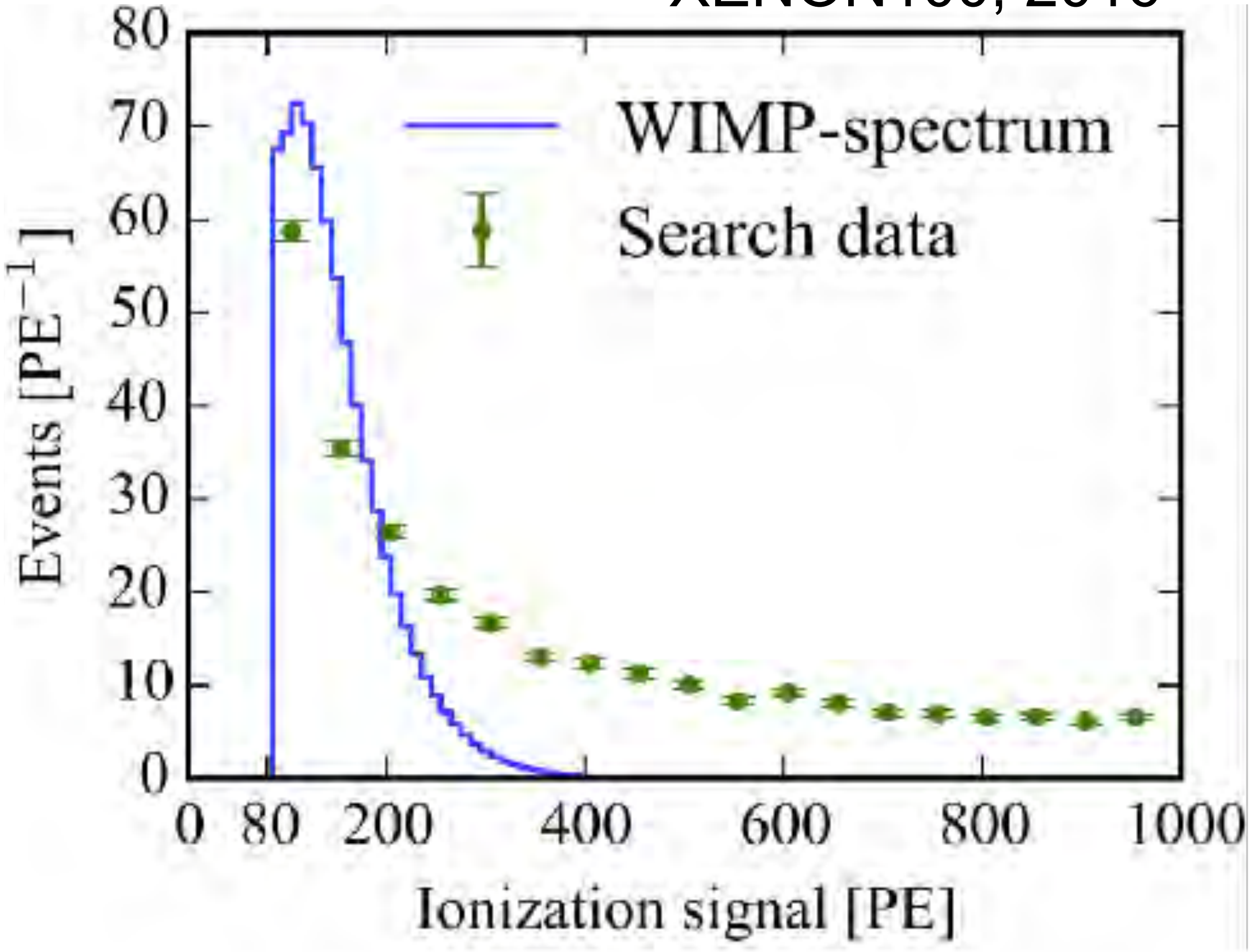


$\tau_\chi/\tau_\alpha \simeq 10^{-4}A^{1/3}Z^2$. Hence our approximation is well justified for light elements; for heavier targets such as xenon, the ratio can become $O(1)$, but only for the innermost electrons. Going beyond the mentioned approximations requires a dedicated atomic physics calculation, which is certainly welcome but well beyond the scope of this paper.

XENON10 & XENON100: S2-only

Kouvaris & Pradler set constraints with S2-only analyses

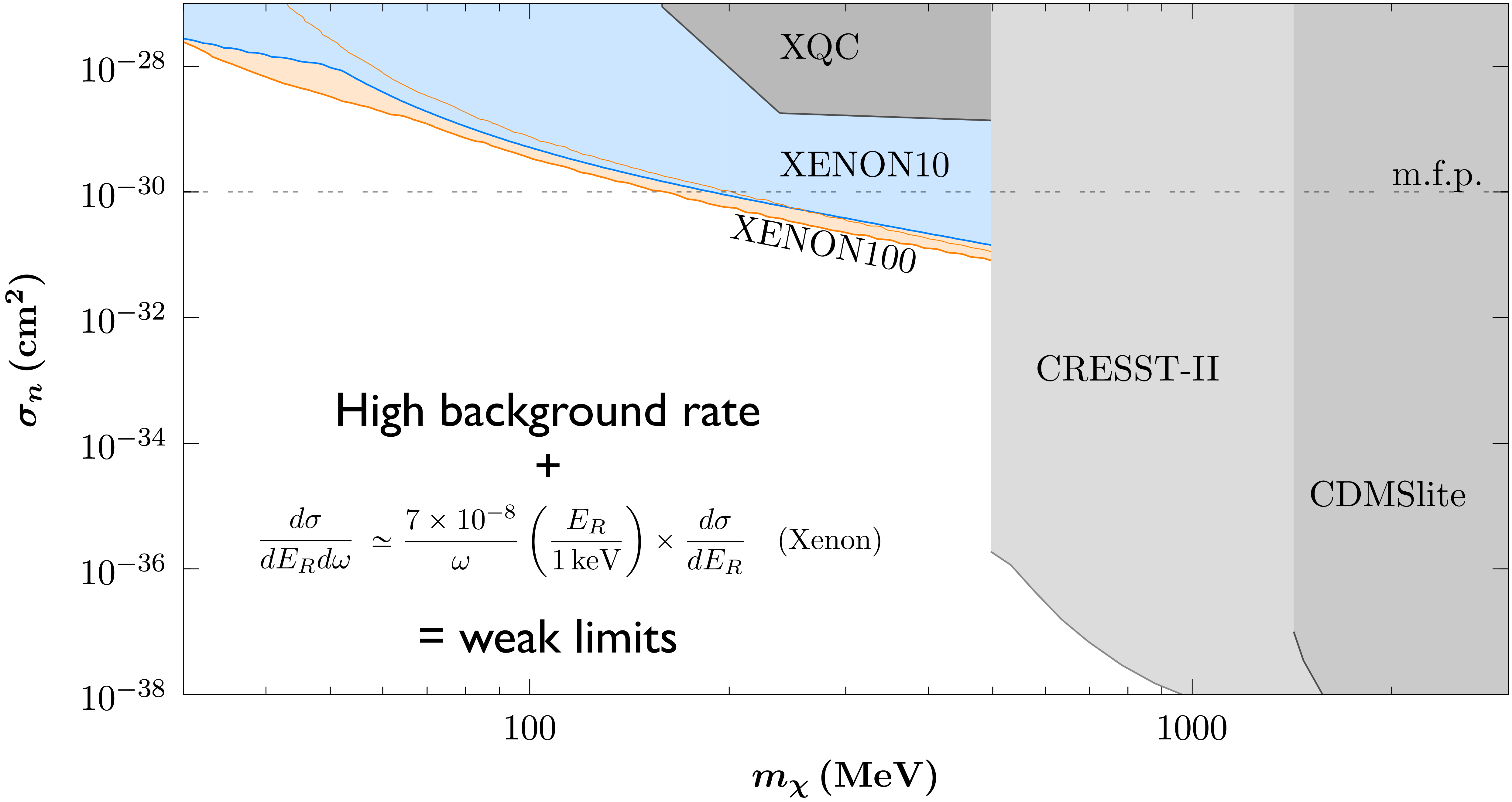

XENON10, 2011


XENON100, 2016

Very high event rates - XENON100 has ~13000 events

XENON10 & XENON100: S2-only

Kouvaris & Pradler set constraints with S2-only analyses



High background rate

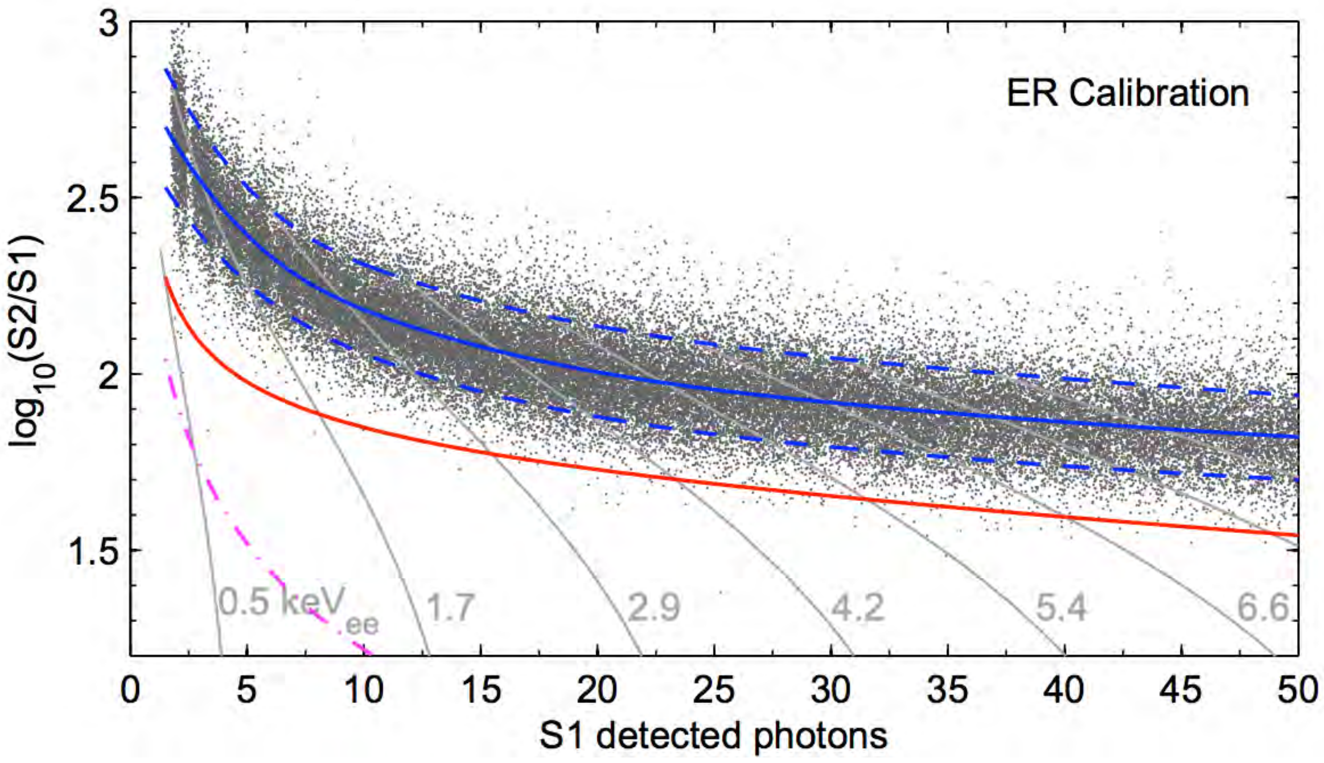
+

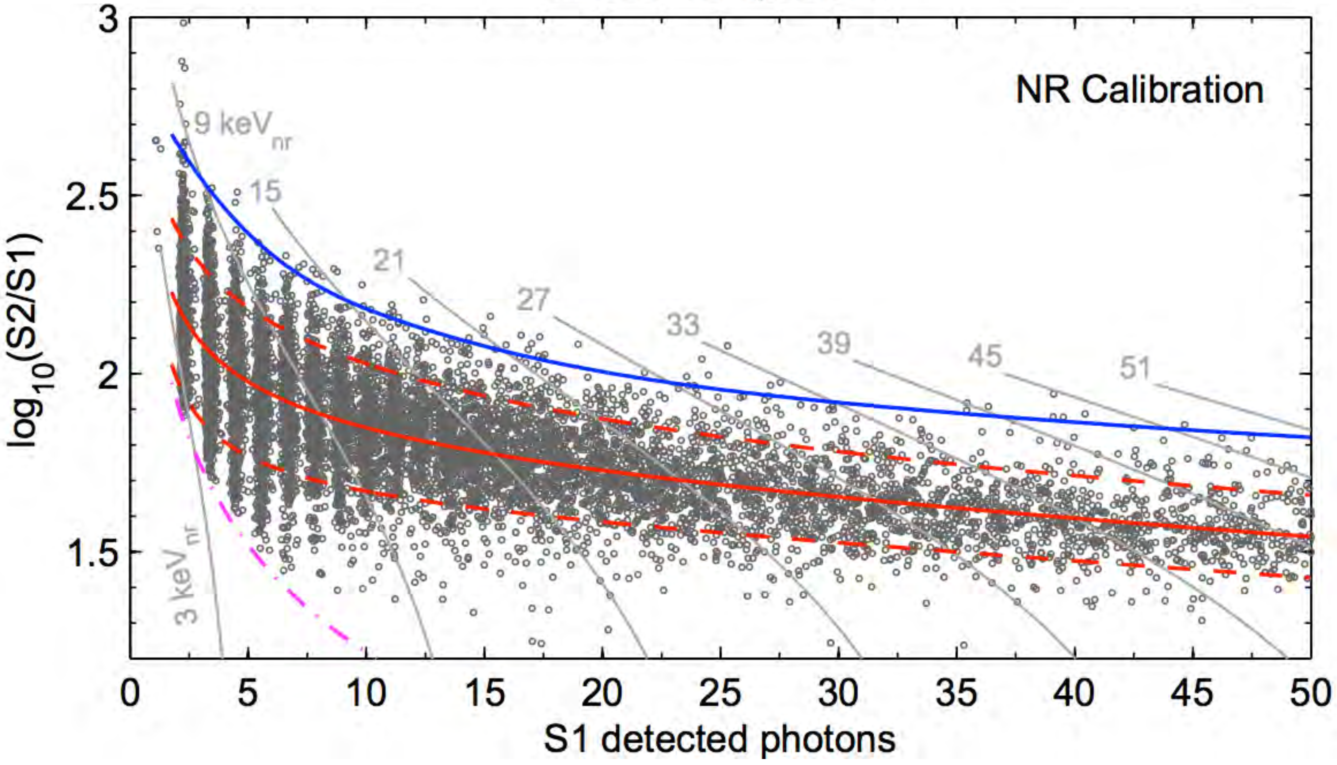
$$\frac{d\sigma}{dE_R d\omega} \simeq \frac{7 \times 10^{-8}}{\omega} \left(\frac{E_R}{1\,\mathrm{keV}}\right) \times \frac{d\sigma}{dE_R} \quad \text{(Xenon)}$$

= weak limits

Dual-phase detectors

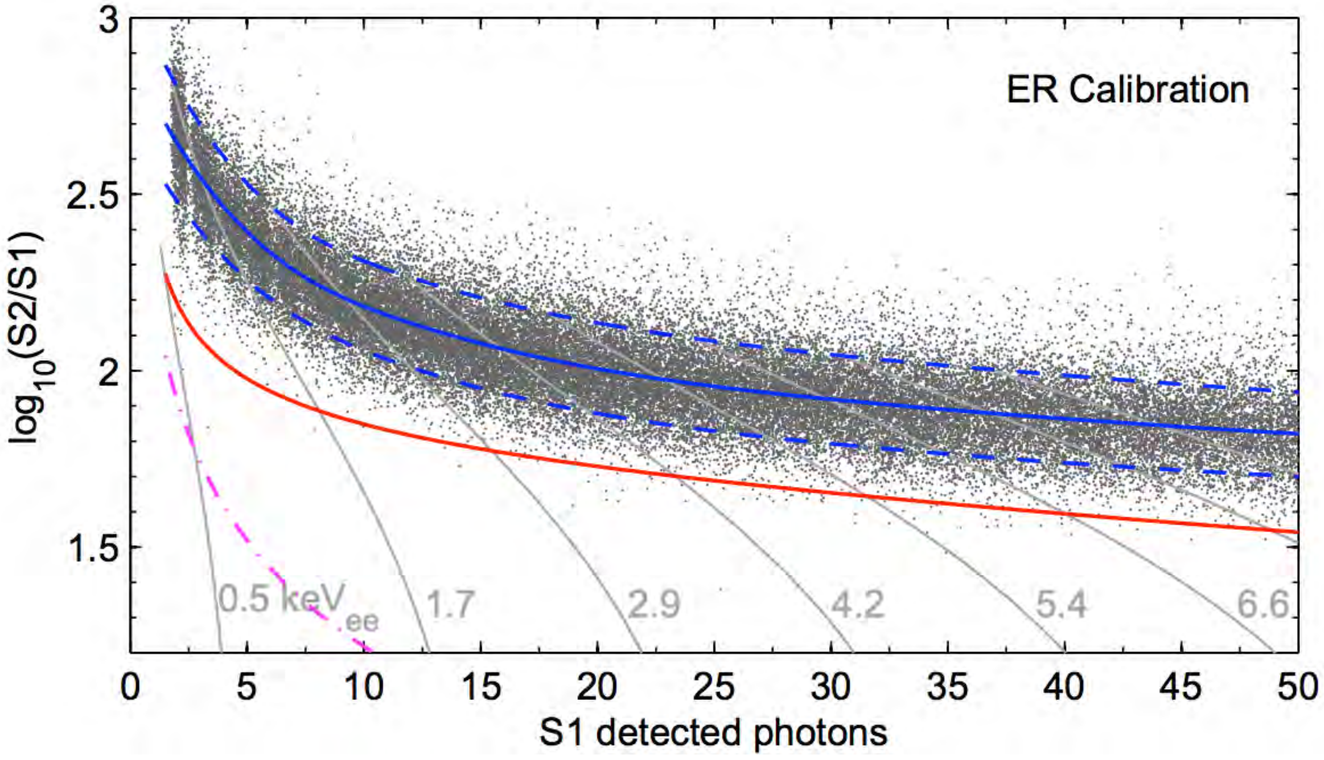
Easy to characterise:
NR events lie in the NR band
and
ER events lie in the ER band

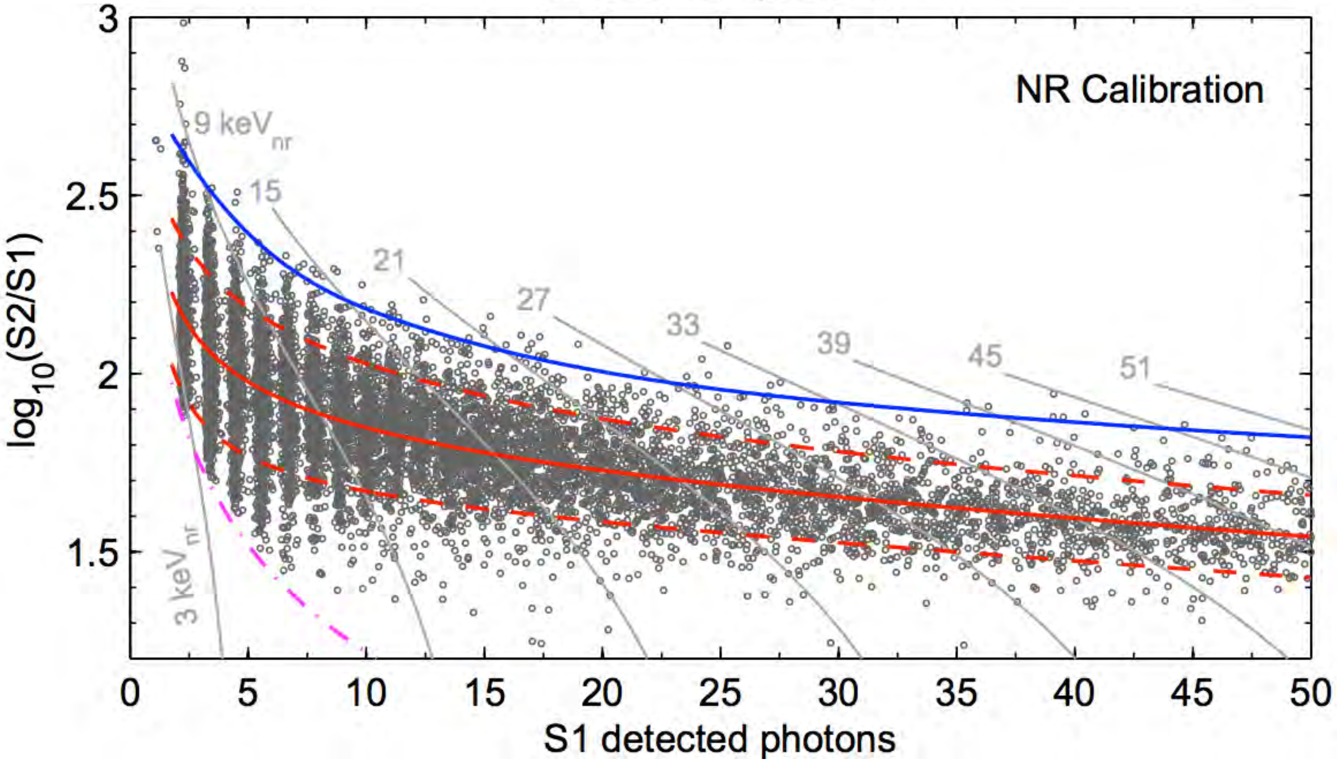




Dual-phase detectors

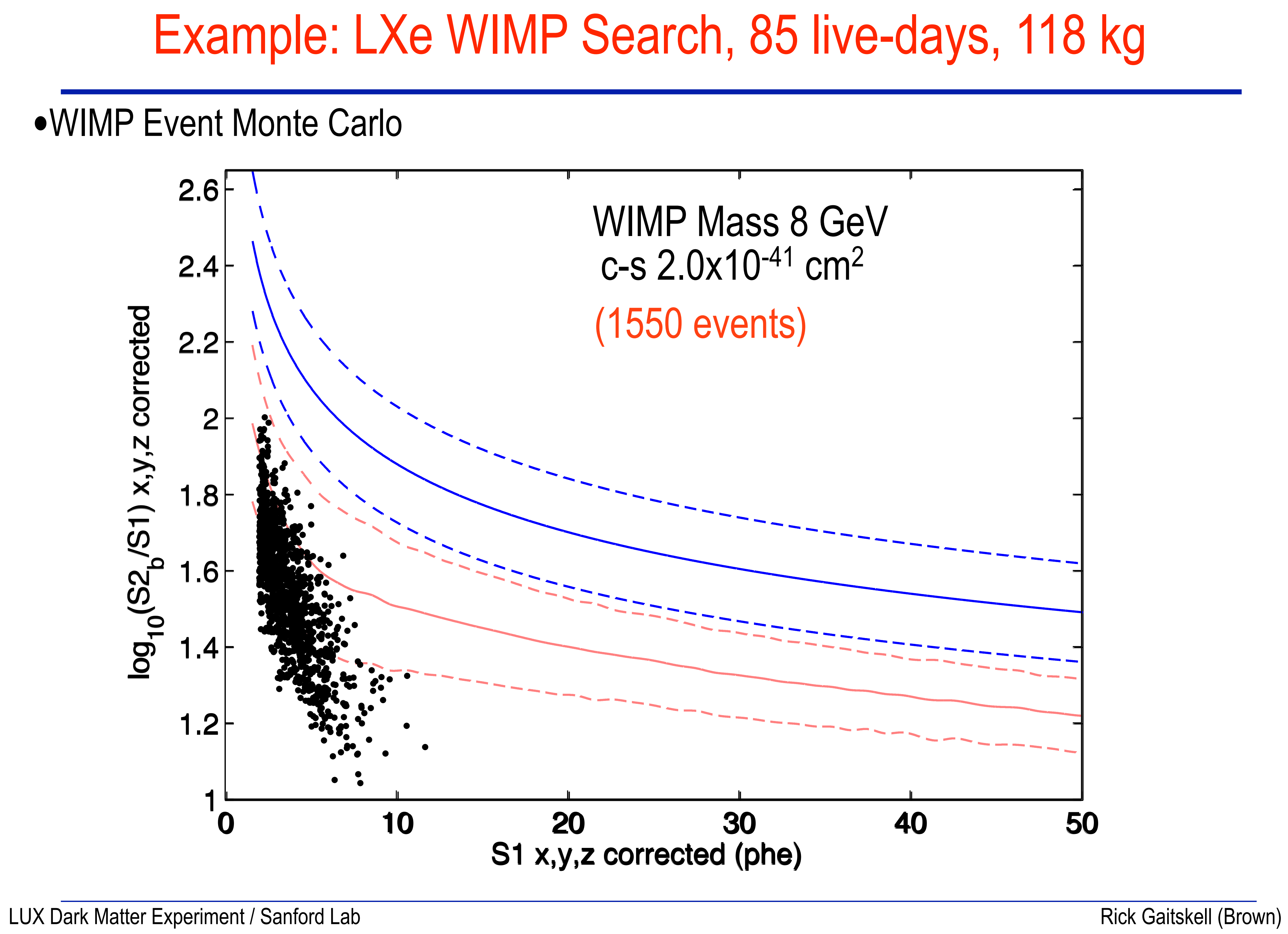
Easy to characterise:
NR events lie in the NR band
and
ER events lie in the ER band
…
?





The behaviour of low energy signals

LUX:



Example: LXe WIMP Search, 85 live-days, 118 kg

- WIMP Event Monte Carlo

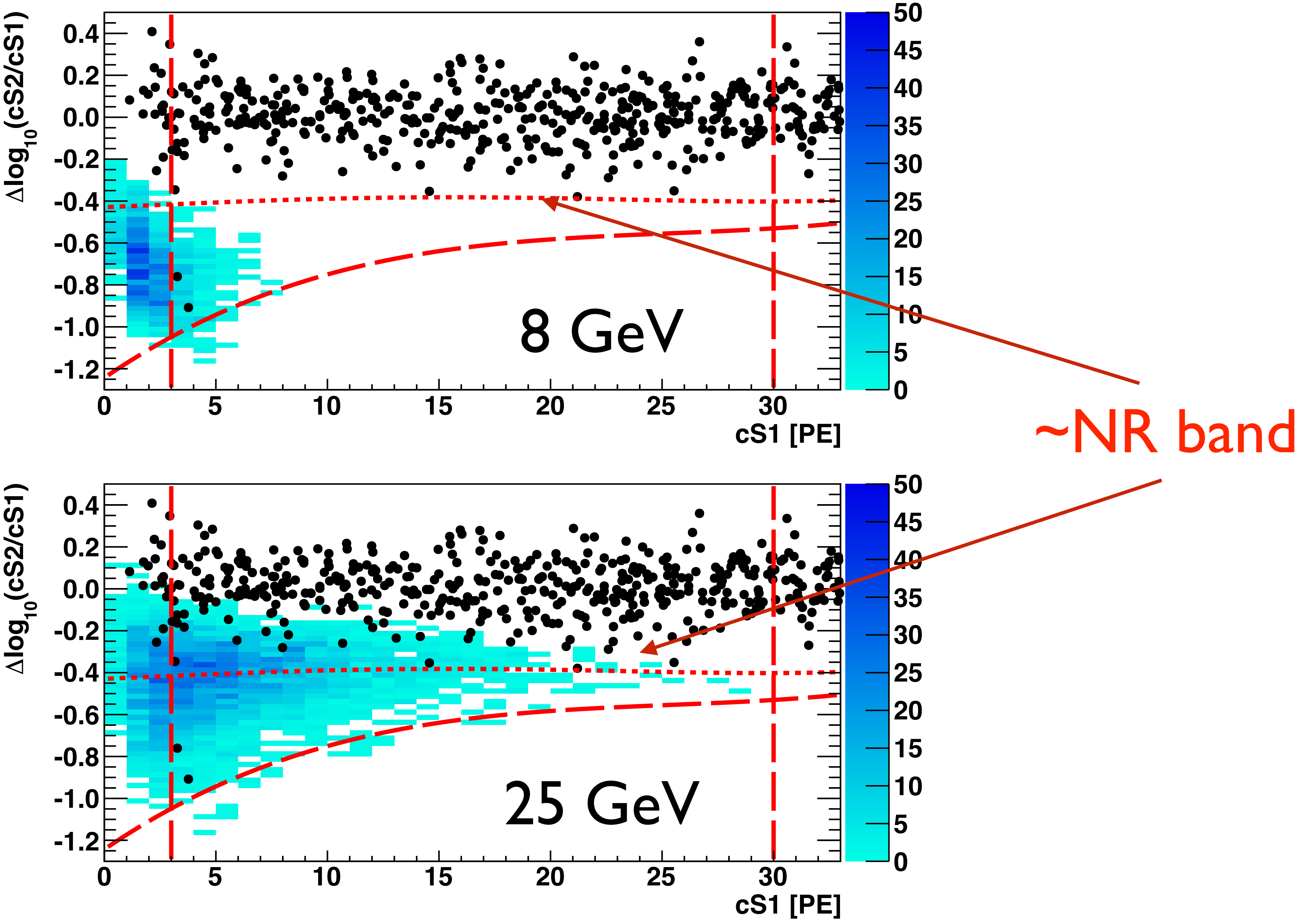
LUX Dark Matter Experiment / Sanford Lab

Rick Gaitskell (Brown)

The behaviour of low energy signals

XENON100:

arXiv:1304.1427



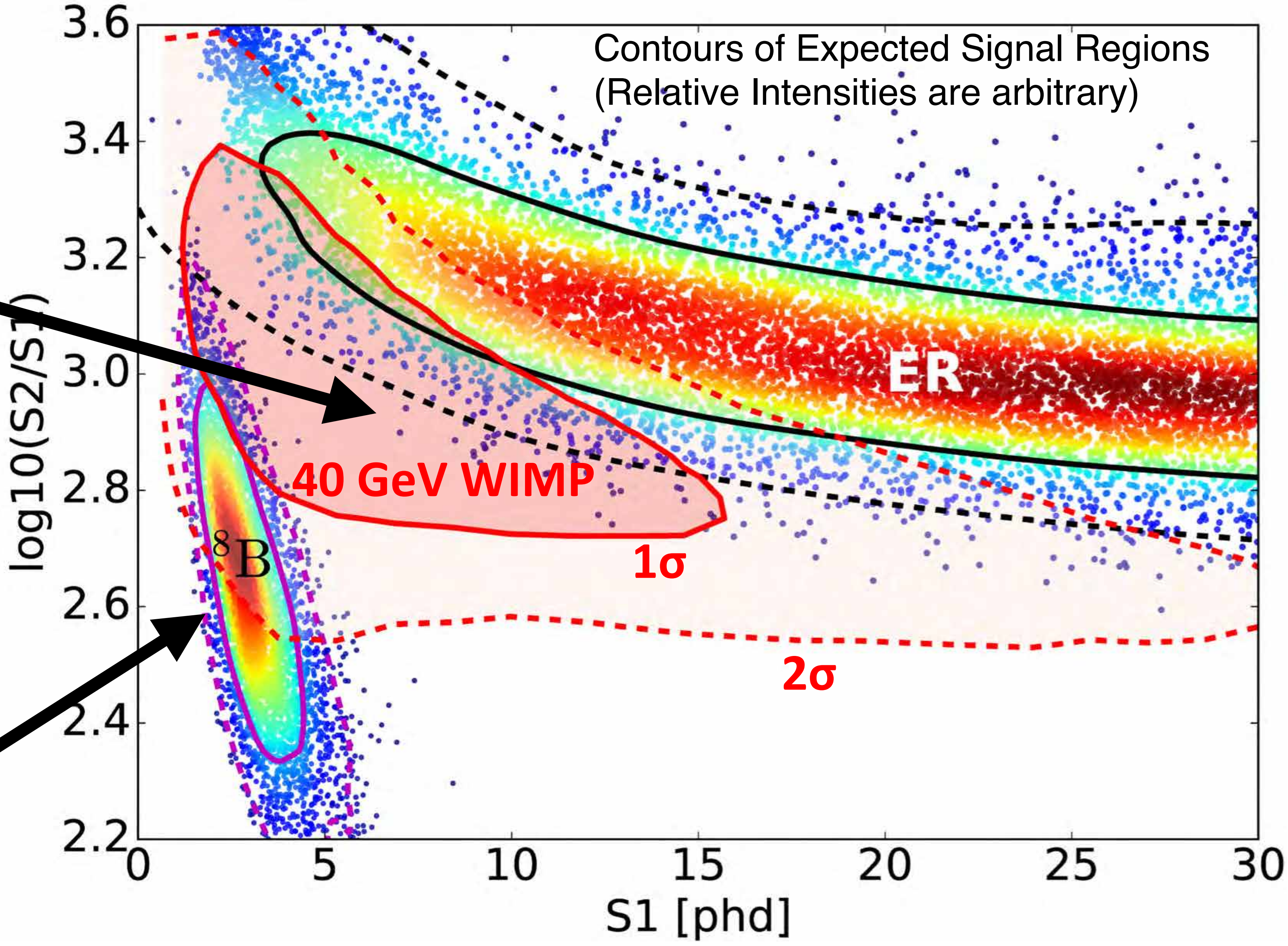
~NR band

The behaviour of low energy signals

LZ WIMP Signal Region Example
- We must also understand 8B signal

NR region

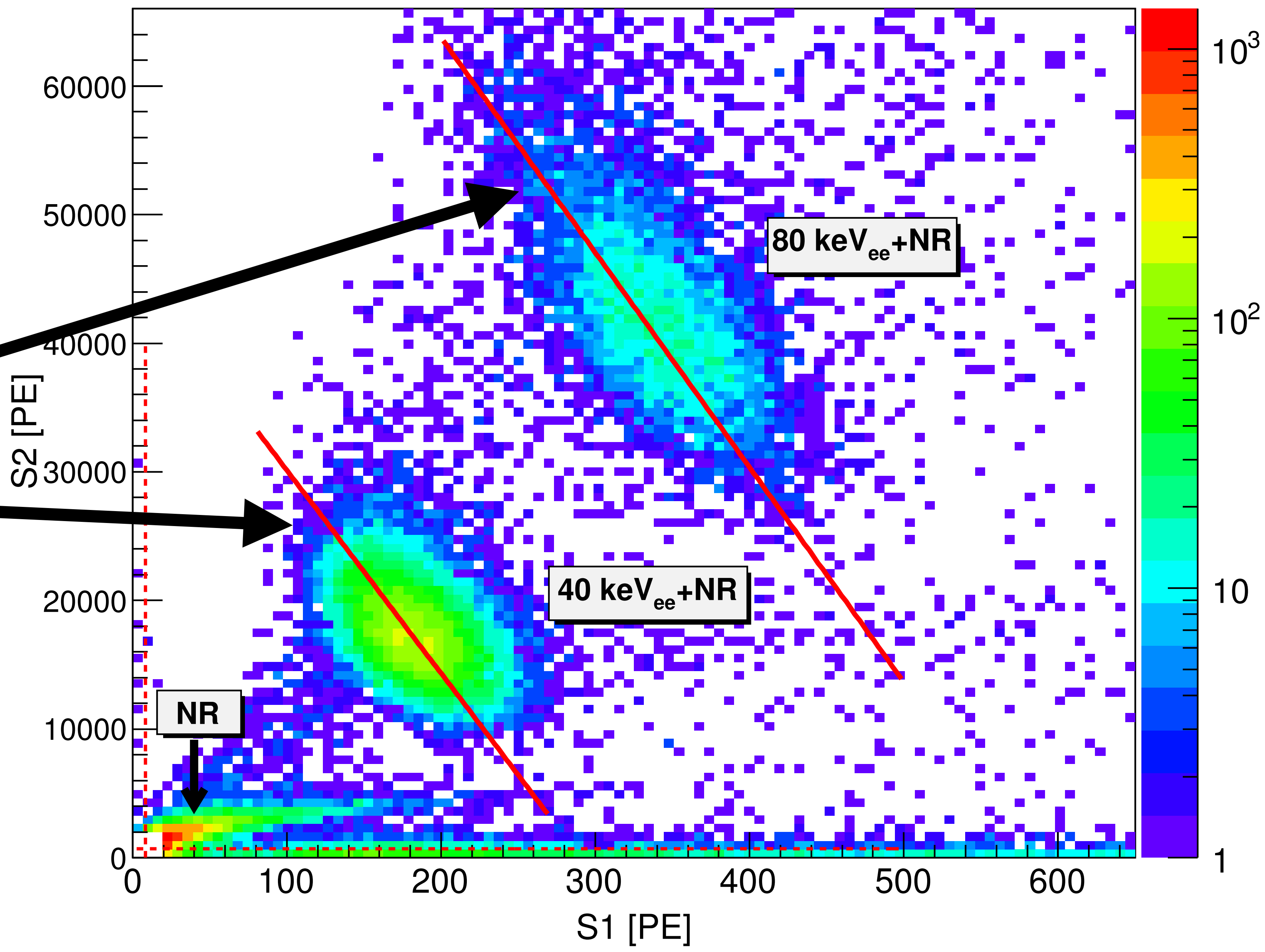
Low energy
nuclear recoil events
(similar to 6 GeV DM)



The behaviour of low energy signals

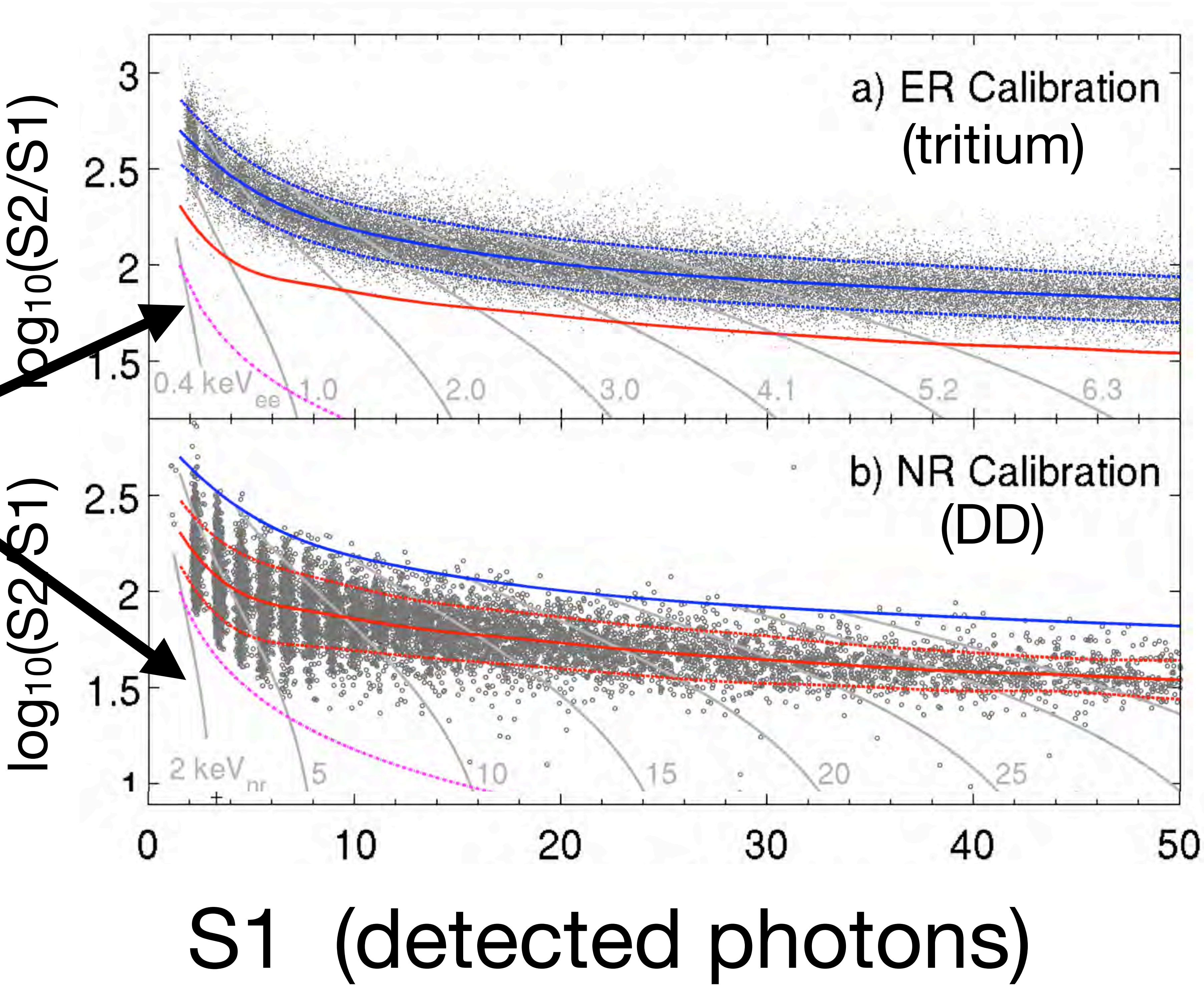
recombination
fluctuations
move the signal
along lines of
constant energy

$$\frac{E_{\mathrm{R}}}{13.7\ \mathrm{eV}} = \frac{\mathrm{S1}}{g_1} + \frac{\mathrm{S2}}{g_2}$$



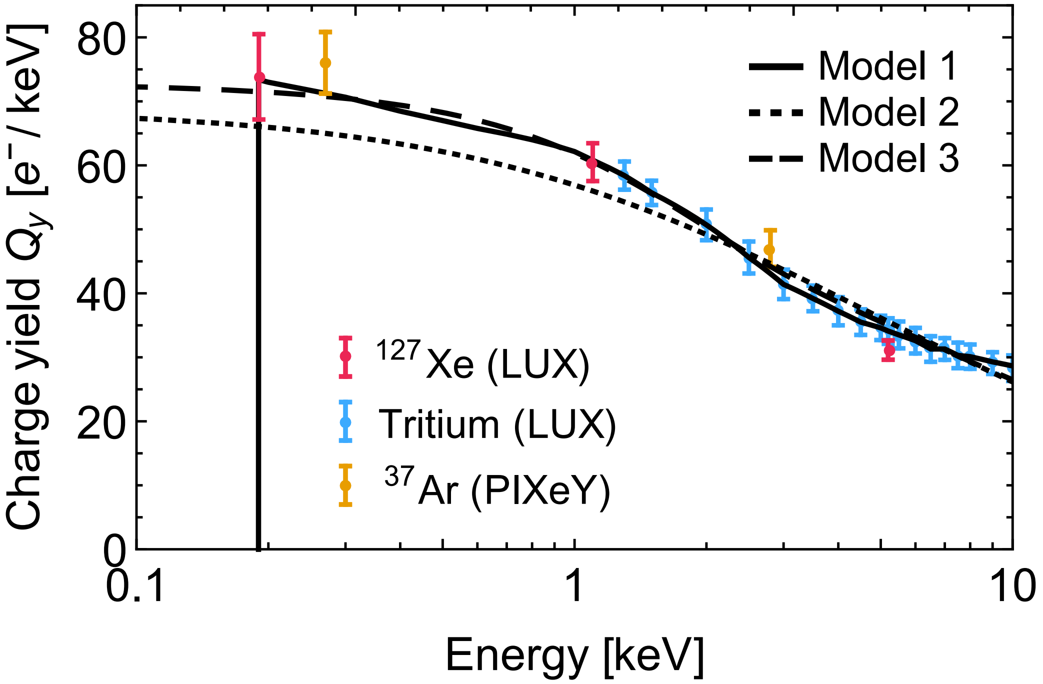
Data from PandaX-I arXiv:1505.00771

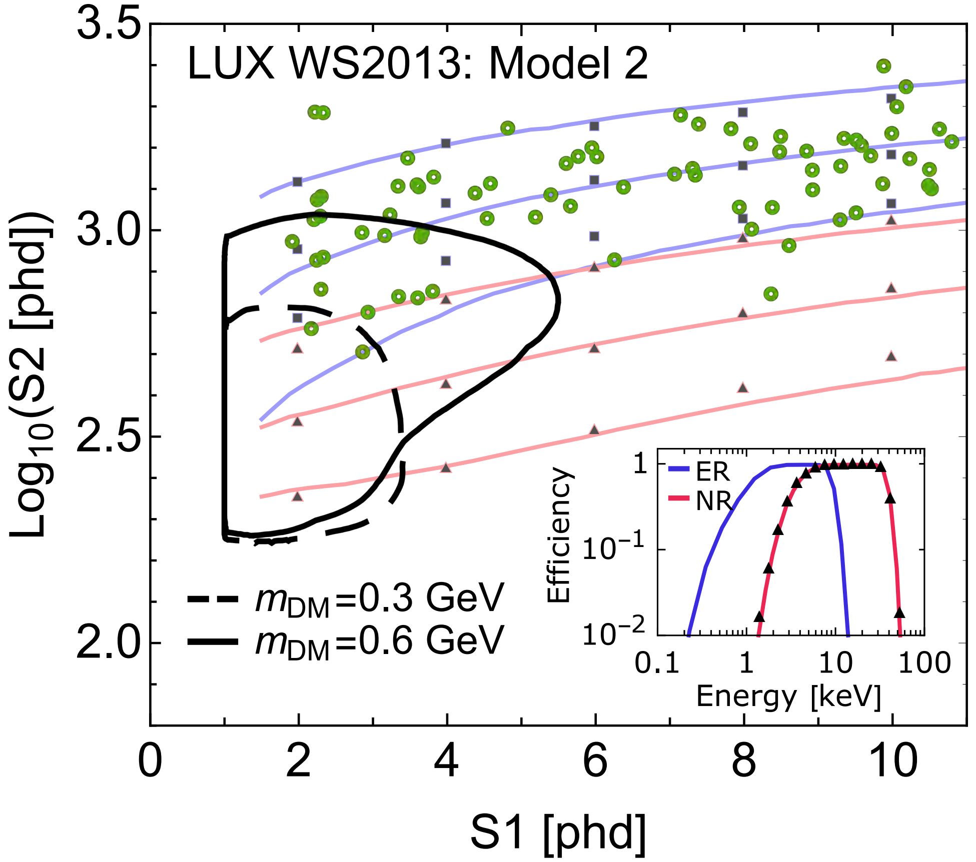
The behaviour of low energy signals

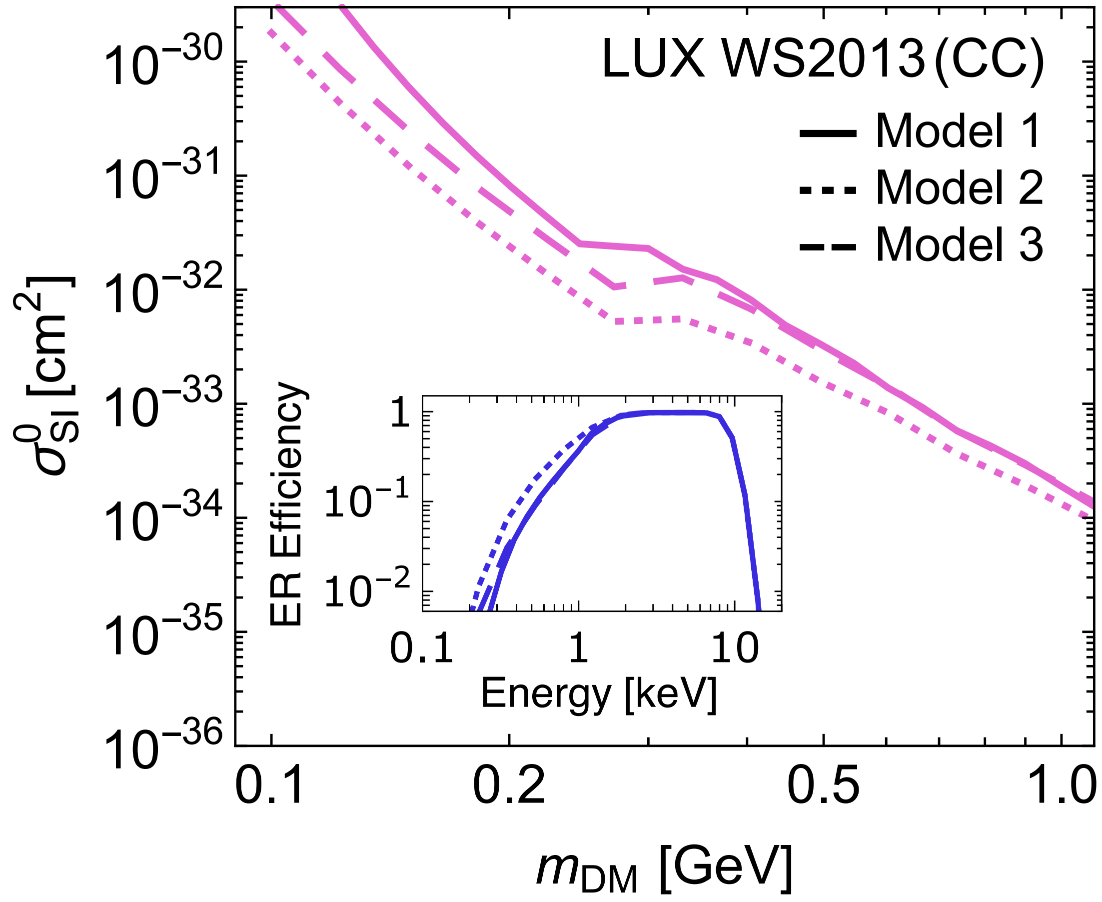


recombination
fluctuations
move the signal
along lines of
constant energy

Different charge yields







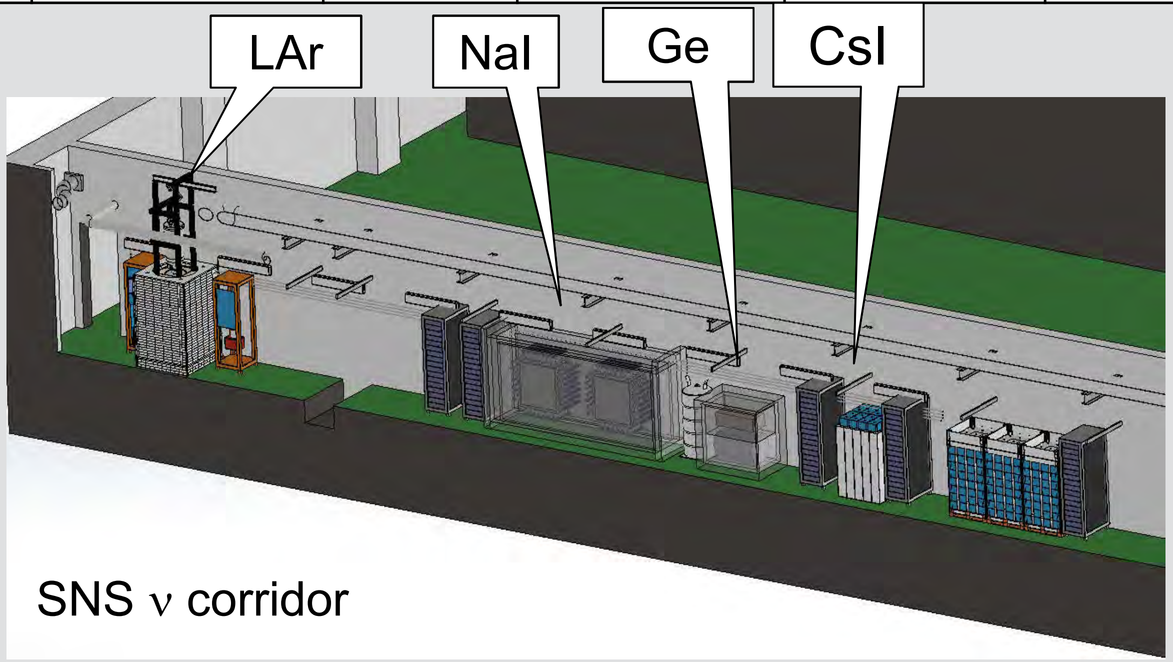
Backup: SN neutrinos

COHERENT scattering

Different detectors will test N^2 dependence of the scattering rate

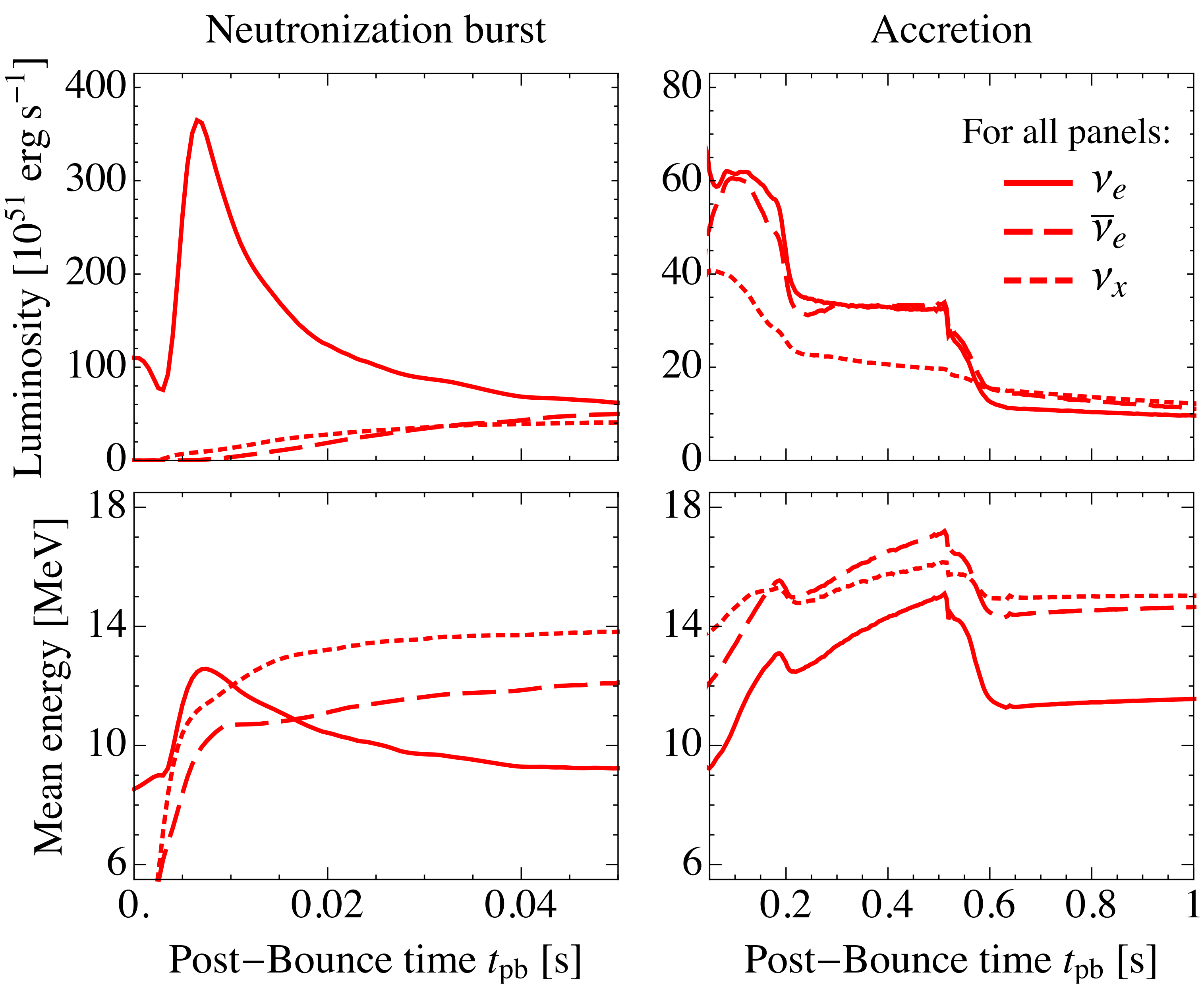
COHERENT detectors

Nuclear Target	Technology	Mass (kg)	source distance (m)	Recoil thresh (keVnr)	Data-taking start date; CEνNS detection goal
CsI[Na]	Scint. Crystal	14	20	6.5	9/2015; 3σ in 2 yr
Ge	HPGe PPC	10	22	5	Fall 2016
NaI[Tl]	Scintillating crystal	185* /2000	28	13	*high-thresh. runs starting July 2016
LAr	Single-phase scintillation	35	29	20	Fall 2016

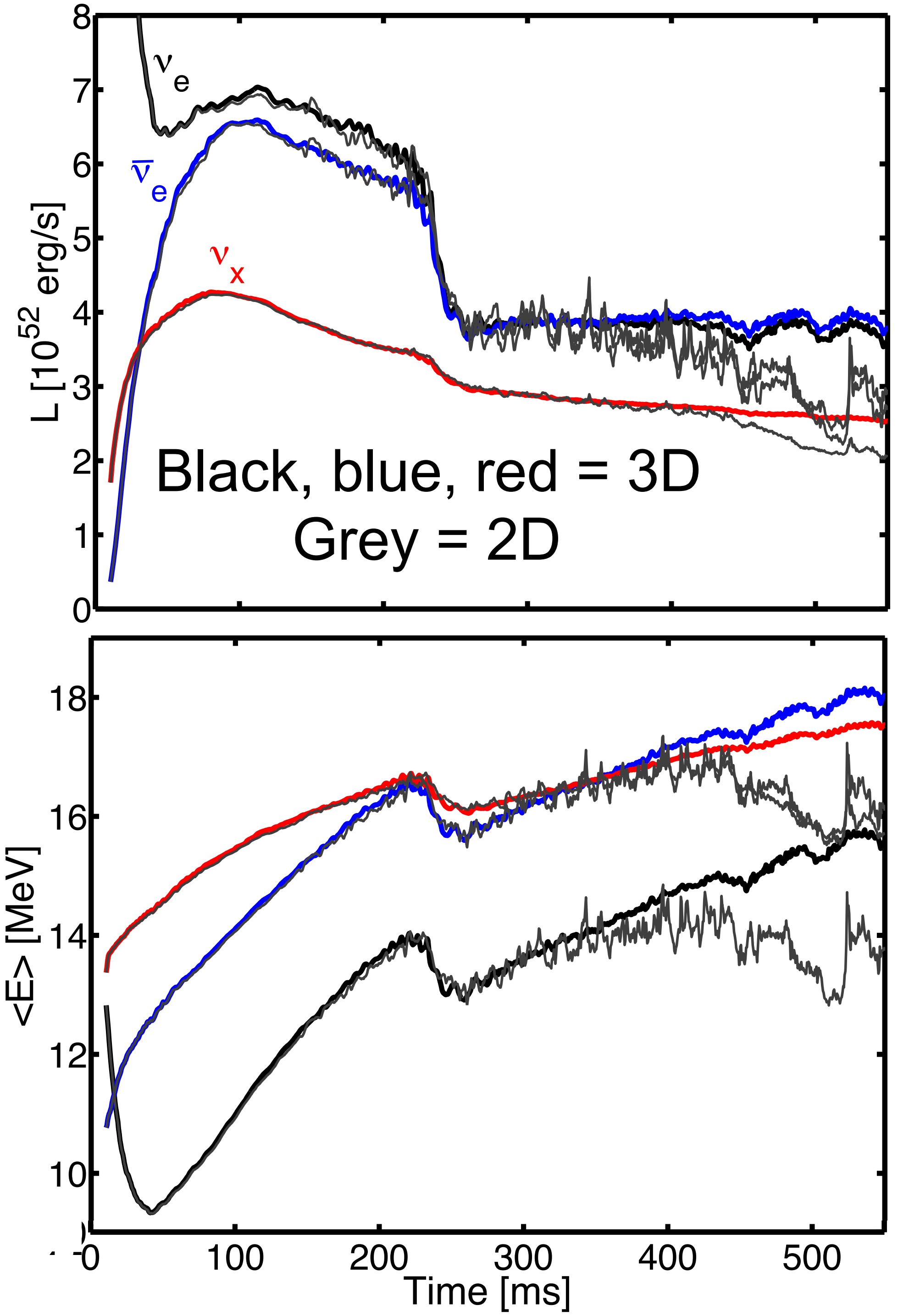


1D vs 2D vs 3D simulations

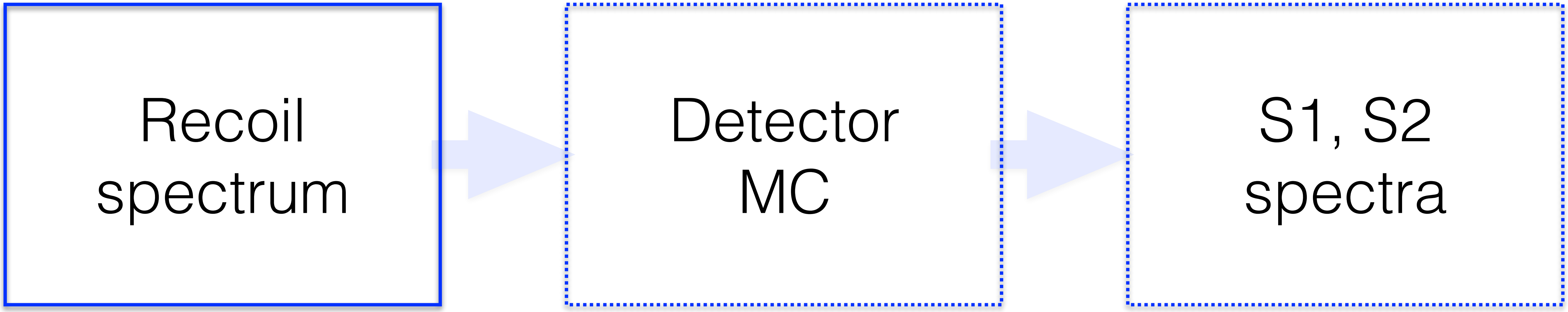
27 Msun 1D:



27 Msun, arXiv:1406.0006



S1 and S2 signal simulation

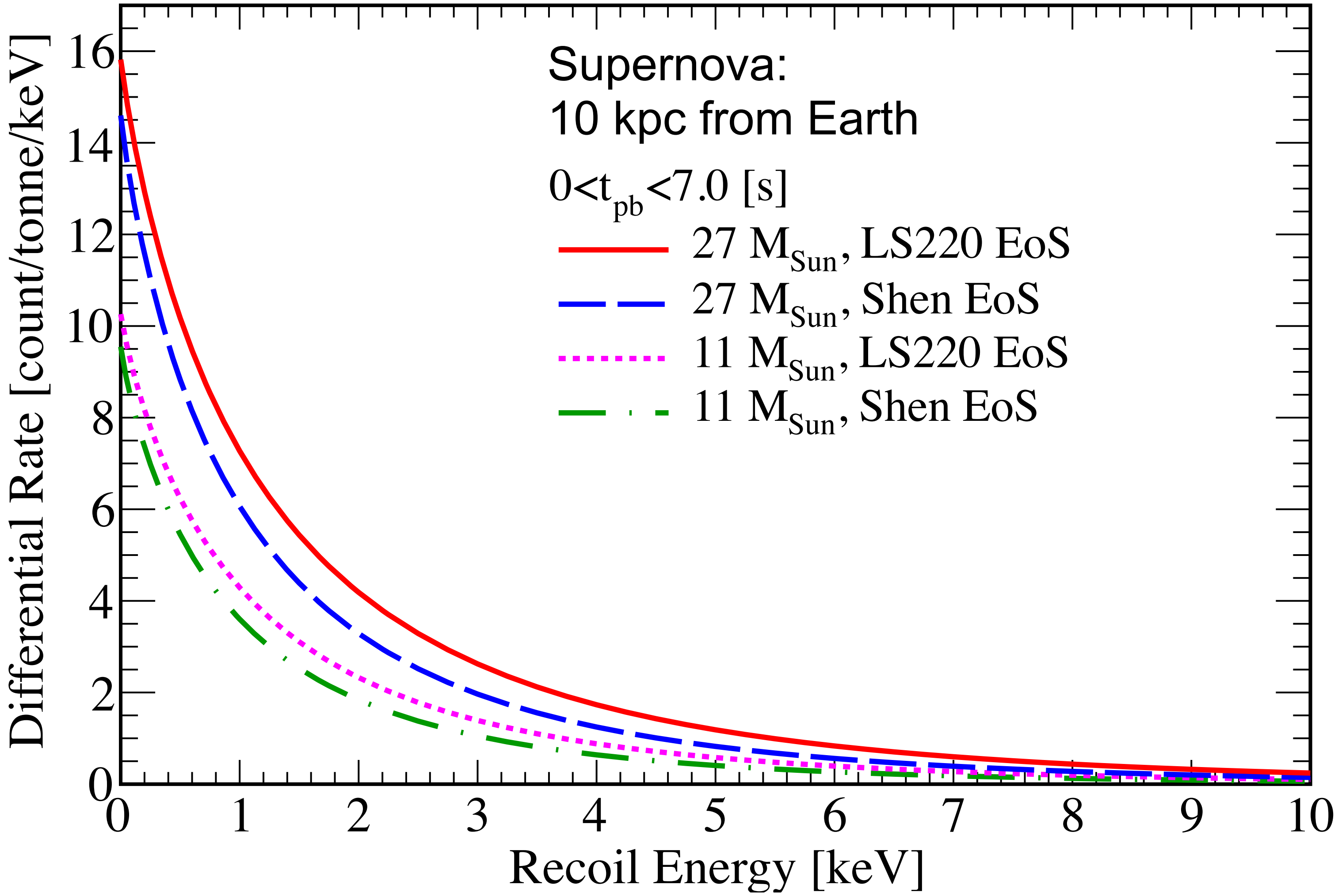


Recoil spectrum

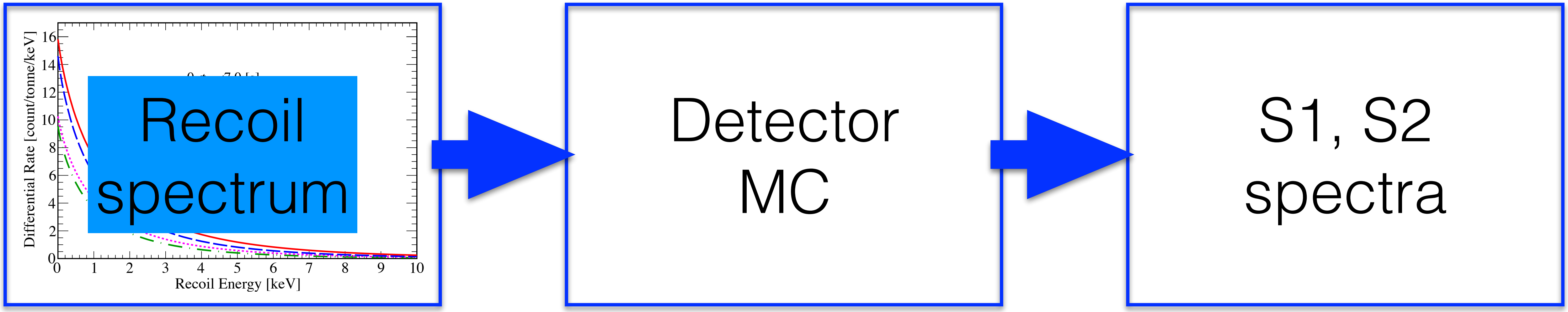
Detector MC

S1, S2 spectra

Recoil energy spectrum:
Rate is strongly
peaked at low energy



S1 and S2 signal simulation



Recoil spectrum

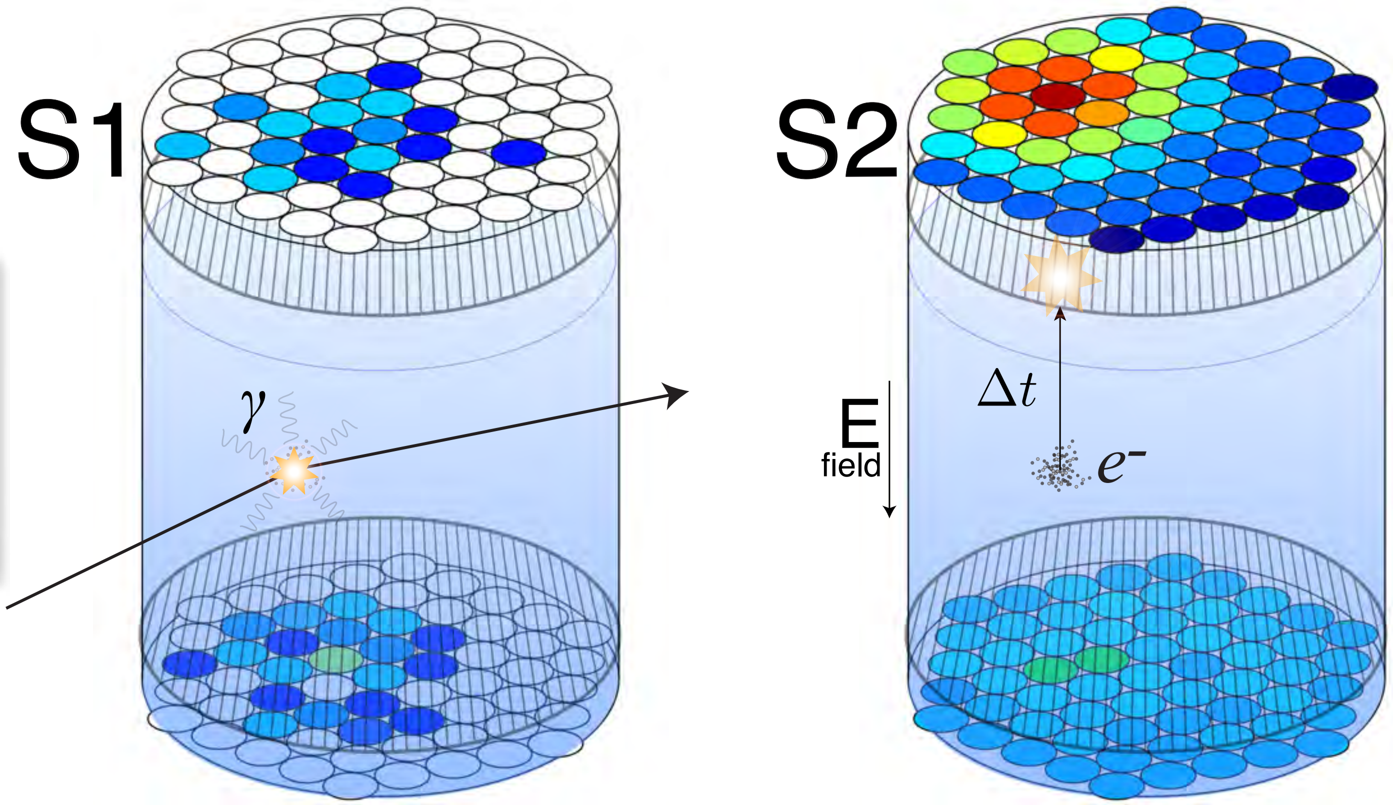
Detector MC

S1, S2 spectra

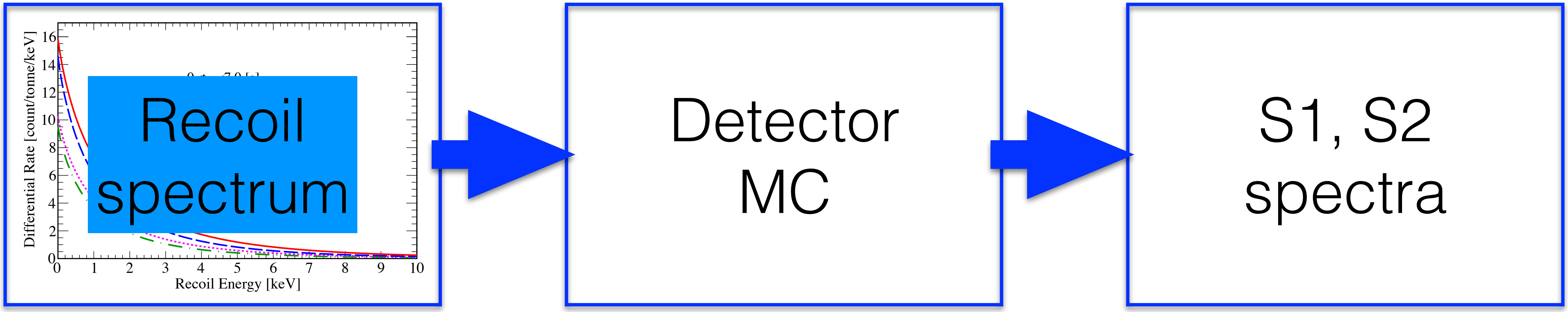
Calculate the signal in terms of the observable signals:

S1: proportional to # photons

S2: proportional to # electrons



S1 and S2 signal simulation

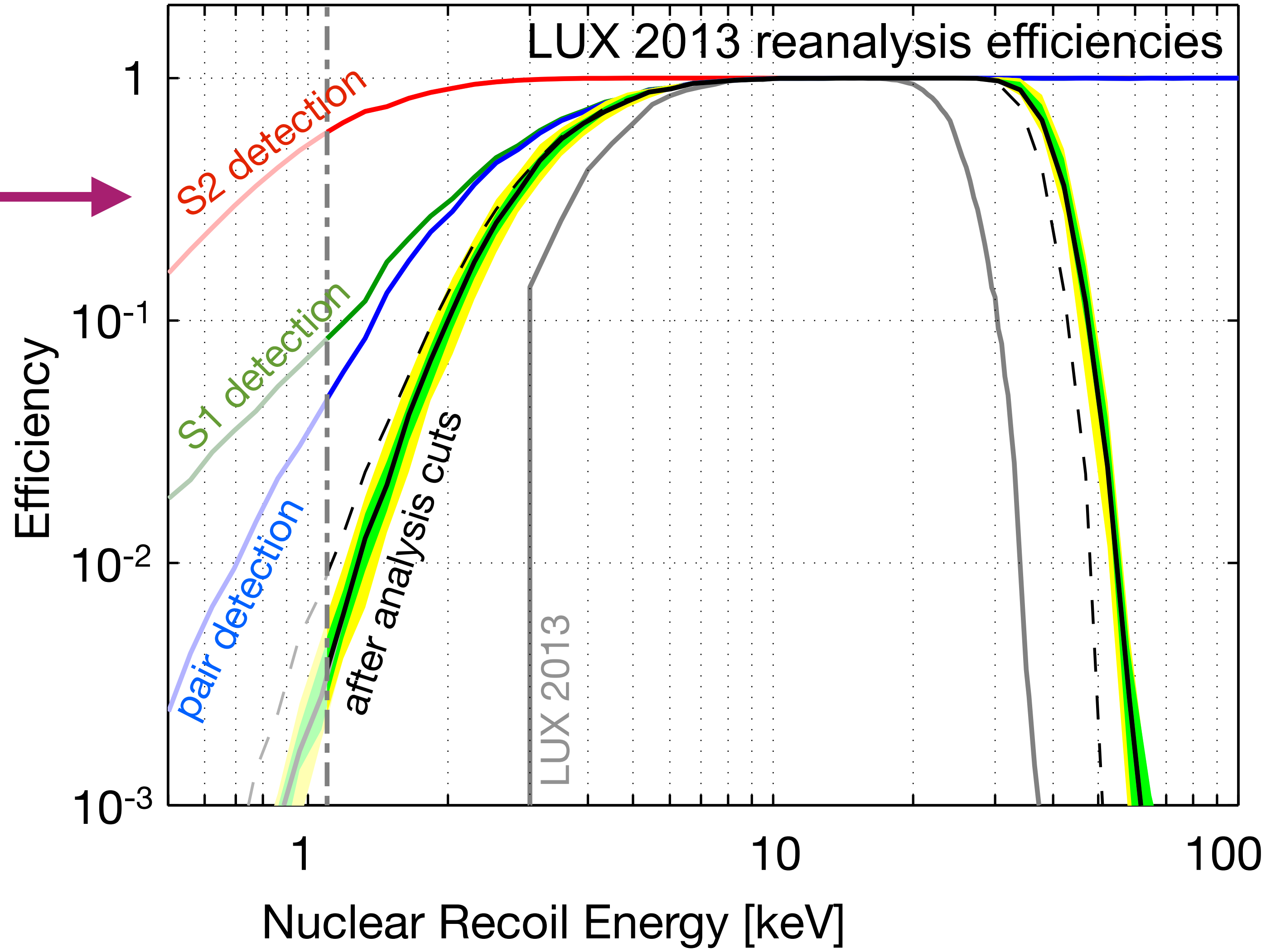


Recoil spectrum

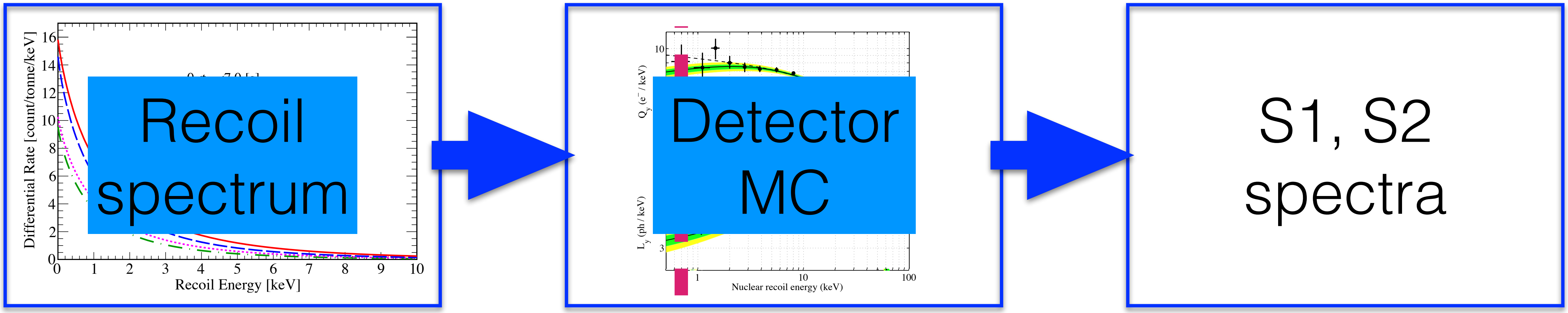
Detector MC

S1, S2 spectra

S2 detection efficiency: *order of magnitude higher* than S1 detection efficiency



S1 and S2 signal simulation

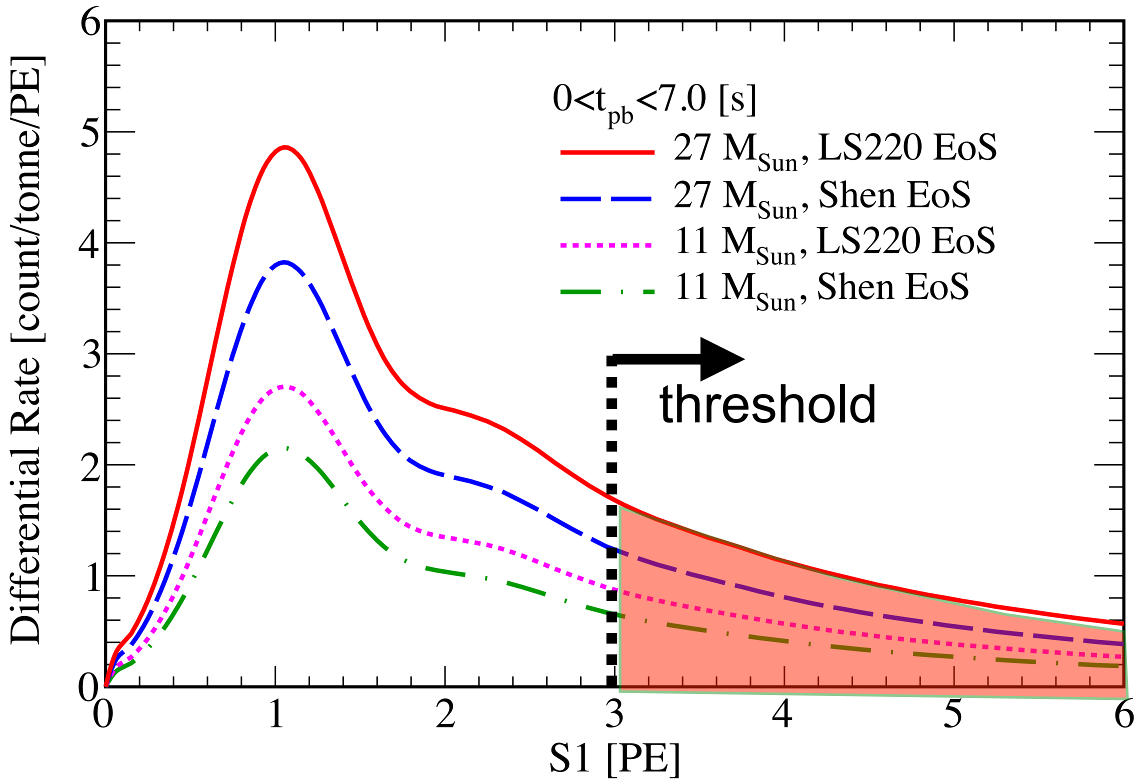


Recoil spectrum

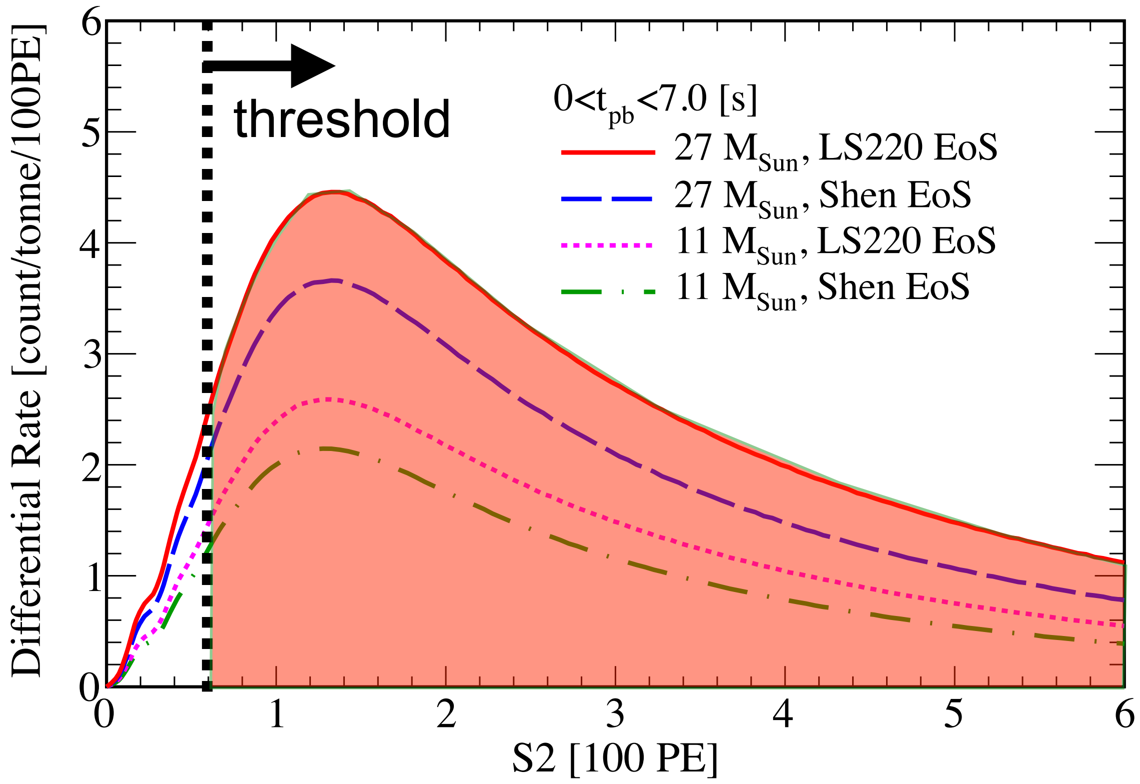
Detector MC

S1, S2 spectra

More events from the S2 channel:

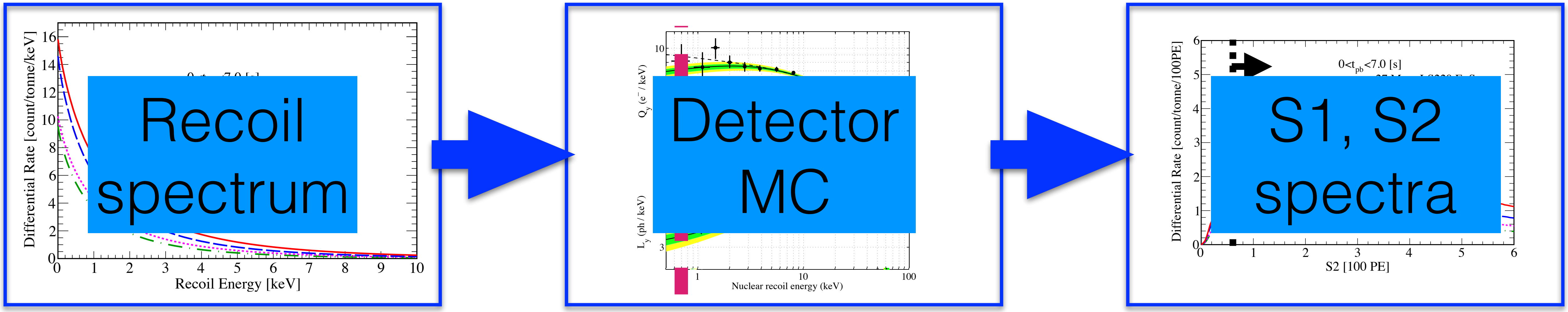


S1 signal: 5.2 events/tonne



S2 signal: 17.6 events/tonne

S2-only analysis

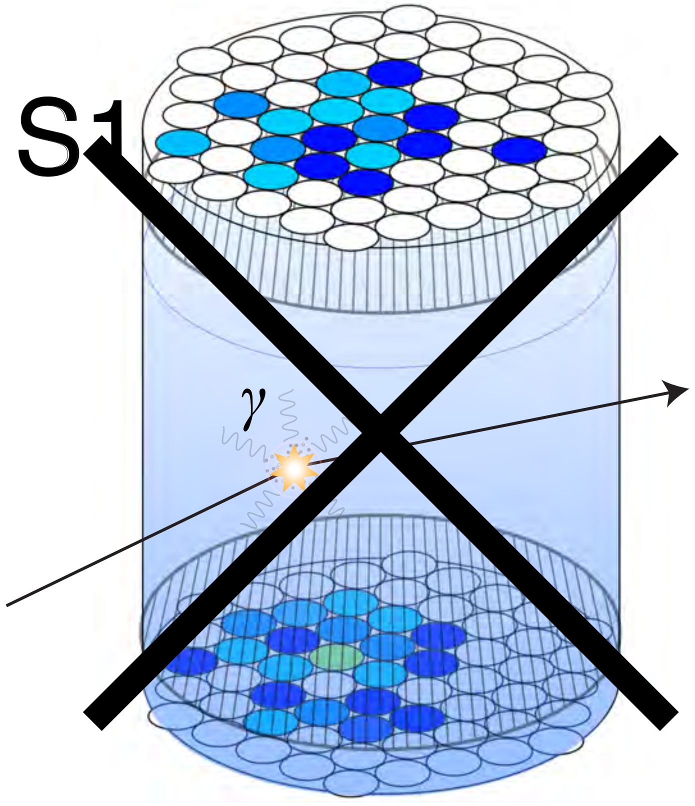


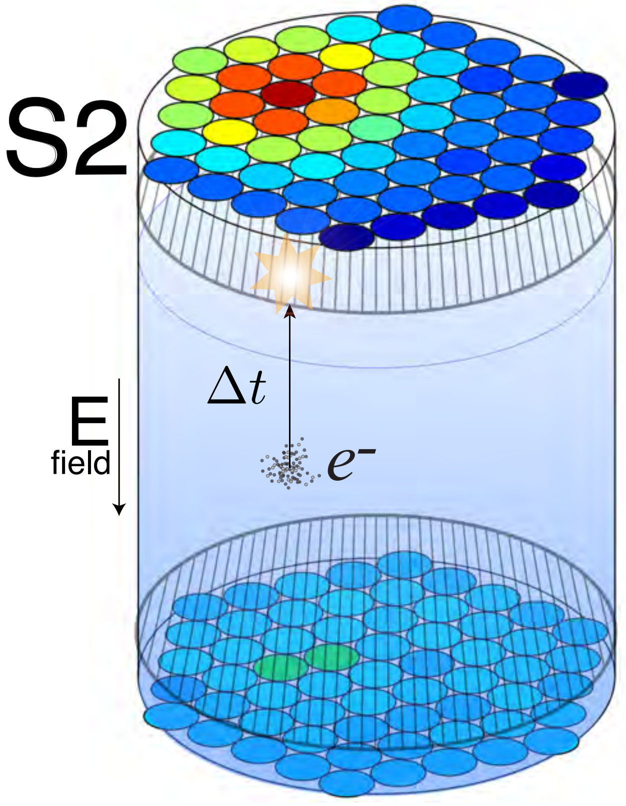
Recoil spectrum

Detector MC

S1, S2 spectra

Perform an S2-only analysis:





S2-only analysis

- Advantage: higher event rate

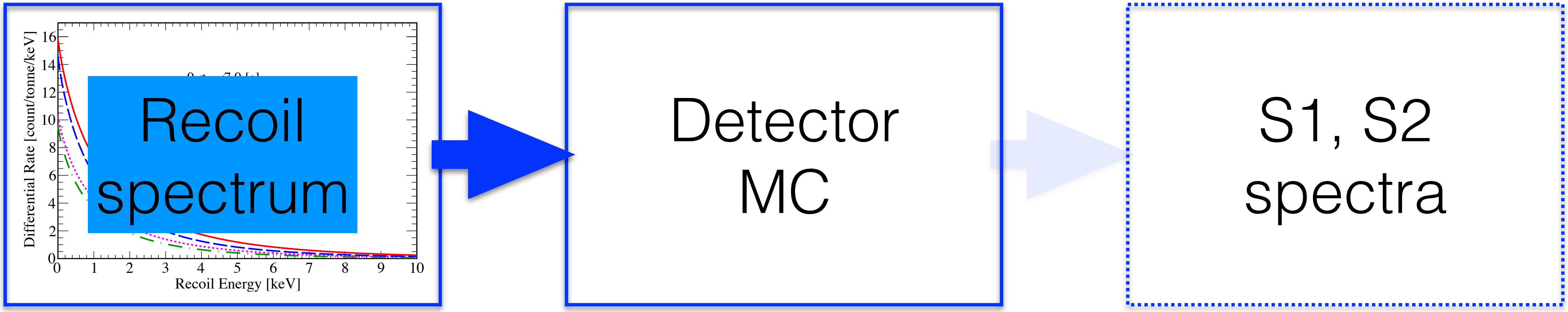
- 'Disadvantage': no background discrimination…

  …but not an issue for neutrino signal (is an issue for DM search):
  - Signal is short (<10 seconds)
  - Background rate is small compared to signal rate

Background estimates:
XENON10: 2.3×10^{-2} events/tonne/s arXiv:1104.3088
XENON100: 1.4×10^{-2} events/tonne/s arXiv:1605.06262

signal: 1.0 - 2.5 events/tonne/s *(40-100 x background)*

S1 and S2 signal simulation



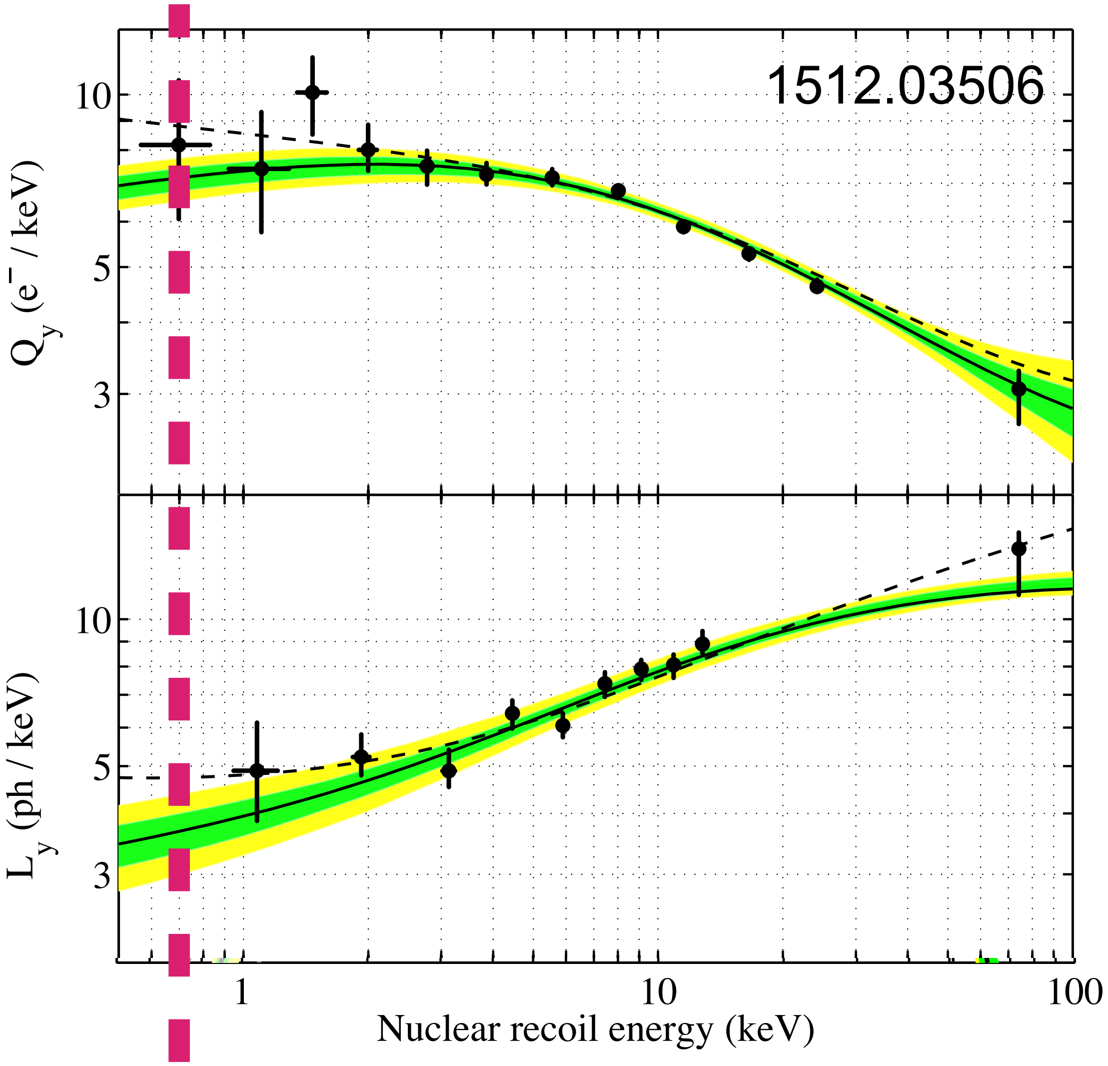
Recoil spectrum

Detector MC

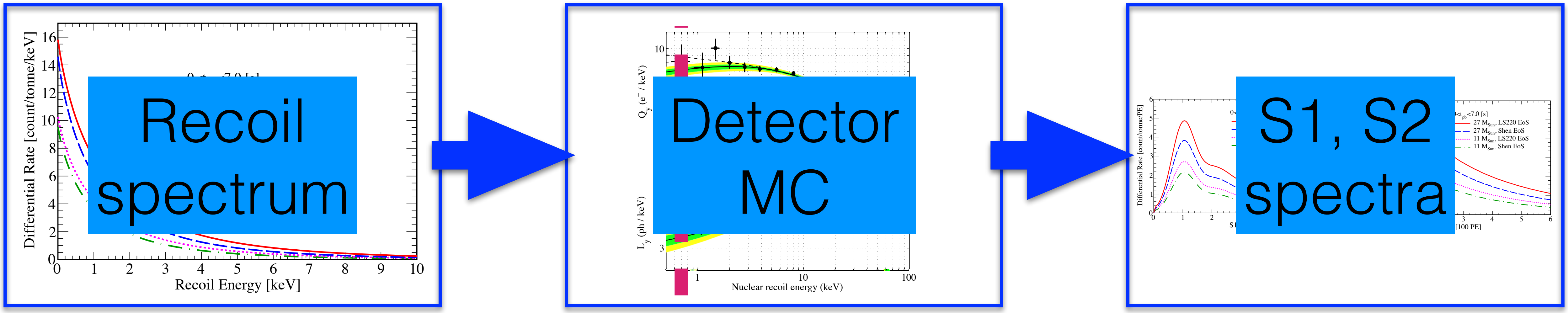
S1, S2 spectra

- Use the LUX light and charge yields:

- Detectors calibrated to low energy (0.7 keV)



Signal simulation: more details

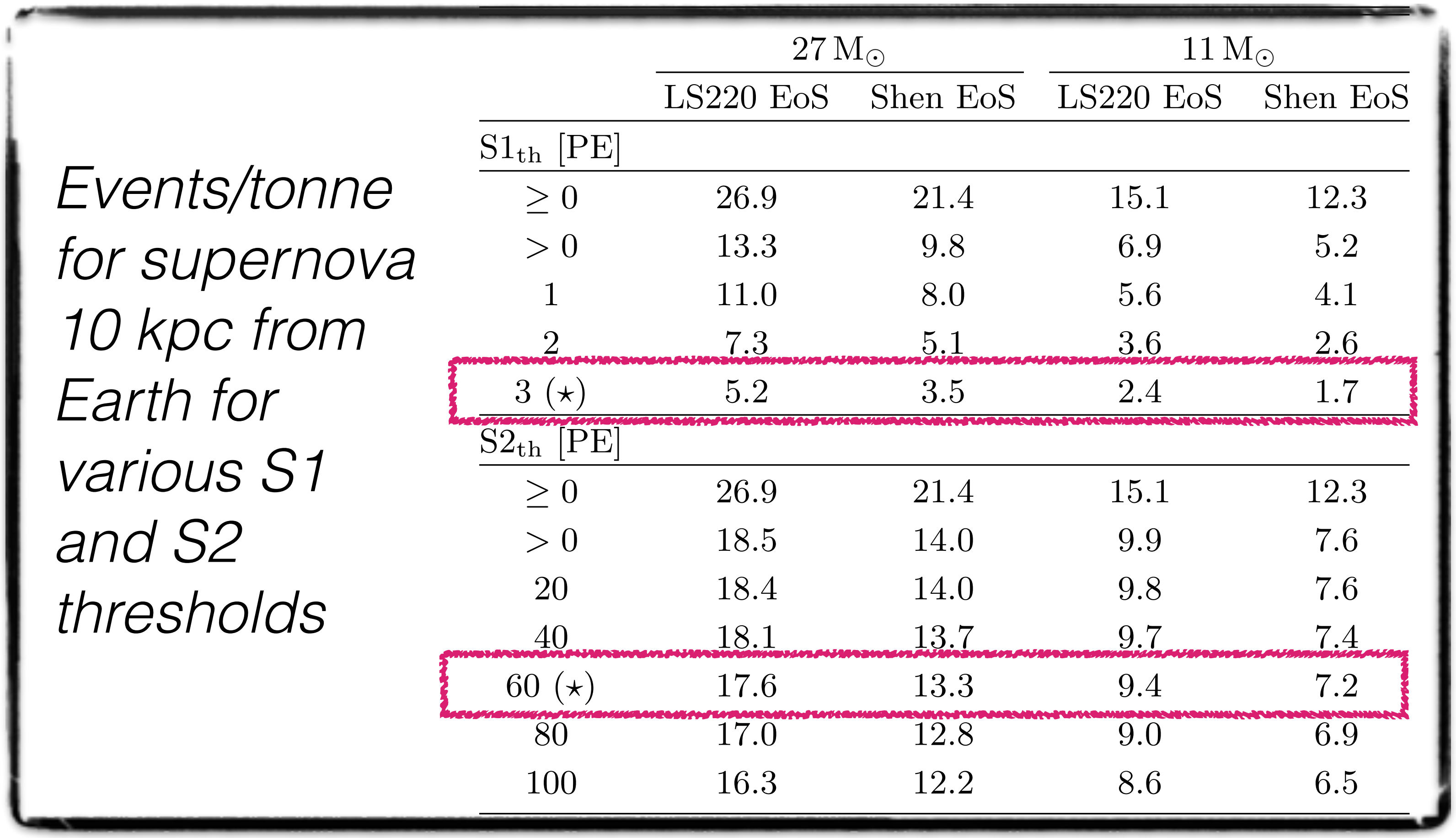

Recoil spectrum

Detector MC

S1, S2 spectra

More events from the S2 channel:

Events/tonne for supernova 10 kpc from Earth for various S1 and S2 thresholds



	$27\,M_\odot$		$11\,M_\odot$	
	LS220 EoS	Shen EoS	LS220 EoS	Shen EoS
$S1_{th}$ [PE]				
≥ 0	26.9	21.4	15.1	12.3
> 0	13.3	9.8	6.9	5.2
1	11.0	8.0	5.6	4.1
2	7.3	5.1	3.6	2.6
3 $(\star)$	5.2	3.5	2.4	1.7
$S2_{th}$ [PE]				
≥ 0	26.9	21.4	15.1	12.3
> 0	18.5	14.0	9.9	7.6
20	18.4	14.0	9.8	7.6
40	18.1	13.7	9.7	7.4
60 $(\star)$	17.6	13.3	9.4	7.2
80	17.0	12.8	9.0	6.9
100	16.3	12.2	8.6	6.5

Requiring an S1 reduces event rate by factor ~3-4

Use an S2-only analysis

SN neutrinos: Low energy uncertainty

TABLE III: The expected number of neutrino events per tonne for various S2 thresholds under different assumptions for Q_y. We compare the Lindhard and Bezrukov models and assume that $Q_y = 0$ for energies below $Q_{y,\min}$. The results are for the 27 $M_\odot$ LS220 EoS progenitor at 10 kpc and integrated over the first 7 s. Similar results hold for other progenitor models. The signal uncertainty in each row is $(\mathrm{S2}_{\max} - \mathrm{S2}_{\min})/(\mathrm{S2}_{\max} + \mathrm{S2}_{\min})$. The Lindhard model with $Q_{y,\min} = 0.7$ keV gives the smallest number of events per tonne and is the benchmark assumption that we have made in this paper.

	27 $M_\odot$ LS220 EoS				
	Lindhard $Q_{y,\min}$		Bezrukov $Q_{y,\min}$		Signal
$\mathrm{S2}_{\mathrm{th}}$ [PE]	0.1 keV	0.7 keV	0.1 keV	0.7 keV	uncertainty
20	22.9	18.4	23.8	18.5	13%
40	21.0	18.1	22.2	18.3	10%
60 ($\star$)	19.4	17.6	20.6	17.9	8%
80	18.1	17.0	19.2	17.5	6%
100	16.9	16.3	17.9	16.9	5%