New things to do with lots of xenon

GRAPPA
GRavitation AstroParticle Physics Amsterdam

UNIVERSITY OF AMSTERDAM

Christopher McCabe

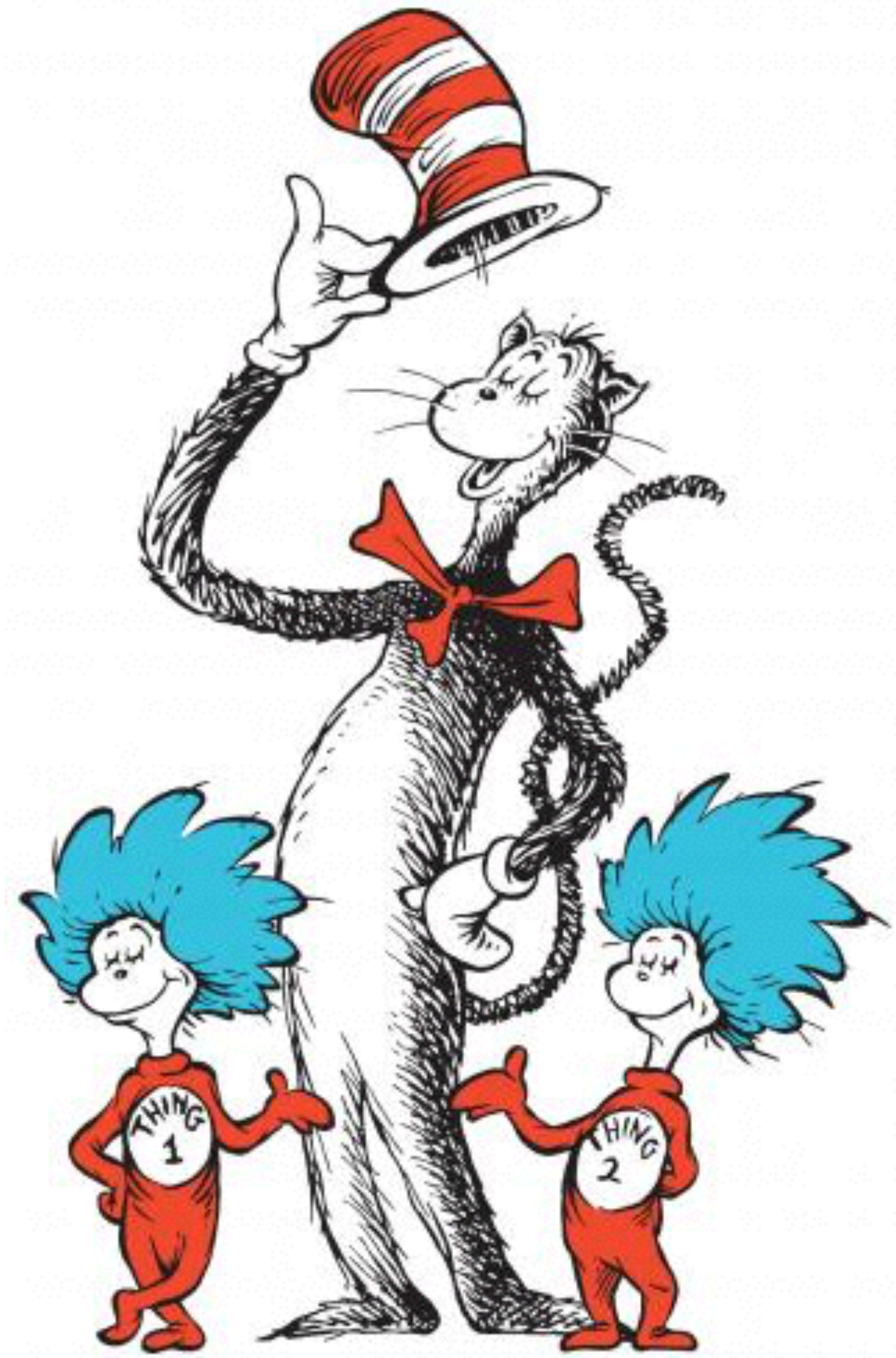
— arXiv:1512.00460, JCAP —

— arXiv:1606.09243, PRD —

6th APS meeting, Château de la Tour, Gouvieux, France - 31st August 2016

Outline

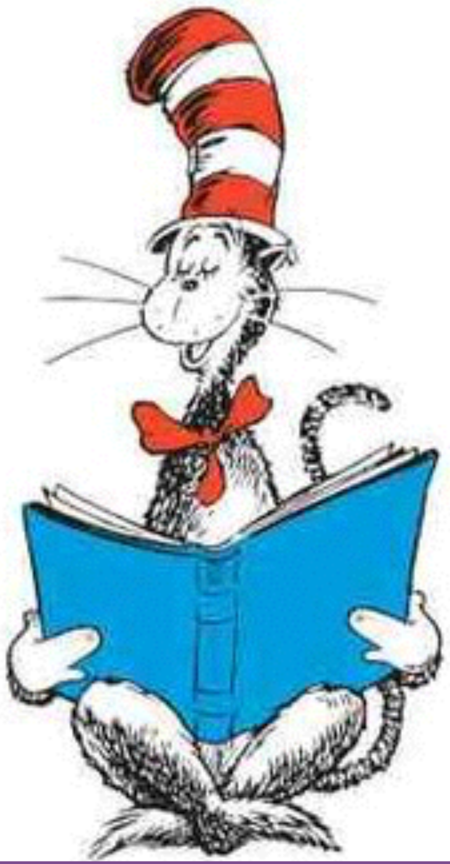
- Motivation
- Thing 1:
  Supernova neutrino detection
- Thing 2:
  DM exciting the xenon nucleus



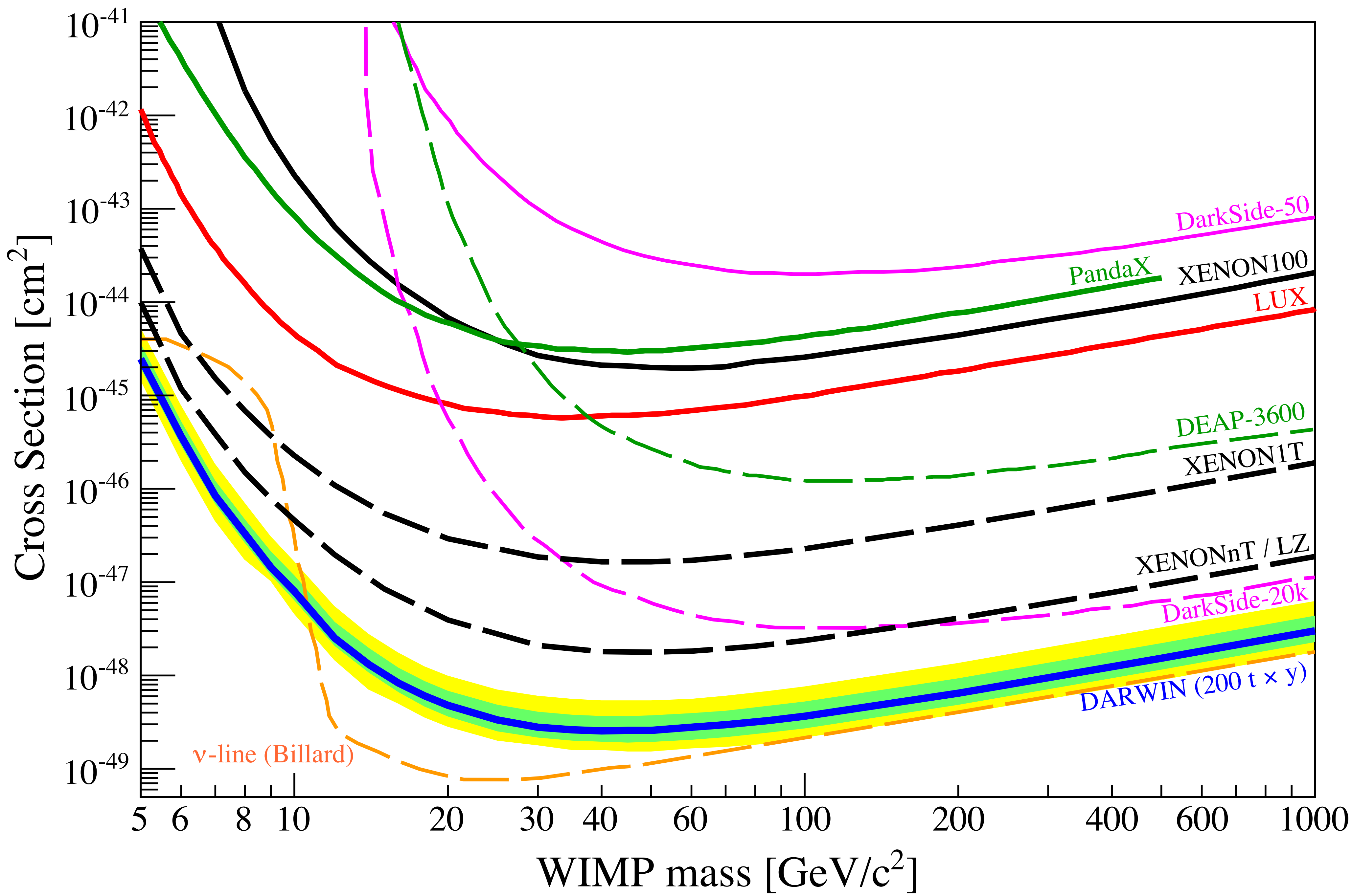
Motivation

Xenon dark matter direct detectors are:

- getting bigger (x 100)
- becoming quieter (background x 0.01)
- better understood (calibrated to ~ 0.1 keV)



Xenon detectors are good at everything

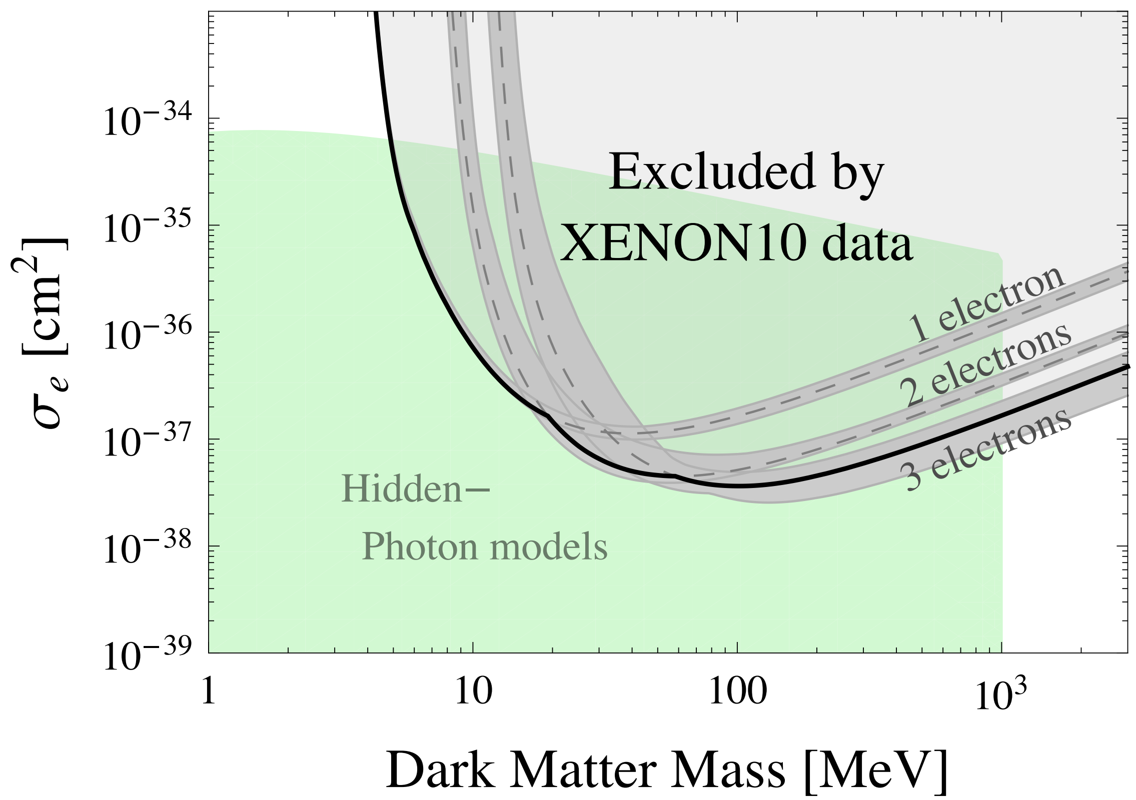


Significant improvements for standard DM…But what else?

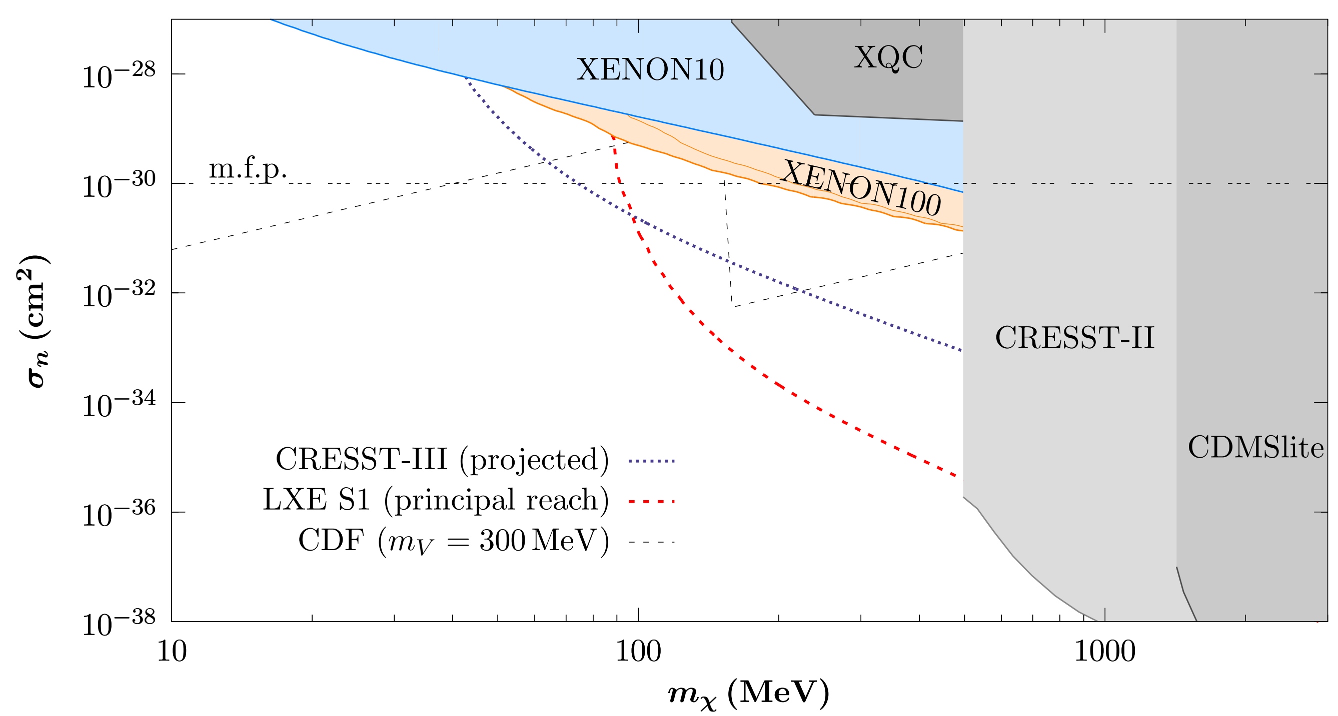
Xenon detectors are good at everything

An aside for Richard: limits on MeV dark matter

Essig et al arXiv:1206.2644



Kouvaris et al arXiv:1607.01789



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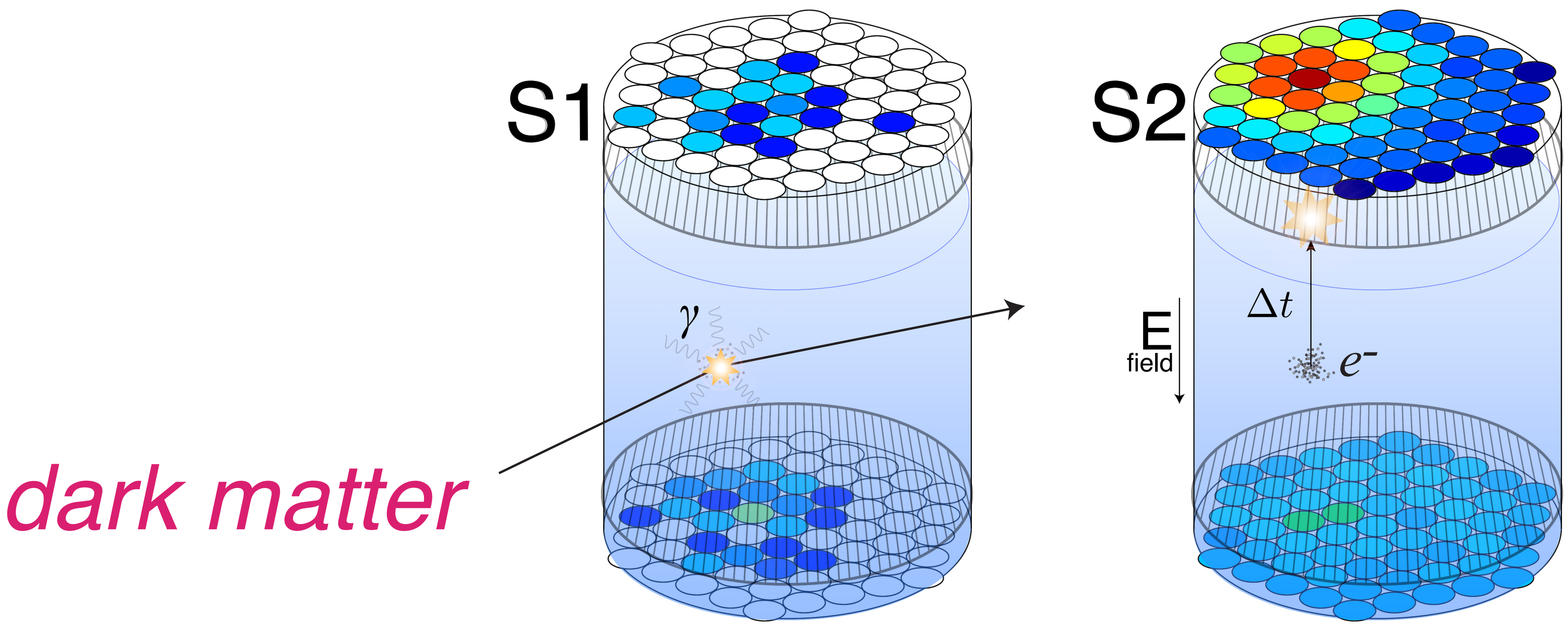
Xenon WIMP detectors

- Dual-phase xenon as *dark matter* detectors

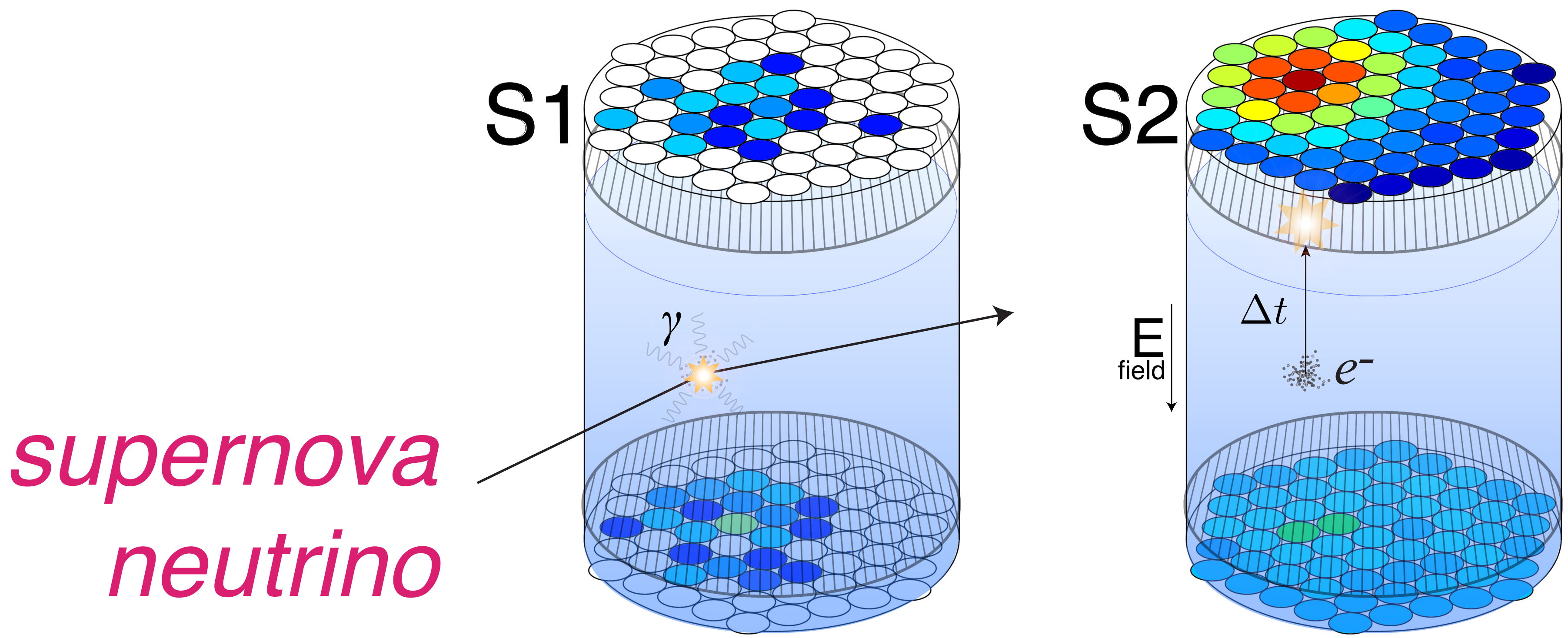


Interaction: unknown

From kinematics: $E_{\rm R} \sim 2.4~{\rm keV} \left(\frac{m_{\rm DM}}{5~{\rm GeV}}\right)^2$

Xenon WIMP detectors

- Dual-phase xenon as *supernova neutrino* detectors



Interaction: neutral current (Z-exchange)

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: an old idea

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. gains from a coherence factor: the cross-section is proportional to (neutron-number)^2
2. responds to all types of neutrinos equally
3. responds to neutrinos in a known way so that the incoming neutrino spectrum may be inferred

PHYSICAL REVIEW D **68**, 023005 (2003)

Supernova observation via neutrino-nucleus elastic scattering in the CLEAN detector

C. J. Horowitz* K. J. Coakley D. N. McKinsey

"Elastic scattering detectors can have yields of a few or more neutrino events per tonne for a supernova at 10 kpc"

Supernova neutrinos: a timely perspective

"Elastic scattering detectors can have yields of a few or more neutrino events per tonne for a supernova at 10 kpc"

Why is it timely to think about this?

Tonne scale experiments are starting to run:

commissioning: XENON1T (~ 2 t)

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

R&D/early plans: DARWIN (~ 40 t)

What physics can we do with these detectors?

Outline

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

Extracting information from:

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

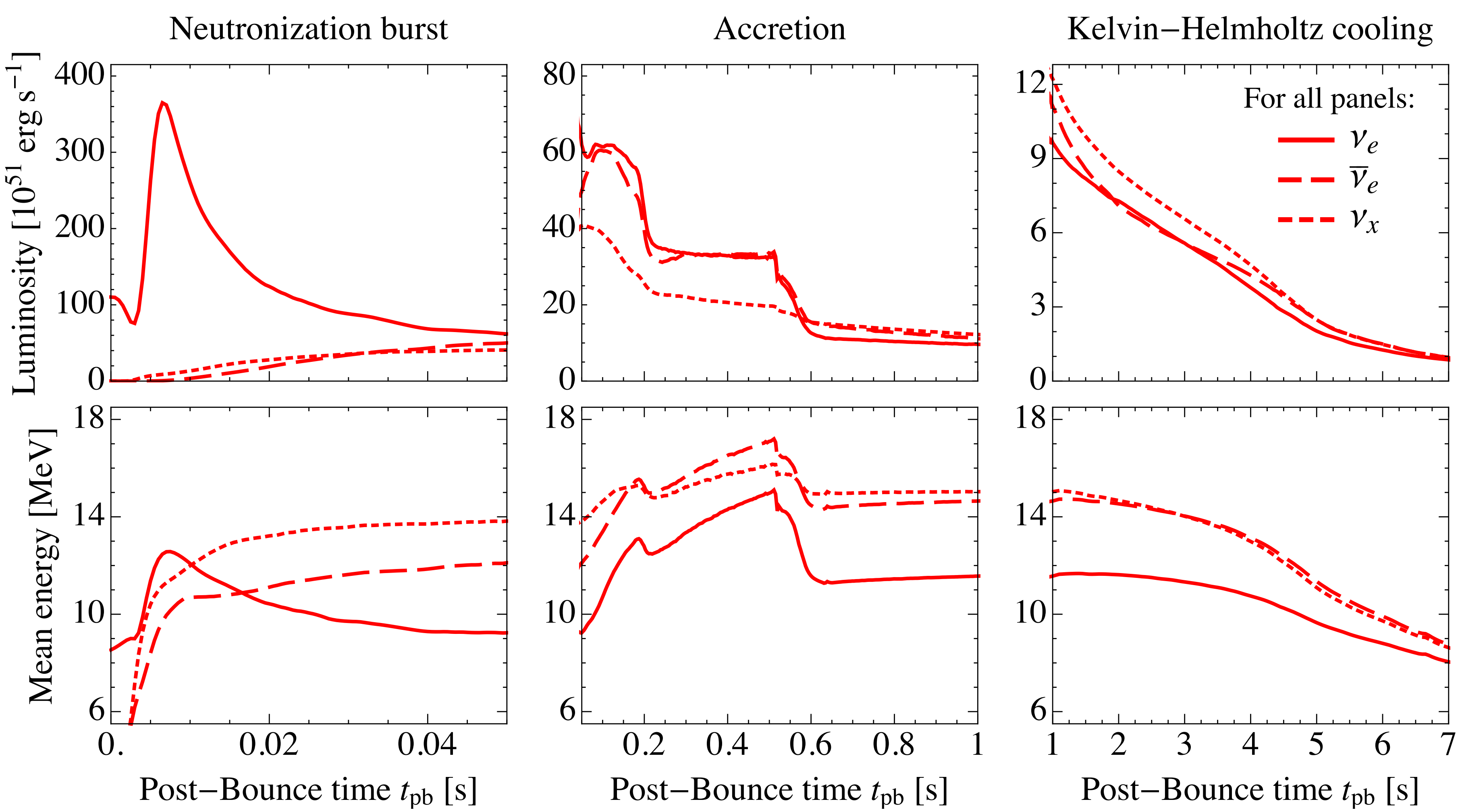
1. Simulating the supernova neutrino signal in a dual-phase xenon detector

Supernova burst neutrino signal

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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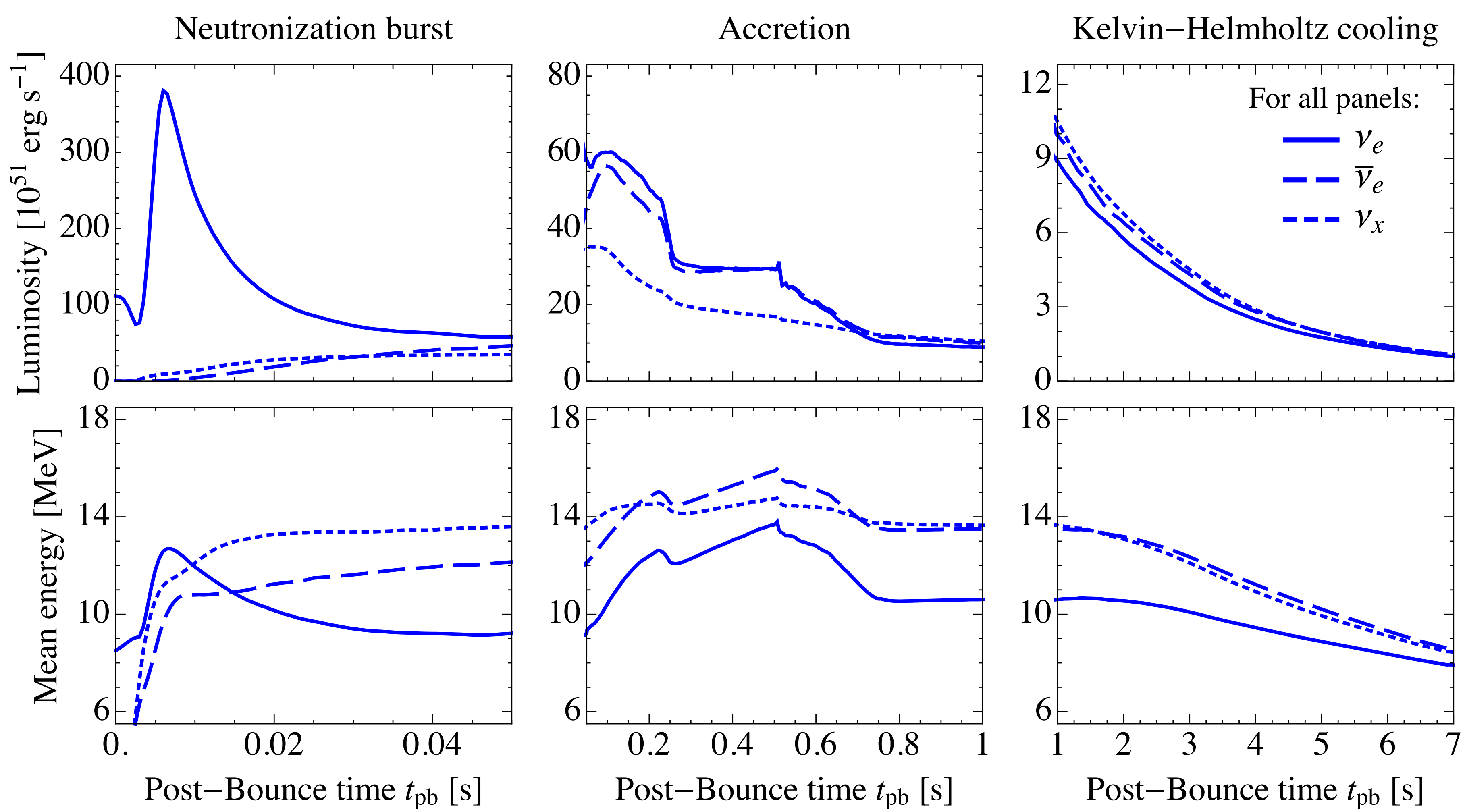

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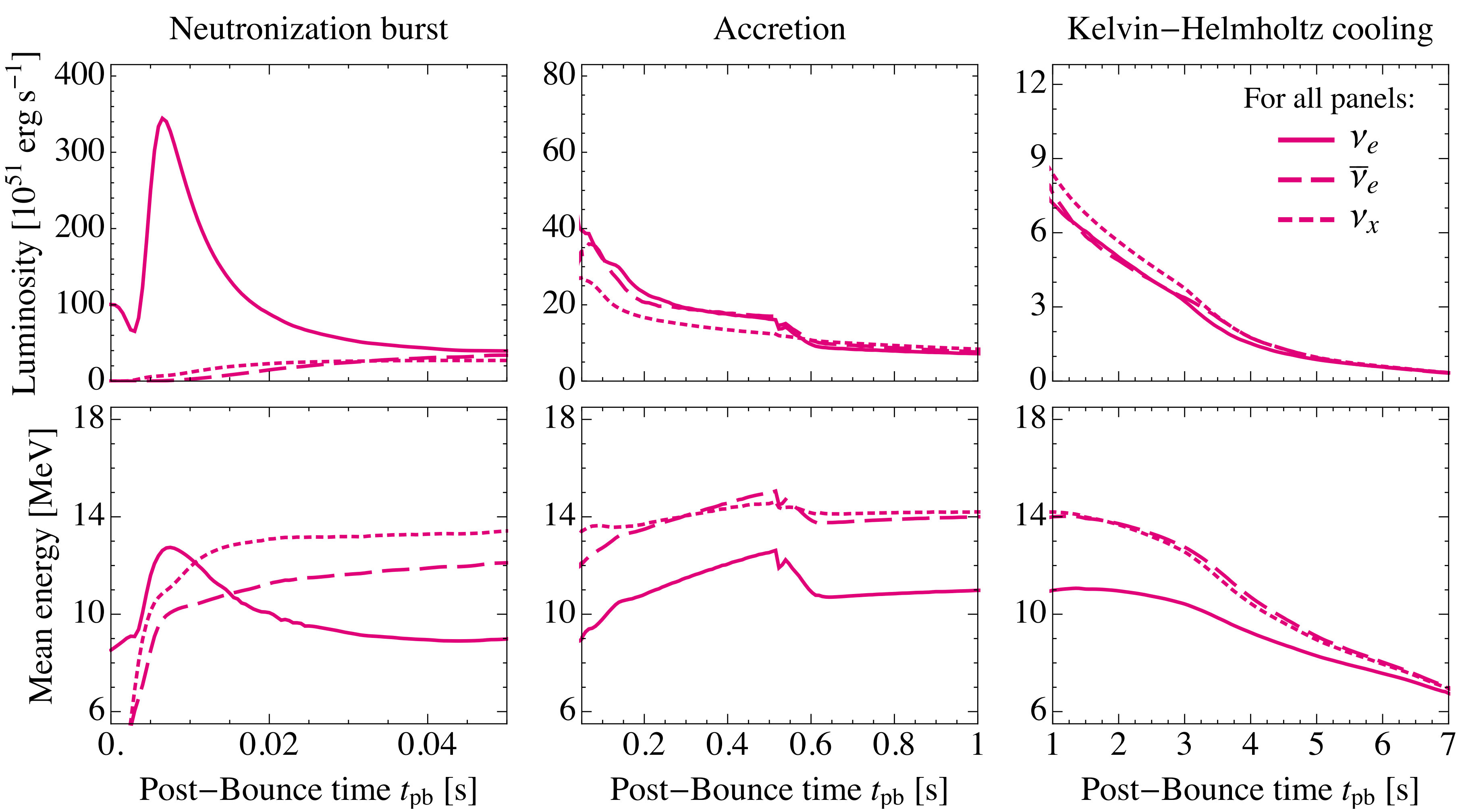

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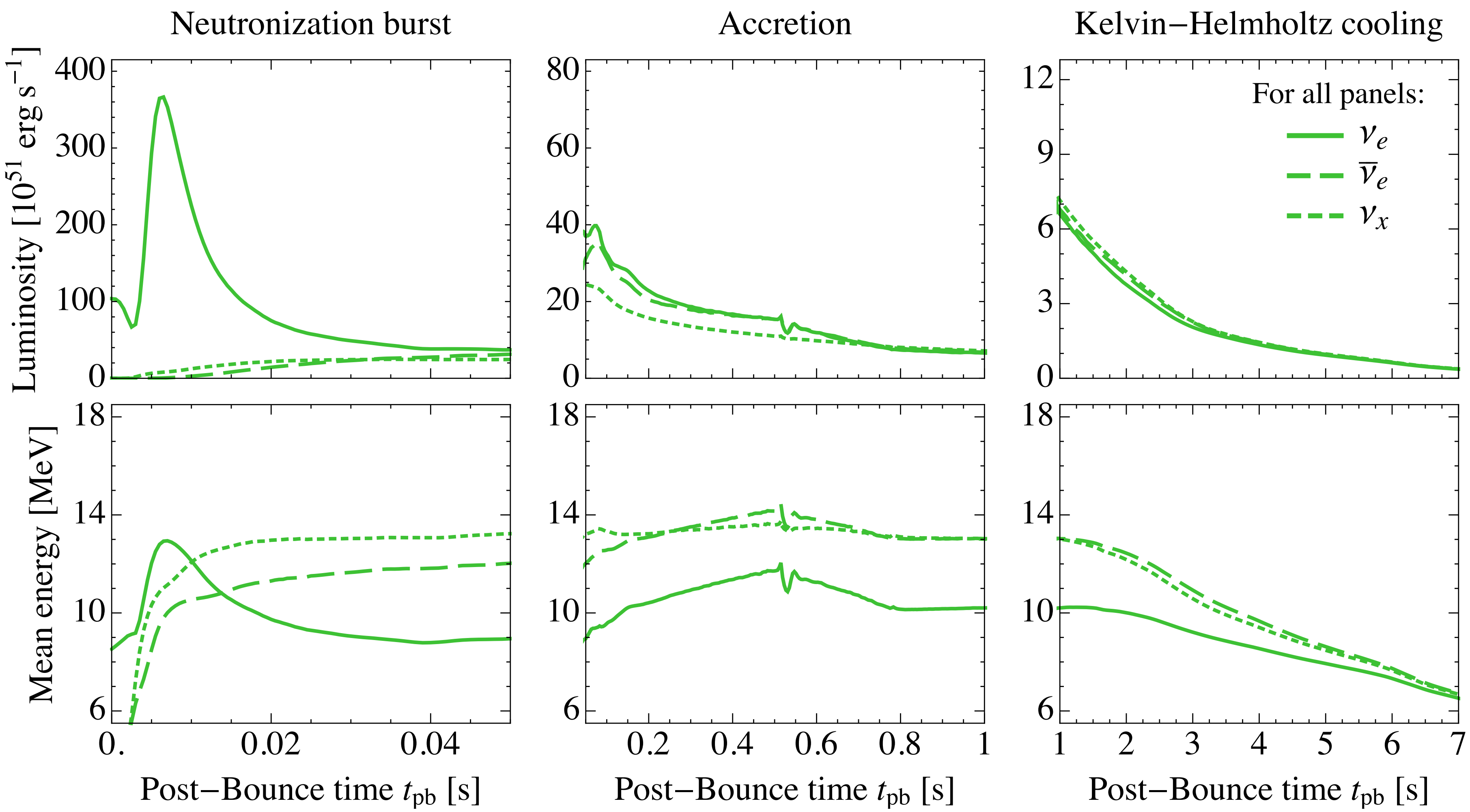
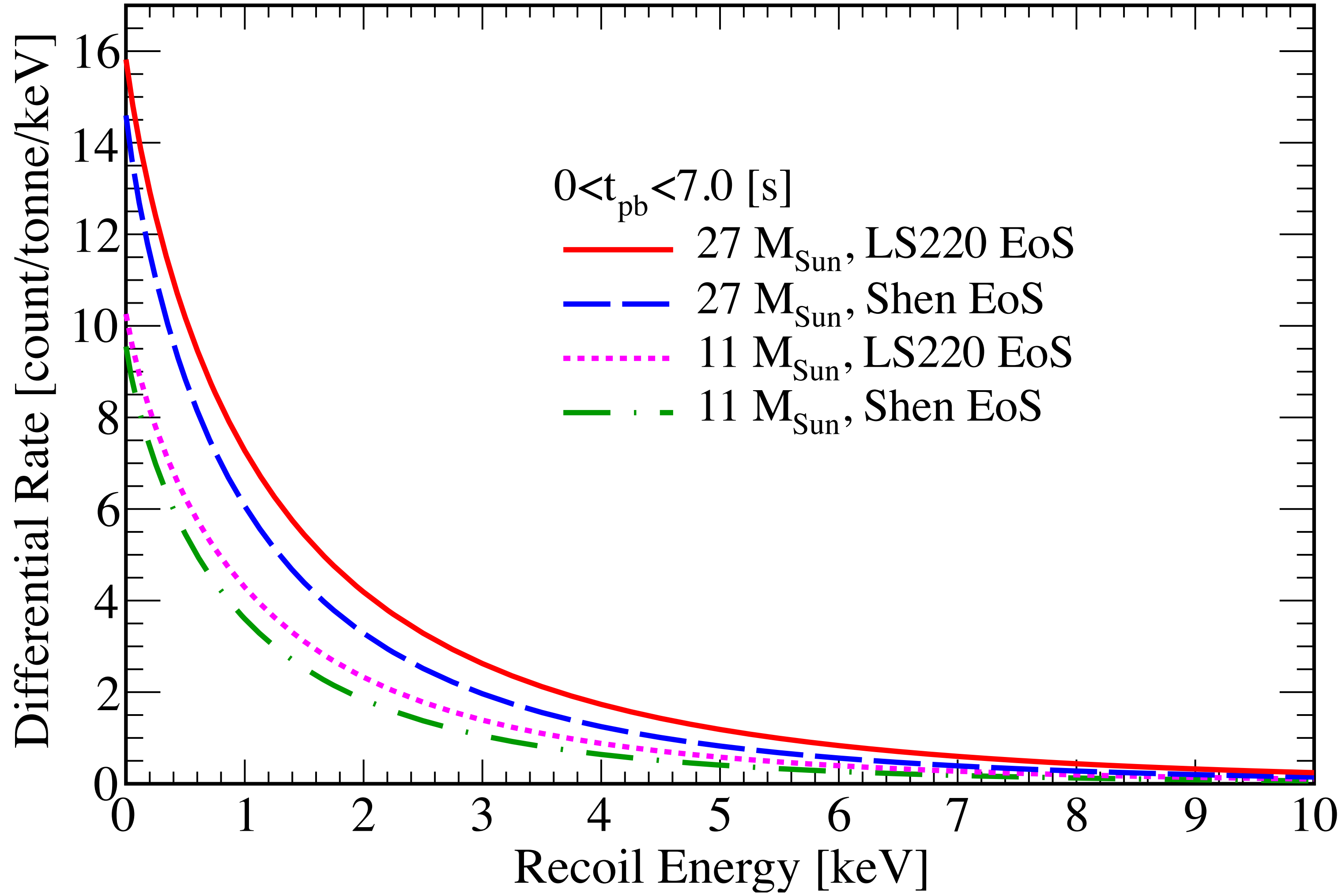


$$\nu_x = \begin{pmatrix} \nu_\mu \\ \bar{\nu}_\mu \\ \nu_\tau \\ \bar{\nu}_\tau \end{pmatrix}$$

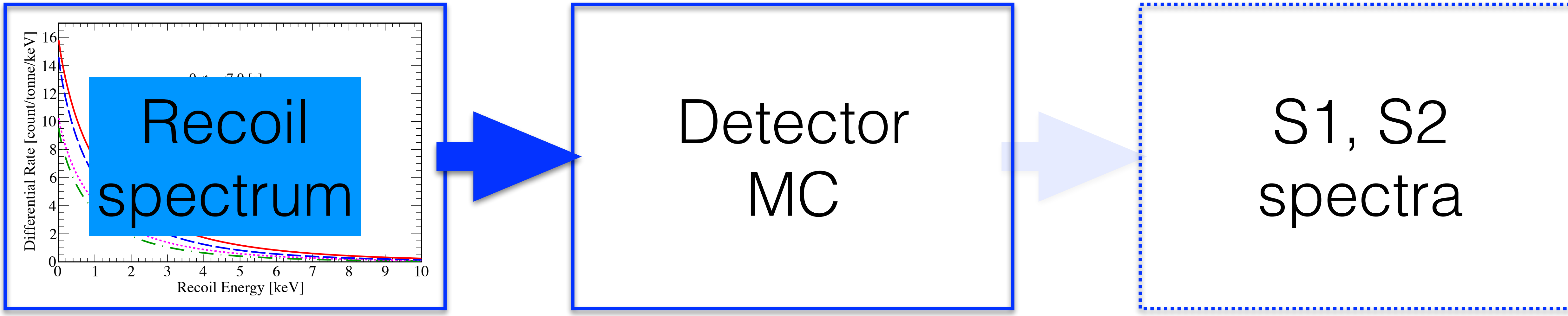
Signal simulation

Recoil spectrum → Detector MC → S1, S2 spectra

Supernova:
10 kpc from Earth

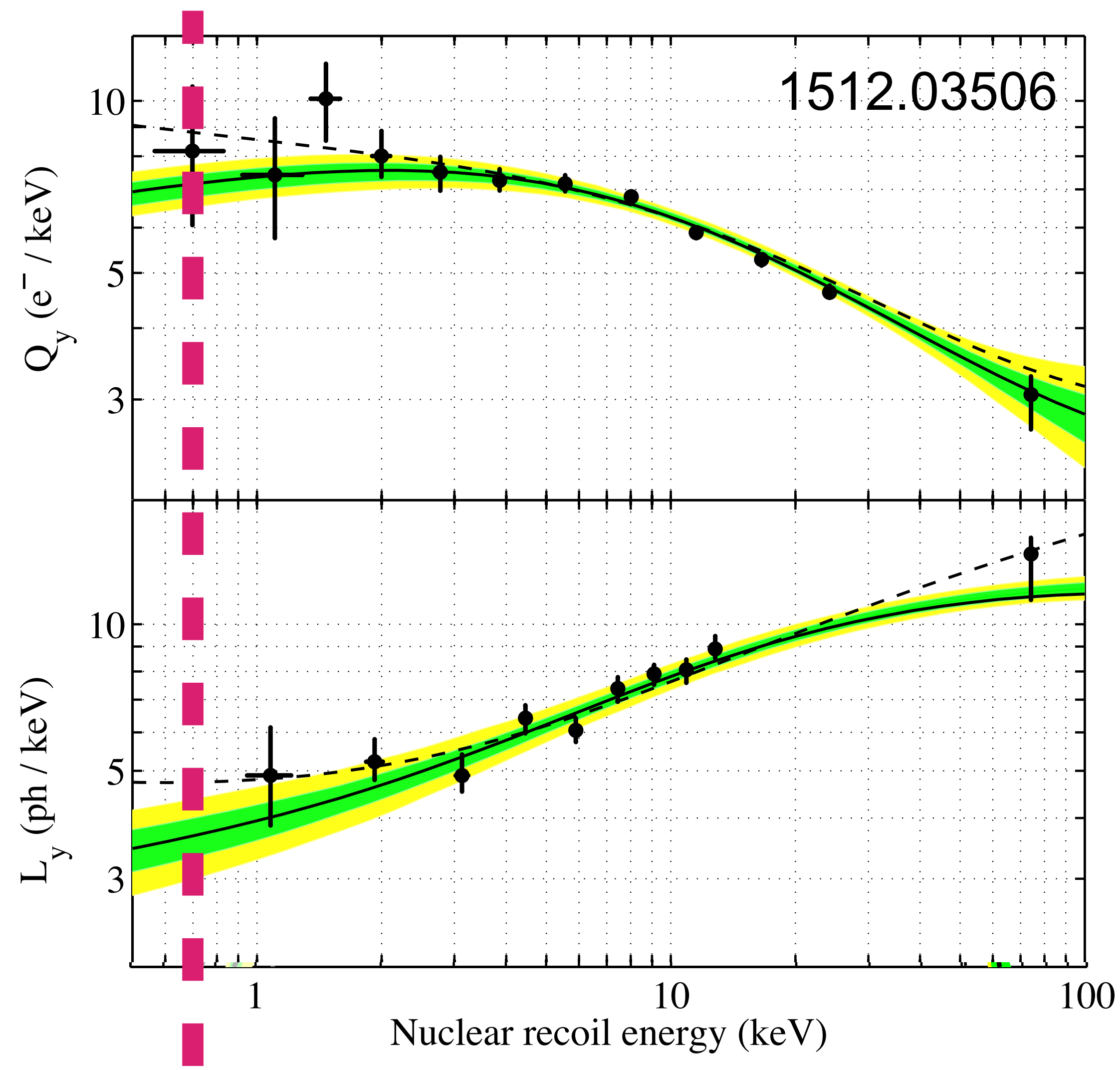


Signal simulation

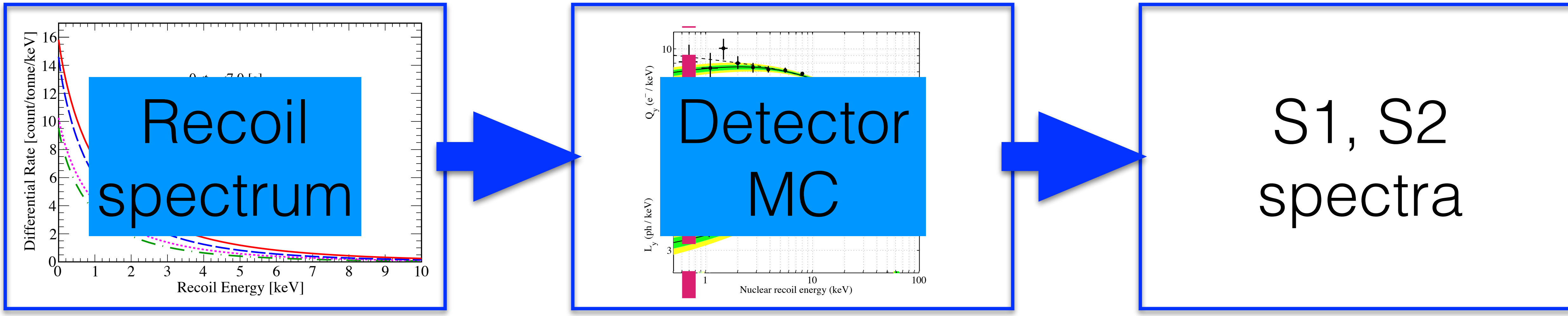


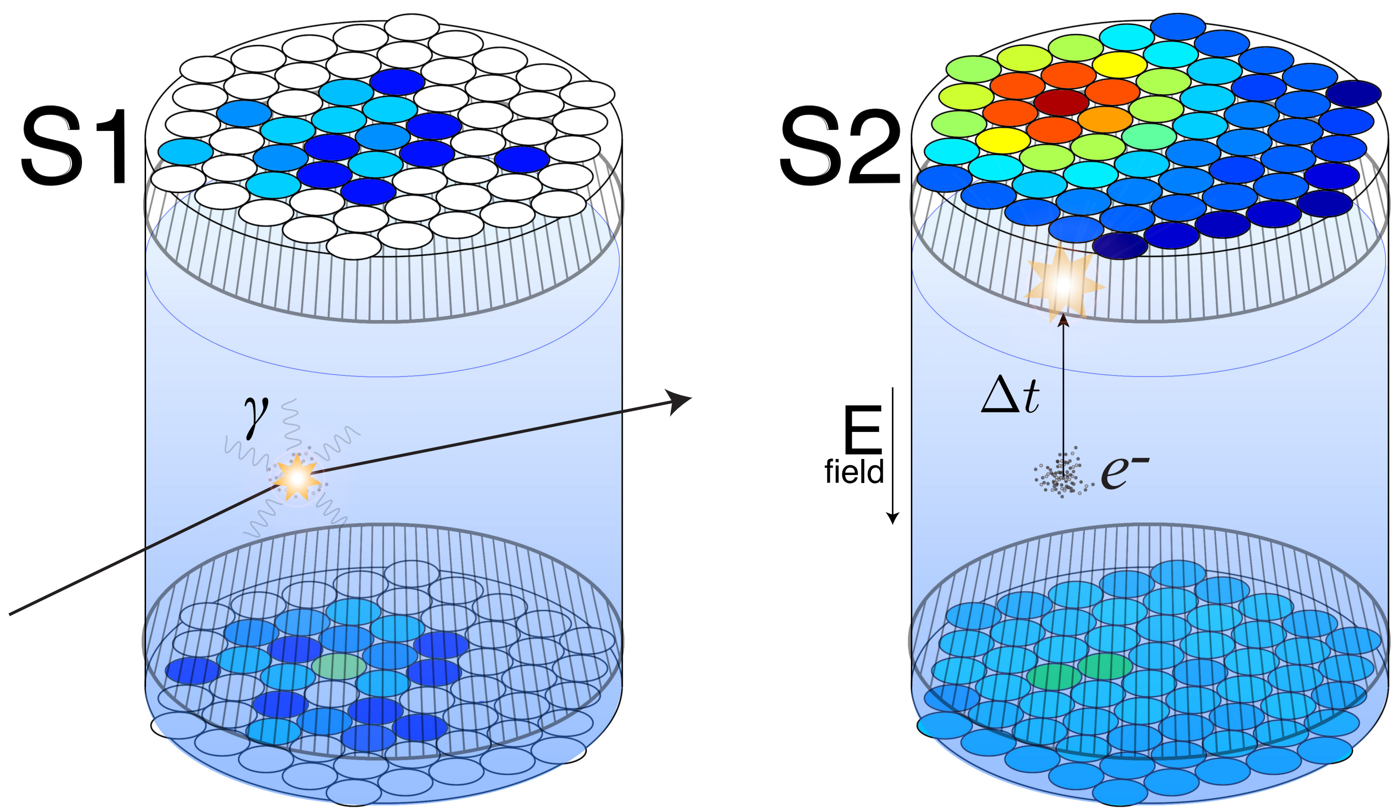
- Detectors calibrated to low energy (0.7 keV)

- Use LUX light and charge yields:

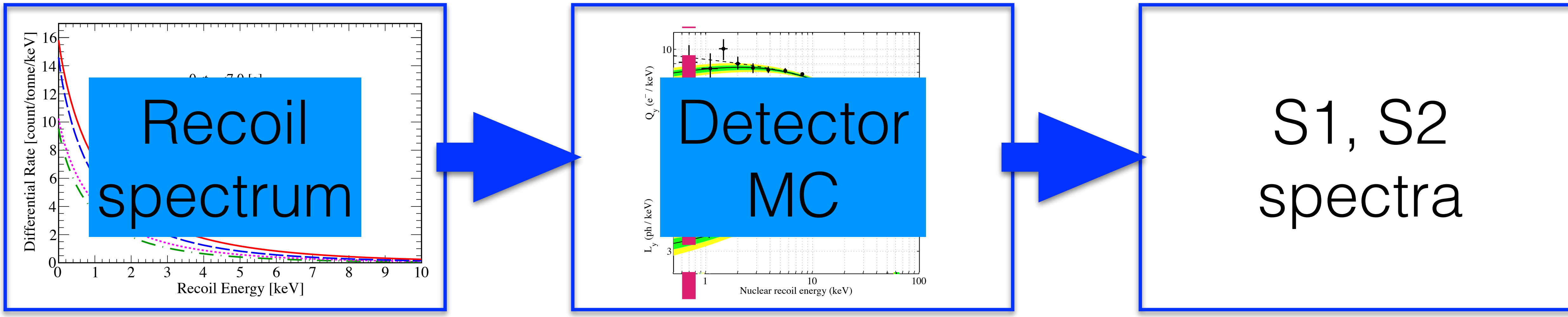


Signal simulation

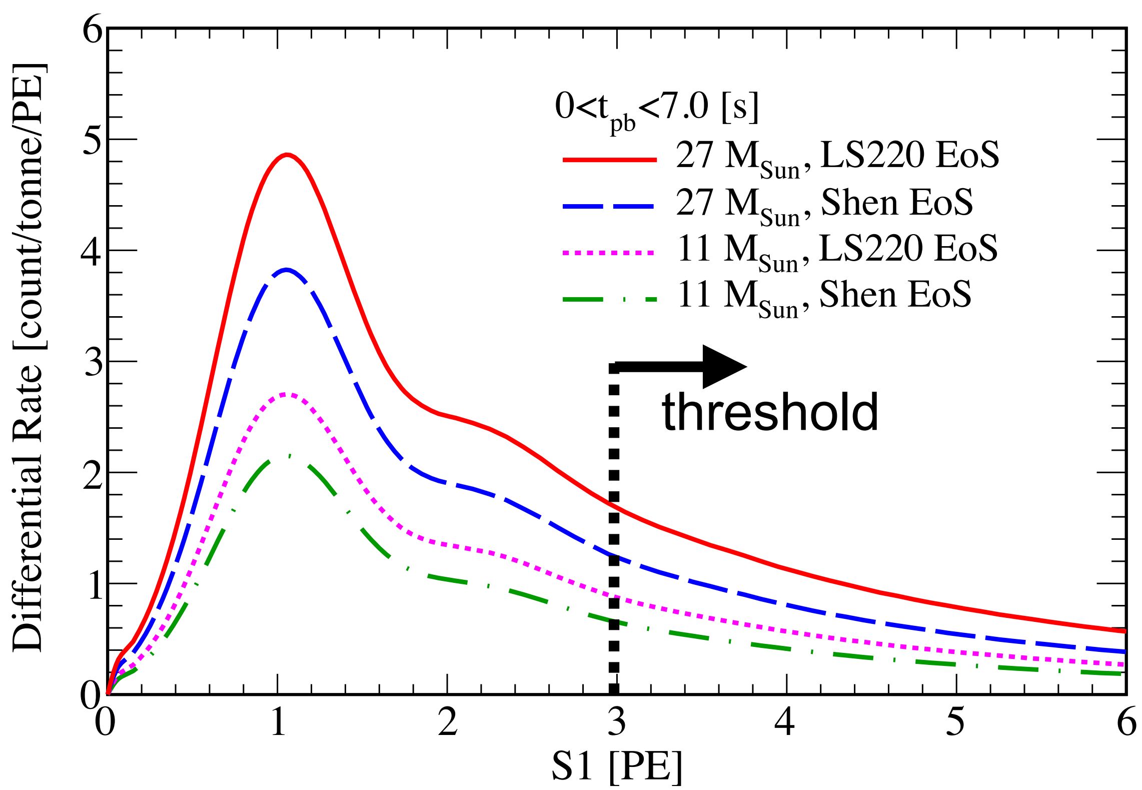


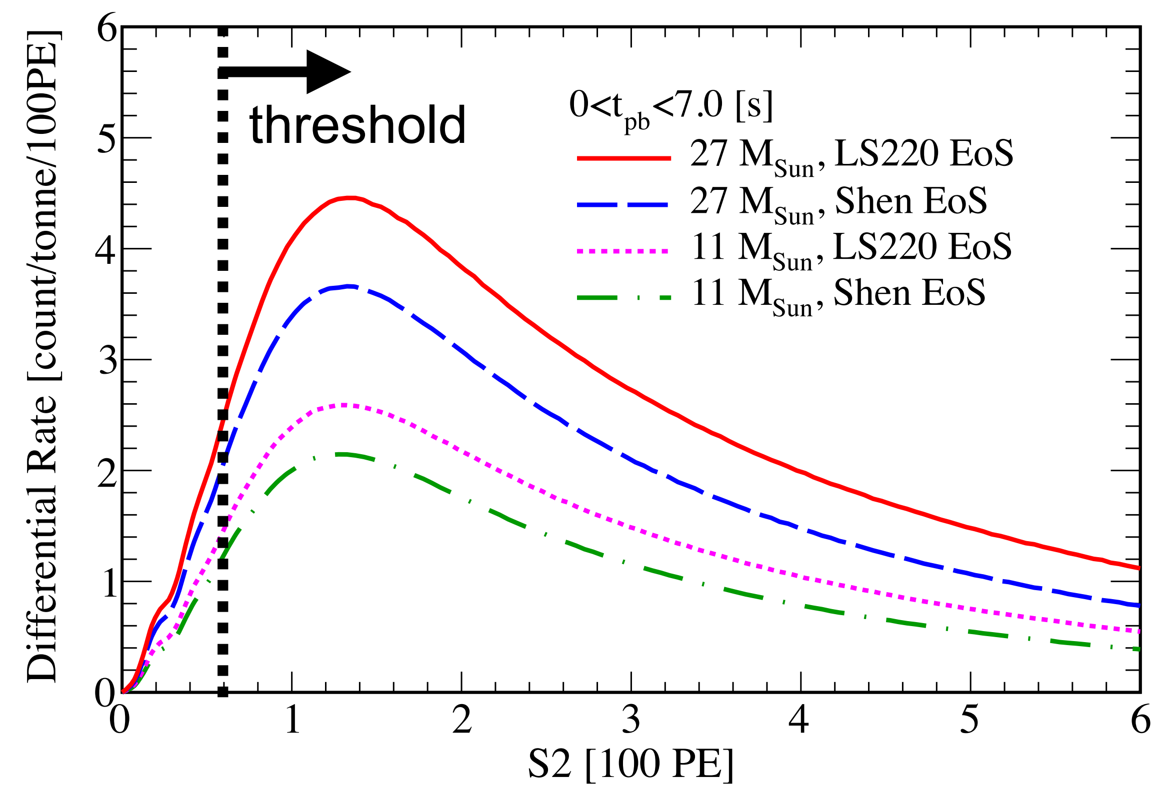


Signal simulation



More events from the S2 channel:





S2 only analysis

- Advantage: higher event rate

- ‘Disadvantages’: no background discrimination…

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

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

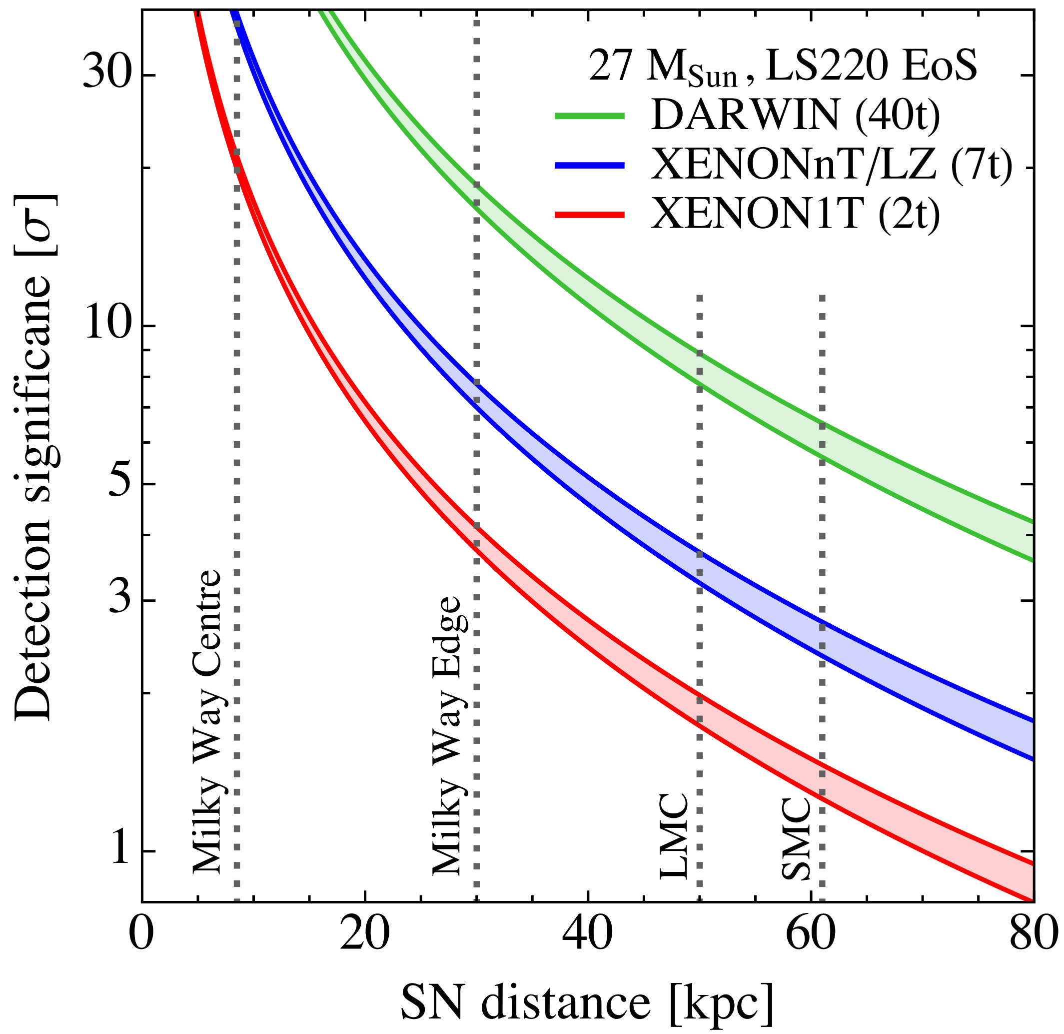
signal: 1-2.5 events/tonne/s *(40-100 x background)*

Extracting information from:

2. the number of events

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 from XENON10 & XENON100 rates

Discovery significance

XENON1T: discovery to 20 kpc
XENONnT/LZ: discovery to Milky Way edge
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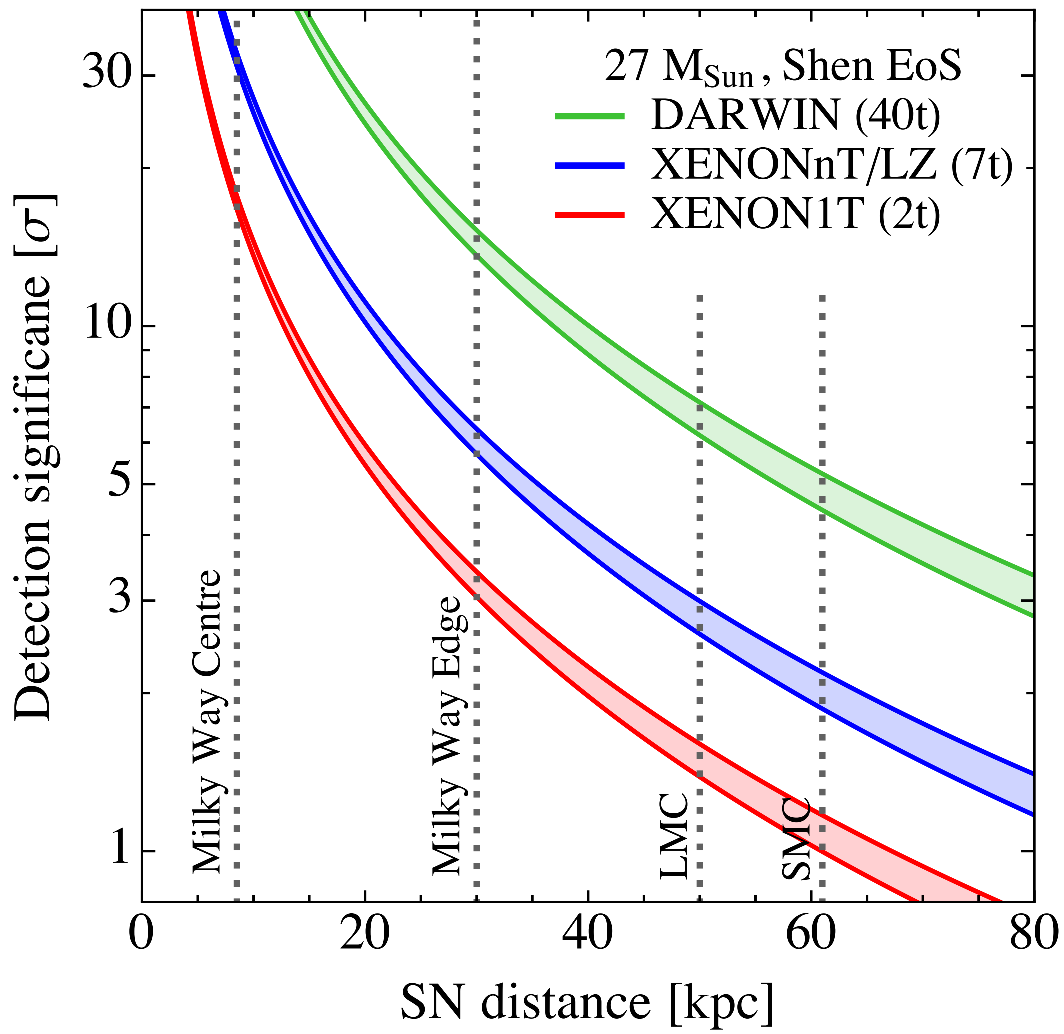

$$\text{XENON1T} : 26.6 \left(\frac{10\ \text{kpc}}{d}\right)^2 \text{events}$$

$$\text{XENONnT/LZ} : 93.1 \left(\frac{10\ \text{kpc}}{d}\right)^2 \text{events}$$

$$\text{DARWIN} : 532 \left(\frac{10\ \text{kpc}}{d}\right)^2 \text{events}$$

Background estimate from XENON10 & XENON100 rates

Discovery significance

XENON1T: discovery to 20 kpc
XENONnT/LZ: discovery to Milky Way edge
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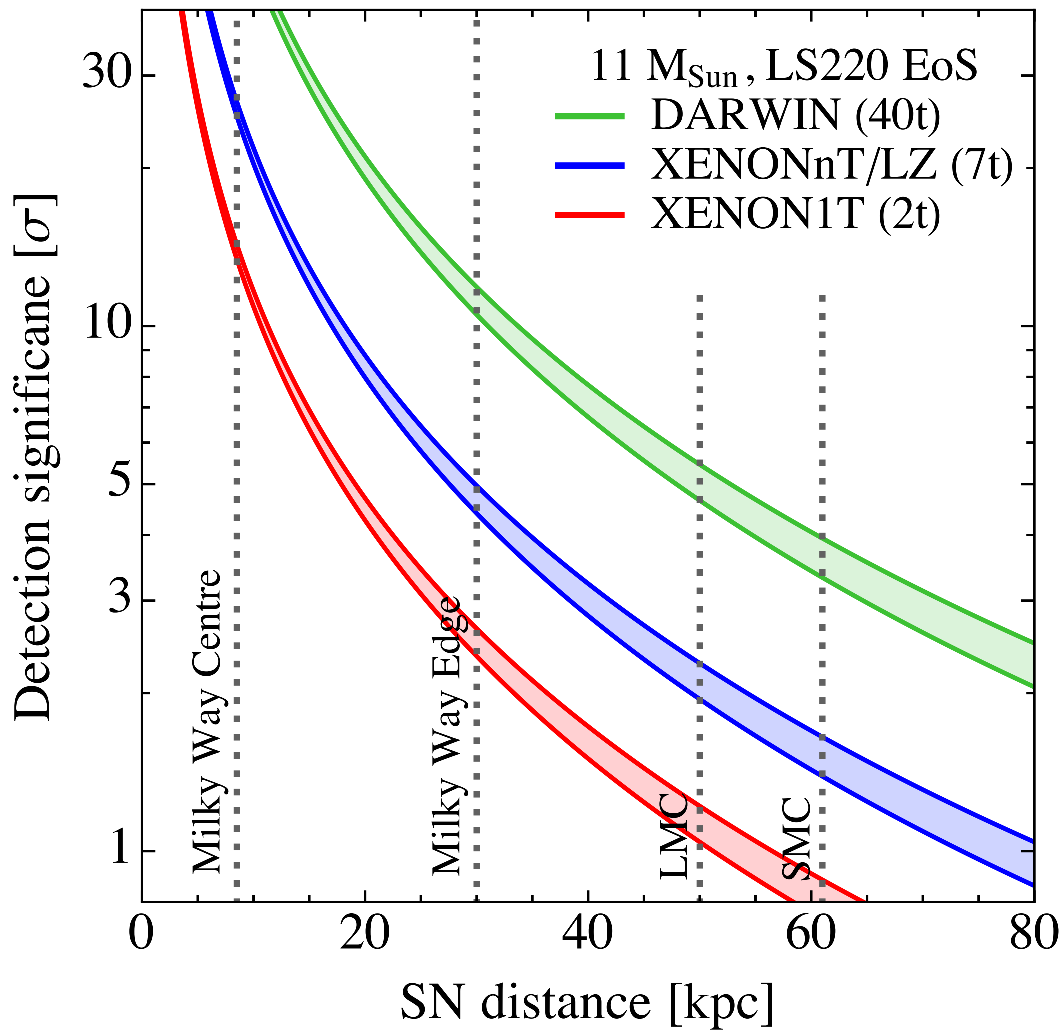

$$\text{XENON1T} : 18.8 \left(\frac{10\ \text{kpc}}{d}\right)^2 \text{events}$$

$$\text{XENONnT/LZ} : 65.8 \left(\frac{10\ \text{kpc}}{d}\right)^2 \text{events}$$

$$\text{DARWIN} : 376 \left(\frac{10\ \text{kpc}}{d}\right)^2 \text{events}$$

Background estimate from XENON10 & XENON100 rates

Discovery significance

XENON1T: discovery to 20 kpc
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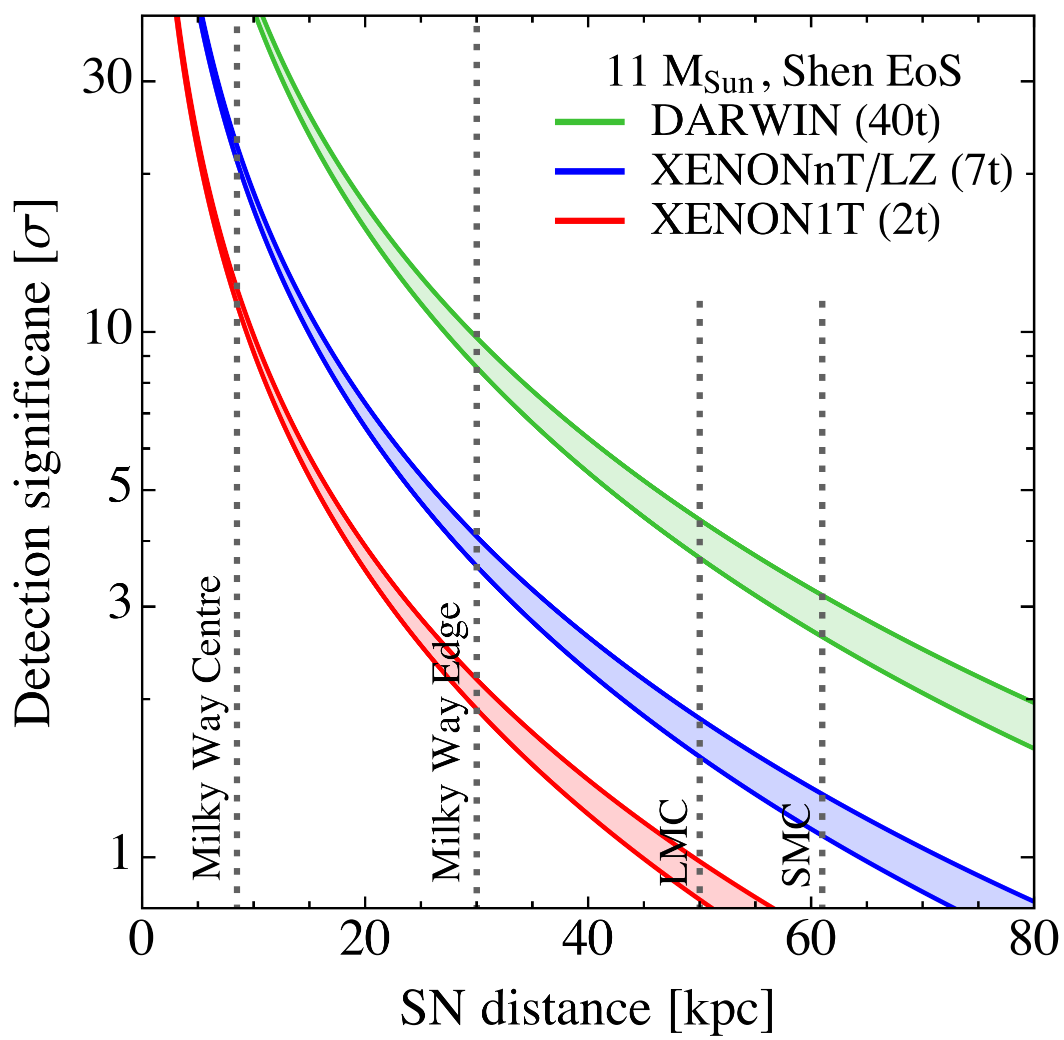


$$\text{XENON1T} : 14.4 \left(\frac{10\ \text{kpc}}{d}\right)^2 \text{events}$$

$$\text{XENONnT/LZ} : 50.4 \left(\frac{10\ \text{kpc}}{d}\right)^2 \text{events}$$

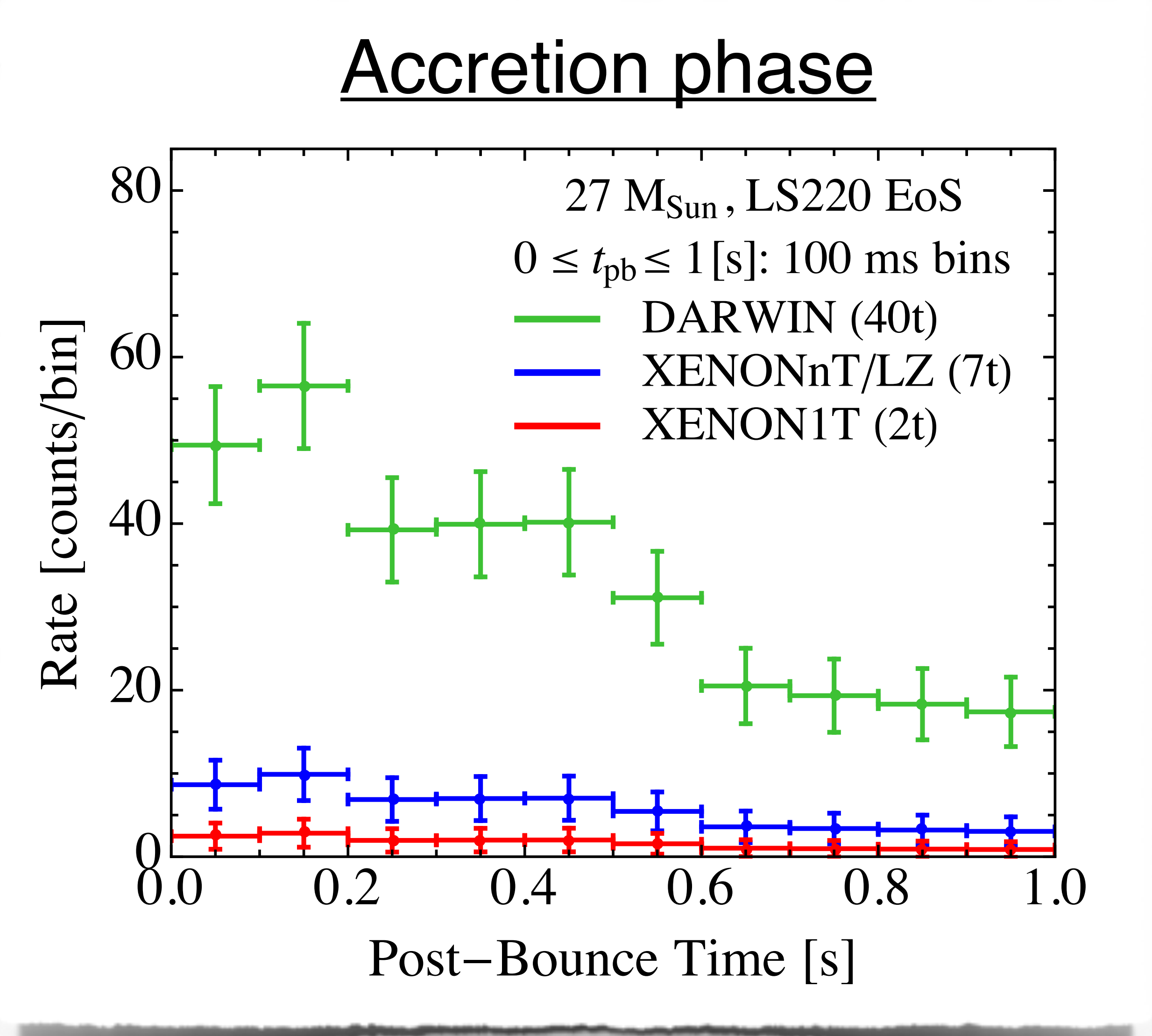
$$\text{DARWIN} : 288 \left(\frac{10\ \text{kpc}}{d}\right)^2 \text{events}$$

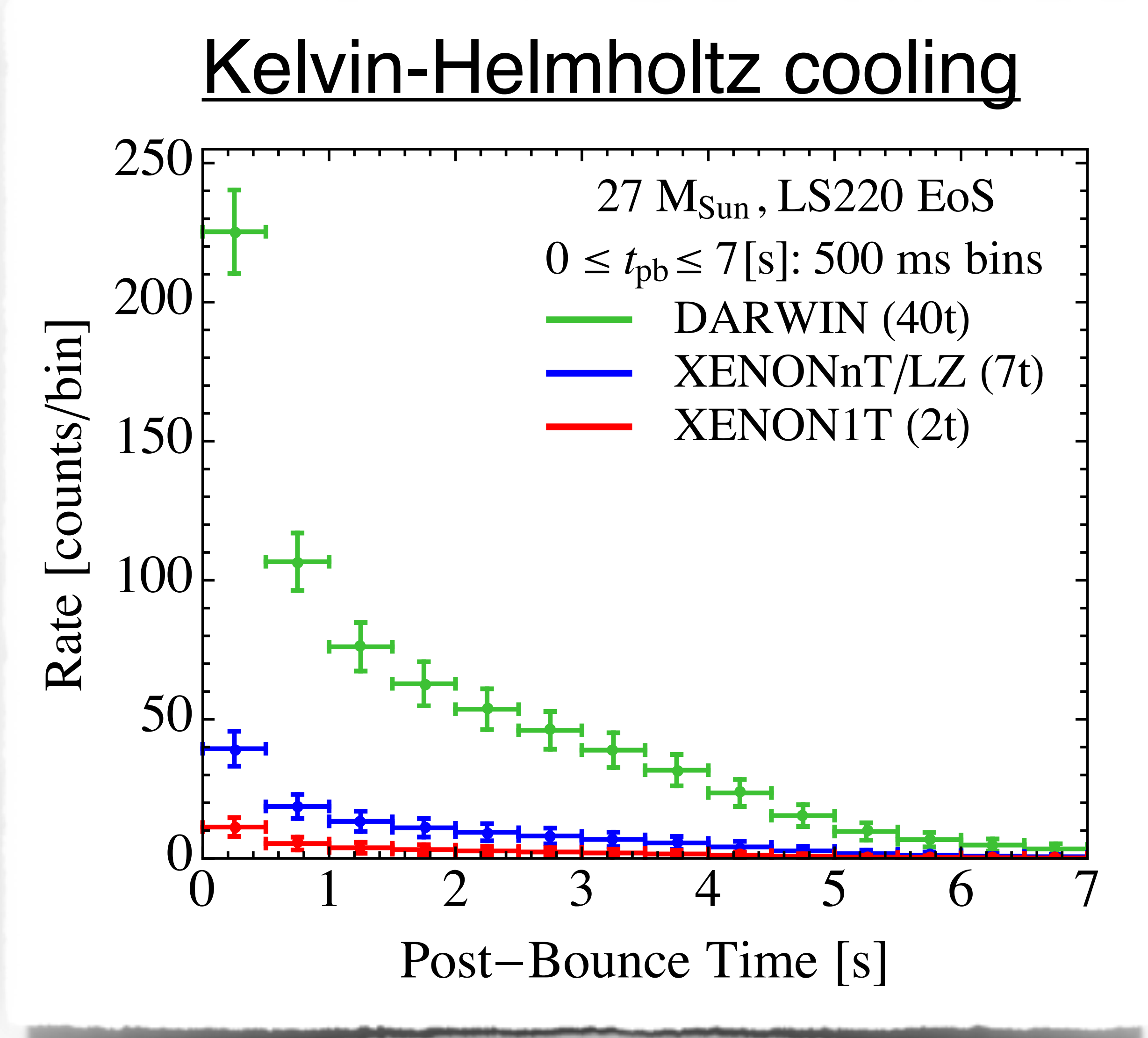
Background estimate from
XENON10 & XENON100 rates

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

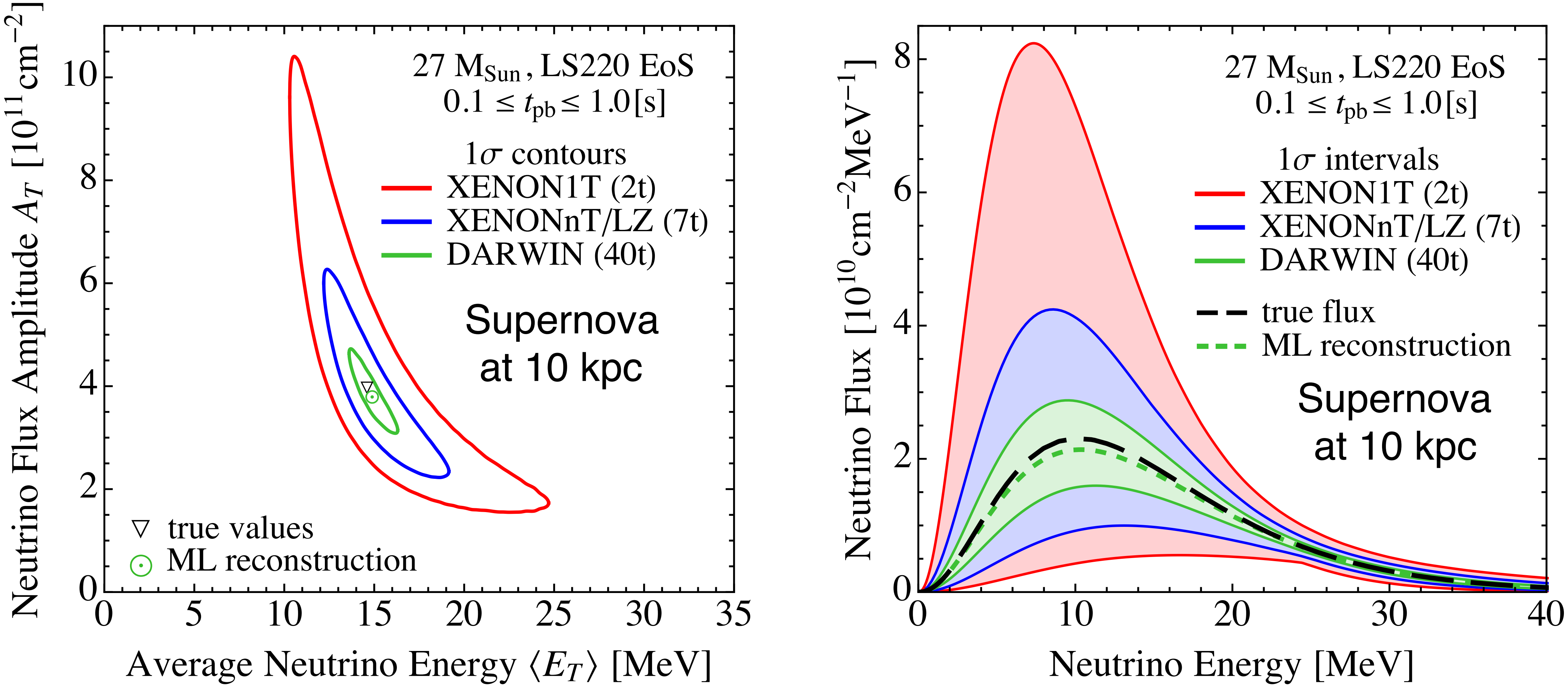
Extracting information from:

3. the shape of the spectral

Spectral rate

- Use S2 spectral information to constrain the 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

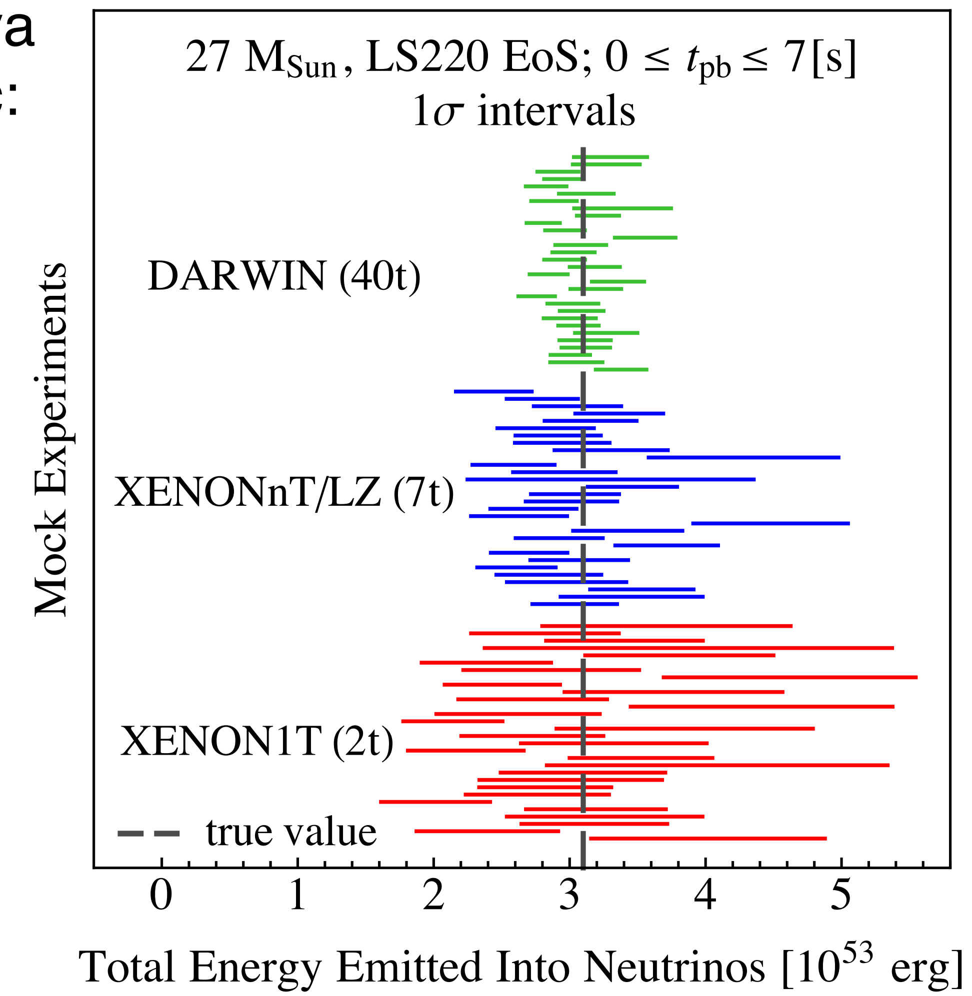


Spectral rate

- Use S2 spectral information to constrain the total neutrino energy
- 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

Supernova at 10 kpc:



precision

$\sim 5\%$

$\sim 10\%$

$\sim 20\%$

- Excellent reconstruction with DARWIN
- XENON1T also good

Physics summary

For a SN at 10 kpc from Earth:

(Recall: 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)	✔	✔	✔	✔

- Unique-selling-point: *sensitive to all neutrino flavours* (not the case for IceCube, DUNE etc)

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- Motivation
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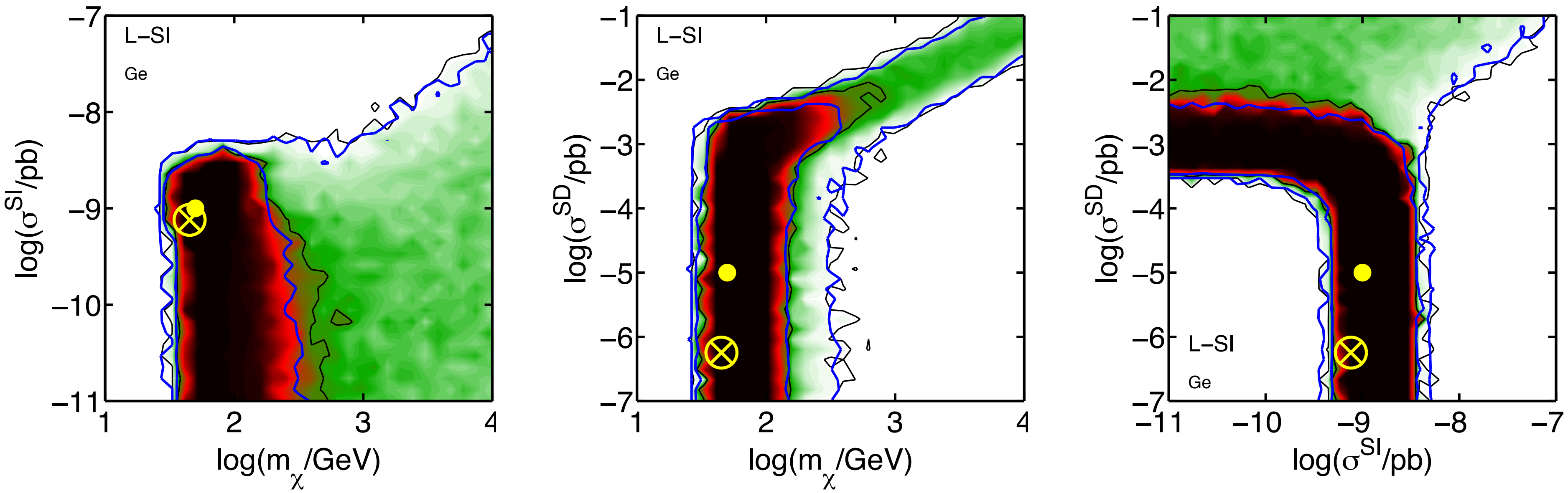
- Thing 2:
  DM exciting the xenon nucleus

Motivation

Example: reconstruction in the usual SI-SD-mass plane

A single experiment cannot determine all the WIMP couplings, a combination of various targets is necessary.



$$\sigma_0^{SI} = 10^{-9}\,\text{pb}$$
$$\sigma_0^{SD} = 10^{-5}\,\text{pb}$$
$$m_W = 50\,\text{GeV}$$
$$\epsilon = 300\,\text{kg yr}$$

We use simulated data to assess the reconstruction of DM parameters

Prospects for SuperCDMS (Ge)

Recent talk by David Cerdeno

An old idea…

- The original direct detection paper:

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

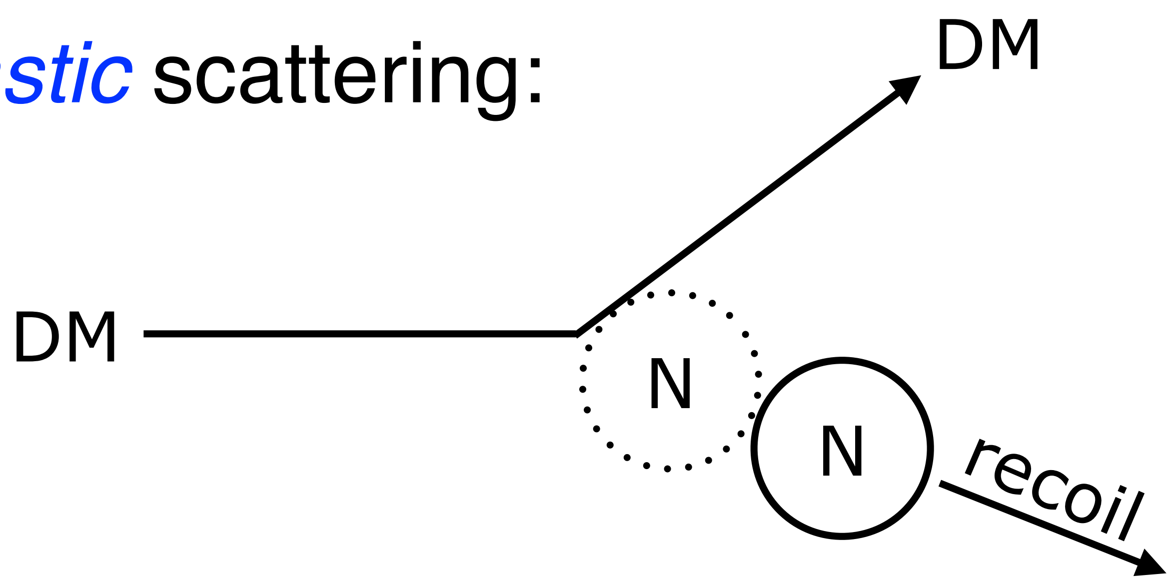
Aside from the detector proposed in Ref. 5, an interesting possibility is to detect dark-matter particles via inelastic rather than elastic scattering from nuclei.

Outline

1. What is it?
2. Why is it interesting?
3. Can it ever be detected?

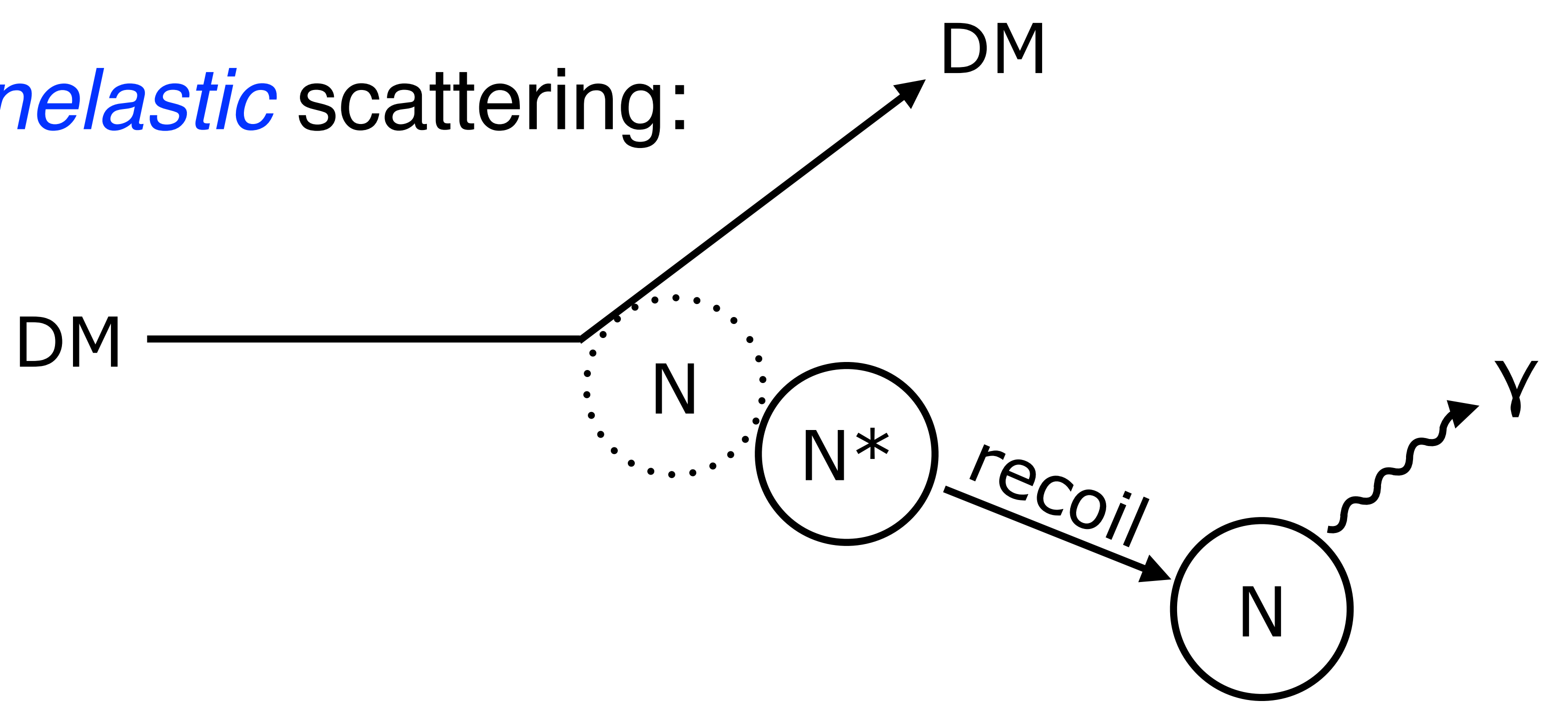
What is it?

elastic scattering:



measure:
N's recoil energy

inelastic scattering:



measure:
N's recoil energy
+ *photon energy*

Xenon is an ideal target

- Two isotopes are good candidates:

^{129}Xe

Natural abundance: 26.4%

Lowest excitation: **39.6 keV**

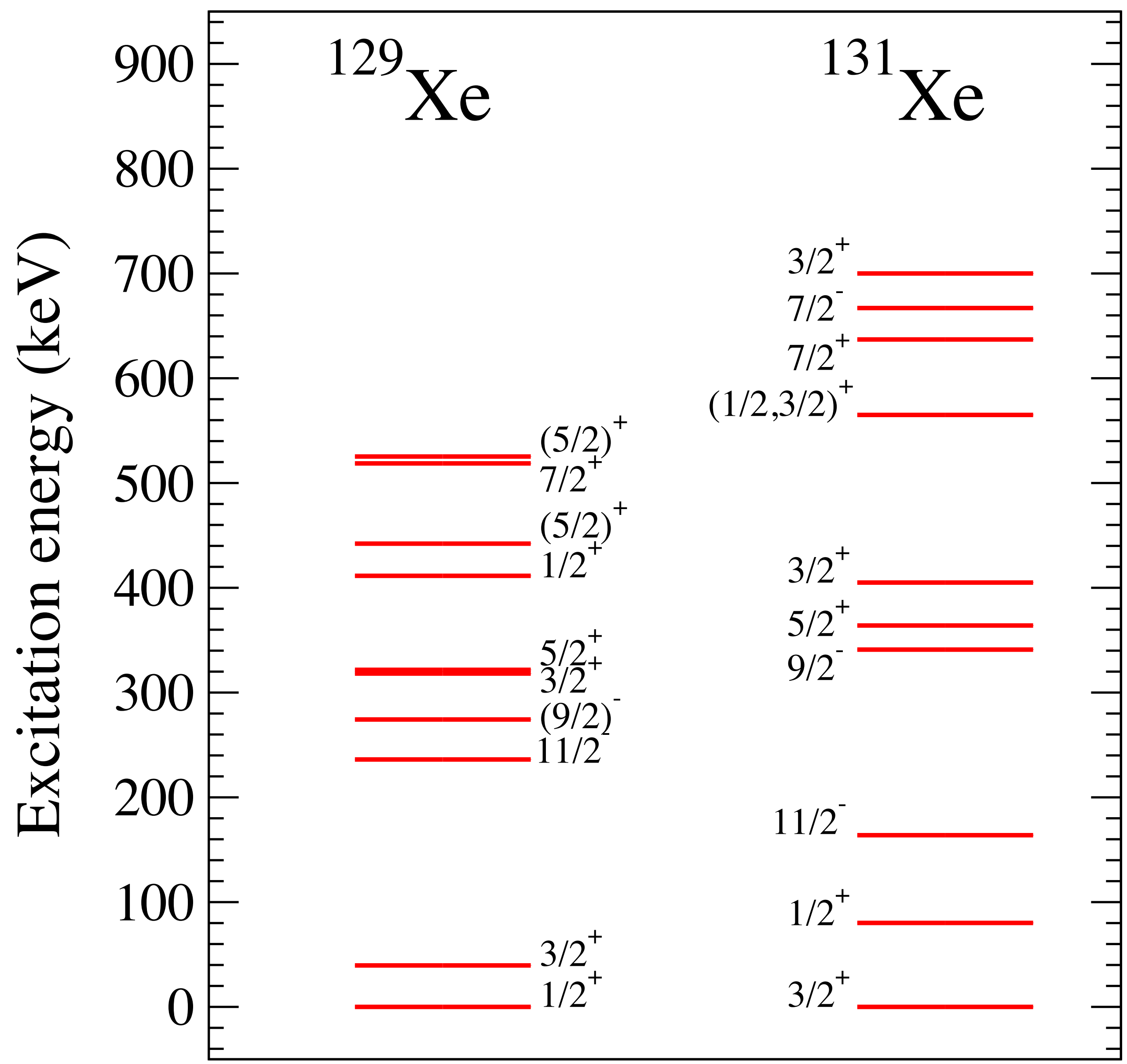
Lifetime: 0.97 ns

^{131}Xe

Natural abundance: 21.2%

Lowest excitation: **80.2 keV**

Lifetime: 0.48 ns



Previous studies

- Previous searches with single phase-detectors:

Limits on WIMP-^{129}Xe inelastic scattering

P. Belli [a], R. Bernabei [a], V. Landoni [a], F. Montecchia [a], W. Di Nicolantonio [b], A. Incicchitti [b], D. Prosperi [b], C. Bacci [c], D.J. Dai [d]

[a] *Dipartimento di Fisica, Universitá di Roma "Tor Vergata" and INFN, sez. Roma2, Rome, Italy*
[b] *Dipartimento di Fisca, Universitá di Roma "La Sapienza" and INFN, sez. Roma, Rome, Italy*
[c] *Dipartimento di Fisica, Universitá di Roma III and INFN, sez. Roma, Rome, Italy*
[d] *IHEP, Chinese Academy, P.O. Box 918/3, Beijing 100039, China*

Received 20 May 1996; revised manuscript received 27 June 1996

PTEP

Prog. Theor. Exp. Phys. **2014**, 063C01 (11 pages)
DOI: 10.1093/ptep/ptu064

Search for inelastic WIMP nucleus scattering on ^{129}Xe in data from the XMASS-I experiment

- *No limits/studies for two-phase detectors (LUX, XENON)*

Outline

1. What is it?
   - *Excite nucleus: measure recoil + photon*

2. Why is it interesting?

3. Can it ever be detected?

Why is it interesting?

★ **Tells us about the dark matter-quark interaction**

Inelastic scattering *is not* A^2 enhanced

★ **Only measurable for spin-dependent interactions**

➡ Elastic and inelastic scattering rates comparable

Baudis et al 1309.0825   Vietze et al 1412.6091

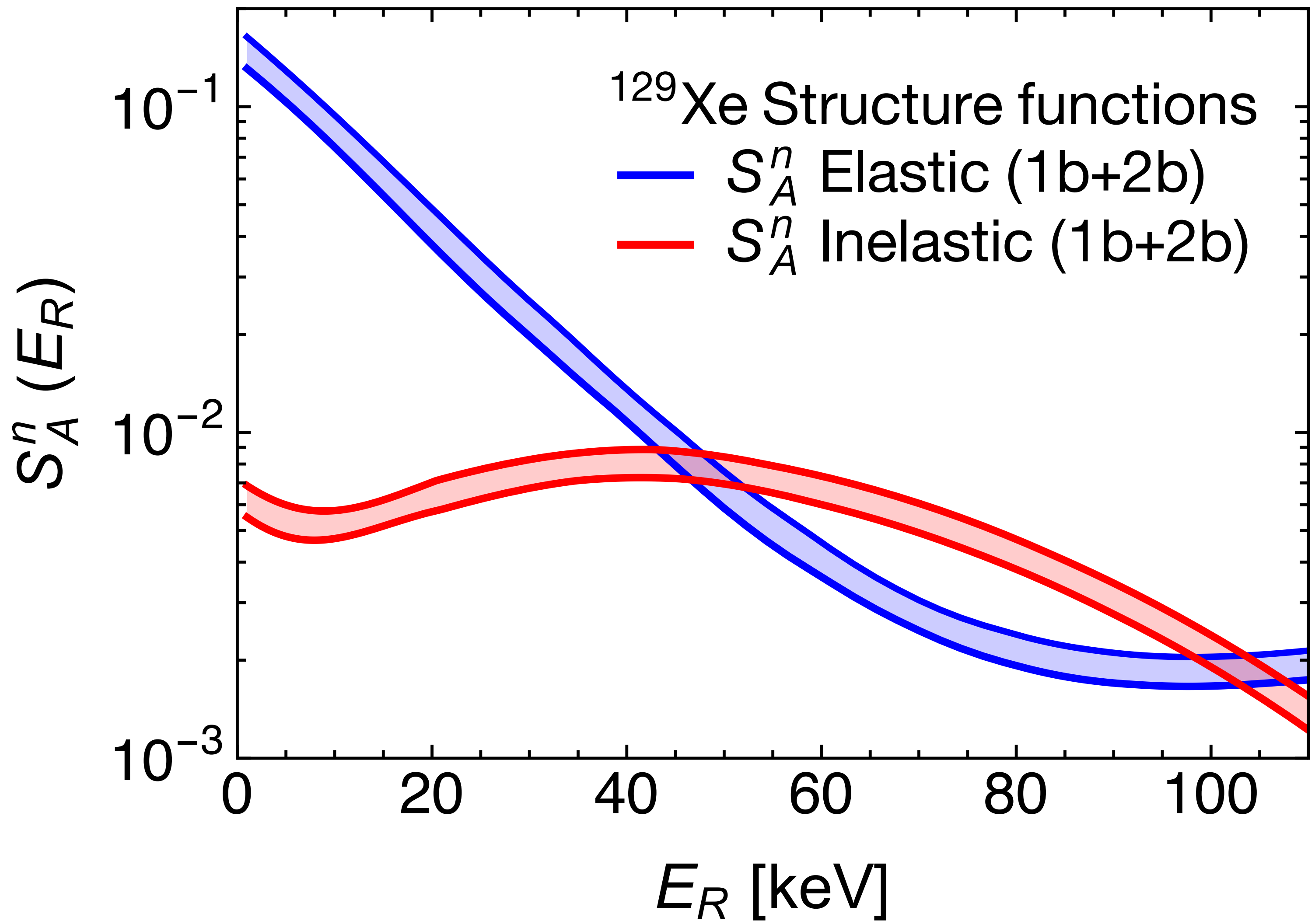
Spin dependent (SD)

- Rate depends on the structure functions (SF)

$$\frac{d\sigma}{dE_{\mathrm{R}}} \propto S_A^n = \left|\langle \mathrm{Xe}^* | \bar{\psi}_q \gamma_\mu \gamma^5 \psi_q | \mathrm{Xe} \rangle\right|^2$$

- Inelastic SF factor ~10 smaller than elastic SF

Naive estimate: after discovery, need a detector at least ~10 times larger to detect inelastic signal ✔



Baudis et al 1309.0825

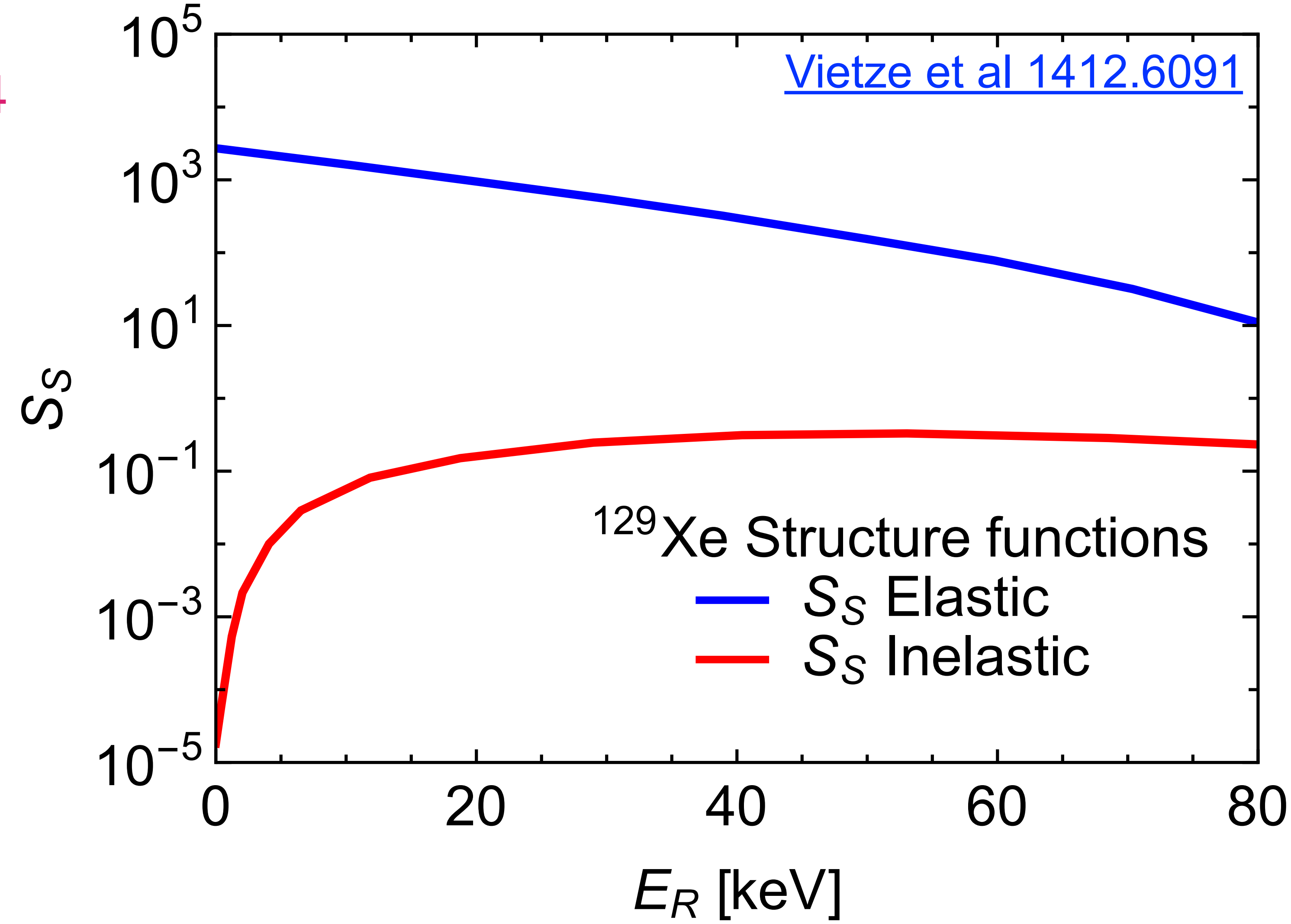
Spin Independent (SI)

- Rate depends on the structure functions (SF)

$$\frac{d\sigma}{dE_{\rm R}} \propto S_S = \left|\langle {\rm Xe}^* | \bar{\psi}_q \psi_q | {\rm Xe} \rangle\right|^2$$

- Inelastic SF factor ~10^4 smaller than elastic SF

Naive estimate: after discovery, need a detector at least ~10^4 times larger to detect inelastic signal ✗



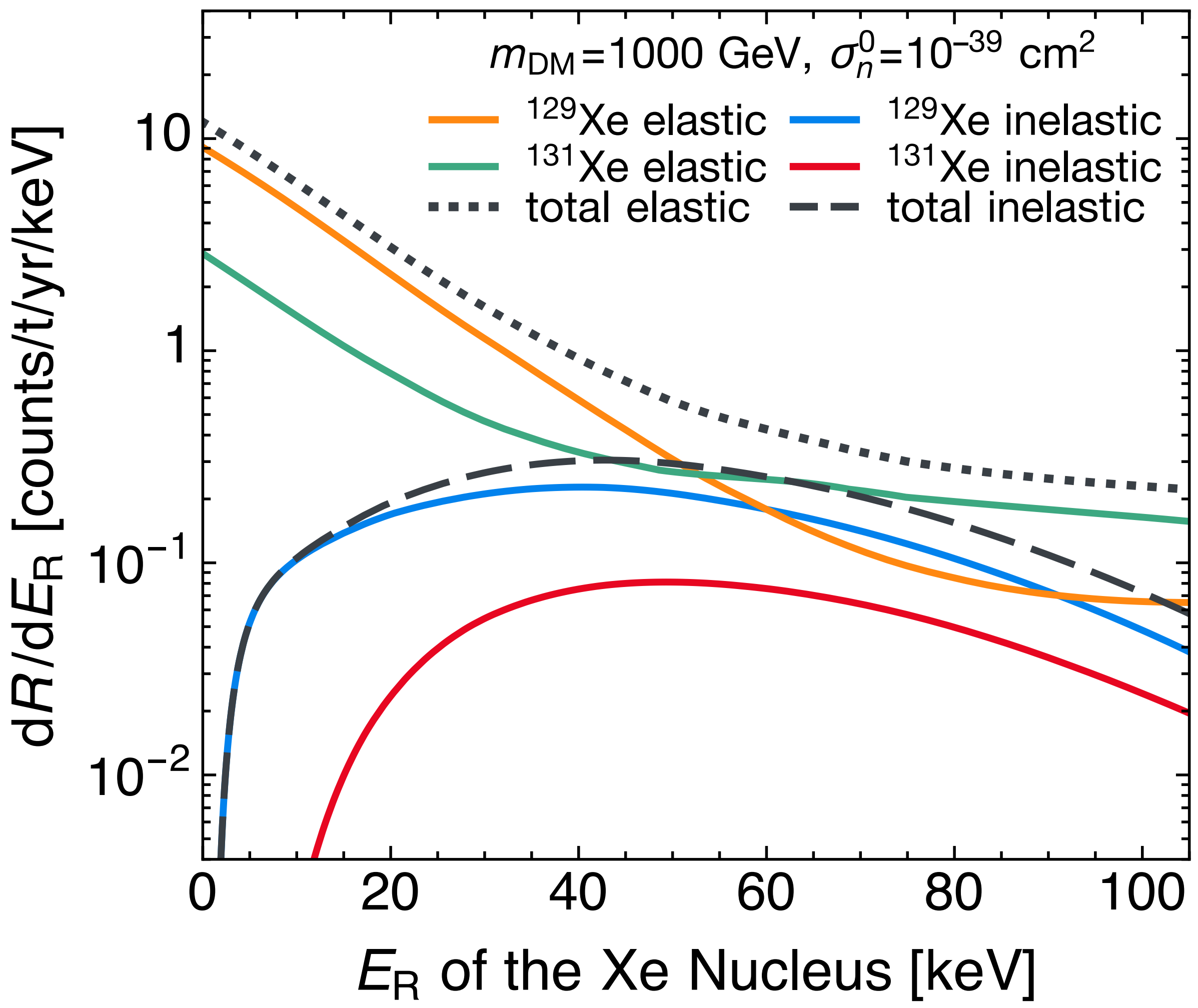
★ **Only measurable for spin-dependent interactions**

Outline

1. What is it?
   - *Excite nucleus: measure recoil + photon*
2. Why is it interesting?
   - *Discriminate between SI and SD interactions*
3. Can it ever be detected?

Spin dependent signal rates

- Rate as a function recoil energy (not directly measured)

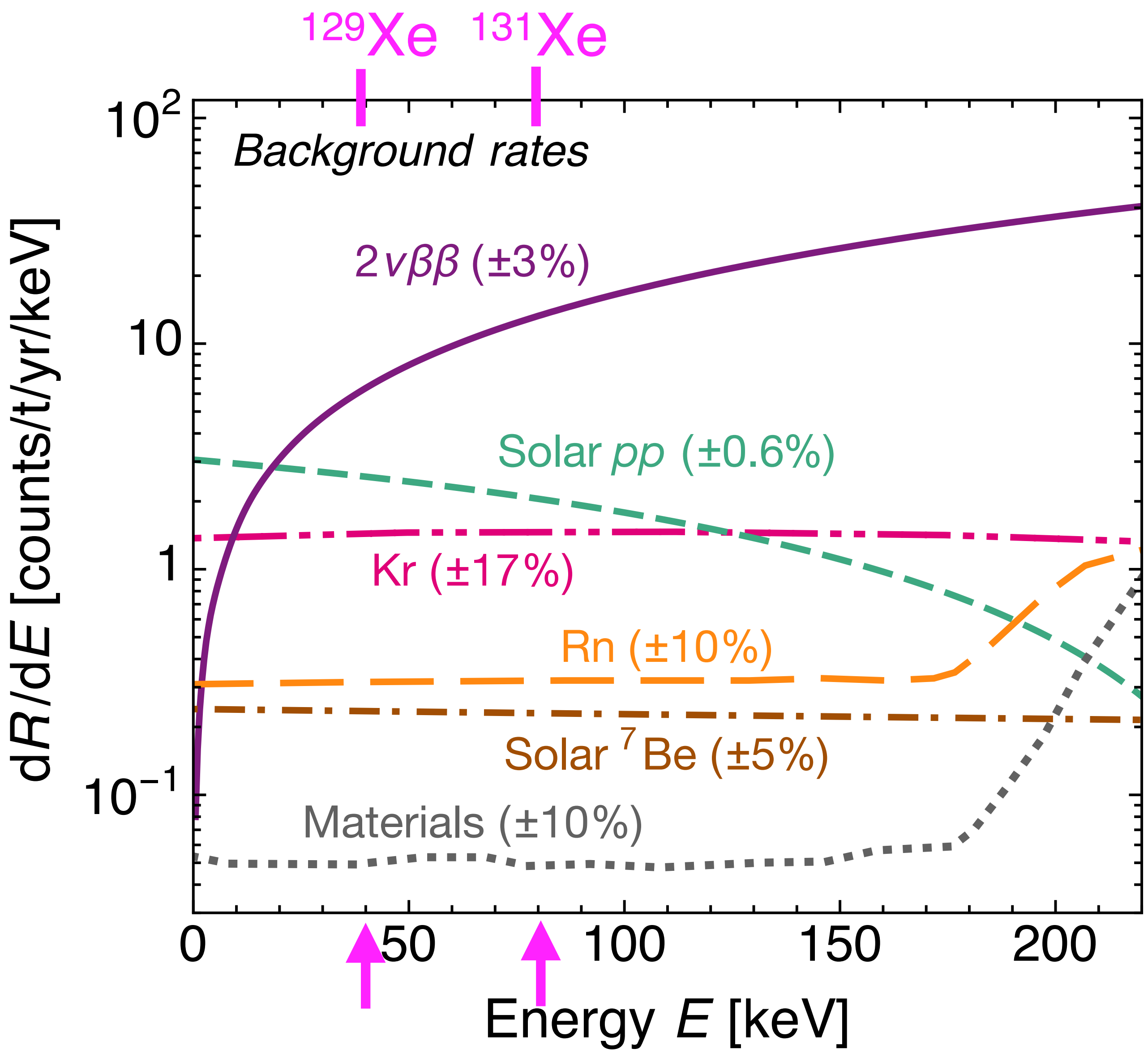


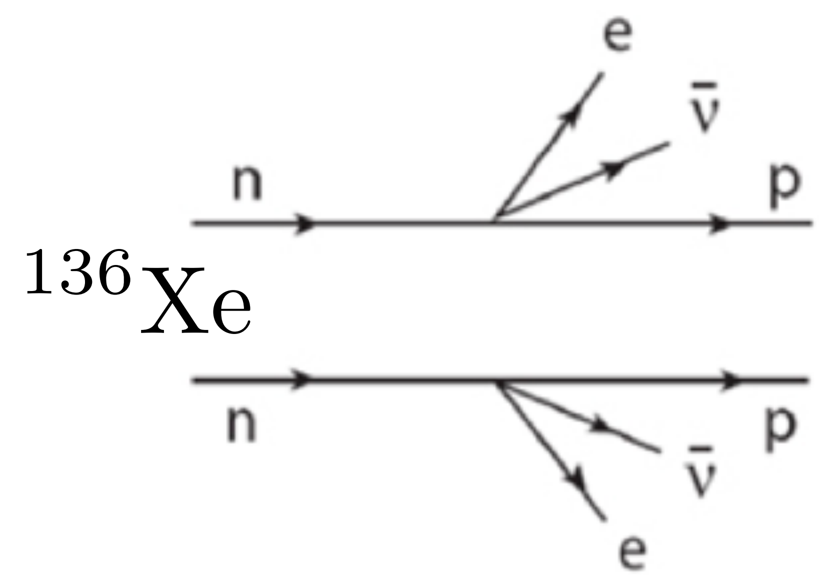
- Inelastic rate smaller by factor ~10-100
  ➡ Always see an elastic signal first

Background rate

- Background spectra expected in LZ/XENONnT:

LZ Design: 1509.02910

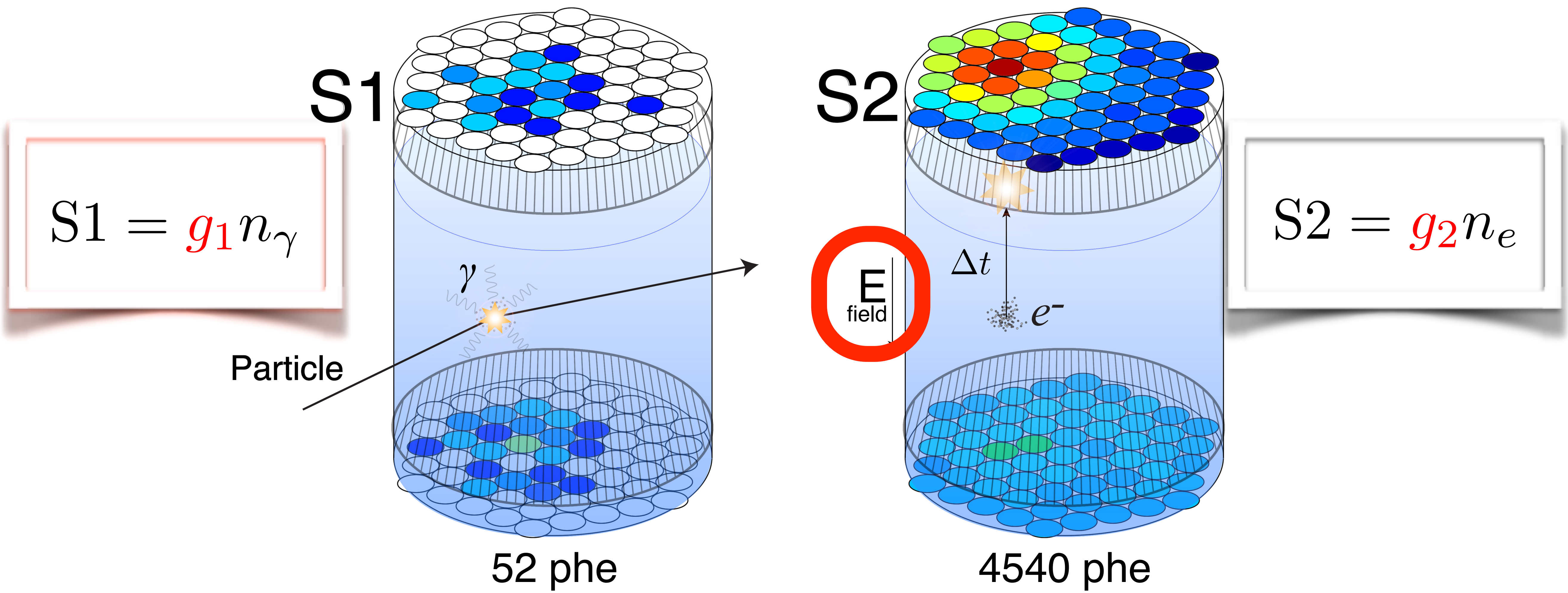




- *2-neutrino — 2-beta decay of ^{136}Xe dominates above 20 keV*

Two-phase xenon detectors

- Express the signal in terms of measured quantities:



g_1, g_2 and drift field are the crucial parameters

Mock detectors

- I'll consider two benchmark scenarios:

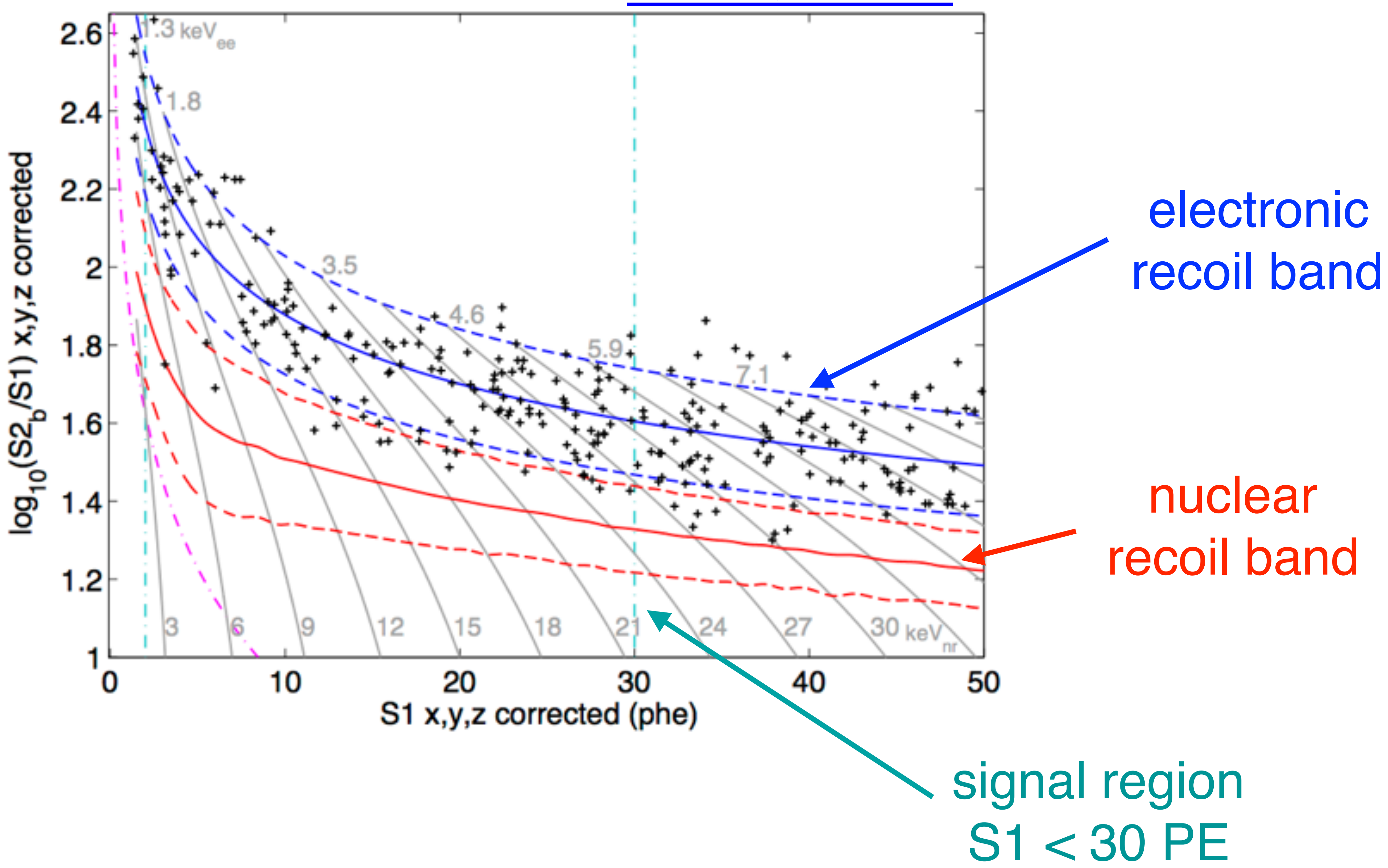
XenonA200	*XenonB1000*
g_1=0.07 PE/γ	g_1=0.12 PE/γ
g_2=12.5 PE/e (50% extraction efficiency)	g_2=50 PE/e (100% extraction efficiency)
drift field=200 V/cm	drift field=1000 V/cm

- Model of photon & electron numbers based on NEST

Szydagis et al 1106.1613 Lenardo et al 1412.4417

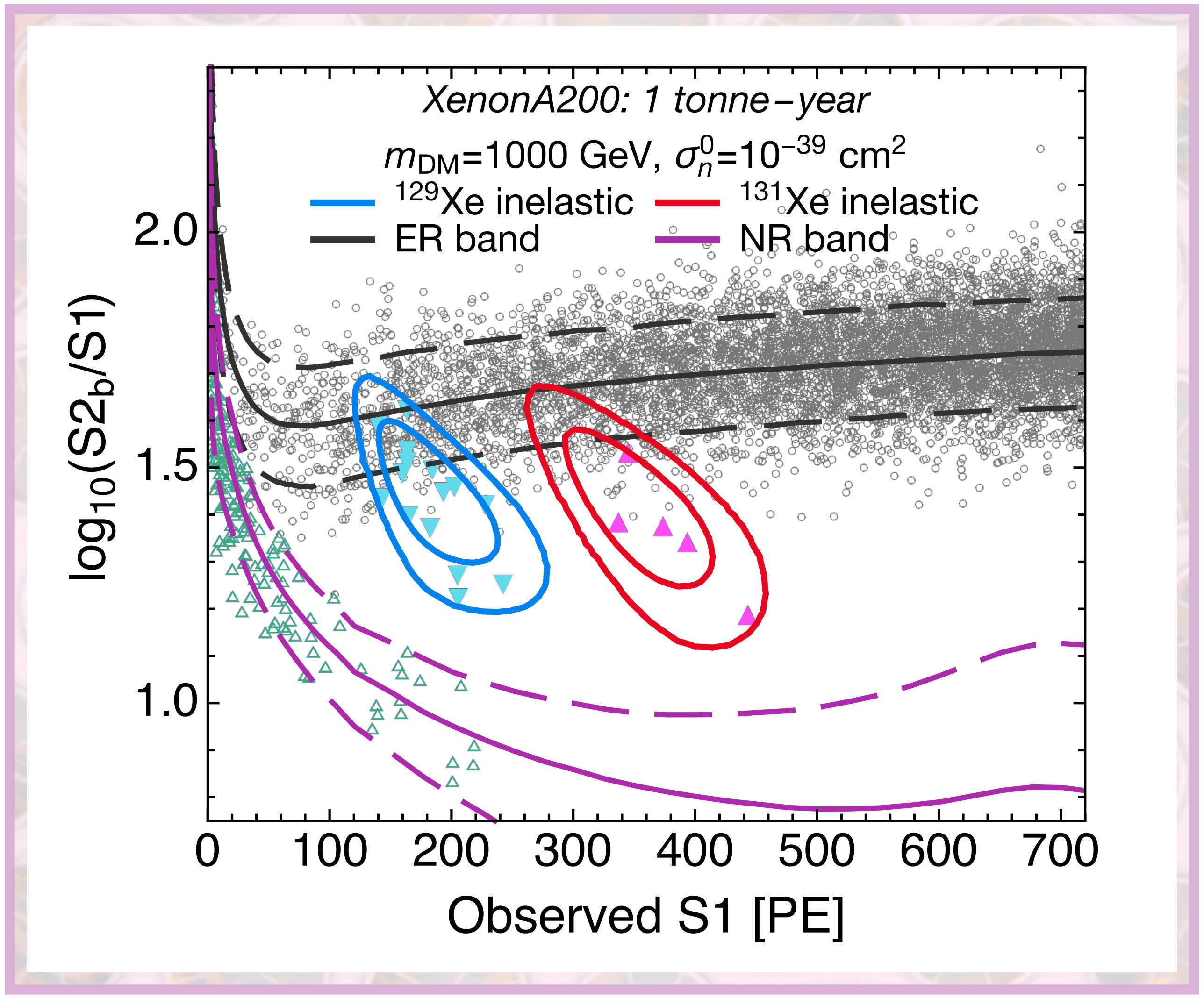
Reminder: Usual signal plane

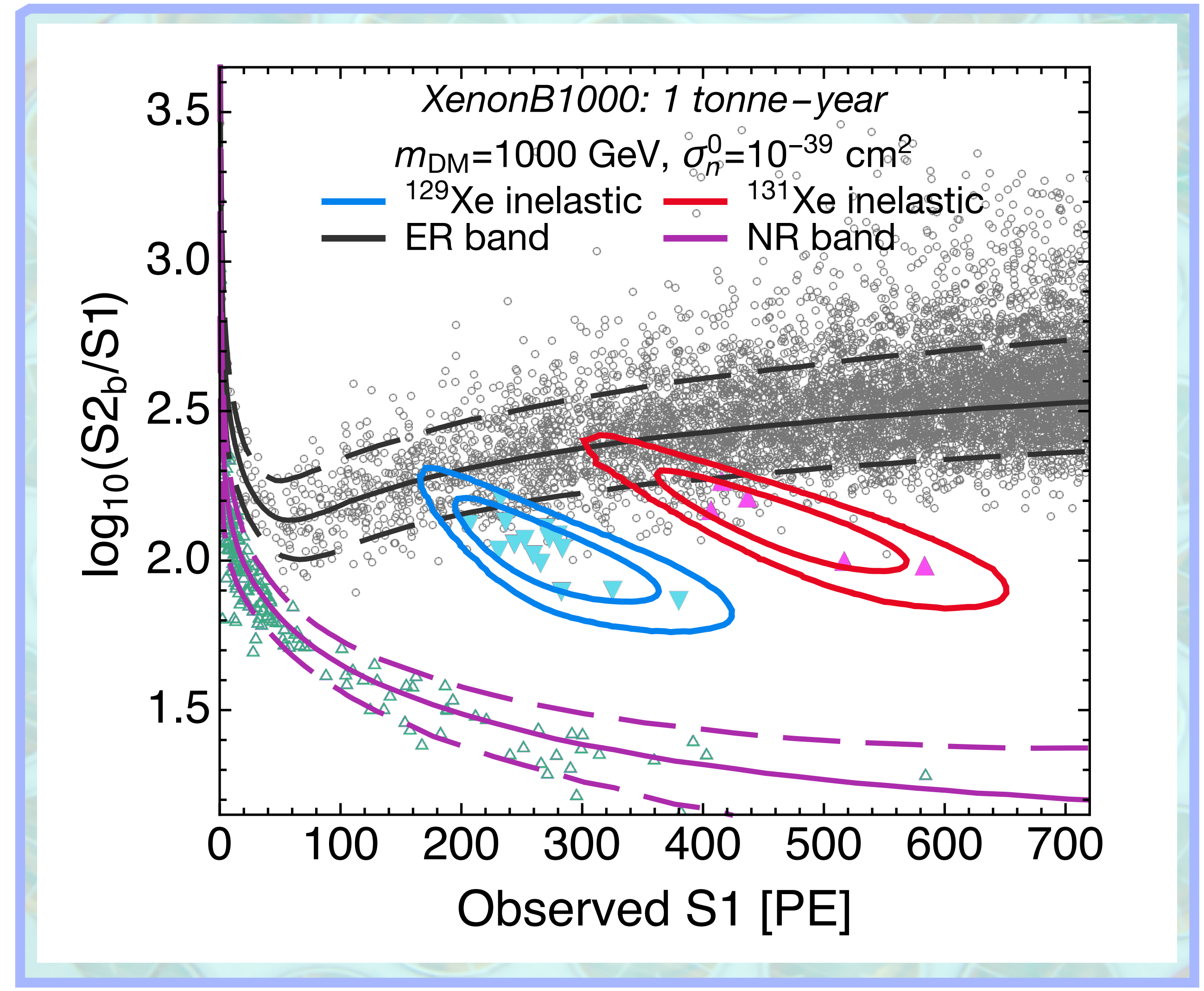
LUX arXiv:1310.8214



The signal regions

- Signal region at *higher values* of S1

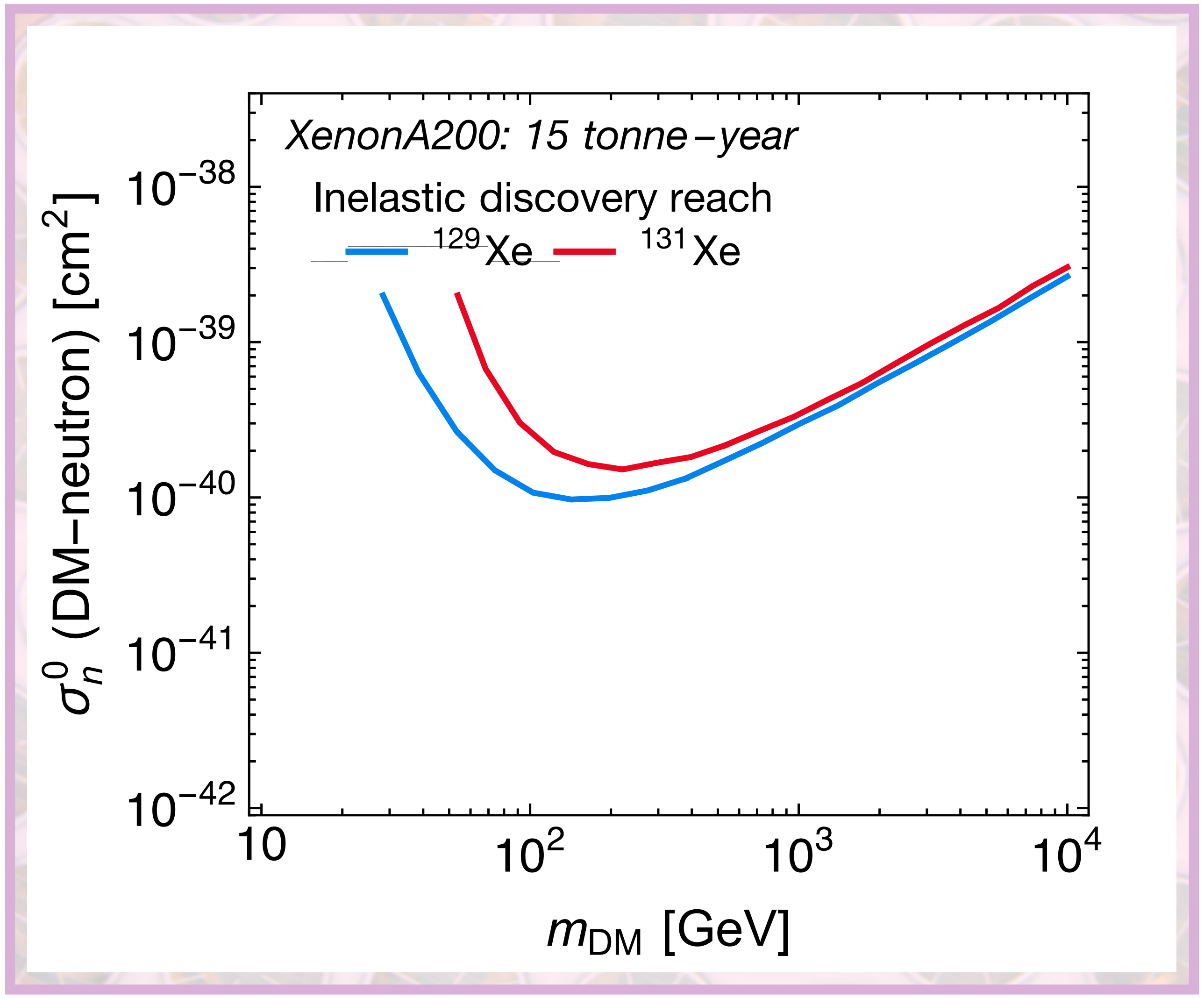


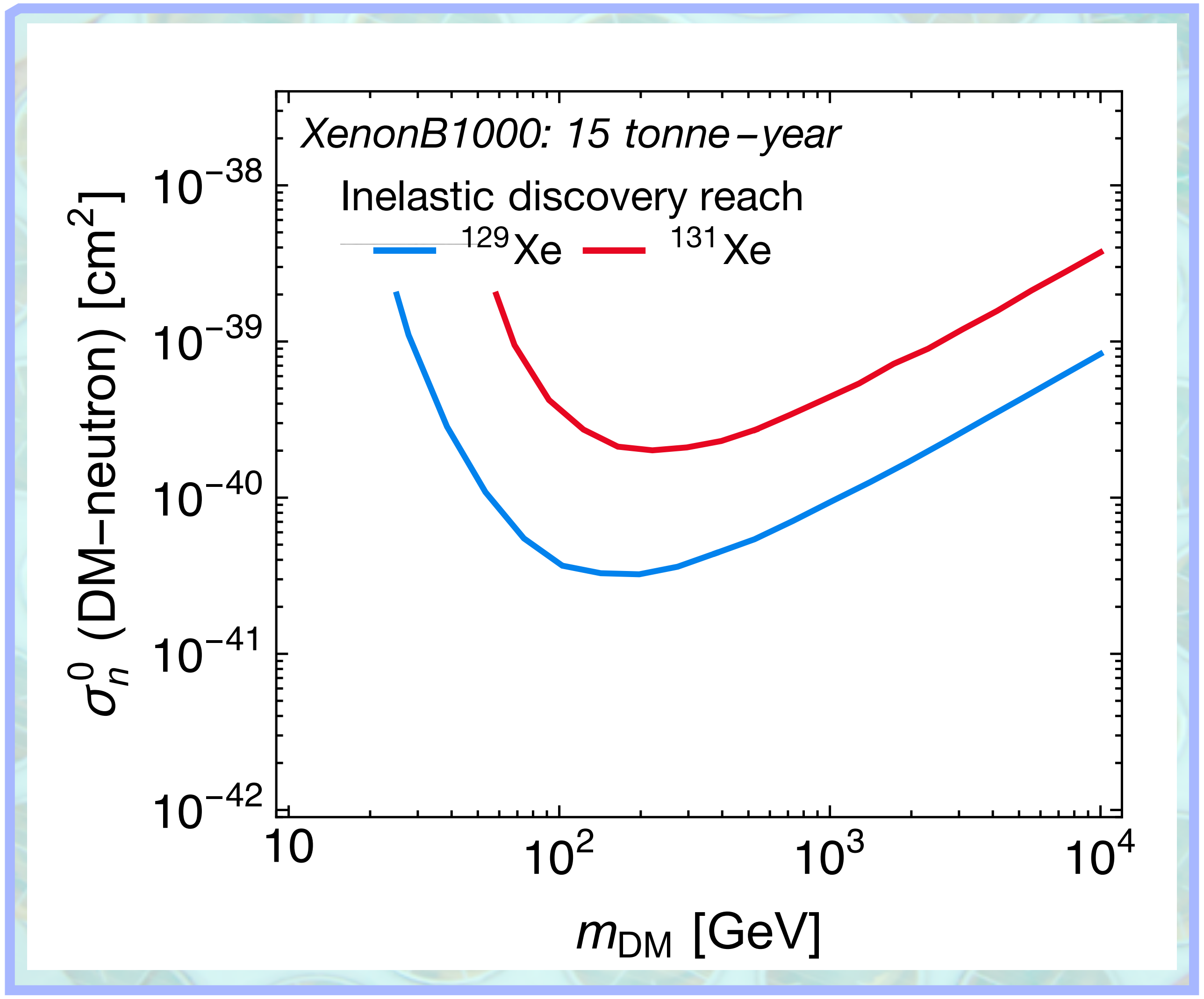


- Large backgrounds…some signal-to-background discrimination
- Better discrimination for higher drift fields

Discovery limit

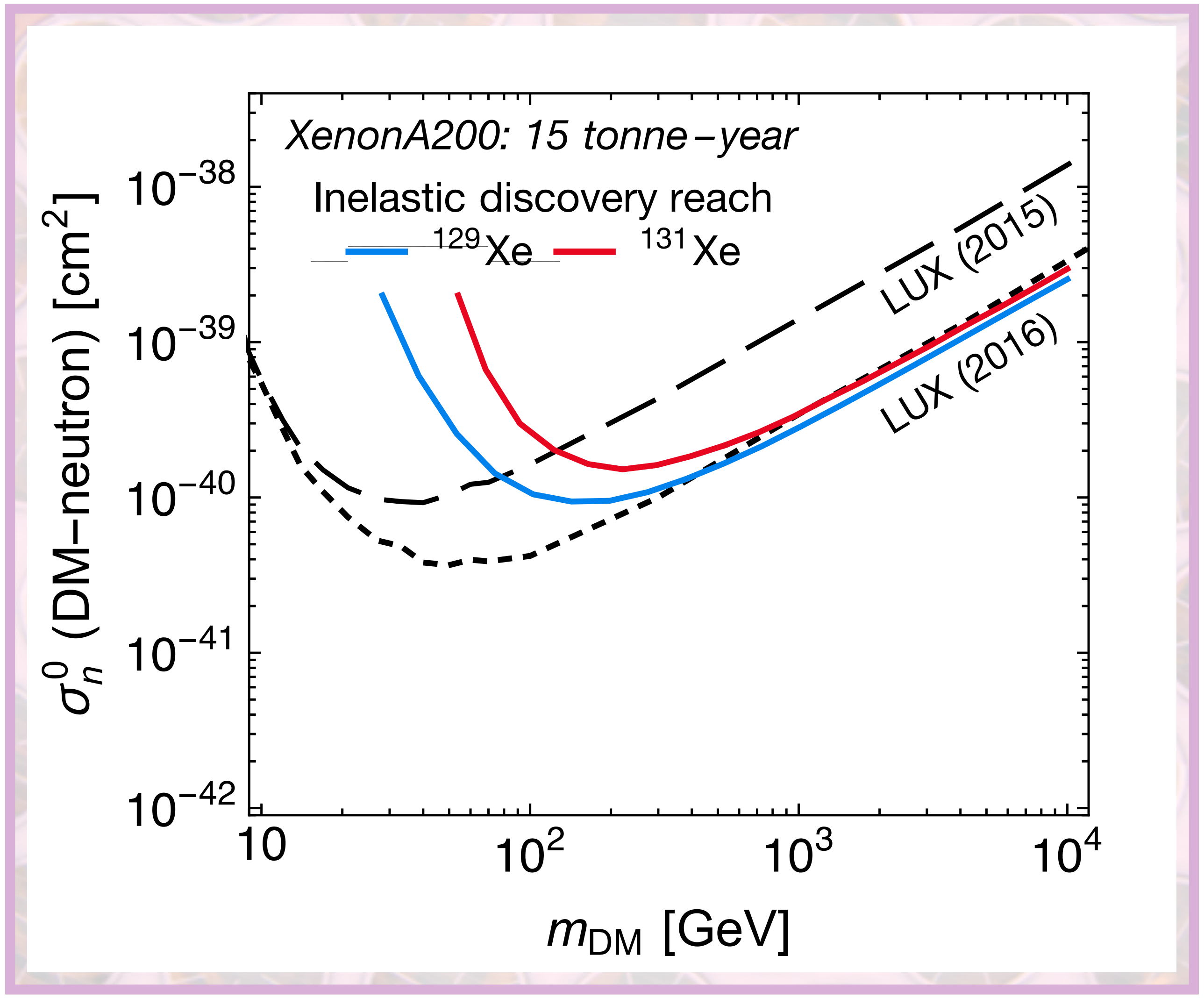
- Smallest cross-section for a discovery: XENONnT/LZ exposure

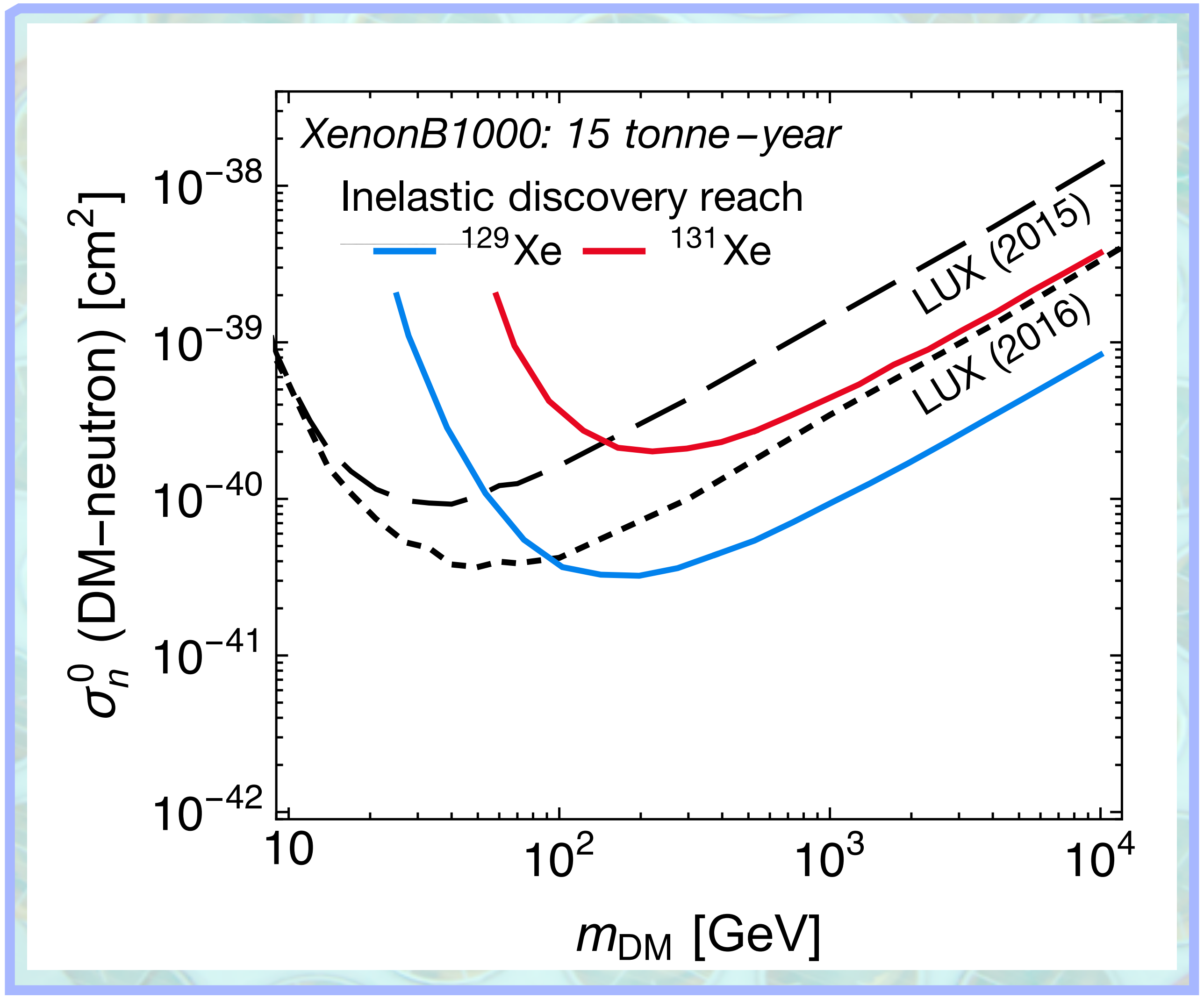




Discovery limit

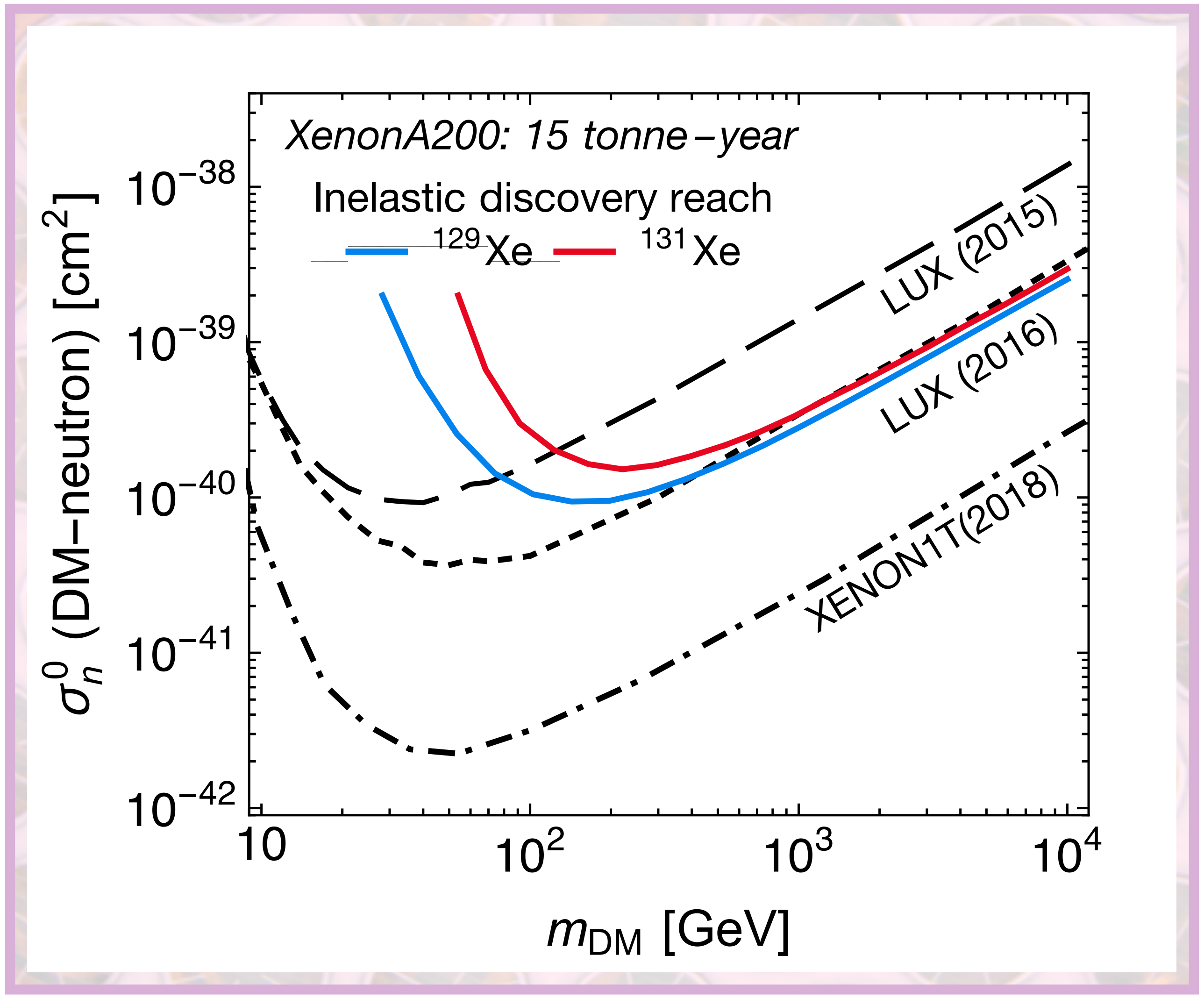
- Compare discovery limit with current constraints (elastic scatters)

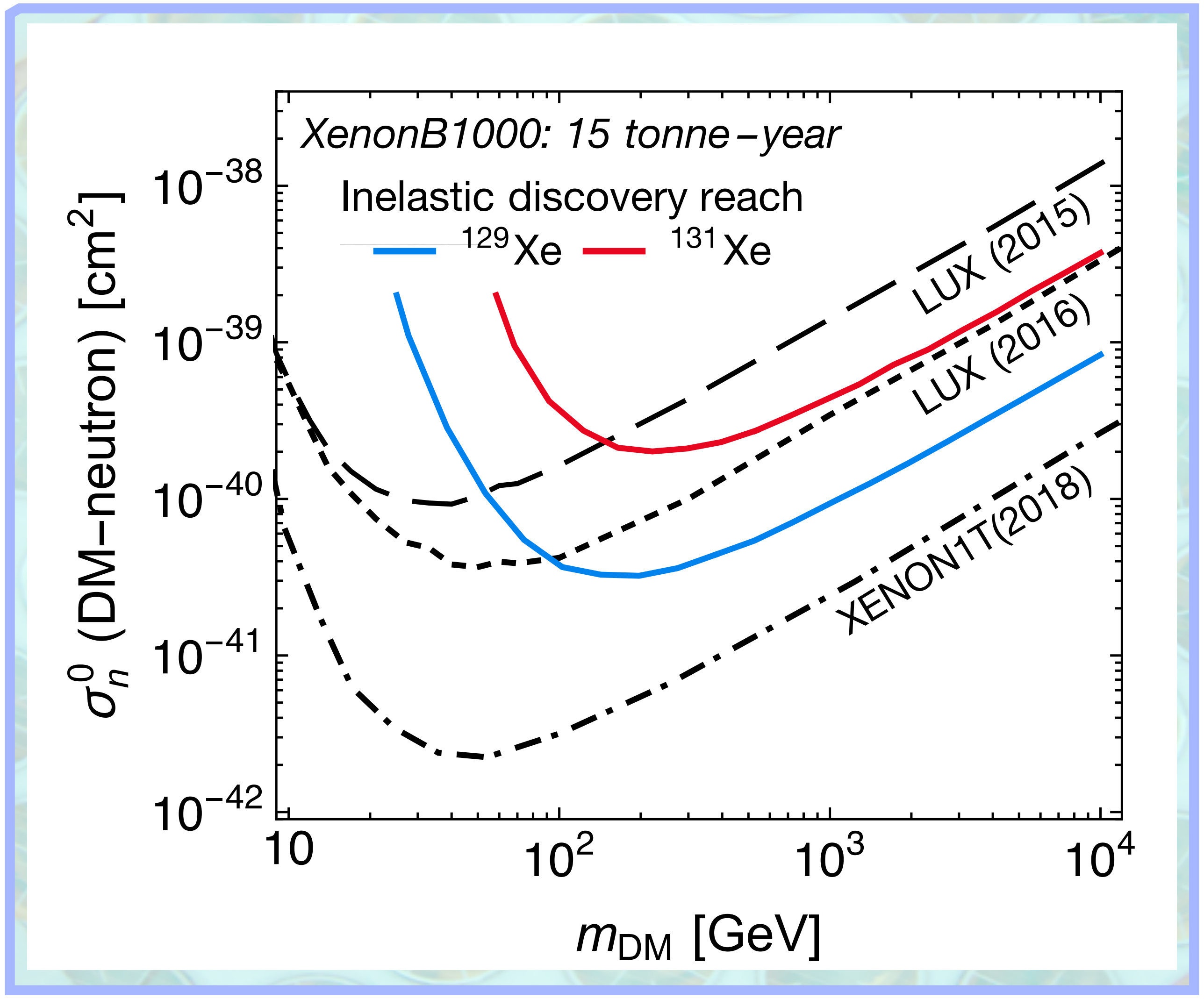




Discovery limit

- Compare discovery limit with current/future (elastic) constraints

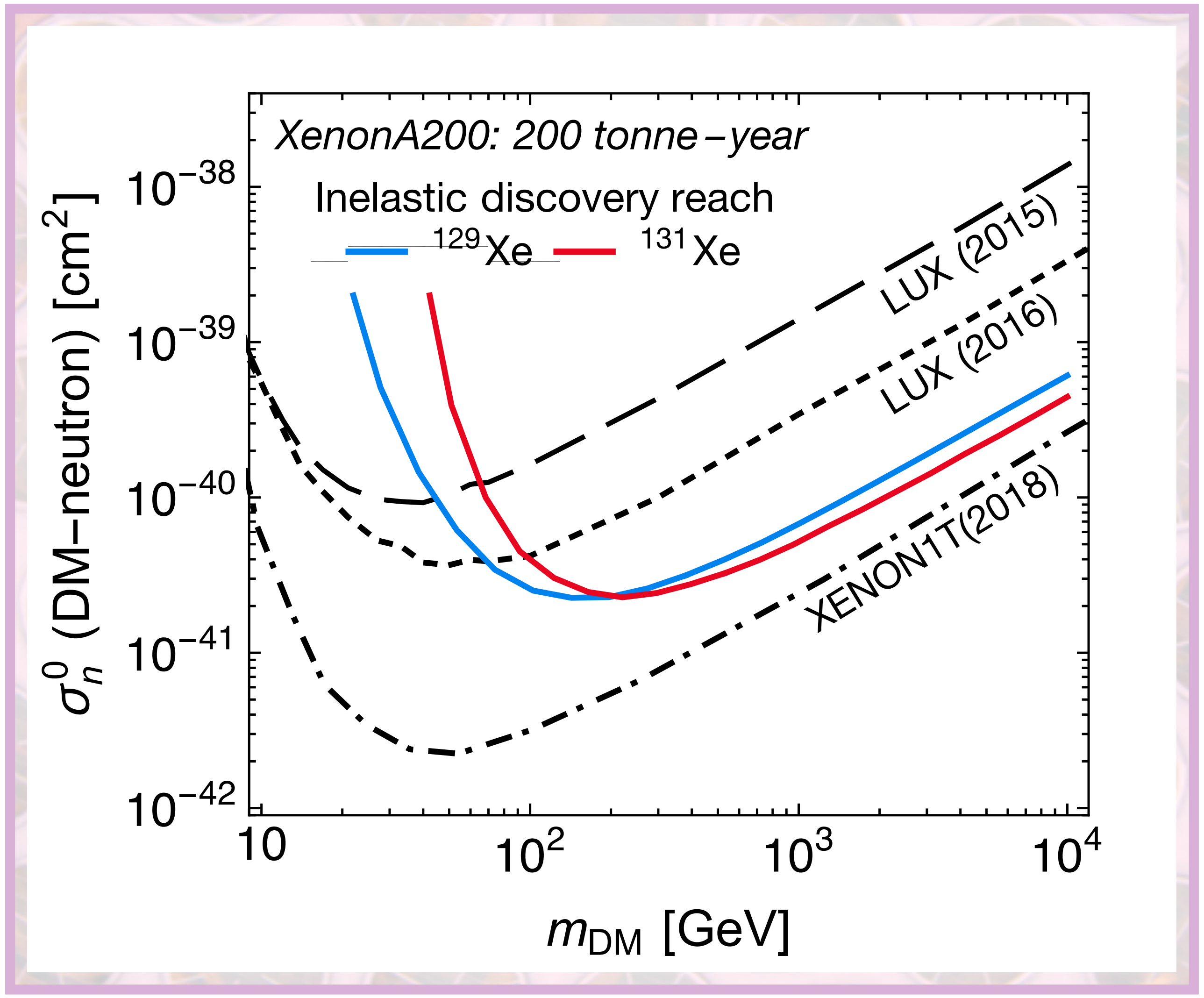


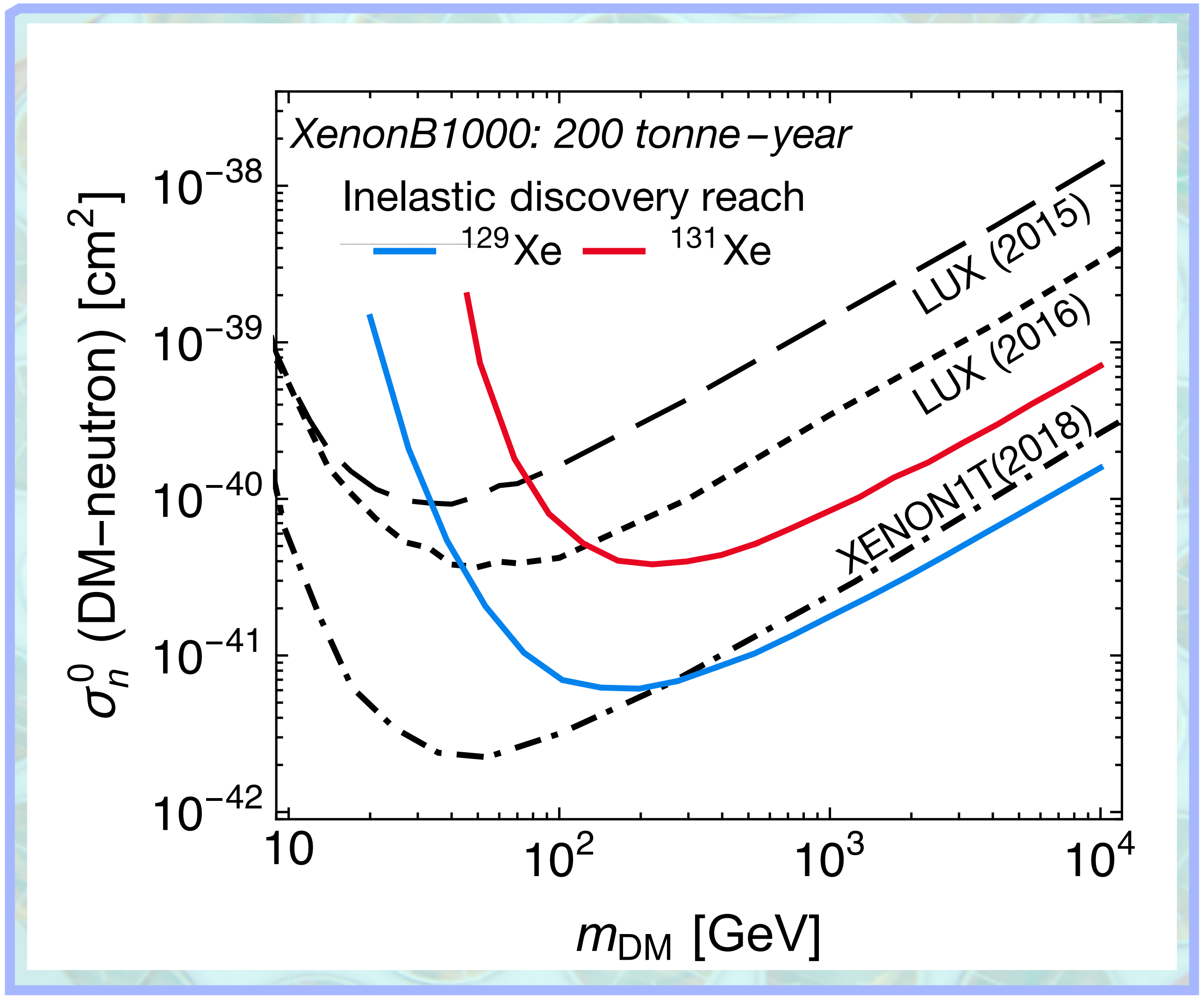


- Detectable if XENON1T make (elastic) discovery in next run

Discovery limit

- Discovery limit for DARWIN exposure





- Detectable if XENON1T make (elastic) discovery in next run

Outline

1. What is it?
   - *Excite nucleus: measure recoil + photon*
2. Why is it interesting?
   - *Discriminate between SI and SD interactions*
3. Can it ever be detected?
   - *Yes*

Physics summary

- Dark matter can excite the ^{129}Xe and ^{131}Xe isotopes
  - *signal will help to distinguish spin-independent and spin-dependent interactions*
- Signal is always smaller than elastic rate
  ➡ Could it be detected?

Yes!

Requires an (elastic scattering) discovery signal in XENON1T

New things to do with lots of xenon

- Thing 1:
  Supernova neutrino detection

- Thing 2:
  DM exciting the xenon nucleus

Thank you