Prospects for dark matter detection with inelastic transitions of xenon

GRAPPA
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— arXiv:1512.00460 —

HEPP & APP meeting, University of Sussex, Brighton - 22nd March 2016

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.

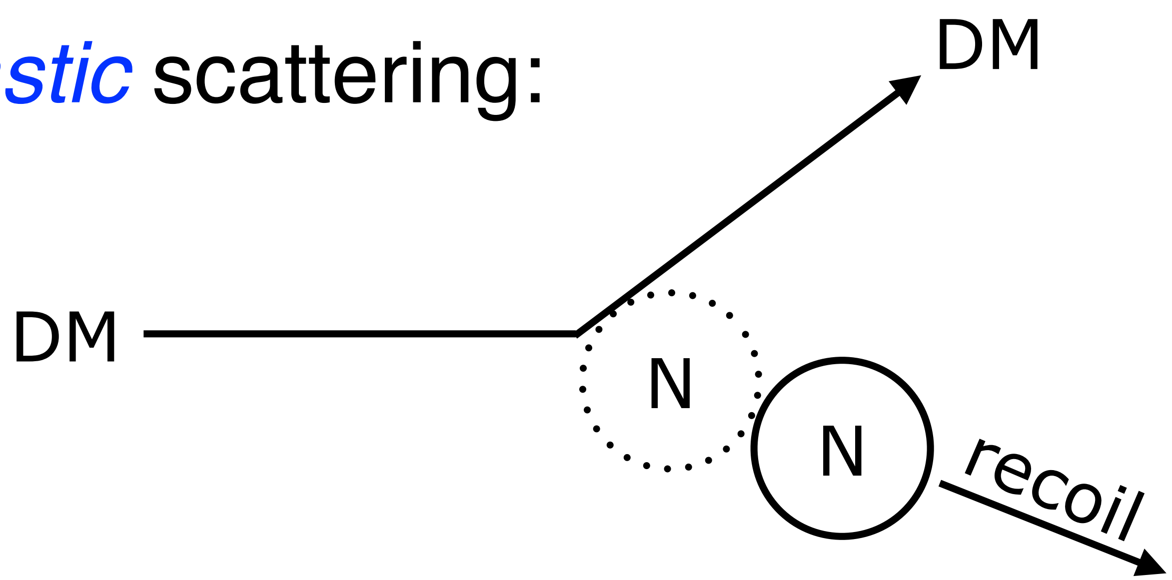
An old idea… Inelastic scattering

- What is it?
- Why is it interesting?
- Why consider it now?

Can it ever be detected?

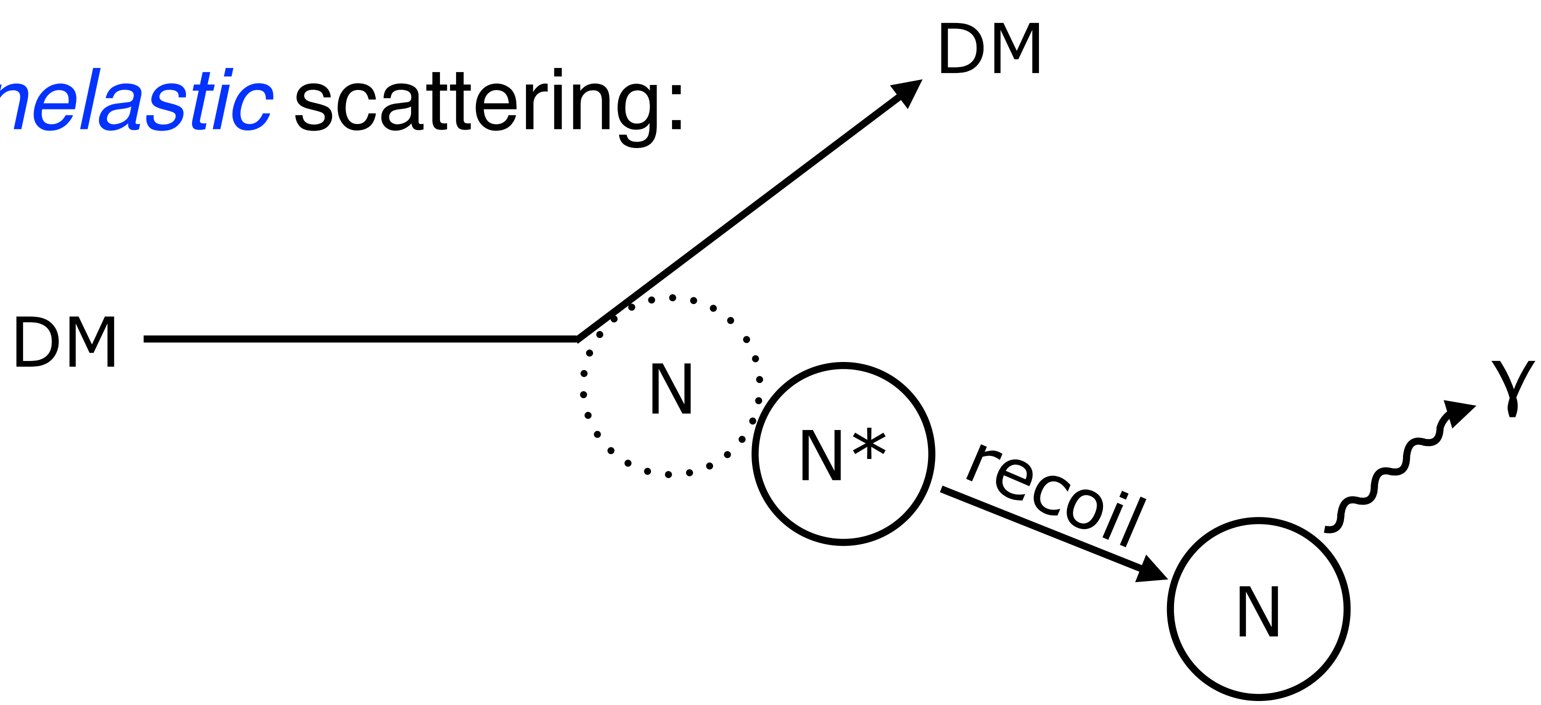
What is it?

elastic scattering:



measure:
N's recoil energy

inelastic scattering:



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

Why is it interesting?

Inferring properties of dark matter is difficult!
We should search for all signals that provide information

★ **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

Vietze et al arXiv:1412.6091

What is a good target?

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

★ Ideal target should have

i. good spin-dependent sensitivity

ii. a low lying excitation $(\lesssim E_{\mathrm{DM-kinetic}} \approx 100~\mathrm{keV})$

What is a good target?

Why Xenon?

- 47.6% of xenon sensitive to spin-dependent interactions:

^{129}Xe

Natural abundance: 26.4%

Lowest excitation: **39.6 keV**

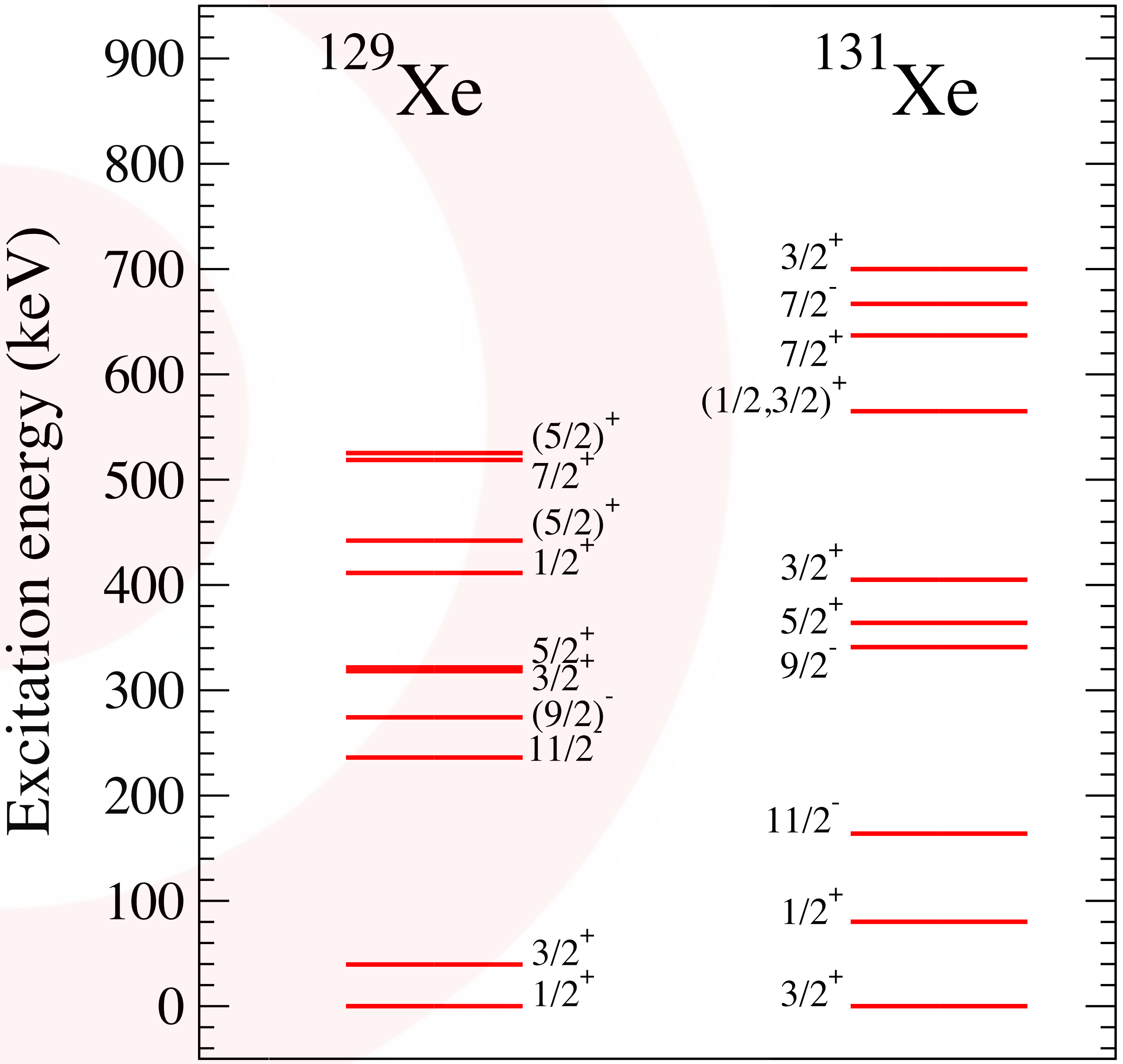
Lifetime: 0.97 ns

^{131}Xe

Natural abundance: 21.2%

Lowest excitation: **80.2 keV**

Lifetime: 0.48 ns



Why now?

We can quantify the signal and background

- Nuclear structure functions known (needed for signal)

  Baudis et al 1309.0825

- Backgrounds are more-or-less known
- Future detector properties are more-or-less known

Previous studies

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]

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PTEP

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

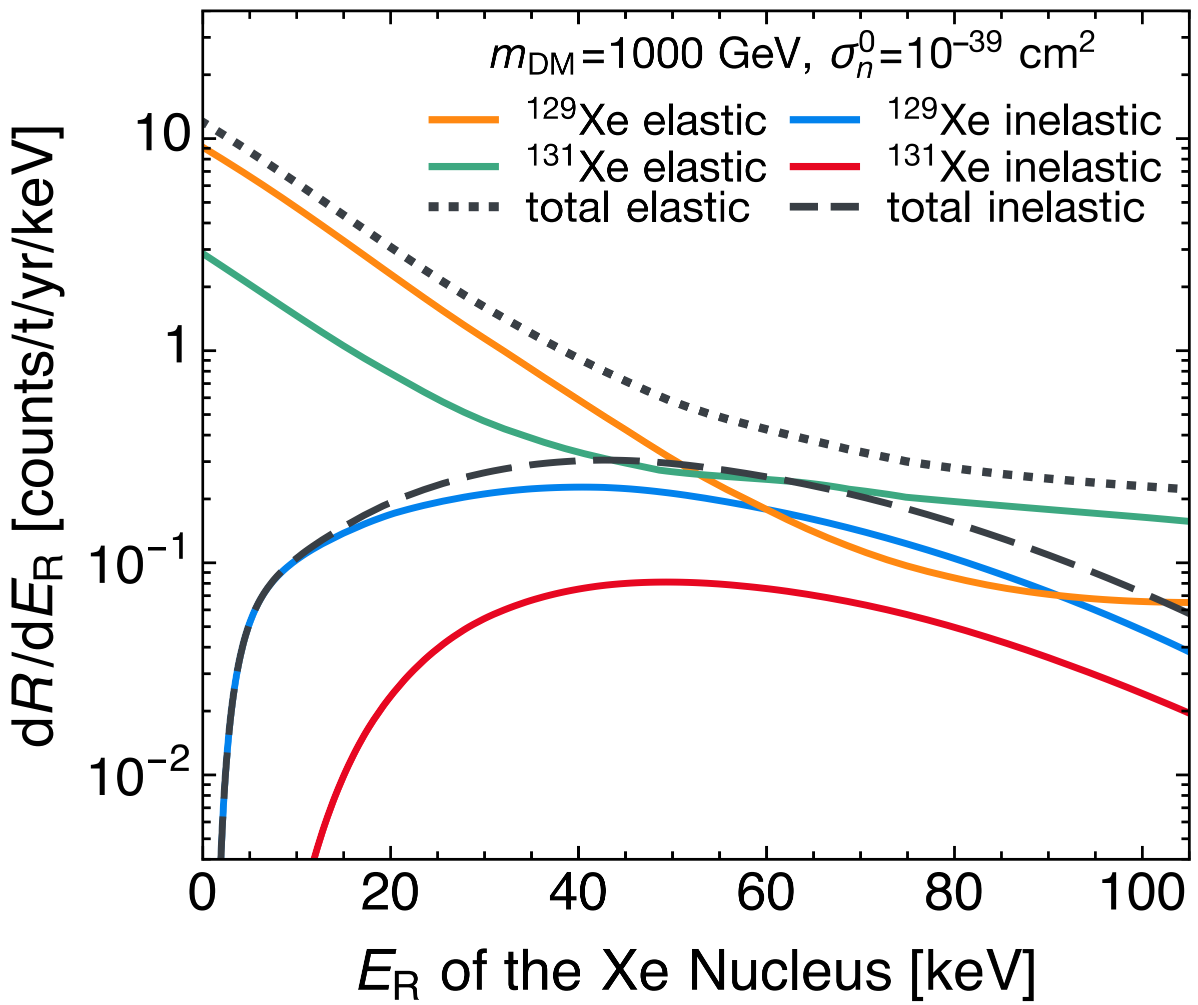
Search for inelastic WIMP nucleus scattering on ^{129}Xe in data from the XMASS-I experiment

- Previous searches with single phase-detectors
- *No limits or studies for two-phase detectors (LUX, XENON)*

Can it ever be detected
with a two-phase detector?

The signal rate

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

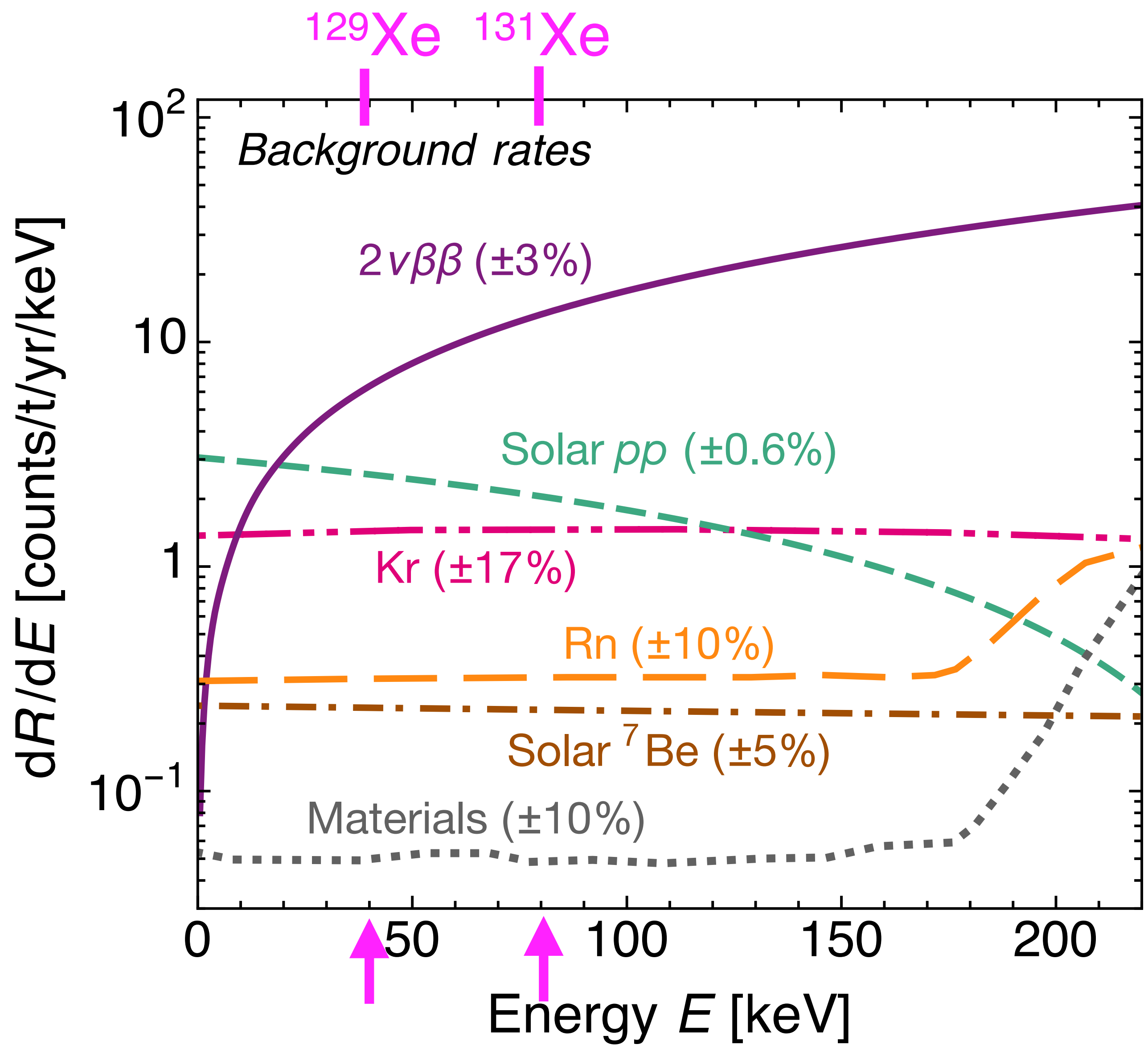


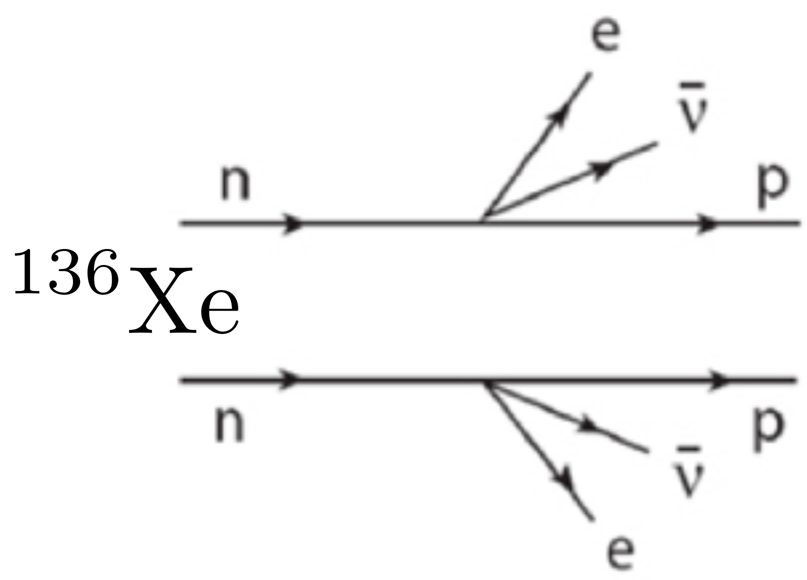
- Inelastic rate smaller by factor ~100
  ➡ Always see an elastic signal first

The background rate

- Background spectra expected in LZ/XENONnT:

LZ Design: 1509.02910



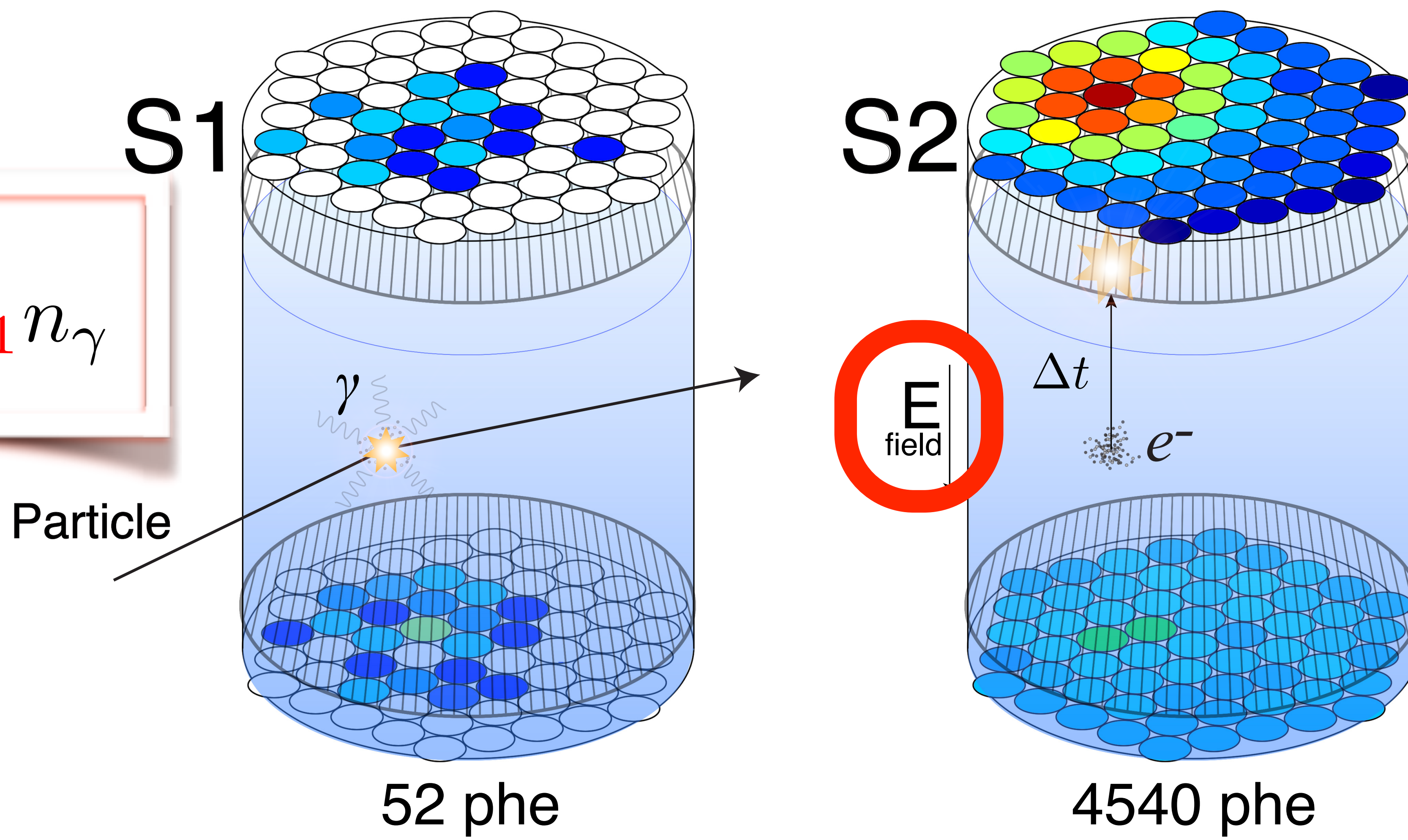


- *2-neutrino — 2-beta decay of ^{136}Xe dominates above 20 keV*

Two-phase xenon detectors

- Express the signal in terms of measured quantities:

$$S1 = g_1 n_\gamma$$



$$S2 = g_2 n_e$$

g_1, g_2 and drift field are the crucial parameters

Mock detectors

- I'll consider two benchmark scenarios:

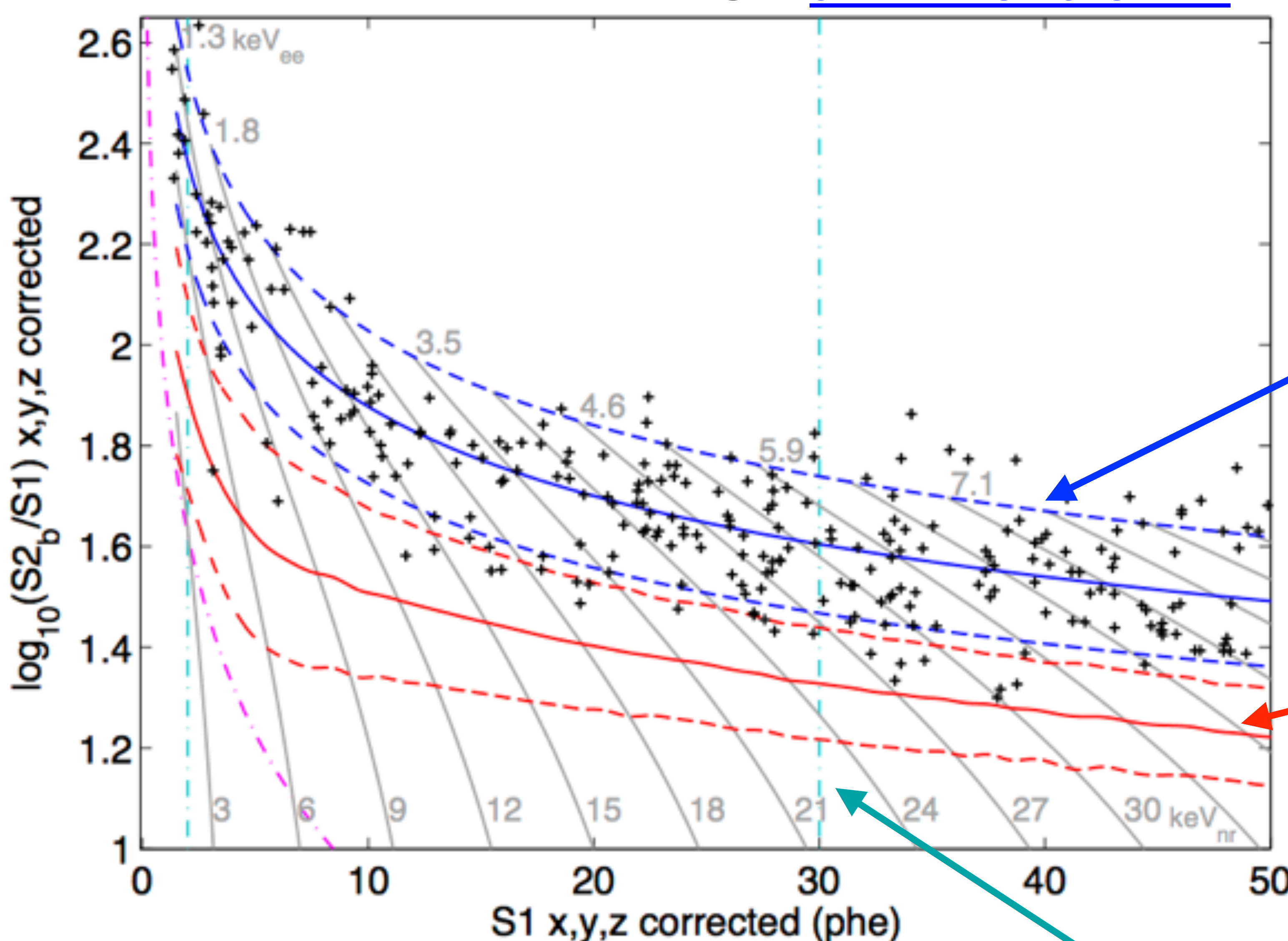
XenonA200	*XenonB1000*
g_1=0.07 PE/γ	g_1=0.12 PE/γ
g_2=12.5 PE/e (50% extraction efficiency)	g_2=50 PE/e (100% extraction efficiency)
drift field=200 V/cm	drift field=1000 V/cm

- 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



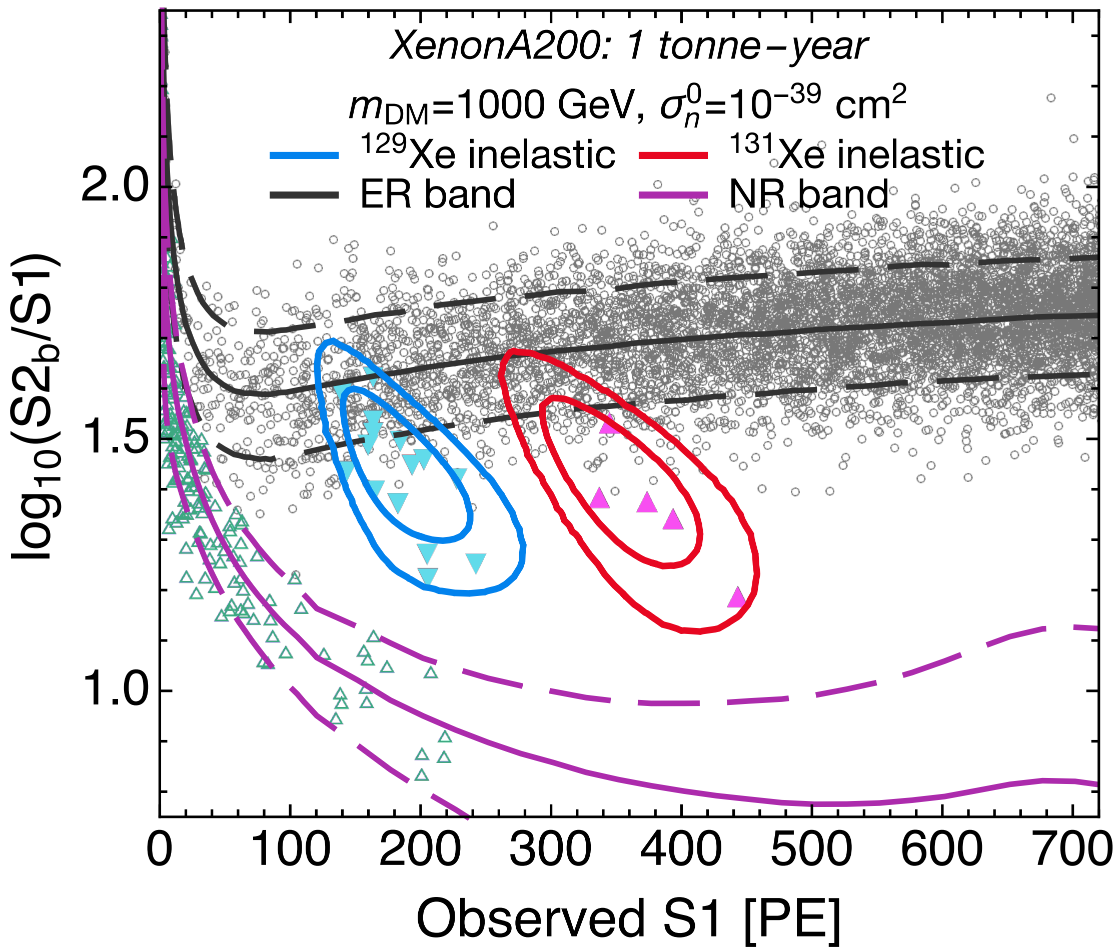
electronic recoil band

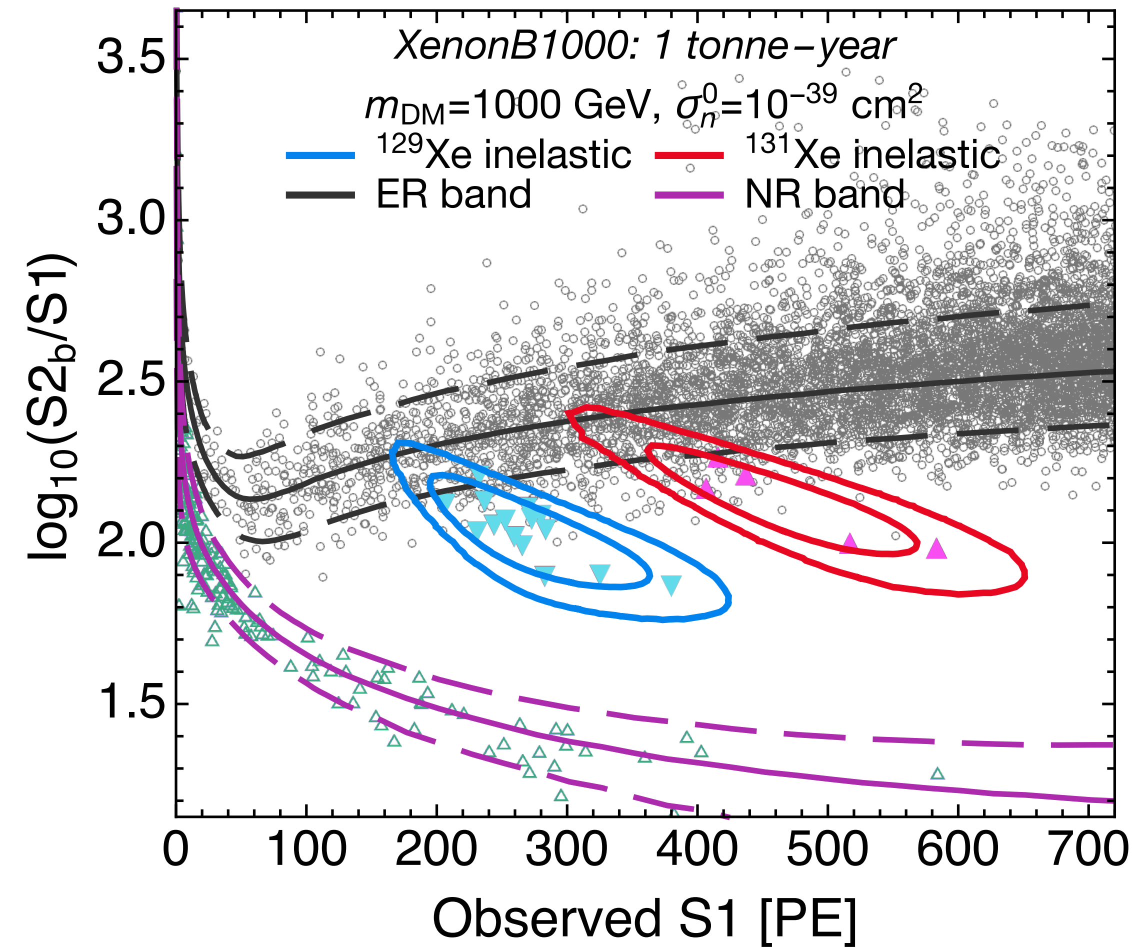
nuclear recoil band

signal region S1 < 30 PE

Background versus signal

- Signal region at *higher values* of S1





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

Discovery limit

- Quantify the sensitivity of future experiments with a 'discovery limit' Billard et al 1110.6079

The smallest cross-section at which 90% of experiments can make a 3σ detection of the signal

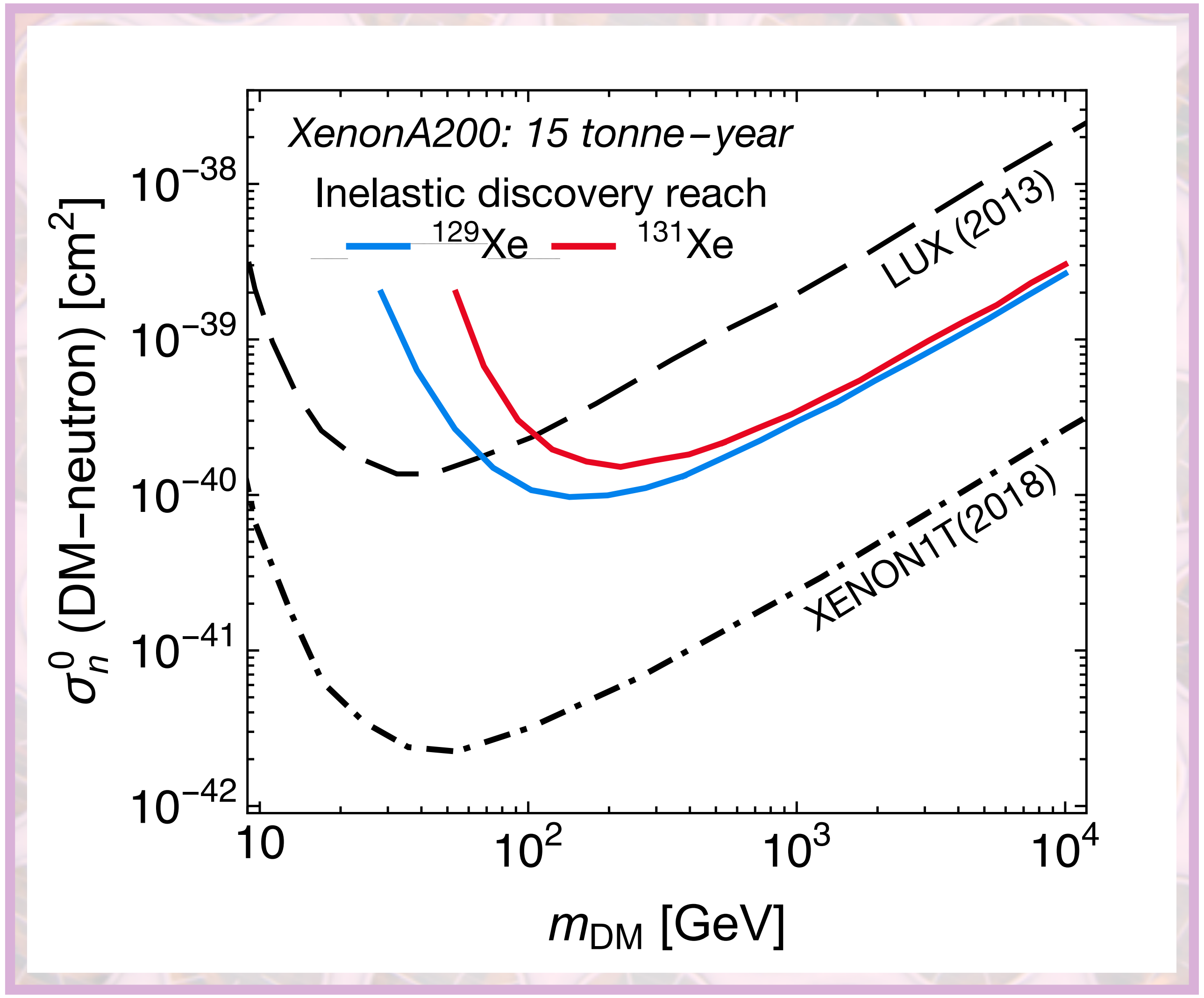
- Profile likelihood ratio:

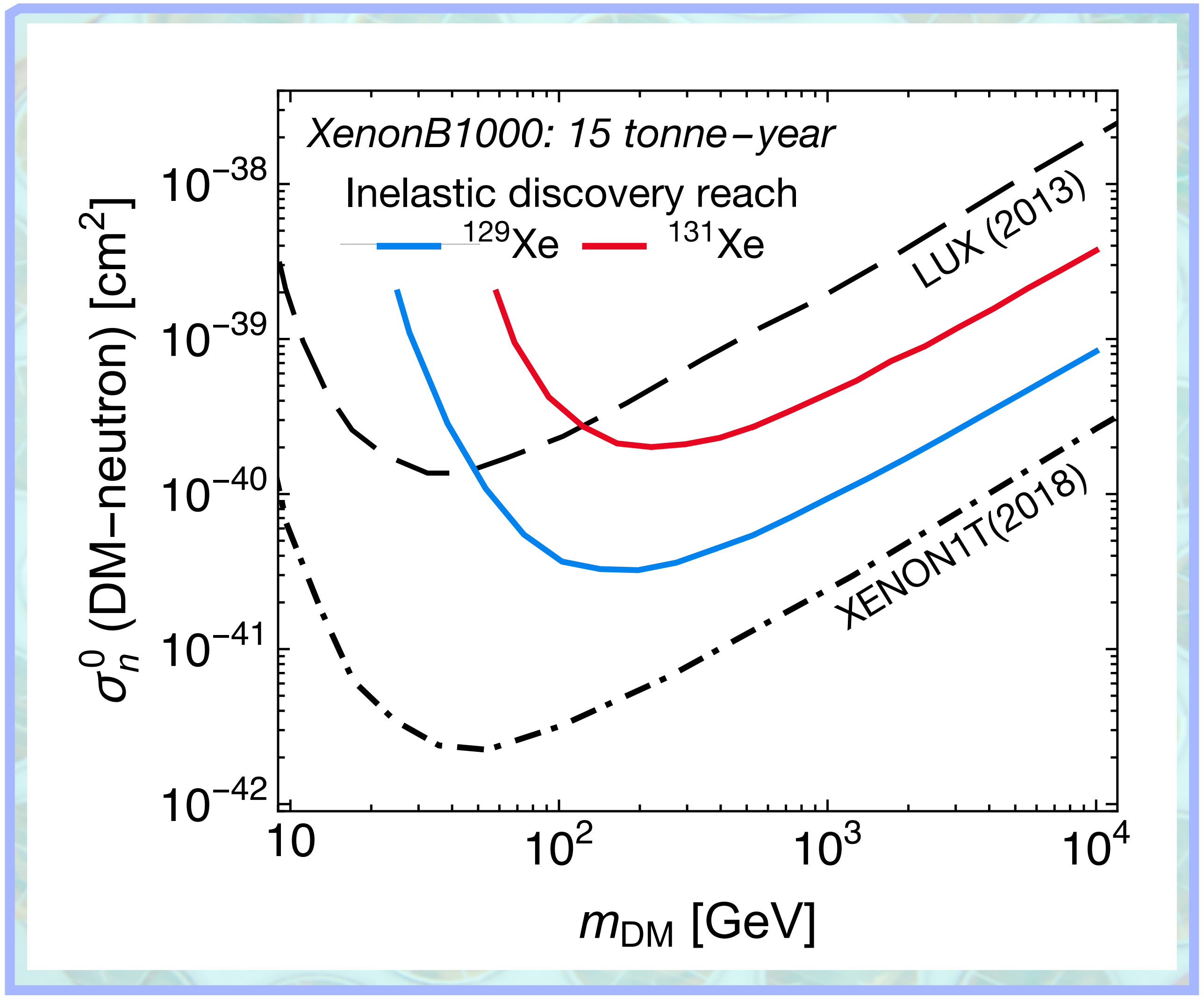
$$\lambda(0) = \frac{L(\sigma_n^0 = 0, \hat{\hat{\vec{A}}}_{\mathrm{BG}})}{L(\hat{\sigma_n^0}, \hat{\vec{A}}_{\mathrm{BG}})}$$

- Include background uncertainties

Discovery limit

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





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

Summary

- Dark matter can excite the ^{129}Xe and ^{131}Xe isotopes
  - *signal will tell us more about the DM-quark interaction*

- Signal is always smaller than elastic rate

  ➡ Can it be detected?

Yes!

…if there is an (elastic) discovery signal
in the next run of XENON1T

Thank you

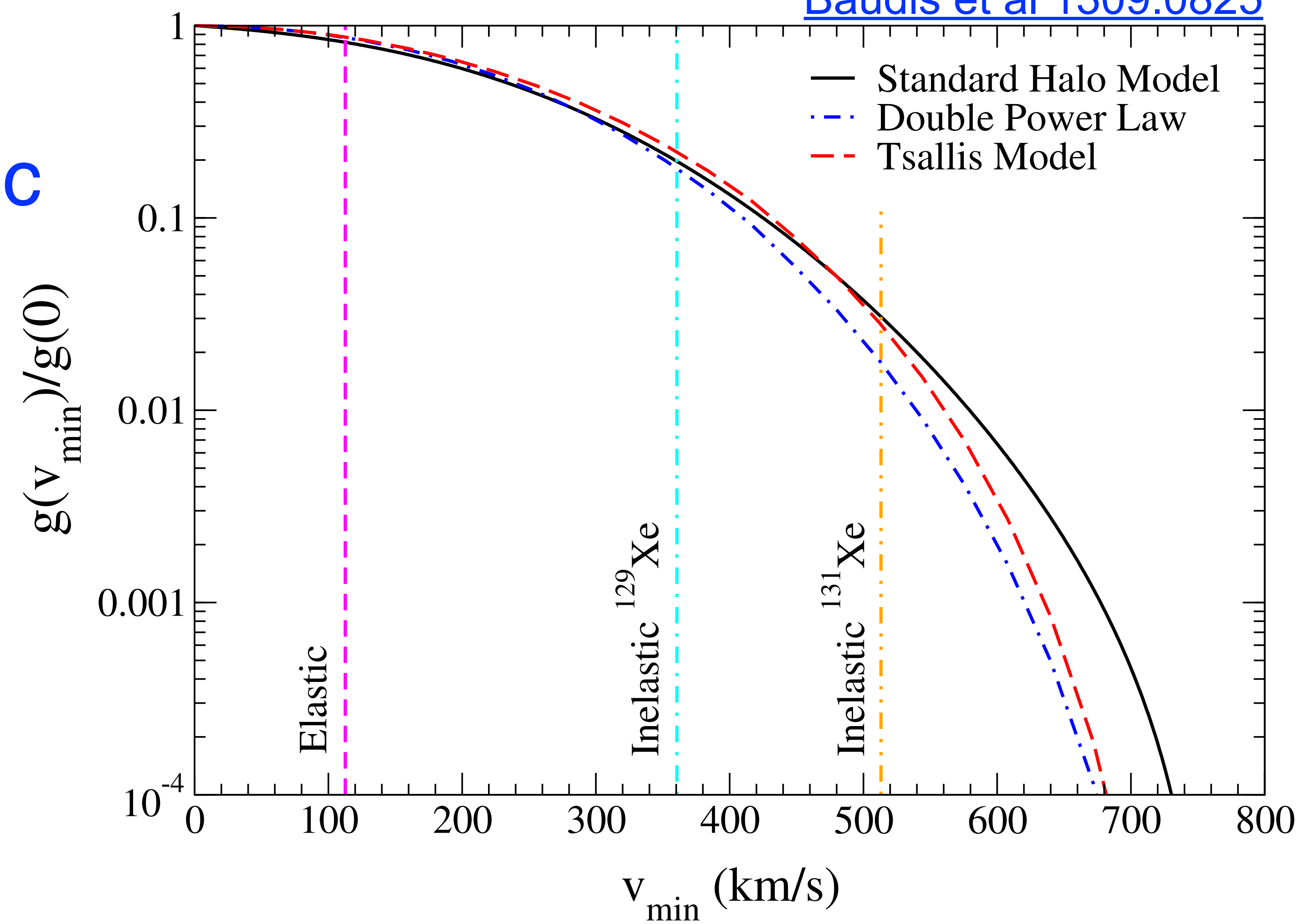
Backup

Scattering rate

- Rate depends on the DM velocity distribution:

$$\frac{dR}{dE_{\rm R}} \propto g(v_{\min}) = \int_{v_{\min}} d^3v \, \frac{f(v)}{v}$$

Baudis et al 1309.0825



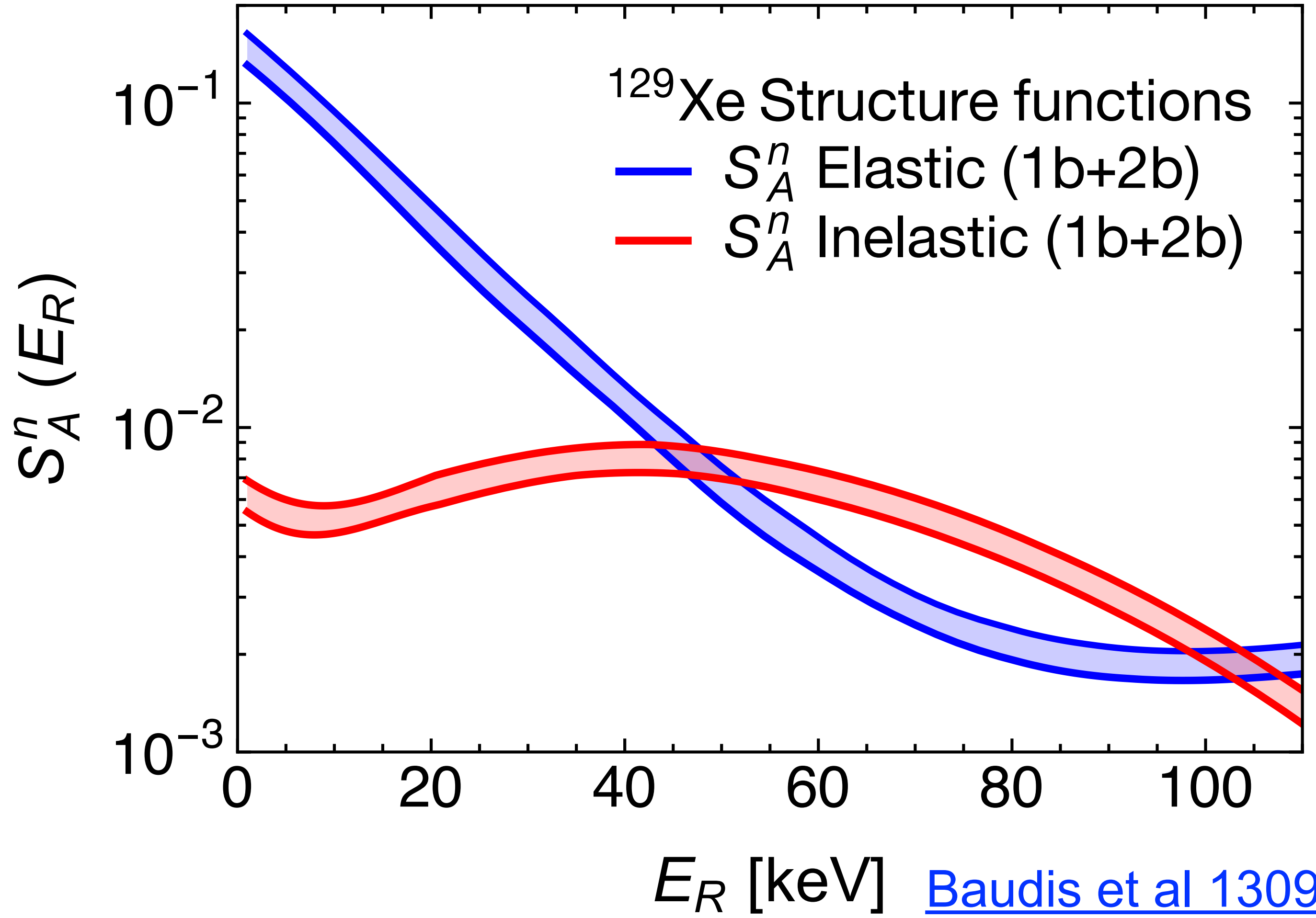
- $v_{\rm min}$ is higher for inelastic (DM kinetic energy must also excite the nucleus)
- This suppresses the inelastic rate by factor ~10

Structure functions

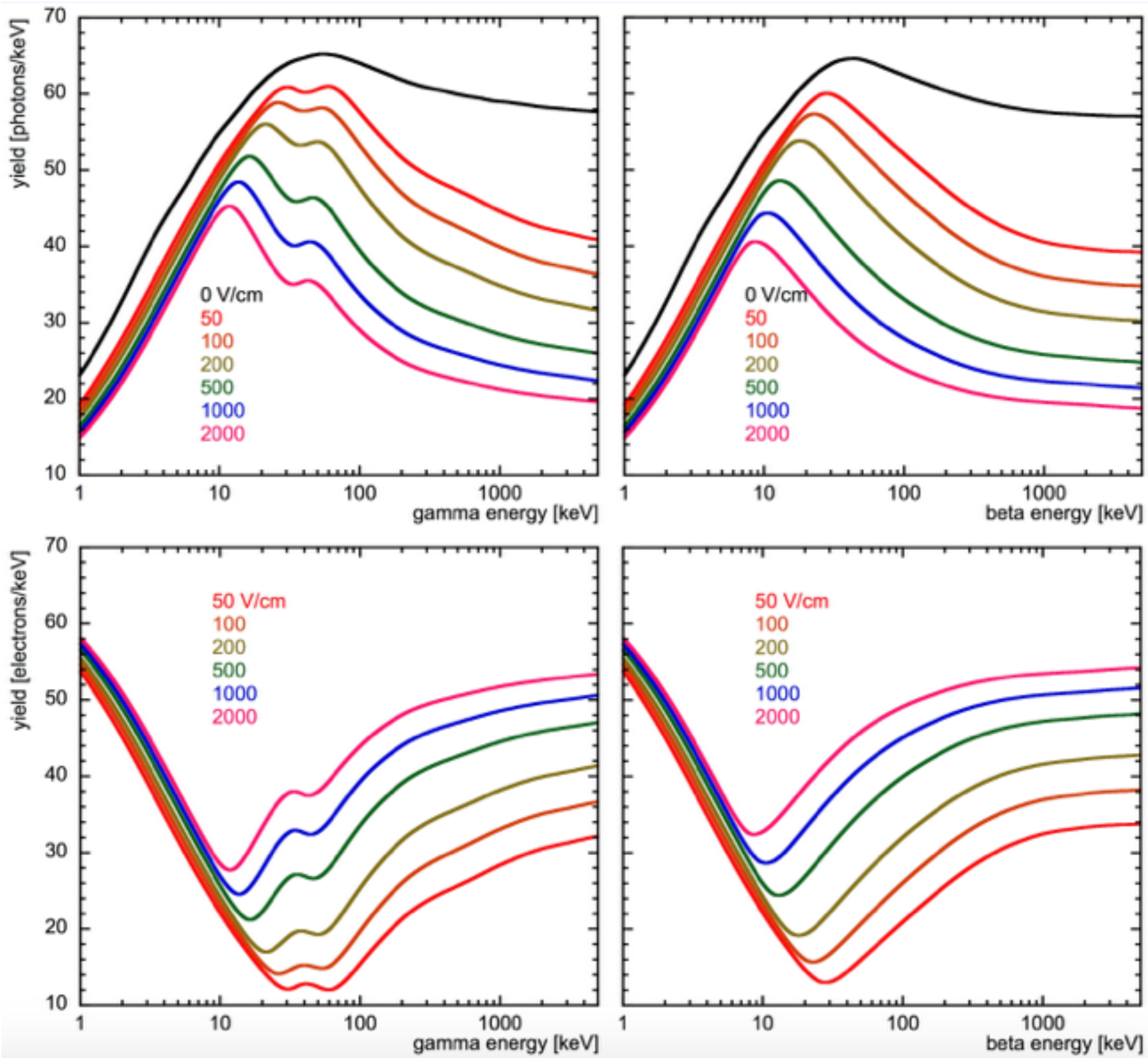
- Known for axial-vector interaction: $\mathcal{L} \propto -\bar{\chi}\gamma^{\mu}\gamma^{5}\chi \cdot \sum_{q} A_q \bar{\psi}_q \gamma_{\mu}\gamma^{5}\psi_q$
- Rate depends on the structure functions

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

- Smaller for inelastic
  (Small E_R most relevant)
- This suppresses the inelastic rate by factor ~10



Baudis et al 1309.0825



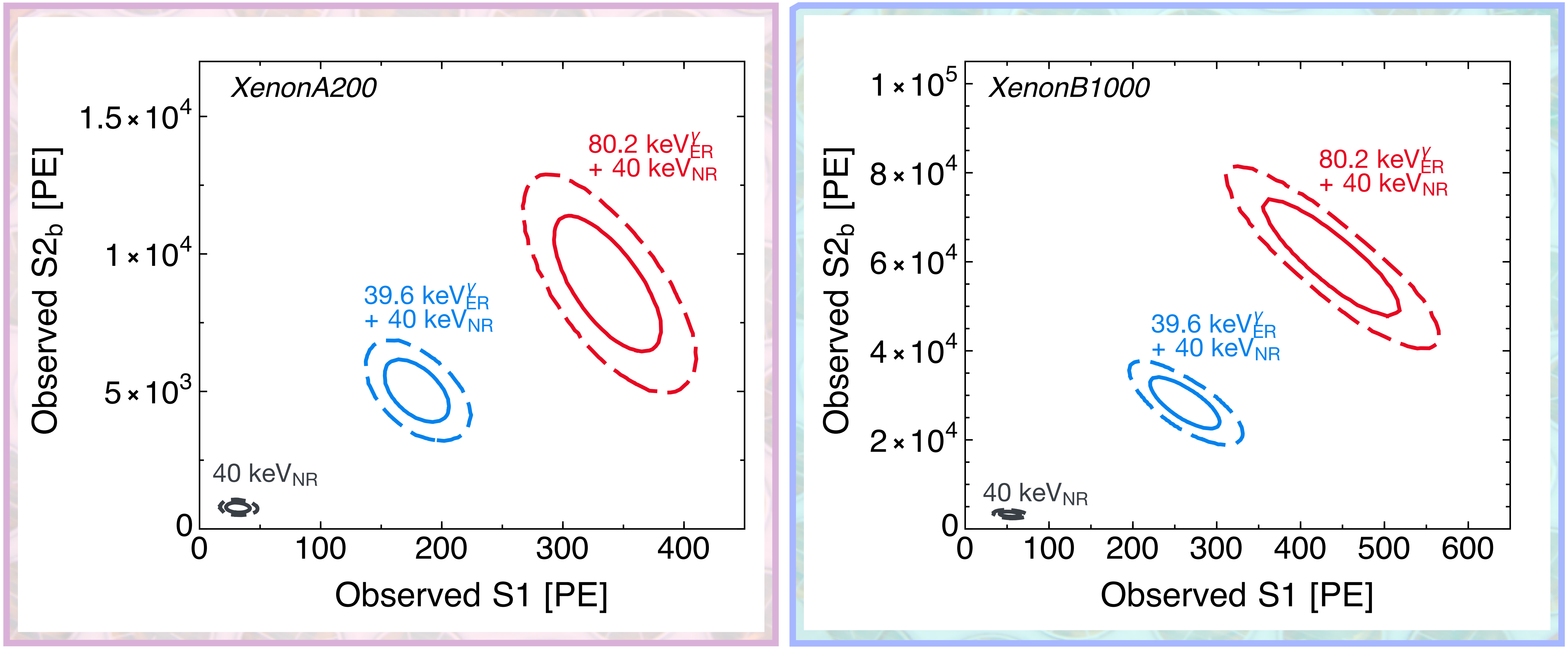
Gammas have shorter tracks, more recombination (r bigger) so n_e smaller, n_{gamma} bigger

$$n_e = n_{\rm i} - r n_{\rm i}$$

$$n_\gamma = n_{\rm ex} + r n_{\rm i}$$

Mock signals

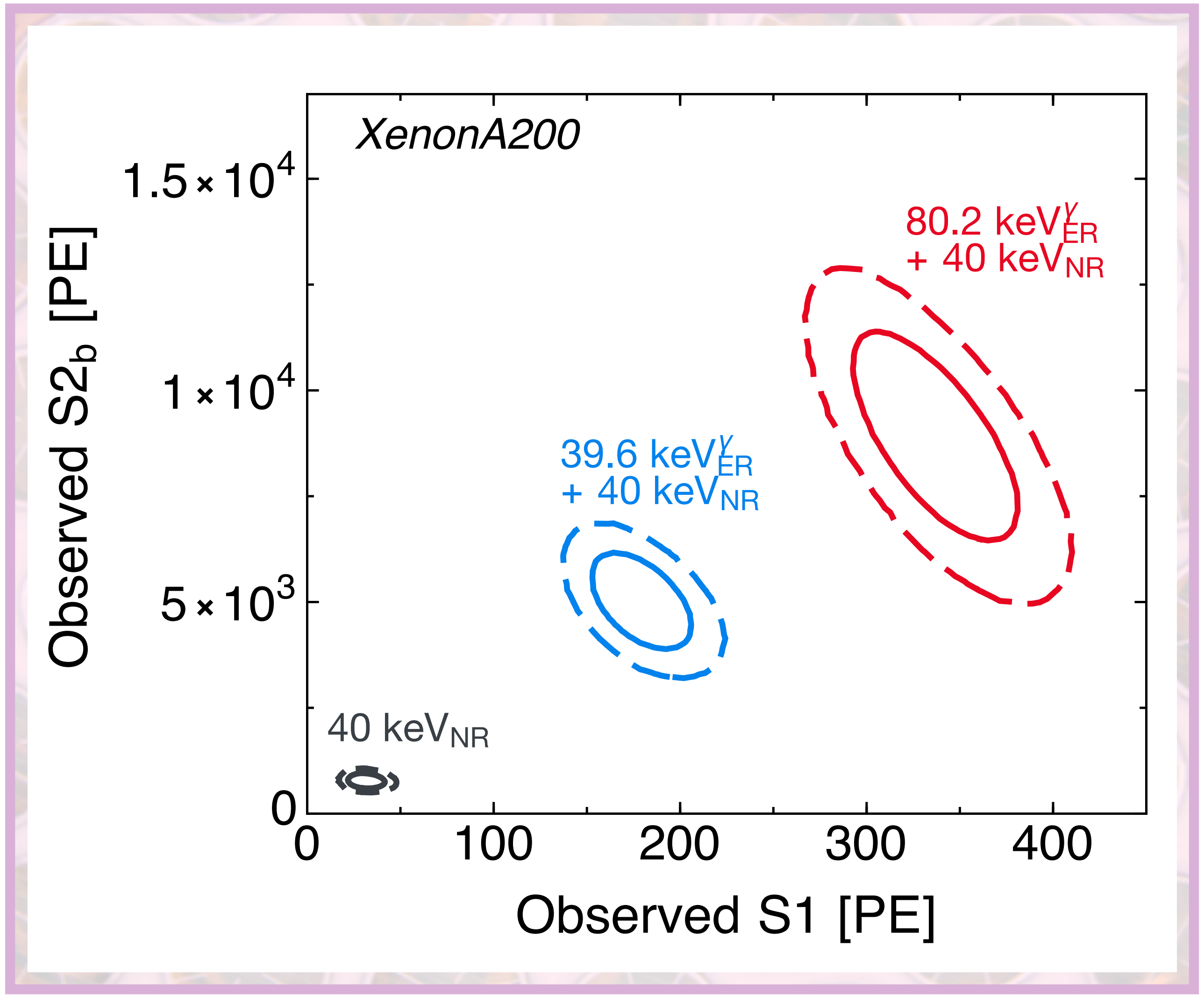
- Include detector and recombination fluctuations

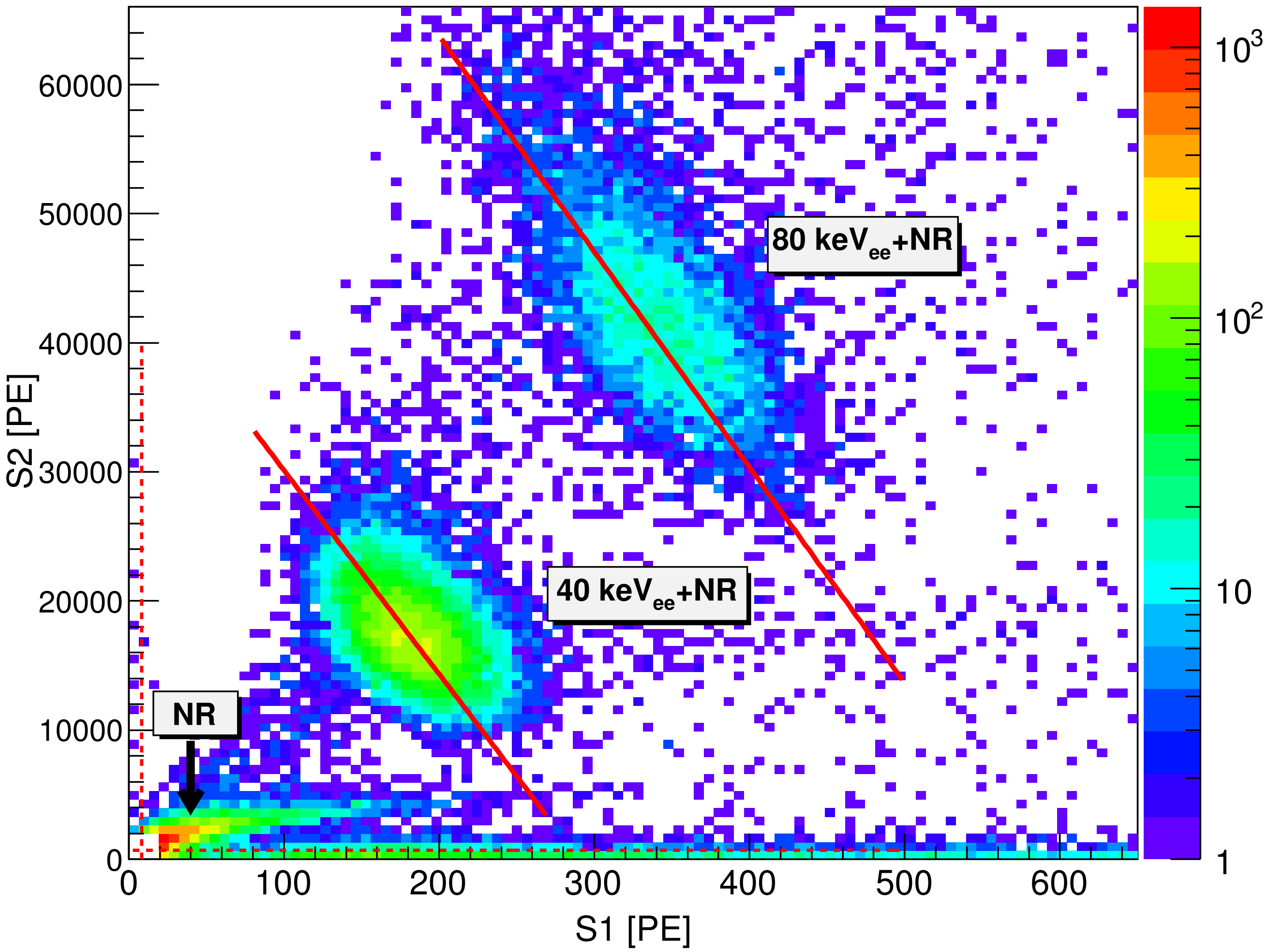


- For same energy, electronic recoils produce a *much larger* S1 and S2

Mock signals

- Looks like real data… 😃





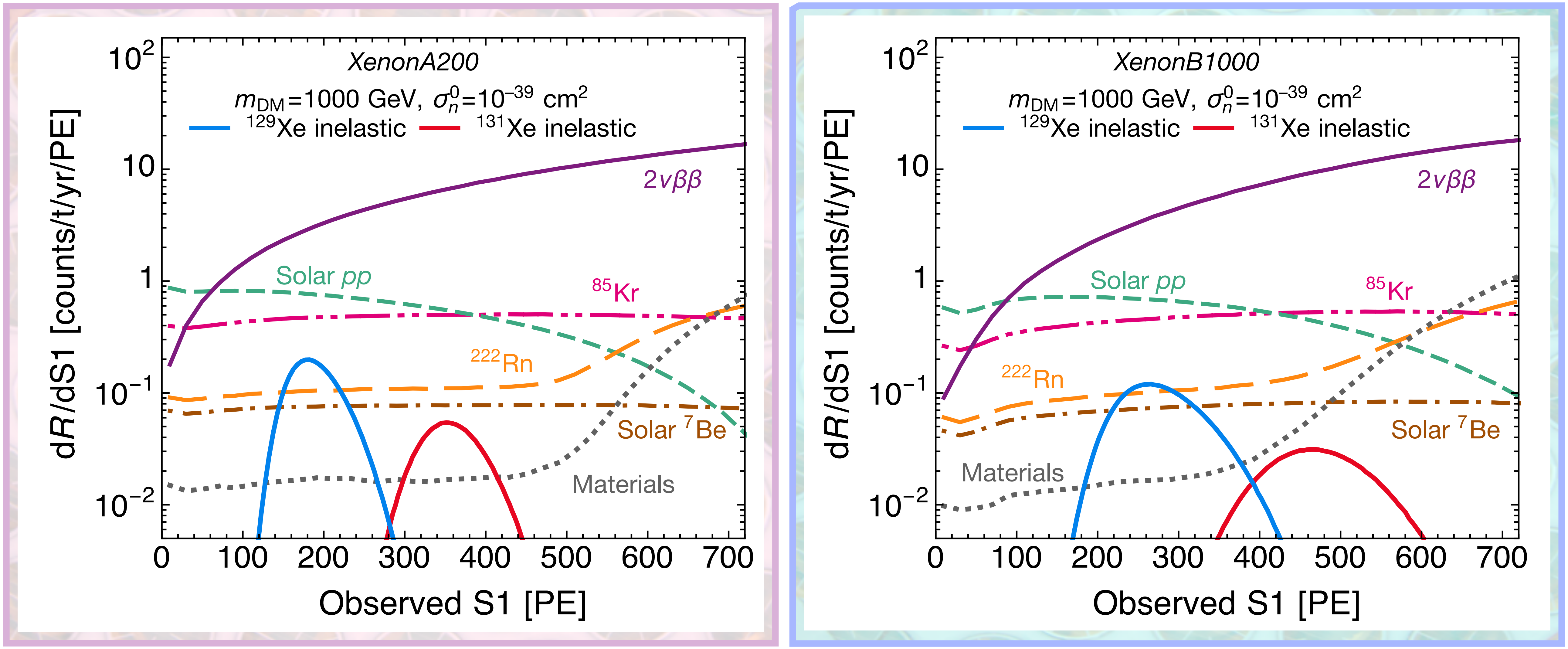
Data from PandaX-I arXiv:1505.00771

$$\lambda(0) = \frac{L(\sigma_n^0 = 0, \hat{\hat{\vec{A}}}_{\rm BG})}{L(\hat{\sigma}_n^0, \hat{\vec{A}}_{\rm BG})}$$

$$L(\sigma_n^0, \vec{A}_{\rm BG}) = \frac{\left(\mu_{\rm DM} + \sum_{j=1}^{6} \mu_{{\rm BG}j}\right)^N}{N!} \exp\left(-\mu_{\rm DM} + \sum_{j=1}^{6} \mu_{{\rm BG}j}\right) \cdot \prod_{m=1}^{6} L_m(A_{{\rm BG}m})$$
$$\cdot \prod_{i=1}^{N} \left[\frac{\mu_{\rm DM}}{\mu_{\rm DM} + \sum_{k=1}^{6} \mu_{{\rm BG}k}} f_{\rm DM}({\rm S1}_i, \log_{10}({\rm S2_b}/{\rm S1})_i) \right.$$
$$\left. + \sum_{j=1}^{6} \frac{\mu_{{\rm BG}j}}{\mu_{\rm DM} + \sum_{k=1}^{6} \mu_{{\rm BG}k}} f_{{\rm BG}j}({\rm S1}_i, \log_{10}({\rm S2_b}/{\rm S1})_i) \right],$$

Single-phase experiments

- Detecting this signal could be difficult…



…impossible for single phase (S1-only)?

Improvements?

- Larger exposure
  ➡ background dominated so only scales with the square root

- Could reduce backgrounds

- Largest: 2-beta—2-neutrino decay of ^{136}Xe
  ➡ Remove the ^{136}Xe isotope

- Try to search for displaced the S2 signal from the recoil and photon?