Prospects for dark matter detection with inelastic transitions of xenon

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preliminary results
—work in progress—

TeVPA, Tokyo, Japan - 27th October 2015

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.

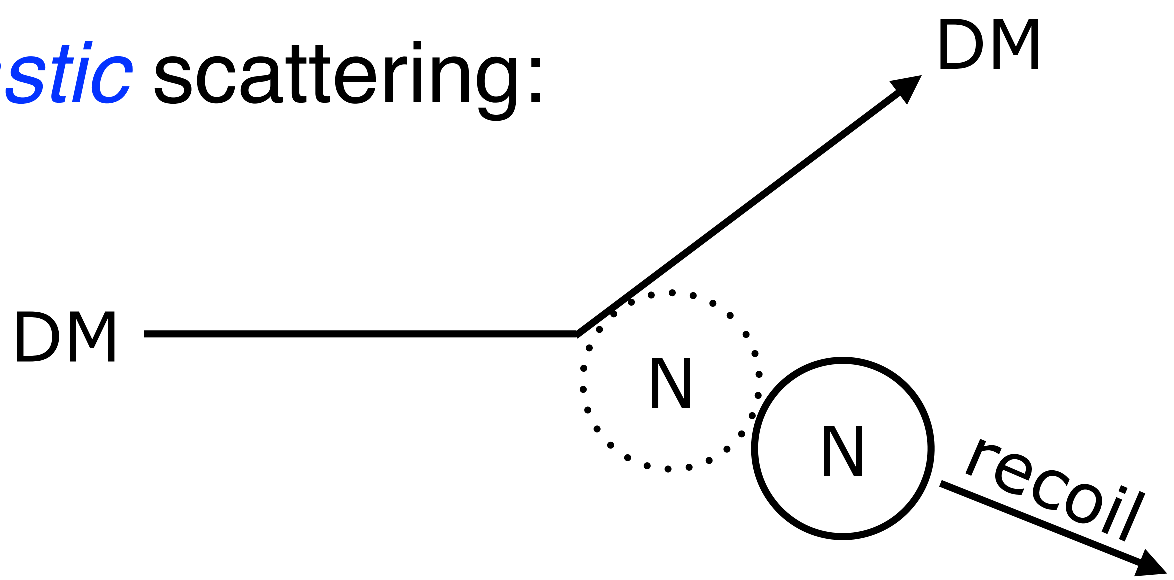
An old idea… Inelastic scattering

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

Can it ever be detected?

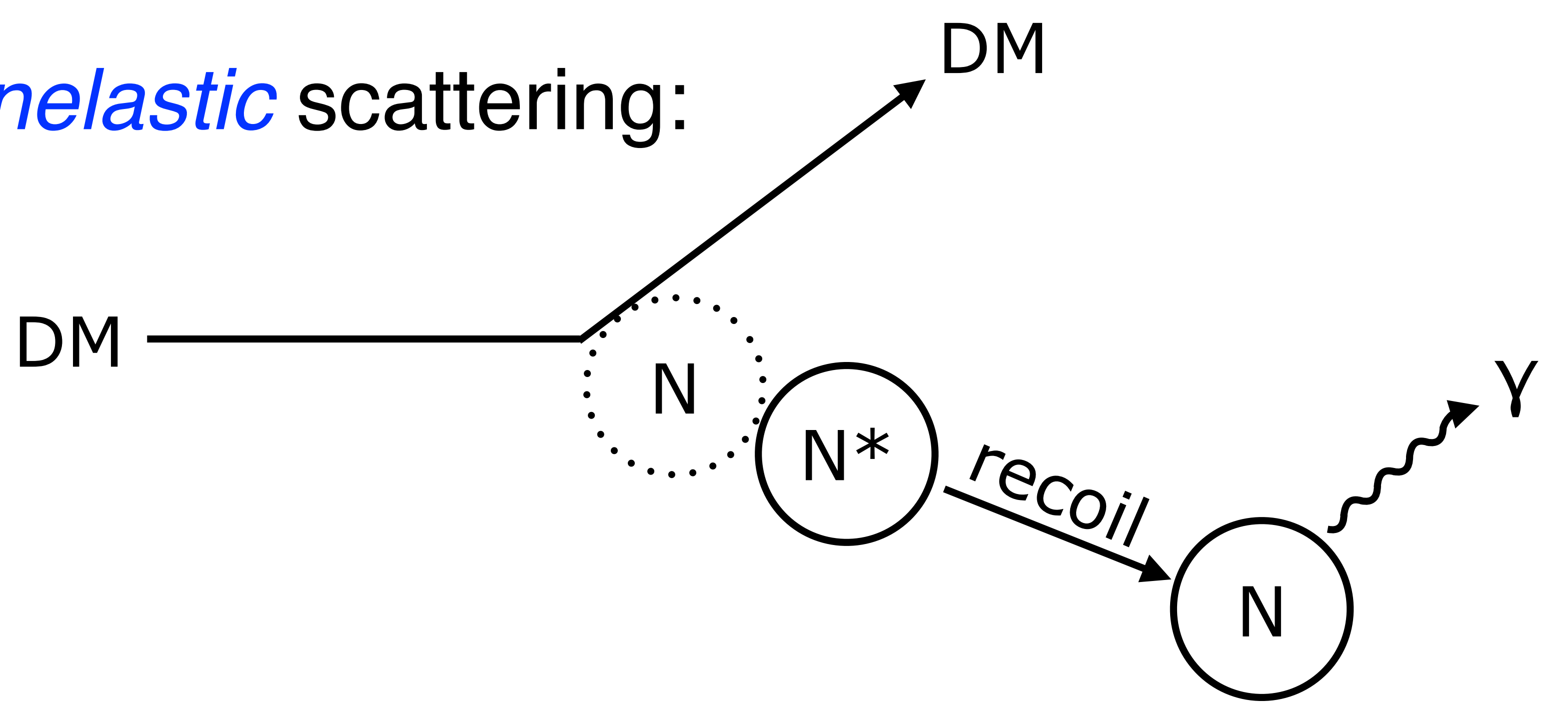
What is it?

elastic scattering:



measure:
N's recoil energy

inelastic scattering:



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

What is a good target?

Why Xenon?

Inelastic scattering *is not* A^2 enhanced

★ Only accessible for spin-dependent interactions

➡ Elastic and inelastic scattering rates comparable

Vietze et al arXiv:1412.6091

★ Ideal target should have

i. good spin-dependent sensitivity

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

Why Xenon?

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

^{129}Xe

Natural abundance: 26.4%

Lowest excitation: **39.6 keV**

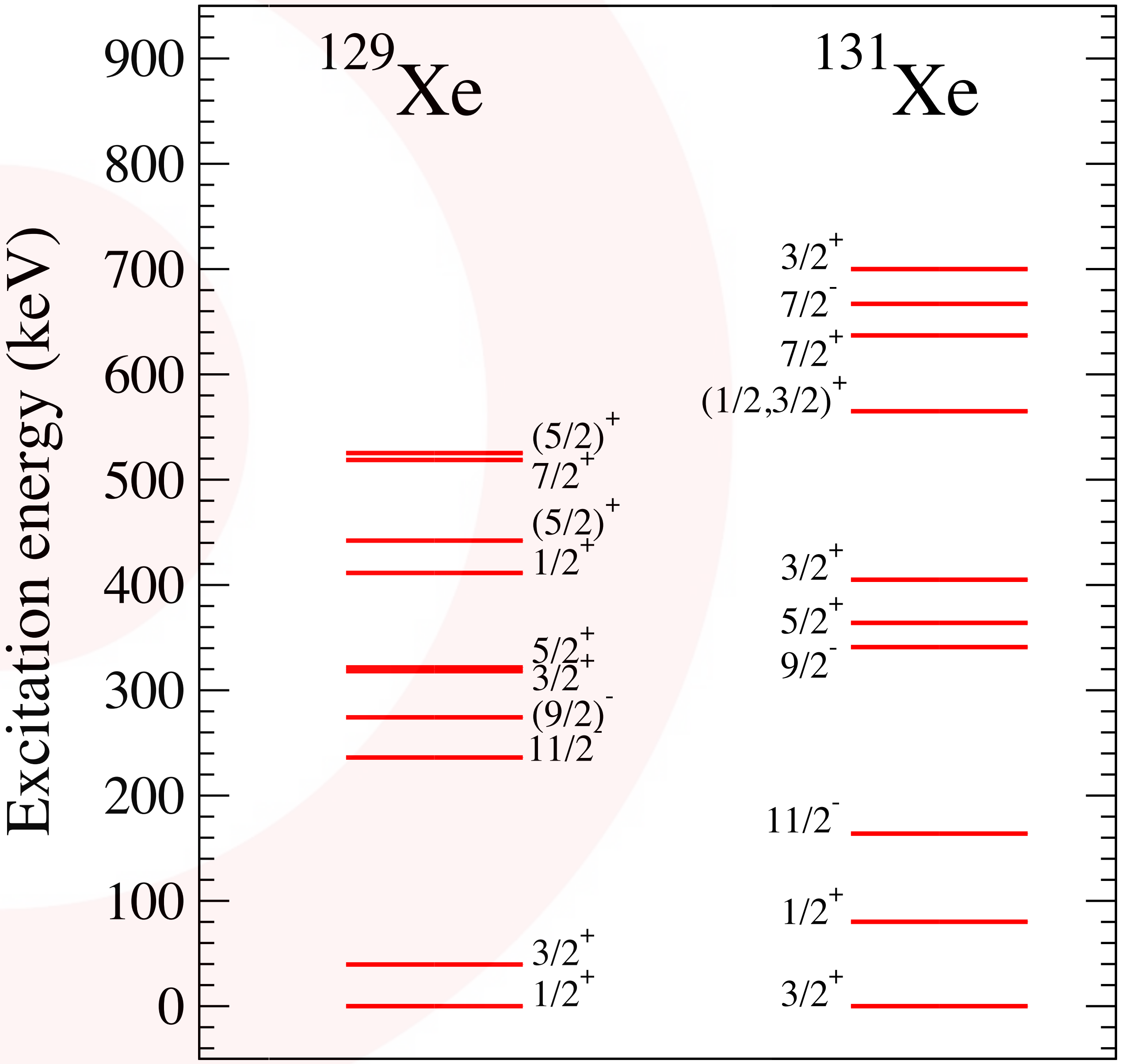
Lifetime: 0.97 ns

^{131}Xe

Natural abundance: 21.2%

Lowest excitation: **80.2 keV**

Lifetime: 0.48 ns



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)*

Why is it interesting?

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

- A detection should:

- give independent evidence for dark matter scattering
- point strongly to a spin-dependent interaction
- help with mass reconstruction (because of different kinematics)

Why now?

We can accurately quantify the signal and background

- Structure functions known (needed for cross-section)
- Backgrounds are more-or-less known
- Future detector properties are more-or-less known

An old idea… Inelastic scattering

Can it ever be detected?

Scattering rate

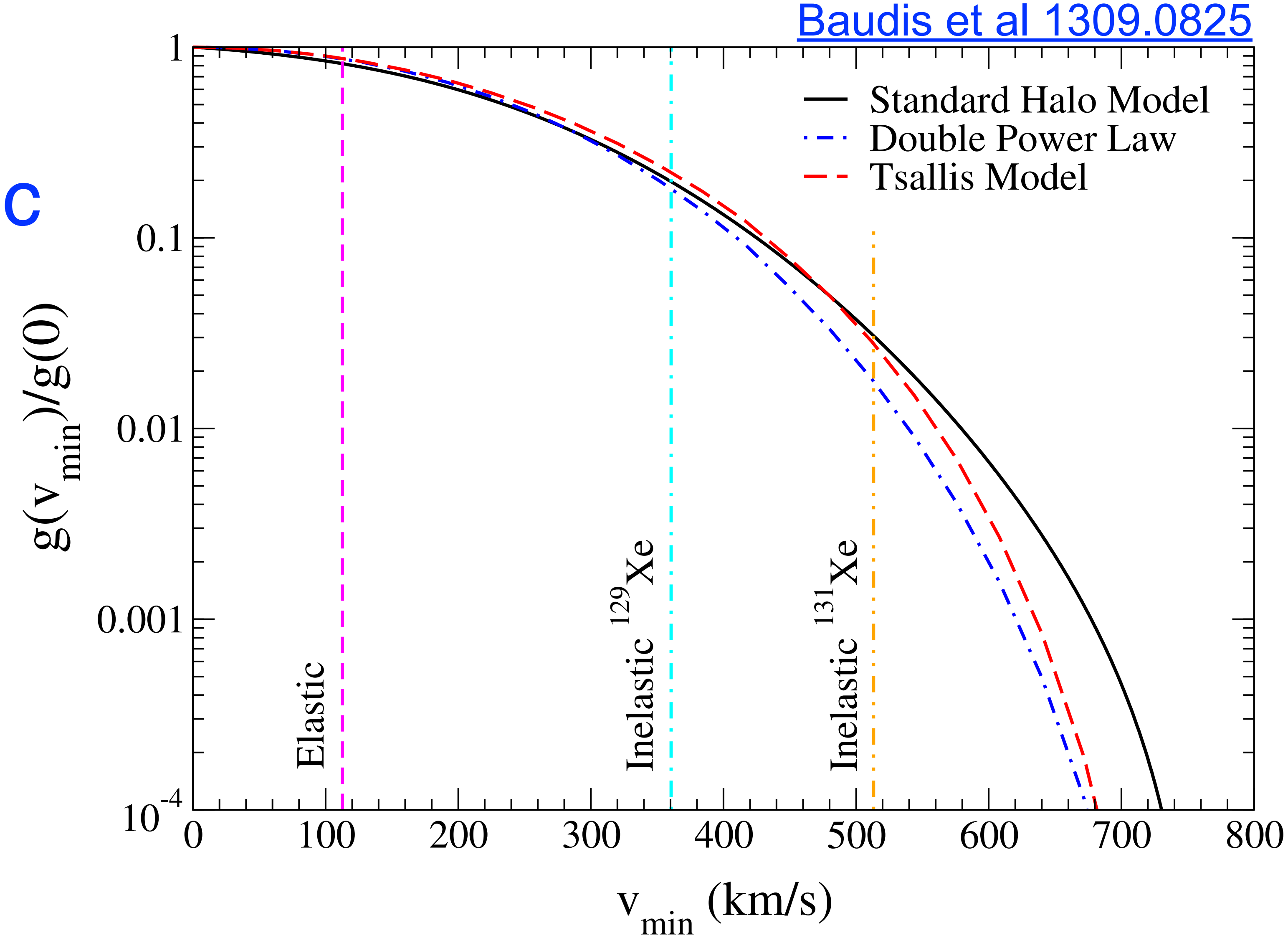
- Rate depends on the DM velocity distribution:

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

- v_{min} is higher for inelastic (DM kinetic energy must also excite the nucleus)

- This suppresses the inelastic rate by factor ~10

Baudis et al 1309.0825



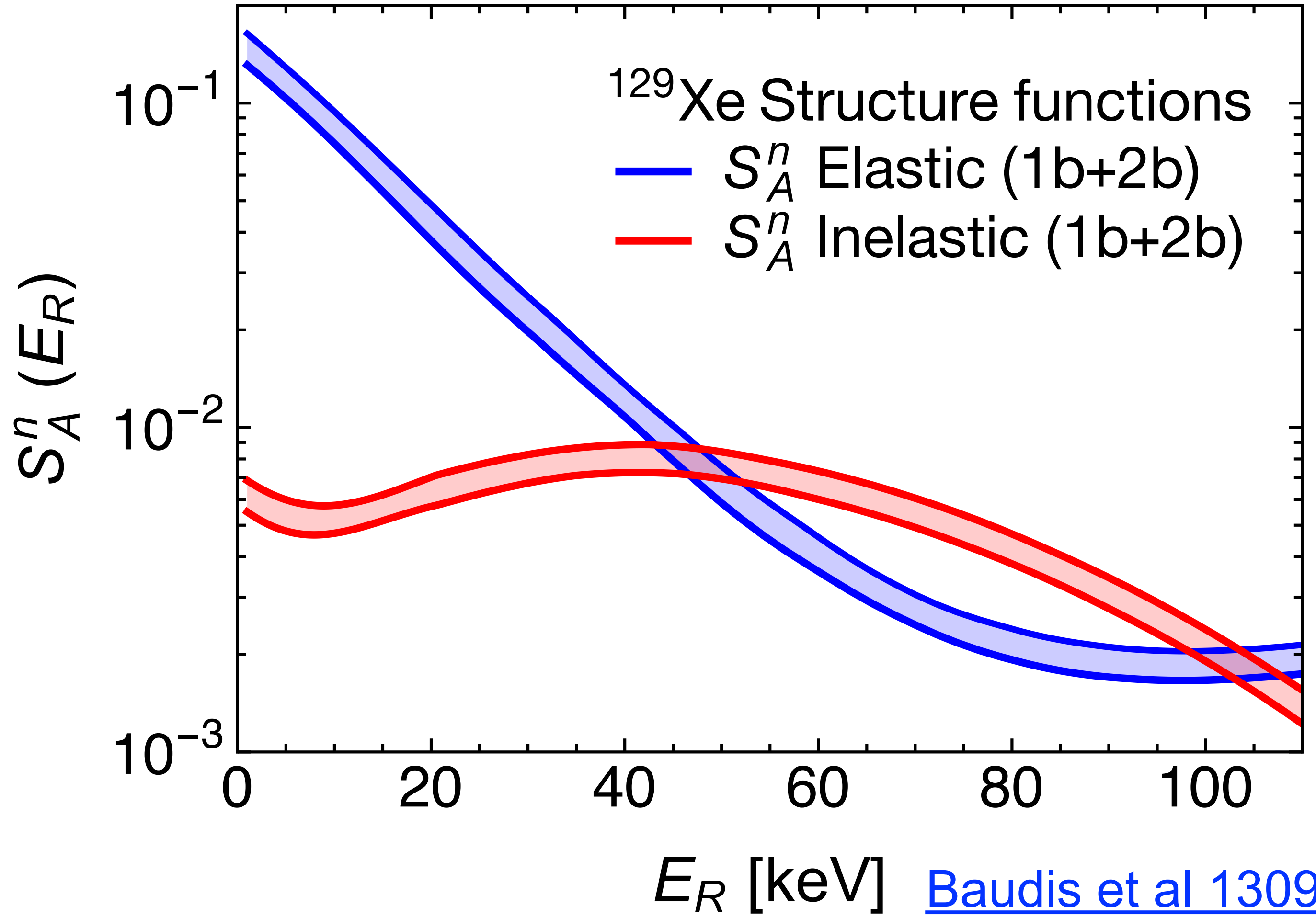
Structure functions

- 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

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

- Smaller for inelastic
  (Small E_R most relevant)

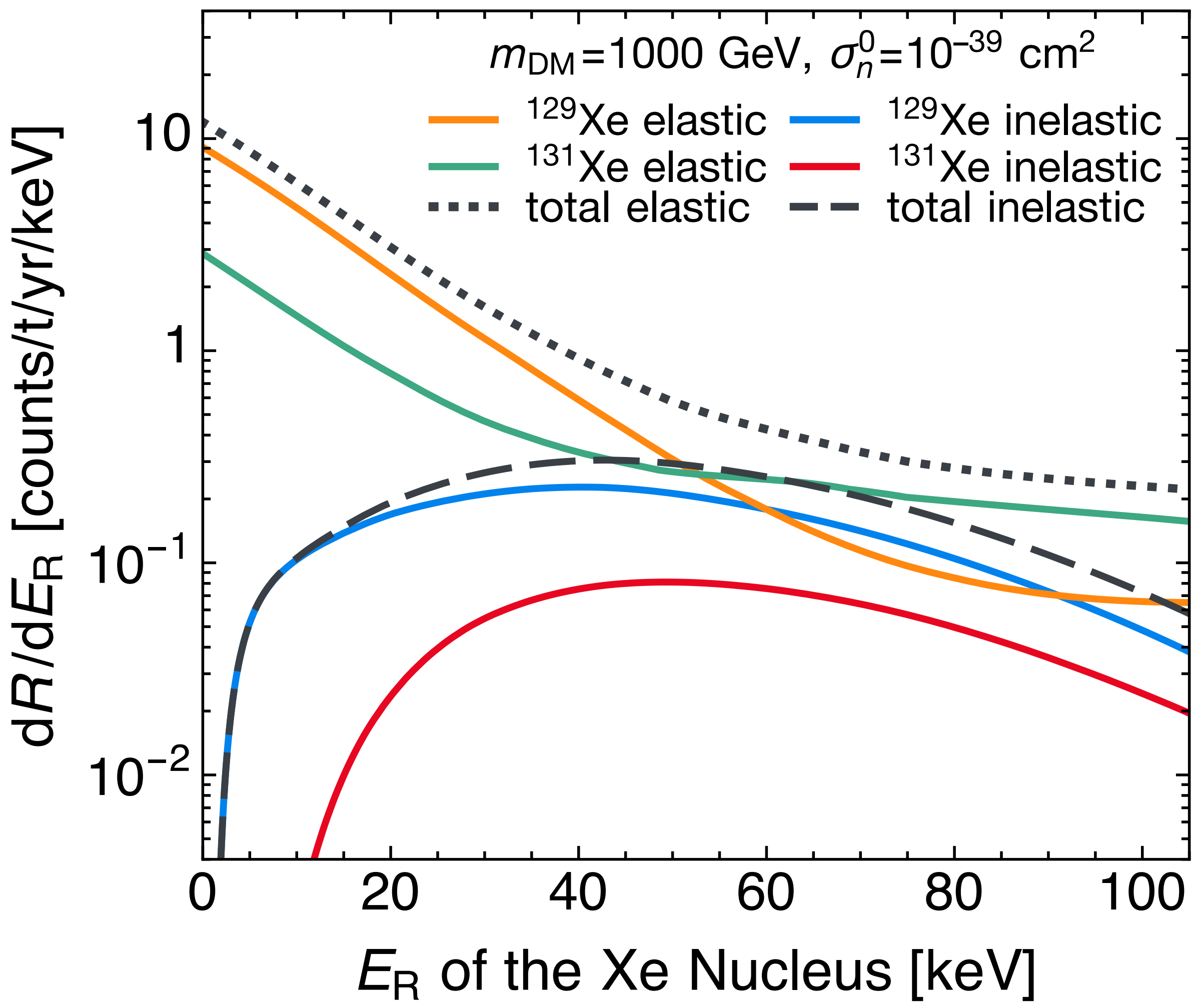
- This suppresses the inelastic rate by factor ~10



Baudis et al 1309.0825

The rate

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

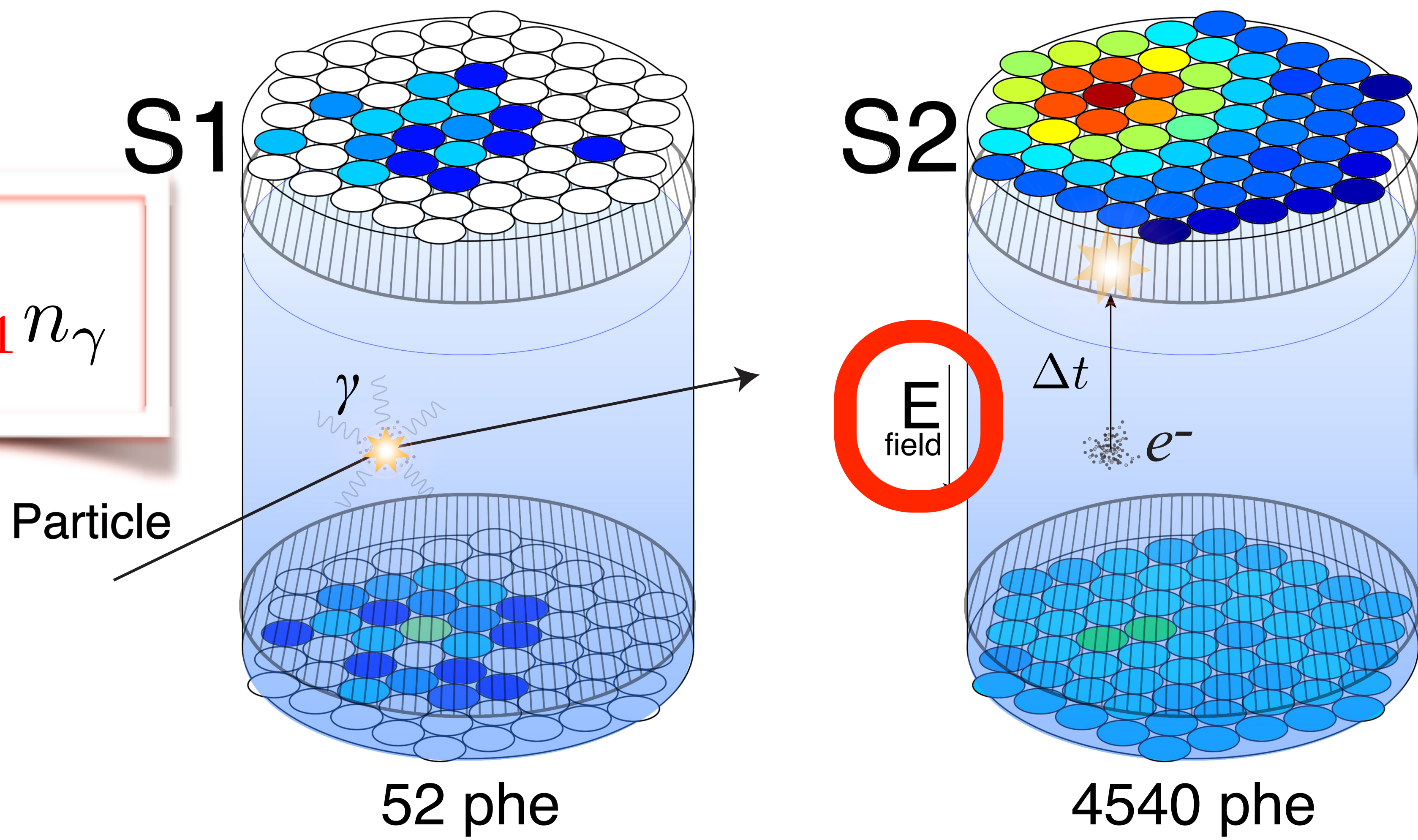


- Inelastic rate smaller by factor ~100
  ➡ Always see an elastic signal first

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:

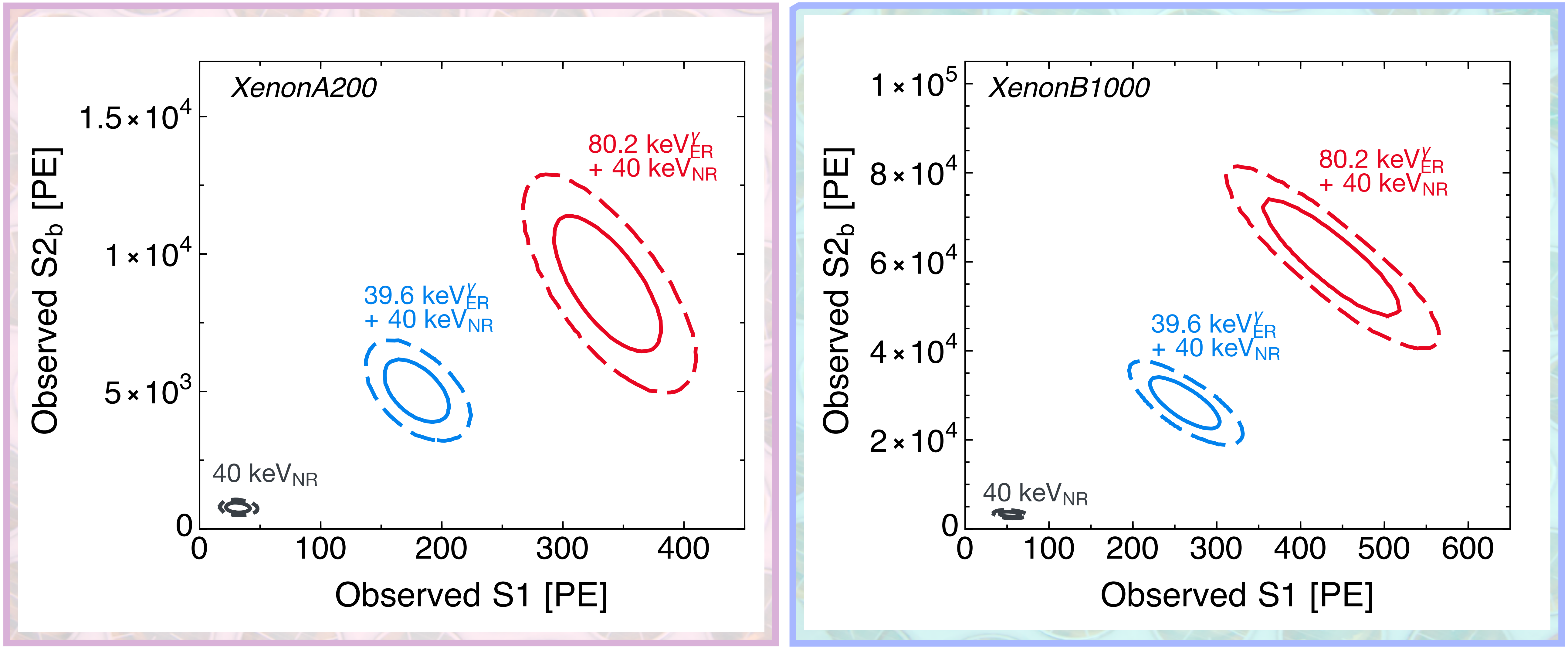
XenonA200	*XenonB1000*
g_1=0.07 PE/ɣ	g_1=0.12 PE/ɣ
g_2=12.5 PE/e (50% extraction efficiency)	g_2=50 PE/e (100% extraction efficiency)
drift field=200 V/cm	drift field=1000 V/cm

- Number of photons & electrons modelled with NEST

Szydagis et al 1106.1613

Mock signals

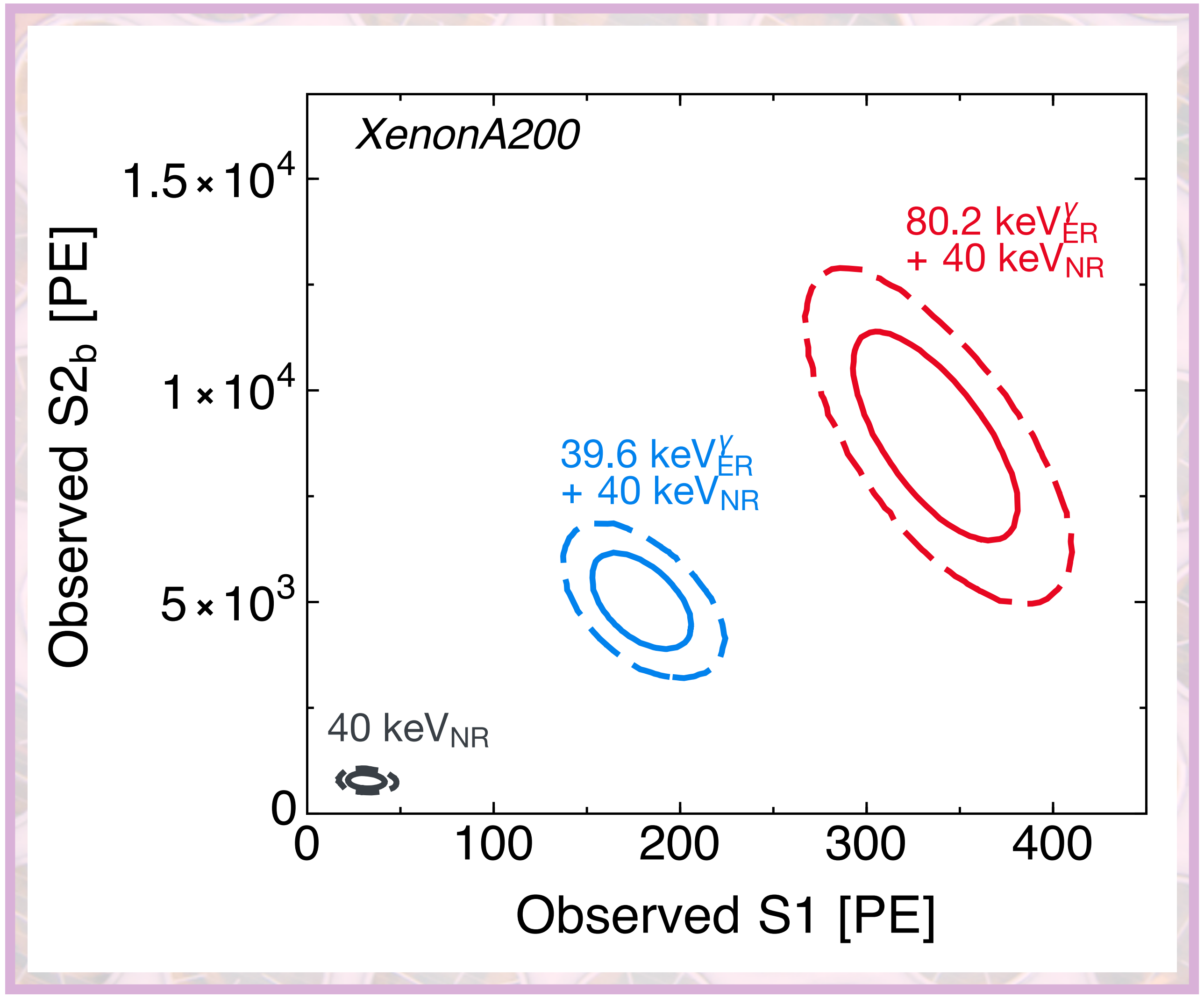
- Include detector and recombination fluctuations

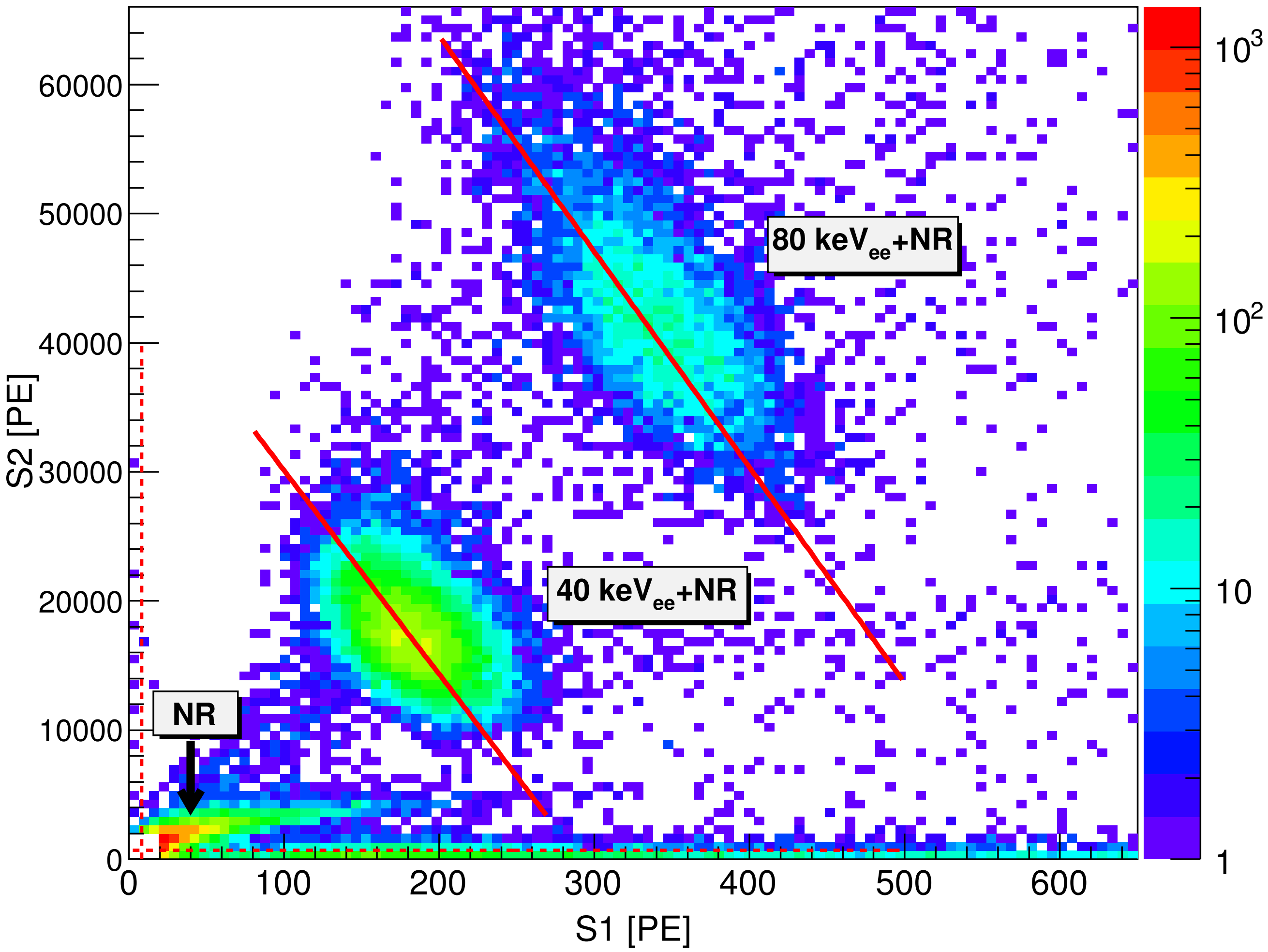


- For same energy, electronic recoils produce a *much larger* S1 and S2

Mock signals

- Looks like real data… 😃



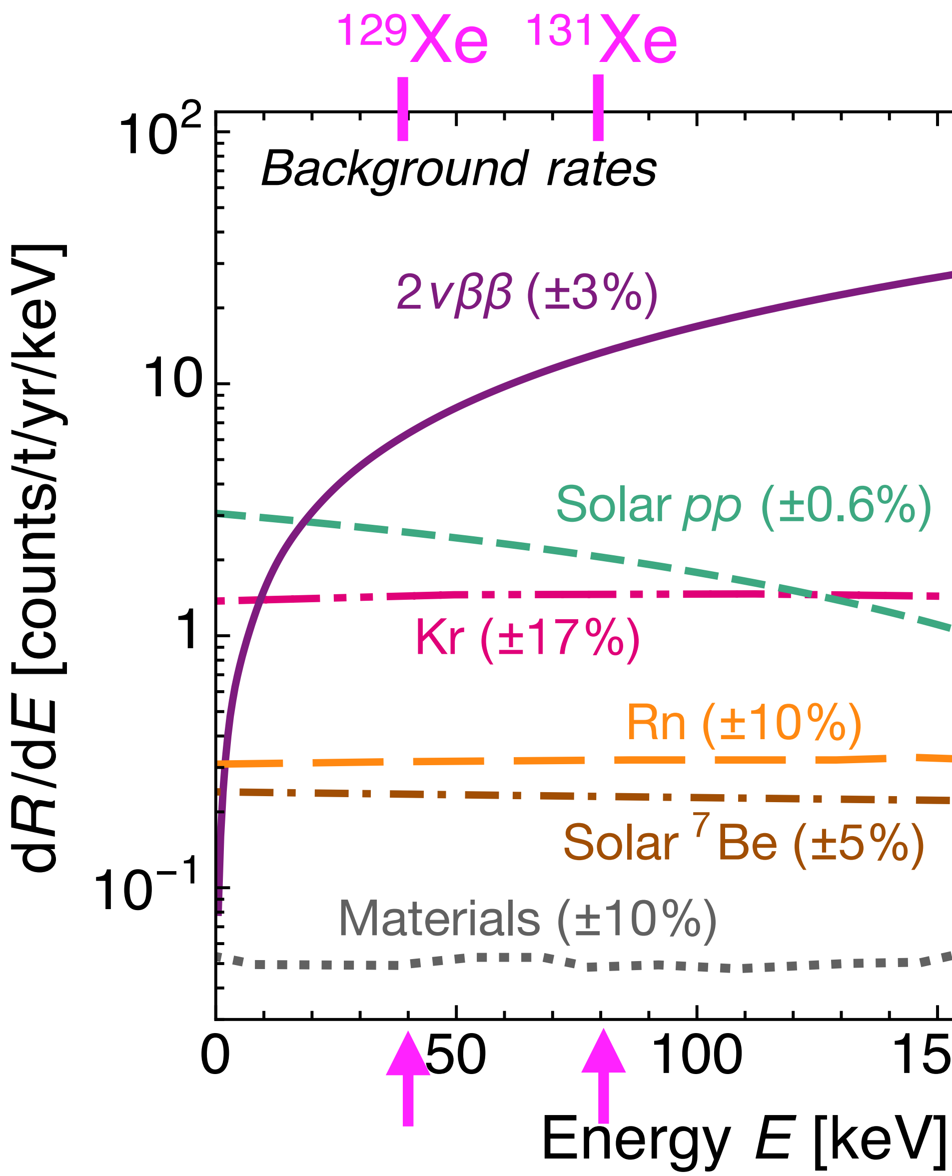


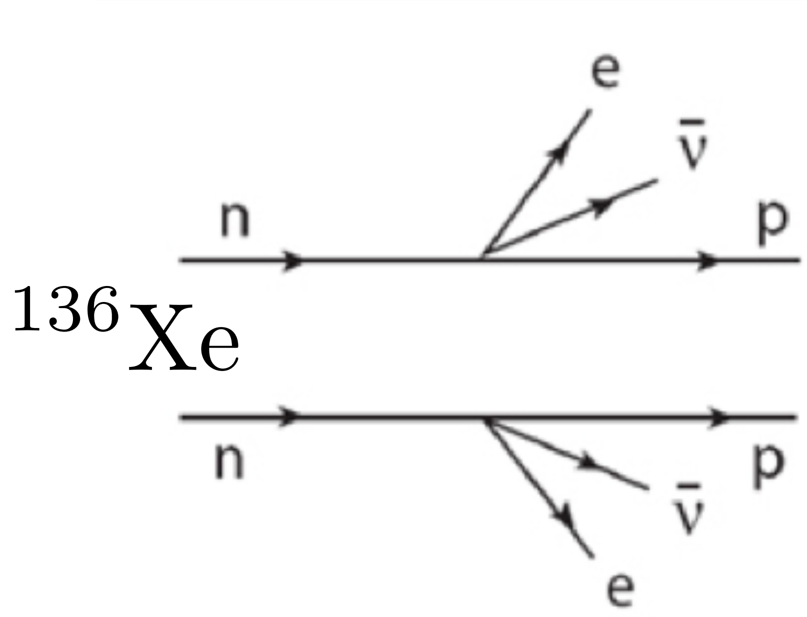
Data from PandaX-I arXiv:1505.00771

Background

- Background spectra expected in LZ/XENONnT:

LZ Design: 1509.02910

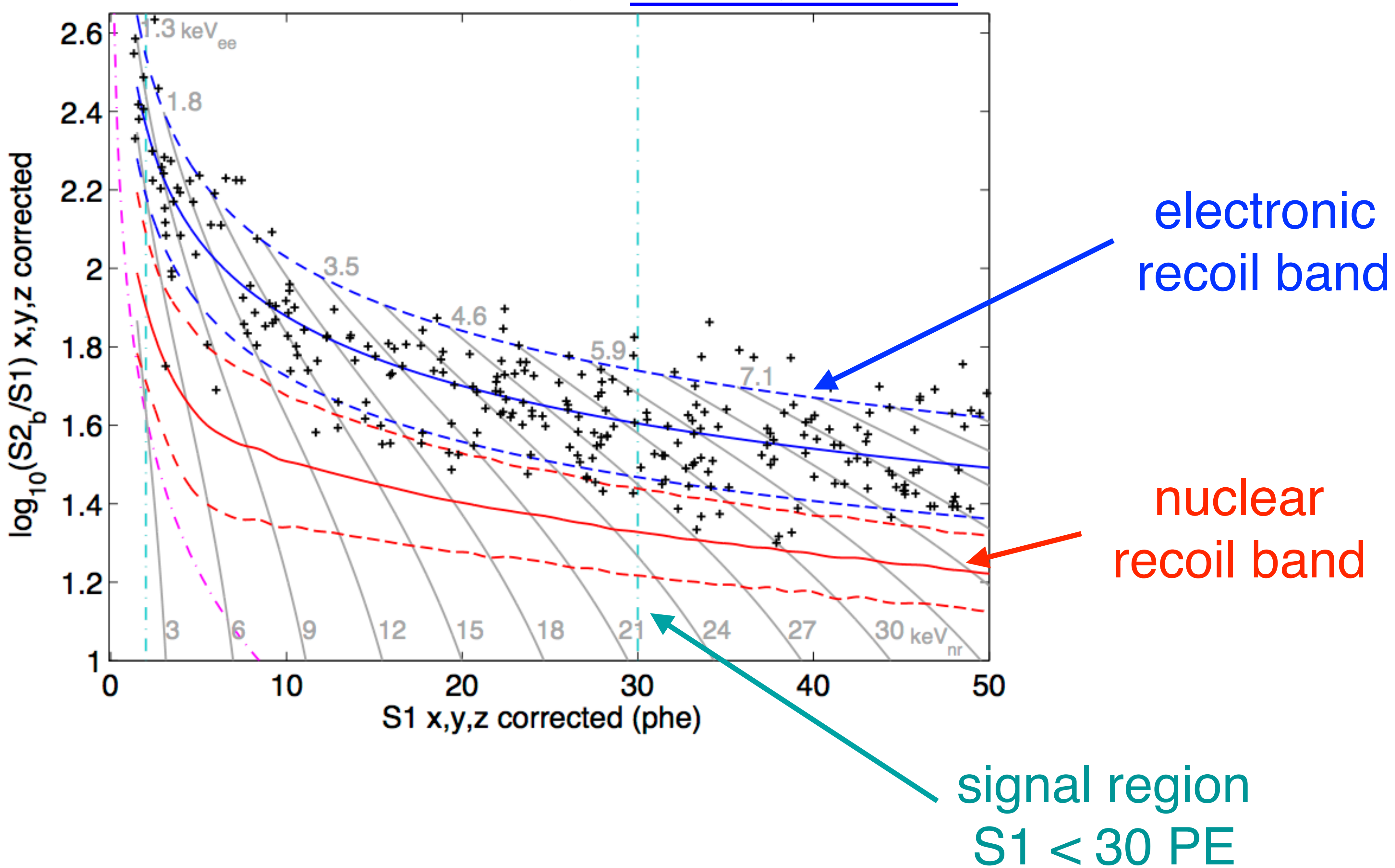




- *2-neutrino — 2-beta decay of ^{136}Xe dominates above 20 keV*

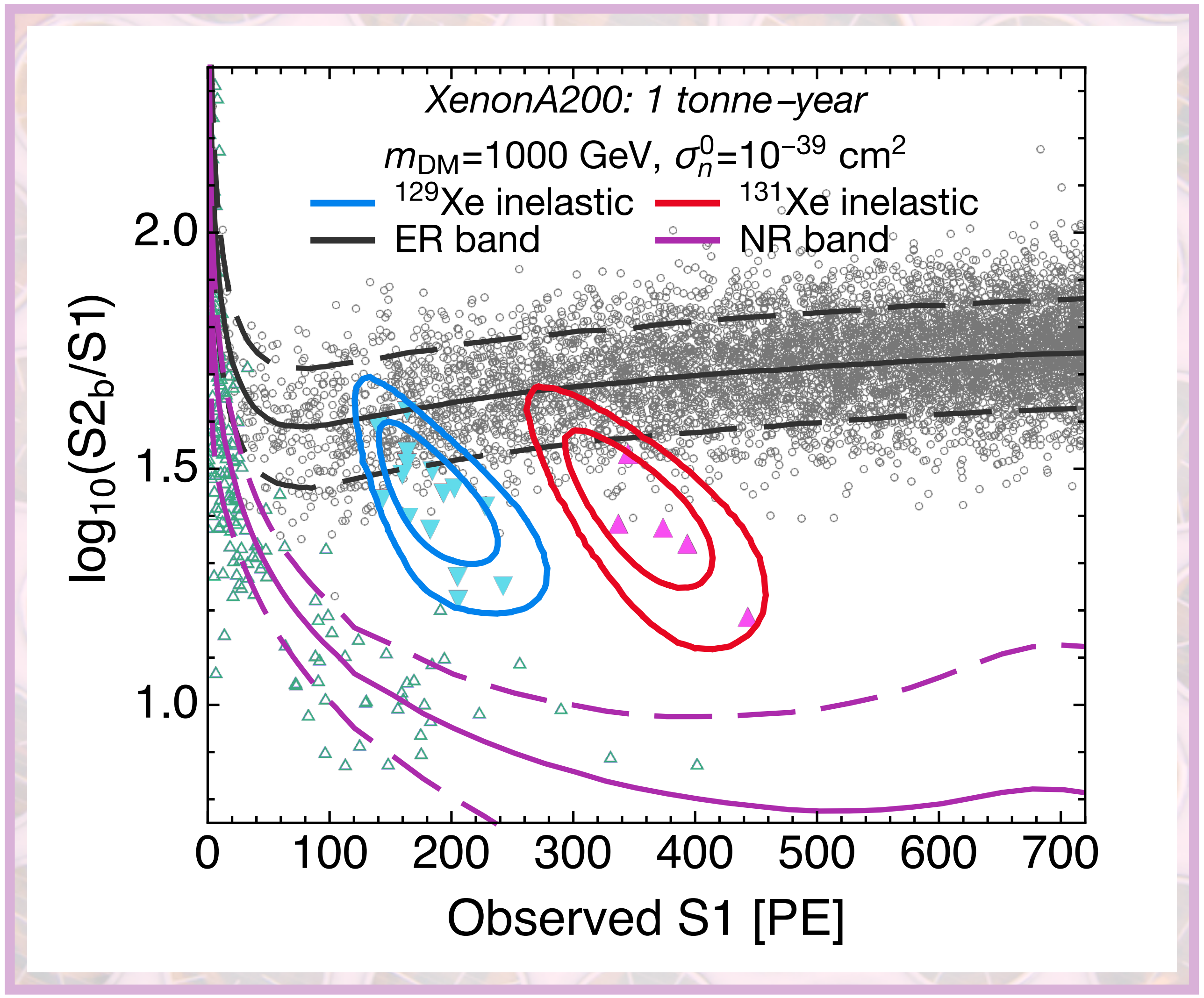
Reminder: Usual signal plane

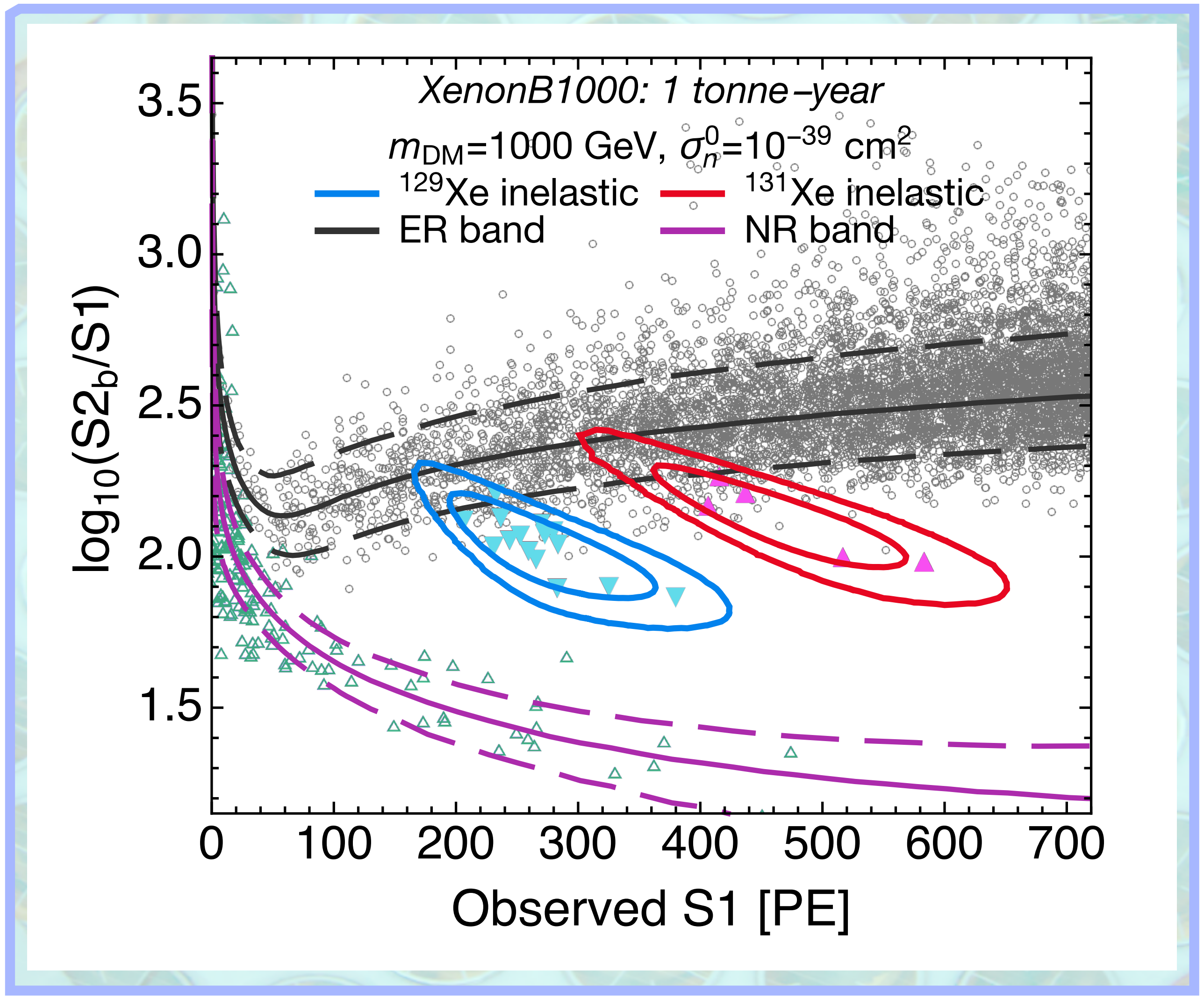
LUX arXiv:1310.8214



Background versus signal

- Signal region at *higher values* of S1





- Large backgrounds…but some 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

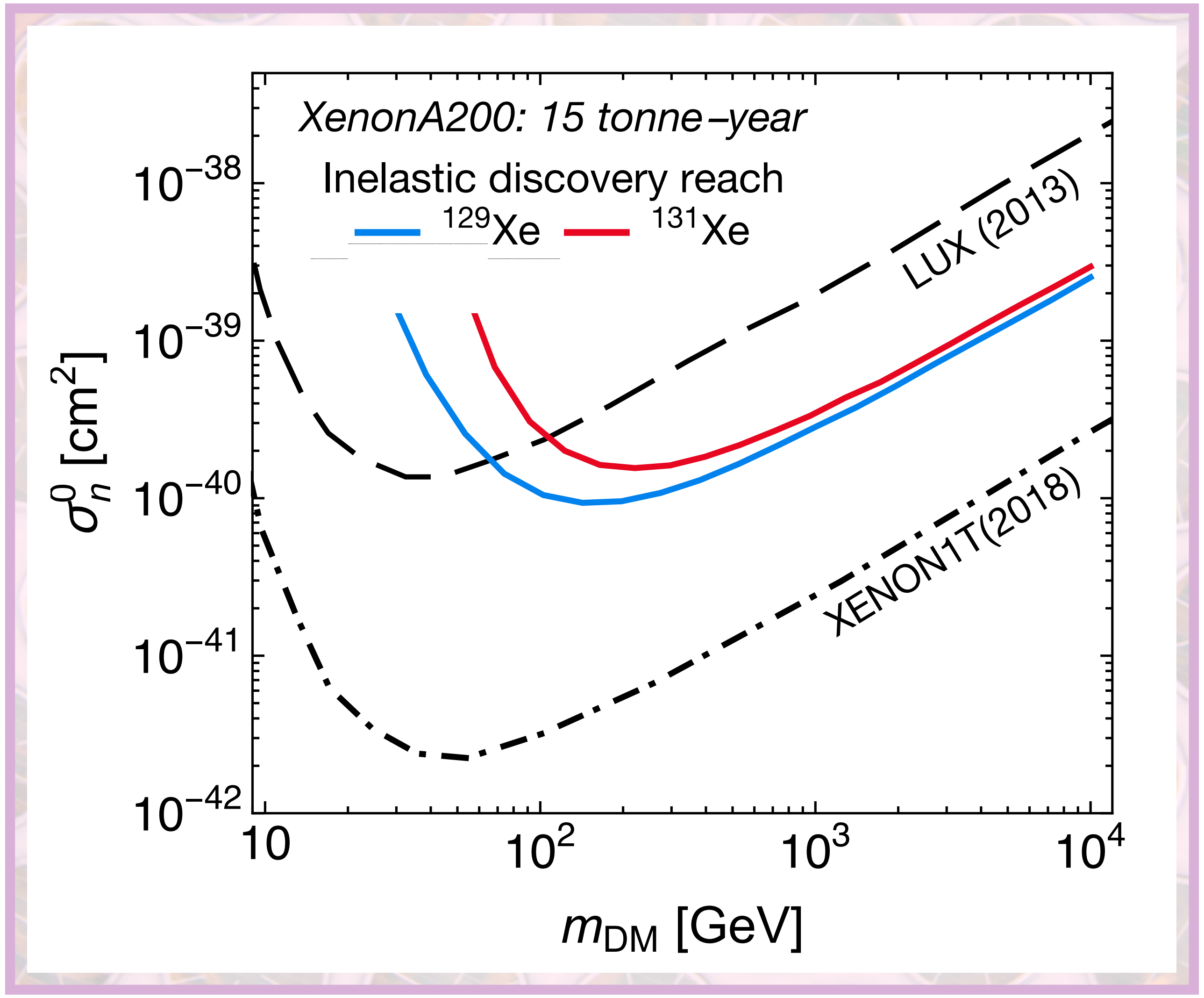
- Profile likelihood ratio:

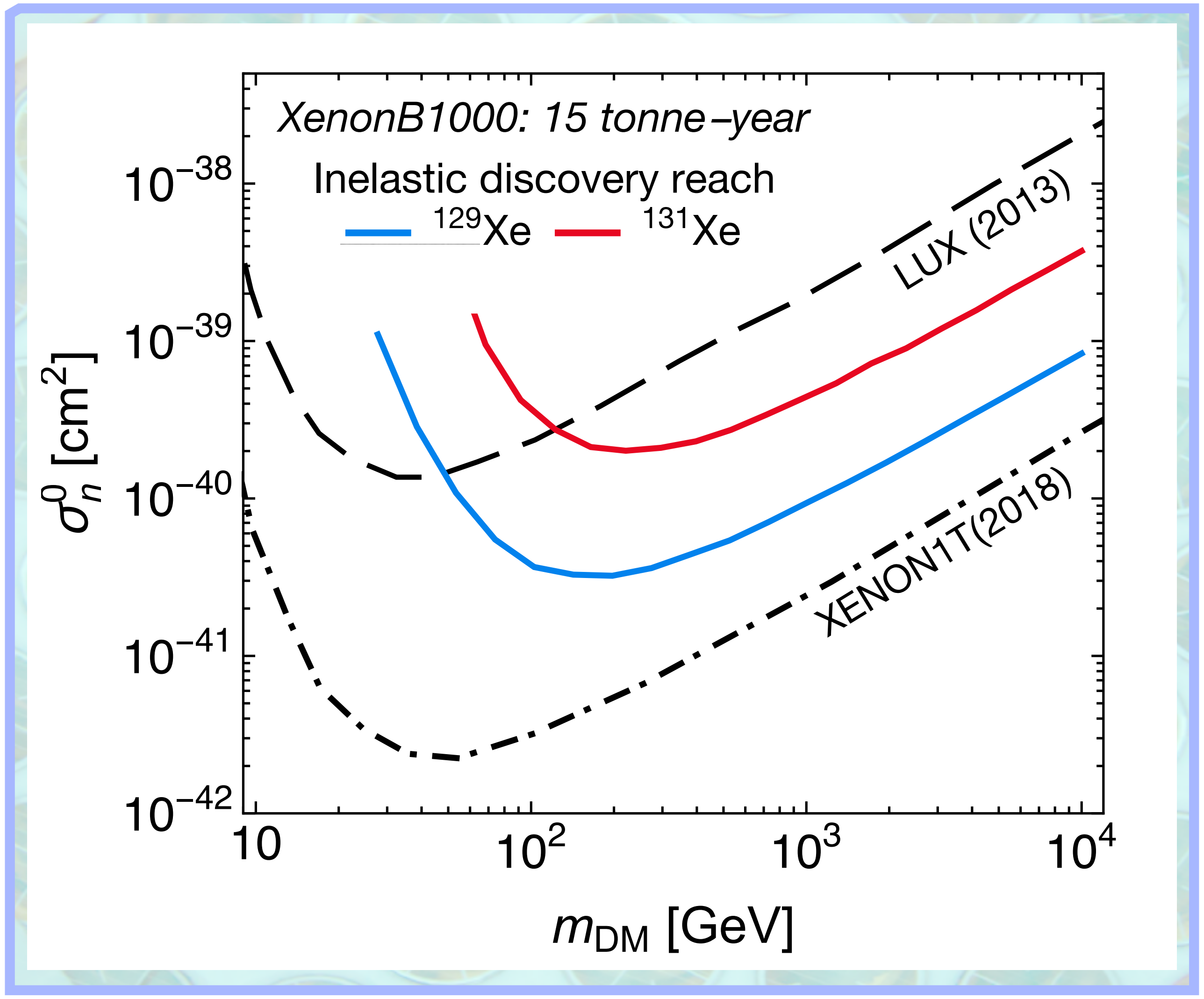
$$\lambda(0) = \frac{L(\sigma_n^0 = 0, \hat{\hat{\vec{A}}}_{\mathrm{BG}})}{L(\hat{\sigma_n^0}, \hat{\vec{A}}_{\mathrm{BG}})}$$

- Include background uncertainties

Discovery limit

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





- Detectable if XENON1T make discovery in next run

Summary

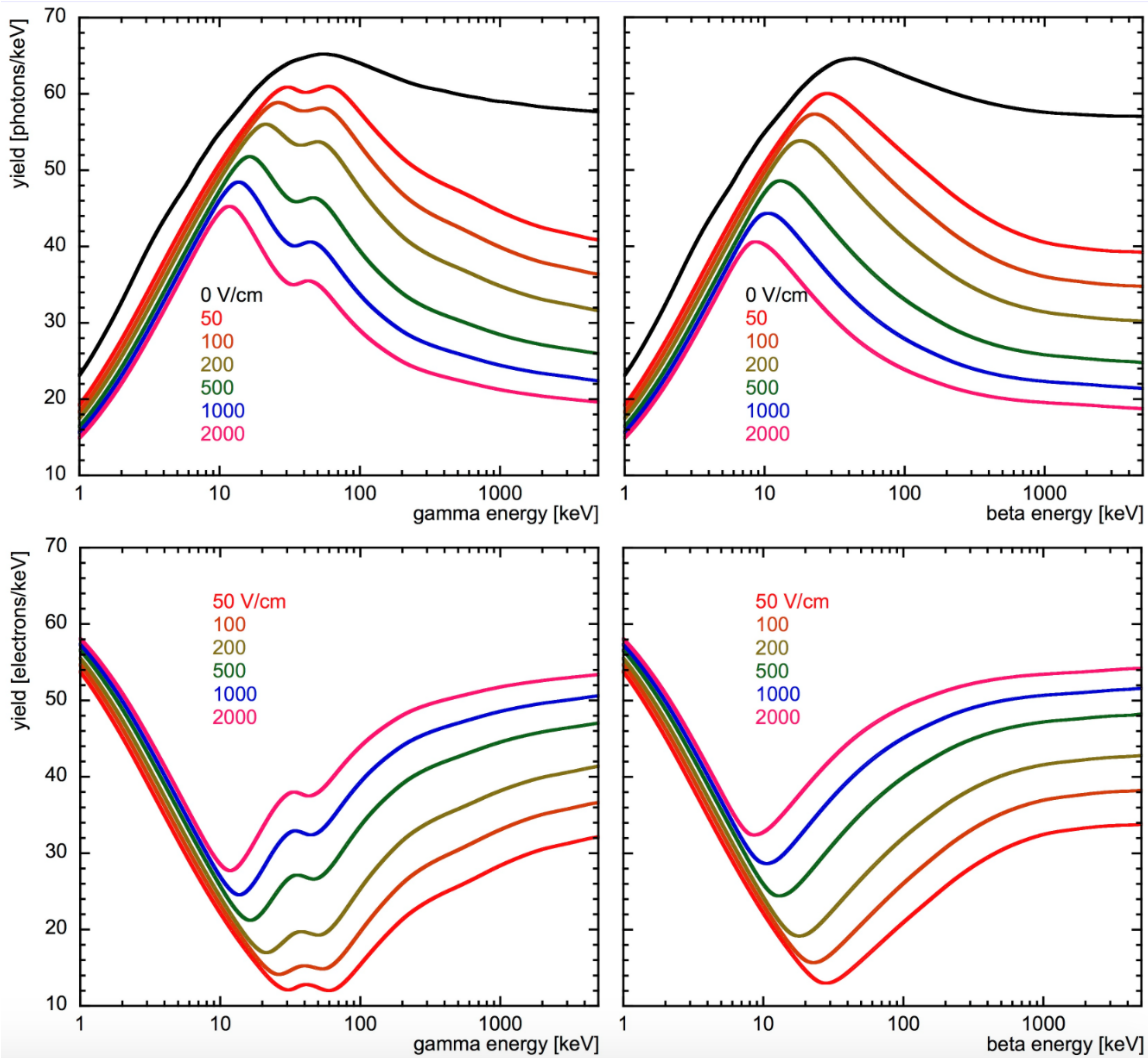
- Dark matter can excite the ^{129}Xe and ^{131}Xe isotopes
  ➡ signal is nuclear recoil + photon
- Signal is always smaller than elastic rate
  ➡ Can it be detected?

Yes!

…need an (elastic) discovery signal
in the next run of XENON1T

Thank you

Backup



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

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

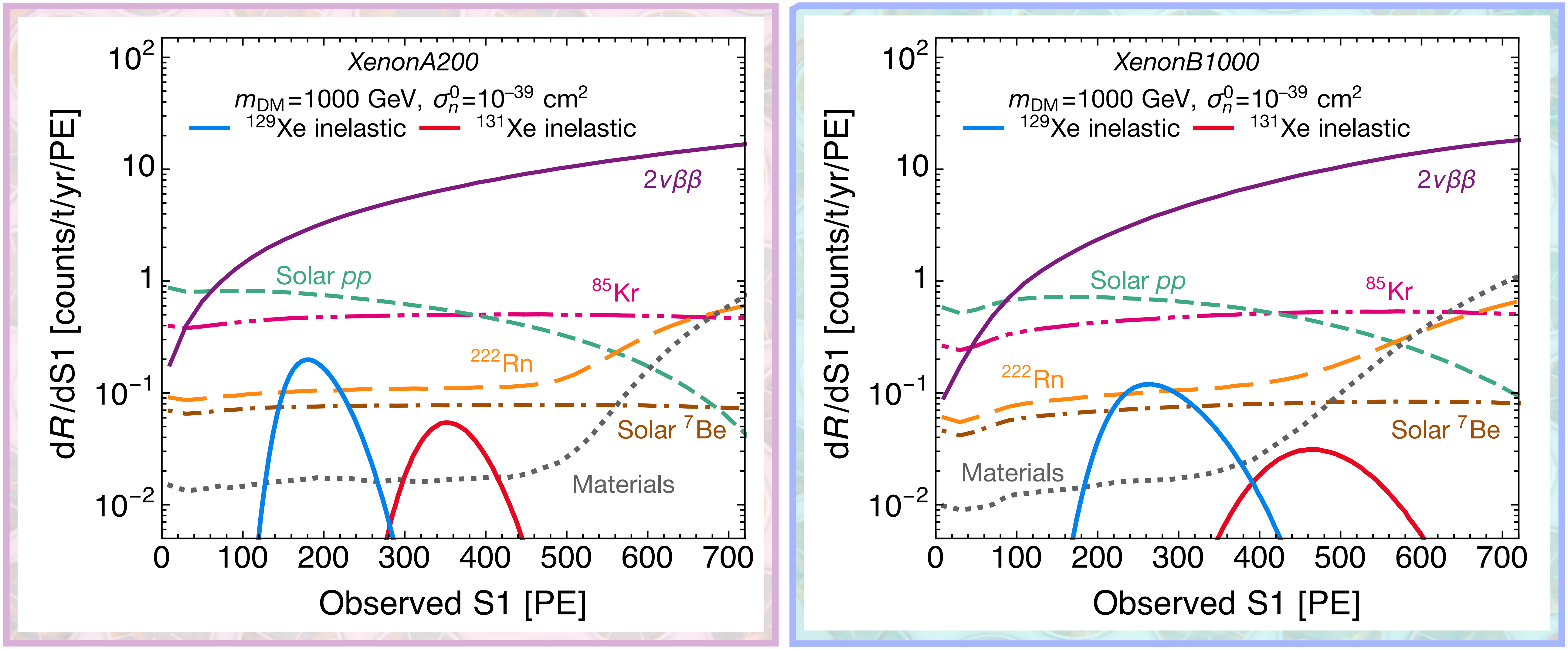
$$n_\gamma = n_{\rm ex} + r n_{\rm i}$$

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

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

Single-phase experiments

- Detecting this signal could be difficult…



…impossible for single phase (S1-only)?

Improvements?

- Could have a 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?