Prospects for dark matter detection with inelastic transitions of xenon

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preliminary results
—work in progress—

TAUP, Torino, Italy - 10th September 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.

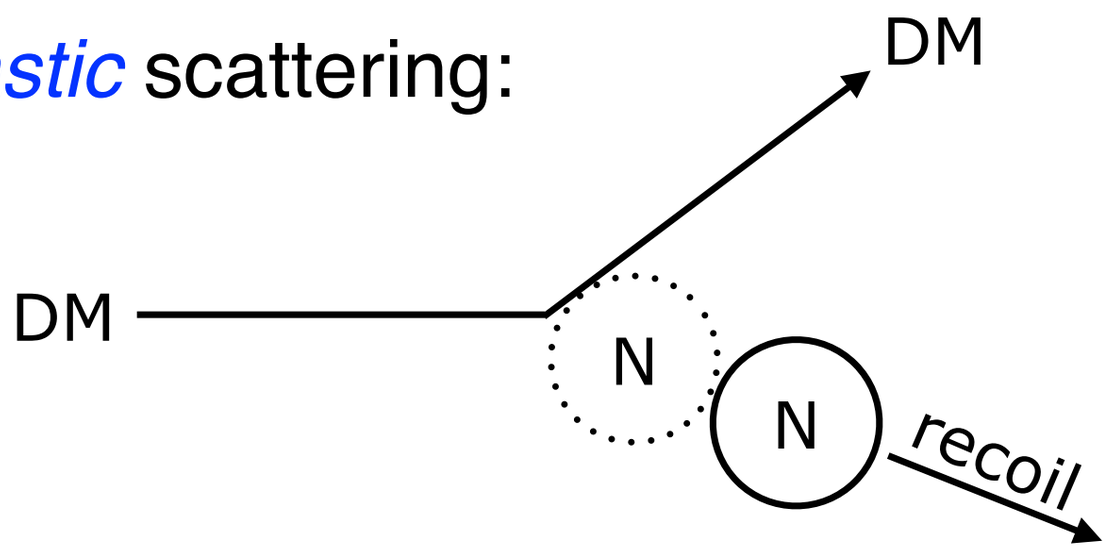
An old idea… Inelastic scattering

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

Can it ever be detected?

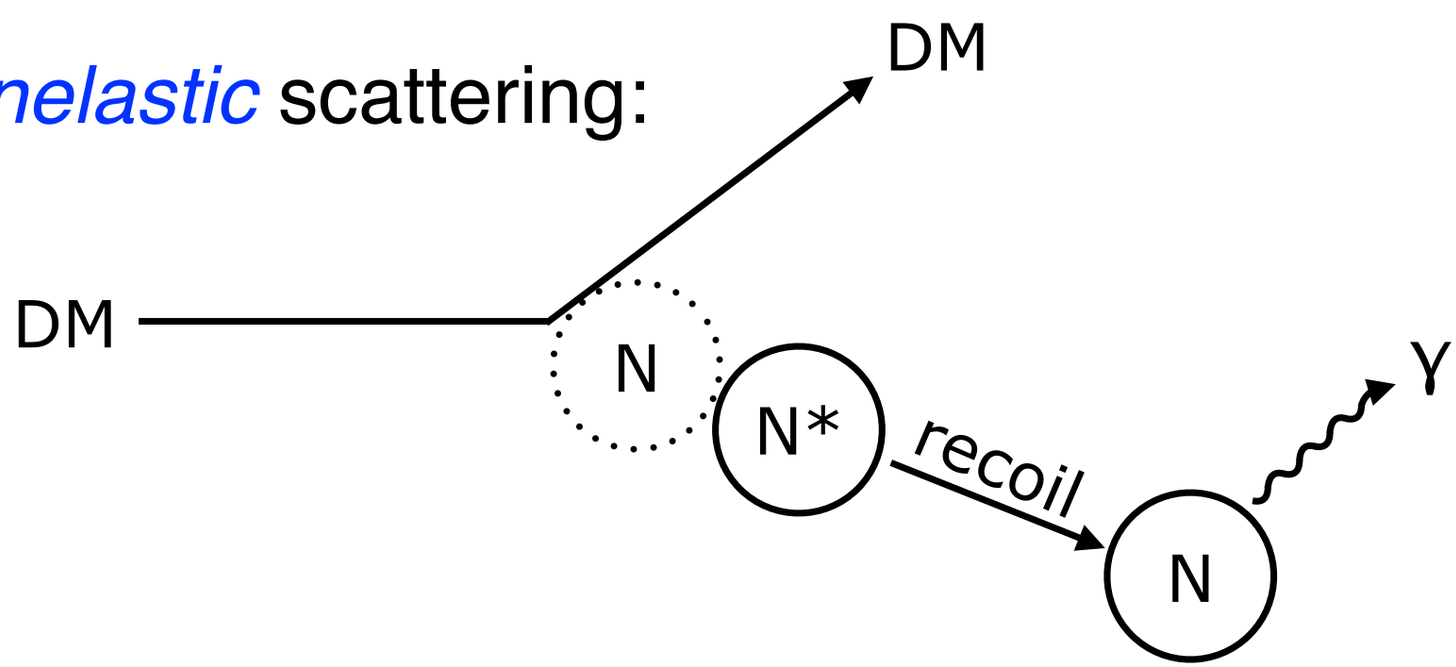
What is it?

elastic scattering:



measure:
N's recoil energy

inelastic scattering:



measure:
N's recoil energy
+ photon energy

What is a good target?

Inelastic scattering *is not* coherently enhanced

- Hopeless to look for it with spin-independent interactions
  ➡ inelastic rate is $A^2 \approx 10^4$ smaller arXiv:1412.6091

- Spin-dependent interactions *are not* A^2 enhanced
  ➡ Elastic and inelastic scattering rates more comparable

★ Ideal target has good spin-dependent sensitivity
…and a low lying excitation

What is a good target?

What is a good target?

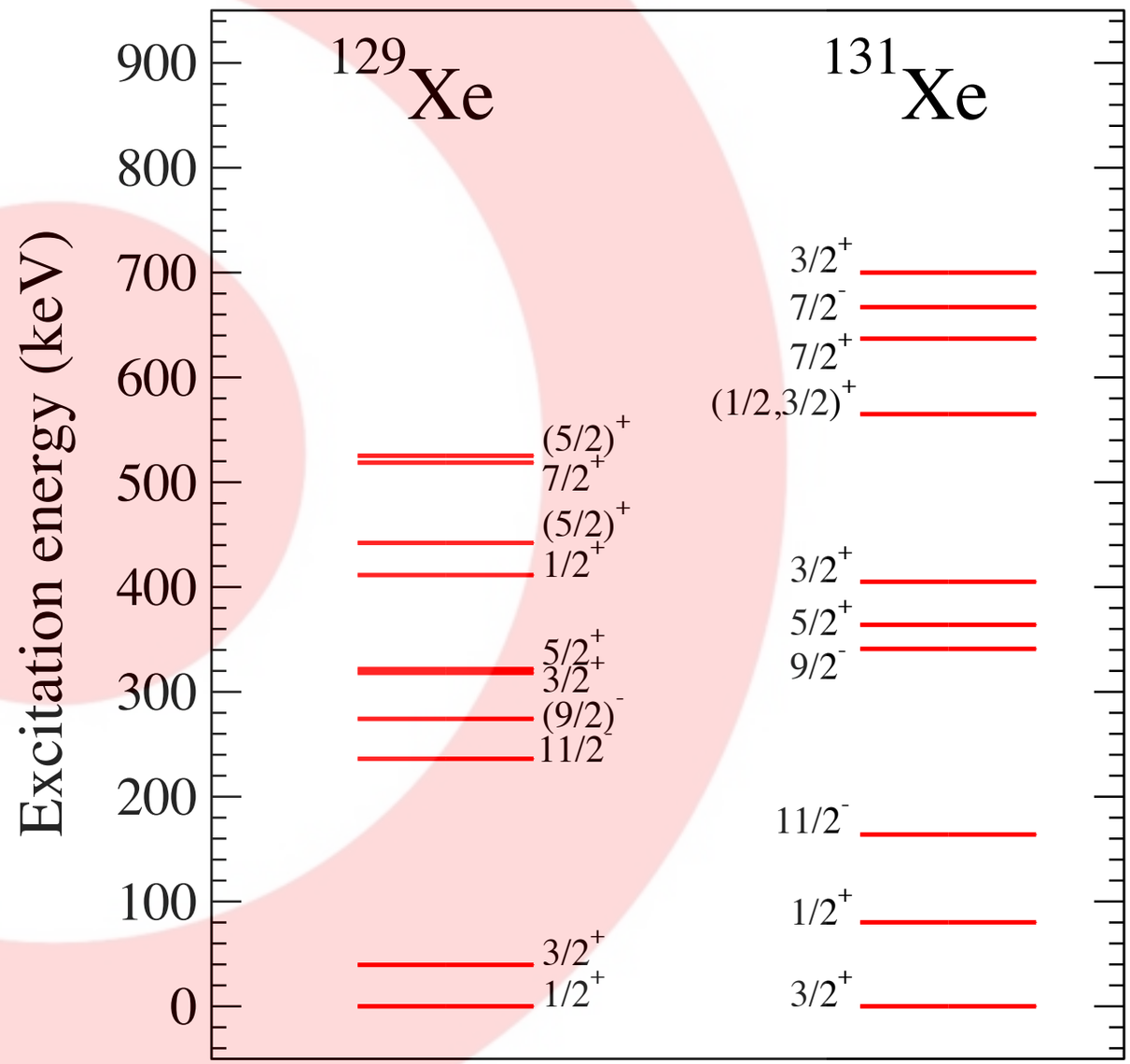
- Xenon: two isotopes are sensitive to spin-dependent interactions:

^{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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[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*

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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*

Why is it interesting?

- A detection would:

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

Inferring properties of dark matter is difficult - why not search for a signal that will provide more information?

Why now?

We can accurately quantify the signal and background

- Precise calculation of structure functions available
- Future detector properties are more-or-less known
- Backgrounds are more-or-less known

An old idea… Inelastic scattering

Can it ever be detected?

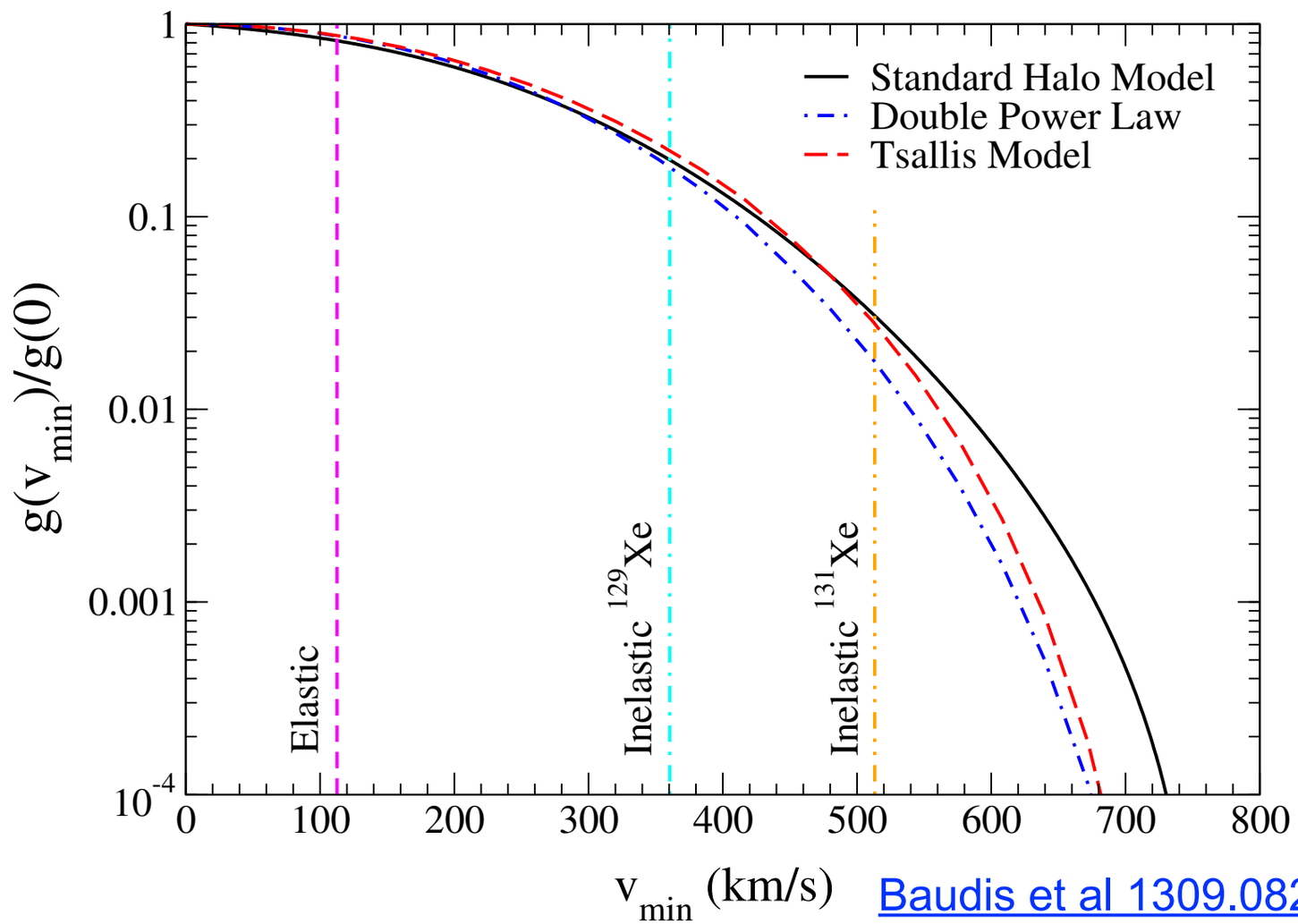
Scattering rate

- The form of the scattering rate is the same as usual:

$$\frac{dR}{dE_{\rm R}} = \frac{1}{m_A}\frac{\rho_{\rm DM}}{m_{\rm DM}}\int_{v_{\rm min}} d^3v\, v\, f_{\rm DM}(\vec{v}+\vec{v}_{\rm E})\frac{d\sigma}{dE_{\rm R}}$$

- $v_{\rm min}$ is higher (DM kinetic energy excites the nucleus and causes the recoil)

- This suppresses the inelastic rate



Baudis et al 1309.0825

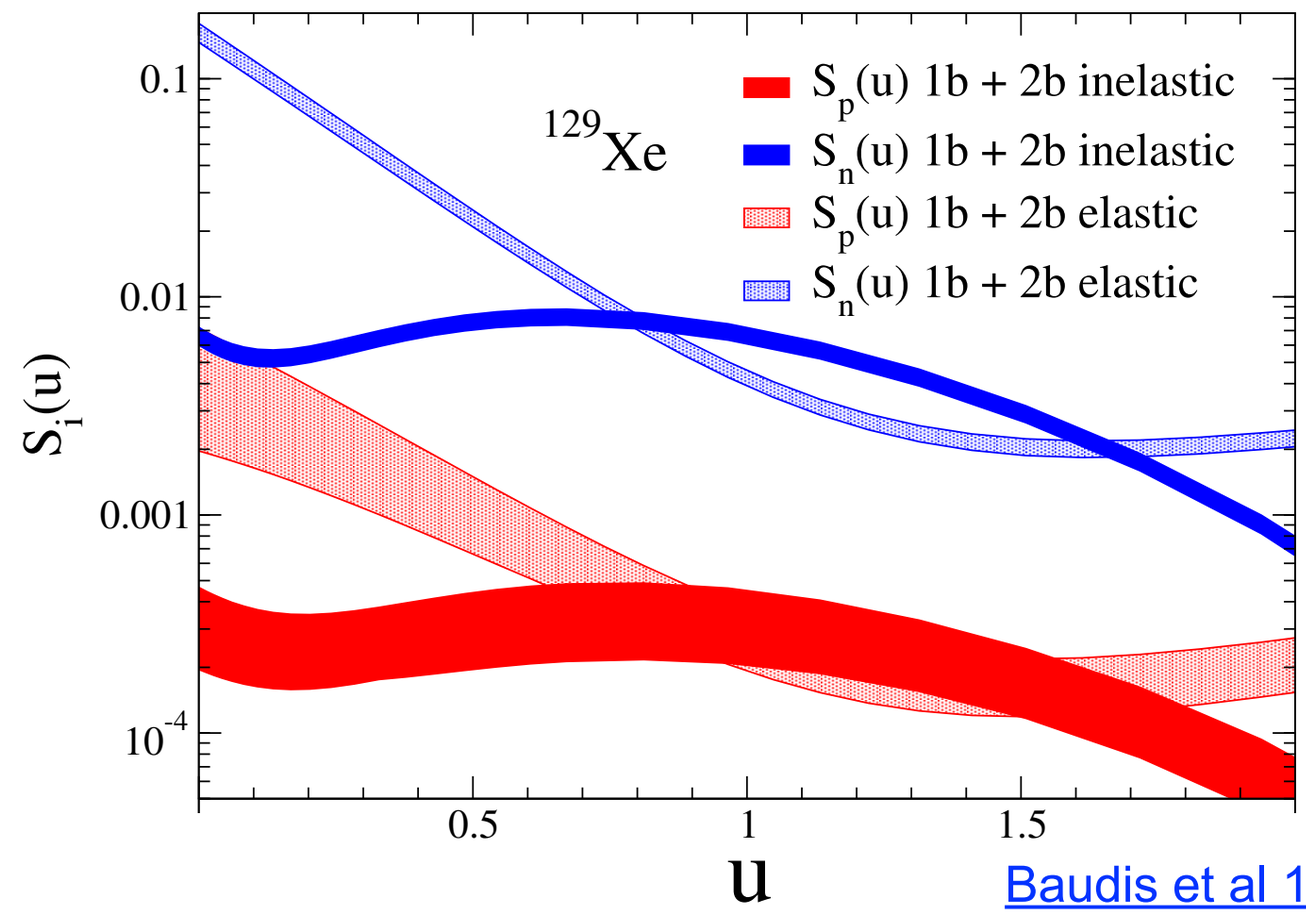
Structure functions

- Only consider axial-vector interaction: $\mathcal{L} \propto -\bar{\chi}\gamma^{\mu}\gamma^{5}\chi \cdot \sum_{q} A_q \bar{\psi}_q \gamma_\mu \gamma^5 \psi_q$
- The form of the cross-section is the same…

$$\frac{d\sigma}{dE_{\mathrm{R}}} = \sum_{A={}^{129}\mathrm{Xe},\,{}^{131}\mathrm{Xe}} \frac{4\pi}{3} \frac{m_A}{2\mu_n^2} \frac{\sigma_n^0}{v^2} \frac{f_A}{2J_A+1} S_A^n(E_{\mathrm{R}})$$

…but the structure functions are different:
(u=1 approx. E=60 keV)

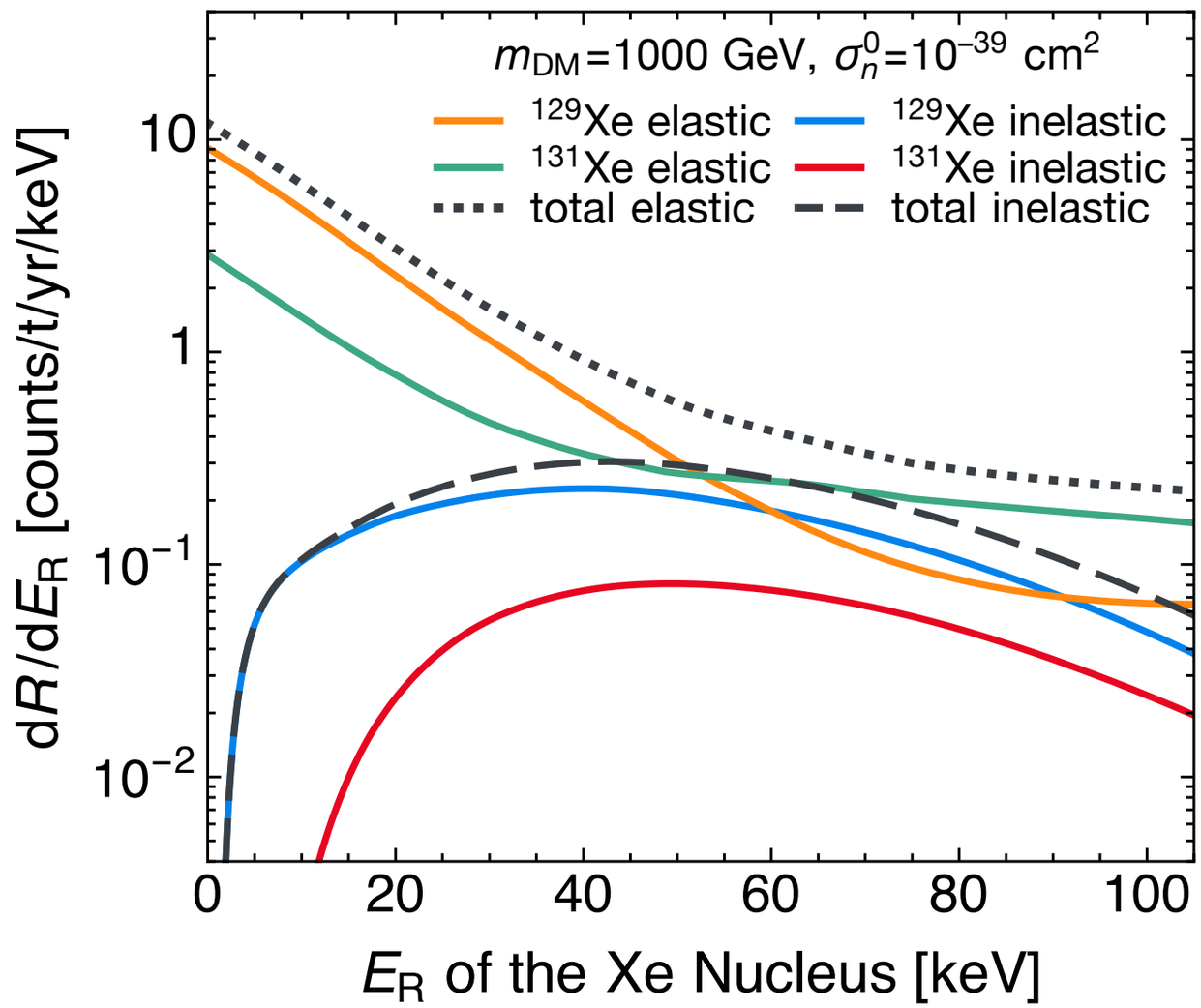
- This suppresses the inelastic rate



Baudis et al 1309.0825

The rate

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

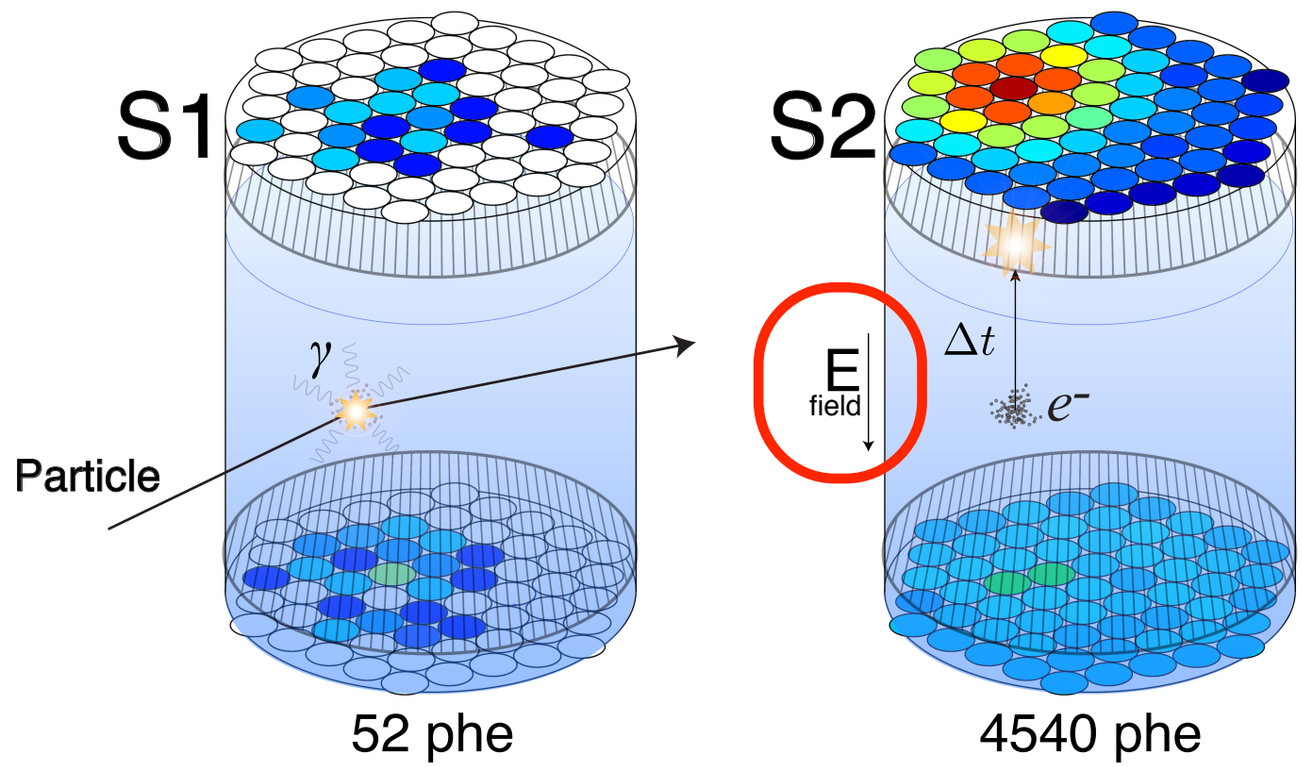


- Inelastic rate smaller because of kinematics (v_{min}) and nuclear structure functions

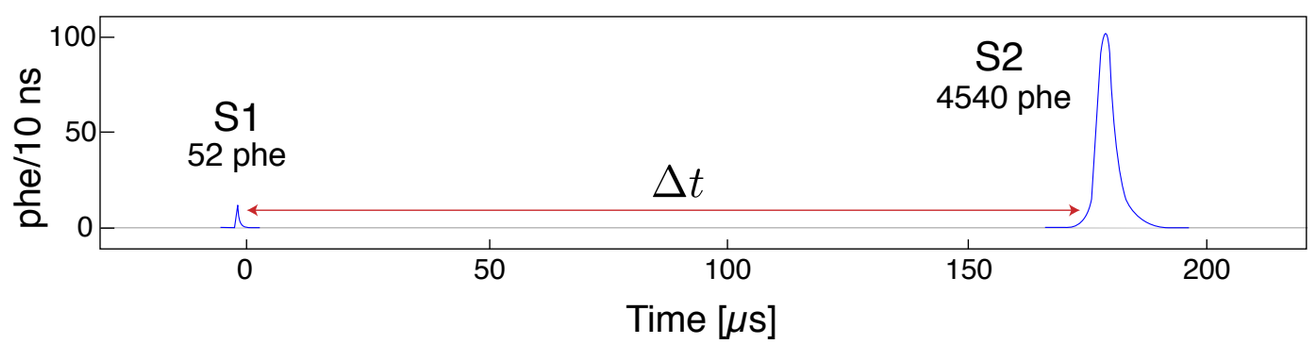
Mock detectors

- Express the signal in terms of measured quantities:

$$\mathrm{S1} = g_1 n_\gamma$$



$$\mathrm{S2} = g_2 n_e$$



- Drift field is also crucial

Mock detectors

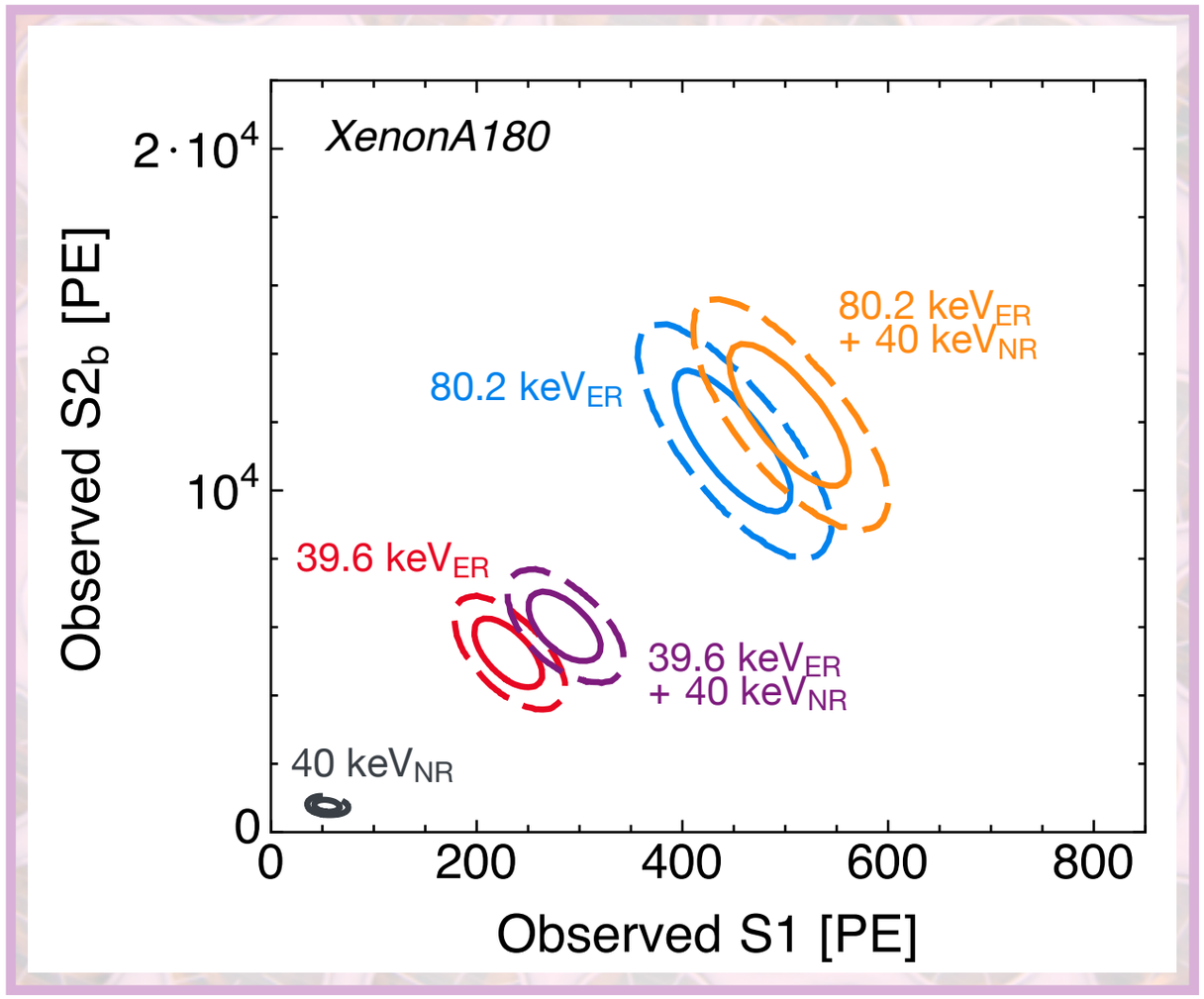
- I'll consider two scenarios:

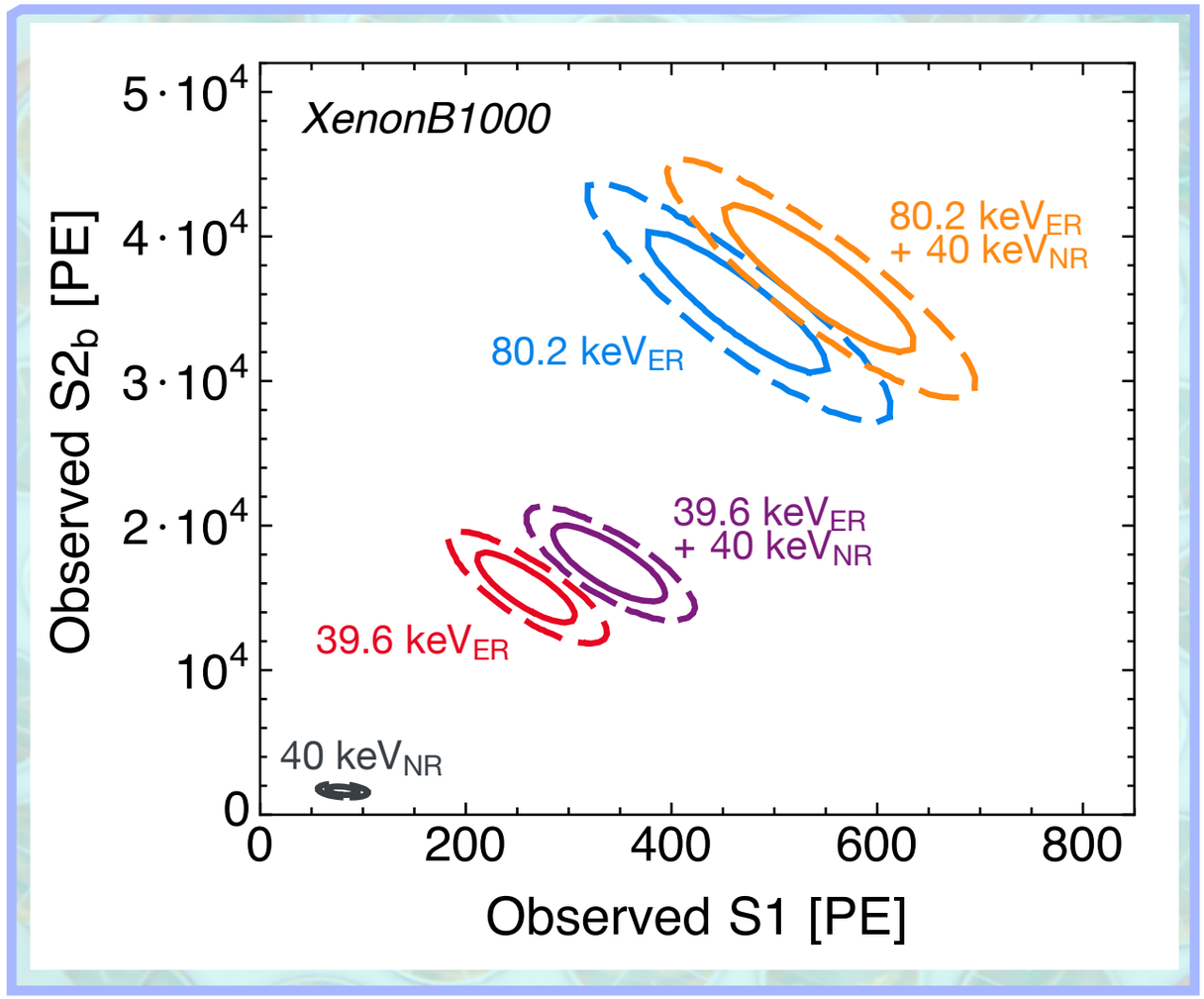
XenonA180	*XenonB1000*
g_1=0.12 PE/γ	g_1=0.18 PE/γ
g_2=12.5 PE/e (50% extraction efficiency)	g_2=25 PE/e (100% extraction efficiency)
drift field=180 V/cm	drift field=1000 V/cm

- Model number of photons & electrons with NEST

Mock signals

- Include detector and recombination fluctuations

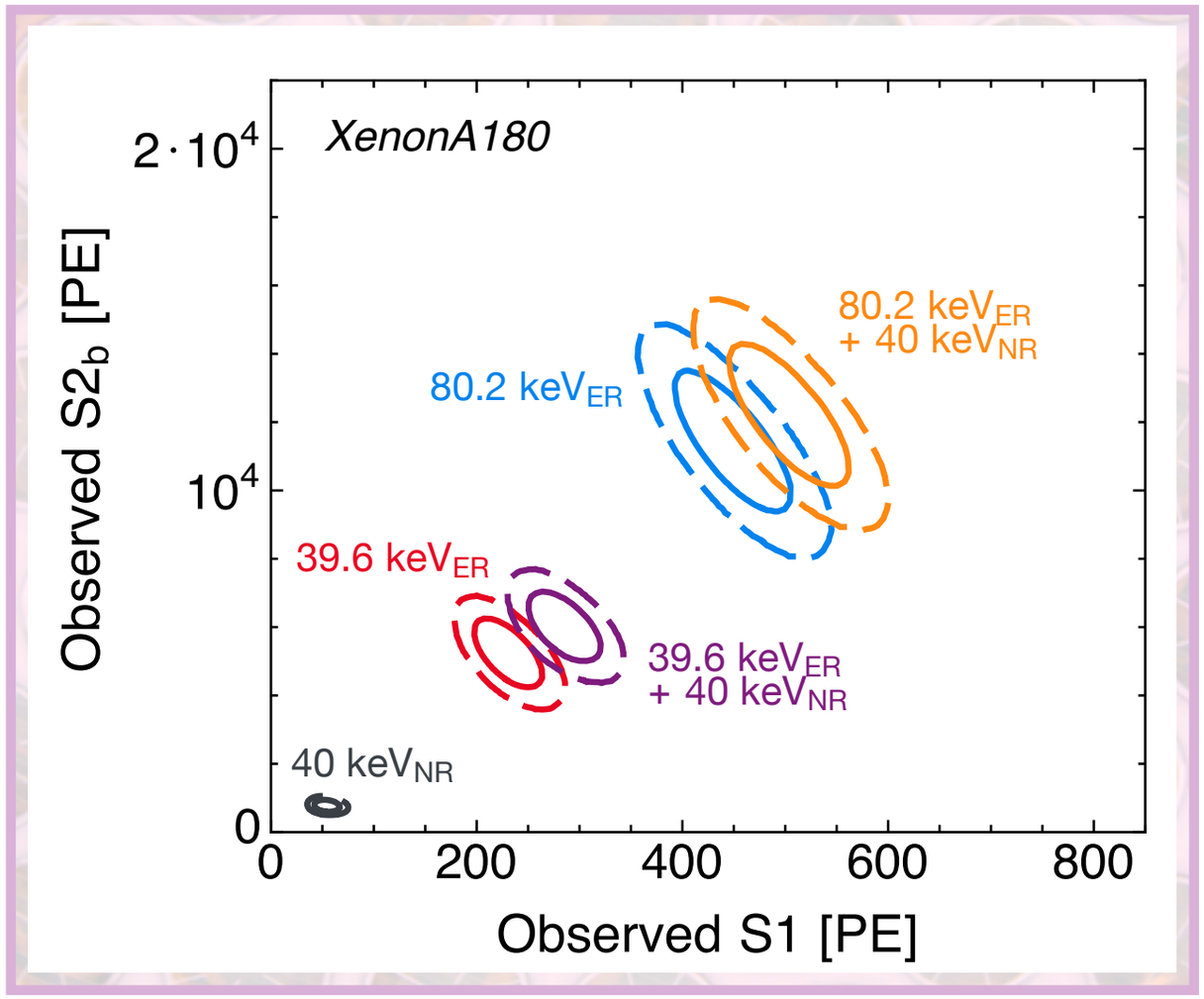


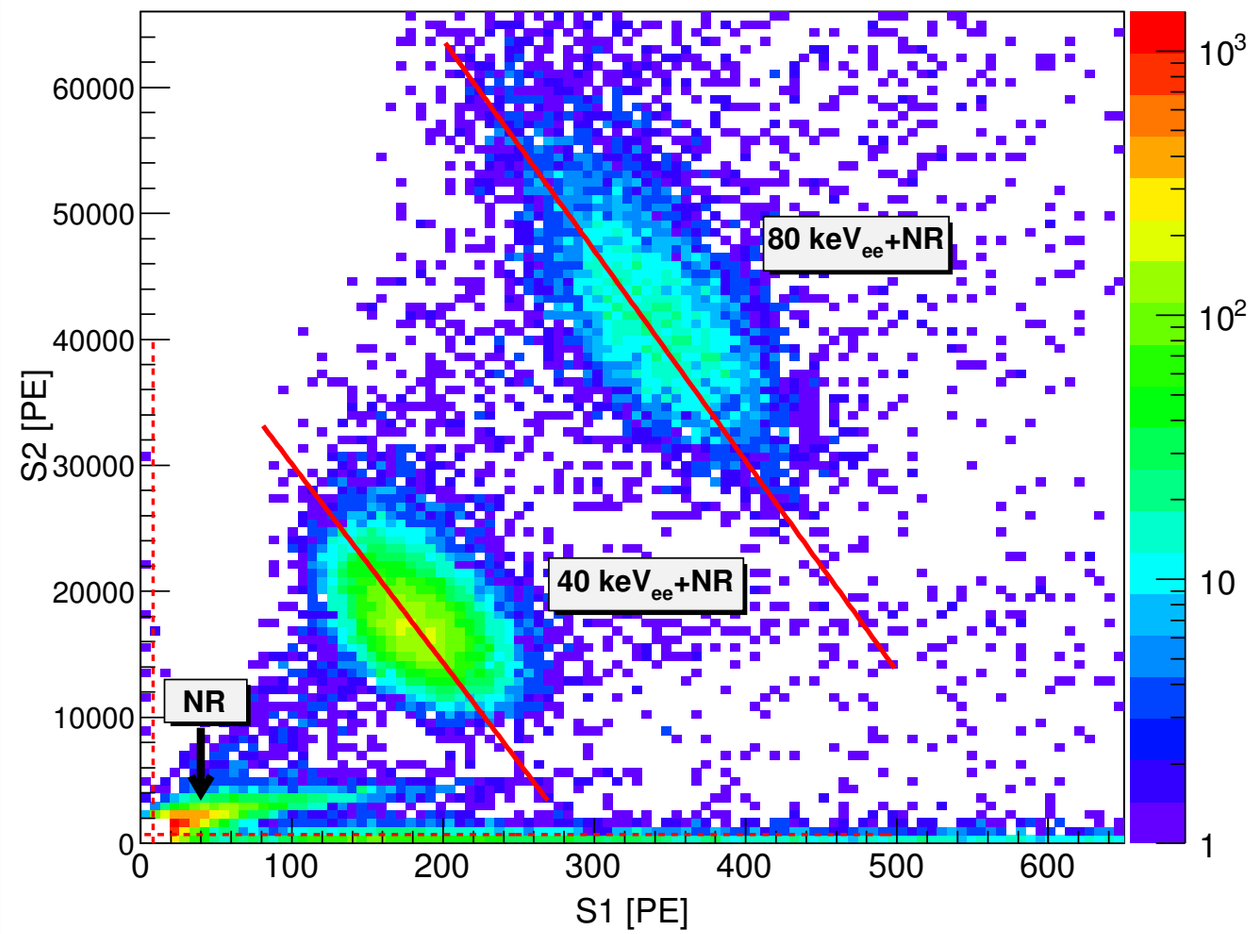


- For same energy, electronic recoils produce a much larger S1 and S2

Mock signals

- Looks like real data… 😃

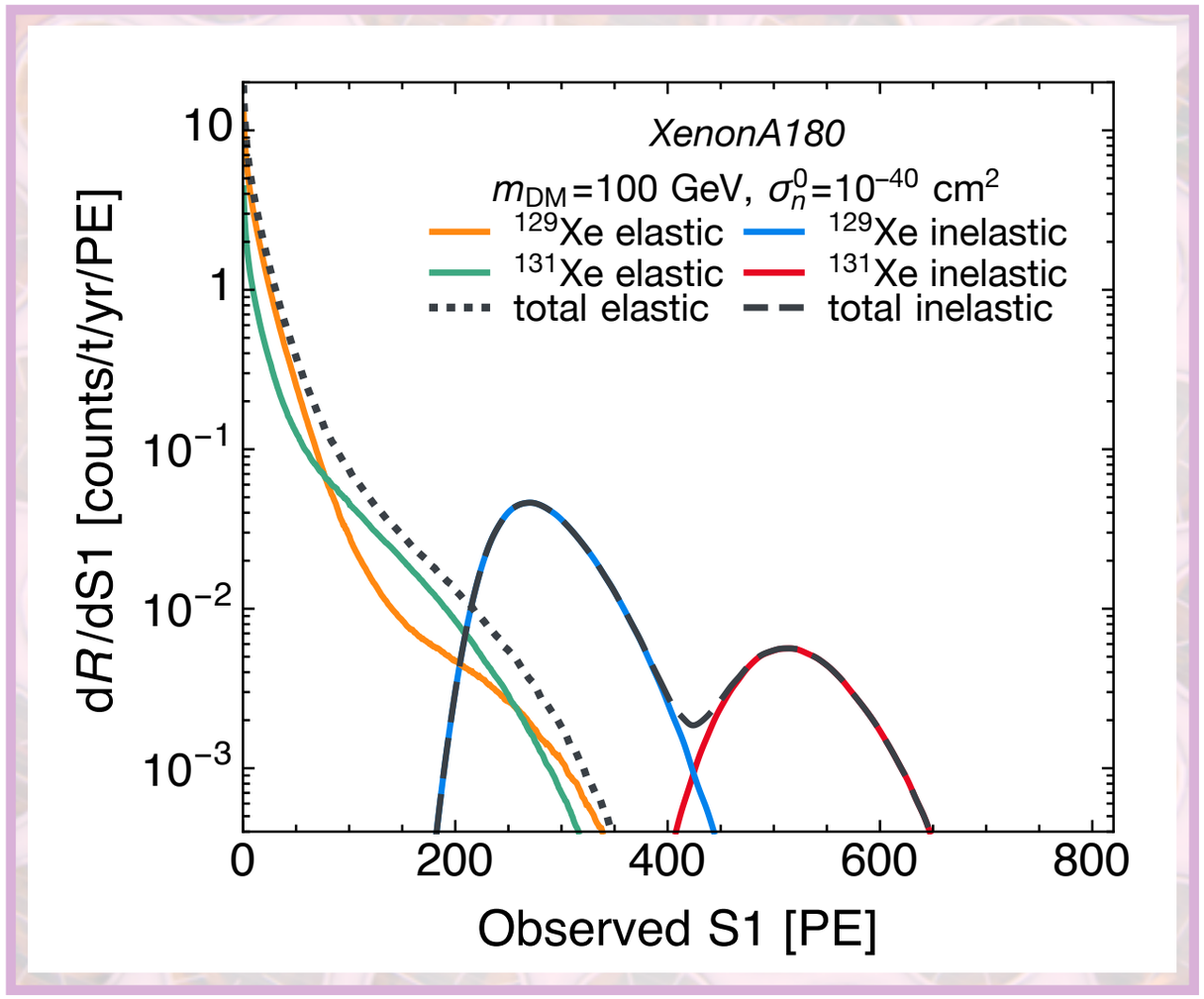


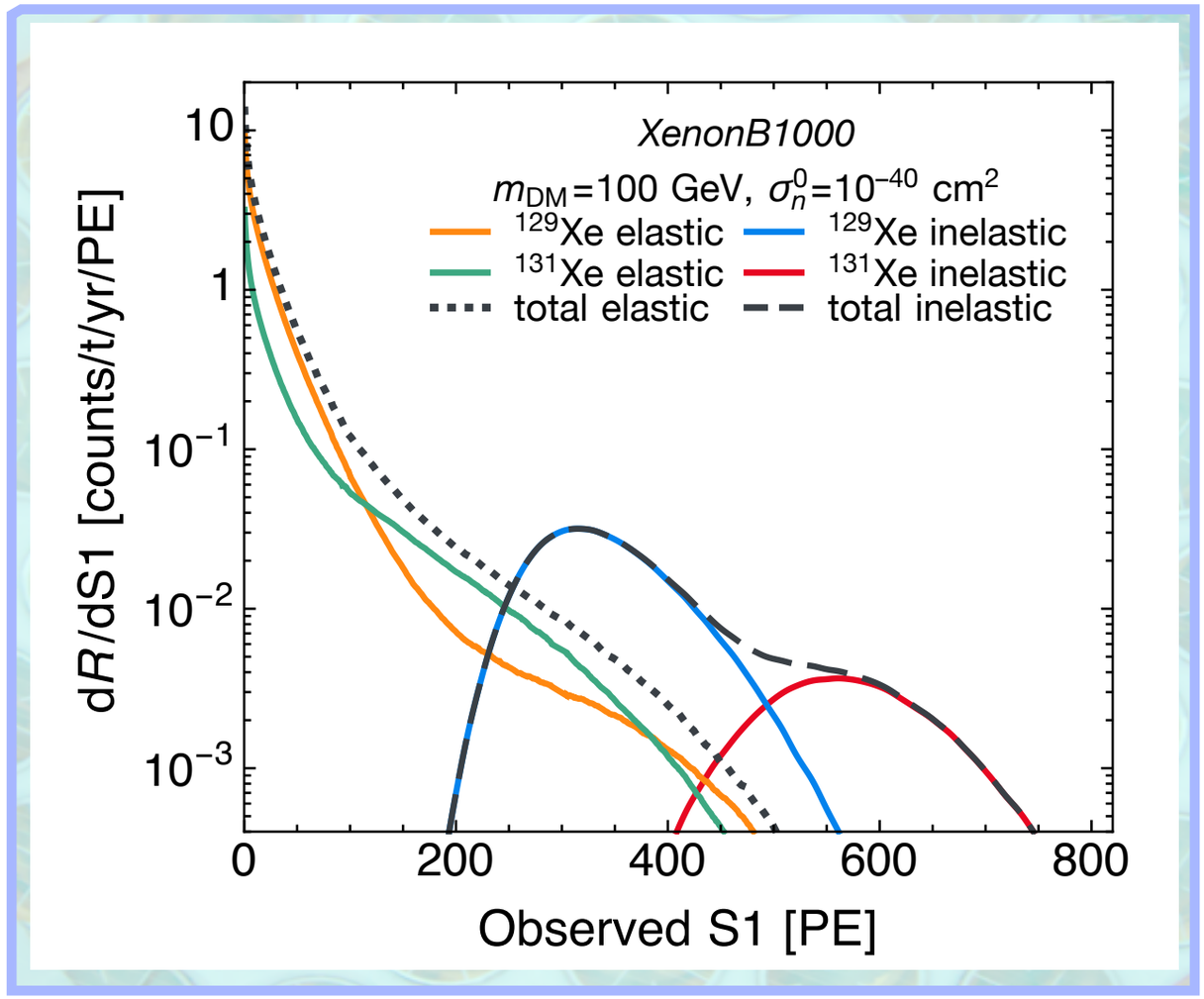


Data from PandaX-I arXiv:1505.00771

Scattering rate

- The scattering rate (for single phase)

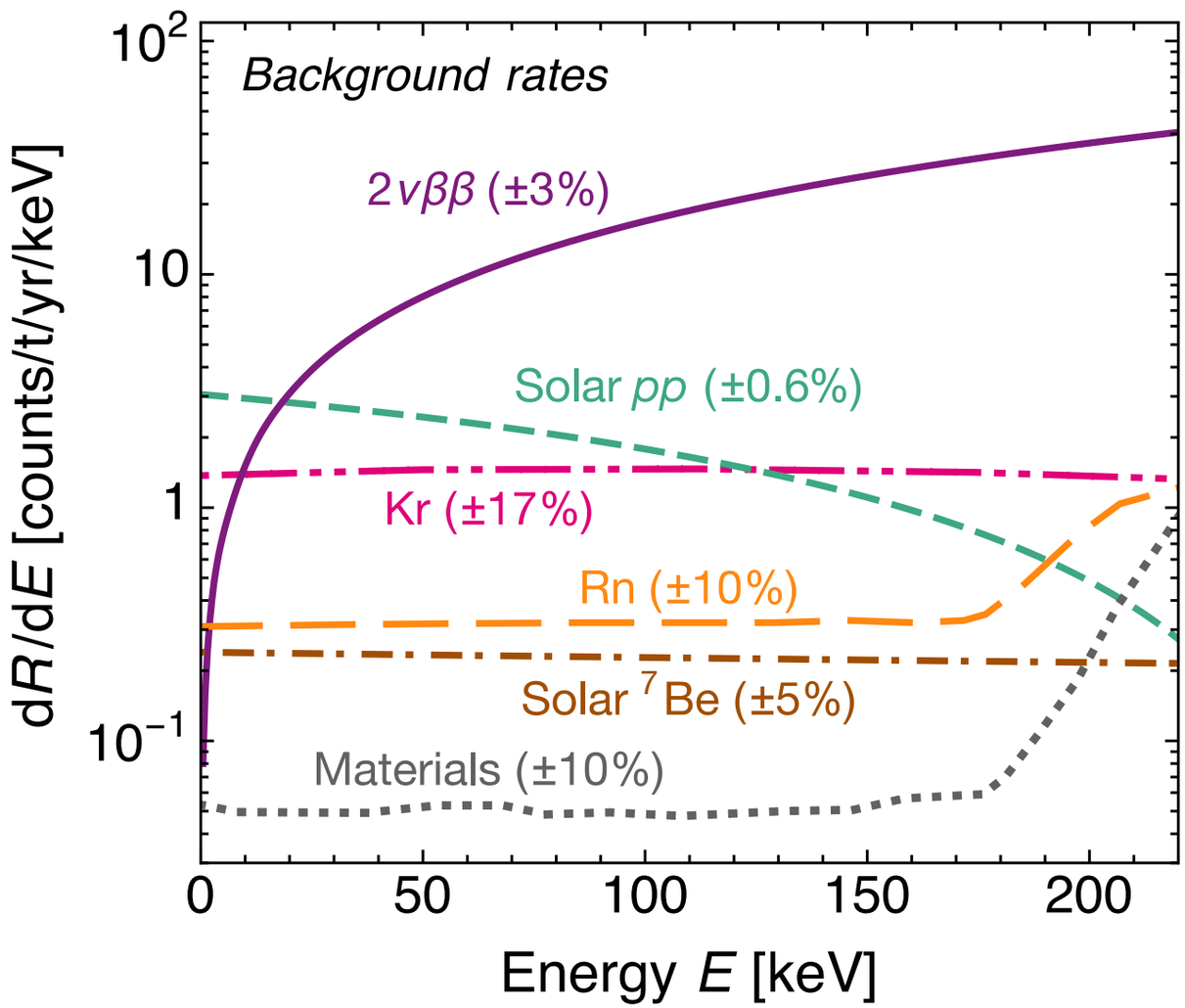




- Rates similar for both mock scenarios
- *Clear that discovery is always with elastic scattering*

Background

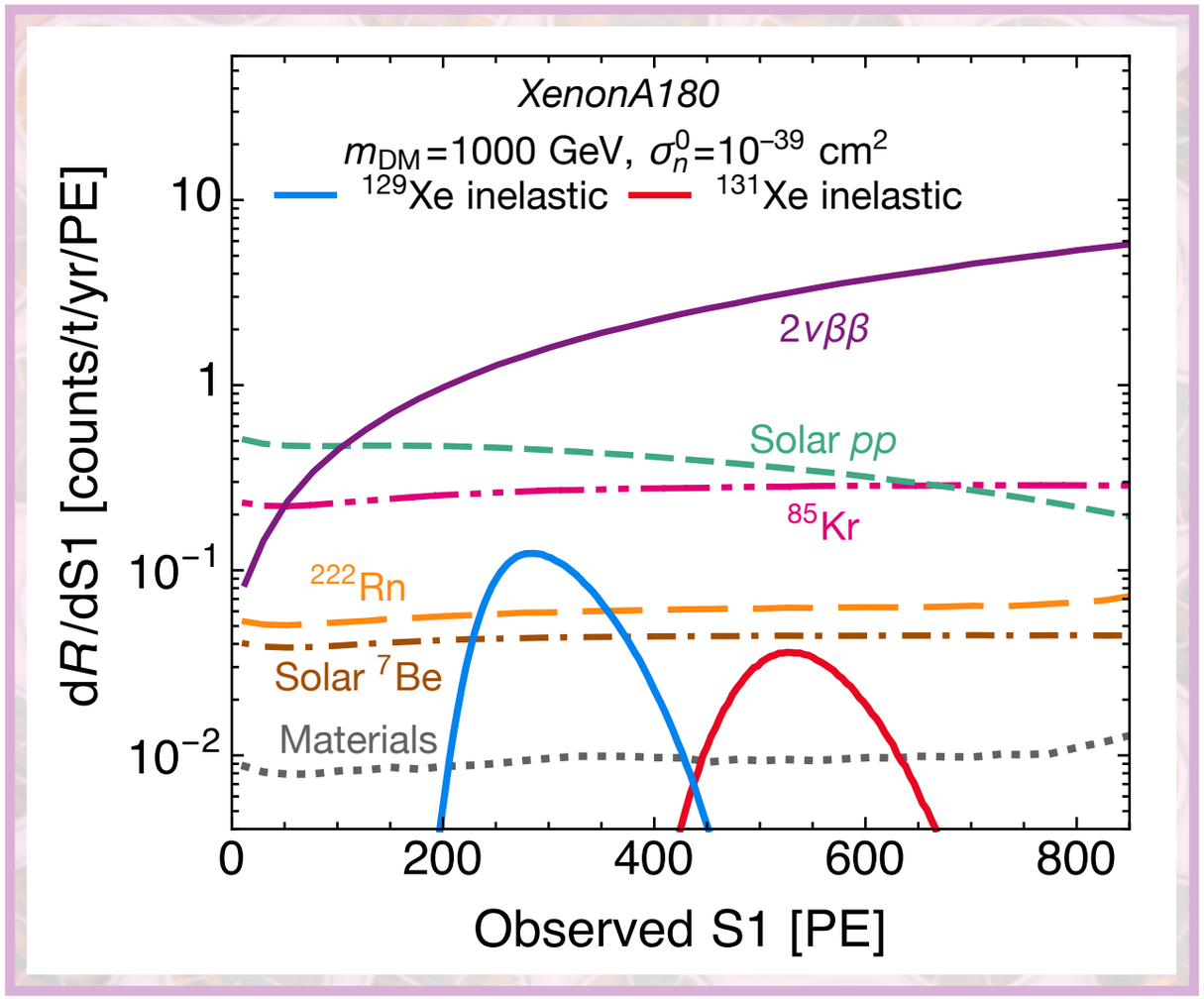
- We need to model the backgrounds:

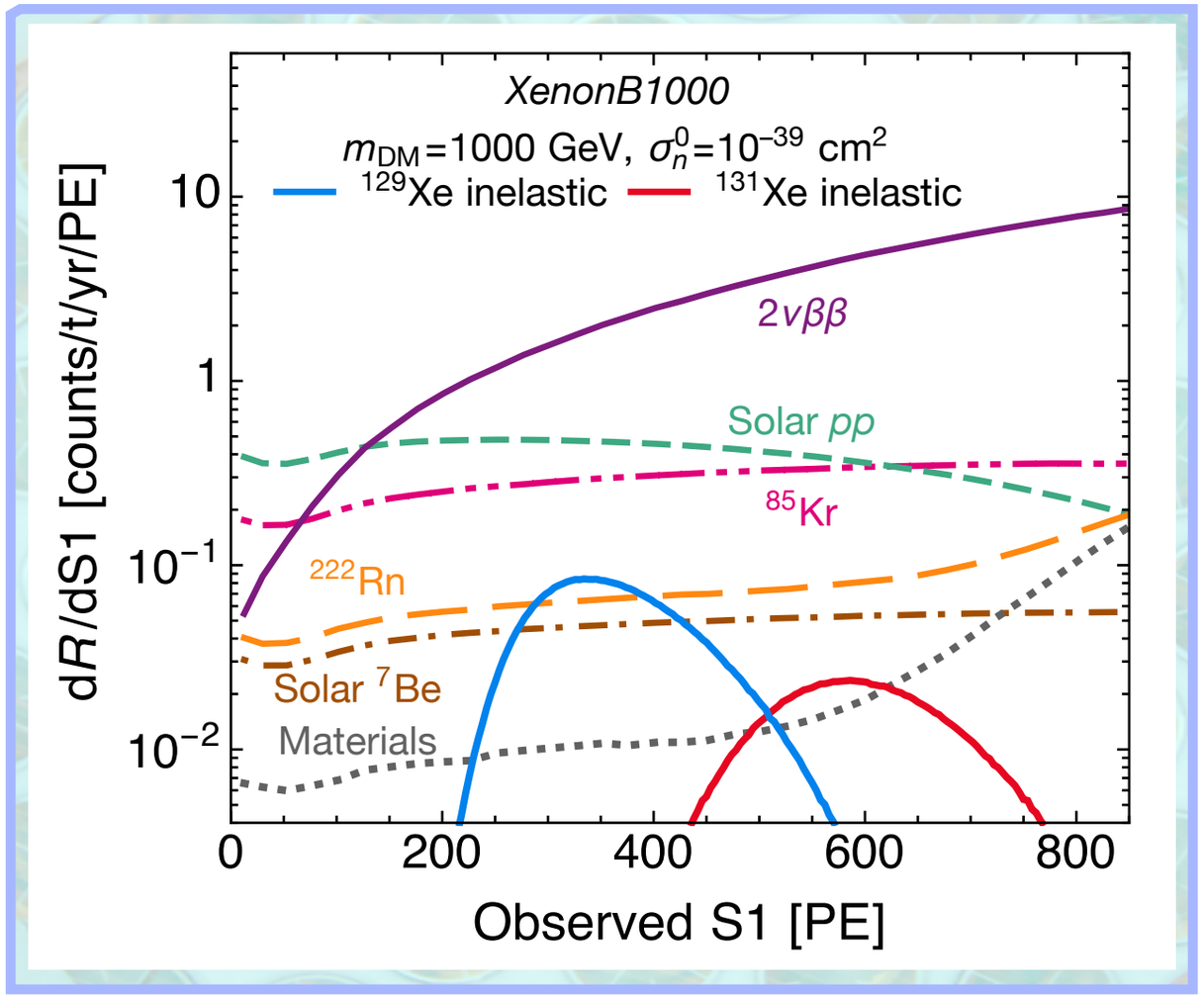


- *2-beta—2-neutrino decay of ^{136}Xe dominates*

Background versus signal

- Detecting this signal could be difficult…

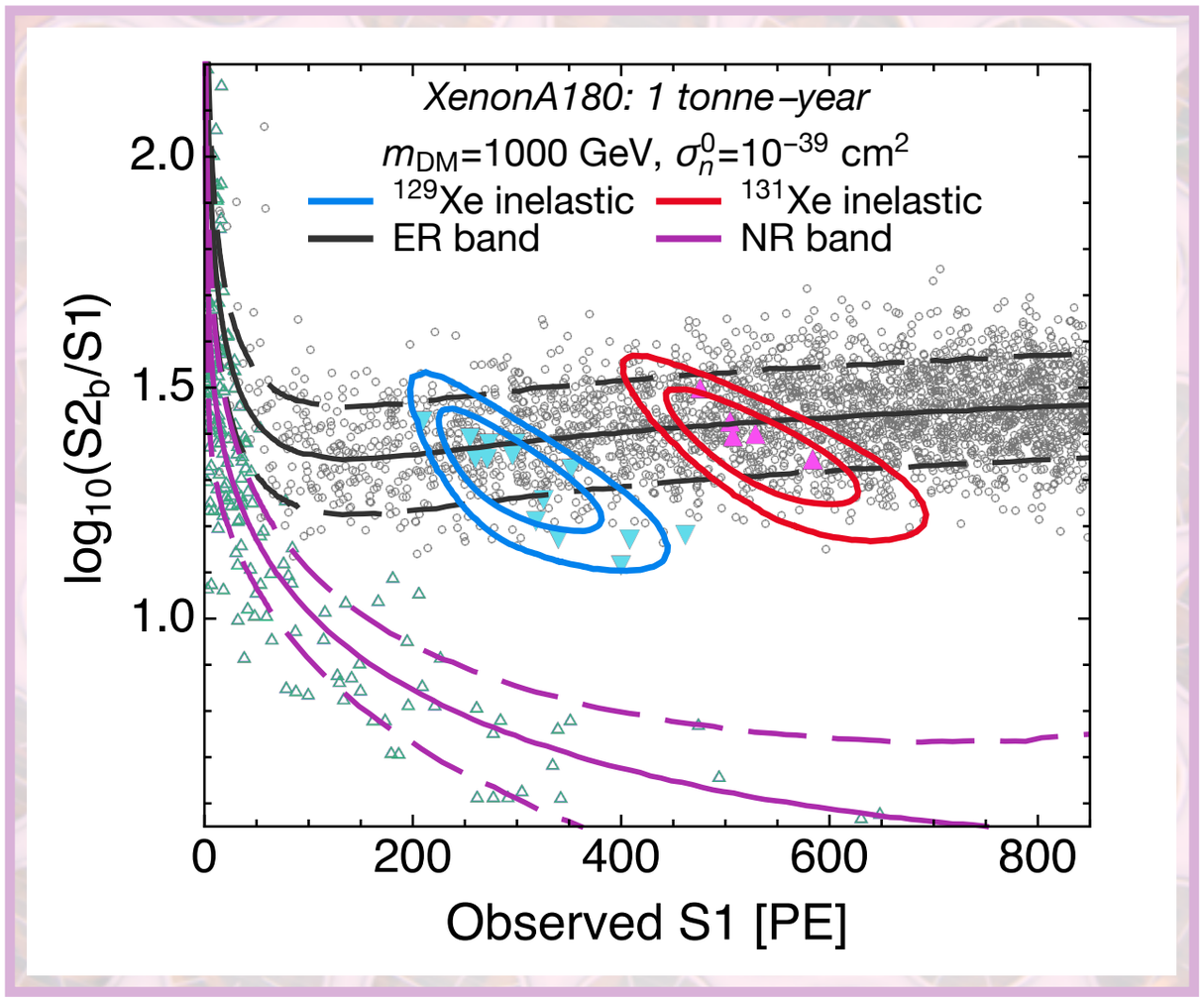


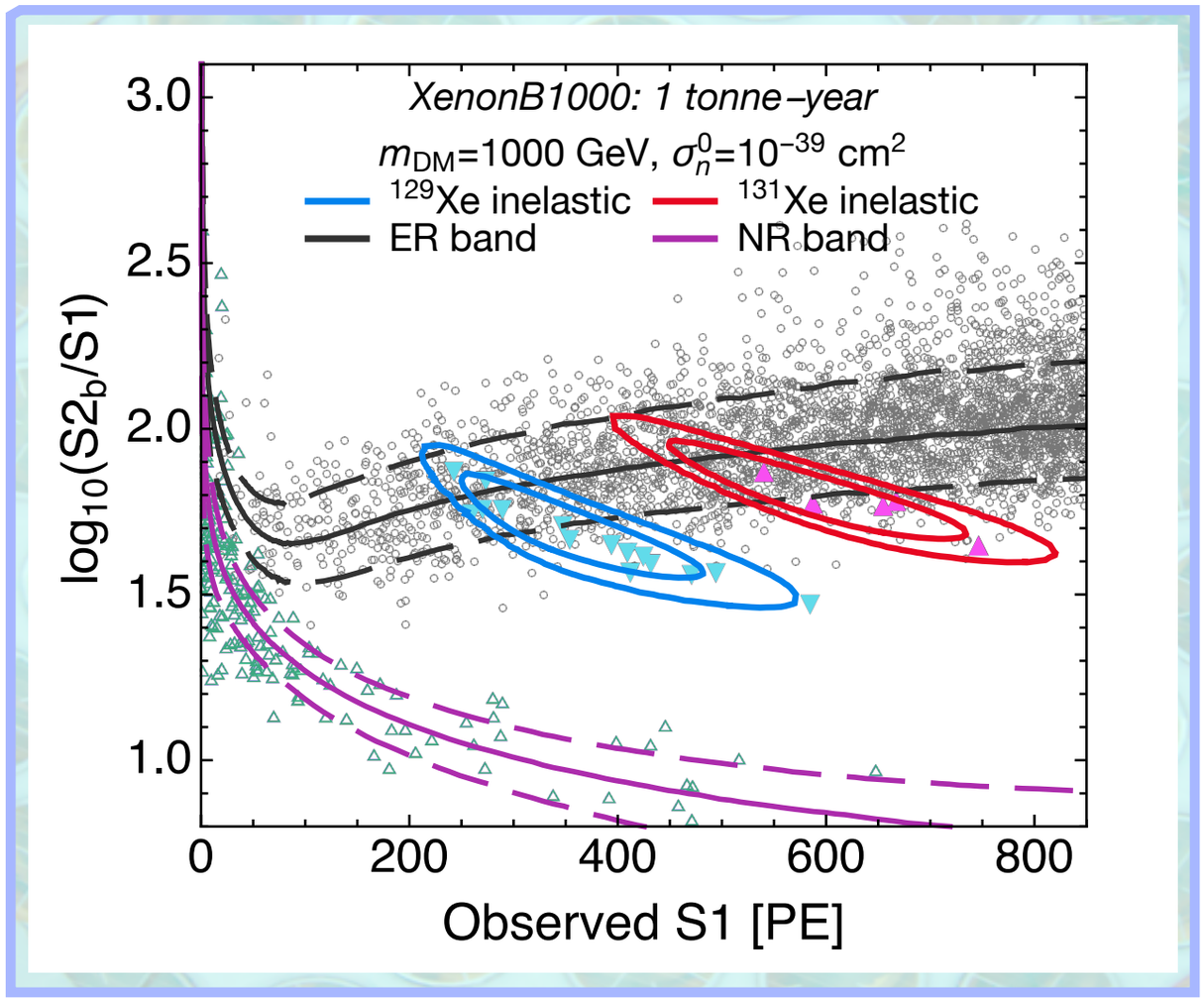


…impossible for single phase (S1-only)?

Background versus signal

- Two-phase experiments help:





- Some signal-to-background discrimination
- Better 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

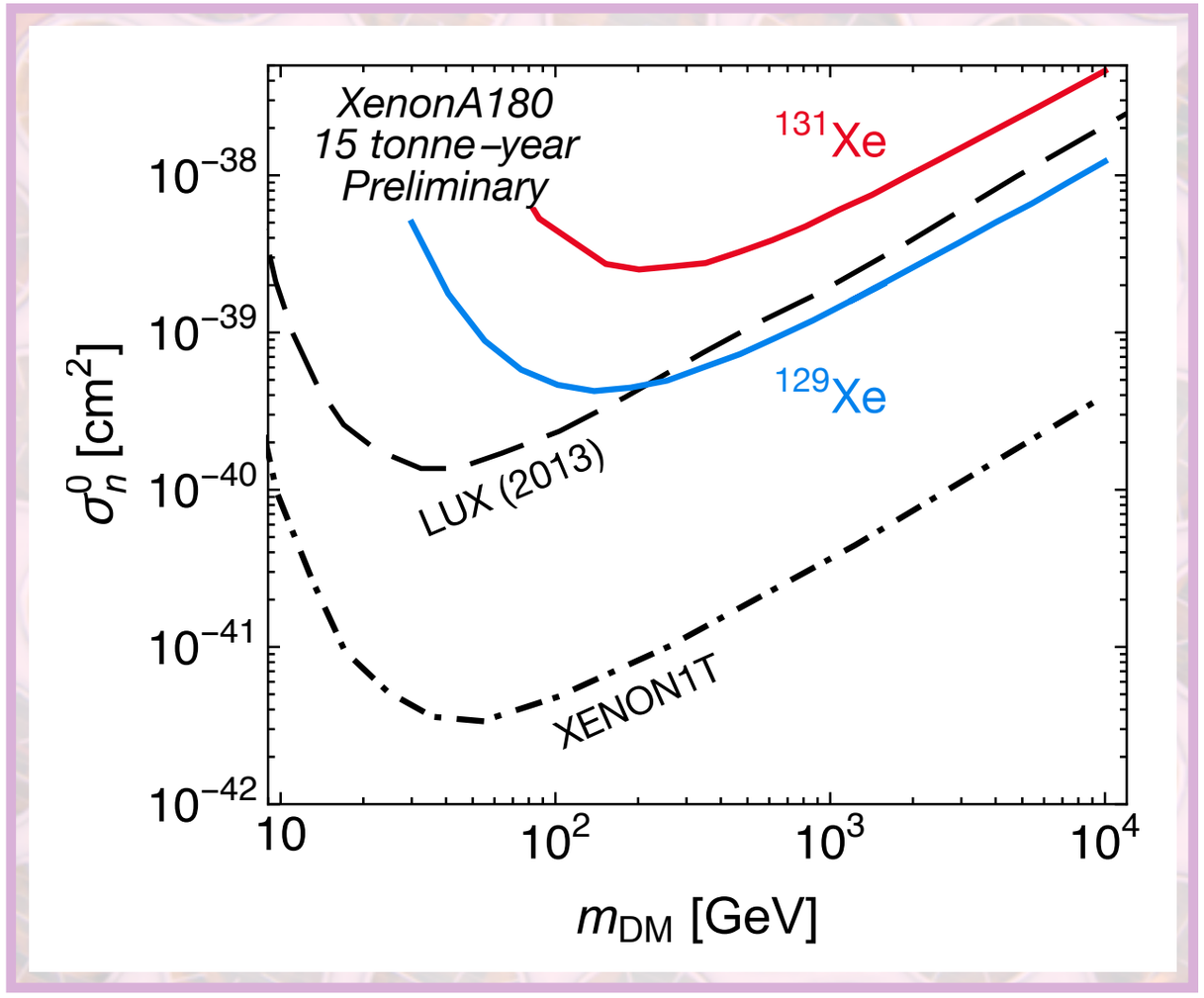
- Profile likelihood ratio:

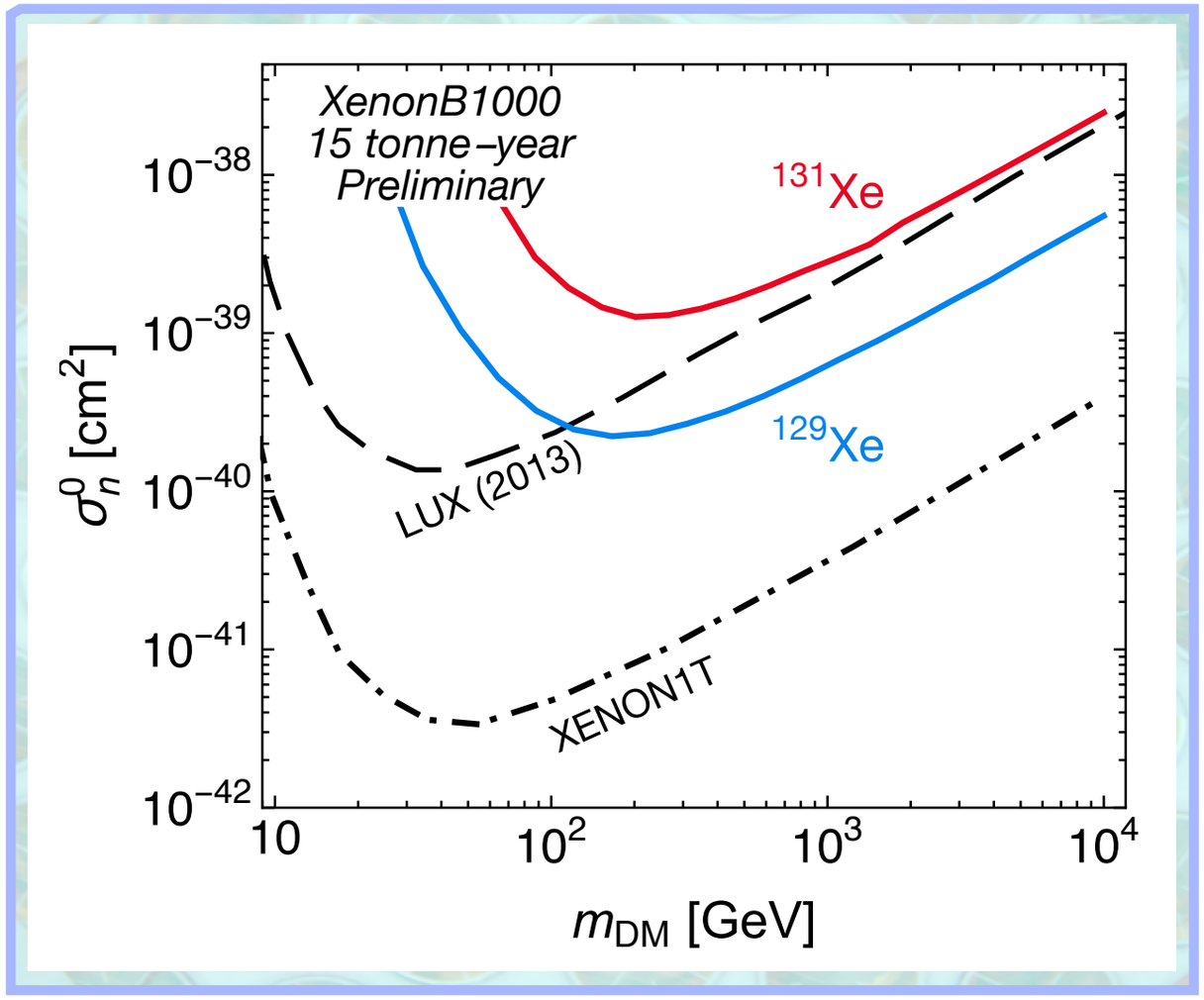
$$\lambda(0) = \frac{\mathscr{L}(\sigma_p = 0, \hat{\hat{R}}_b, \hat{\hat{\vec{\nu}}})}{\mathscr{L}(\hat{\sigma}_p, \hat{R}_b, \hat{\vec{\nu}})}$$

- Include background and signal (v_{esc}) uncertainties

Discovery limit

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





- Better sensitivity for higher drift fields
- ^{131}Xe excitation is not detectable
- ^{129}Xe detectable if LUX/XENON1T make discovery in next run

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?

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?

No: for ^{131}Xe

Yes: for ^{129}Xe
…need an (elastic) discovery signal
in the next run of LUX or XENON1T

Thank you