Precision Measurement Of Nuclear Recoil Ionization Yields For Low Mass Wimp Searches

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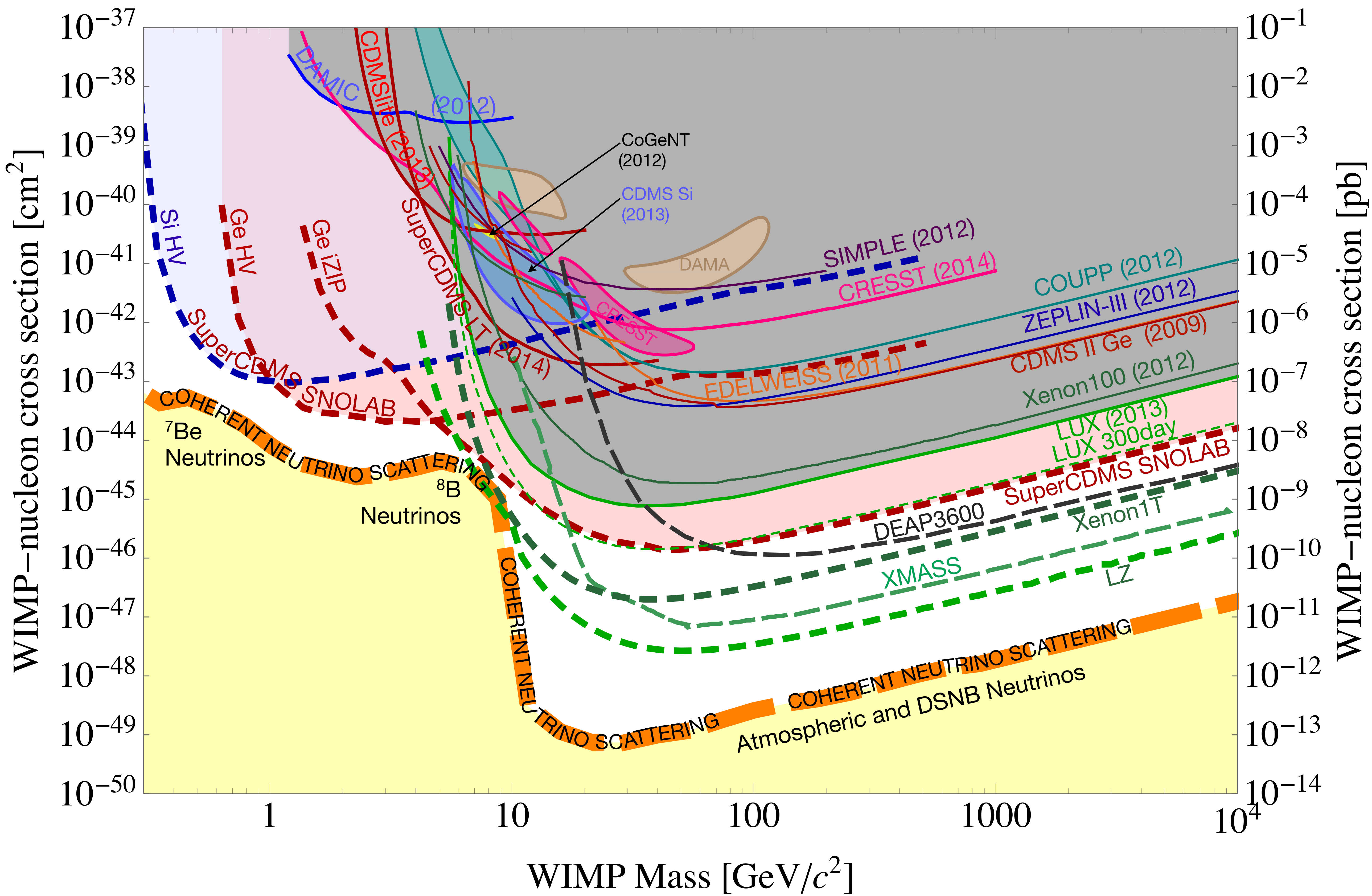
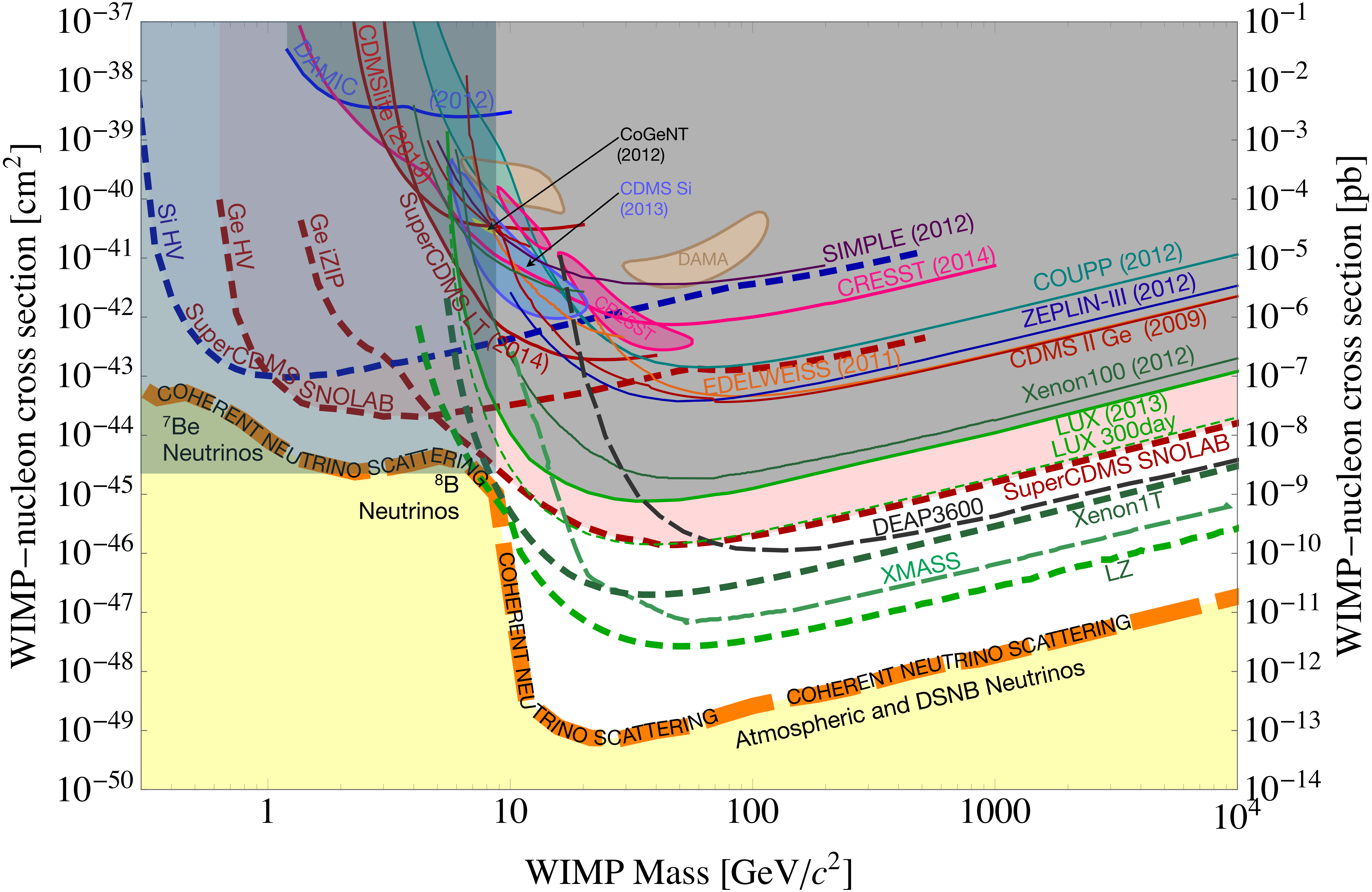
The SuperCDMS Collaboration

… in 2015



SuperCDMS and HV Detectors Sensitivity

The WIMP Search Landscape

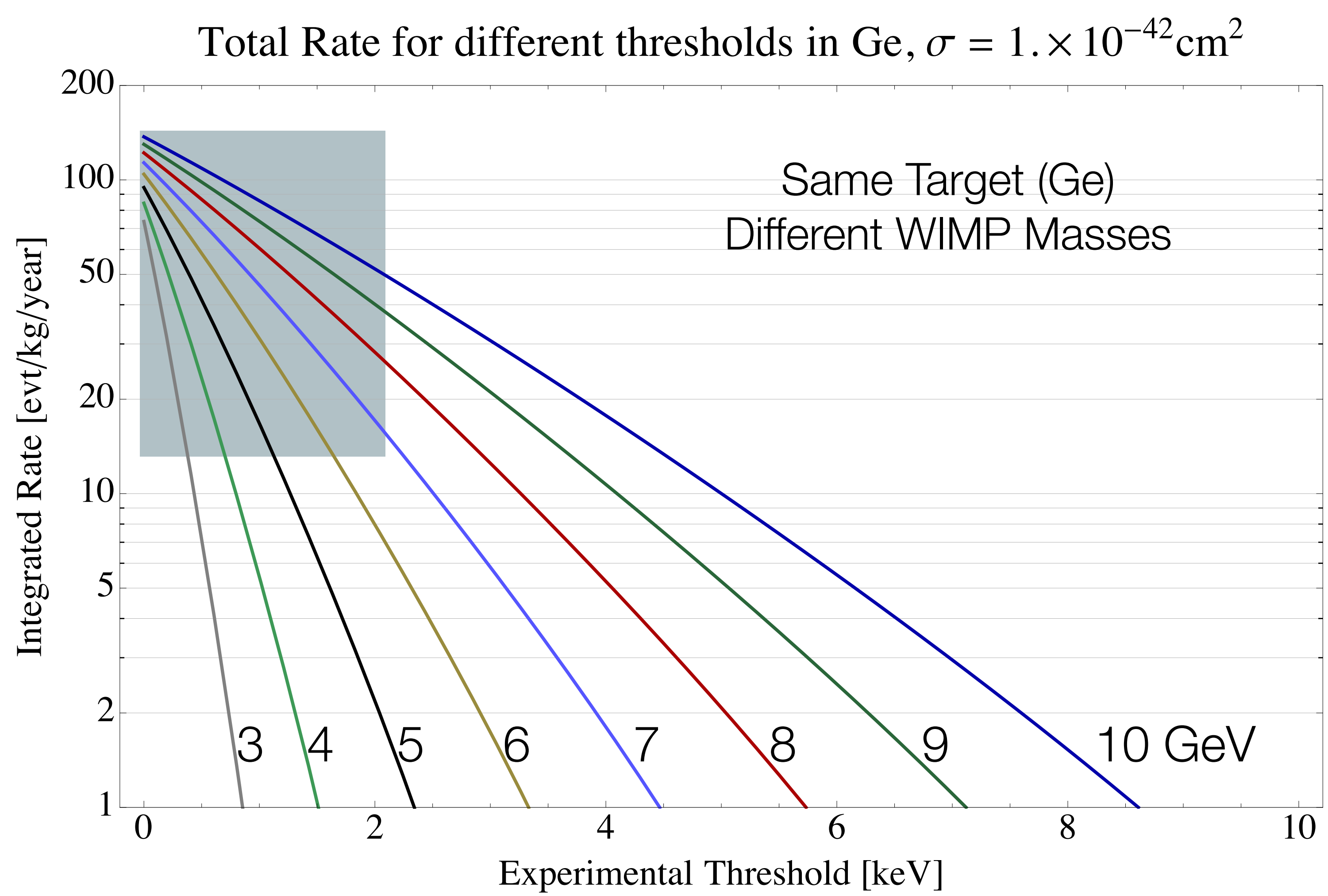


SuperCDMS and HV Detectors Sensitivity

The WIMP Search Landscape

The main theme

Now that we're in the low-mass wimp search era, how can we push the measurement of nuclear recoil ionization yield down to as as low an energy as possible using cryogenic crystal (Ge/Si) detector technology?



Defining Ionization Yield in Crystal Detectors

- For a given interaction with recoil energy E_{recoil} all of the recoil's energy goes into the various "prompt" channels, e.g. in Ge:

$$E_{recoil} = E_{phonon-prompt} + E_{ioniz.}$$

- Additional, delayed energy will go into the phonon channel due to
  1. The e-h recombining at the electrodes and
  2. Luke phonon emission from drifting charges. We define the **total phonon energy** as:

$$E_{phon.} = E_{phonon-prompt} + n_{eh}\mathcal{E}_{eh} + n_{eh}eV$$

- $\mathcal{E}$ is the average amount of energy it takes to create an e-h pair. n_{eh} is the number of e-h pairs that reach the electrodes, and *e*V is the voltage across the detector times the electron's charge.

- Since $E_{ioniz.} = n_{eh}\,\mathcal{E}$, we get:

$$E_{phon.} = E_{recoil} + E_{ioniz.}\frac{eV}{\mathcal{E}_{eh}}$$

Ways to measure *y* and σ_y

- For any determination of y, we need to measure two quantities independently: E_{recoil} and E_{ioniz}.

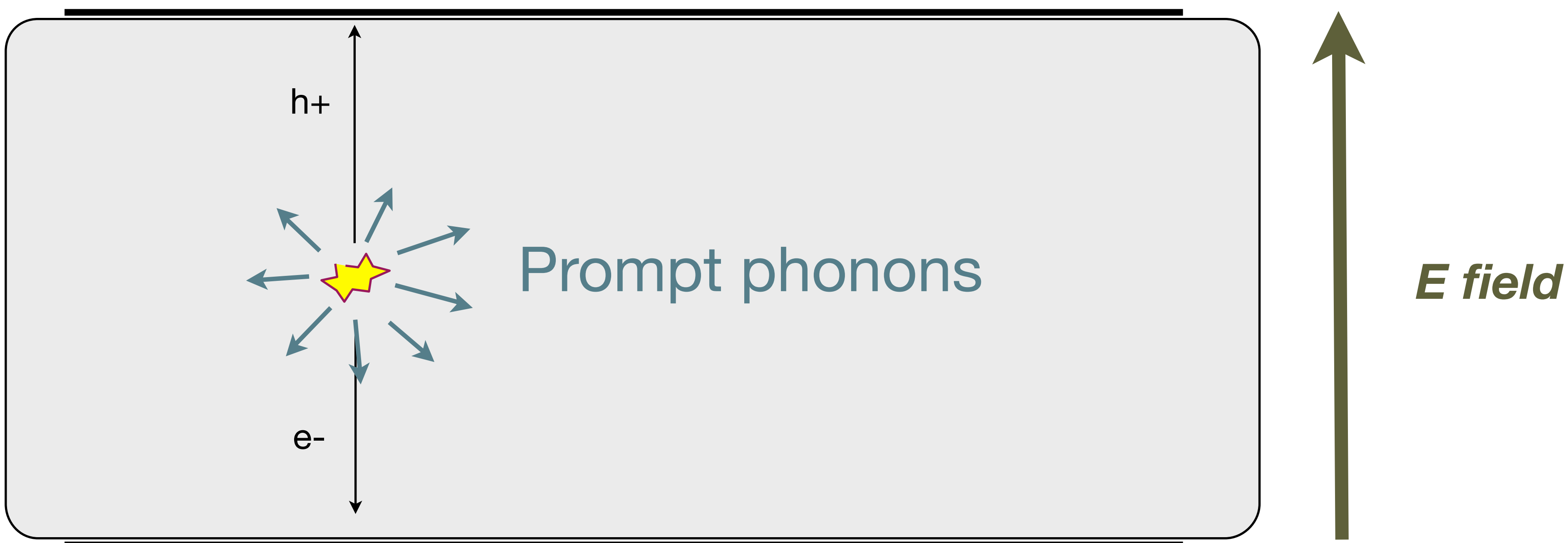
$$y = \frac{E_{ioniz.}}{E_{recoil}} \longrightarrow \sigma_y = \sqrt{\frac{\sigma_{rec}^2}{E_{rec}^2} + \frac{\sigma_{ion}^2}{E_{ion}^2}}$$

- We need to be able to measure both quantities with (similar) good resolution

The SuperCDMS HV Detector Operation

- Phonon-based charge amplification

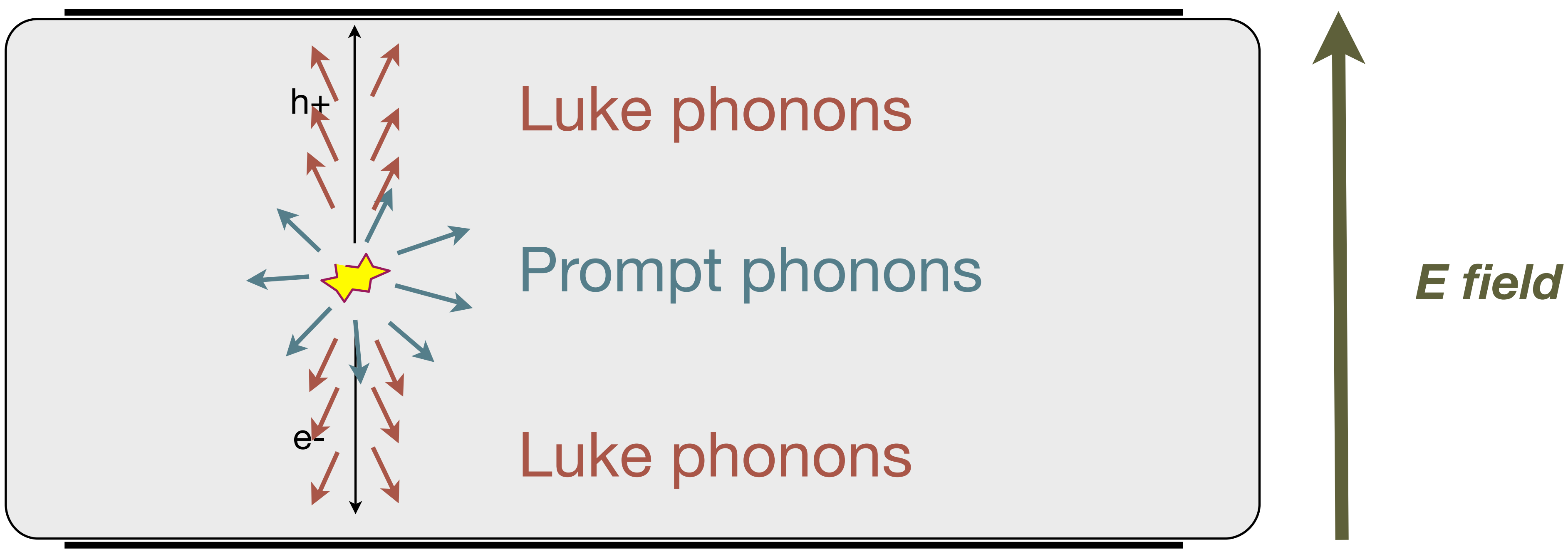
Phonon energy = E_{recoil}



The SuperCDMS HV Detector Operation

- Phonon-based charge amplification

$$\text{Phonon energy} = E_{recoil} + E_{Luke}$$
$$= E_{recoil} + n_{eh}\,eV$$



Ways to measure y and σ_y using a HV detector

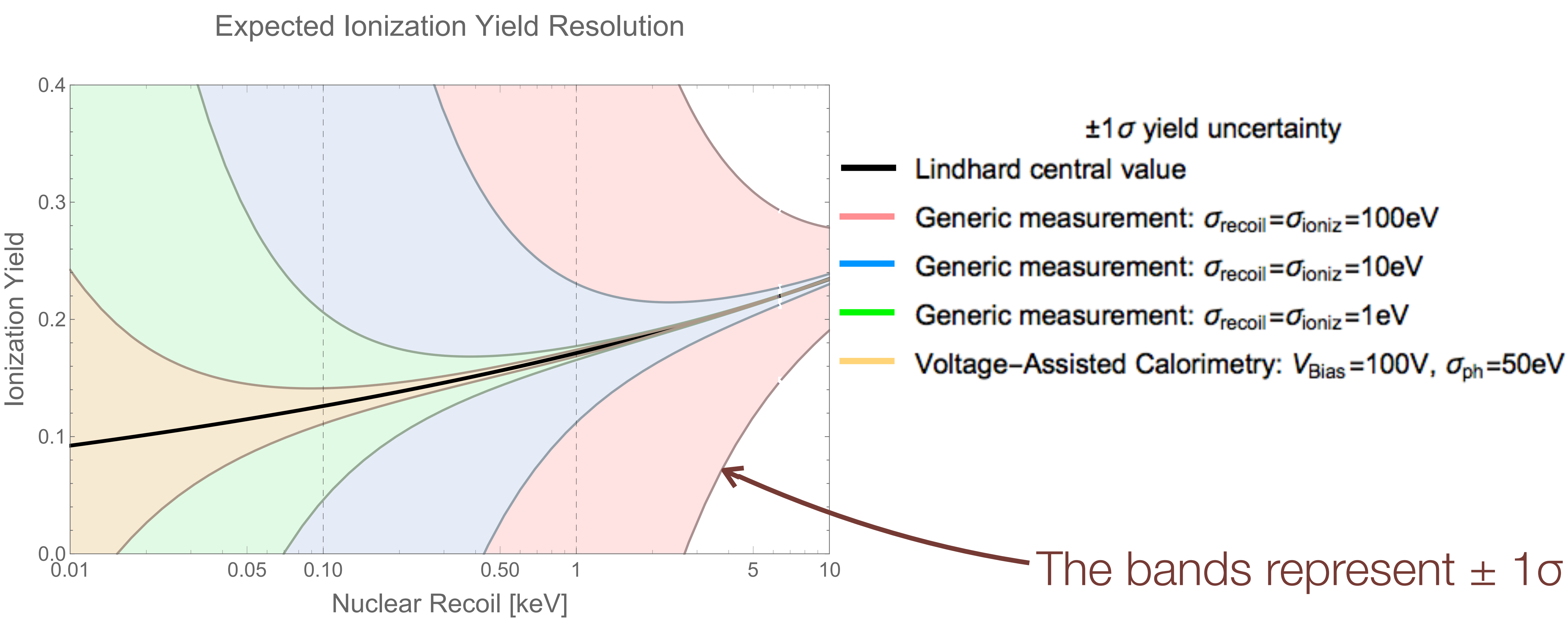
- With a HV detector we measure $E_{phon.}$ only, which effectively gives us $E_{ioniz.}$ with a very good resolution.
- By measuring the recoiling particle's scattering angle we can determine kinematically the recoil energy E_{recoil} with a very good resolution.

$$y = \frac{\mathcal{E}_{eh}}{eV}\left(\frac{E_{phon.}}{E_{recoil}} - 1\right) \longrightarrow \sigma_y = \frac{\sqrt{E_{rec}^2\sigma_{ph}^2 + E_{ph}^2\sigma_{rec}^2}}{\frac{eV}{\mathcal{E}_{eh}}E_{rec}^2}$$

Look at that nice big
number in the denominator

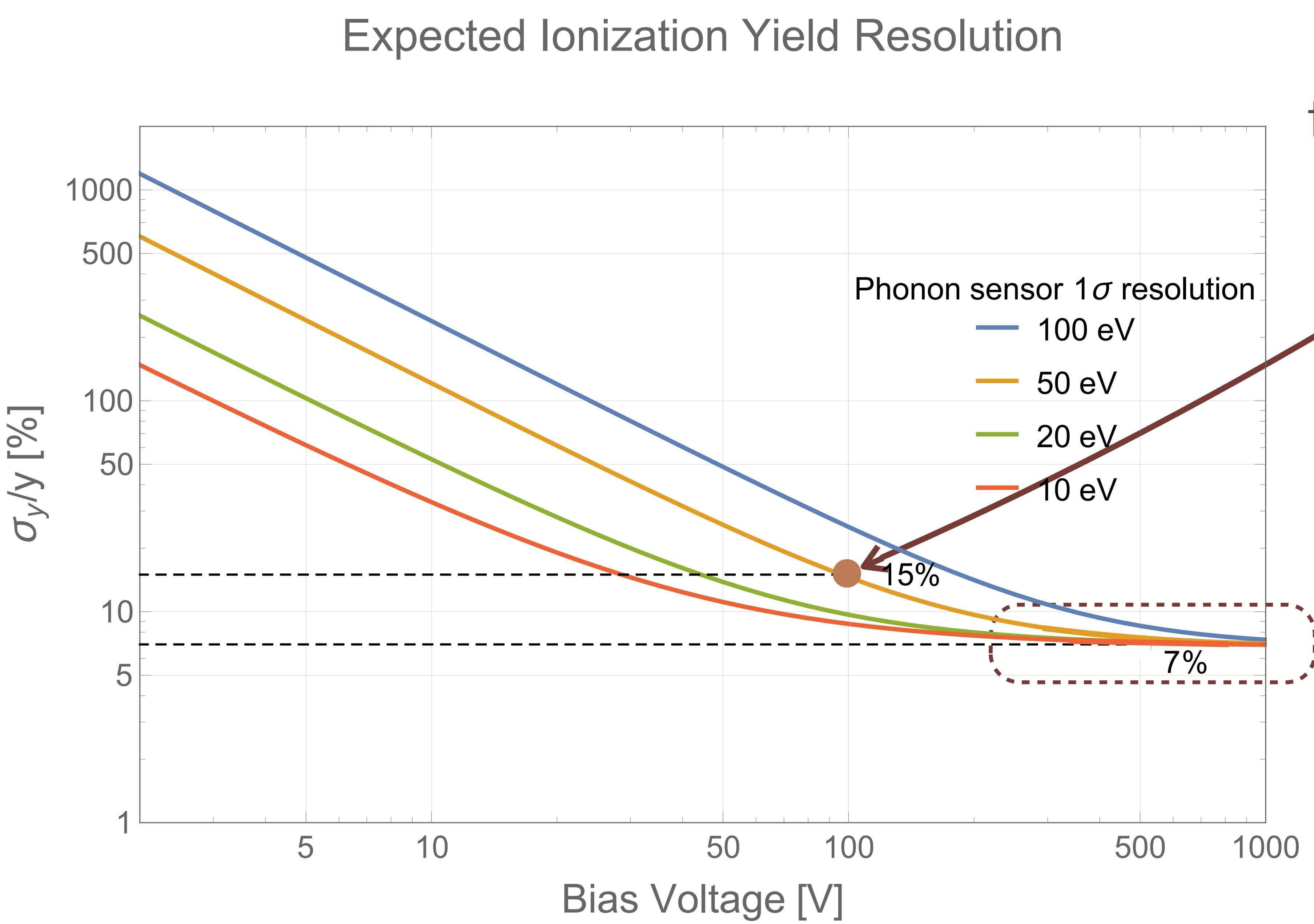
Taming the low energy divergence

- Comparing the ±1σ yield uncertainty bands for a “generic" yield measurement with $\sigma_{recoil} = \sigma_{ioniz}$ vs a Voltage-Assisted Calorimetric measurement (HV detector)
  - Assuming: σ_{phon} = 50 eV, $\sigma_{recoil} \equiv \delta\phi = 1°$, V=100V.



Yield resolution vs V at σ_{phon} = 100 eV

- The x-axis is the operating bias voltage, and the different colors are various phonon resolutions



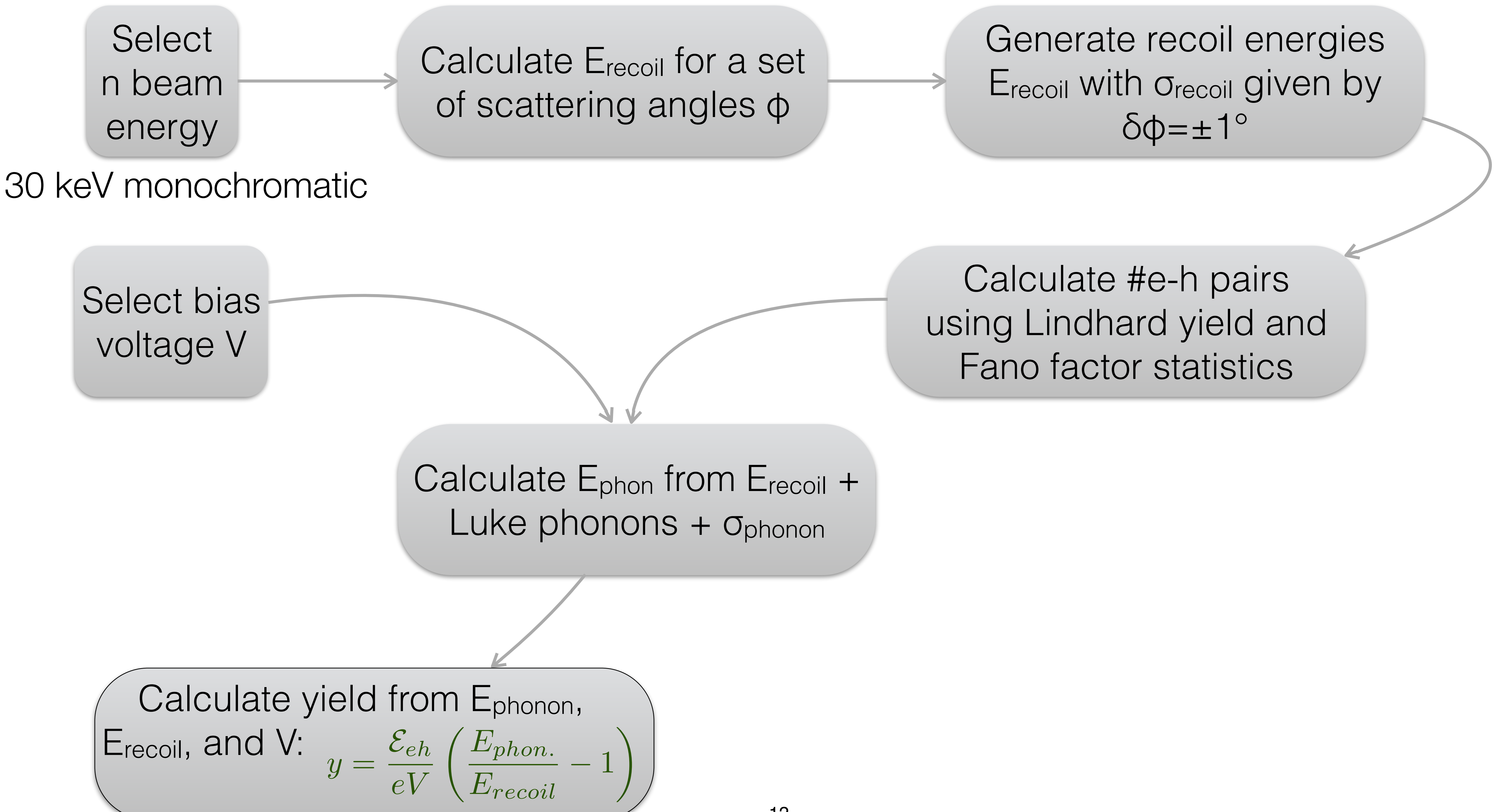
This point corresponds to the orange bands on the previous page at 100 eV recoil

At this point the σ_{recoil} ≡ $\delta\phi$=1° begins to dominate

0^{th} round calculations

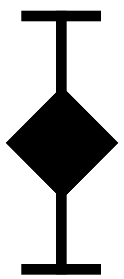
The basic simulation

Simulating the “ideal" experiment

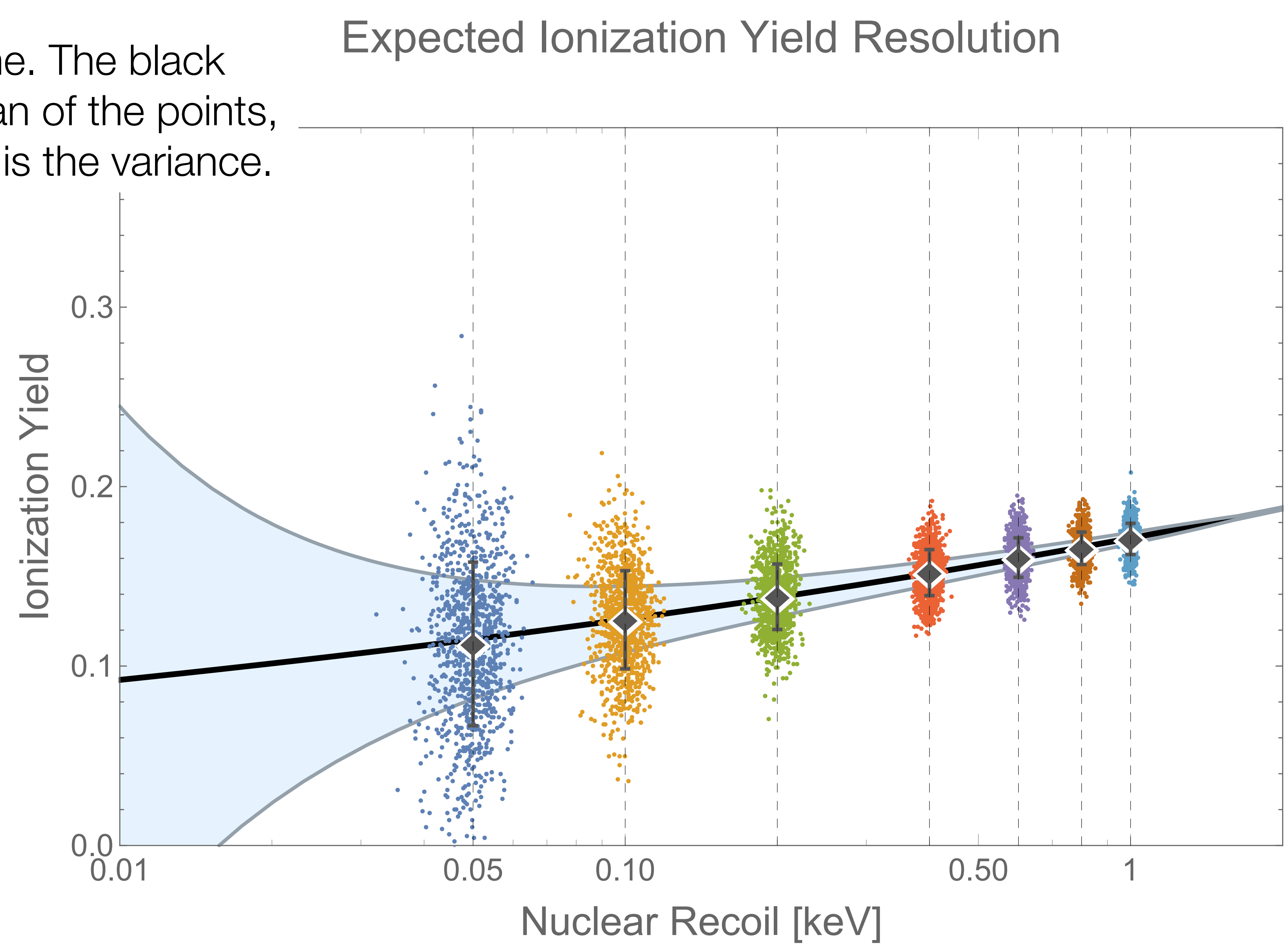


The “Baseline" Simulation: Ge target

- Parameters:
  - $E_k(n)$=30 keV, σ_{phon}=50 eV, σ_{recoil}≡± 1°, V=100V, F=0.13

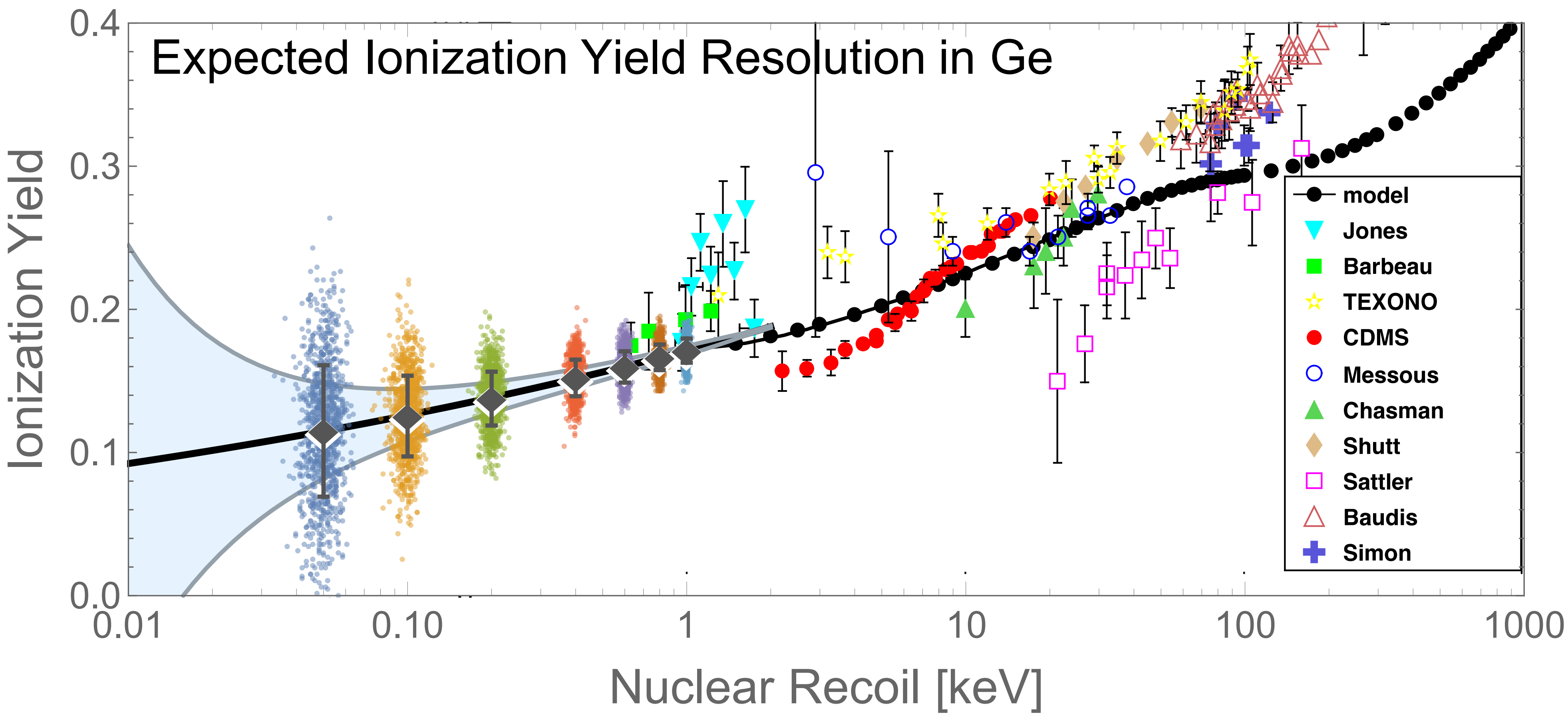


No fit was done. The black box is the mean of the points, the bar height is the variance.



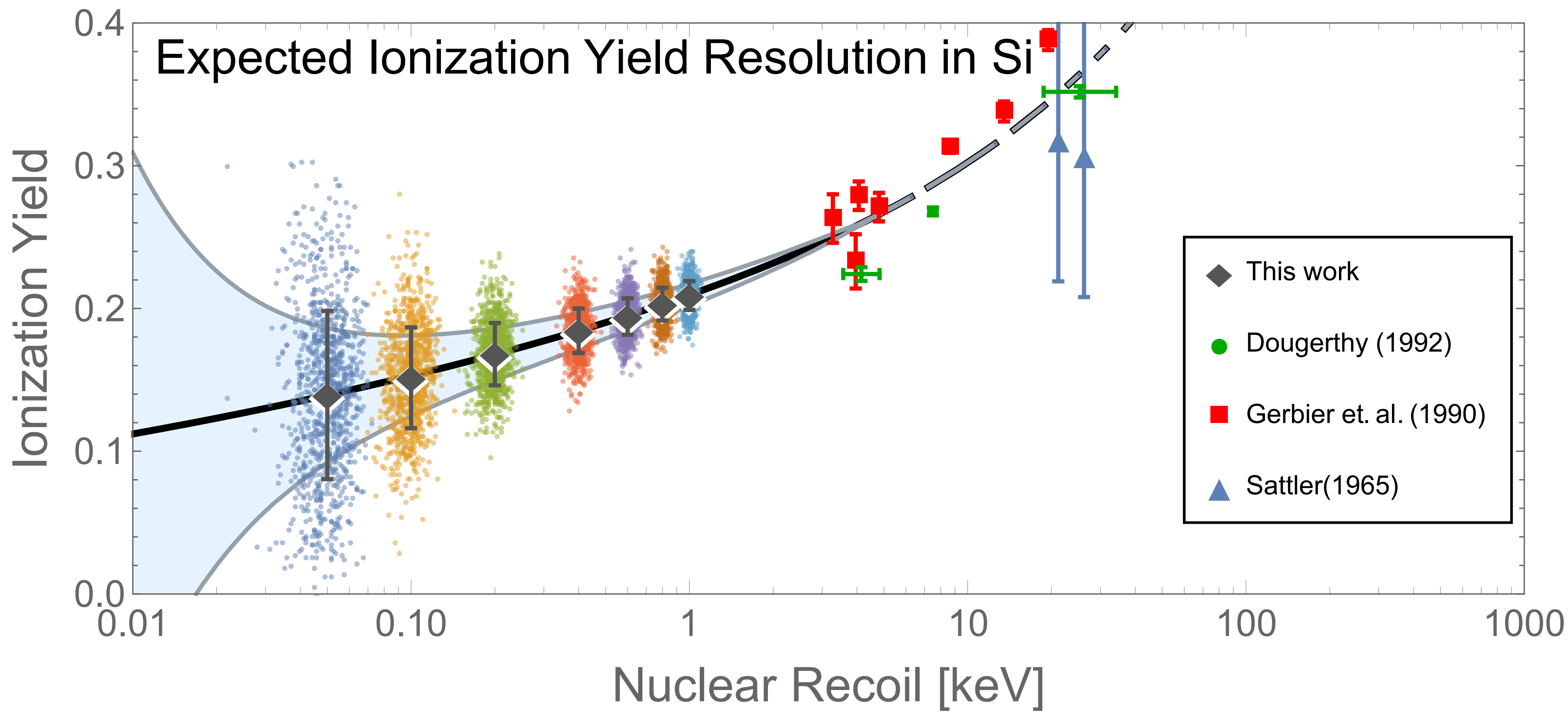
The “Baseline" Simulation: Ge target

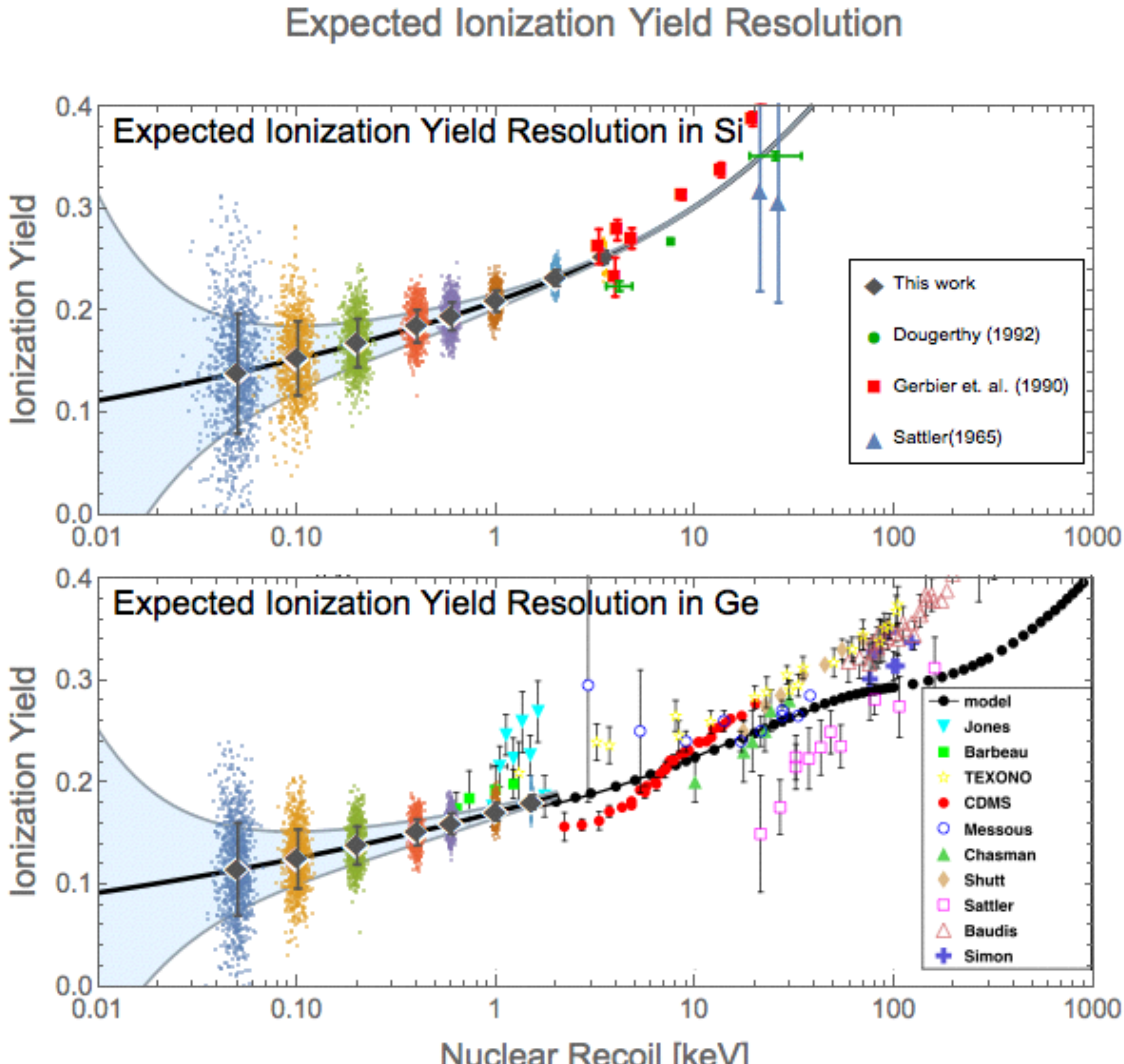
- Parameters:
  - $E_k(n)$=30 keV, σ_{phon}=50 eV, σ_{recoil}≡± 1°, V=100V, F=0.13
  - This is how the data would fit in with current knowledge



The “Baseline" Simulation: Si target

- Parameters:
  - $E_k(n)$=30 keV, σ_{phon}=50 eV, $\sigma_{recoil}\equiv\pm$ 1°, V=100V, F=0.13
  - This is how the data would fit in with current knowledge

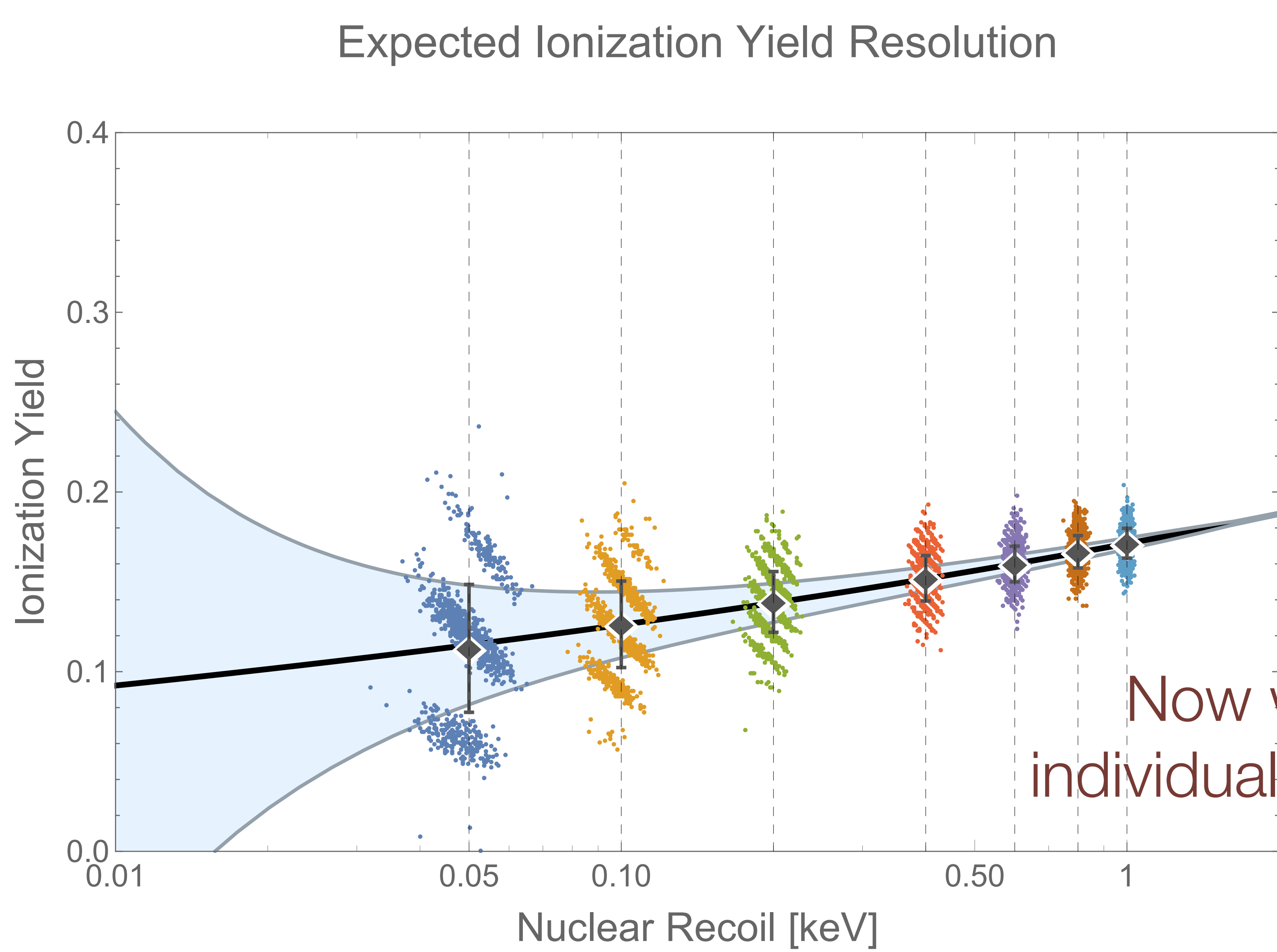




Expected Ionization Yield Resolution
Expected Ionization Yield Resolution in Si
Ionization Yield
0.0
0.1
0.2
0.3
0.4
0.01
0.10
1
10
100
1000
This work
Dougerthy (1992)
Gerbier et. al. (1990)
Sattler(1965)
Expected Ionization Yield Resolution in Ge
Ionization Yield
model
Jones
Barbeau
TEXONO
CDMS
Messous
Chasman
Shutt
Sattler
Baudis
Simon
Nuclear Recoil [keV]

A “Still Not-Totally-Crazy” Simulation: Ge target

- Parameters:
  - $E_k(n)$=30 keV, σ_{phon}=10 eV, $\sigma_{recoil} \equiv \pm$ 1°, V=100V, F=0.13



Now we’re seeing individual electrons/holes

1^{st} round calculations

Performing the measurement

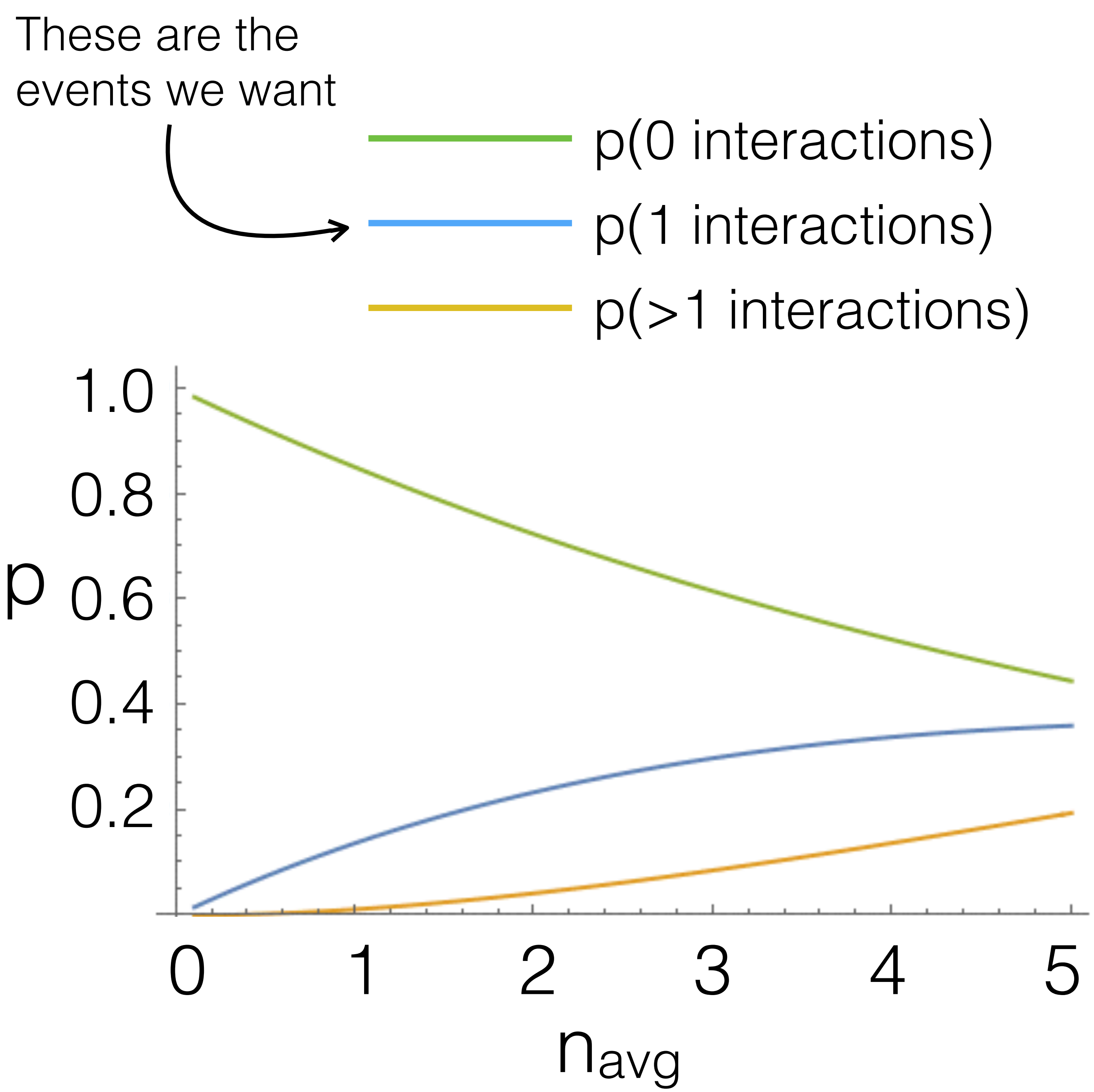
Multiple interactions in a detector

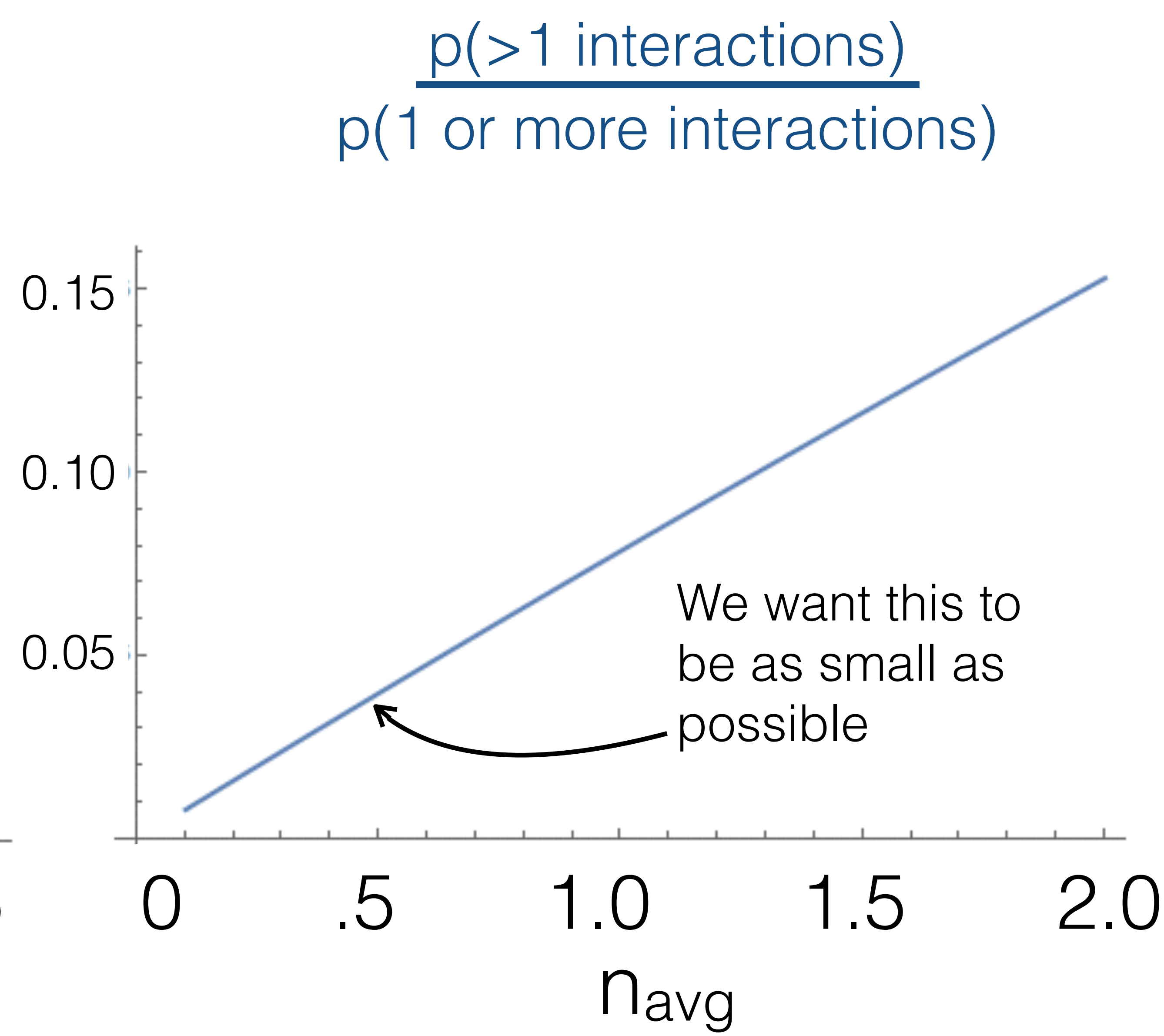
- There are two types of multiple interactions to consider
  1. One neutron undergoing multiple scatters
  2. Different neutrons from the same bunch undergoing coincident scatters
- Can’t really identify one from the other

One neutron scattering multiple times in a detector

- 30 keV Neutron m.f.p. in …
  - Ge: 23 mm → probability of a neutron interacting in a 4mm thick detector is 18%.
    i.e. probability of NOT interacting at all is 82%
  - Si: 118 mm → probability of a neutron interacting in a 4mm thick detector is 3%.
    i.e. probability of NOT interacting at all is 97%

Probability of n simultaneous interactions vs n_{avg}





n_{avg} = average number

Minimizing multiple interactions

- To achieve a multiple interaction to single interaction ratio of < 3% requires that $n_{avg}=0.4$
- At $n_{avg}=0.4$, the probability of a single interaction from a neutron bunch = 6%
- Limiting the maximum interaction rate in the detector to 100 Hz (to avoid pileup, assuming 1 ms decay time) gives a desired bunch frequency of 1/600μs.
- The combination of bunches arriving every 600μs with $n_{avg}=0.4$ is feasible with the TUNL facility

2nd round calculations

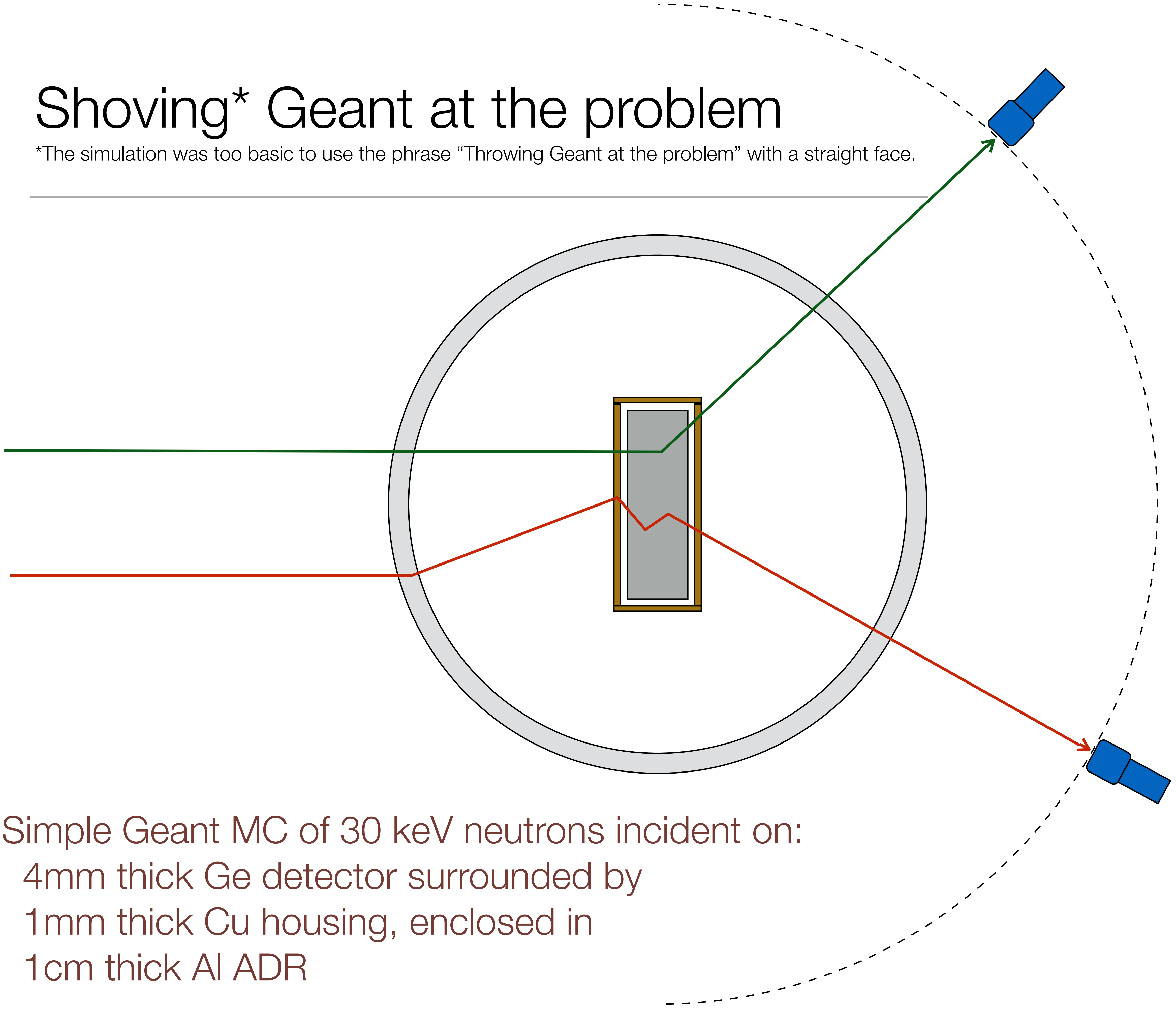
Some “unwanted" effects

Neutron interactions prior to the detector

- Assuming a perfectly monochromatic neutron beam with no angular spread is incident on the experiment
  - Look at effect of neutrons interacting in the material surrounding the detector on the “purity" of the incident beam

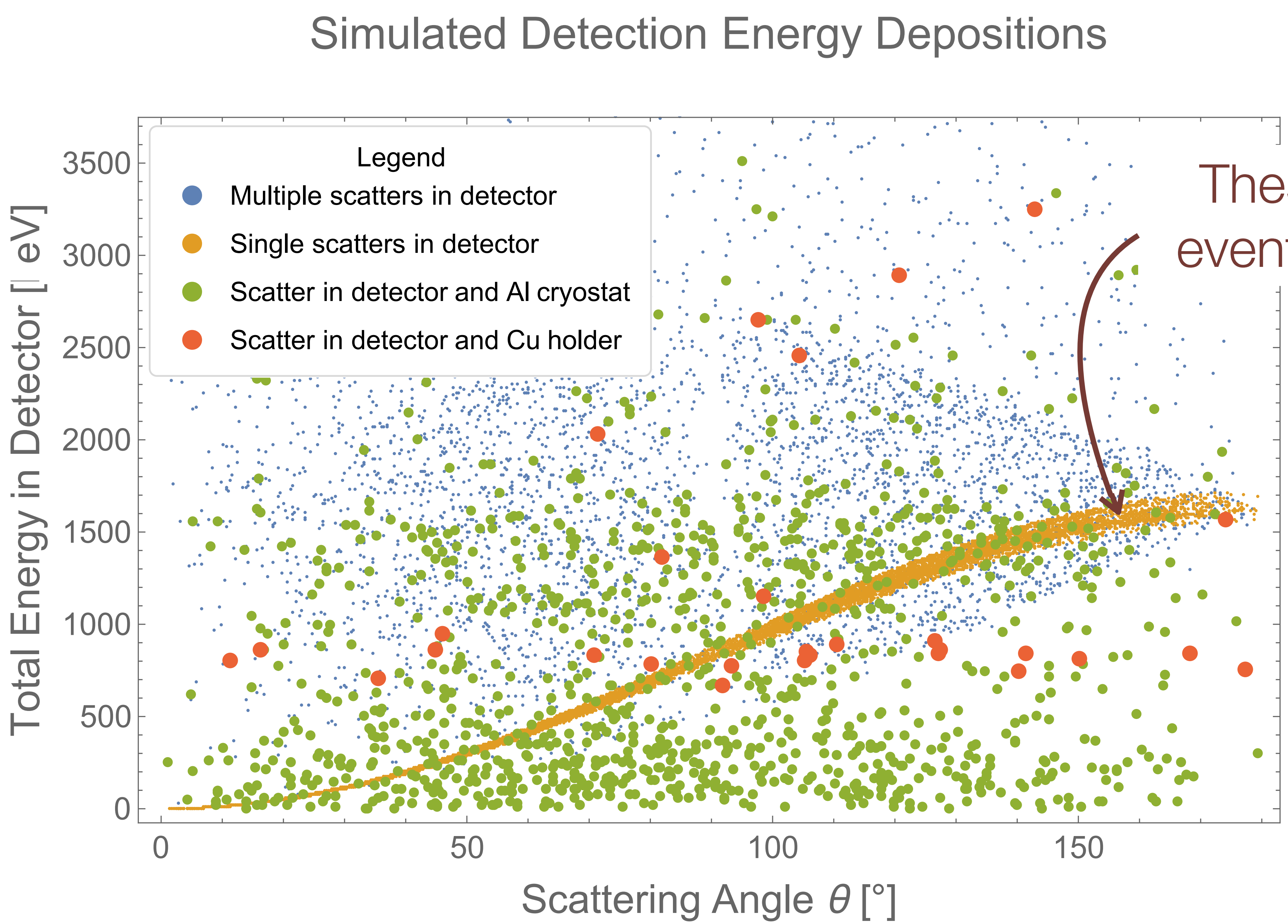
Shoving* Geant at the problem

*The simulation was too basic to use the phrase "Throwing Geant at the problem" with a straight face.



Simple Geant MC of 30 keV neutrons incident on:
4mm thick Ge detector surrounded by
1mm thick Cu housing, enclosed in
1cm thick Al ADR

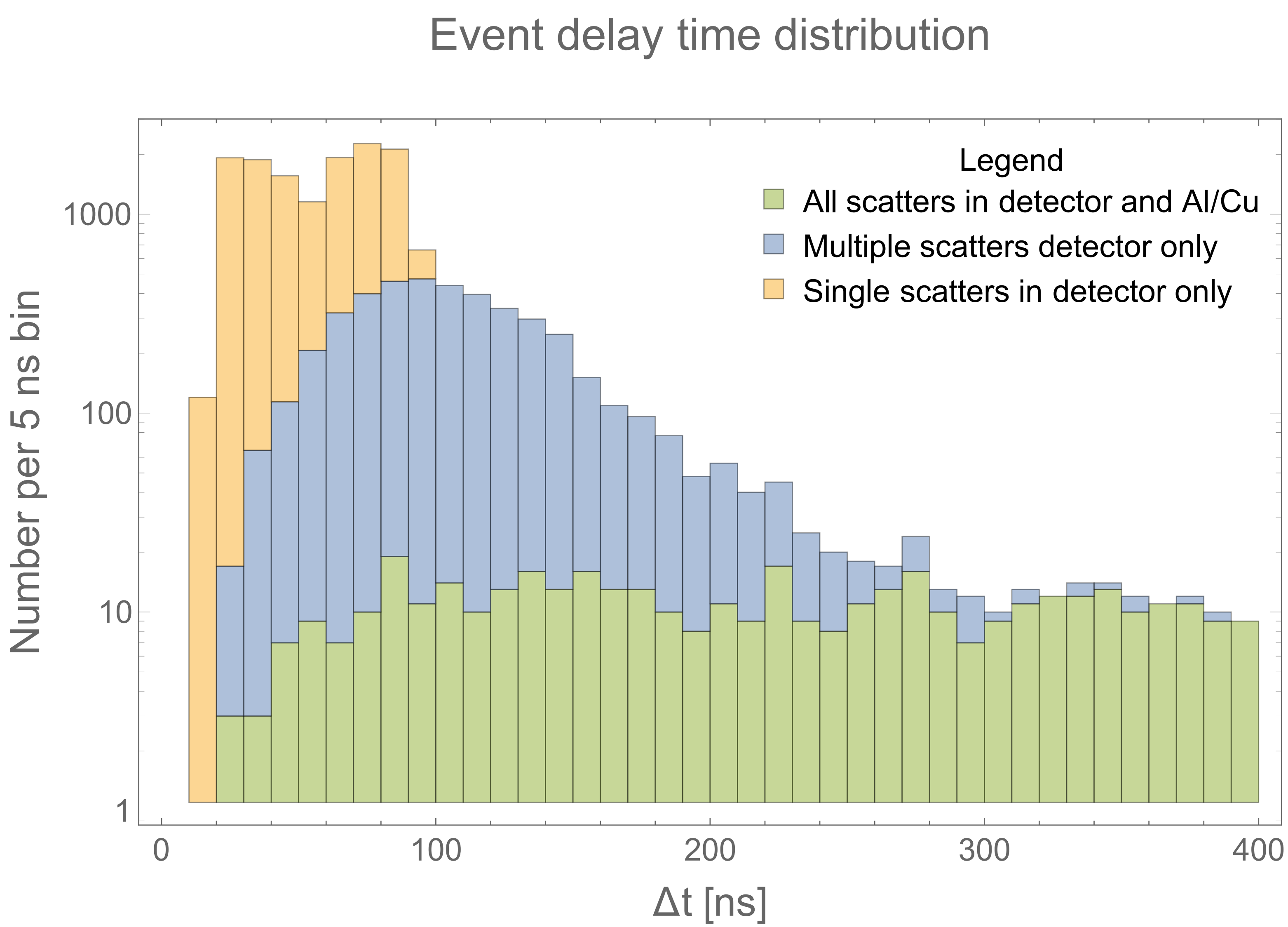
Recoil Energy vs Scattering Angle



These are the events we want

Can use timing information

- The neutrons are slow enough that the timing between the neutron bunch and its detection in a PMT depends on the recoil energy in the ZIP.

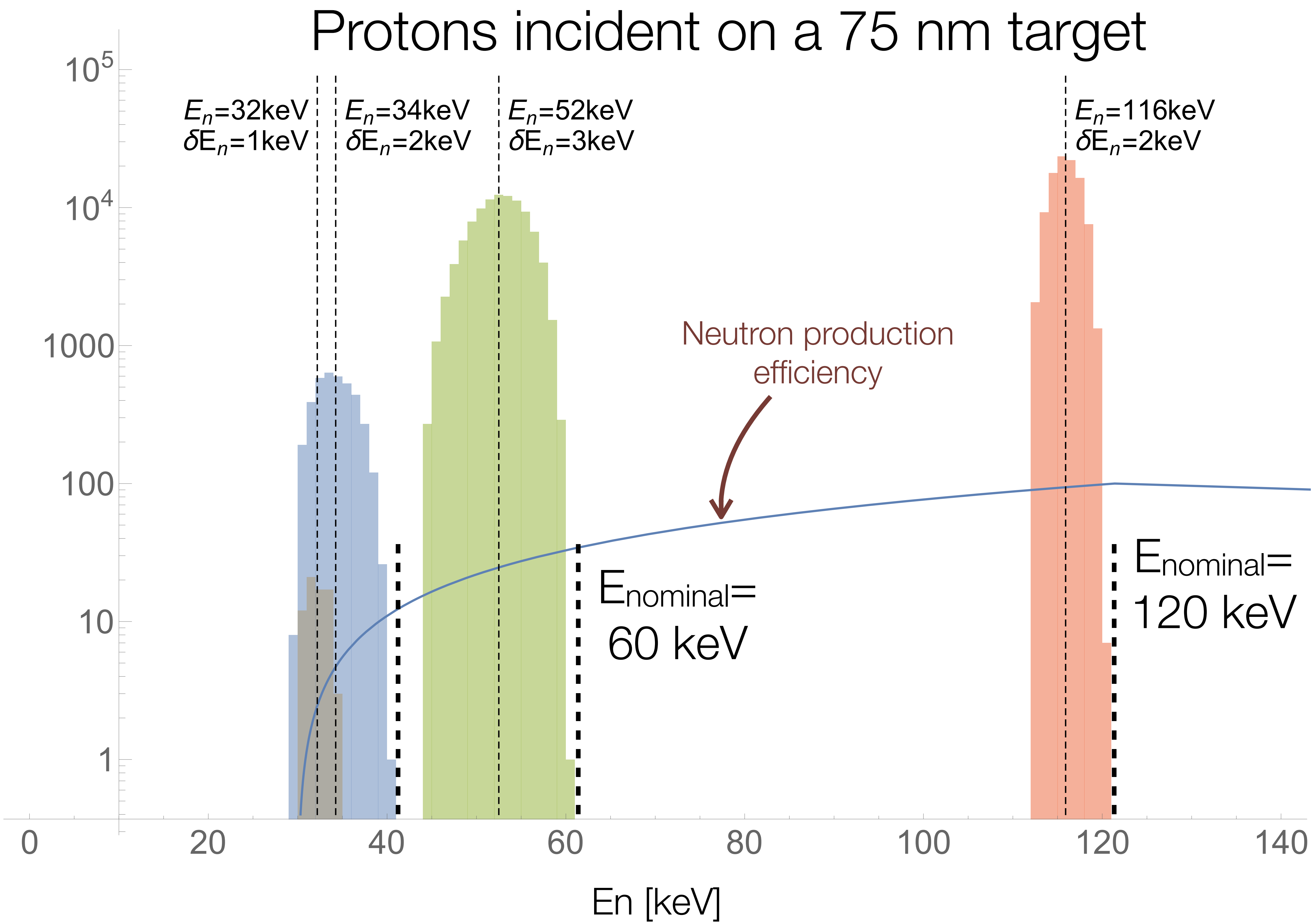


- A timing cut can clean up the data quite a bit
- In reality things are much better that this histogram indicates, since this includes all events at all energies
  - Looking in specific energy bins the contamination is ≲ 1%.

How monochromatic is the n beam?

- Energy loss of the proton beam due to scattering in the LiF target prior to the production of the neutrons will introduce an energy spread in the neutron beam
  - For 1.88-1.92 MeV protons incident on a 75 nm thick LiF target average proton energy loss due to scattering is ~2.5 keV, up to 5 keV
  - For 1.88-1.92 MeV protons incident on a 500 nm thick LiF target average proton energy loss due to scattering is ~8.0 keV, up to 15 keV
  - Results in spread of neutron energies

Neutron energy spread due to LiF thickness



Recovering from the neutron energy spread

- Timing measurement of the neutron interactions can help recover the initial (pre-scattering) neutron energy
  - At 30 keV, a time of flight difference of 5ns allows us to identify $\delta E_n = 0.25$ keV
  - At 120 keV, a time of flight difference of 5ns allows us to identify $\delta E_n = 2$ keV
- Choosing the optimal tradeoff between neutron production rate and energy resolution will be done in upcoming Geant simulations

Final thoughts

almost the end

Calibration of SuperCDMS detectors with a photoneutron source

- Lauren Hsu will give a presentation about ongoing efforts to measure yield in the SuperCDMS detectors using photoneutron sources. **<u>Thu, Session III</u>**

Conclusions

- Measuring the ionization yield below 1 keV nuclear recoil requires measuring the ionization produced to within a few electron-hole pairs
- Phonon-based charged amplification using our HV detectors will allow us to attain this charge resolution.
- A dedicated HV detector running at a neutron beam facility will enable the first measurements of yield in the energy range of 100 eV—1 keV, in Si and Ge.
- Verifying, or measuring any deviations from, Lindhard behavior in this energy range and at the operating temperature and E field is essential for interpreting future low-mass WIMP data.