CYGNUS-TPC kick-off meeting
LNF - April 7-8, 2016

Coherent neutrino scattering from Supernovae, Sun and other sources

Matteo Biassoni
April 7, 2016

OUTLINE

- Neutrino detection with coherent scattering
- Calculation of expected signal for different materials
- Expected signal for different sources:
    - Core collapse supernovae
    - Stopped pion neutrino source
    - Nuclear reactor
    - Sun
- Conclusions

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Neutrino detection processes

Large mass neutrino detectors, as well as proton decay and supernova detection dedicated experiments, are sensitive to neutrinos via:

$\overline{\nu}_e + p \rightarrow n + e^+$	Inverse Beta Decay, dominant @ SN energies	1
$\nu_x + p \rightarrow \nu_x + p$	NC elastic scattering	0.25
$\nu_x + e^- \rightarrow \nu_x + e^-$	CC and NC elastic scattering	0.0025

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Partially sensitive to all neutrino species but with small cross sections and detection efficiencies

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Detectors with heavy element targets can exploit a never observed (but SM!) phenomenon:

$\nu_x + (A, Z) \to \nu_x + (A, Z)$	NC coherent scattering	100

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Detectors with heavy element targets can exploit a never observed (but SM!) phenomenon:

$\boxed{\nu_x + (A,Z) \rightarrow \nu_x + (A,Z)}$	NC coherent scattering	100

Sensitive to all neutrino species with same efficiency
Heavy targets give great advantage

EXPERIMENTAL CHALLENGE:

- nuclear-recoil sensitive detector
- very low energy threshold
- no (or well understood) quenching effects
- particle identification
- directionality (most sources are directional)
- very low background environment

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Signal calculation

Study of a detector sensitivity to neutrinos detection with coherent scattering.

INGREDIENTS:

- neutrino spectra models (Energy, Time) for various sources
- neutrino-target cross section
- nuclear form factor models

OUTPUT:

- calculation of expected signal and background comparison
- comparison of experimental results with theoretical models of:
    - source (SN, Sun, reactors)
    - neutrino propagation (sterile neutrino)
    - neutrino interaction (nuclear form factors)

ν-N Coherent Scattering

For momentum transfer comparable with nuclear size (<1 fm^{-1}), neutrino can interact coherently with all nucleons in the target nucleus.

PROS:

- cross section enhanced by a factor N^2
- NC process ==> flavour independent

CONS:

- small detectable energy (order of few keV)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{G_F^2}{4\pi^2} E^2 (1 + \cos\theta) \frac{Q_w^2}{4} F(Q^2)^2$$

Nuclear weak charge

$$Q_w = N - \left(1 - 4\sin^2\theta_W\right) Z$$

Nuclear form factor

$$F(Q^2) = \frac{3\left(\frac{\sin(QR_0)}{(QR_0)^2} - \frac{cos(QR_0)}{QR_0}\right)}{QR_0} \times \exp\left(-\frac{(Qs)^2}{2}\right)$$

$$R_0^2 = R^2 - 5s^2$$

$$R = (1.2 \times A^{1/3})\mathrm{fm}$$

$$s = 0.5\mathrm{fm}$$

- J. Engel, Physics Letters B, 264, 114 (1991), ISSN 0370-2693.
- P. S. Amanik and G. C. McLaughlin, Journal of Physics G: Nuclear and Particle Physics, 36, 015105 (2009).
- J. Lewin and P. Smith, Astroparticle Physics, 6, 87 (1996), ISSN 0927-6505.

ν-N Coherent Scattering

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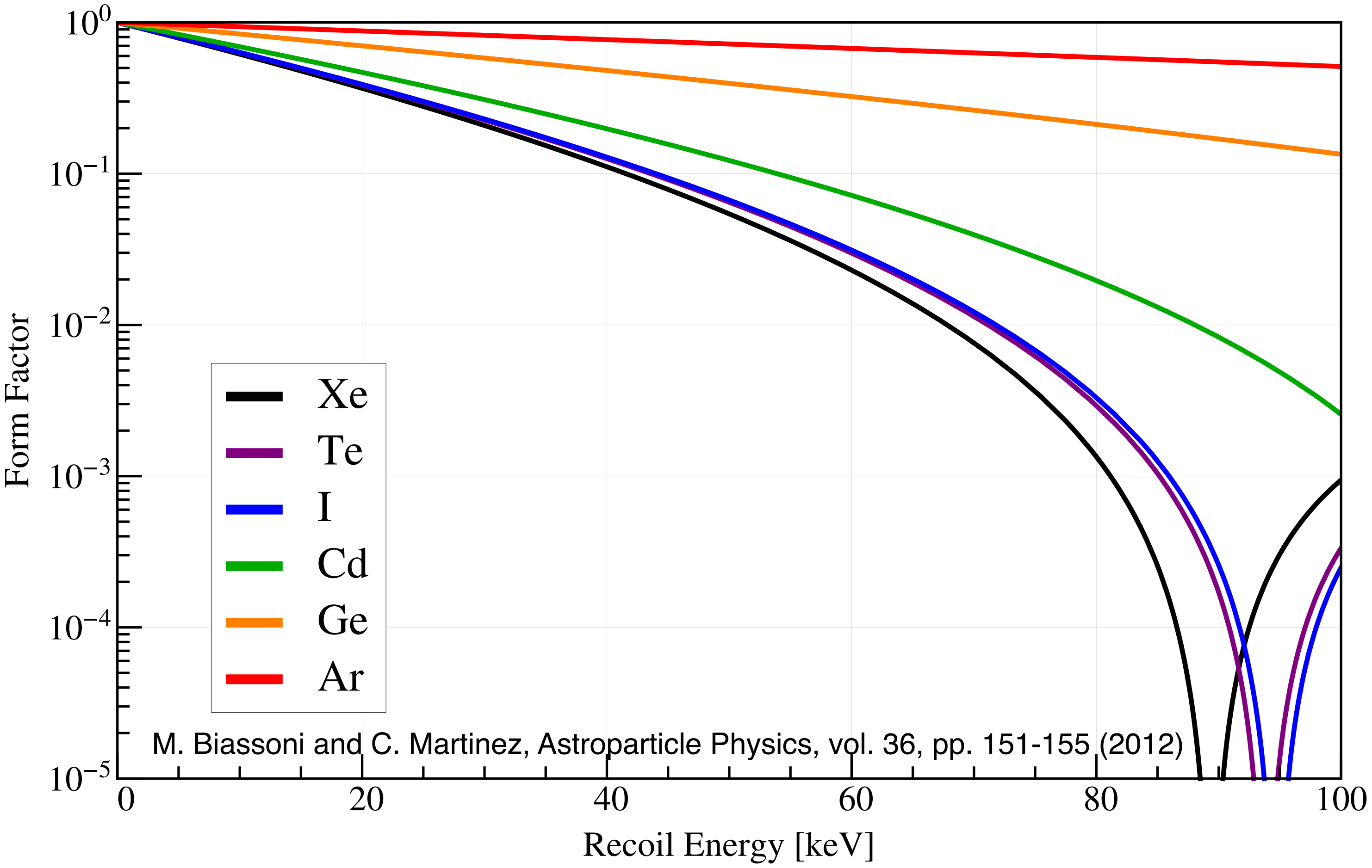
$$\overset{\text{Momentum transfer}}{Q^2} = 2\underset{\text{Neutrino energy}}{E}{}^2(1-\cos\theta) = 2\overset{\text{Nucleus mass}}{M}\underset{\text{Recoil energy}}{T}$$



M. Biassoni and C. Martinez, Astroparticle Physics, vol. 36, pp. 151-155 (2012)

- represents the distribution of weak charge inside the nucleus
- the larger the nucleus, the smaller the momentum that can be transferred to "see" the nucleus coherently
- the larger the nucleus the smaller the recoil energy
- max recoil energy = $2E^2/M$ (1-20keV)
- typical neutrino energy ~ 10MeV

ν-N Coherent Scattering

SIGNAL YIELD

$$Y(T) = \frac{\mathrm{d}N_{\mathrm{events}}}{\mathrm{d}T} =$$

Number of recoil events with energy T

$$= \sum_{\alpha=\mathrm{nuclei}} N_\alpha \iint \mathrm{d}\Omega \mathrm{d}E \times$$

Sum over the different nuclear species in the target, integrate over scattering angle and neutrino energy

$$\times \frac{\mathrm{d}\sigma_\alpha}{\mathrm{d}\Omega}(Q^2, F(Q^2), Q^2_W, A) \times$$

Cross section

$$\times \phi_{\mathrm{tot}}(E) \times$$

Neutrino flux, source

$$\times \delta\left(T - \frac{Q^2}{2M_\alpha}\right)$$

Energy conservation

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Source: Core-collapse SN

CORE-COLLAPSE SUPERNOVA:

- $M_{star} > 9M_{sun}$
- fusion of progressively heavier elements ==> onion structure
- iron: no fusion ==> no net energy ==> only electrons degeneracy pressure
- when iron core mass > Chandrasekhar limit ($1.4M_{sun}$) ==> COLLAPSE
- iron core shrinks and temperature increases
- when core density approaches nuclear density strong interaction and neutron degeneracy prevent further collapse ==> in-falling matter rebounds
- outgoing shockwave dissociates nuclear matter in the core loosing energy and stalling
- at high temperature/density the core cools down via pair annihilation and Z_0 bremsstrahlung (80-90% of total neutrino emission); 0.1% of neutrinos interacting with the stalled shockwave triggers the explosion

$$(A,Z) + \gamma \to \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau} + (A,Z)$$

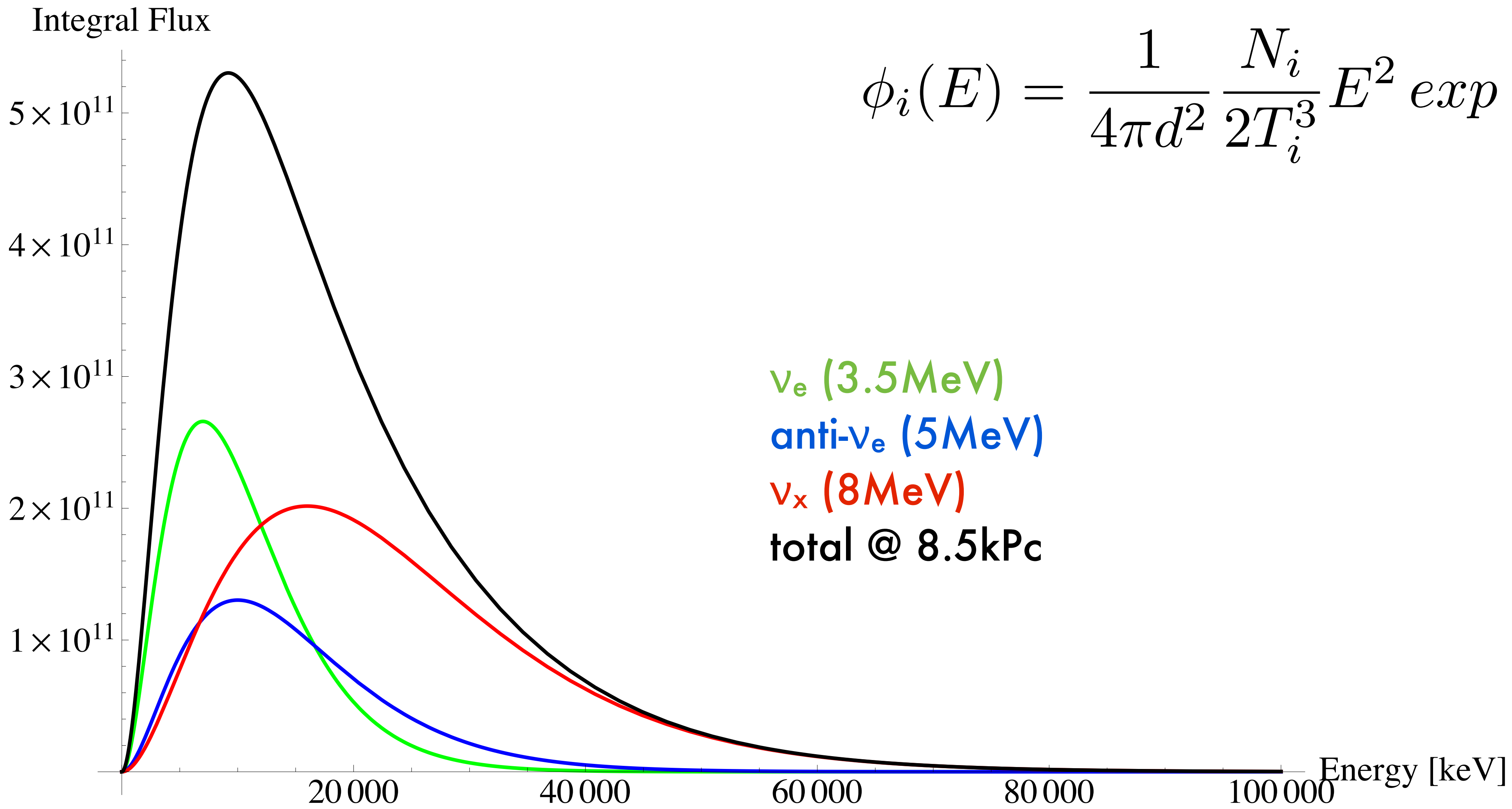
$$e^+ + e^- \to \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}$$

Simplest model: the emission lasts about 10s, with an exponential time profile with 3.5s decay time (SN1987A).

$$N(t) = \frac{N_0}{\tau} \exp\left(-\frac{t}{\tau}\right) \qquad \tau \simeq 3.5\text{s}$$

Source: Core-collapse SN

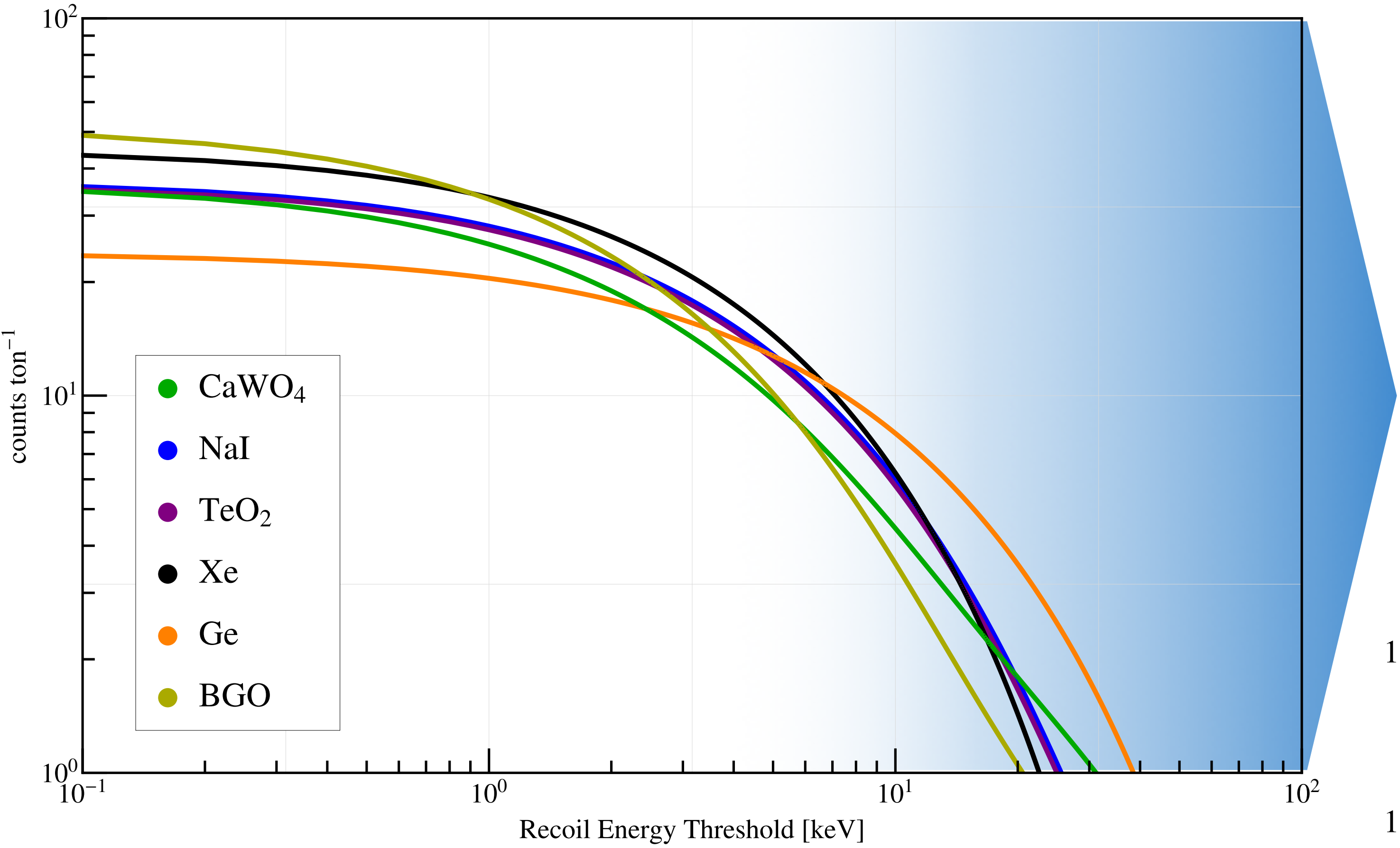
- 10^{53}erg emitted as neutrinos
- equipartition of energy between the six species
- different spectra for ν_e, anti-ν_e and ν_x (due to different free paths = different "neutrinospheres" radii = different temperature at the emission)
- short emission, about 10 sec long bunch of neutrinos expected to reach Earth



$$\phi_i(E) = \frac{1}{4\pi d^2}\frac{N_i}{2T_i^3}E^2\,exp\left(-\frac{E}{T_i}\right)$$

Source: Core-collapse SN

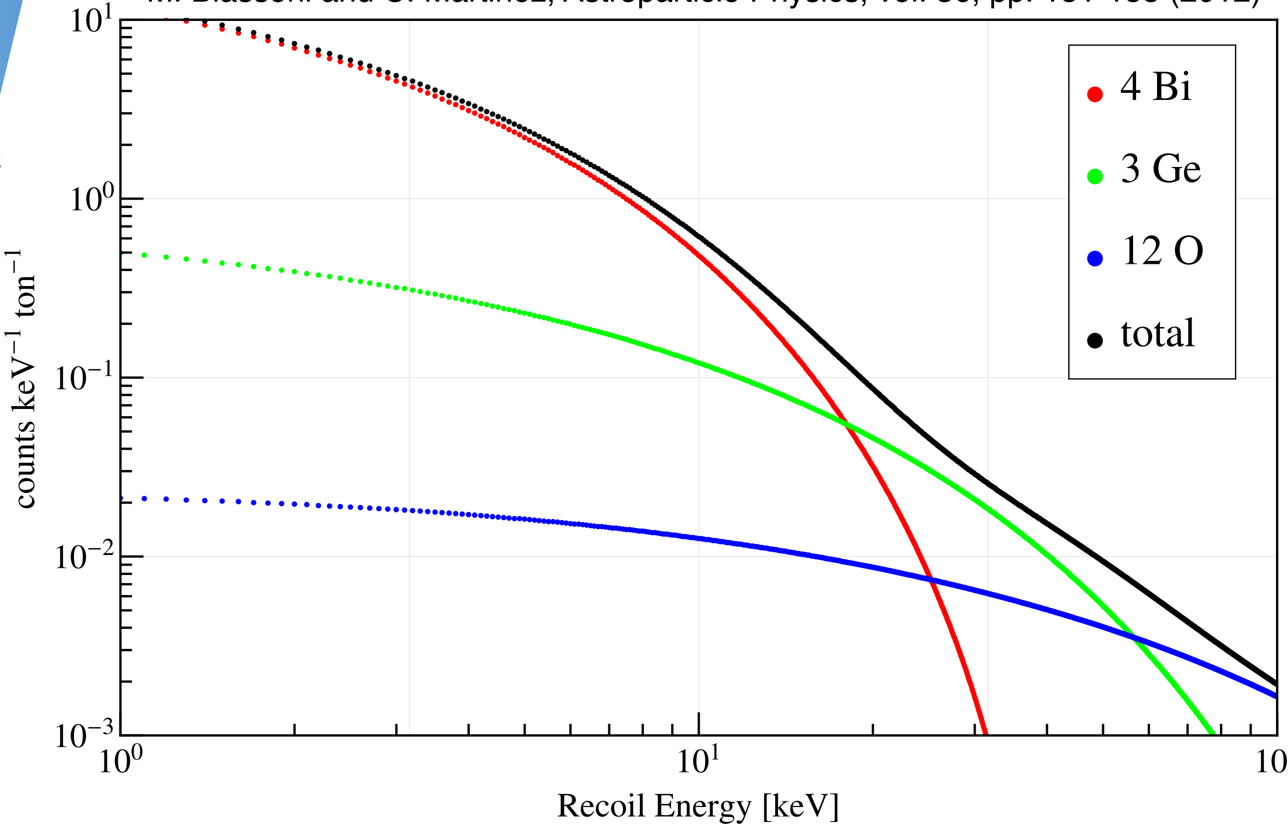
EXAMPLE: expected number of recoils in 1 ton of material



Most of the events have energy below few keV

Kinematics + form factor cut-off

M. Biassoni and C. Martinez, Astroparticle Physics, vol. 36, pp. 151-155 (2012)



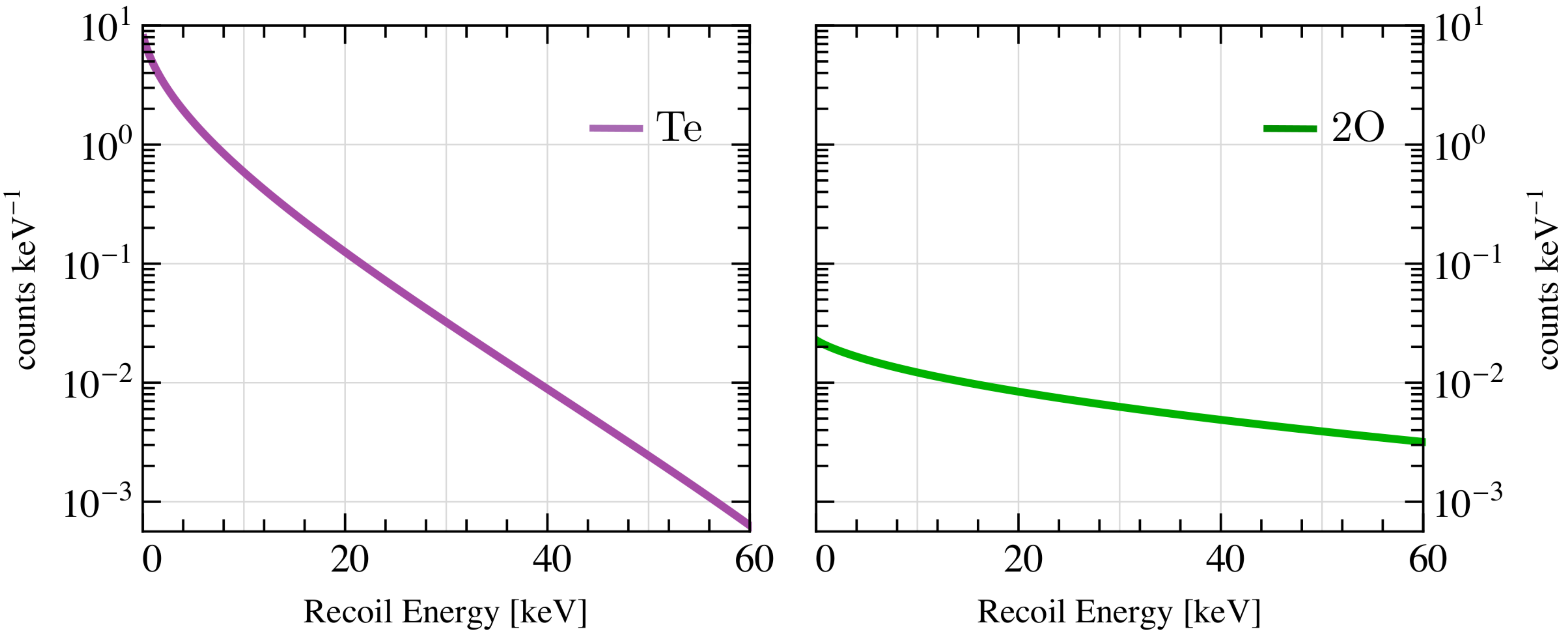
Compounds feature a slightly flatter recoils spectrum due to different contributions from nuclear species

Source: Core-collapse SN

EXAMPLE: CUORE experiment, 741 kg of TeO_2 thermal detectors

Expected signal dominated by Te targets, squeezed in the first few keV

Low threshold detector required

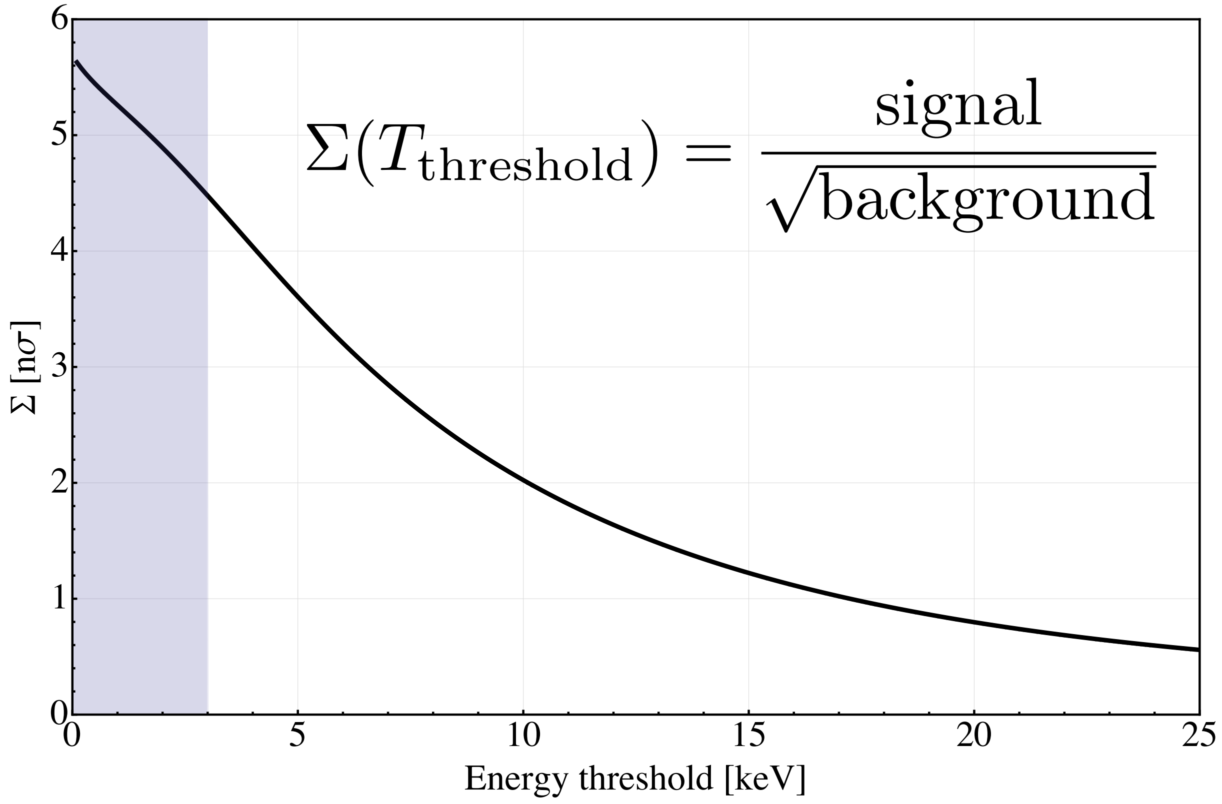


Source: Core-collapse SN

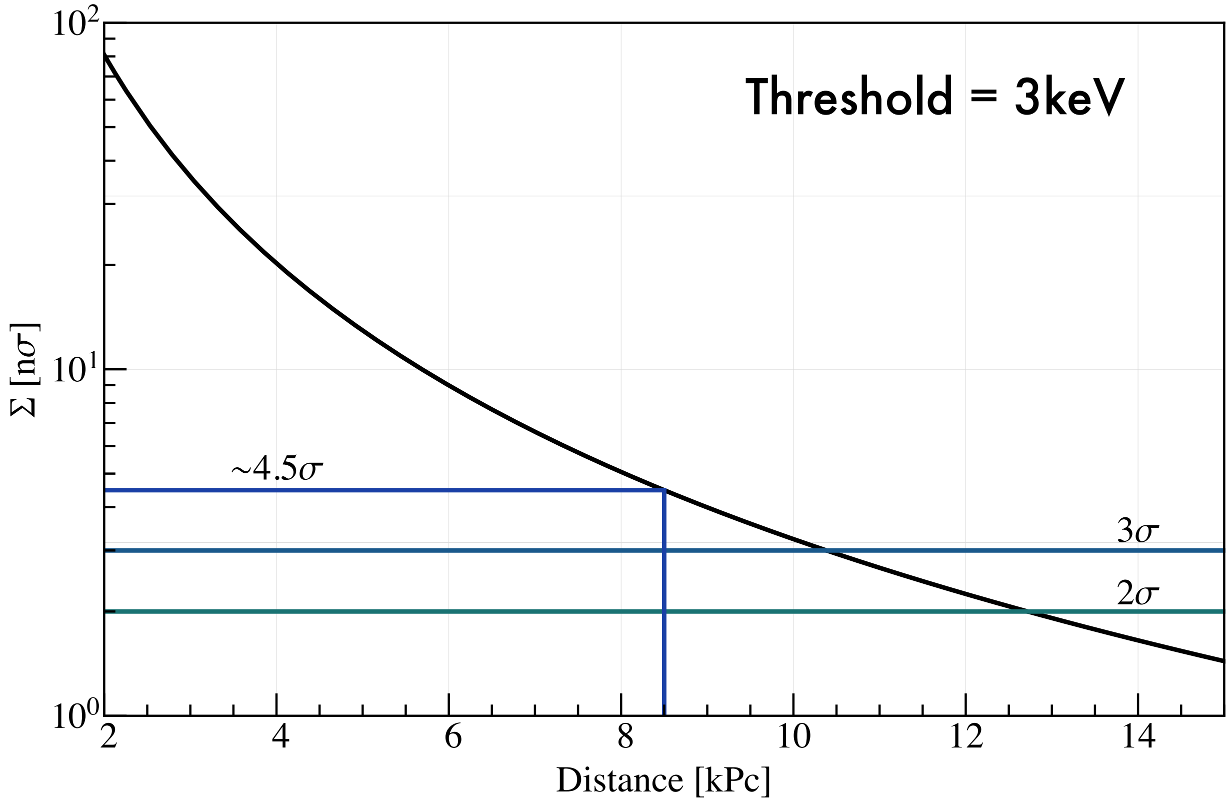
EXAMPLE: CUORE experiment, 741 kg of TeO_2 thermal detectors

Comparison between signal and background: signal observation significance (gaussian approximation, simple counting experiment in 10 seconds window)

Detector performance (threshold and background) extrapolated from prototype runs; significant background reduction is expected in final detector



$$\Sigma(T_{\text{threshold}}) = \frac{\text{signal}}{\sqrt{\text{background}}}$$



Signal from galactic SN clearly observable above background

Source: Core-collapse SN

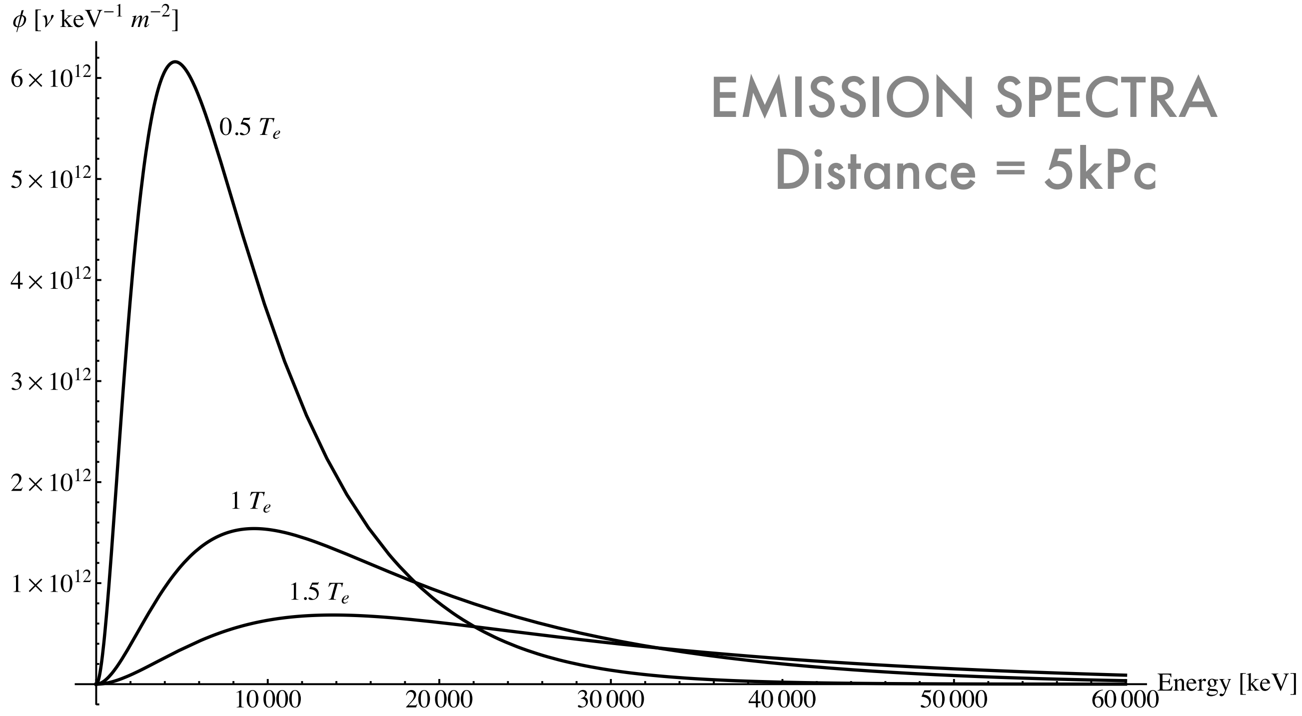
EXAMPLE: CUORE experiment, 741 kg of TeO_2 thermal detectors

In case of supernova observation at known distance *d* (5kPc in this example), a study of some supernova models parameters can be performed.

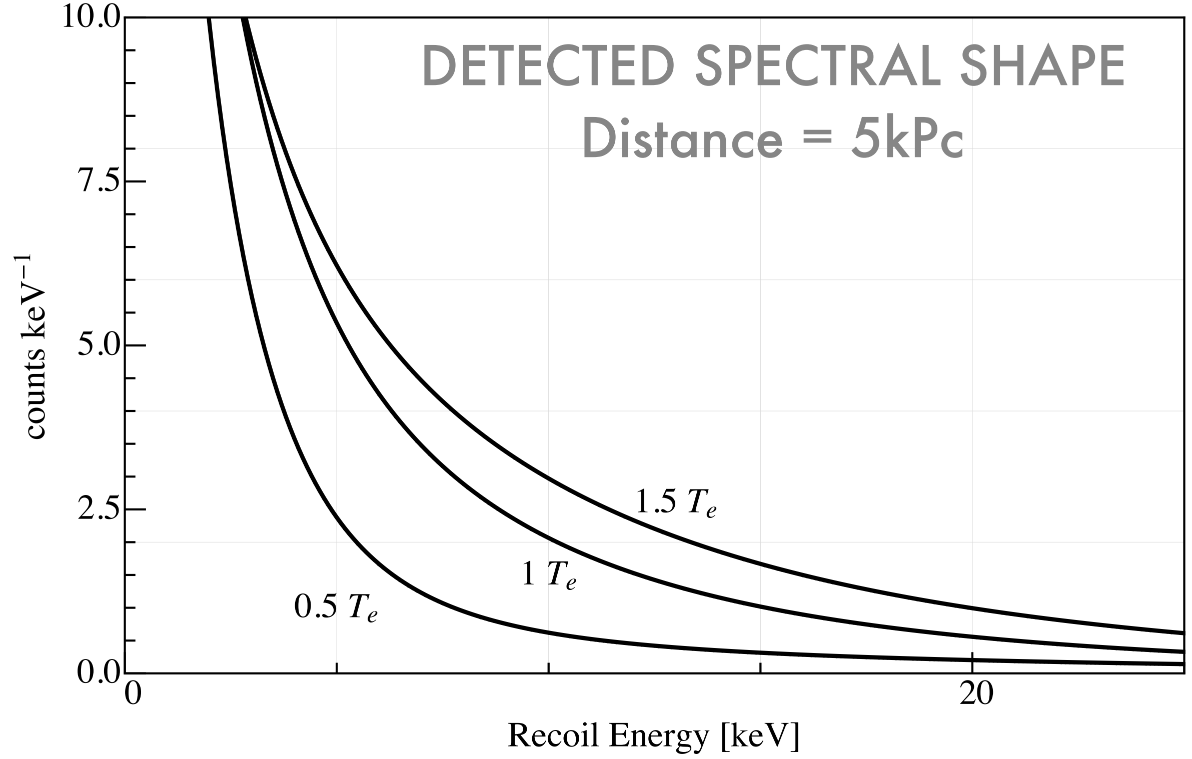
Parameter T_e of neutrino spectrum is changed by 50%, ratio between families temperatures unchanged

T_e >>
smaller flux, harder spectrum
T_e <<
larger flux, softer spectrum

Balance between flux, cross section and form factor ==> different SPECTRAL SHAPES



EMISSION SPECTRA
Distance = 5kPc



DETECTED SPECTRAL SHAPE
Distance = 5kPc

Source: Core-collapse SN

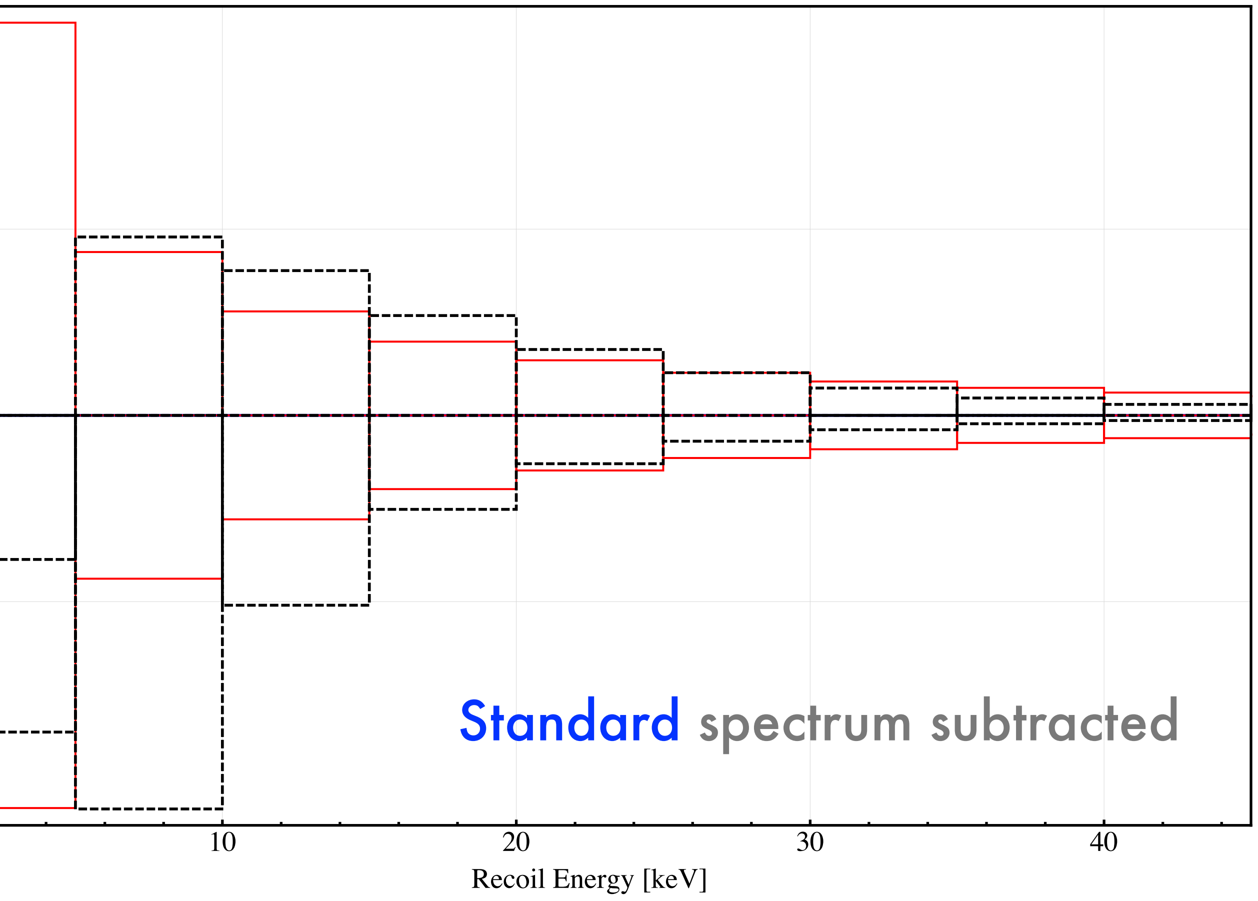
EXAMPLE: CUORE experiment, 741 kg of TeO_2 thermal detectors

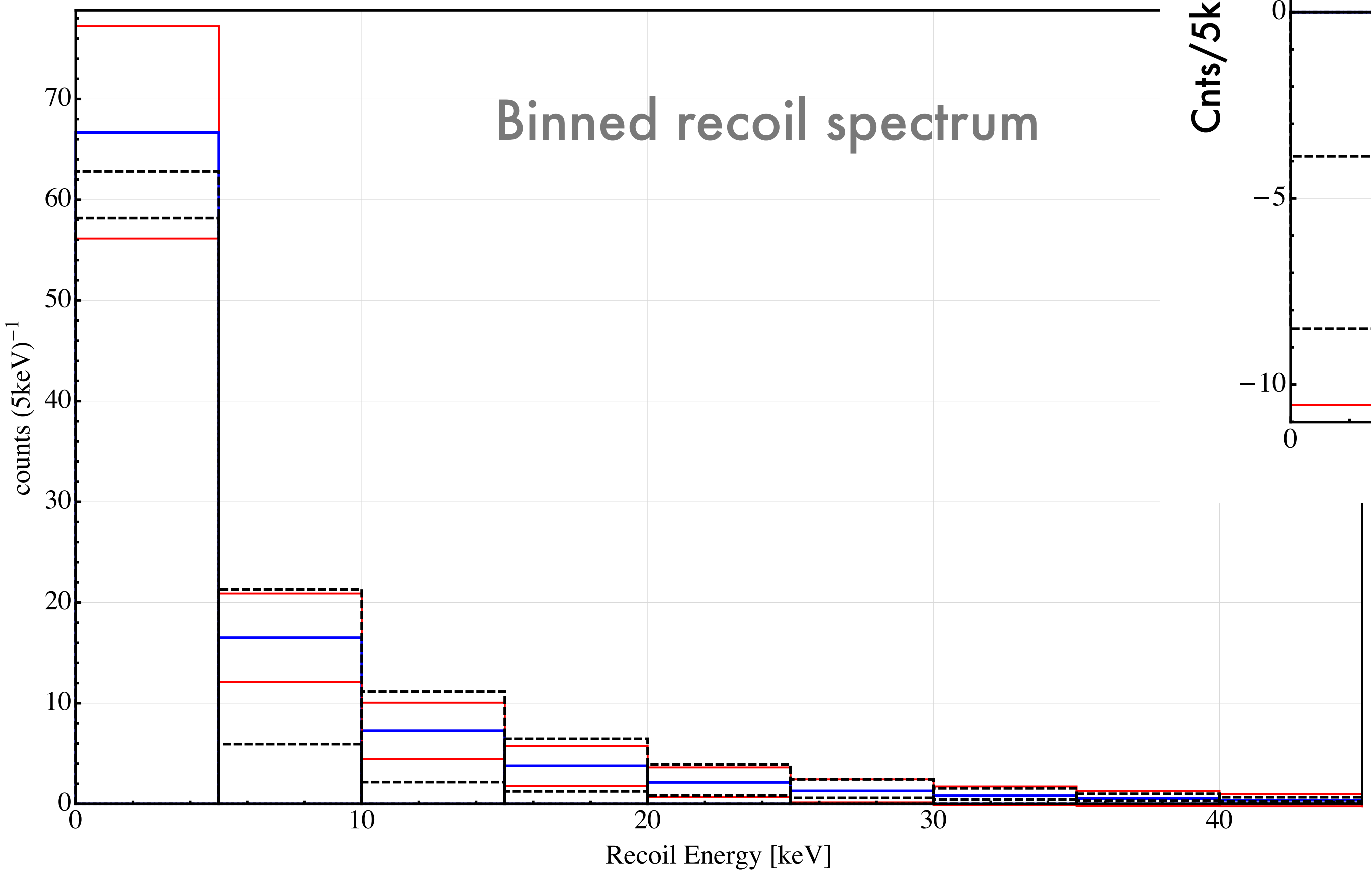
Can the three different models be discriminated?

Binned spectra with signal and background statistical fluctuations:

- standard value of T_e
- T_e changed by 50%
- standard value plus 1sigma fluctuations

Model independent
"thermometer" of SN emission





NB: errors include background fluctuations; DIRECTIONAL detection would improve sensitivity (zero-background)

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Source: Stopped pion source

Neutrino detection via neutrino-nucleus coherent scattering for an artificial source.

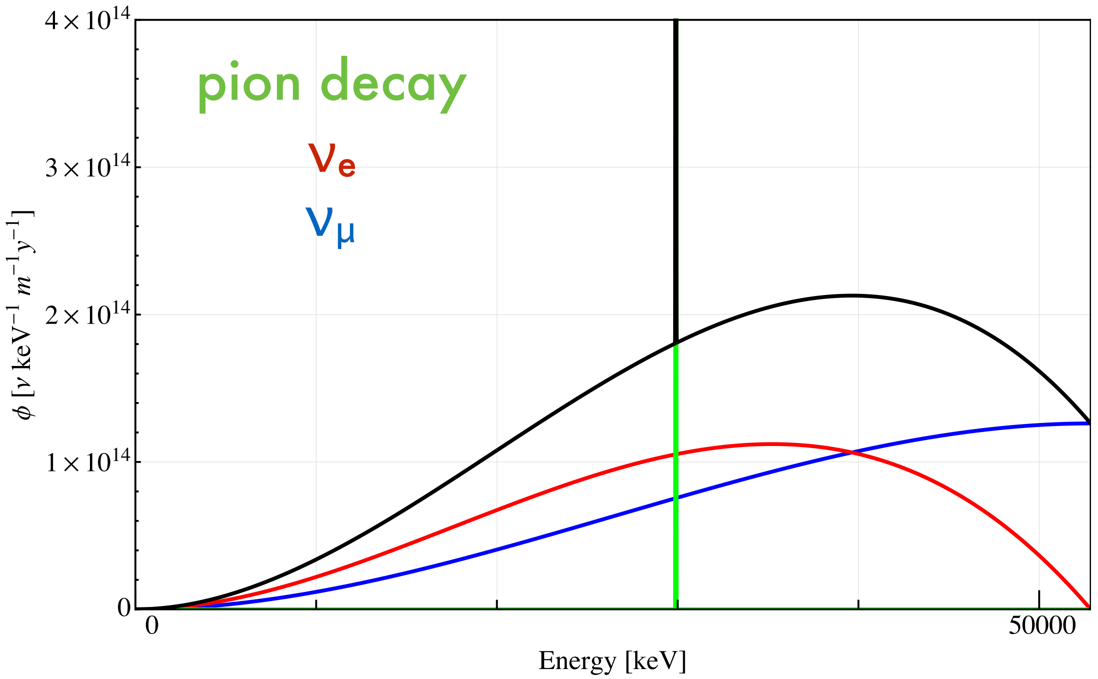
Possible physics outcome:

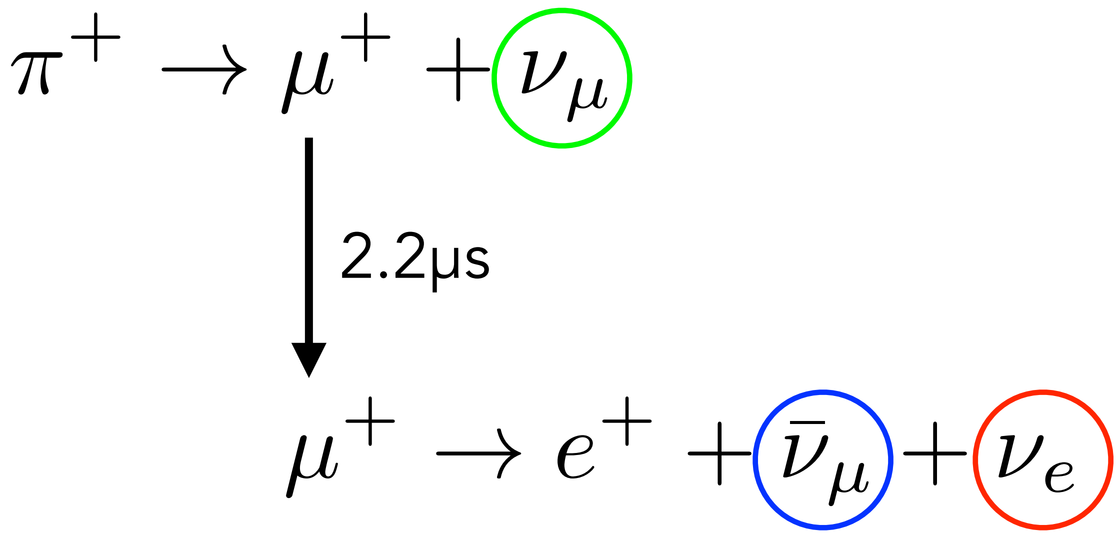
- coherent scattering observation and cross section precise measurement
- nuclear form factor precision measurement with weak interaction probes
- oscillation and sterile neutrino studies?

Source: SNS stopped pion neutrino source

- prompt muon nu from pion decay at rest
- delayed muon anti-nu and electron nu from muon decay at rest

PHYSICAL REVIEW D 73, 033005 (2006)





$$\pi^+ \rightarrow \mu^+ + \boxed{\nu_\mu}$$

2.2μs

$$\mu^+ \rightarrow e^+ + \boxed{\bar{\nu}_\mu} + \boxed{\nu_e}$$

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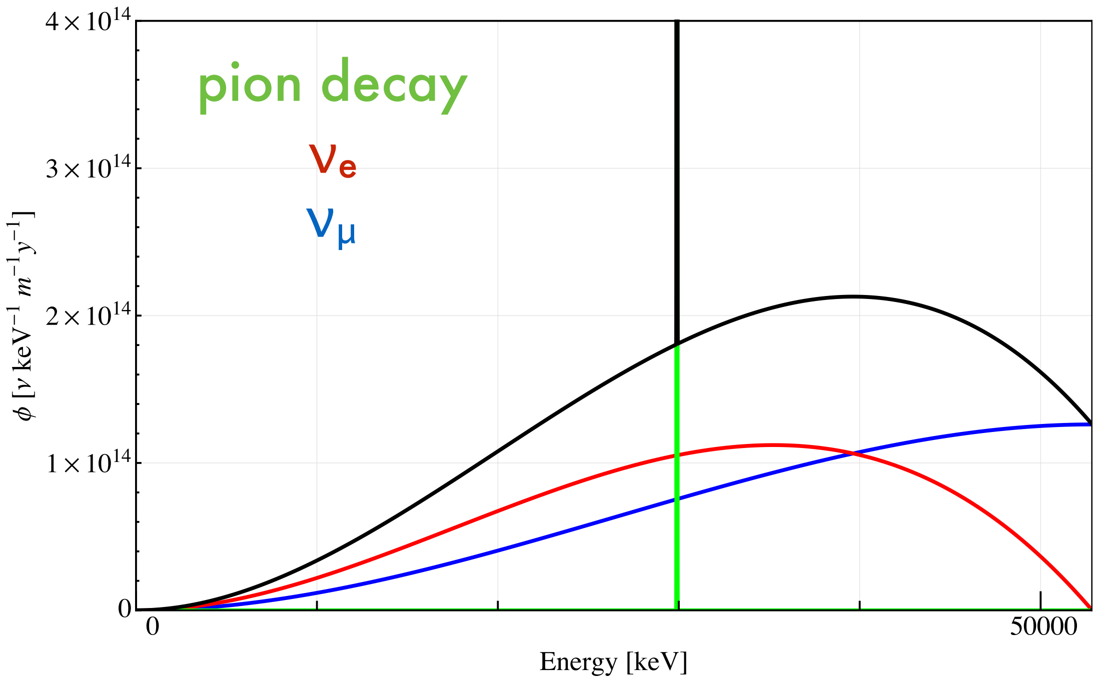
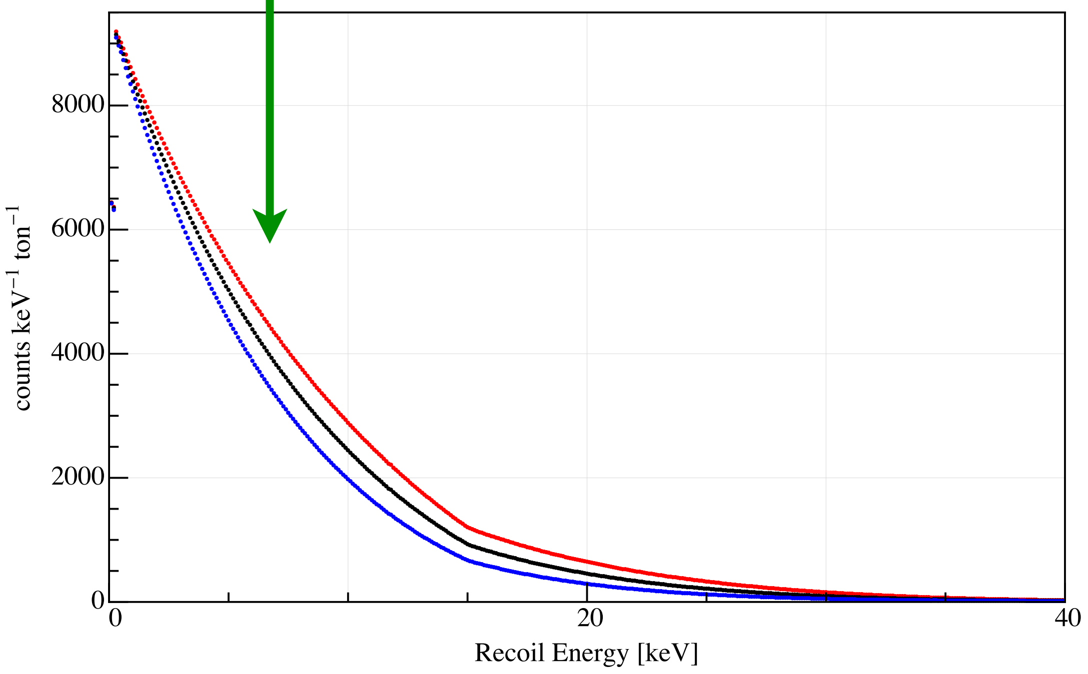
$$s = 0.5\text{fm}$$

±20%



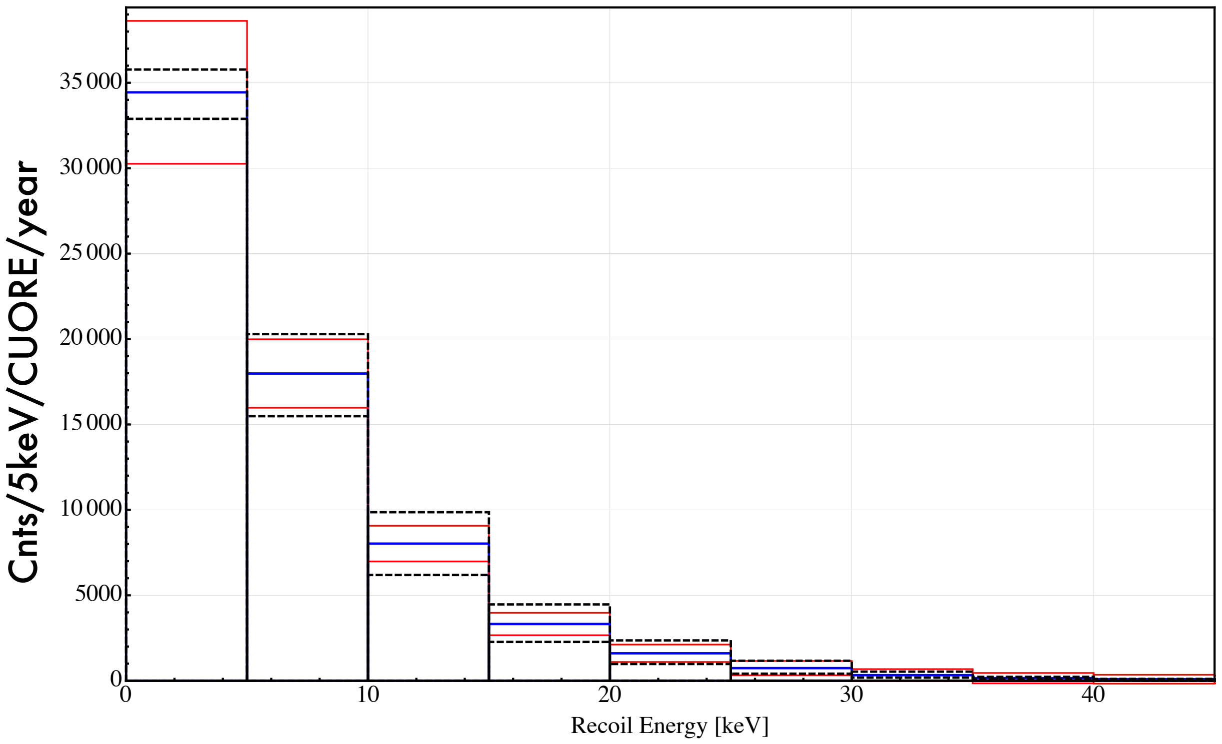


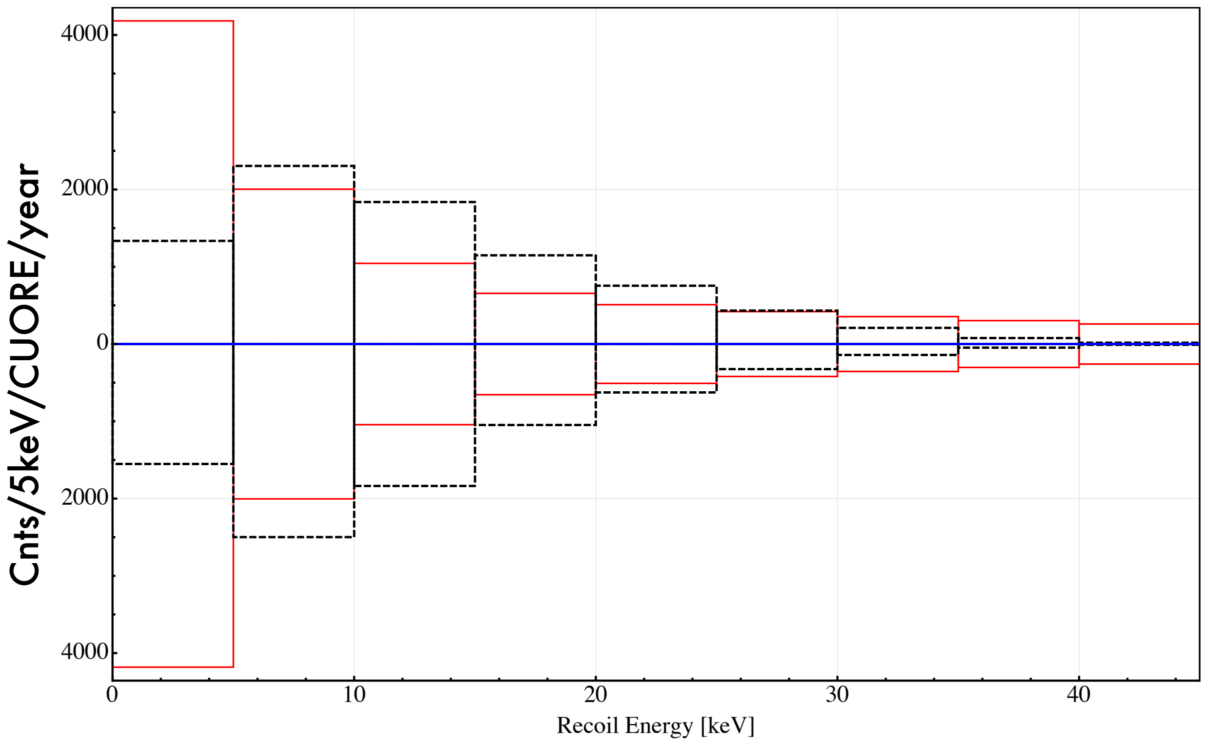
Source: Stopped pion source

EXAMPLE: CUORE experiment, 741 kg of TeO_2 thermal detectors
1 year data-taking, 20m from source

Recoil spectrum binned @5keV

expected number of events for standard form factor model
number of events for ±20% variation of R in the form factor
experimental uncertainty = source flux + statistical fluctuation





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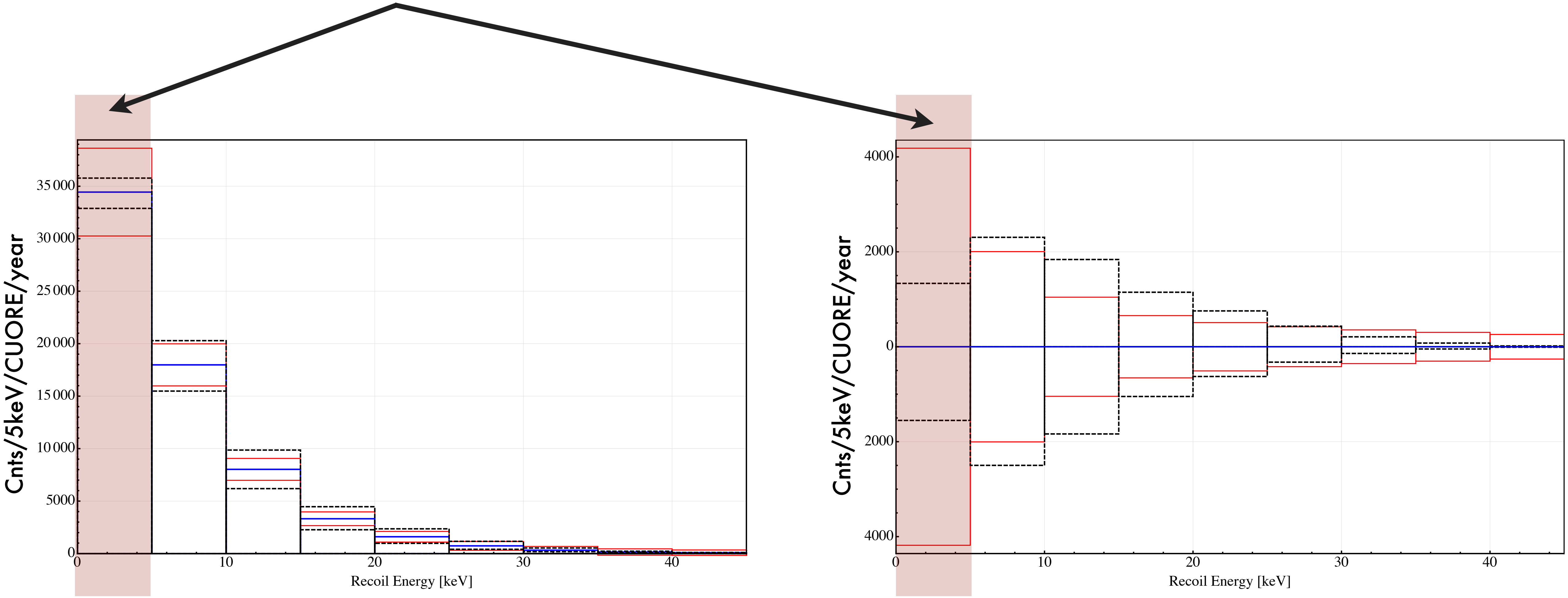
form factors converge to 1



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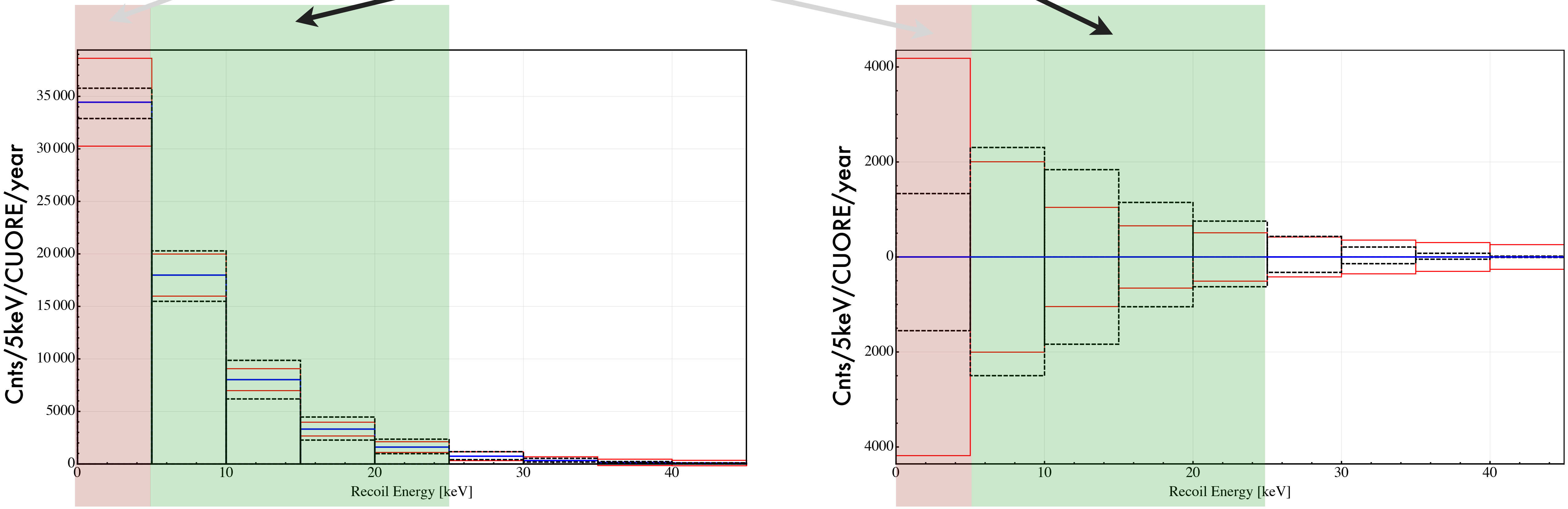
sensitive region



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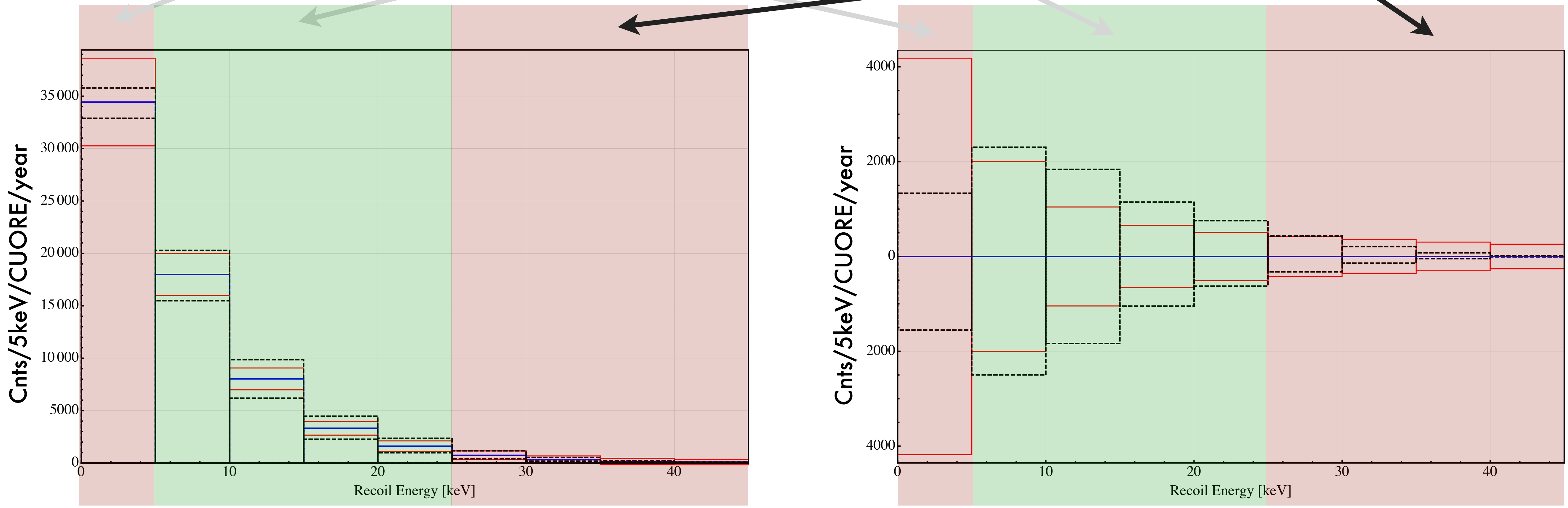
sensitive region

statistical fluctuations dominates



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Source: nuclear reactor

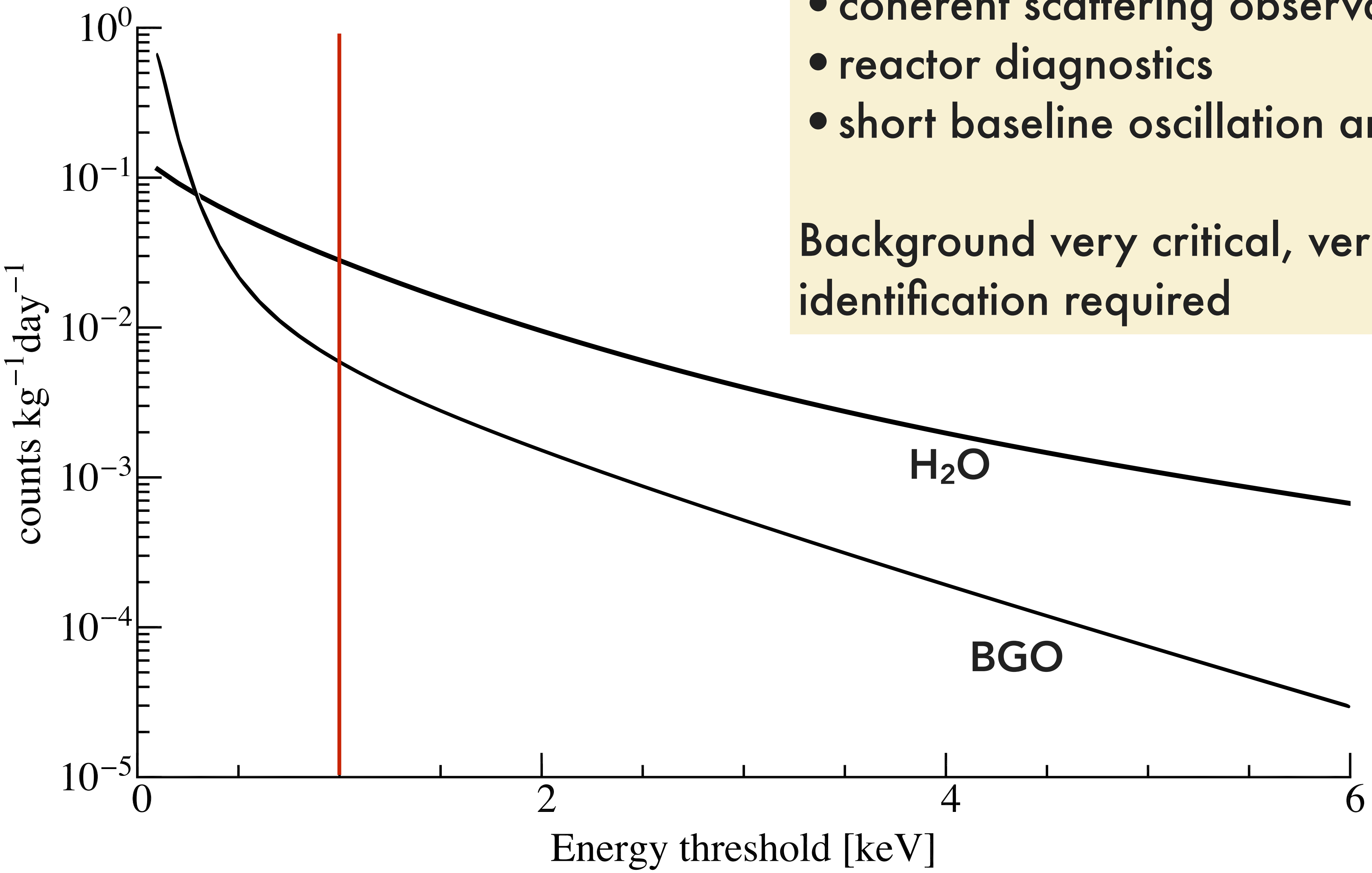
EXAMPLE: BGO and H_2O, 5 m from core

Simple approximation for neutrino fluxes: 250kW research reactor, 210MeV/fission, only ^{235}U

Possible physics outcome:

- coherent scattering observation with on/off source
- reactor diagnostics
- short baseline oscillation and sterile neutrino studies?

Background very critical, very effective particle identification required



@1keV threshold

BGO: ~6 cnts/day/ton

H_2O: ~30 cnts/day/ton

doi:10.1016/j.phpro.2012.02.465
http://arxiv.org/pdf/1212.1938.pdf

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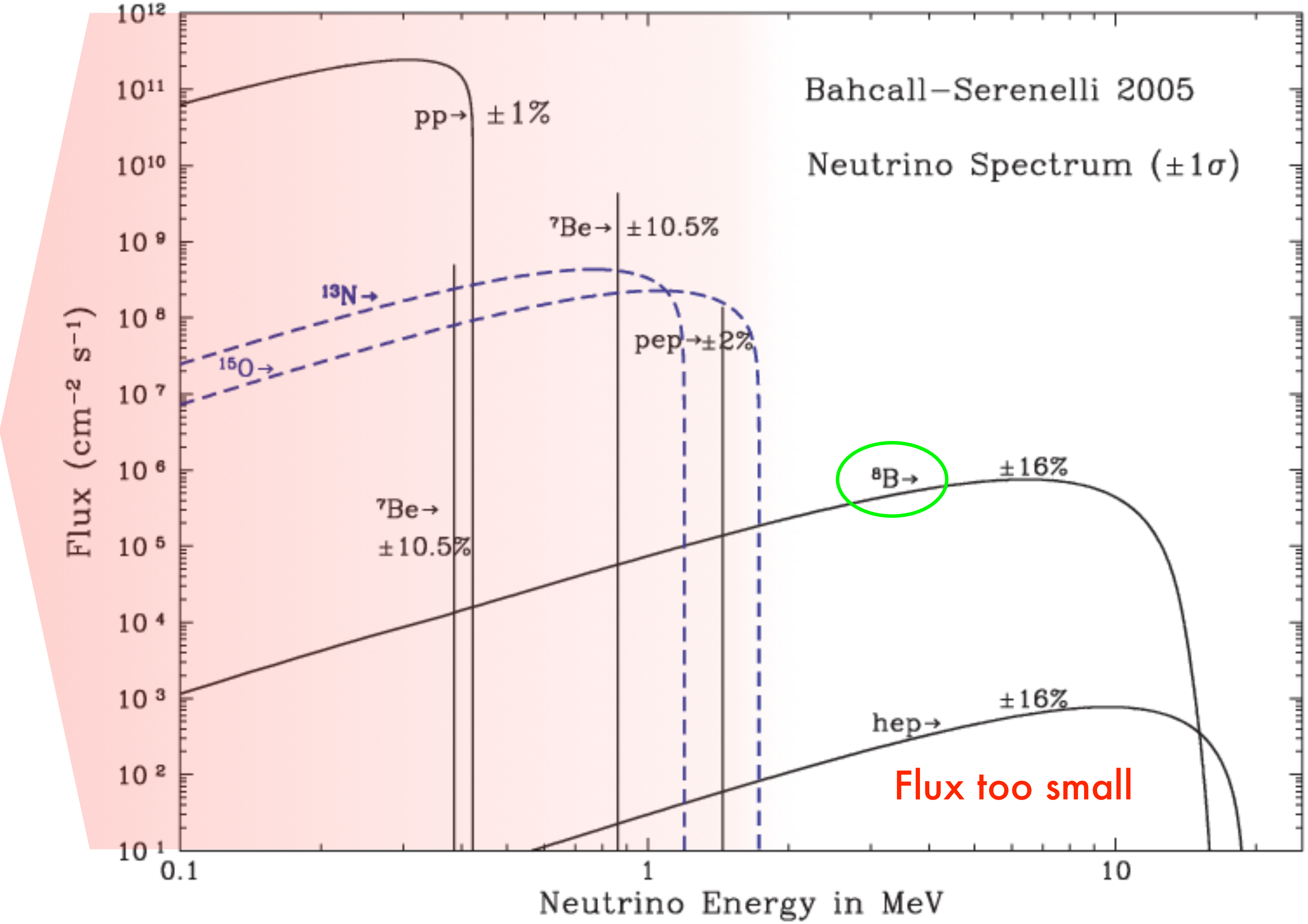
Source: ^{8}B solar flux

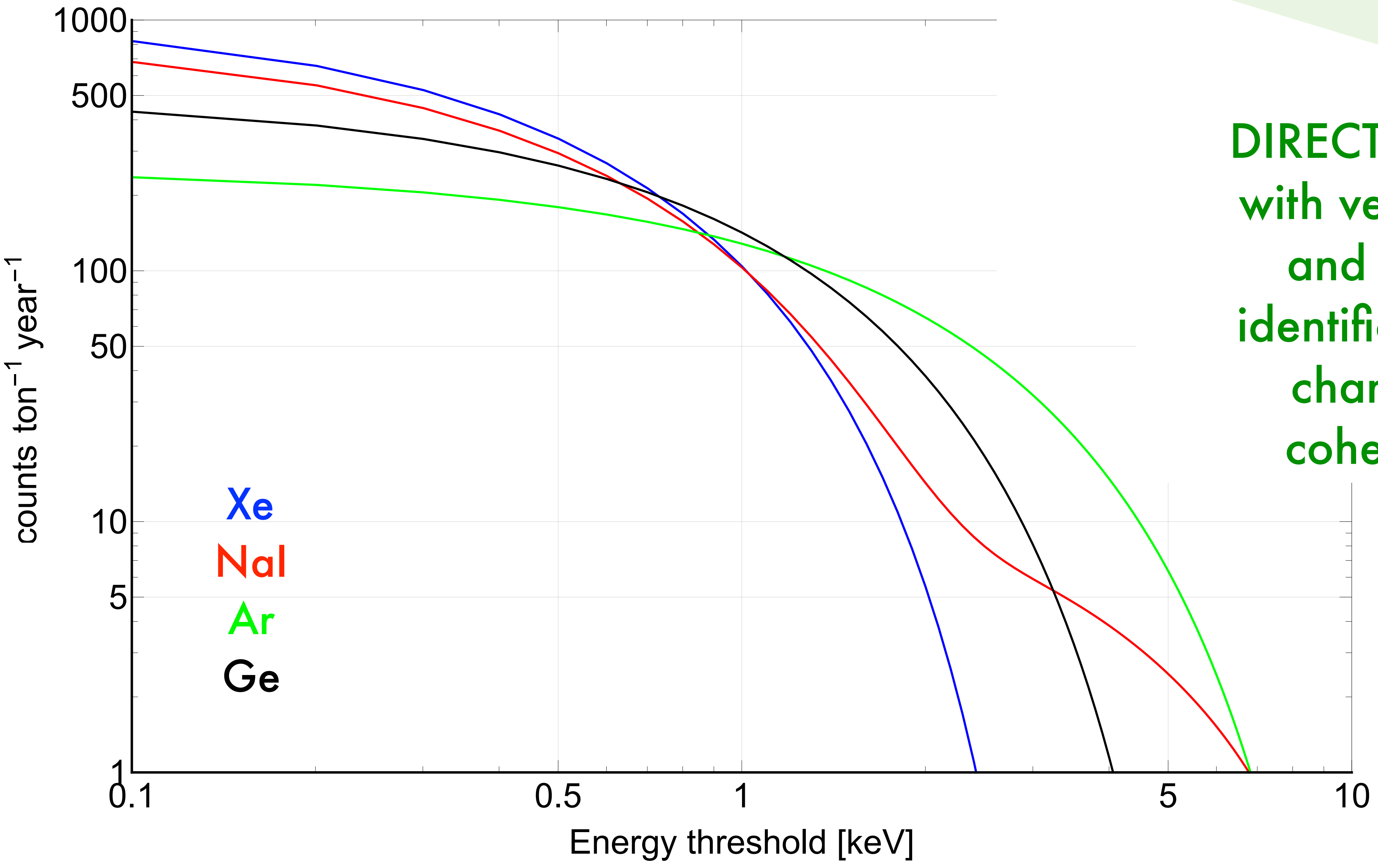
Solar neutrino fluxes from SSM: only detectable component is ^{8}B



Source: ^{8}B solar flux

Plug ^{8}B into events yield calculation…

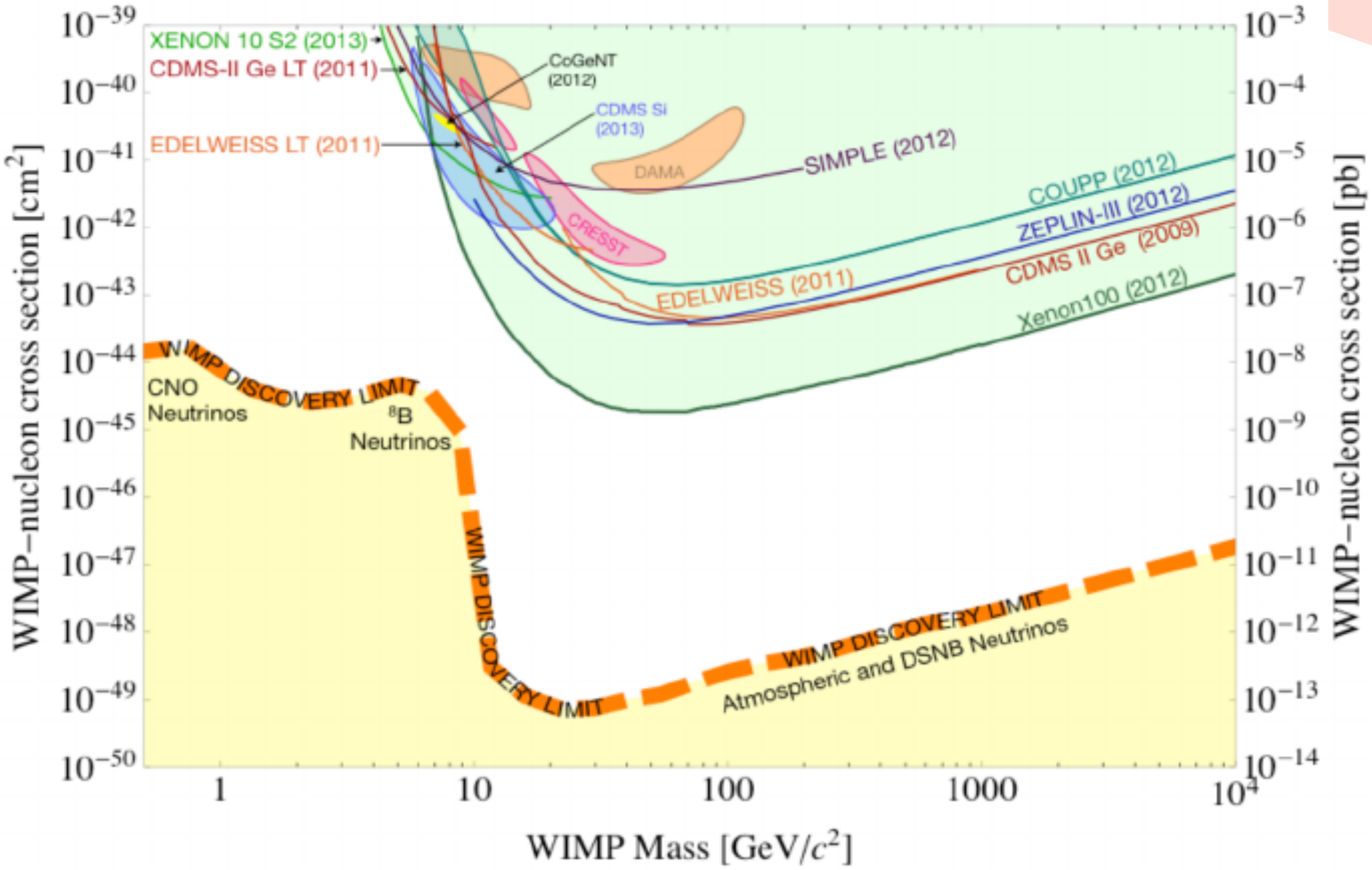
~1000 events with zero threshold
~100 events with 1keV threshold
strong directional signature



DIRECTIONAL detectors with very low threshold and nuclear recoil identification = first real chance to observe coherent scattering

Source: ^{8}B solar flux

But… Background for WIMPs direct detection?



- with zero threshold: $\sim 10^{-45}$ cm^2
- increasing threshold: exploit spectral shape to reject ^{8}B neutrinos **but** loose sensitivity for light WIMPs

DIRECTIONAL detectors allows for complete rejection

CONCLUSIONS

- Neutrino coherent scattering never observed
- Observation is a result by itself
- Can give insights into nuclear physics
- Election tool for “temperature” measure of SN neutrino emission
- Solar neutrinos from ^8B are both a possible interesting source and a background for WIMPs searches
- Any source with energies in the 10-50MeV range is a candidate
- Relatively small detectors are needed, but low energy (sub-keV) performance are critical
- Directional detection of nuclear recoils would be a breakthrough, allowing for a clear signal identification for all the considered sources

Exciting experimental challenge