Skirmishes on the LDM frontier

territorial disputes over the low-recoil region in direct detection

Josef Pradler

Johns Hopkins University

"Light Dark Matter"
University of Michigan
April 15, 2013

Outline

1. New feeble signals at the direct DM detection threshold
   “Claiming territory over the low recoil region”

   - Dark Photons => Haipeng An’s talk this morning

     1304.3461 (PLB)
     1302.3884
     with **Haipeng An** and **Maxim Pospelov**

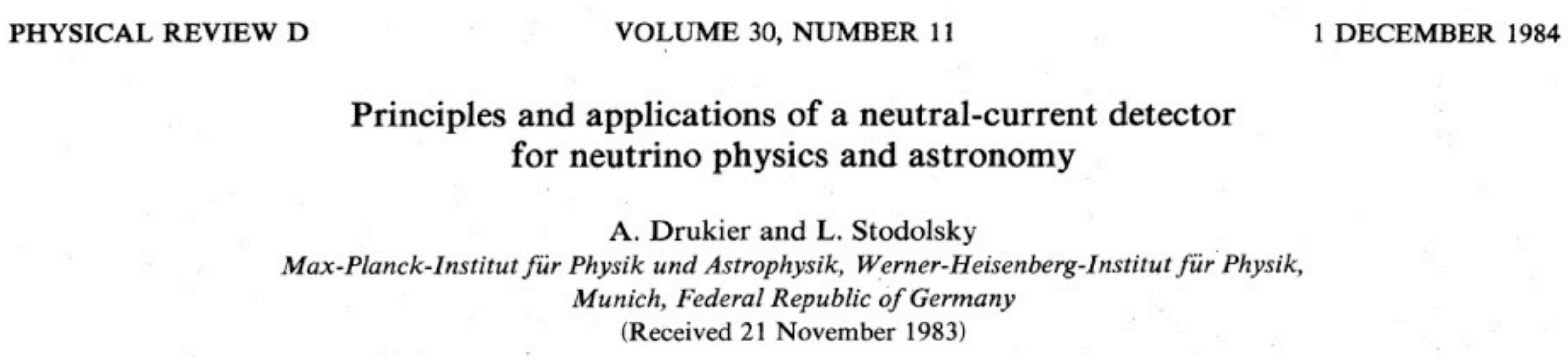
   - New neutrino signals in direct detection

     1203.0545 (PRD) with **Maxim Pospelov**

2. A critical look at DAMA’s Dark Matter claim

   1210.5501 (PLB) with **Balraj Singh** and **Itay Yavin**
   1210.7548 with **Itay Yavin**

A vision of a
true neutrino observatory



PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky

Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik,
Munich, Federal Republic of Germany

(Received 21 November 1983)

- superconducting grains in filler material in magnetic field
- at low temperatures specific heat ~ T^3

=> single scatter of neutrino can make grain conducting

=> magnetic field collapses, induces electric signal in detector

coherent neutrino-nucleus scattering

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{8\pi} G_F^2 E_\nu^2 \left[Z(4\sin^2\theta_W - 1) + N \right]^2 (1+\cos\theta)$$

- coherent enhancement N^2 for MeV-scale neutrinos from

  => spallation sources, supernovae, reactors, sun, earth
- cross section grows quadratically with neutrino energy
- helicity conservation forbids back-scattering

coherent neutrino-nucleus scattering

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{8\pi} G_F^2 E_\nu^2 \left[Z(4\sin^2\theta_W - 1) + N \right]^2 (1 + \cos\theta)$$

- coherent enhancement N^2 for MeV-scale neutrinos from

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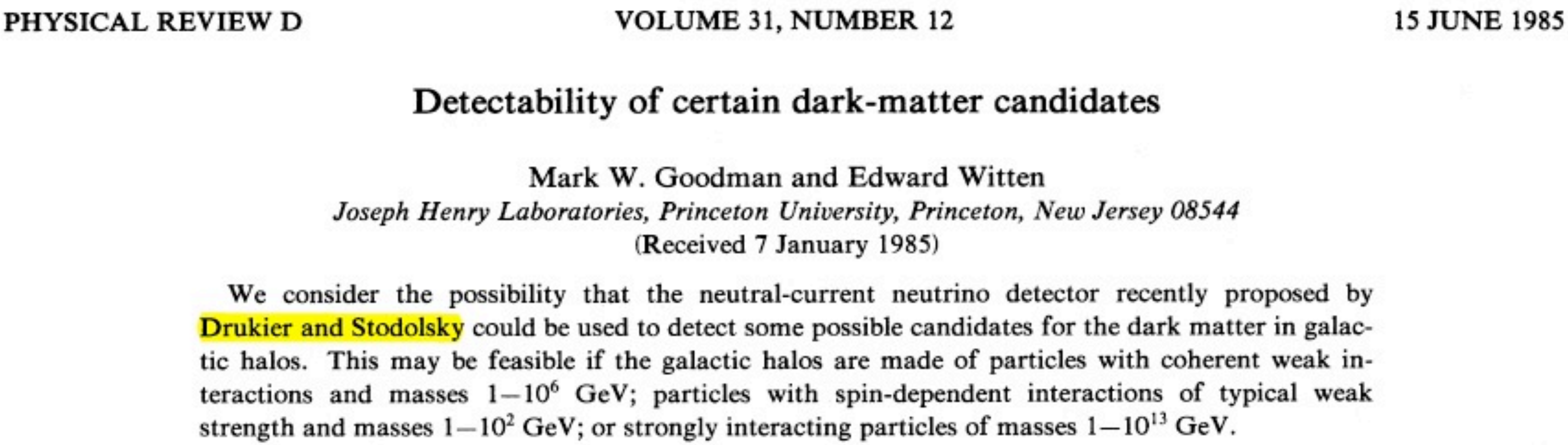
- cross section grows quadratically with neutrino energy
- helicity conservation forbids back-scattering

(this process has not yet been observed)

=> direct DM detection

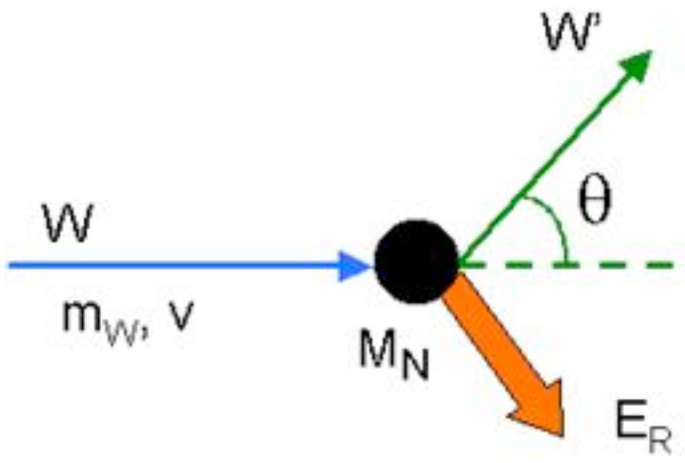


PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

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)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

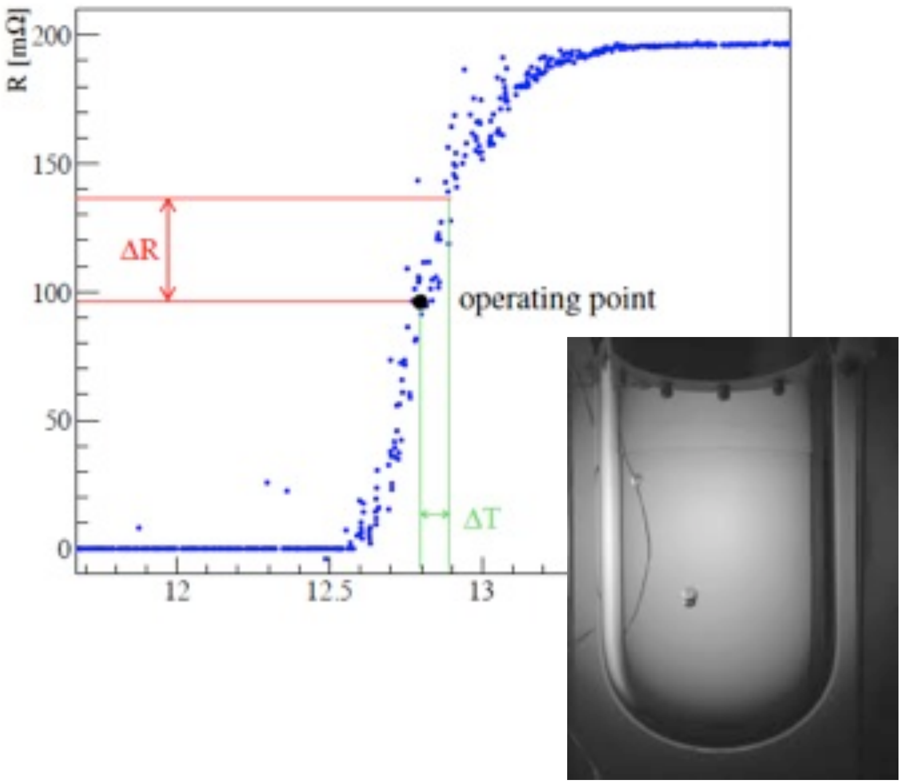


E_R ~ keV

Witten 1985

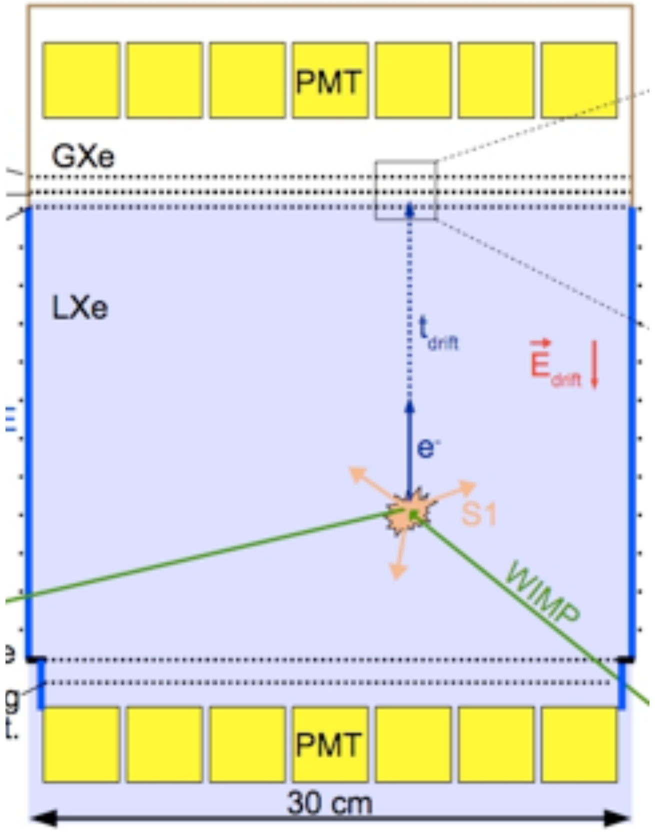
=> direct DM detection

- nuclear recoil can be picked up in various channels:



heat

scintillation



ionization

WIMPs vs. solar neutrinos

- flux

$$\Phi_{DM} = \frac{\rho_0 v}{m_{DM}} \sim 10^5\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \left(\frac{100\,\mathrm{GeV}}{m_{DM}}\right)$$

$$\Phi_{pp} = 6 \times 10^{10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$\Phi_{^8\mathrm{B}} = 6 \times 10^{6}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

- cross section

$$\sigma = 10^{-44}\,\mathrm{cm}^2 \times \sigma_{44} A^2 \left(\frac{\mu_N}{\mu_n}\right)^2$$

$$\sigma \simeq 10^{-44}\,\mathrm{cm}^2 \times N^2 \left(\frac{E_\nu}{1\,\mathrm{MeV}}\right)^2$$

- recoil

$$E_R^{\max} = \frac{(2\mu_N v)^2}{2m_N} \sim \begin{cases} 20\,\mathrm{keV}\left(\frac{A}{20}\right) \\ \qquad (m_N \ll m_{DM}) \\ 4\,\mathrm{keV}\left(\frac{m_{DM}}{20\,\mathrm{GeV}}\right)^2\left(\frac{100}{A}\right) \\ \qquad (m_{DM} \ll m_N) \end{cases}$$

$$E_R^{\max} = \frac{(2E_\nu)^2}{2m_N}$$

$$\sim 0.1\,\mathrm{keV}\left(\frac{20}{A}\right)\left(\frac{E_\nu}{1\,\mathrm{MeV}}\right)^2$$

“baryonic” neutrinos ν_b

M. Pospelov PRD 2011

- introduce new left-handed neutrino species ν_b together with gauged $U(1)_b$
- ν_b couples to quarks, but not to leptons
- breaking of $U(1)_b$ gives new gauge field V_μ mass

$$\mathcal{L}_B = \overline{\nu}_b \gamma^\mu (i\partial_\mu - g_l q_b V_\mu)\nu_b - \frac{1}{3} g_b \sum_q \bar{q}\gamma^\mu q V_\mu - \frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu + \mathcal{L}_m.$$

ν_b — sterile under SM-gauge group

ν_b — active under $U(1)_b$

“baryonic” neutrinos ν_b

M. Pospelov PRD 2011

- for $Q^2 \ll m_V^2$ effective Lagrangian reads

$$\mathcal{L}_{\rm eff} = -G_B j^\mu_{NCB} \sum_{N=n,p} \overline{N}\gamma_\mu N, \qquad G_B = q_b \frac{g_b g_l}{m_V^2}$$

$$j^\mu_{NCB} = \overline{\nu}_b \gamma^\mu \nu_b$$

- measure interaction strength in units of G_F :

$$\mathcal{N} = \frac{|G_B|}{G_F} \simeq 100 \times \left(\frac{3\,\mathrm{GeV}}{m_V}\right)^2 \left(\frac{g_l g_b}{10^{-2}}\right)$$

“baryonic” neutrinos ν_b

M. Pospelov PRD 2011

- **crucial insight:**

$$\frac{\sigma_{\nu_b N}(\text{elastic})}{\sigma_{\nu_b N}(\text{inelastic})} \sim \frac{A^2}{E_\nu^4 R_N^4} \sim \mathcal{O}(10^8)$$

this ratio makes direct detection
experiments competitive with large scale neutrino experiments

- For solar flux, deuteron breakup in SNO does not constrain scenario

direct detection of solar ν_b

like SM-neutrinos with $G_F^2 (N/2)^2 \to G_B^2 A^2$

$$\frac{dR(t)}{dE_R} = N_T \left[\frac{L_0}{L(t)}\right]^2 \sum_i \Phi_i \int_{E_\nu^{\min}} dE_\nu \, \frac{df_i}{dE_\nu} \frac{d\sigma}{dE_R} P_b(t, E_\nu)$$

appearance probability

overall flux
modulation

average over
neutrino spectrum i

$$L(t) = L_0 \left\{ 1 - \epsilon \cos\left[\frac{2\pi(t - t_0)}{1\,\mathrm{yr}}\right]\right\}$$

$$L_0 = 1\,\mathrm{AU}$$

$$t_0 \simeq 3\ \mathrm{Jan}\ \ (\mathrm{perihelion})$$

$$\epsilon = 0.0167\ \ (\mathrm{eccentricity})$$

direct detection of ν_b

$$\frac{dR(t)}{dE_R} = N_T \left[\frac{L_0}{L(t)}\right]^2 \sum_i \Phi_i \int_{E_\nu^{\mathrm{min}}} dE_\nu \, \frac{df_i}{dE_\nu} \frac{d\sigma}{dE_R} P_b(t, E_\nu)$$

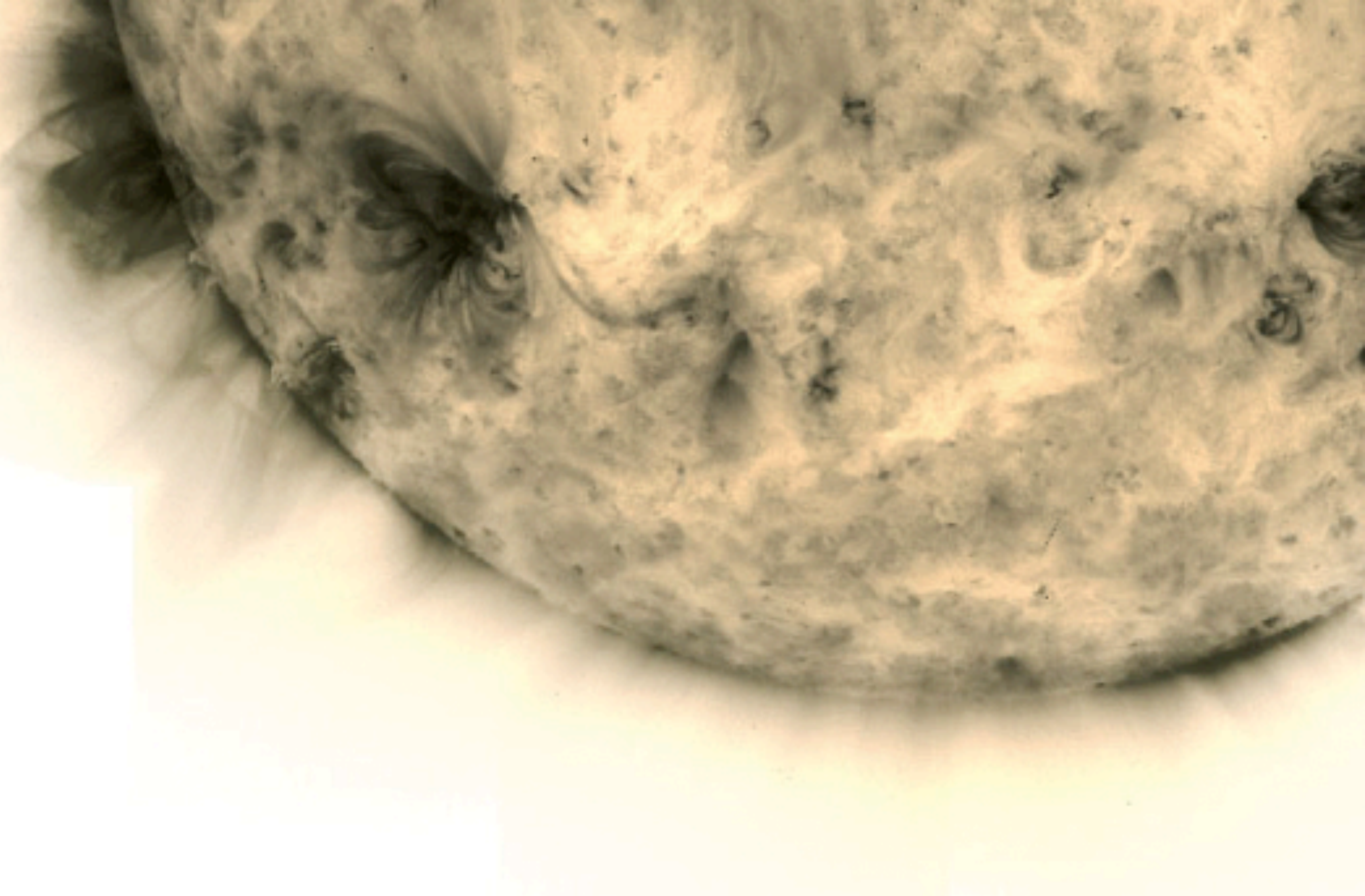
more modulation here

$$\frac{L_{\mathrm{osc}}}{L_0} \simeq 0.5 \times \left(\frac{10^{-10}\,\mathrm{eV}}{\Delta m^2}\right) \left(\frac{E_\nu}{10\,\mathrm{MeV}}\right)$$

oscillation-length on the order sun-earth distance

=> **flip phase** for high energy part of the neutrino spectrum? **explain DAMA**?

Appearance probability



- considering small values in Δm_b^2 standard solar story unfolds

$$P_b(\text{earth}) \simeq \sin^2(2\theta_b)\sin^2\left[\frac{\Delta m_b^2 L(t)}{4E}\right]$$

(from a tribimaximal ansatz assuming mixing to ν_2)

[see also arXiv:1103.3261]

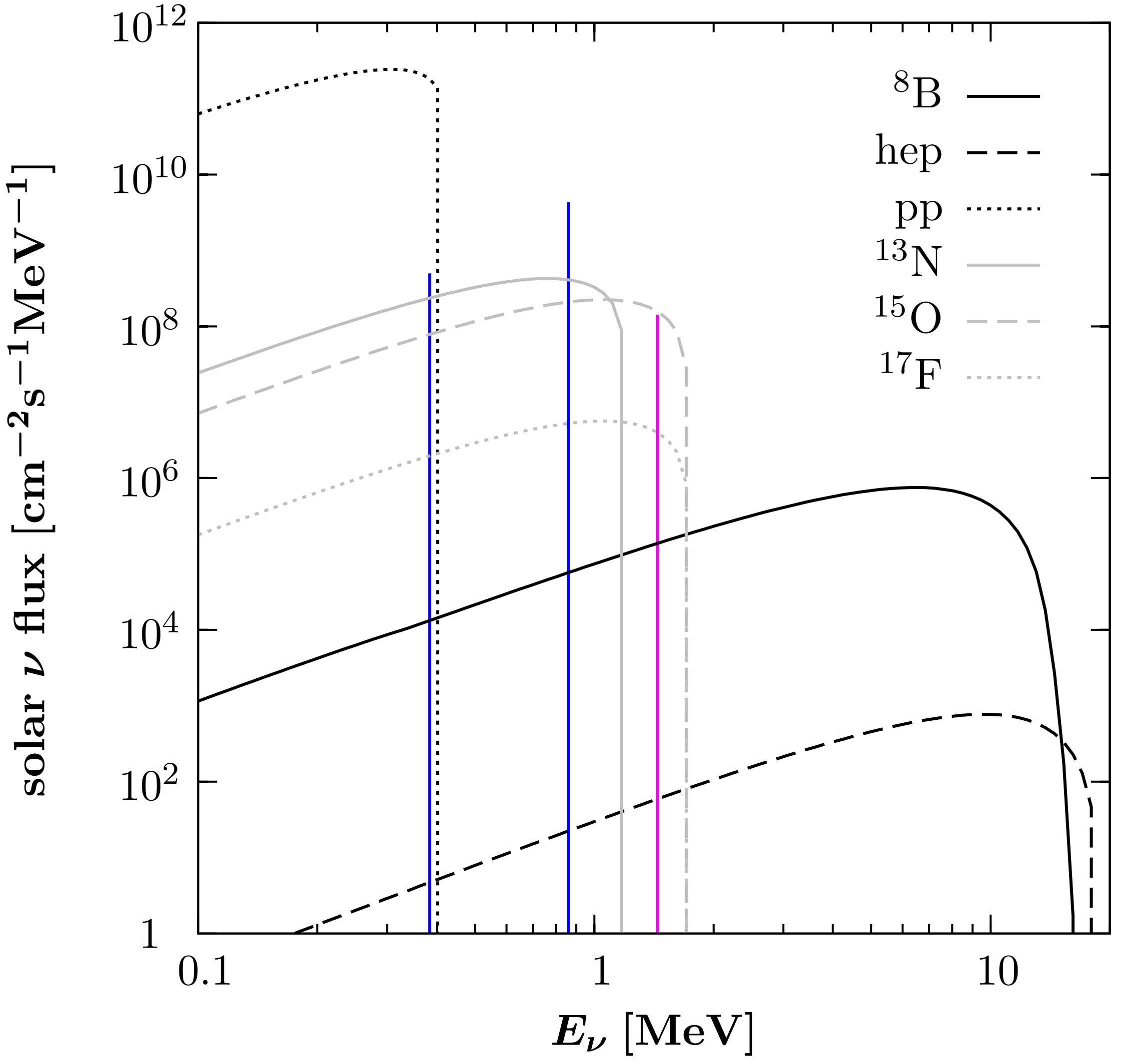
$$\Big\downarrow$$

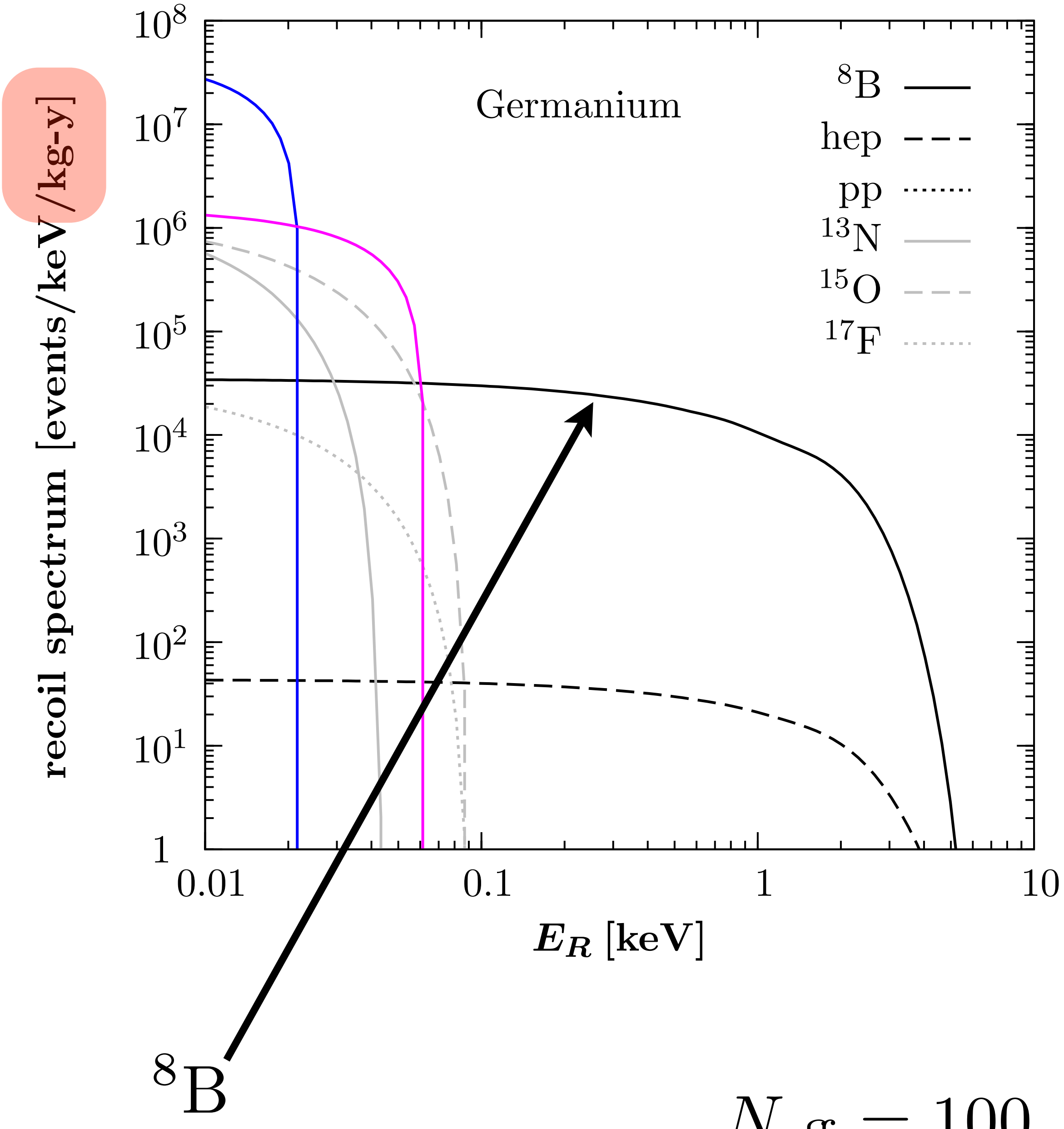
$$\mathcal{N}_{\text{eff}}^2 \equiv \frac{\mathcal{N}^2}{2} \times \sin^2 2\theta_b$$

=> for fast oscillations $P_b G_B^2 \to \mathcal{N}_{\text{eff}}^2 G_F^2$

direct detection of ν_b

$A_{\mathrm{Ge}} = 70 - 76$

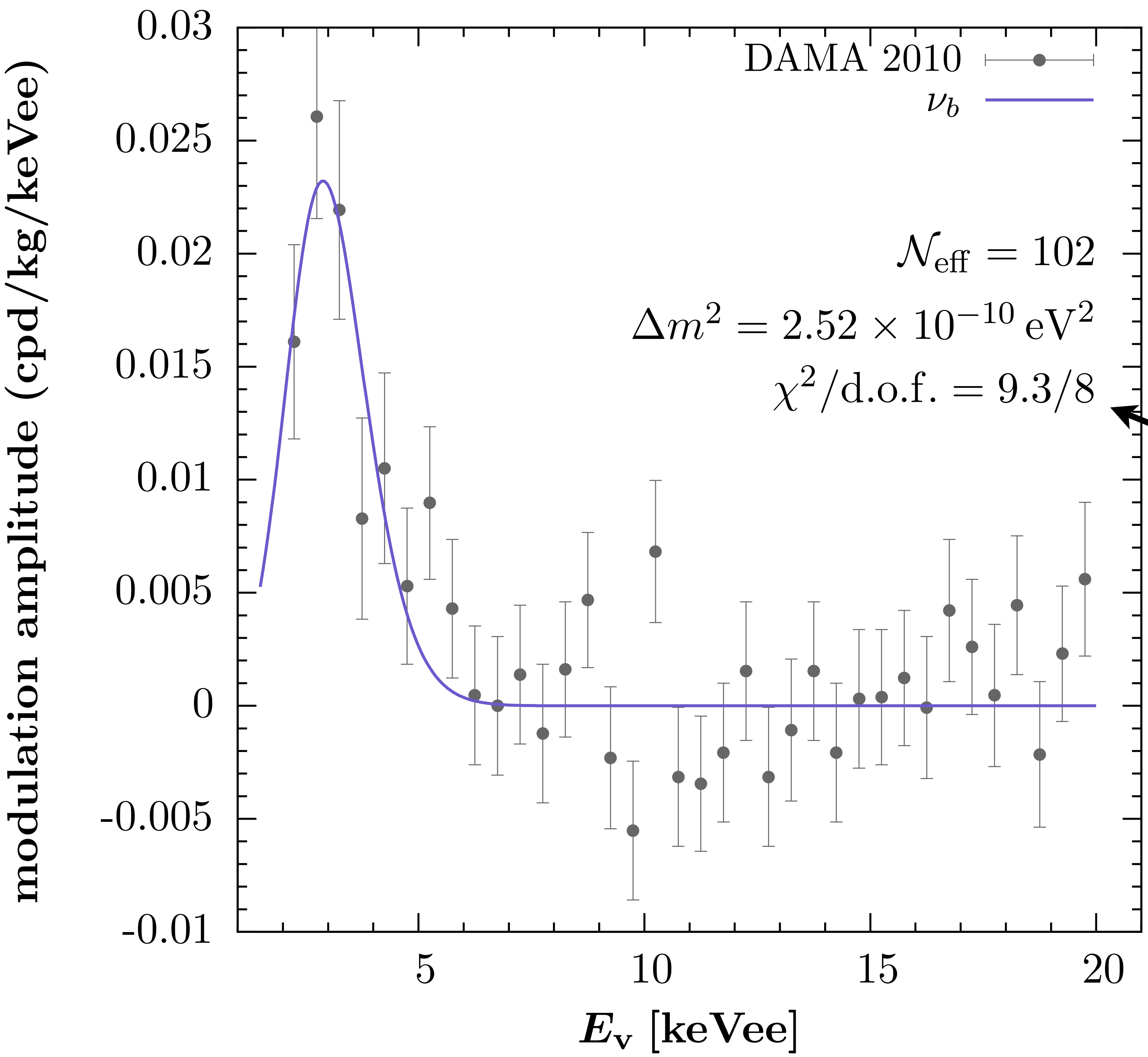




$N_{\mathrm{eff}} = 100$

DAMA

modulation amplitude



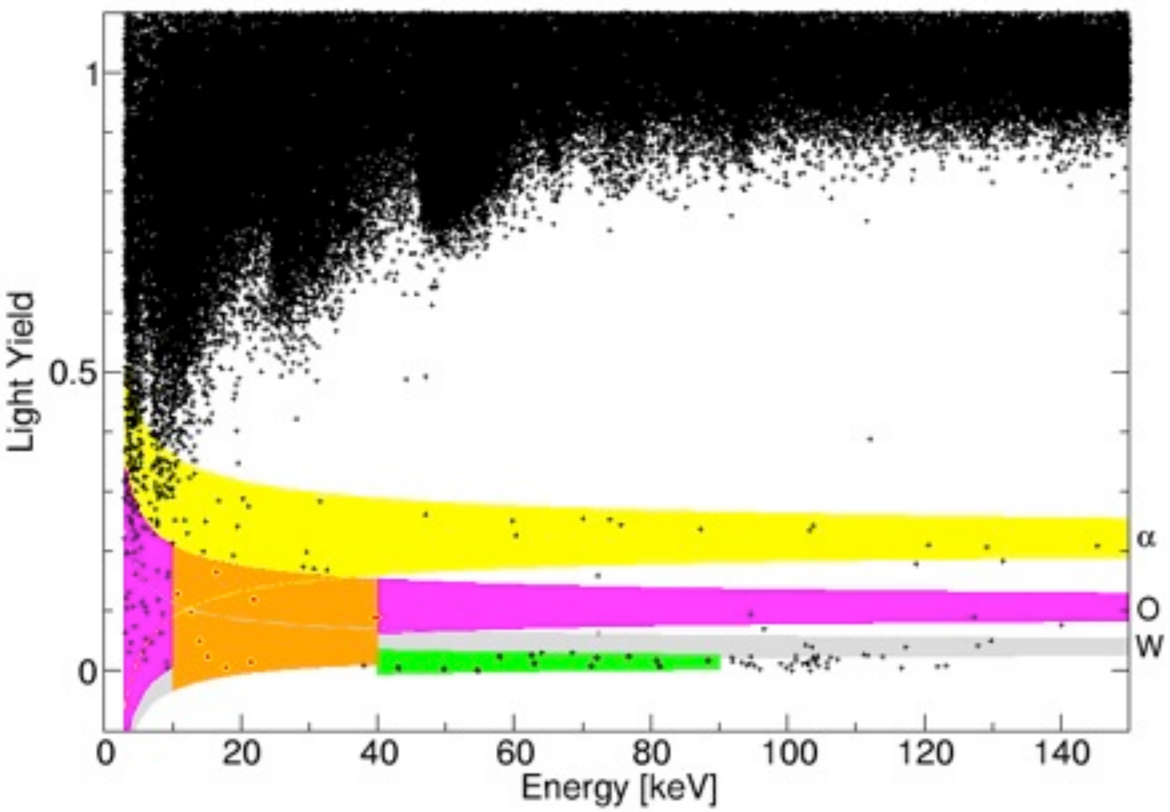
fit only first 10 bins

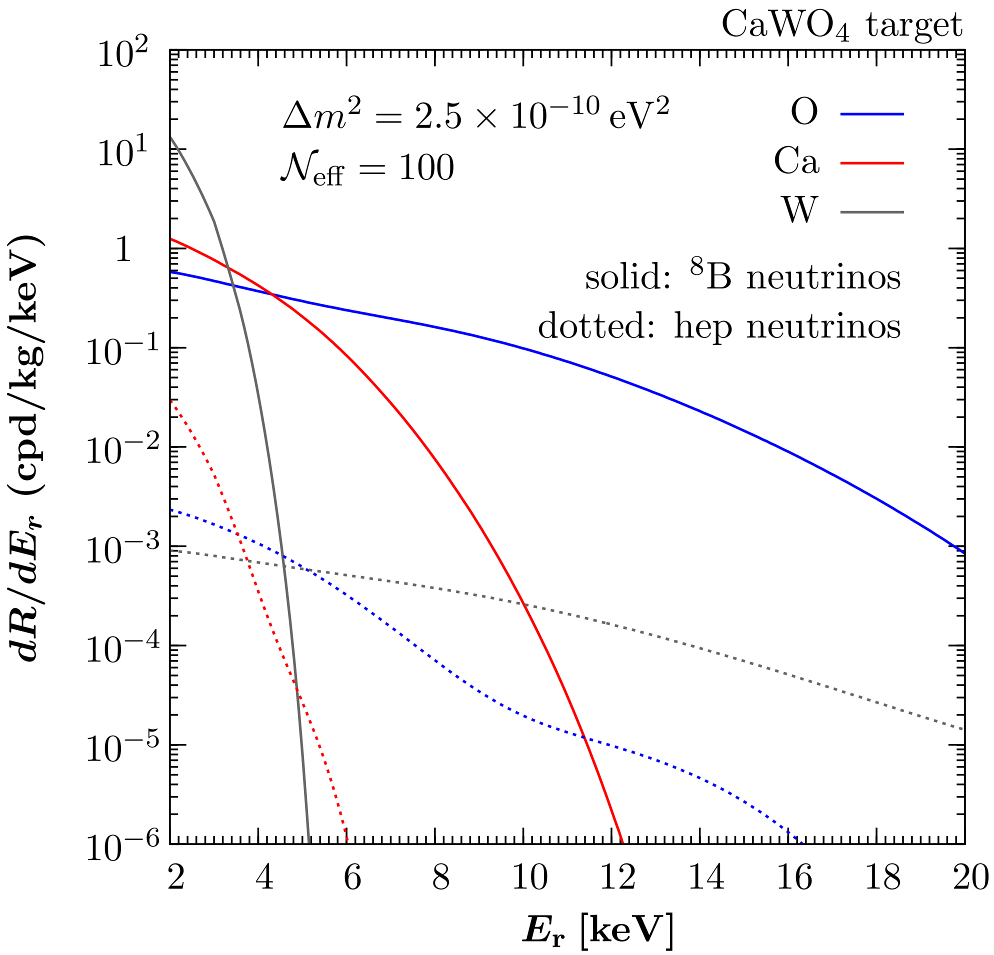
CRESST-II

signal

Angloher et al EPJC 2012

- 8 $CaWO_4$ crystals, measure scintillation light and phonons from nuclear recoil
- in a nutshell: 67 events in acceptance region - half of which are attributed to backgrounds



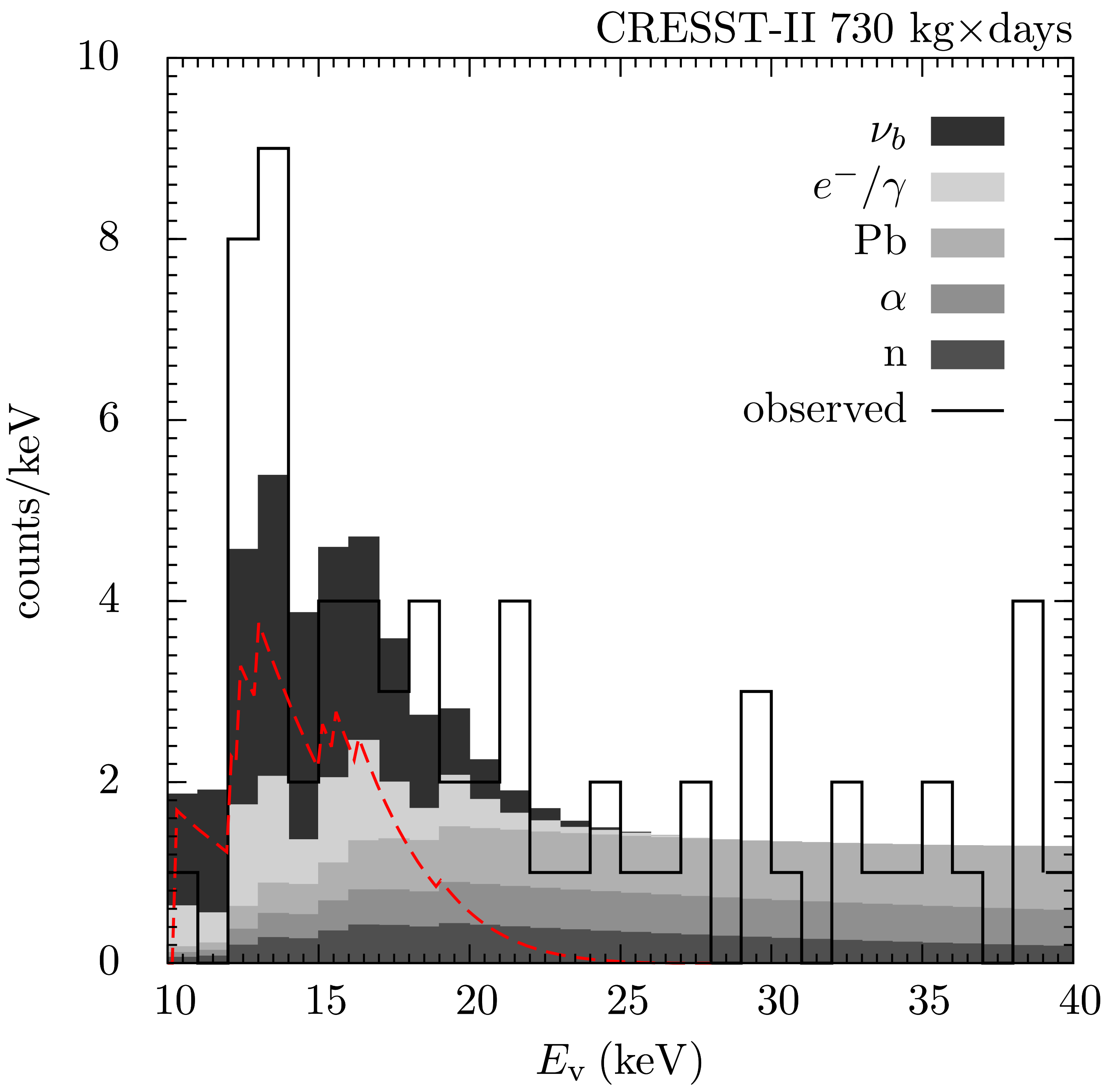


CRESST-II

fits

- we follow CRESST in their modeling of backgrounds

  => e/gamma events known
  => other bkg. essentially flat



CRESST-II

fits

- we follow CRESST in their modeling of backgrounds

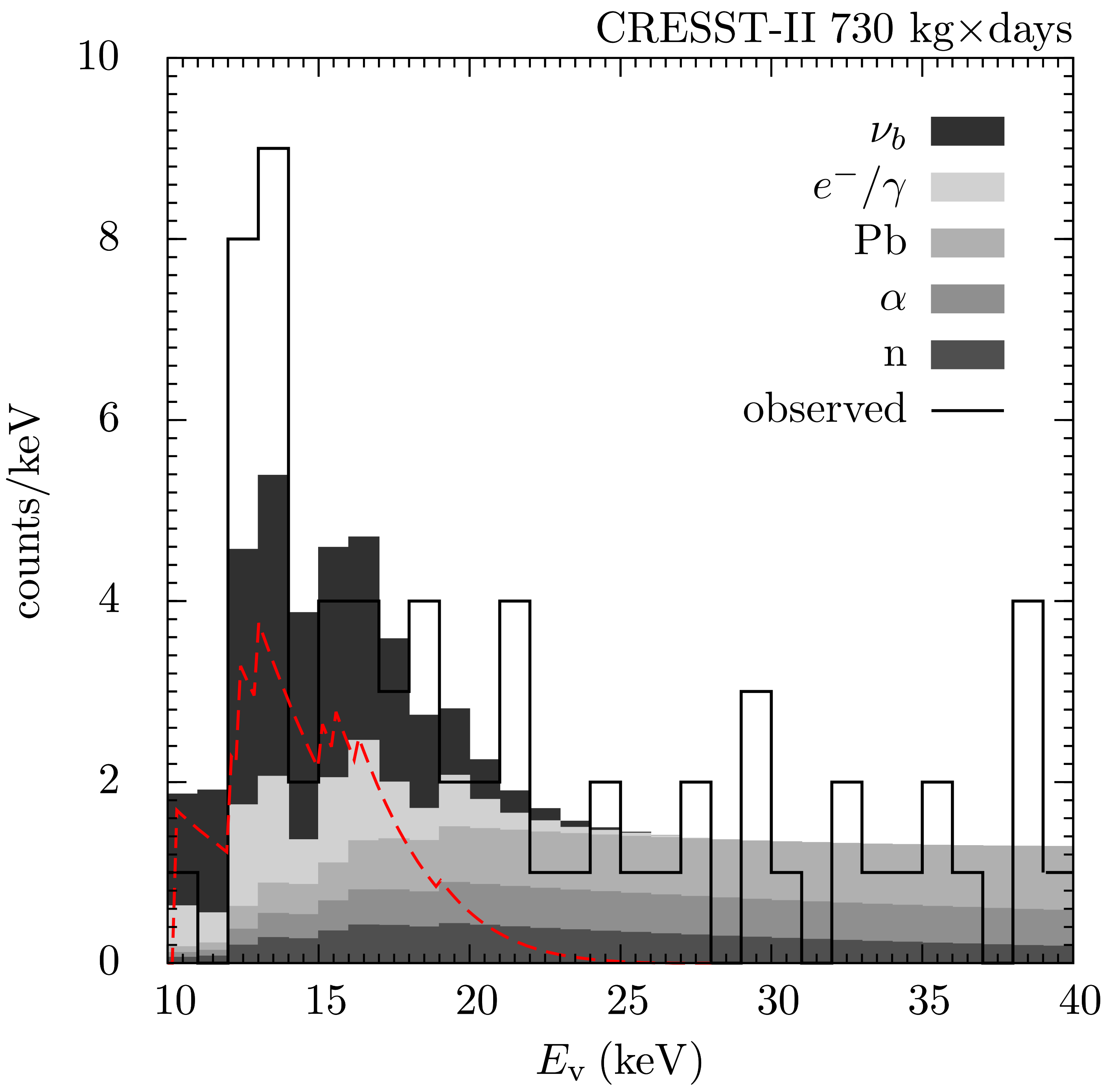
  => e/gamma events known
  => other bkg. essentially flat

- use Poisson log-Likelihood to fit ν_b

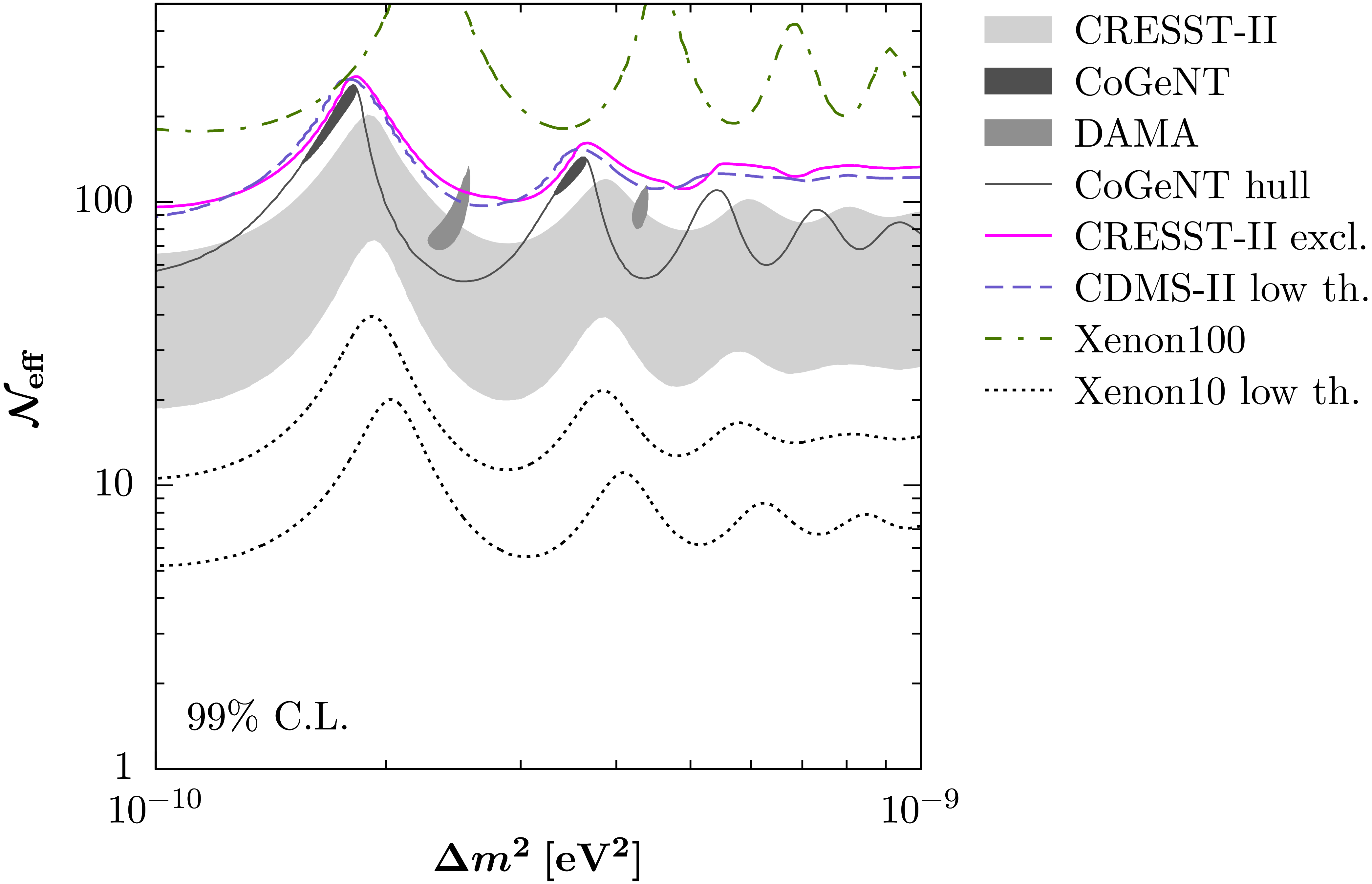
$$\chi_P^2 = 2\sum_i \left[y_i - n_i + n_i \ln\left(\frac{n_i}{y_i}\right)\right]$$

- best fit yields

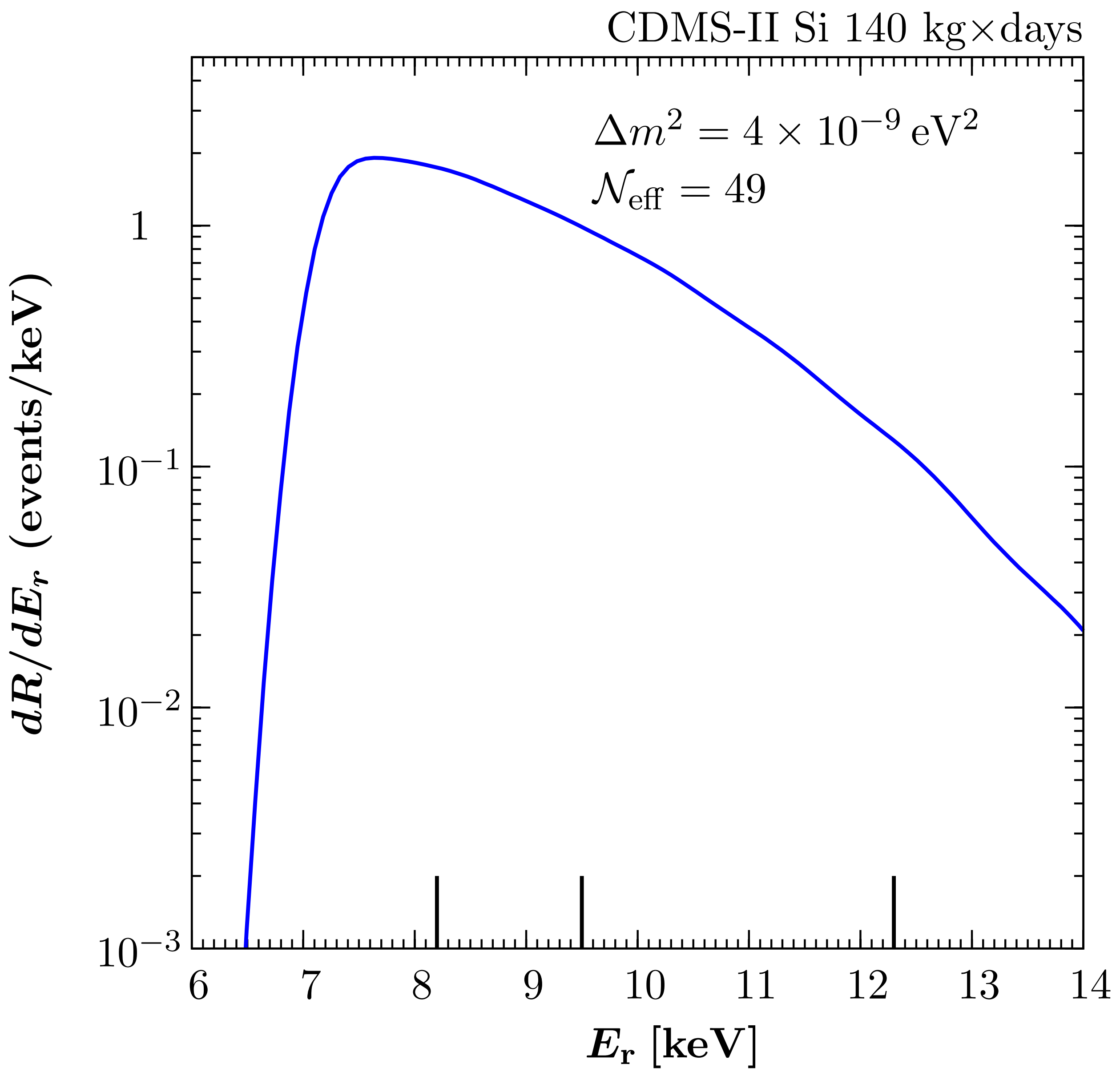
$\chi_P^2/\mathrm{d.o.f.} = 27.8/28$ (recoil spectrum only)

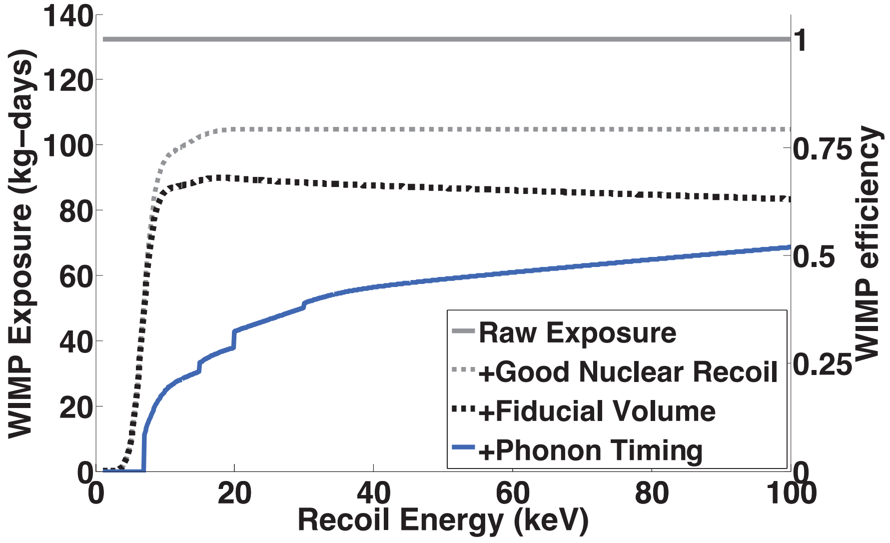


direct detection experiments as neutrino$_b$ observatories



reg CDMS-II Si as of today

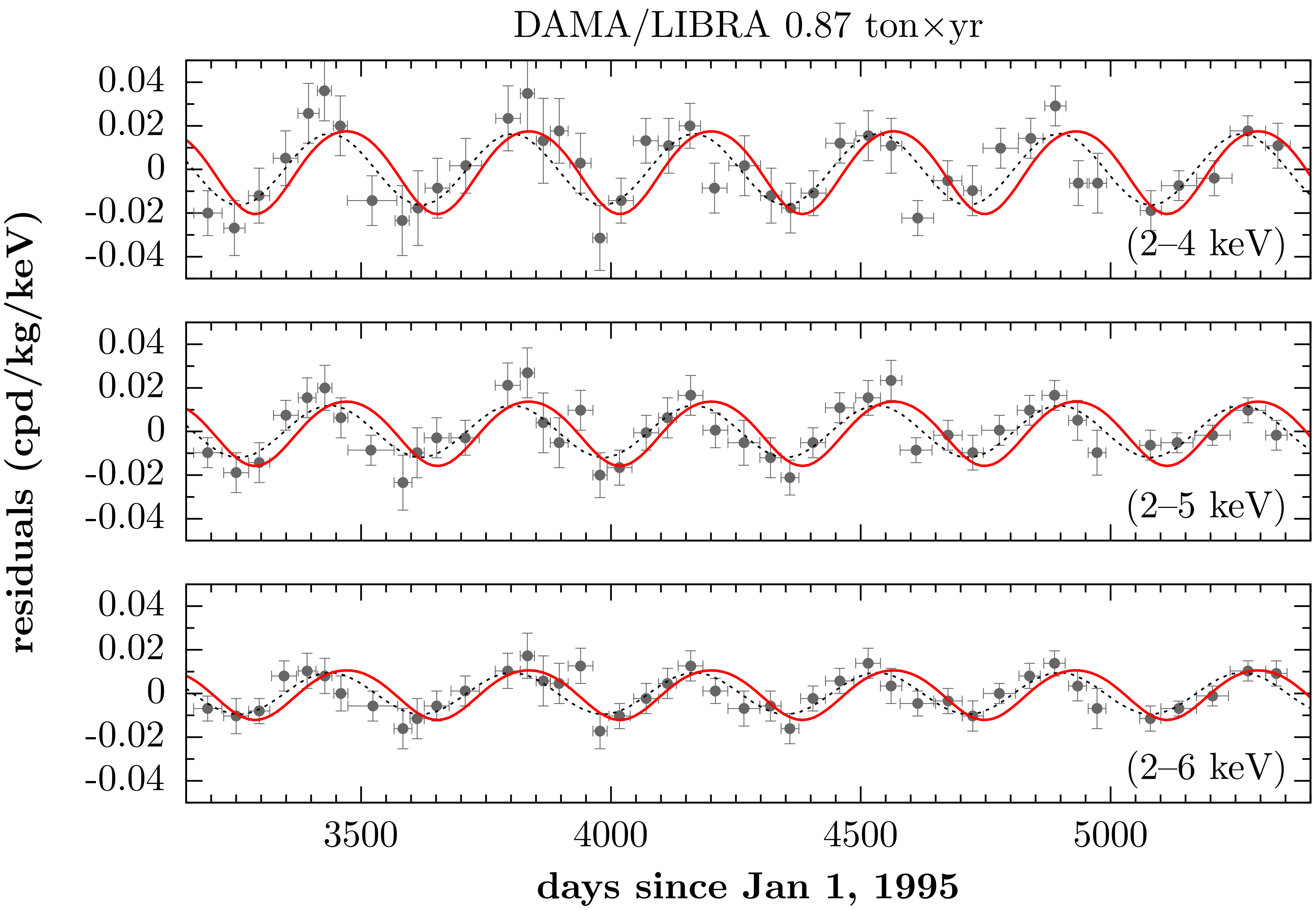




Agnese et al. 2013

DAMA

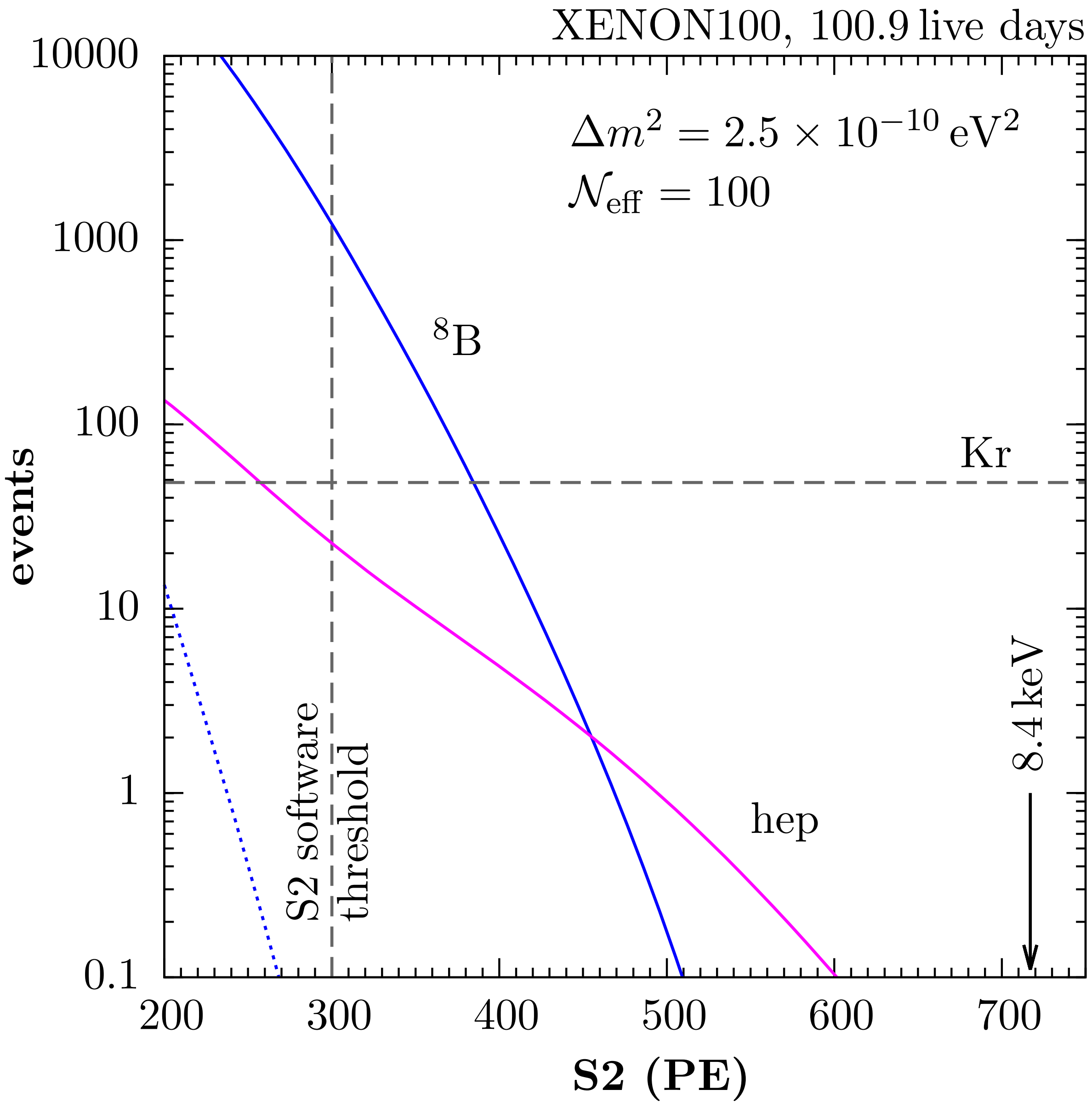
time series



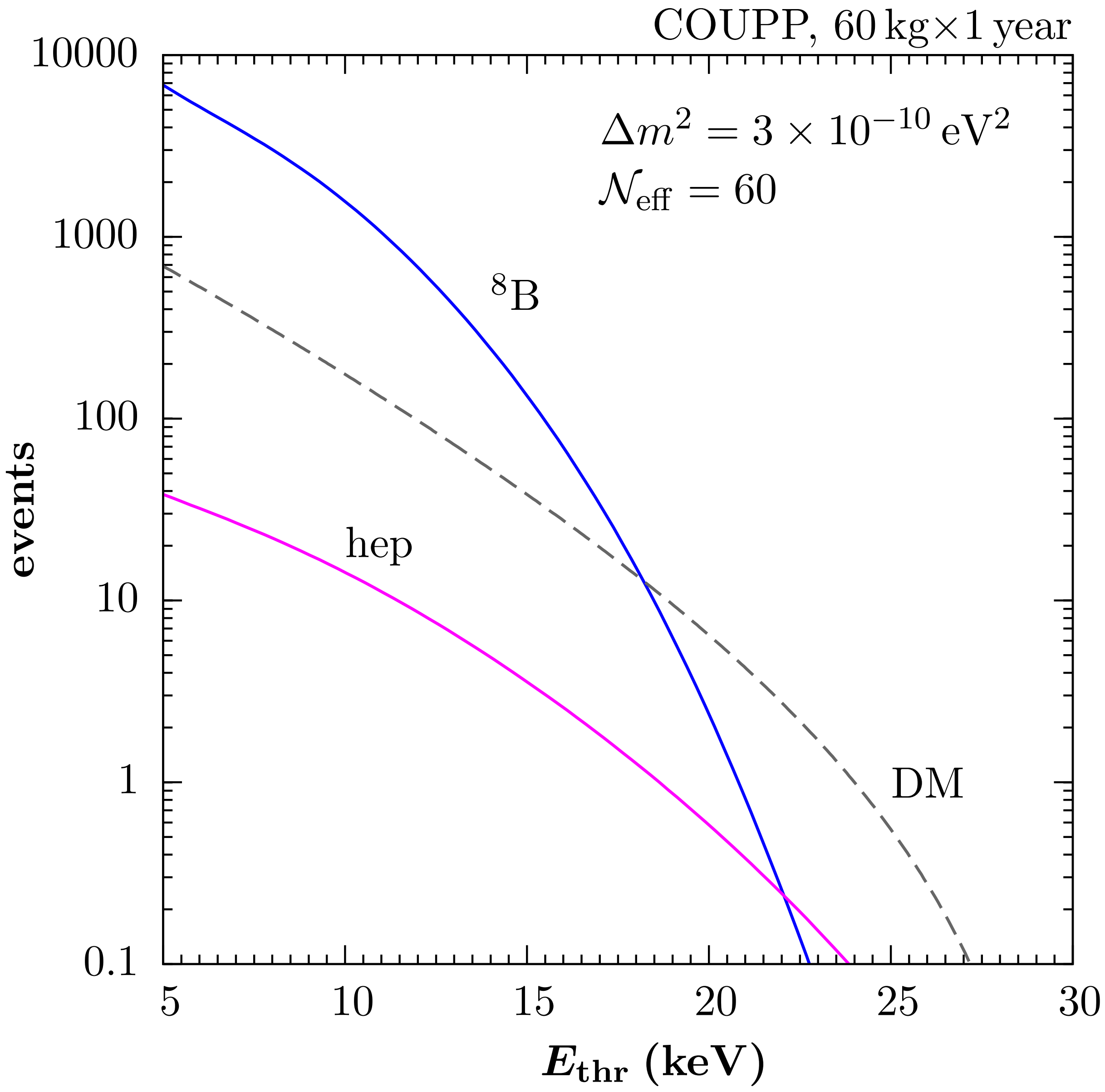
phase off by one month! :(

Outlook

direct detection



prediction for Xenon100
low-threshold analysis



prediction for COUPP
bubble chamber (CF_3I)

Outlook

direct detection

- even lighter targets (He) are even better! Neutrinos give more recoil than WIMPs (χ)

$$\frac{E_R^{\max}(\nu)}{E_R^{\max}(\chi)} = \frac{E_\nu^2}{v^2 \mu_\chi^2} \simeq 25 \times \left(\frac{E_\nu}{10\,\mathrm{MeV}}\right)^2 \left(\frac{4\,\mathrm{GeV}}{\mu_\chi}\right)^2$$

- directional detection

$\frac{dR}{d\cos\theta_N}$ has strongest "A_{FB}"

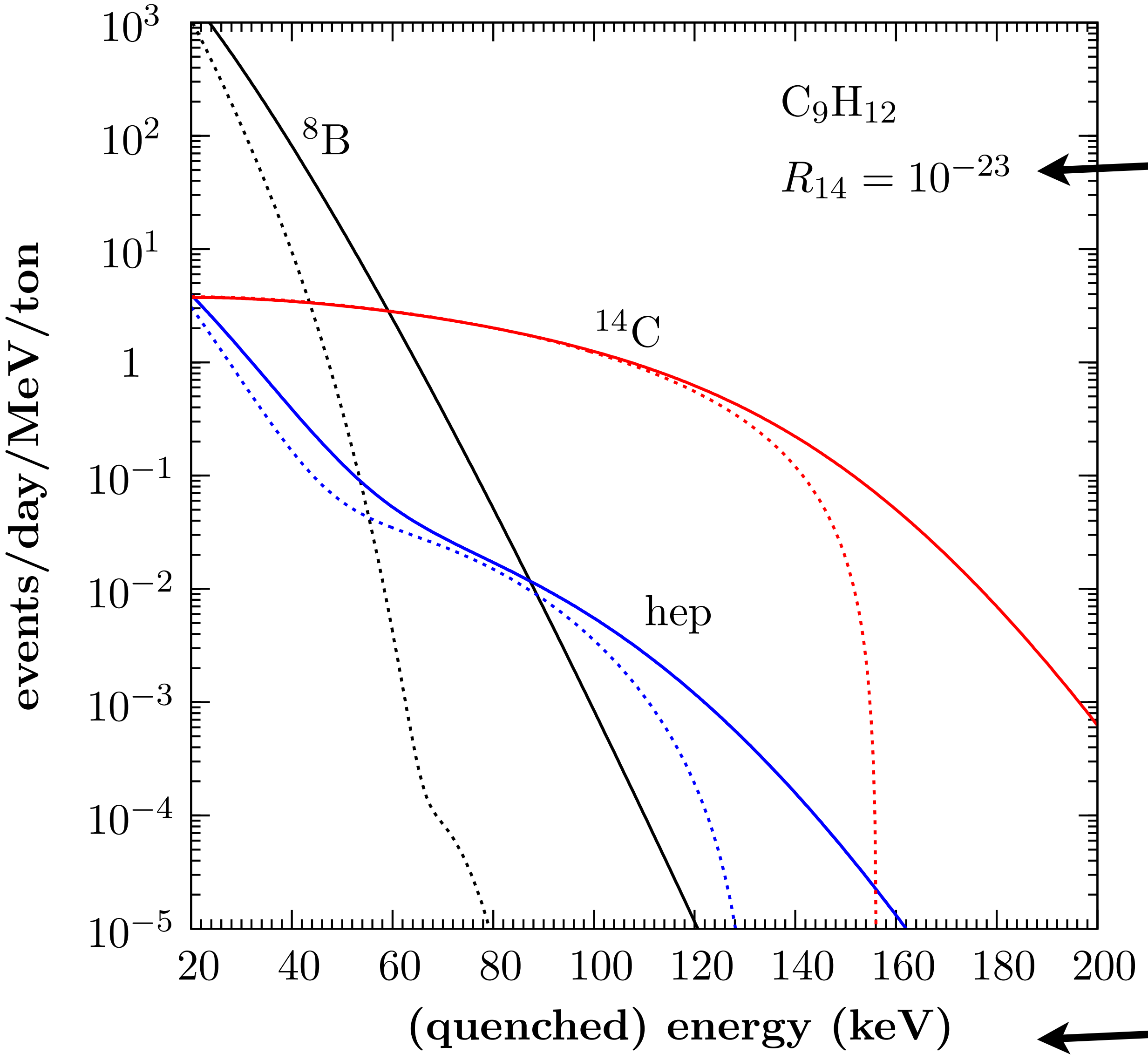
in direction $\mathbf{v}_{\mathrm{avg}}(\chi)$ (WIMPs)

in direction of sun (neutrinos)

Outlook

solar neutrino experiments

- elastic scattering off scintillating mineral oil with ultra-pure setups



Borexino has C14 contamination of 10^{-18}

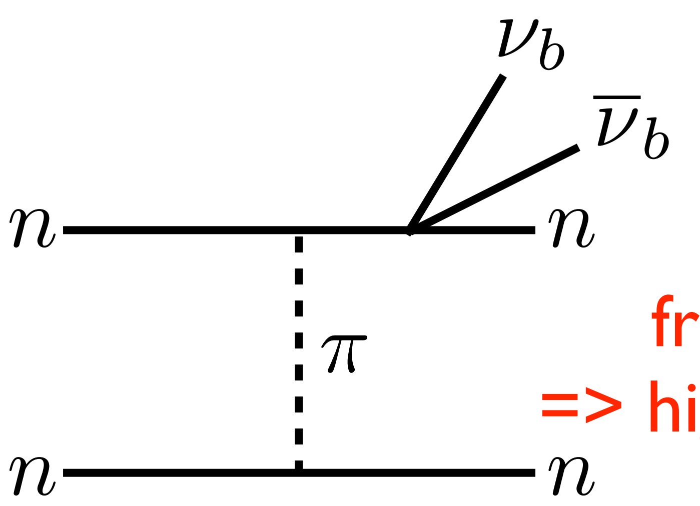
mainly proton recoils

Outlook

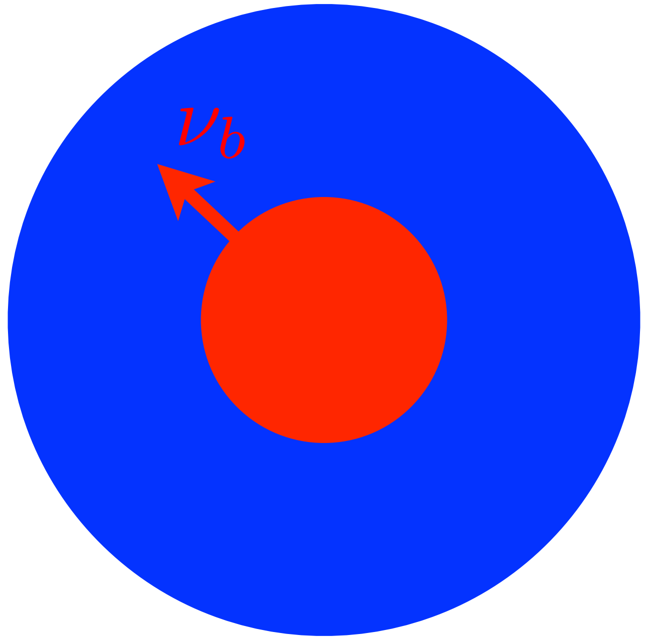
with Liang Dai (JHU)

astrophysical signatures

- supernovae production of ν_b => signal in direct detection possible?



freezes out quickly
=> high initial T spectrum!



insulating scattering sphere

- may affect dynamics of explosions
- sensitivity to truly tiny mass splittings over cosmological distances
- Neff = ?

Part II

apropos DAMA

DAMA signal interpretation
in the presence of backgrounds

observed modulation amplitude $S_m \simeq 0.02\,\mathrm{cpd/kg/keV}$

$$s_m^{\mathrm{obs}} = \frac{S_m}{R} = \frac{S_m}{B + S_0} \simeq 2\%$$

$$S = S_0 + S_m \cos\omega(t - t_0)$$

the higher the background, the stronger the signal must be modulated

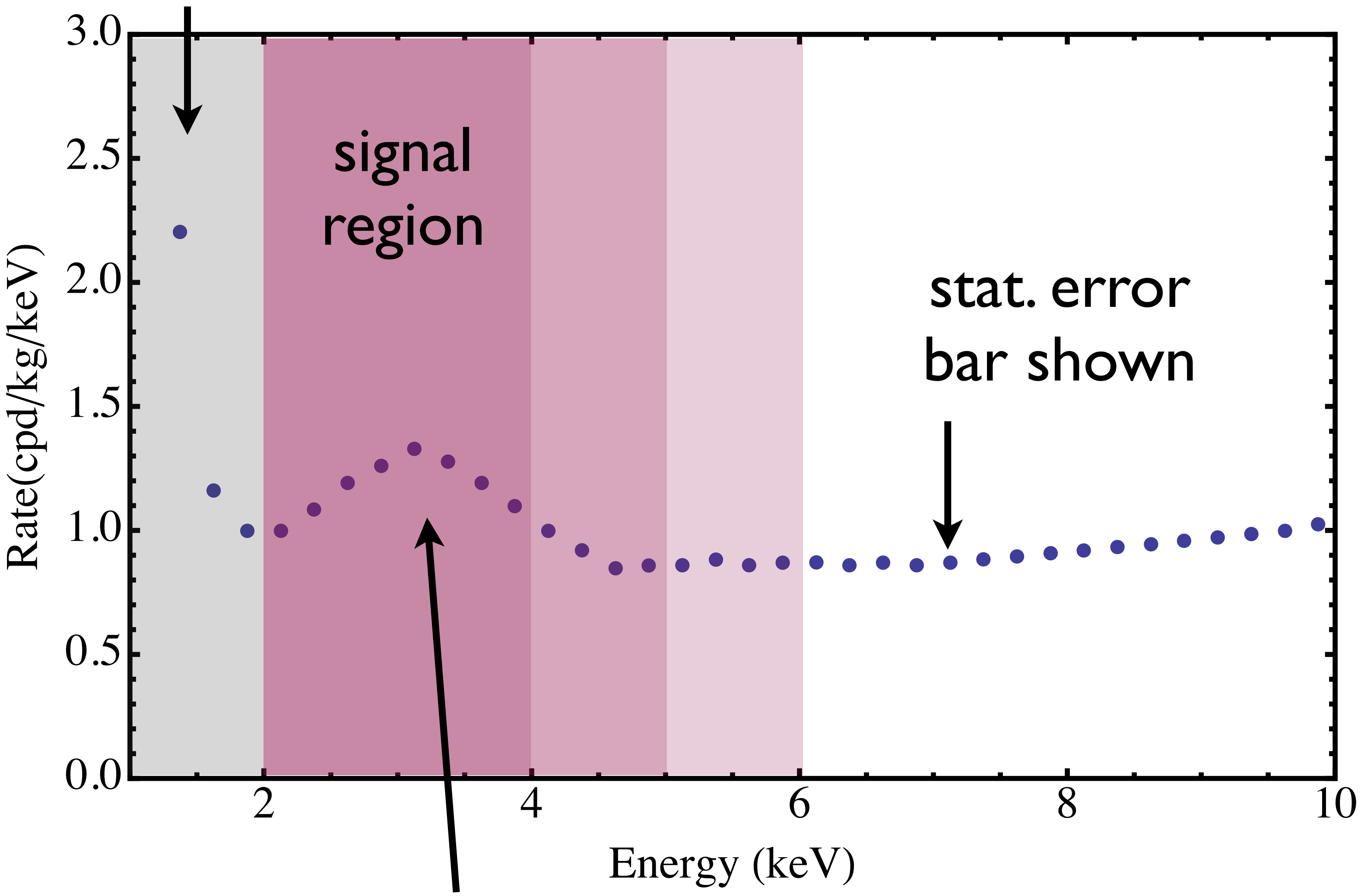
$$s_m^{\mathrm{max}} \geq s_m^{\mathrm{obs}} \left(1 + \frac{B_0}{S_0}\right) \approx 2\% \times \left(1 + \frac{B_0}{S_0}\right)$$

$$s_m^{\mathrm{max}} = S_m / S_0$$

=> take a closer look at the DAMA backgrounds to see what is needed

DAMA signal interpretation
in the presence of backgrounds

noise



signal region

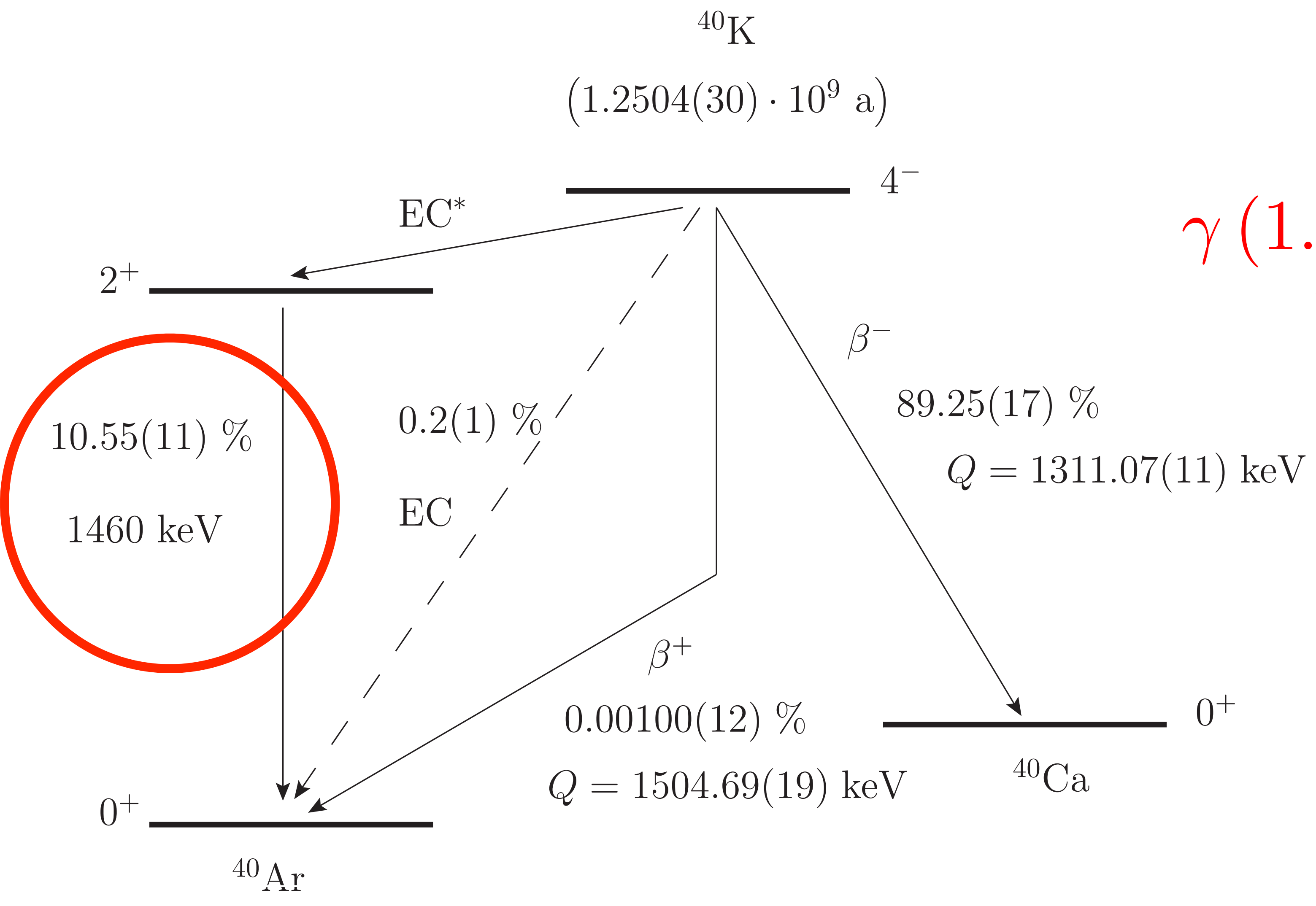
stat. error bar shown

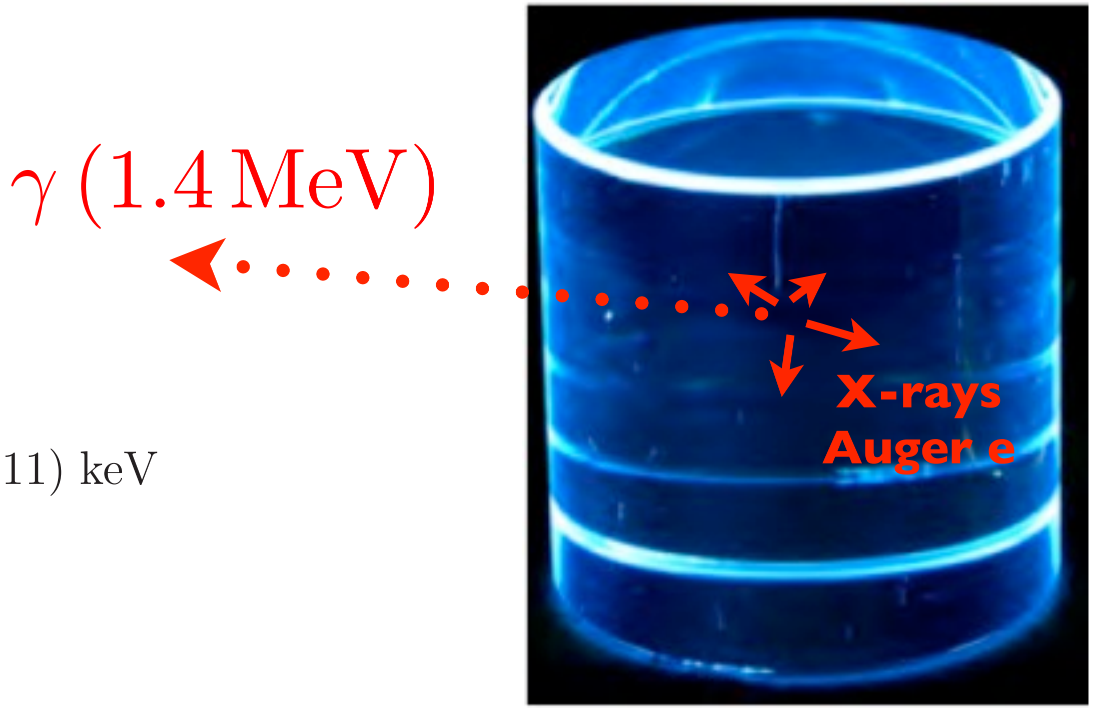
increased backgrounds in the signal region?

- “Single-hit” spectrum (all other detectors act as a veto)

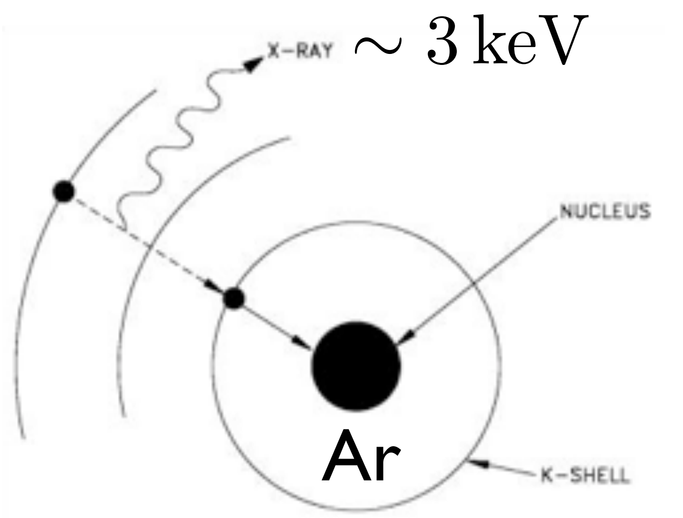
$$R \sim 1\,\mathrm{cpd/kg/keV}$$

Potassium background in DAMA at 3 keV



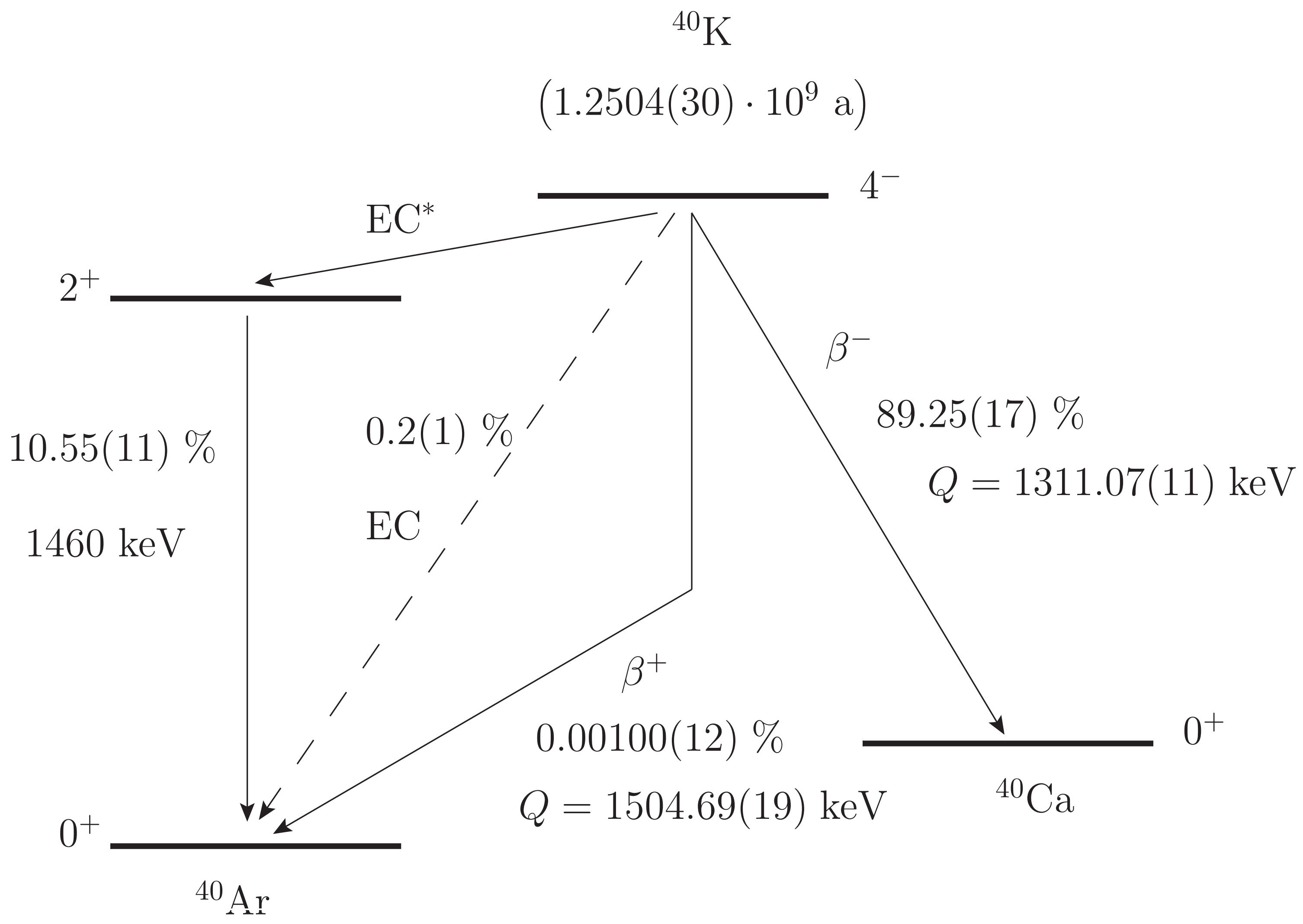


(nuclear recoil $\ll 1$ keV)

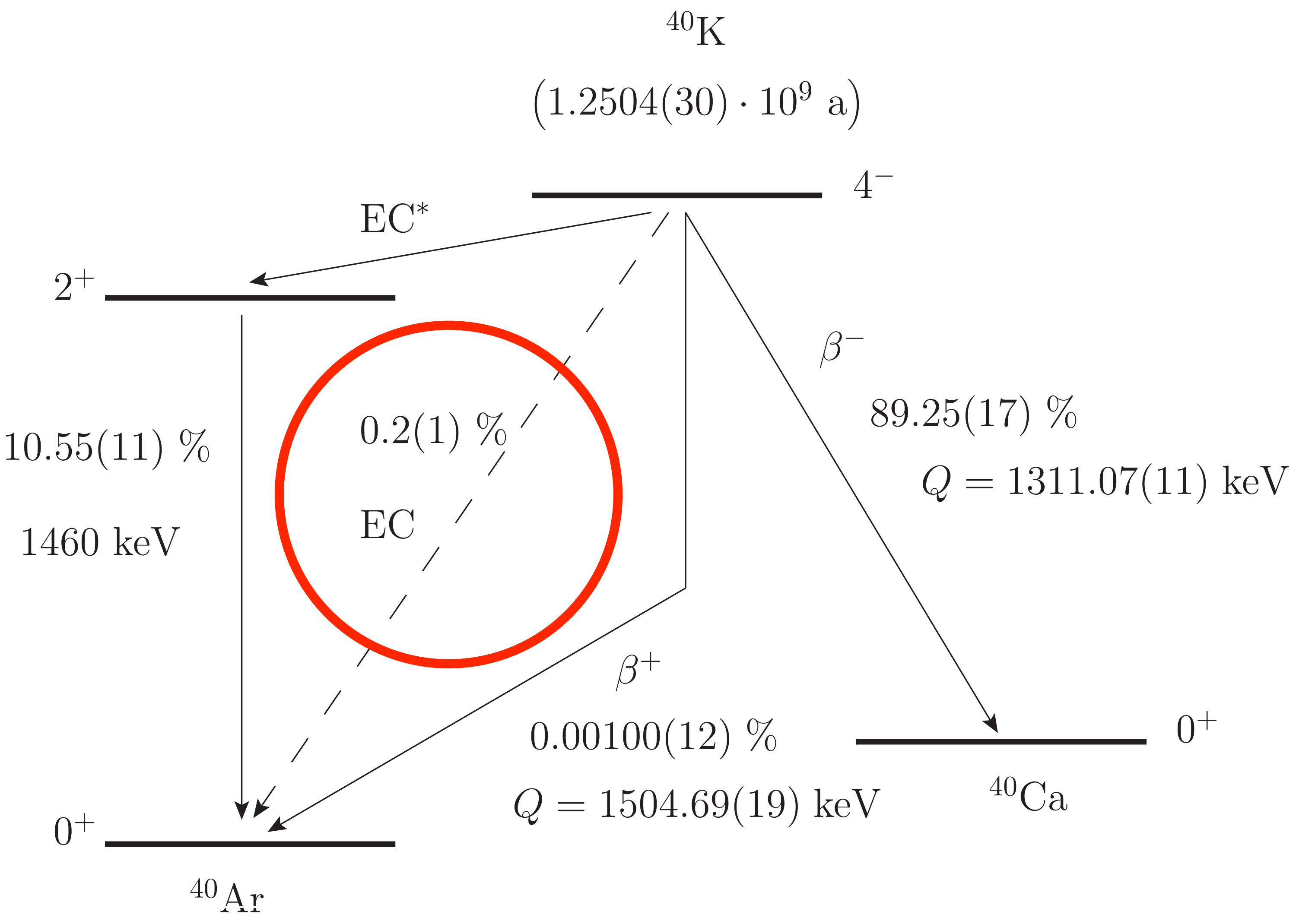


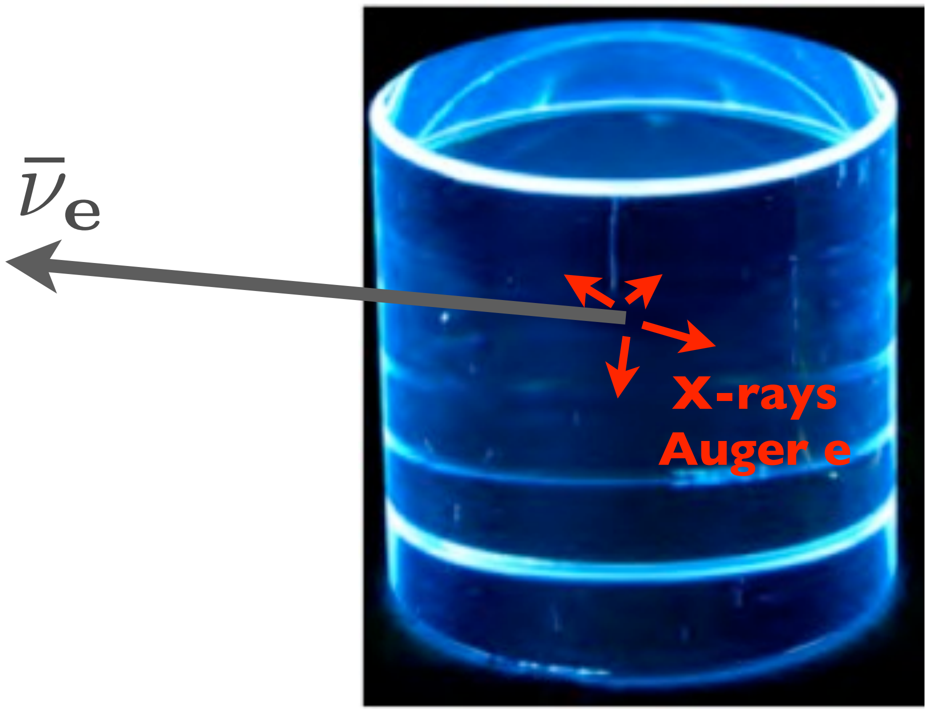
needs MC to find rate at 3 keV
=> we employ the results from Kudryavtsev et al 2010

Potassium background in DAMA
at 3 keV

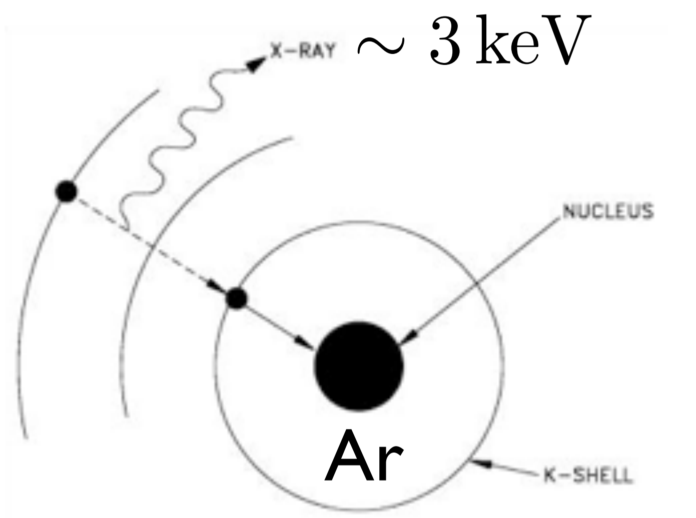


Potassium background in DAMA
at $3\,\mathrm{keV}$

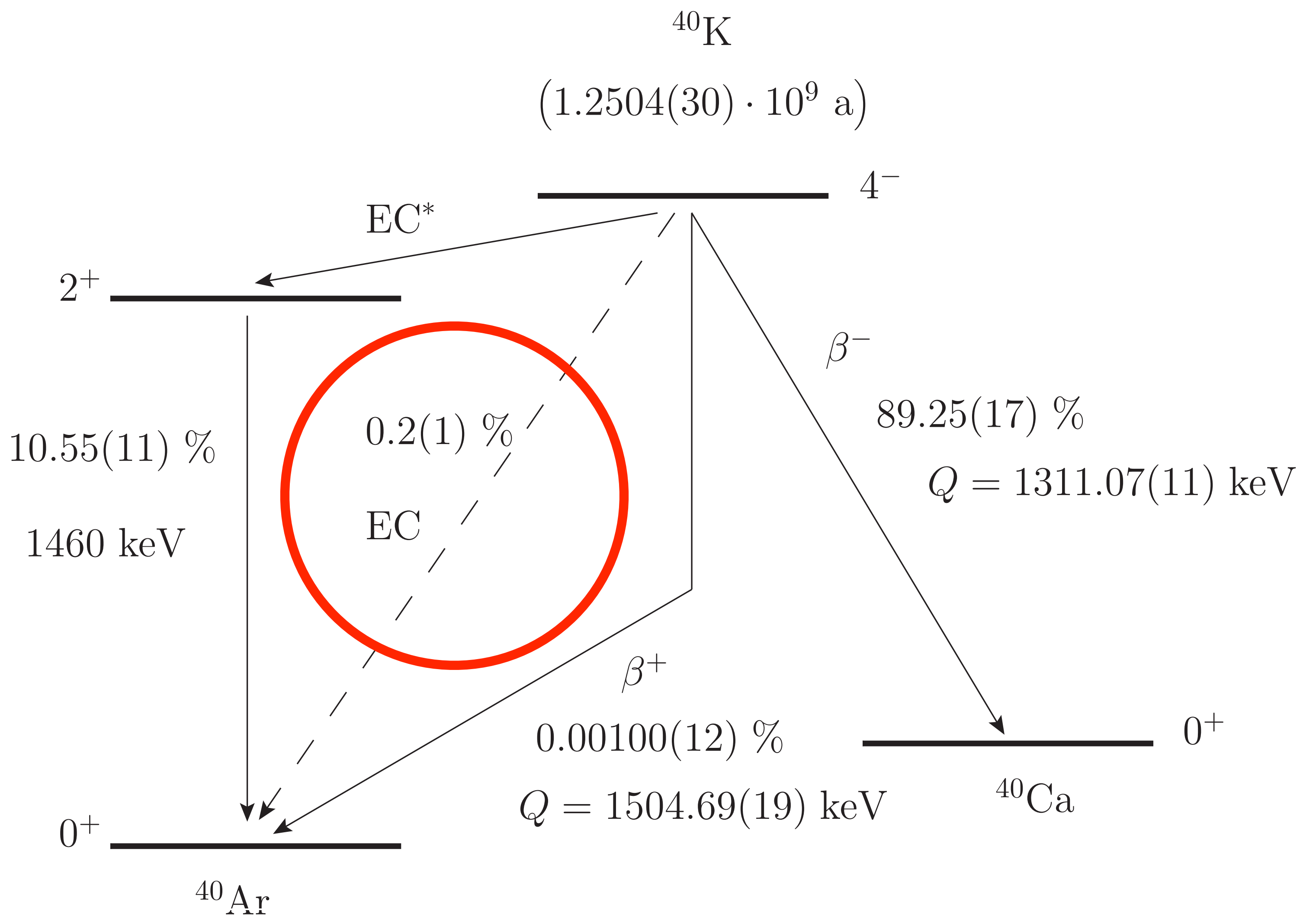




(nuclear recoil $\ll 1\,\mathrm{keV}$)



Potassium background in DAMA
at $3\,\mathrm{keV}$



$^{40}\mathrm{K}$

$(1.2504(30) \cdot 10^{9}\ \mathrm{a})$

4^{-}

EC^{*}

2^{+}

$10.55(11)\ \%$

$1460\ \mathrm{keV}$

$0.2(1)\ \%$

EC

β^{-}

$89.25(17)\ \%$

$Q = 1311.07(11)\ \mathrm{keV}$

β^{+}

$0.00100(12)\ \%$

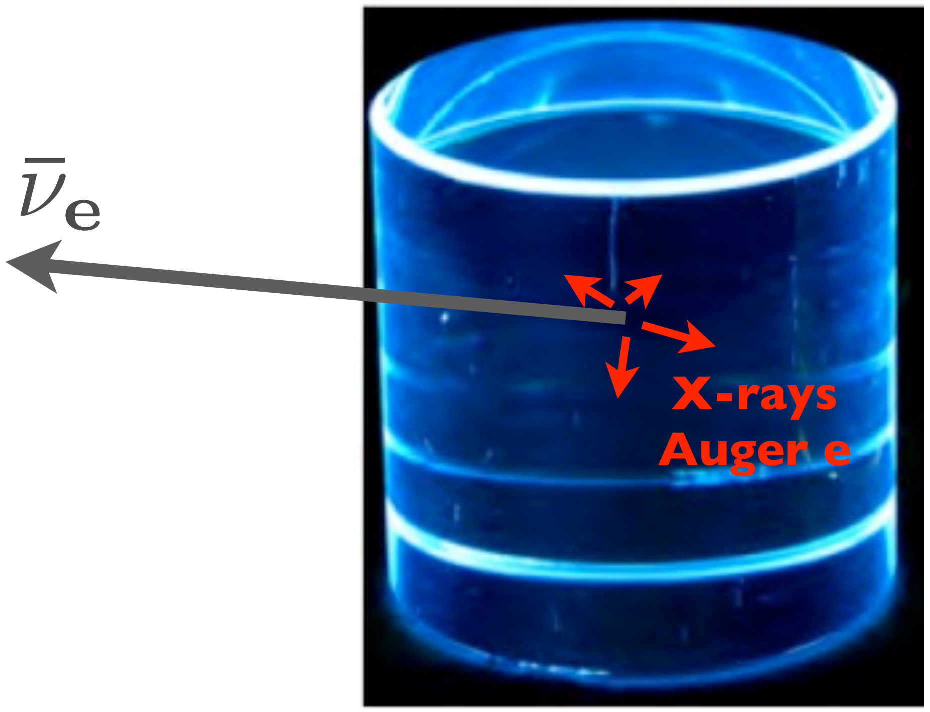
$Q = 1504.69(19)\ \mathrm{keV}$

0^{+}

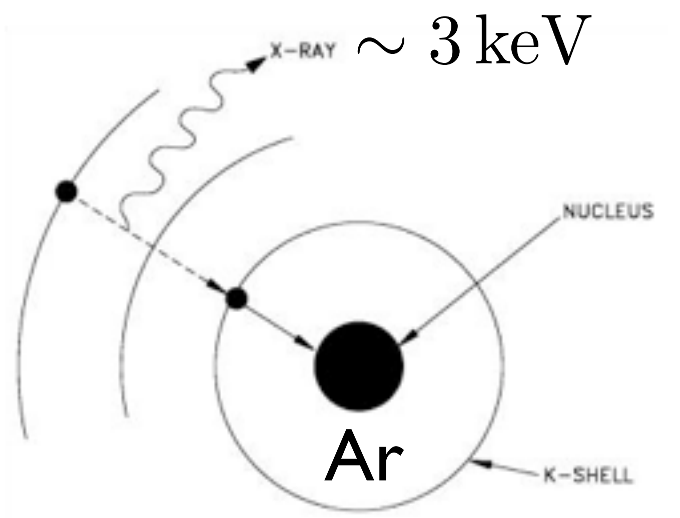
$^{40}\mathrm{Ca}$

0^{+}

$^{40}\mathrm{Ar}$



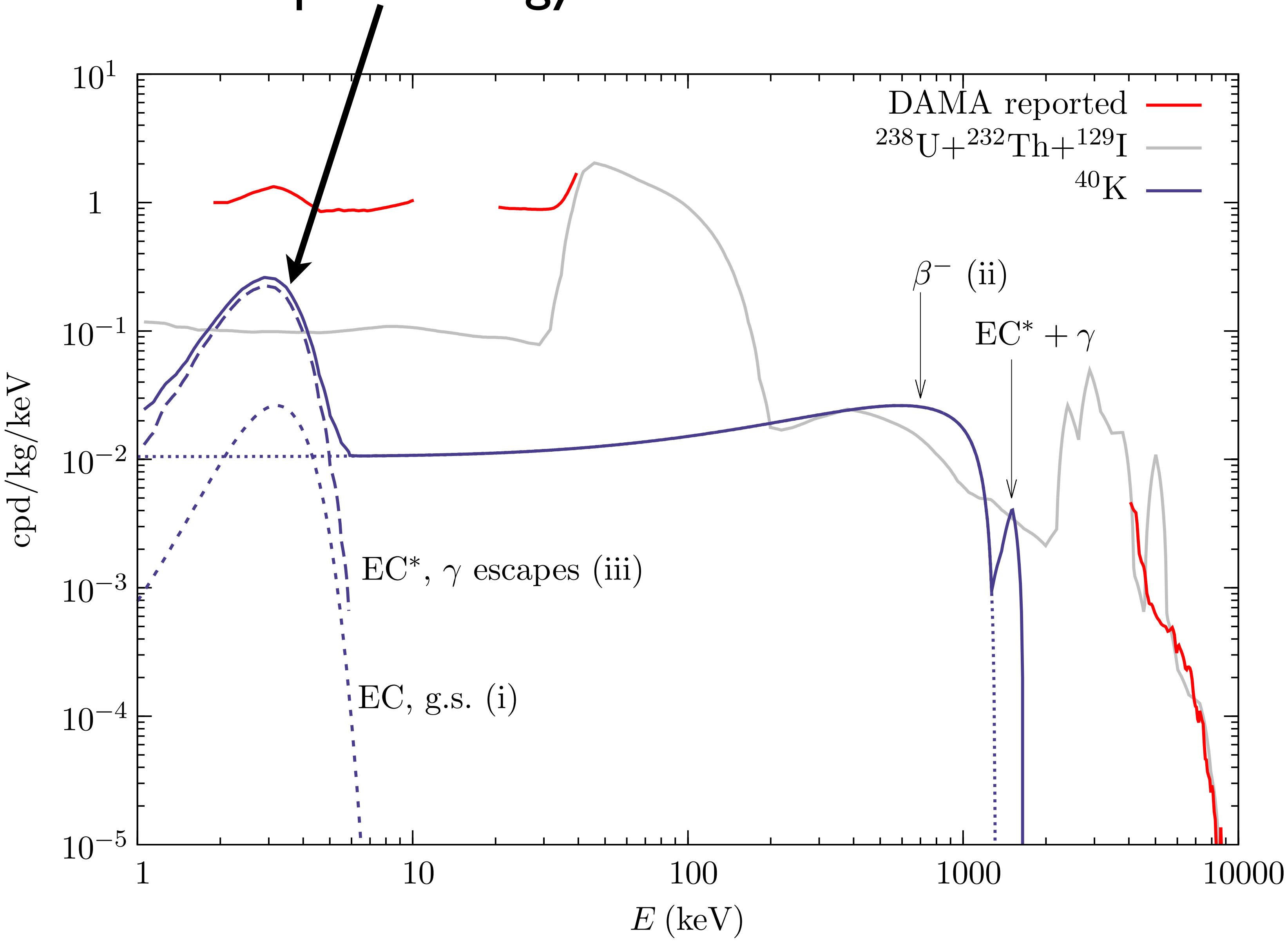
(nuclear recoil $\ll 1\,\mathrm{keV}$)



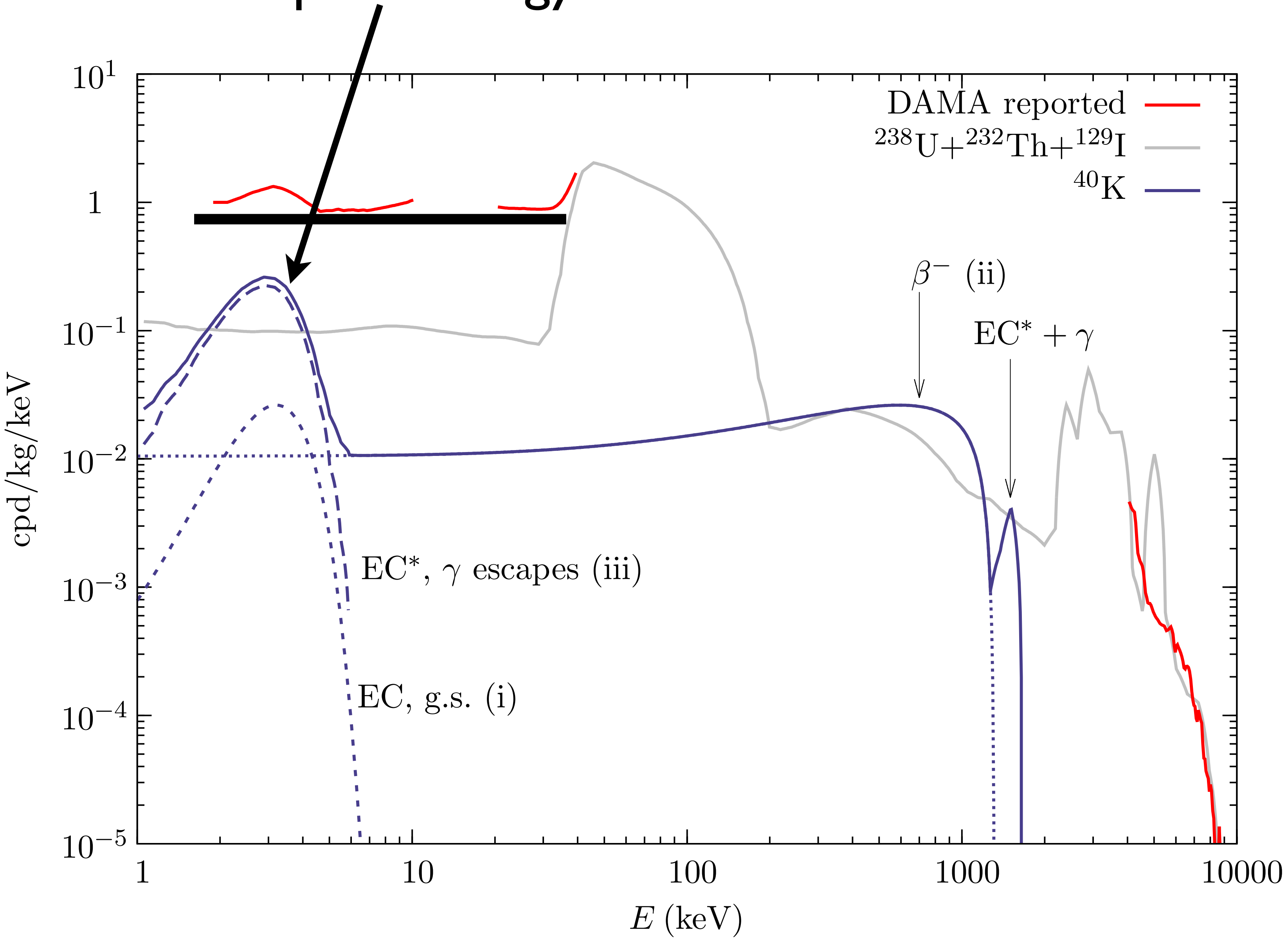
angular momentum change by 4 units,
"3rd forbidden unique weak decay"
=> the ONLY such EC realized in nature

Simulated DAMA spectrum
using reported contaminations

shape = energy resolution



Simulated DAMA spectrum
using reported contaminations


shape = energy resolution

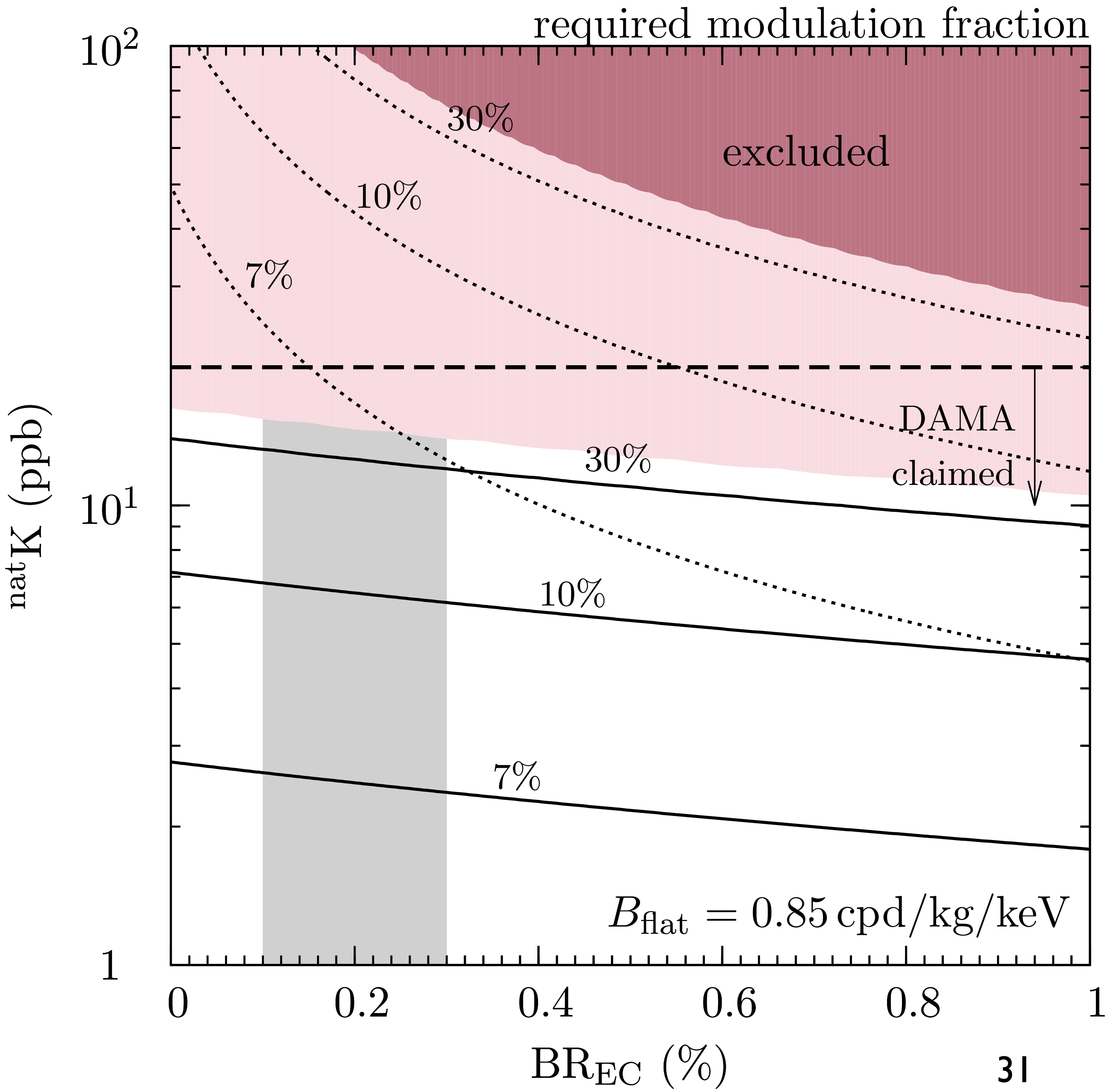
- strong indication of a flat background component

  $$B_{\text{flat}} \simeq 0.85 \text{ cpd/kg/keV}$$

- β^- and Compton background at low energies are **flat!**

  => work out implication for modulation fraction

required modulation fraction if a flat background is present



- challenges standard WIMP scenario with Maxwellian halo:

$$s_m \lesssim 10\%$$

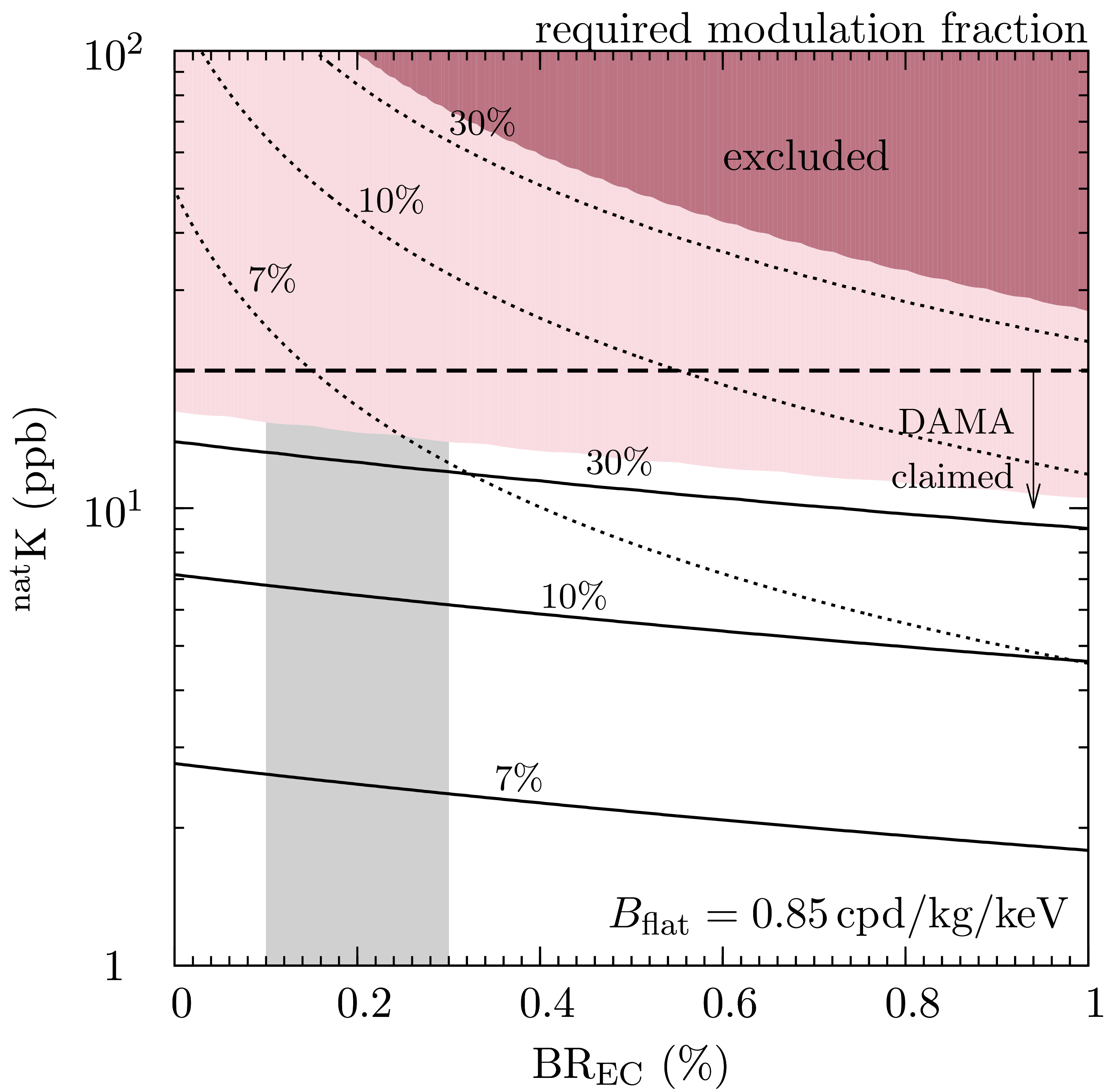
- for 13 ppb potassium contamination

$$s_m \gtrsim 20\%$$

required!

results triggered responses by DAMA
which only raised more questions

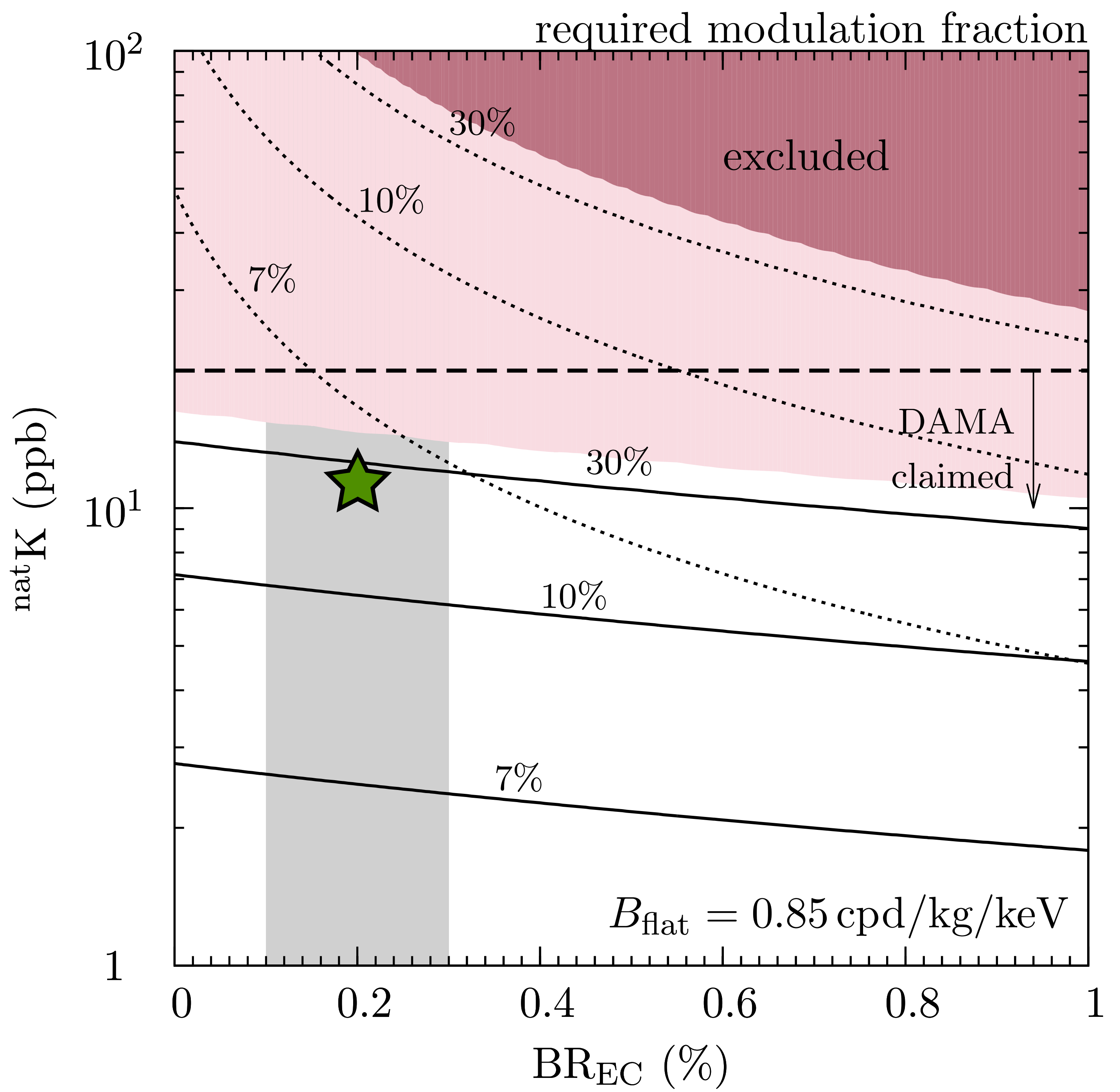
Bernabei et al.
1210.6199
1211.6346



- **critique 1:** potassium is measured at $^{\mathrm{nat}}\mathrm{K} = 13\,\mathrm{ppb}$
- **critique 2:** EC to g.s. is only 10% => our discussion is "captious"
- **critique 3:** upper limit on signal claimed $S_0 \leq 0.25\,\mathrm{cpd/kg/keV}$ => allows for 6-10% modulation!

results triggered responses by DAMA
which only raised more questions

Bernabei et al.
1210.6199
1211.6346



- **critique 1:** potassium is measured at $^{\rm nat}{\rm K} = 13\,{\rm ppb}$

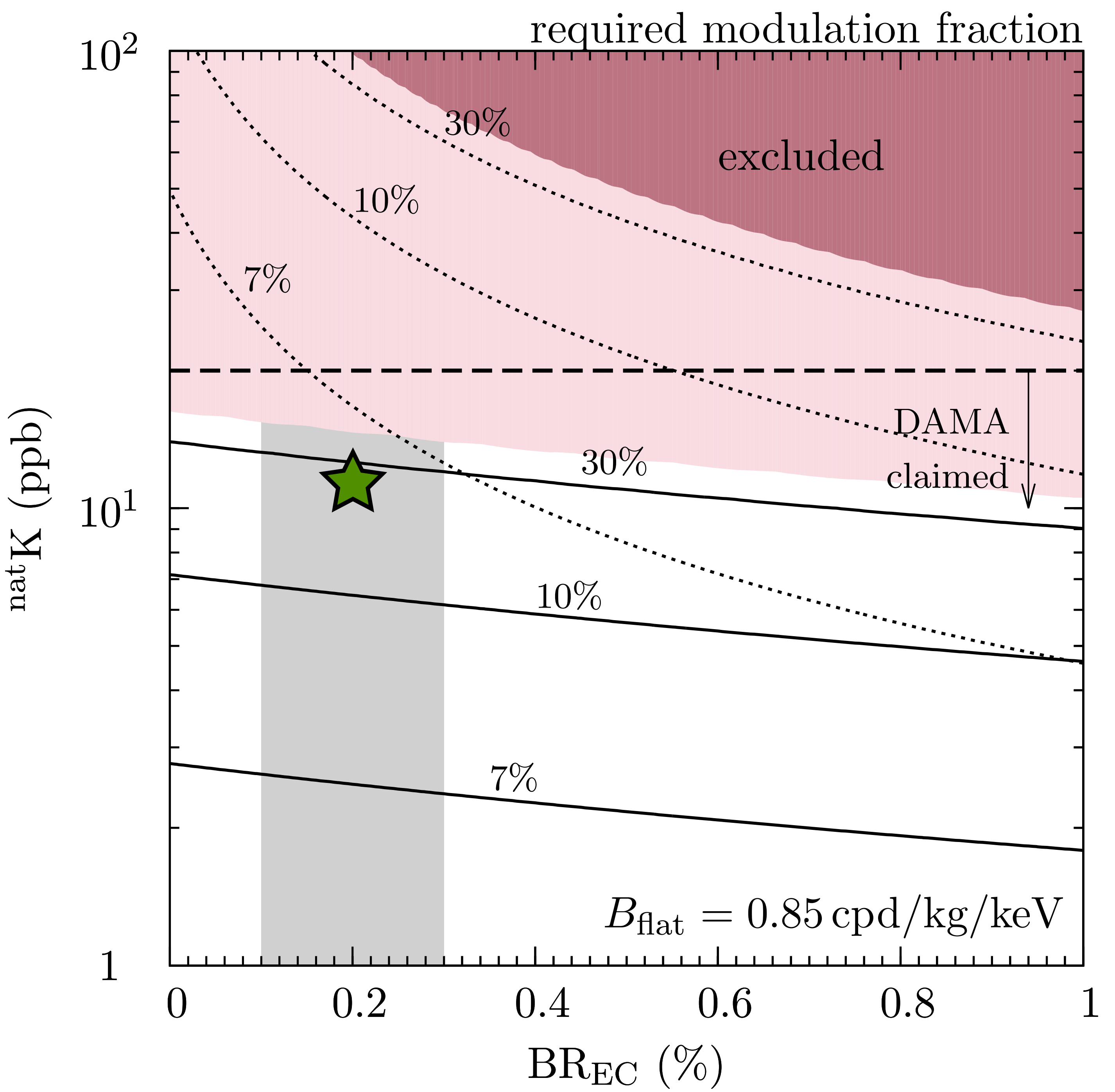
  Great. A new number in print.

- **critique 2:** EC to g.s. is only 10% => our discussion is "captious"

- **critique 3:** upper limit on signal claimed $S_0 \leq 0.25\,{\rm cpd/kg/keV}$ => allows for 6-10% modulation!

results triggered responses by DAMA
which only raised more questions

Bernabei et al.
1210.6199
1211.6346



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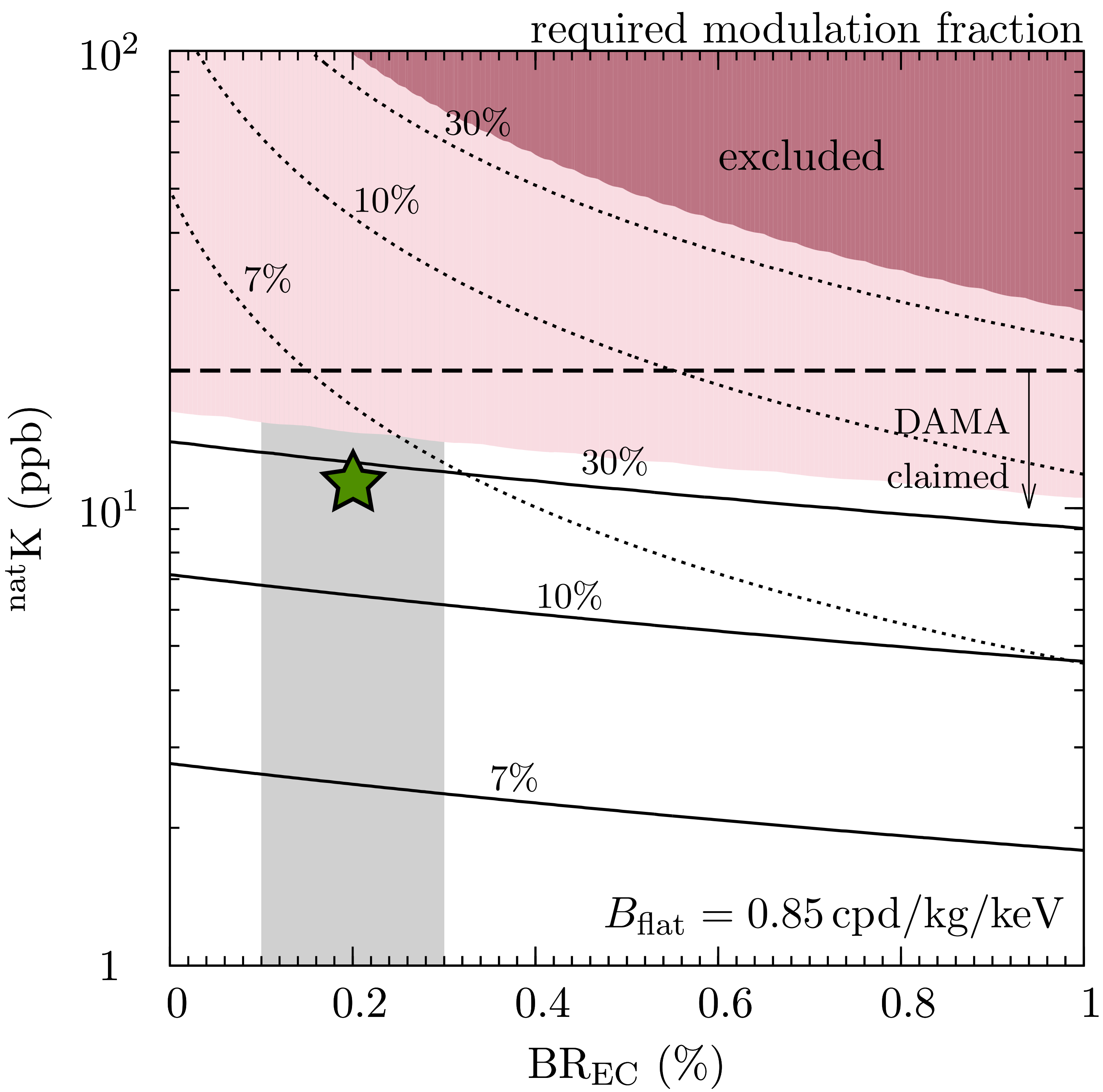

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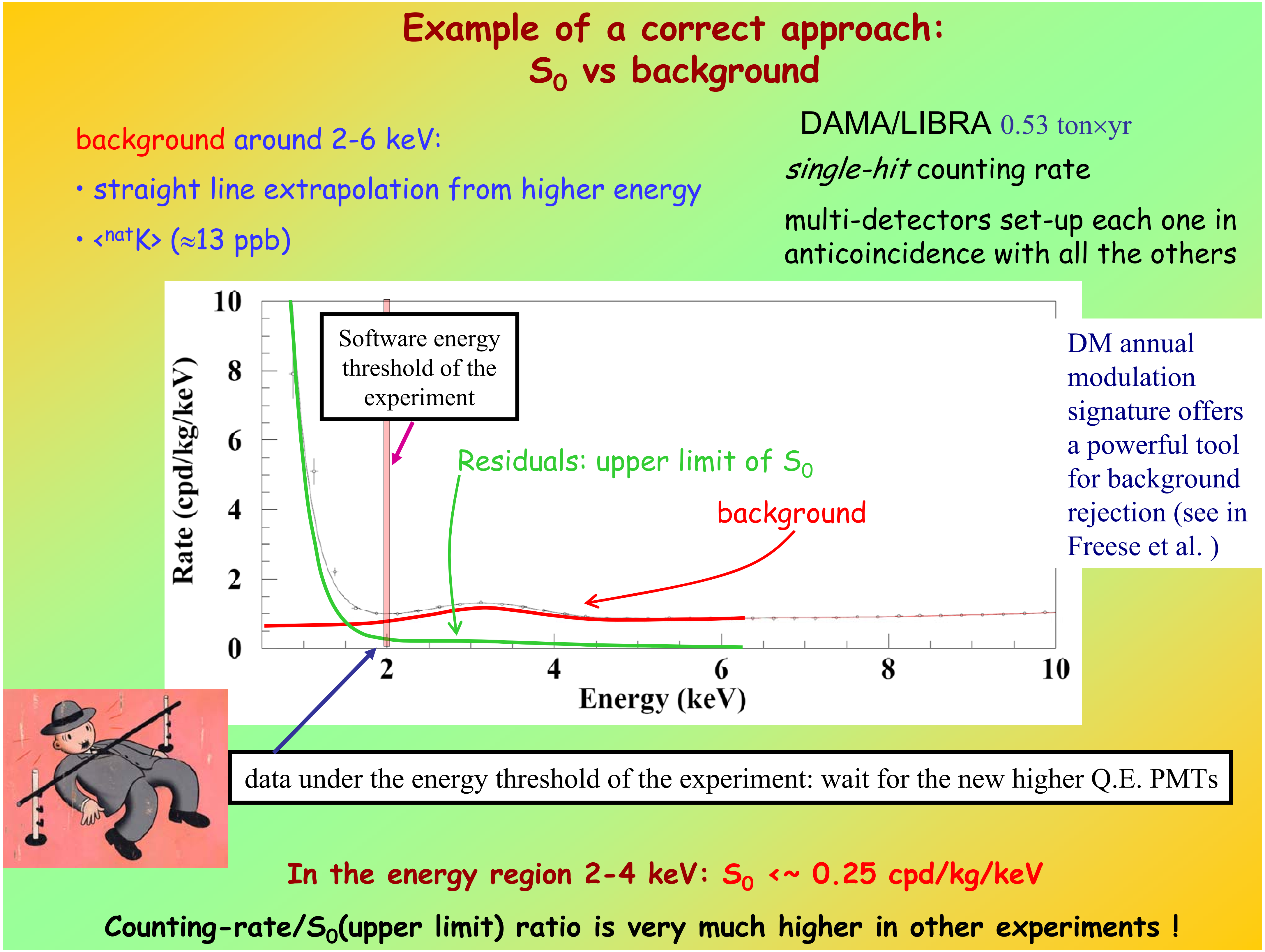
=> let's check.
Requires "slide-forensic".
Number not in print.

referenced by DAMA's reply to our paper:



Example of a correct approach: S_0 vs background

background around 2-6 keV:

- straight line extrapolation from higher energy
- <^{nat}K> (≈13 ppb)

DAMA/LIBRA 0.53 ton×yr

single-hit counting rate

multi-detectors set-up each one in anticoincidence with all the others

DM annual modulation signature offers a powerful tool for background rejection (see in Freese et al.)

data under the energy threshold of the experiment: wait for the new higher Q.E. PMTs

In the energy region 2-4 keV: S_0 <~ 0.25 cpd/kg/keV

Counting-rate/S_0(upper limit) ratio is very much higher in other experiments !

talk by Nozzoli for DAMA, TAUP 2009

results triggered responses by DAMA which only raised more questions

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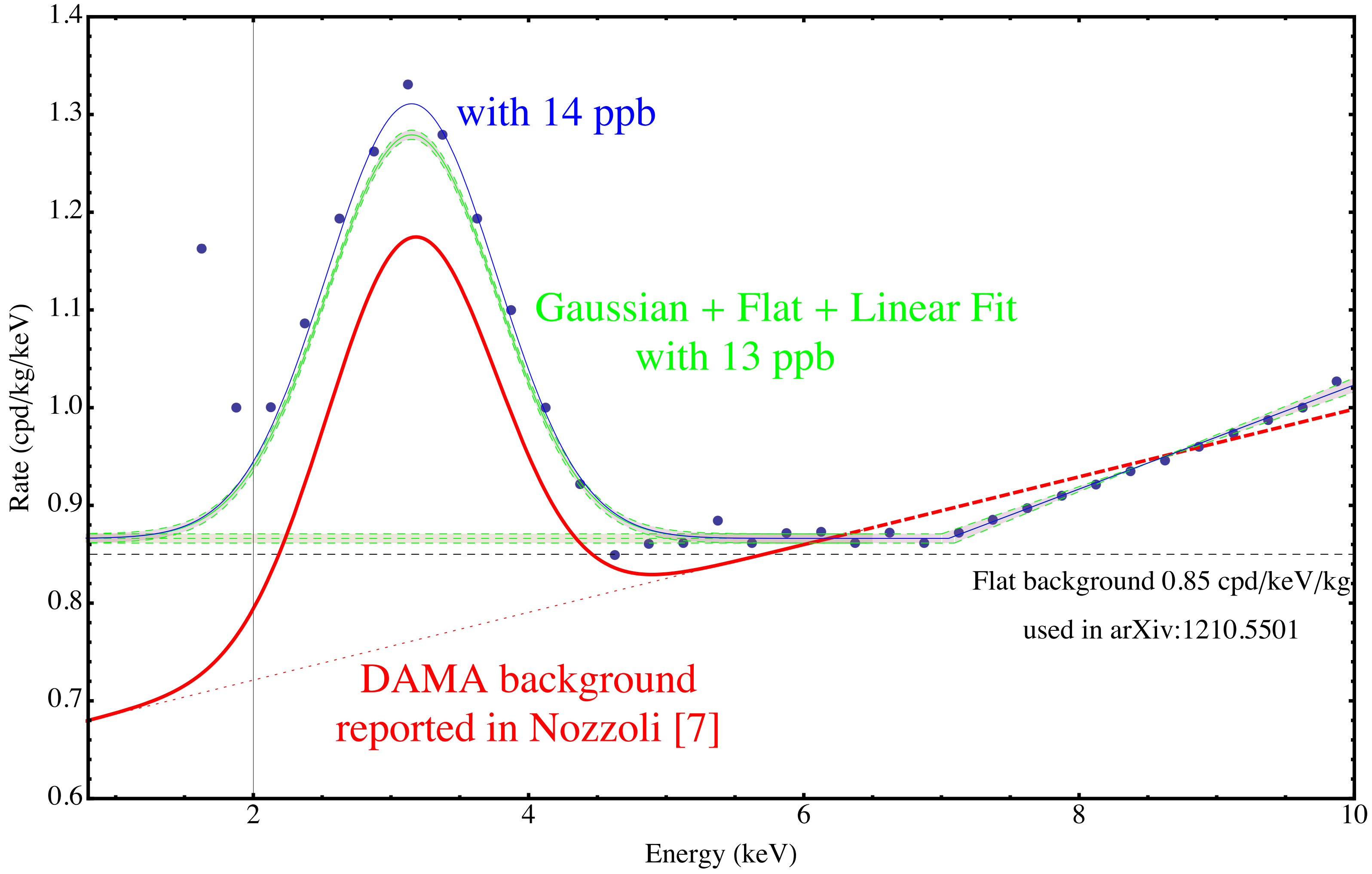


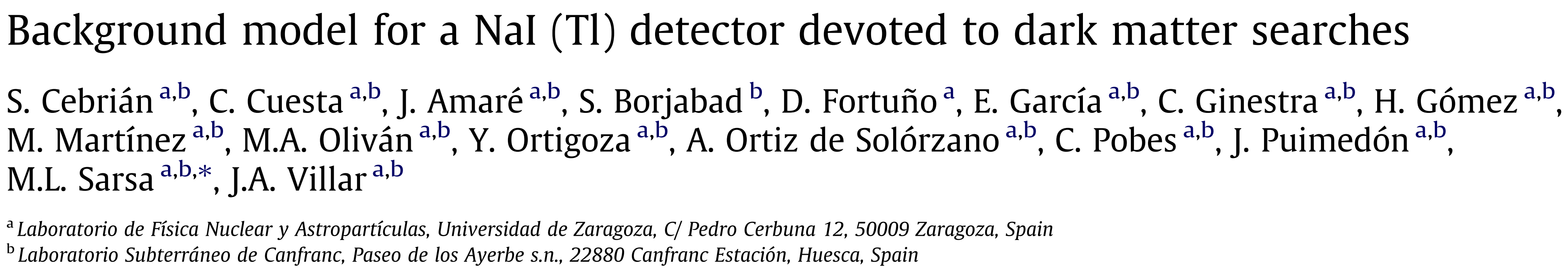
none of our questions/ concerns have been addressed.

instead our assumption of a flat background was criticized as being ad hoc

=> their own model is not supported by data

interpretation of the signal in terms of DM is seen to be very sensitive to assumptions on the background....

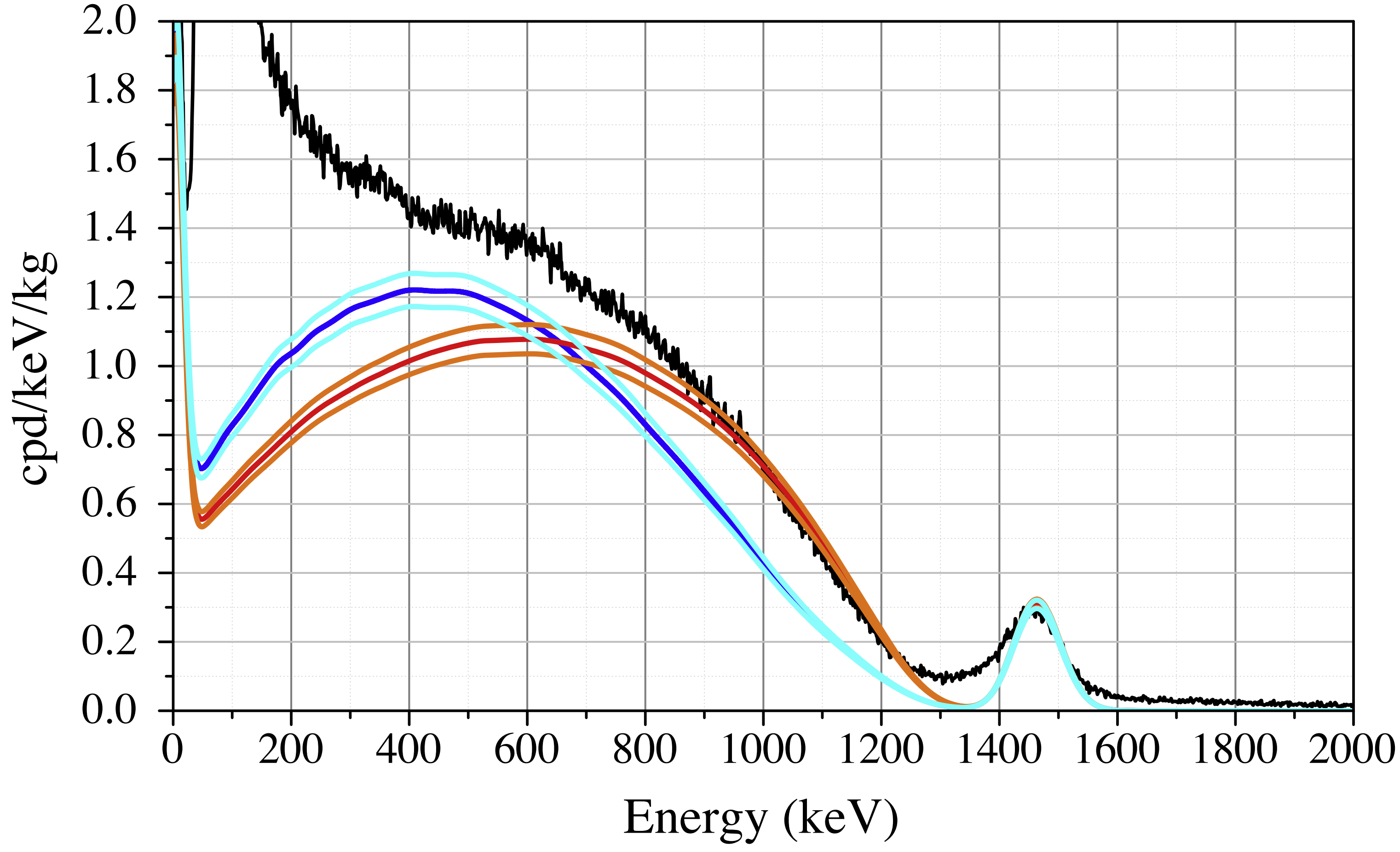
This is how it’s done



Background model for a NaI (Tl) detector devoted to dark matter searches

S. Cebrián [a,b], C. Cuesta [a,b], J. Amaré [a,b], S. Borjabad [b], D. Fortuño [a], E. García [a,b], C. Ginestra [a,b], H. Gómez [a,b],
M. Martínez [a,b], M.A. Oliván [a,b], Y. Ortigoza [a,b], A. Ortiz de Solórzano [a,b], C. Pobes [a,b], J. Puimedón [a,b],
M.L. Sarsa [a,b,*], J.A. Villar [a,b]

[a] *Laboratorio de Física Nuclear y Astropartículas, Universidad de Zaragoza, C/ Pedro Cerbuna 12, 50009 Zaragoza, Spain*
[b] *Laboratorio Subterráneo de Canfranc, Paseo de los Ayerbe s.n., 22880 Canfranc Estación, Huesca, Spain*



DAMA should show us the K40 shoulder

A count rate in DAMA much greater than 0.04 cpd/kg/keV will severely undermine a DM interpretation of the signal.

ANAIS collaboration

Conclusions

- new neutrinos with enhanced baryonic currents can be tested in direct detection experiments

  => "DM-like" signals from new neutrino physics can explain DM anomalies CoGeNT and CRESST-II, unchallenged by other searches

  => upcoming experimental results will conclusively probe the most interesting parameter space

- DAMA data speaks against a "vanilla" Dark Matter interpretation

  => a minimum of 20% modulation in any putative signal may at least be required

  => after a decade of modulation maybe it is time to take a more global look at the data set