Title: Direct Detection Experiments as Neutrino _b Observatories

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Abstract:

# Direct Detection experiments as neutrino observatories

Josef Pradler

Perimeter Institute

with Maxim Pospelov

*Unravelling Dark Matter*
*Sept 25, 2011*

# Stodolsky's 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

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- helicity conservation forbids back-scattering

(this process has not yet been observed)

# => direct DM detection

HYSICAL 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.

Witten 1985

# WIMPs vs. 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

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

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

# => direct DM detection

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# SM neutrinos from the sun as a future background

## 1 ton x year

| Target | T>0 keV | T>2 keV | T>5 keV | T>10 keV |
|---|---|---|---|---|
| $^{12}$C | 235.7 | 191.8 | 104.1 | 36.0 |
| $^{19}$F | 378.0 | 204.4 | 88.8 | 13.3 |
| $^{40}$Ar | 804.8 | 231.4 | 21.0 | <1.0 |
| $^{76}$Ge | 1495.0 | 111.5 | <1.0 | <1.0 |
| $^{132}$Xe | 2616.9 | 14.7 | <1.0 | <1.0 |

[Monroe 2007]

(we are not too far away from this)

# "baryonic" neutrinos$_{\nu_b}$

*M. Pospelov arXiv:1103.3261*

- introduce new left-handed neutrino species $\nu_b = P_L \nu_b$ together with gauged $U(1)_b$
- $\nu_b$ couples to quarks, but not to leptons
- breaking of $U(1)_b$ gives new gauge field $V_\mu$ mass

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

$\nu_b$
- sterile under SM-gauge group
- active under $U(1)_b$

# "baryonic" neutrinos$_{\nu_b}$

*M. Pospelov arXiv:1103.3261*

- 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 $G_F$:

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

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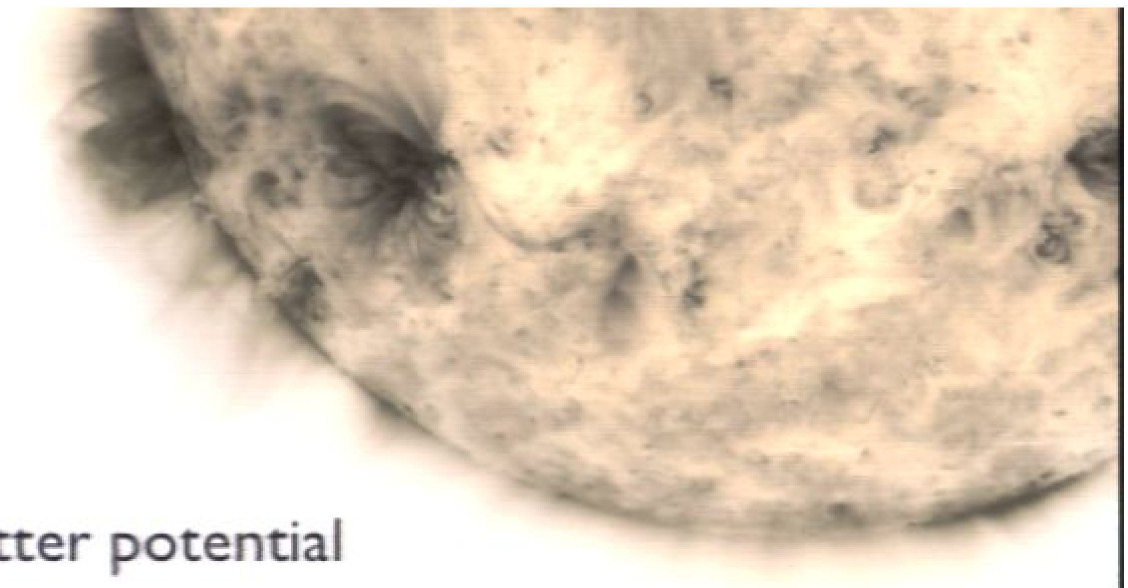
- baryonic neutrino can get mass from $\nu_R$

$$\mathcal{L}_m = \frac{1}{2} N_L^T C^\dagger M N_L + \text{h.c.}, \quad N_L = \begin{pmatrix} \nu_b' \\ \nu_L' \\ \nu_R'^C \end{pmatrix}, \quad M = \begin{pmatrix} 0 & 0^T & v_b b^T \\ 0 & 0 & m_D^T \\ v_b b & m_D & m_R \end{pmatrix}$$

- neutrinos talk via mass mixing => "sterile-active" oscillations

$$n_{kL} = \sum_\alpha U^*_{k\alpha} \nu_{\alpha L}, \quad U = \begin{array}{c} \\ e \\ \mu \\ \tau \\ b \end{array} \begin{array}{c} \begin{array}{cccc} 1 & 2 & 3 & 4 \end{array} \\ \begin{pmatrix} & & & \cdot \\ & U_{\text{PMNS}} & & \cdot \\ & & & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{pmatrix} \end{array}$$



# matter effects

- forward scattering induces matter potential

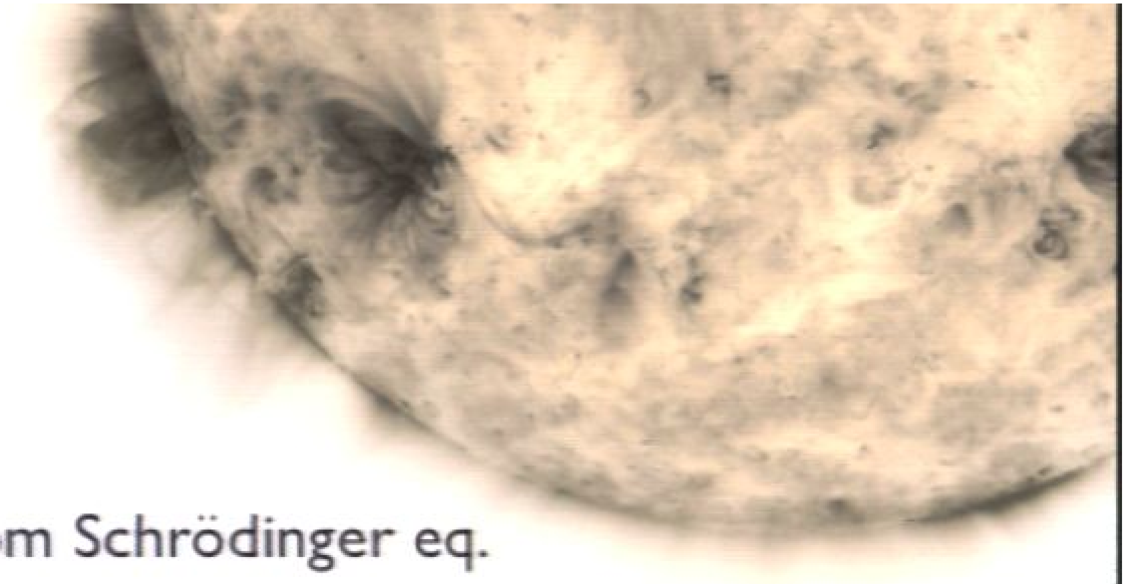
$$V_{NCB} = \pm q_b \mathcal{N} G_F n_B \left(Y_N + 2Y_{\nu_b}\right), \qquad Y_f = \frac{n_f - n_{\overline{f}}}{n_B},$$

$$V_{NCB} : V_{CC} : V_{NC} = q_b \mathcal{N} : \sqrt{2} X_p : -\sqrt{2}(1 - X_p)/2,$$

$X_p =$ mass fraction of protons

=> $\nu_b$ experience largest effect in normal matter for $\mathcal{N} \gg 1$

# matter effects



- flavor transition amplitudes from Schrödinger eq.

$$\frac{d}{dx}\begin{pmatrix}\psi_{\alpha\alpha}\\ \psi_{\alpha b}\end{pmatrix} \simeq \frac{1}{4E}\begin{pmatrix}-\Delta m_b^2\cos 2\theta_b - 2EV_{NCB} & \Delta m_b^2 \sin 2\theta_b\\ \Delta m_b^2 \sin 2\theta_b & \Delta m_b^2\cos 2\theta_b + 2EV_{NCB}\end{pmatrix}\begin{pmatrix}\psi_{\alpha\alpha}\\ \psi_{\alpha b}\end{pmatrix}$$

$$\mathrm{an}\, 2\theta_M = \frac{\tan 2\theta_b}{1 + 2EV_{NCB}/(\Delta m_b^2 \cos 2\theta_b)}$$ matter mixing angle

for $\Delta m_b^2 \cos 2\theta_b \ll 10^{-4}\,\mathrm{eV}^2 \times \left(\frac{E}{10\,\mathrm{MeV}}\right)\left(\frac{\mathcal{N}}{100}\right)\left(\frac{\rho}{\mathrm{g/cm^3}}\right)$

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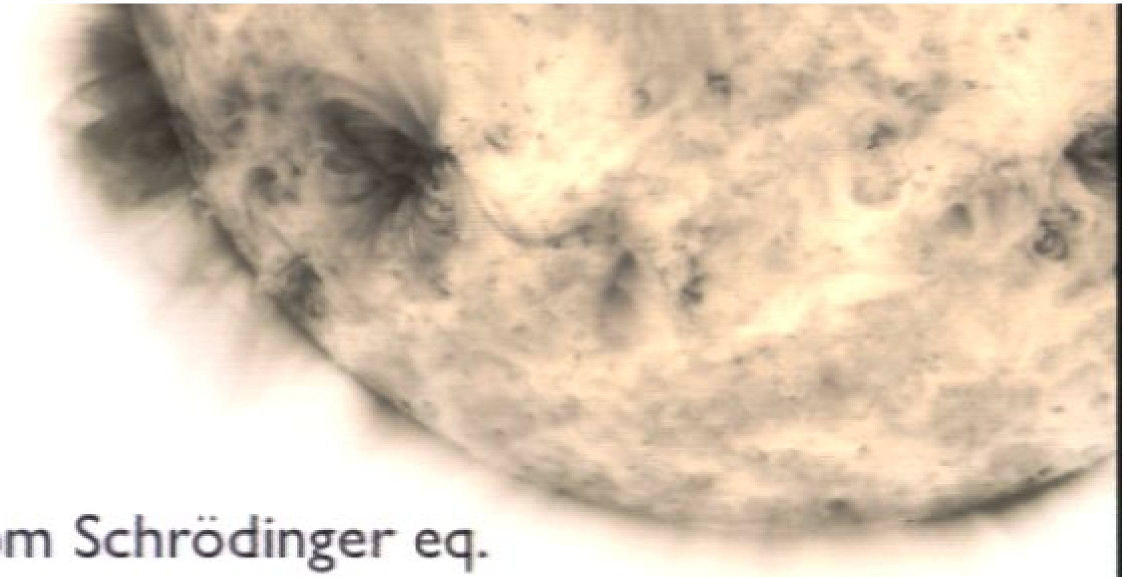

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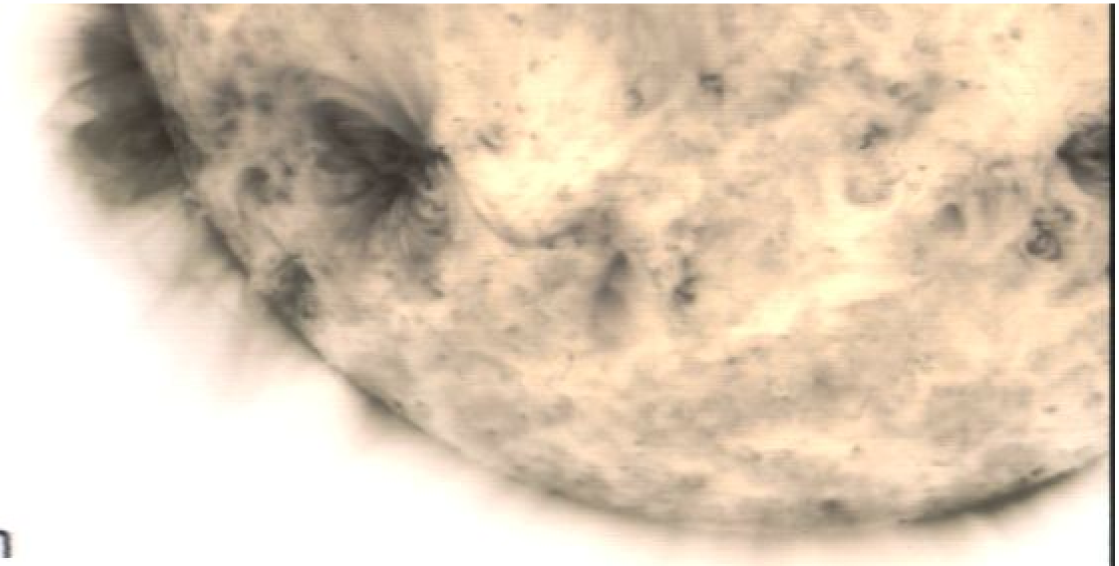

- considering such small values in $\Delta m_b^2$ standard solar story unfolds

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

=> see Maxim's talk

$$\downarrow$$

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

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

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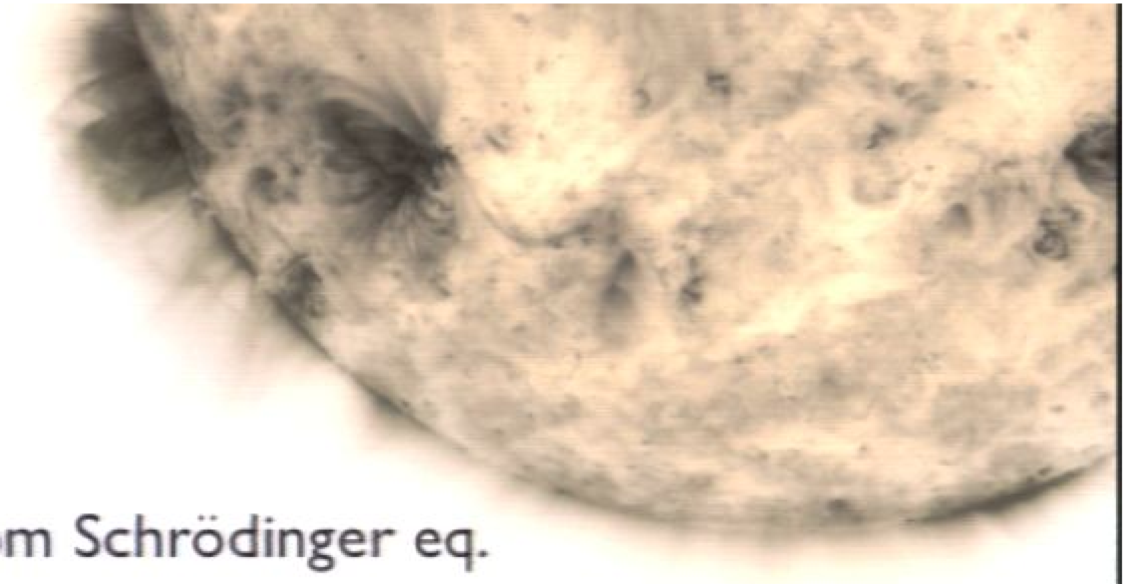

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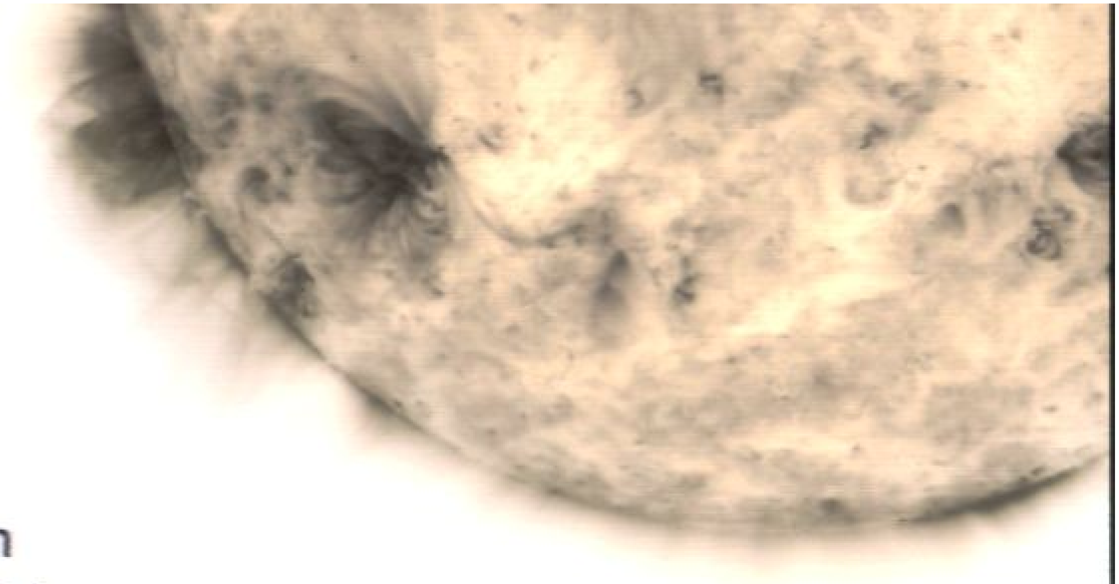

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# direct detection of $\nu_b$

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

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

overall flux modulation

average over neutrino spectrum i

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

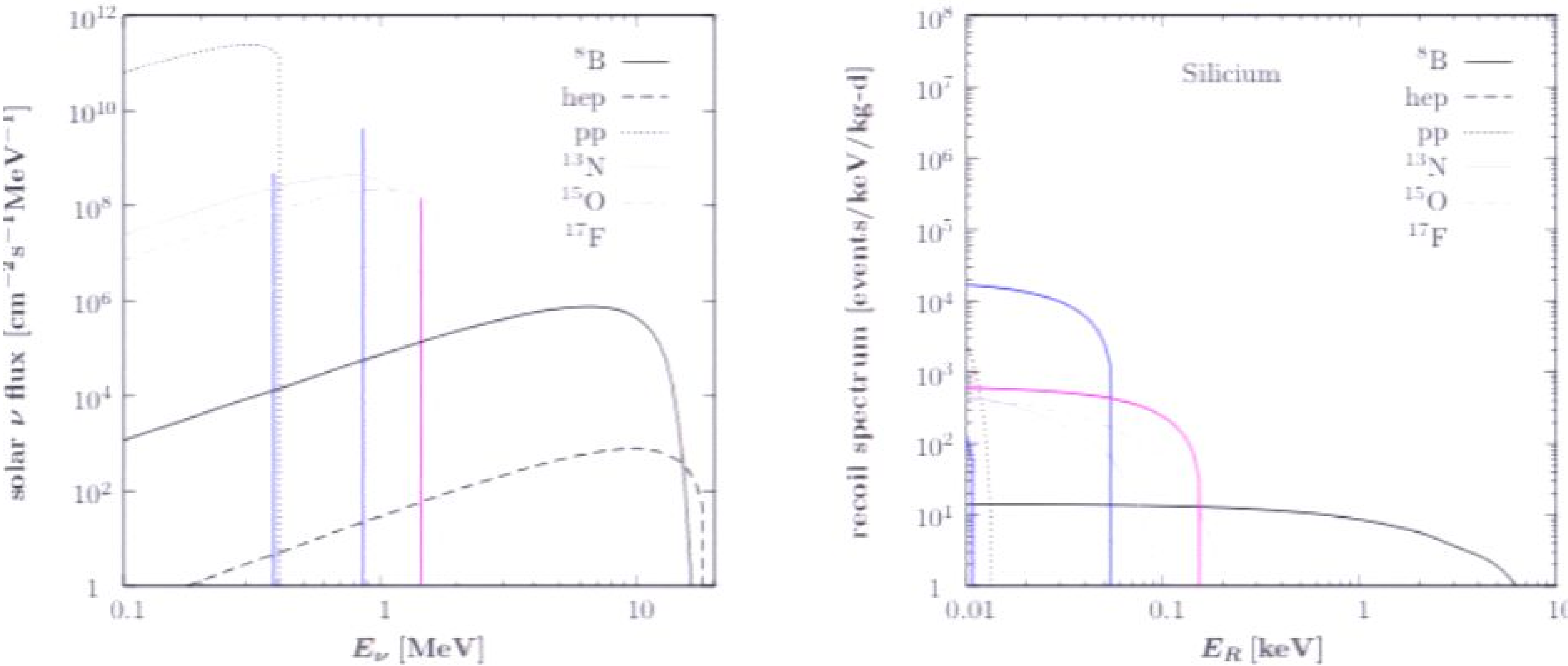
$L_0 = 1\,\mathrm{AU}$

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

$\epsilon = 0.0167$ (eccentricity)

# direct detection of $\nu_b$

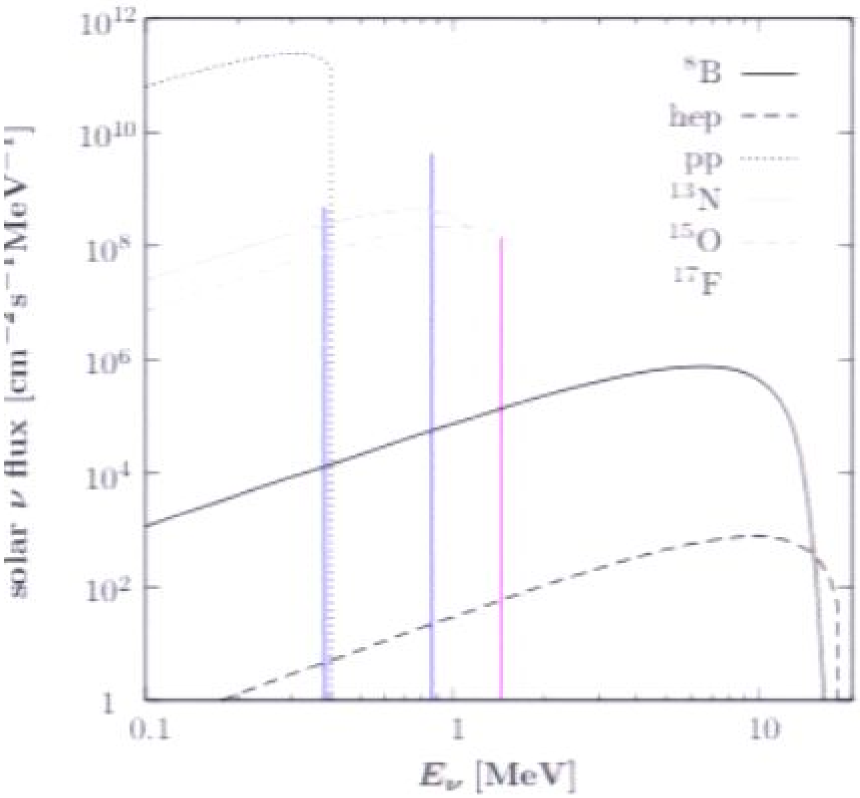
$A_{\rm Si} = 28$



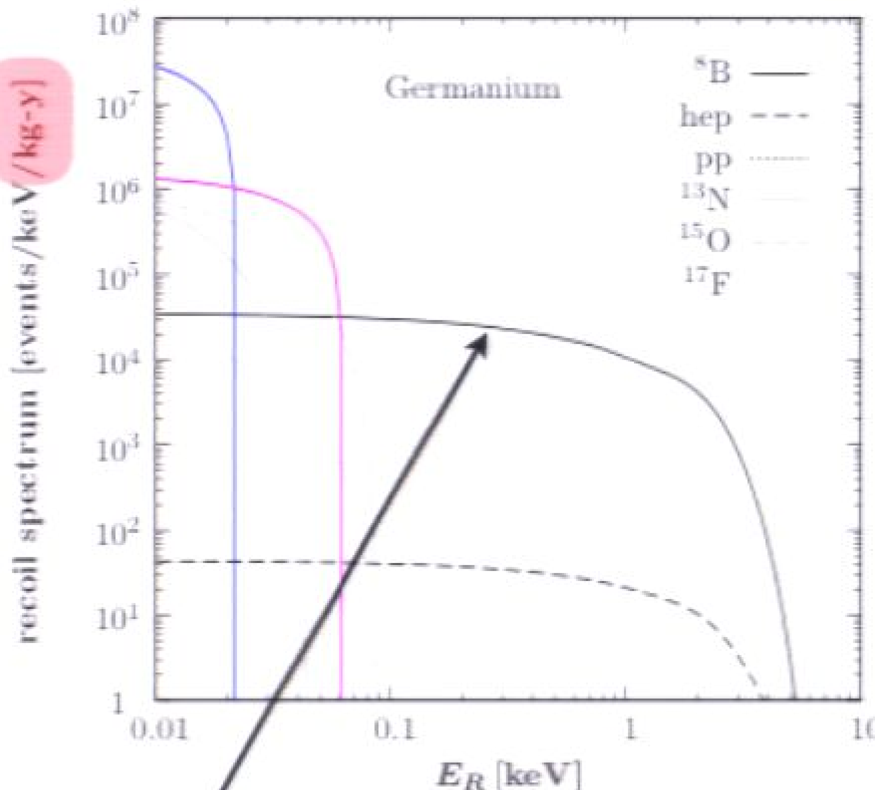

$N_{\rm eff} = 100$

perfect detector)

# direct detection of $\nu_b$




$A_{Ge} = 70 - 76$




$^8$B

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↑

more modulation here

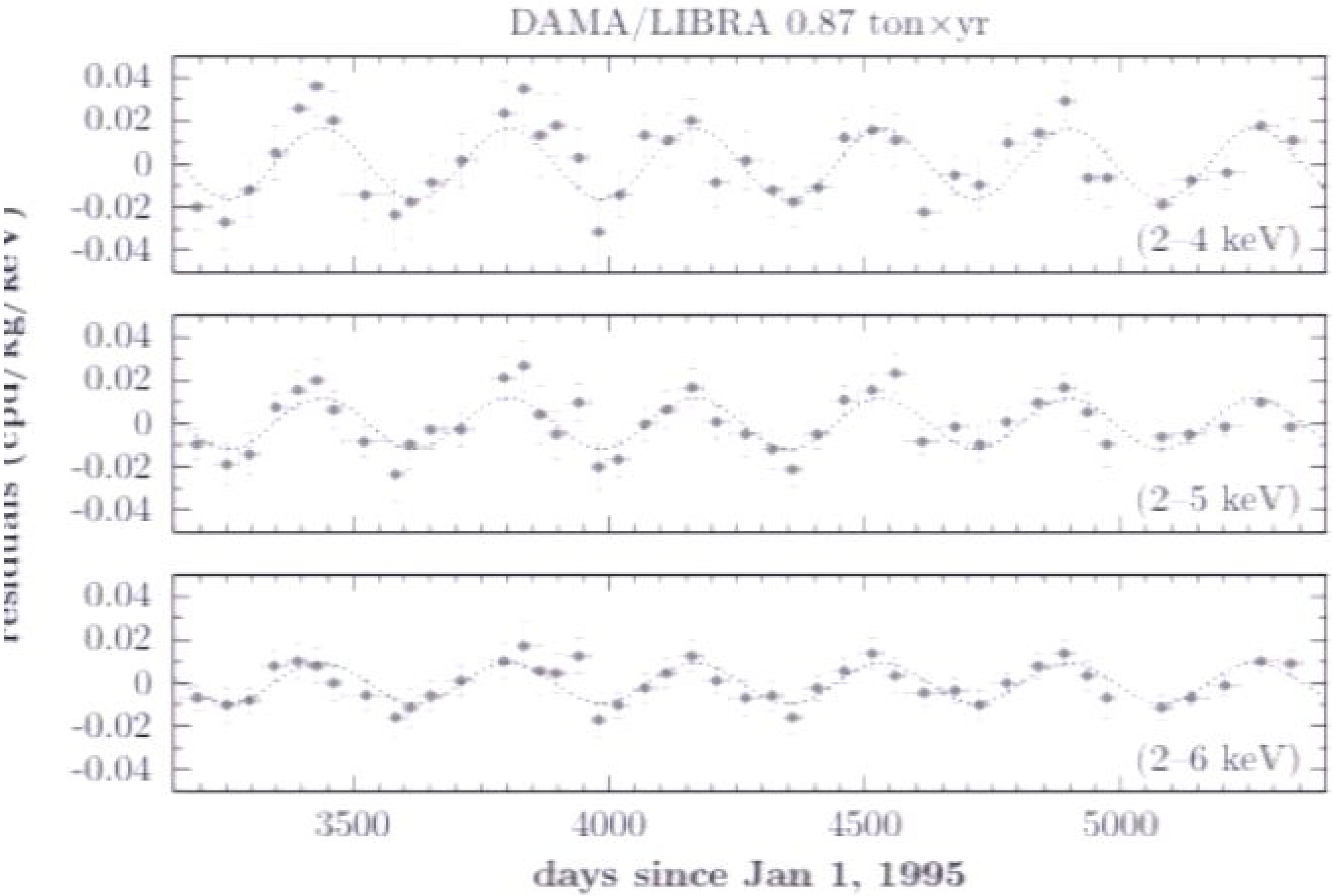
$$\frac{L_{\rm osc}}{L_0} \simeq 0.5 \times \left(\frac{10^{-10}\,{\rm eV}}{\Delta m^2}\right)\left(\frac{E_\nu}{10\,{\rm MeV}}\right)$$

oscillation-length on the order sun-earth distance

=> flip phase for high energy part of the neutrino spectrum!

$\sim 3\%$

# DAMA/LIBRA




- scintillation from NaI-crystals
- 8σ+ modulation
- phase consistent as expected from WIMPs

$t_0 \simeq 2\,\text{June}$

[Bernabei et al. 2010]

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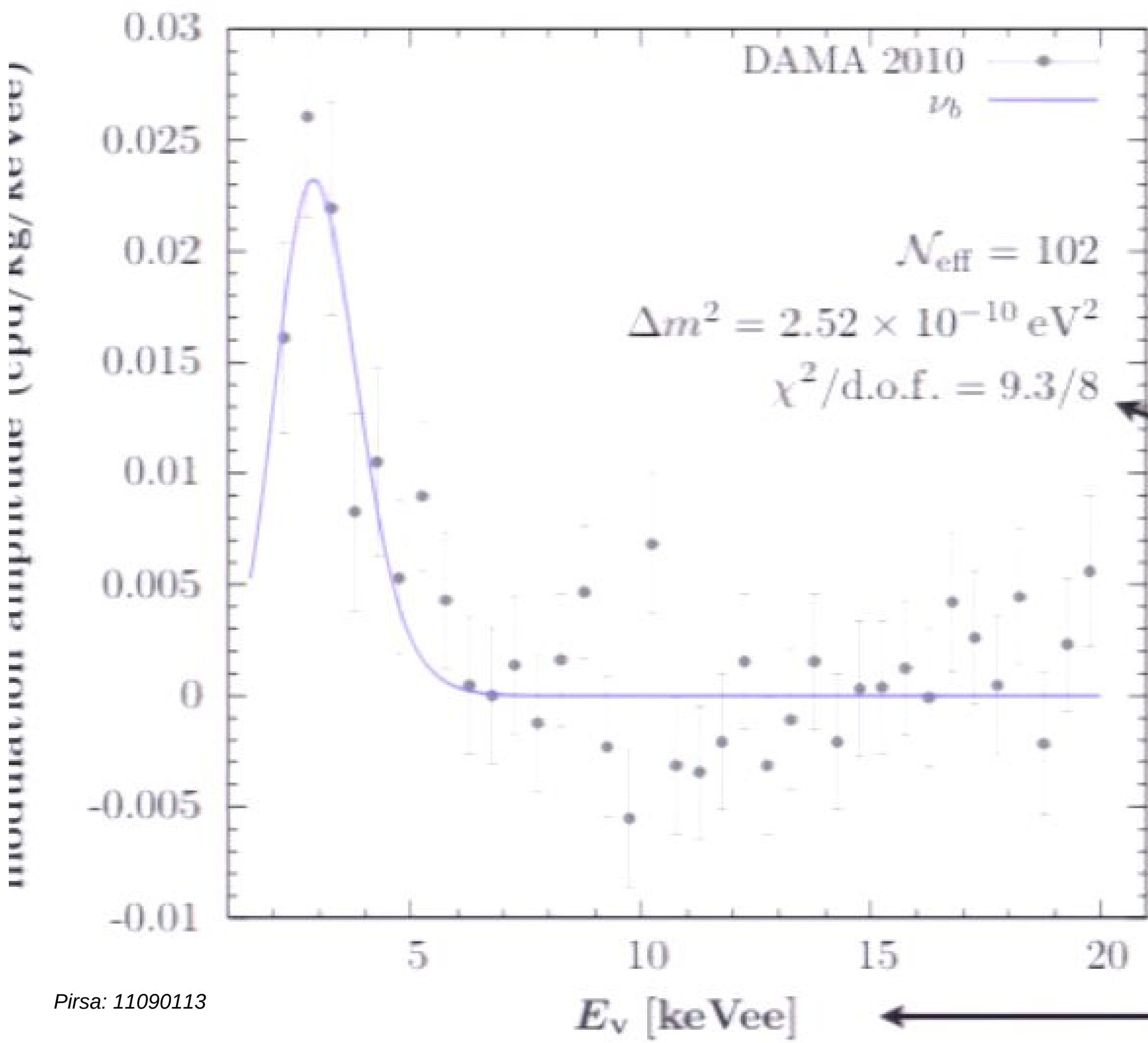
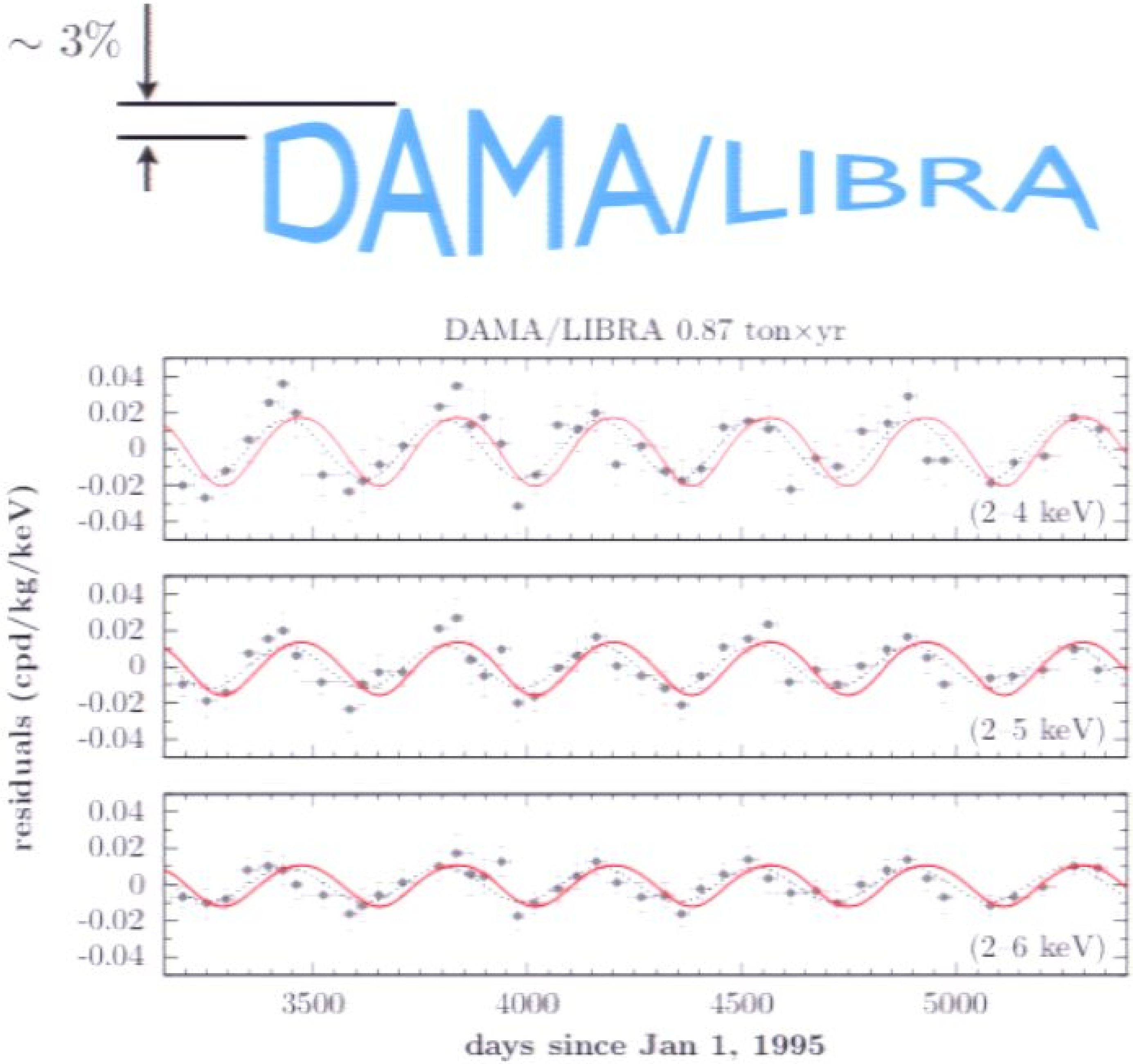



- modulation amplitude

$$S_m = \frac{1}{2}\left( \frac{dR}{dE_\text{v}}\bigg|_{\text{max}} - \frac{dR}{dE_\text{v}}\bigg|_{\text{min}} \right)$$

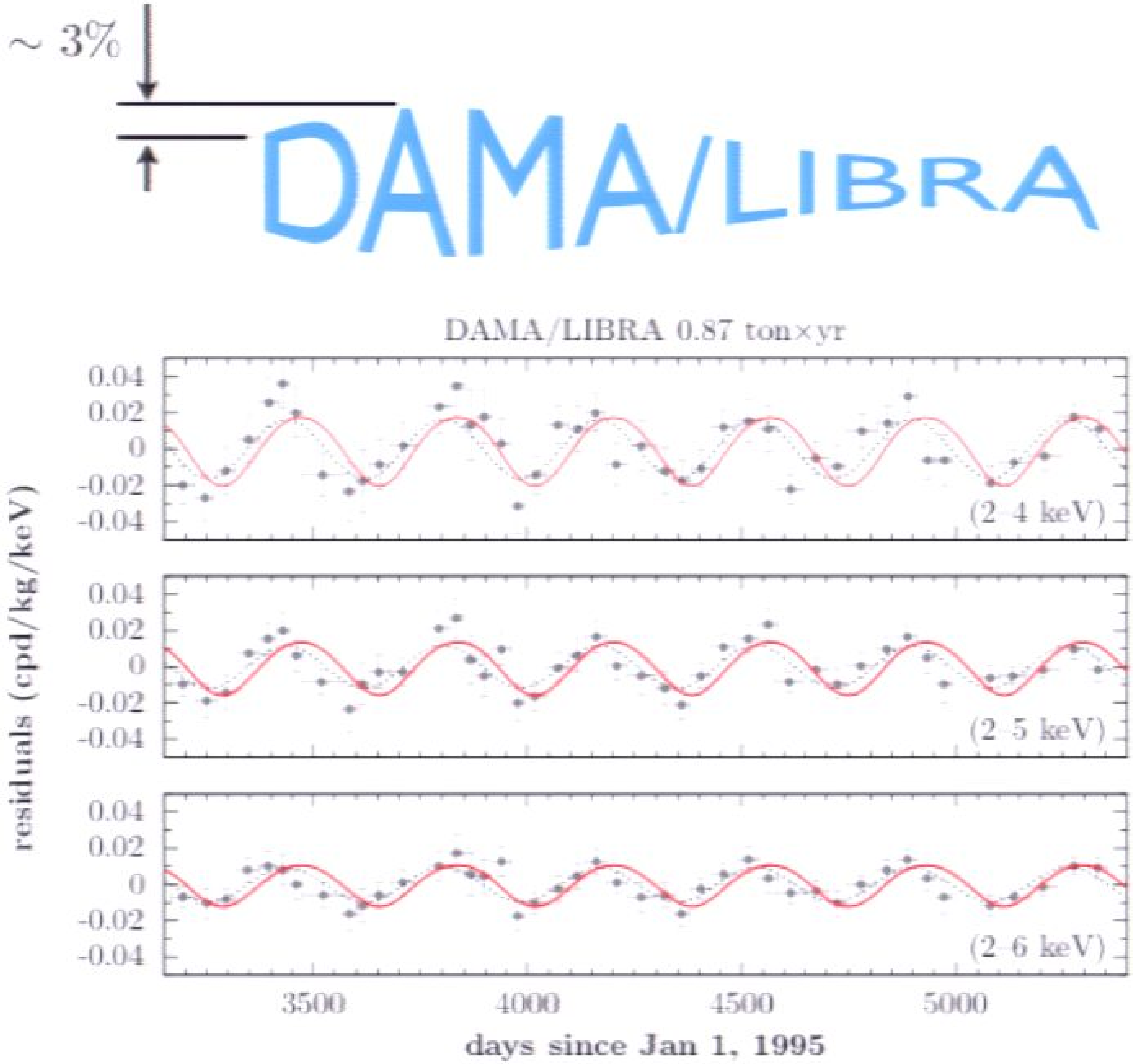
fit only first 10 bins

used Q = 0.3






phase off by ~month!

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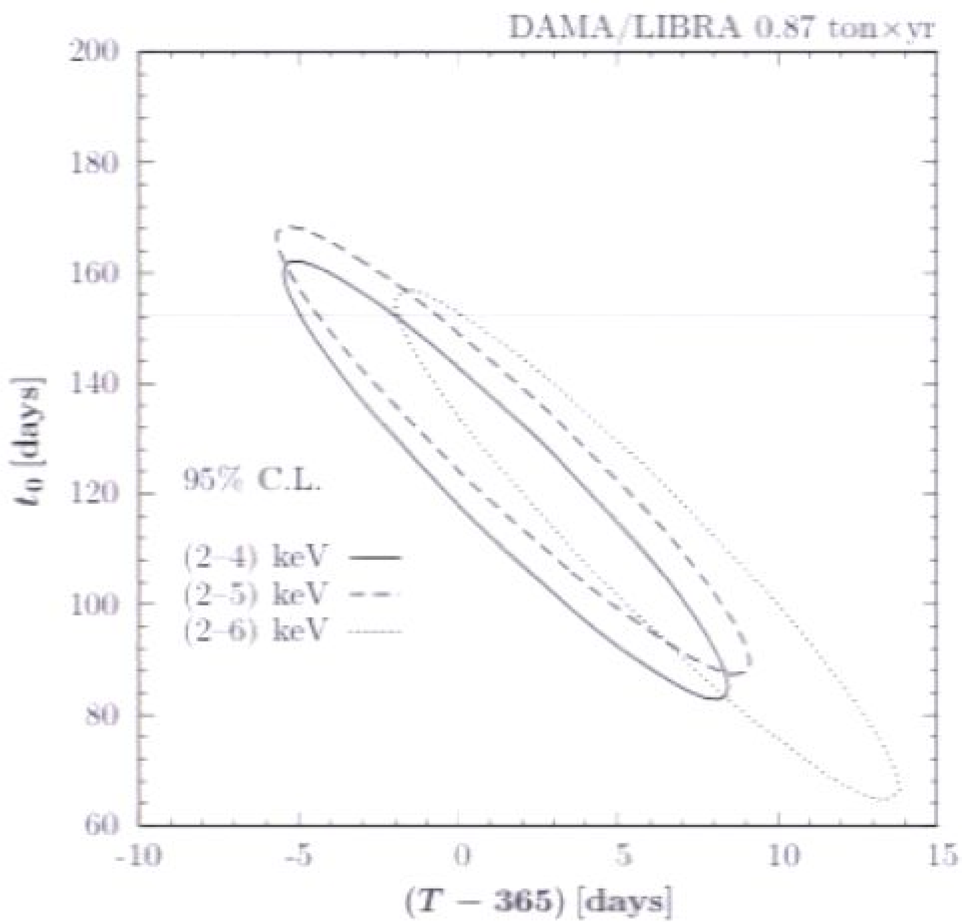
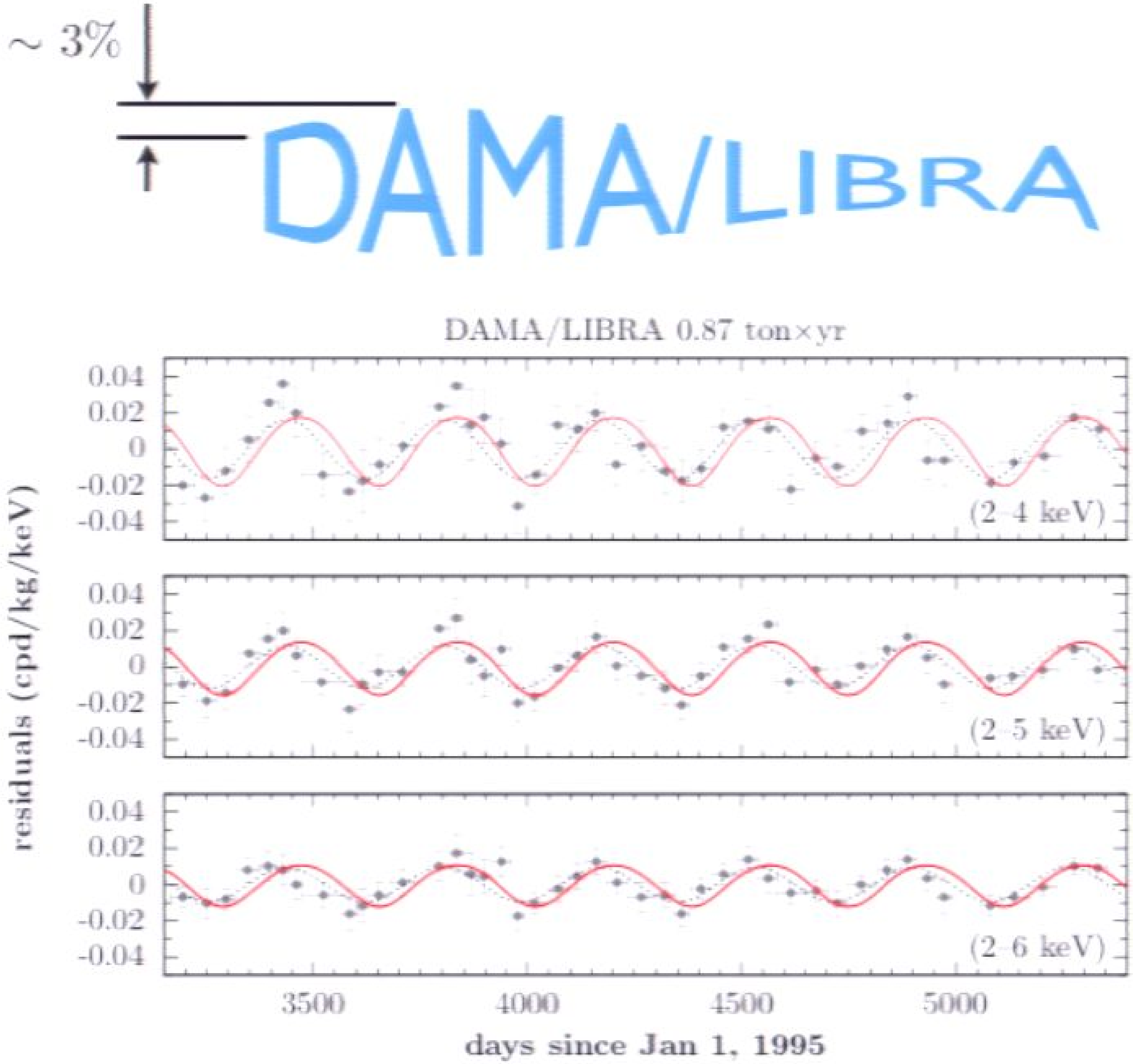



$$f(t) = A\cos\left[\frac{2\pi}{T}(t - t_0)\right]$$

(just for fun)

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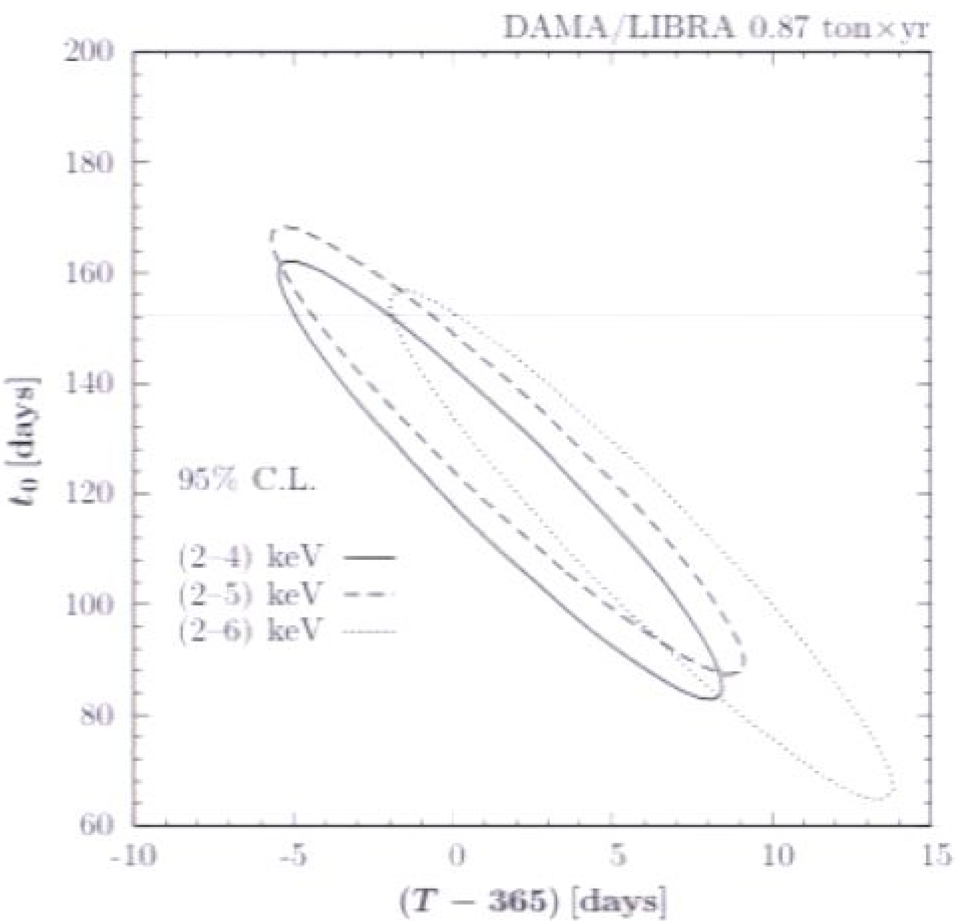


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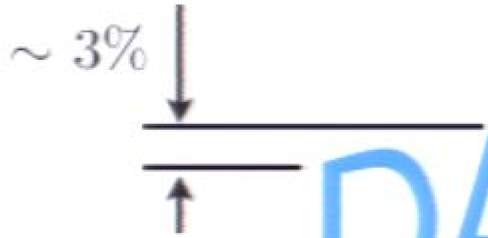


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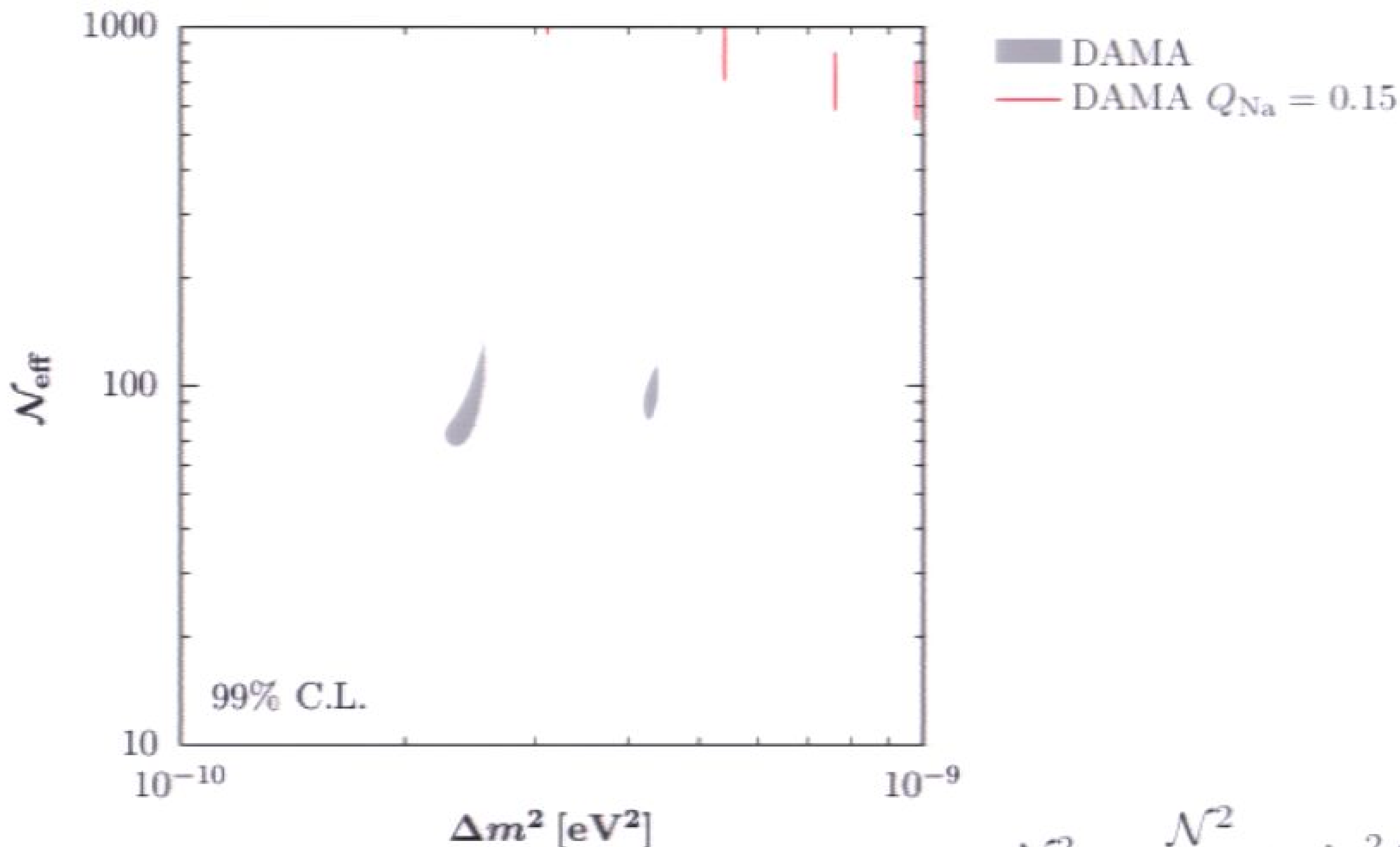


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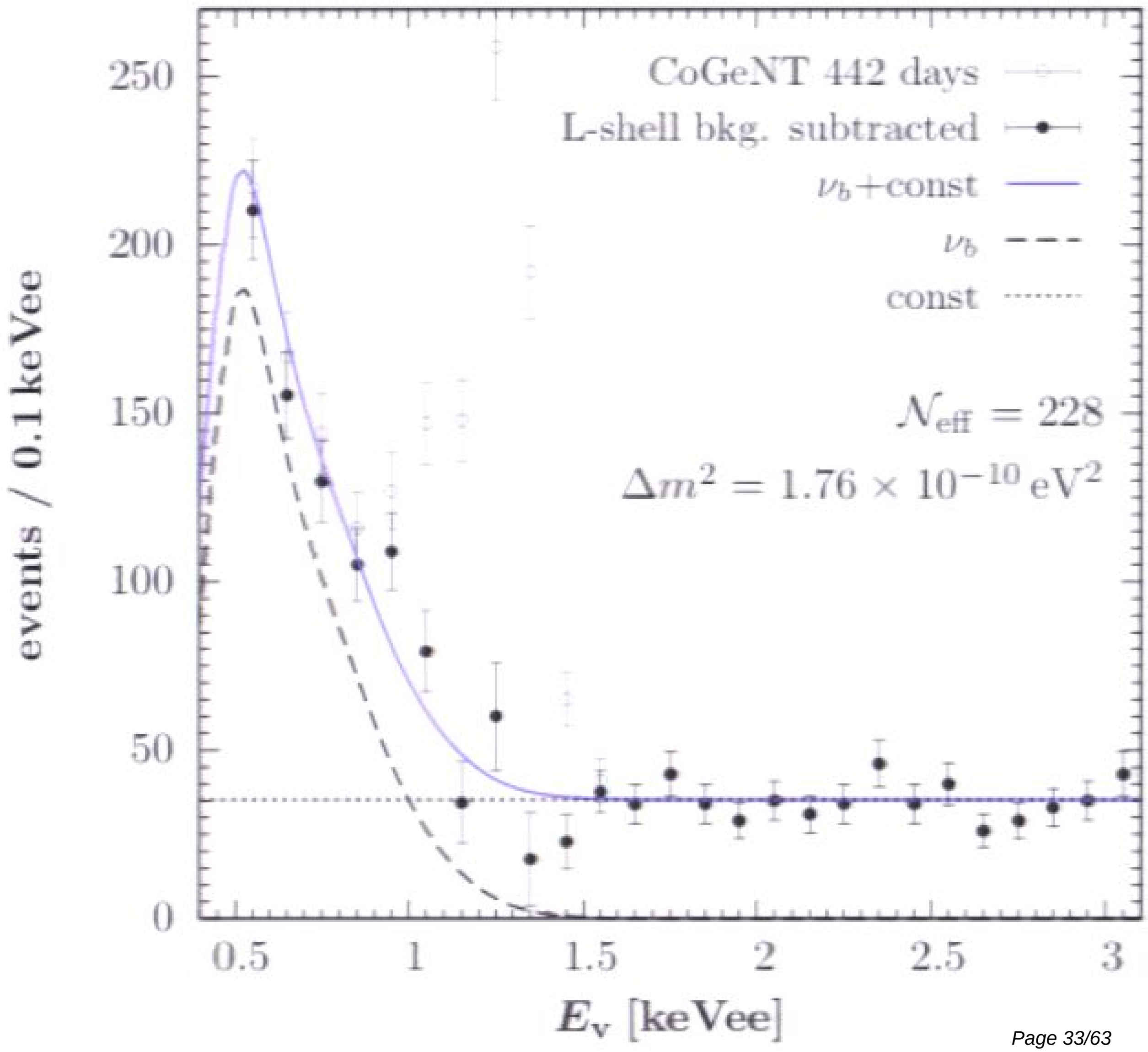
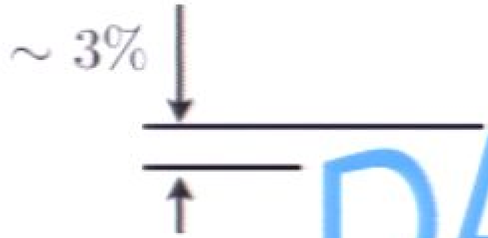



- 442 kg live-days
- Ge-target, ionization
- exponential rise toward low energies
- cosmogenic peaks subtracted
- will not address modulation here!





[Aalseth et al, 2011]

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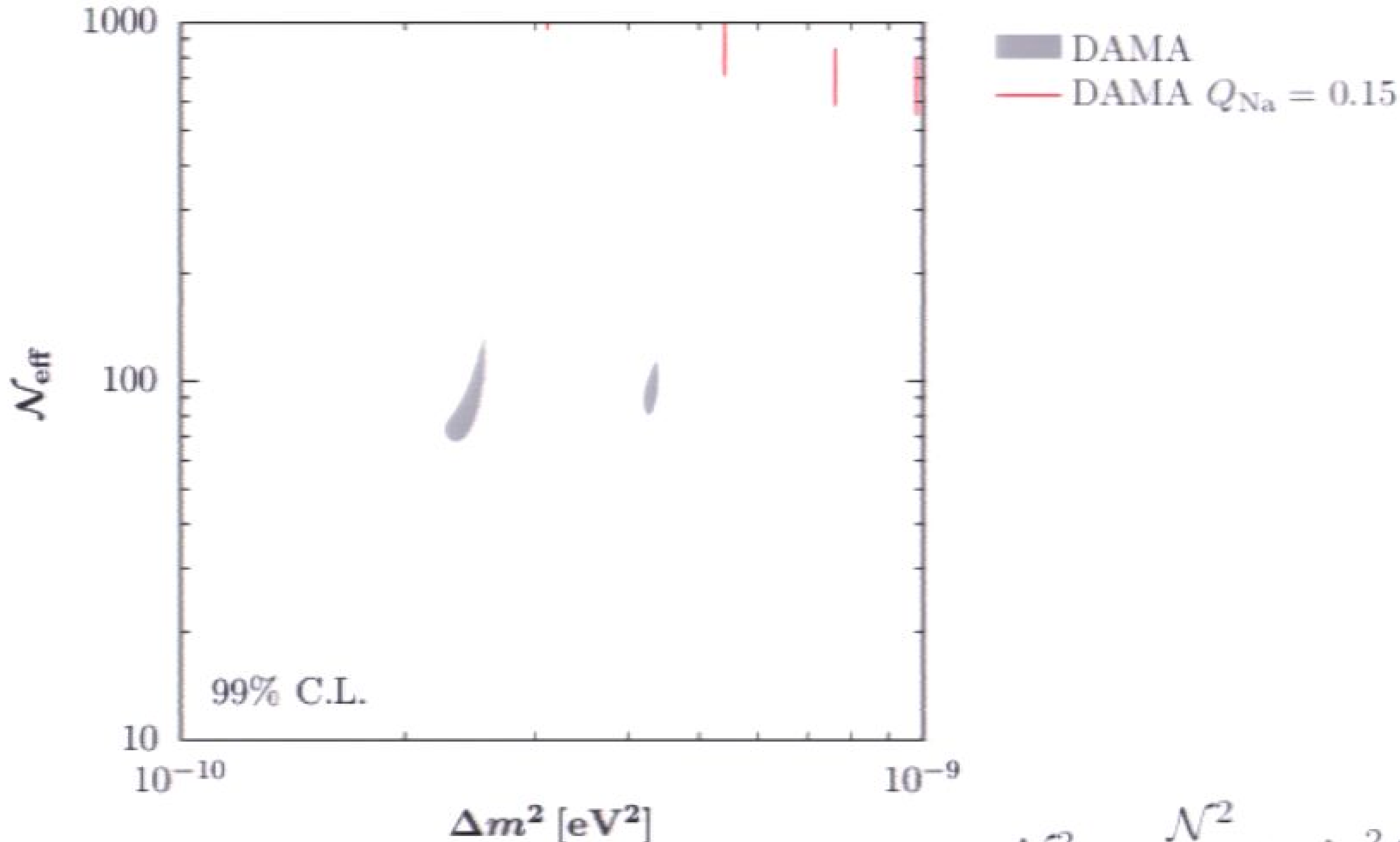


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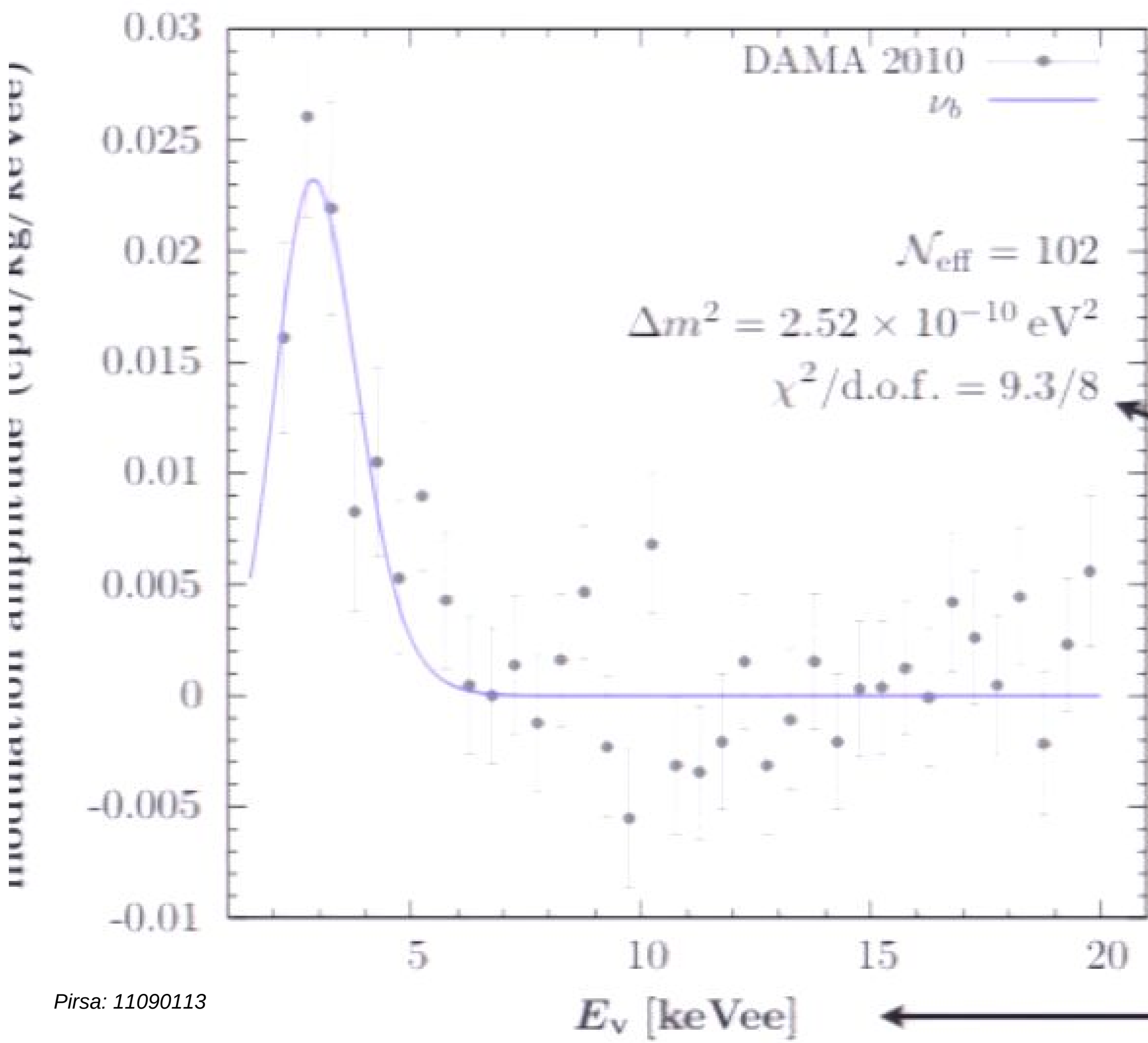


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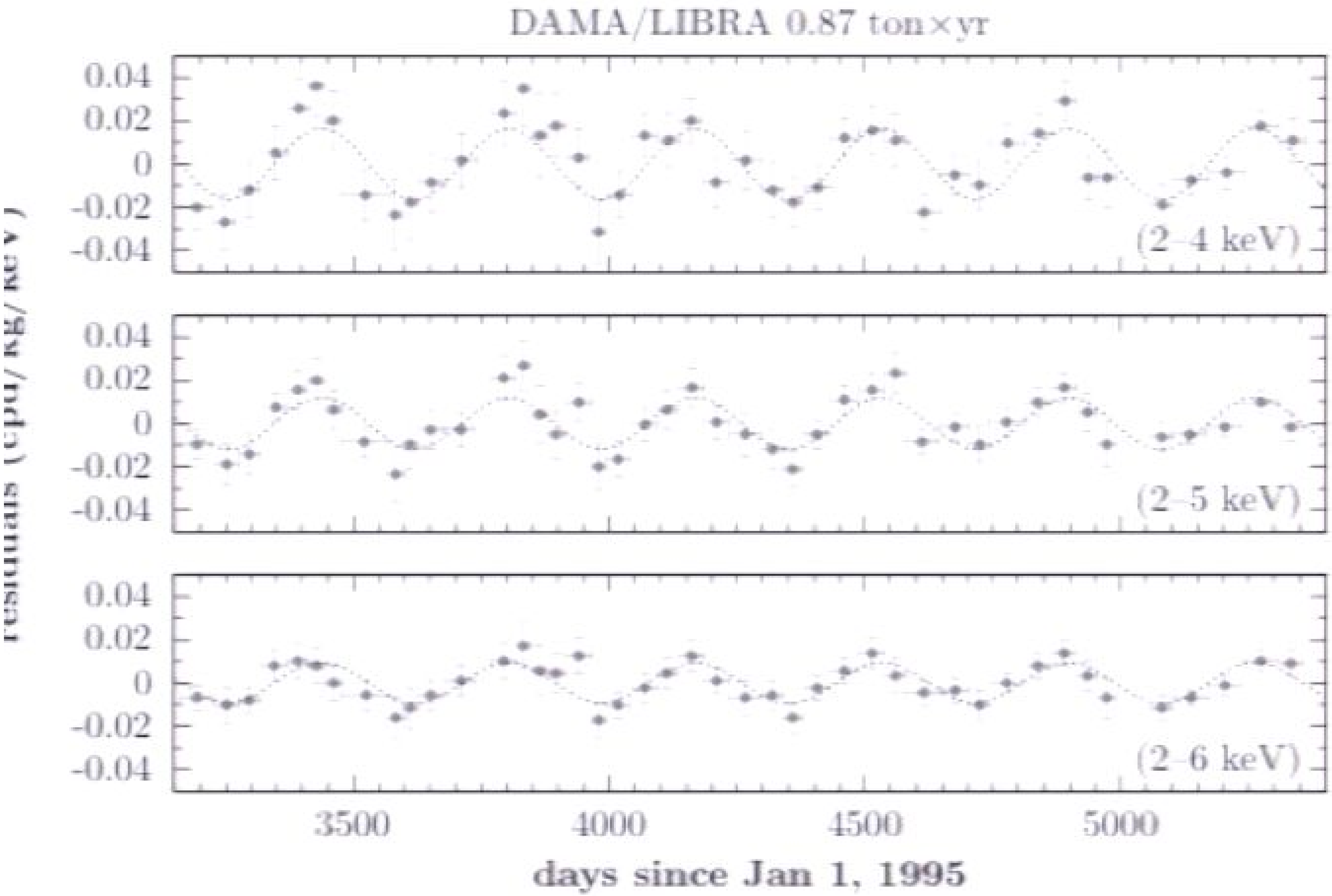


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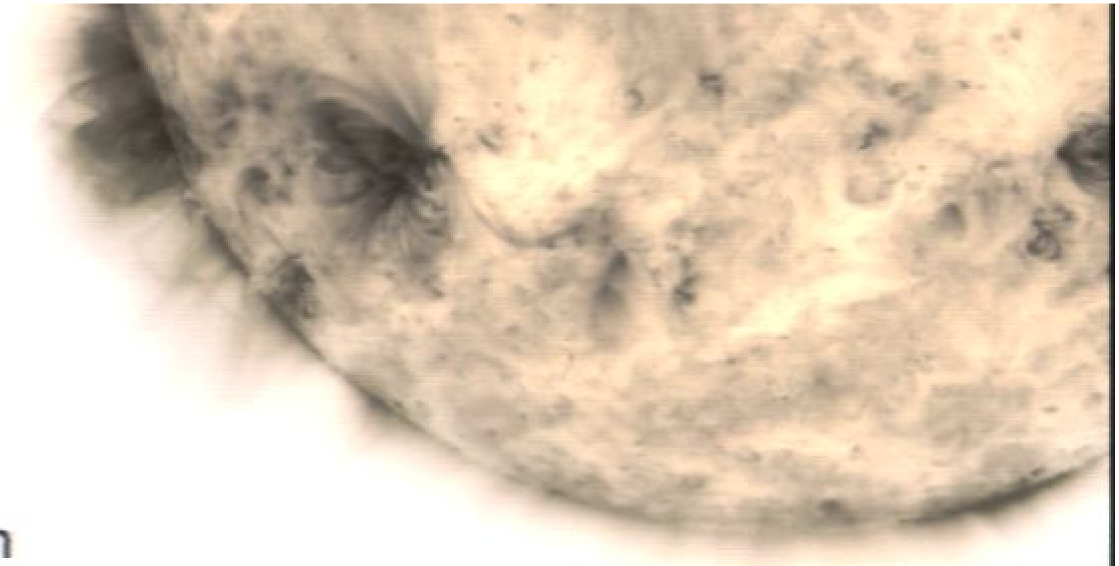
$$L(t) = L_0 \left\{1 - \epsilon \cos\left[\frac{2\pi(t - t_0)}{1\,\mathrm{yr}}\right]\right\}$$

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

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

$\epsilon = 0.0167$ (eccentricity)

# matter effects



- considering such small values in $\Delta m_b^2$ standard solar story unfolds

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

=> see Maxim's talk

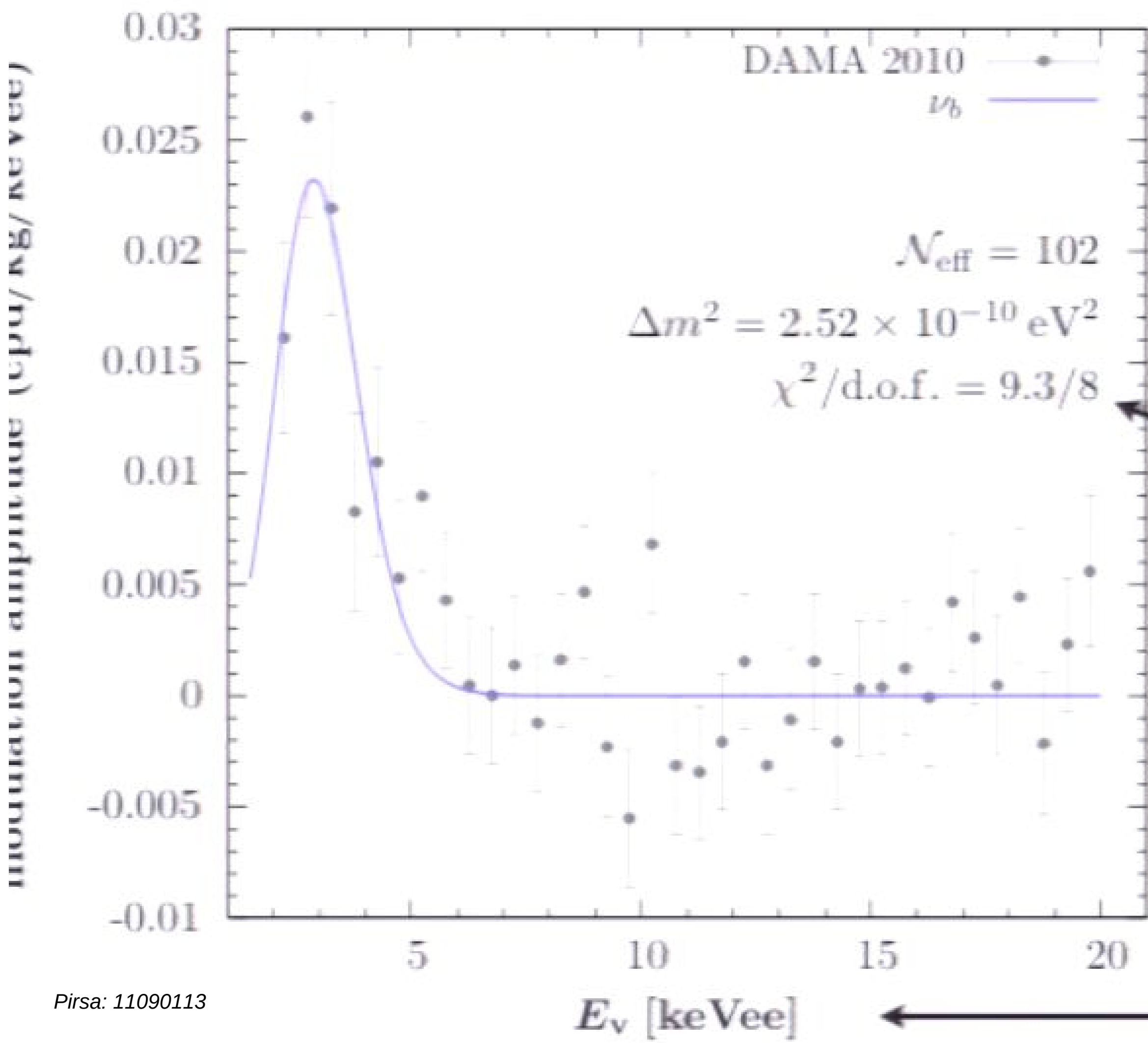
$$\downarrow$$

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

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

$\sim 3\%$

# DAMA/LIBRA




- modulation amplitude

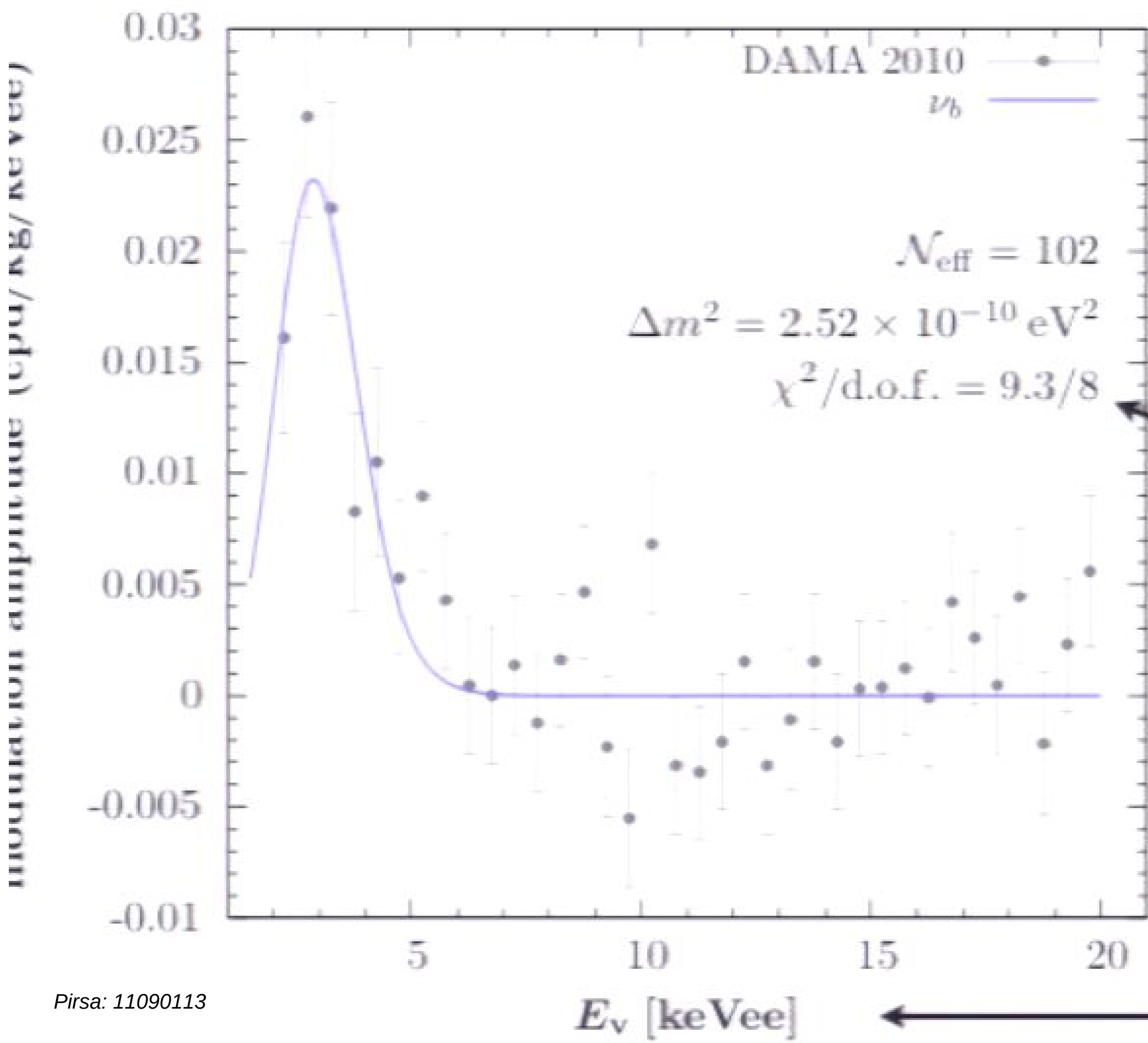
$$S_m = \frac{1}{2}\left( \left.\frac{dR}{dE_{\rm v}}\right|_{\rm max} - \left.\frac{dR}{dE_{\rm v}}\right|_{\rm min} \right)$$

fit only first 10 bins

used Q = 0.3

$\sim 3\%$

# DAMA/LIBRA

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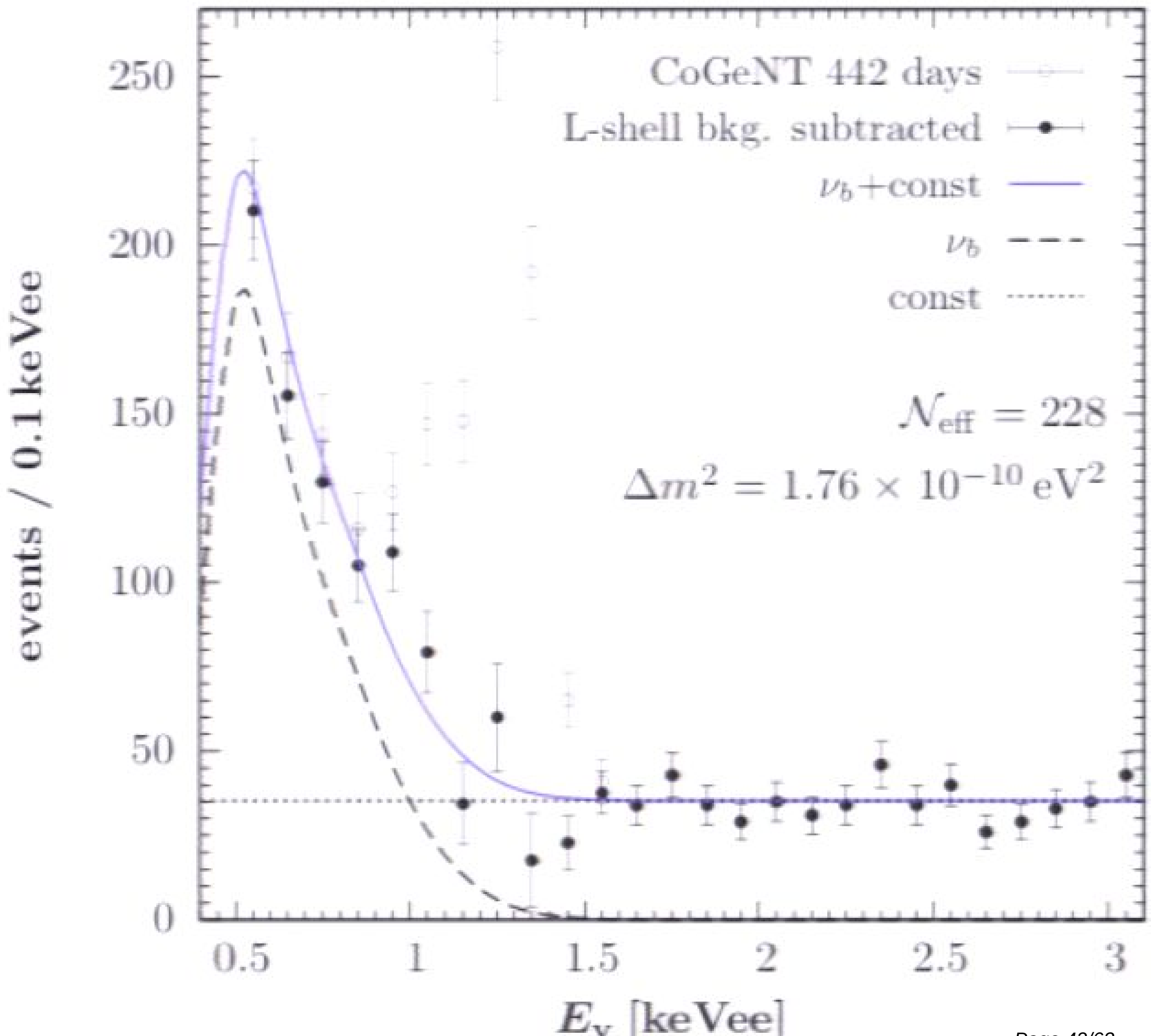
CoGeNT

- 442 kg live-days
- Ge-target, ionization
- exponential rise toward low energies
- cosmogenic peaks subtracted
- will not address modulation here!







[Aalseth et al, 2011]

# CoGeNT

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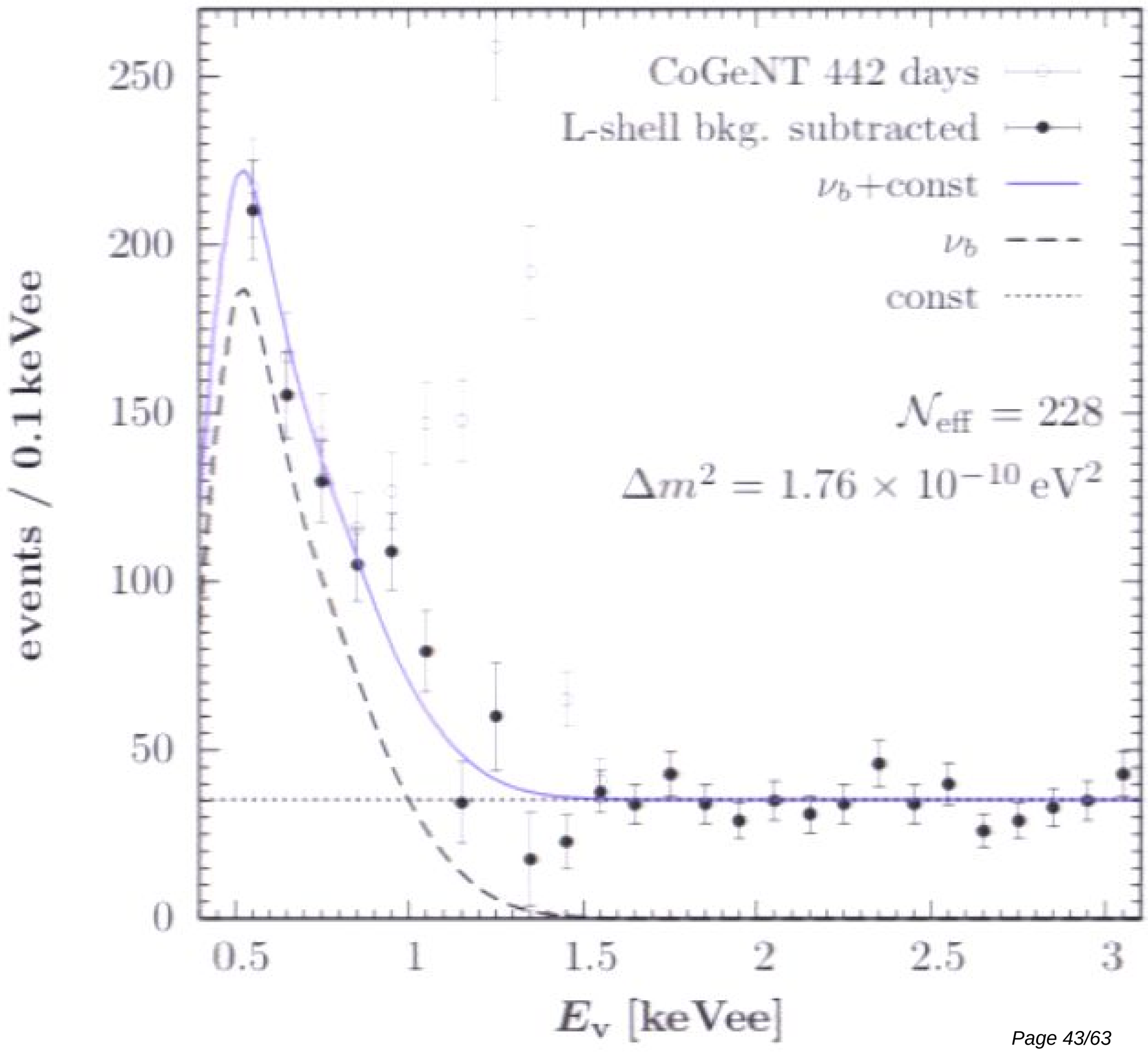
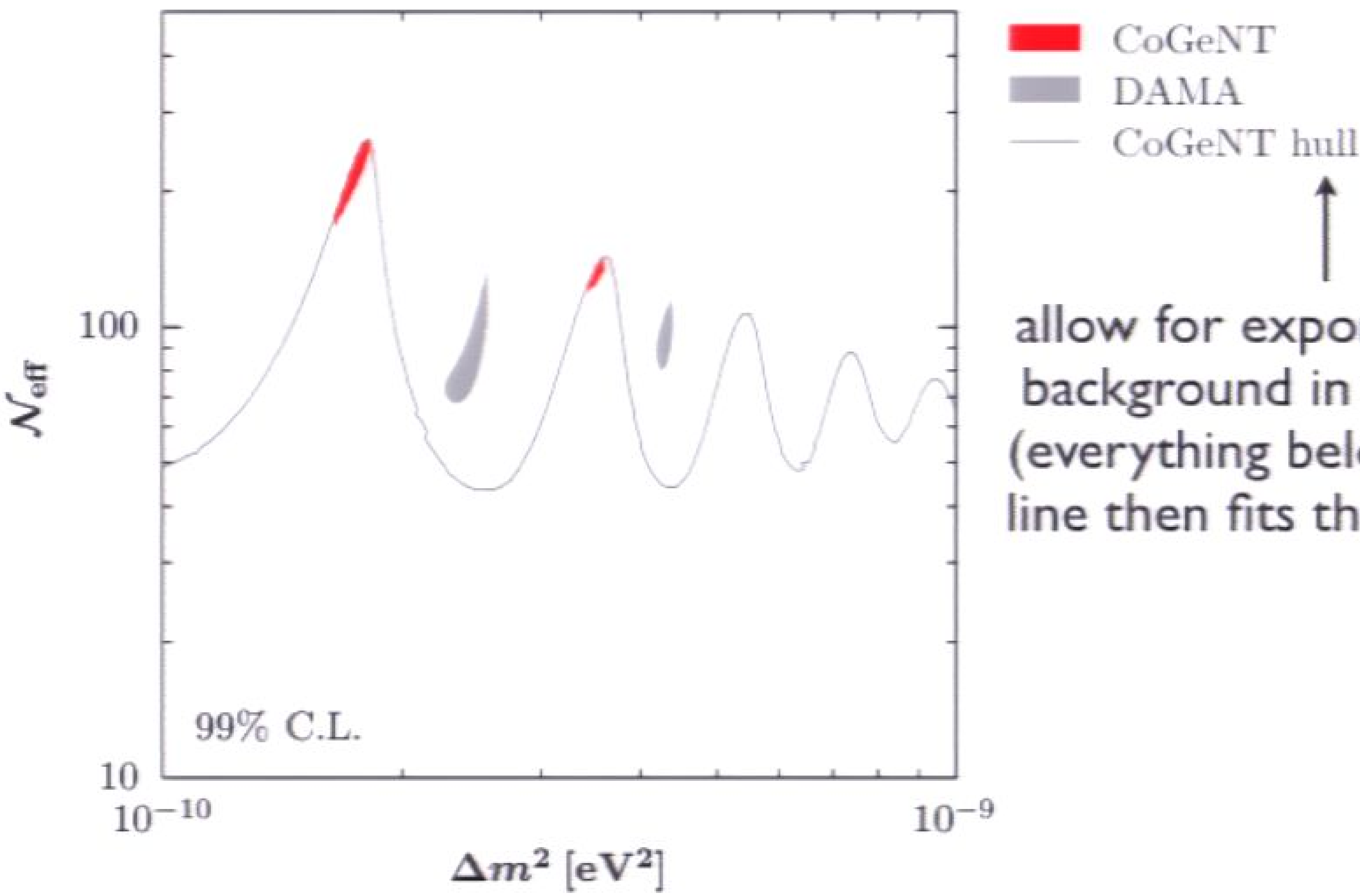





[Aalseth et al, 2011]

# CoGeNT

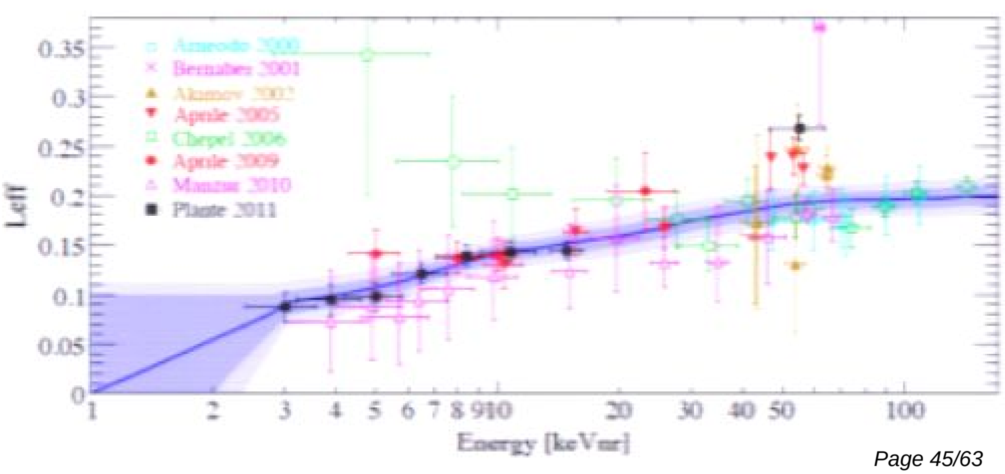



allow for exponential background in the fit (everything below the line then fits the data)

# constraints: XENON100

- 100.9 live-days x 48 kg fiducial;
- 3 events in acceptance region; use "maximum gap" method to set limit
- require S1 $\geq$ 4PE's (scintillation); account for quality and ER rejection cuts; smear with Poissonian resolution
- use $\mathcal{L}_{\rm eff}$ extrapolated to 0 at 2keV

$$S1(E_R) = 3.6\,\mathrm{PE} \times E_R \times \mathcal{L}_{\rm eff}$$








[Aprile et al. 2010]

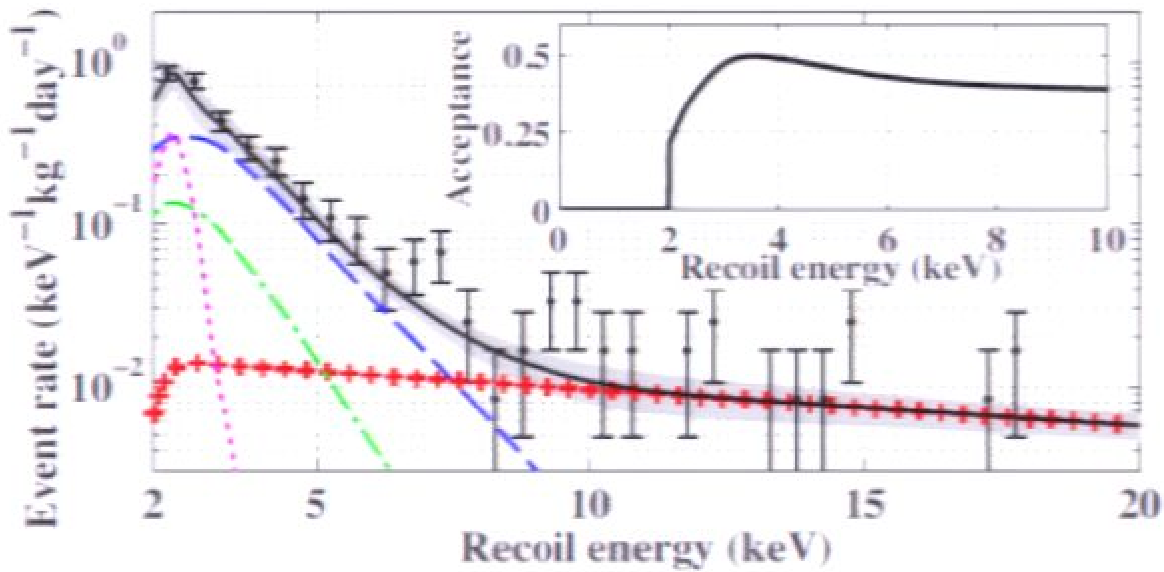
# constraints: CDMS-II low thresh.

- use data from Ge-detectors (same target as CoGeNT)
- "binned Poisson" technique ⟷ sensitivity to $\nu_b$

$$1-\alpha = (1-\alpha_{\rm bin})^{N_{\rm bin}}$$

↑

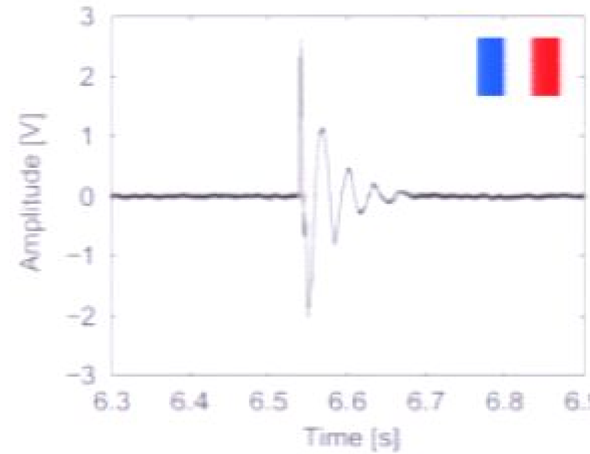
probability to see as few events as observed in one bin




[Z. Ahmed et al, 2010]

(more sophisticated ways to treat detectors may lead to stronger limits)

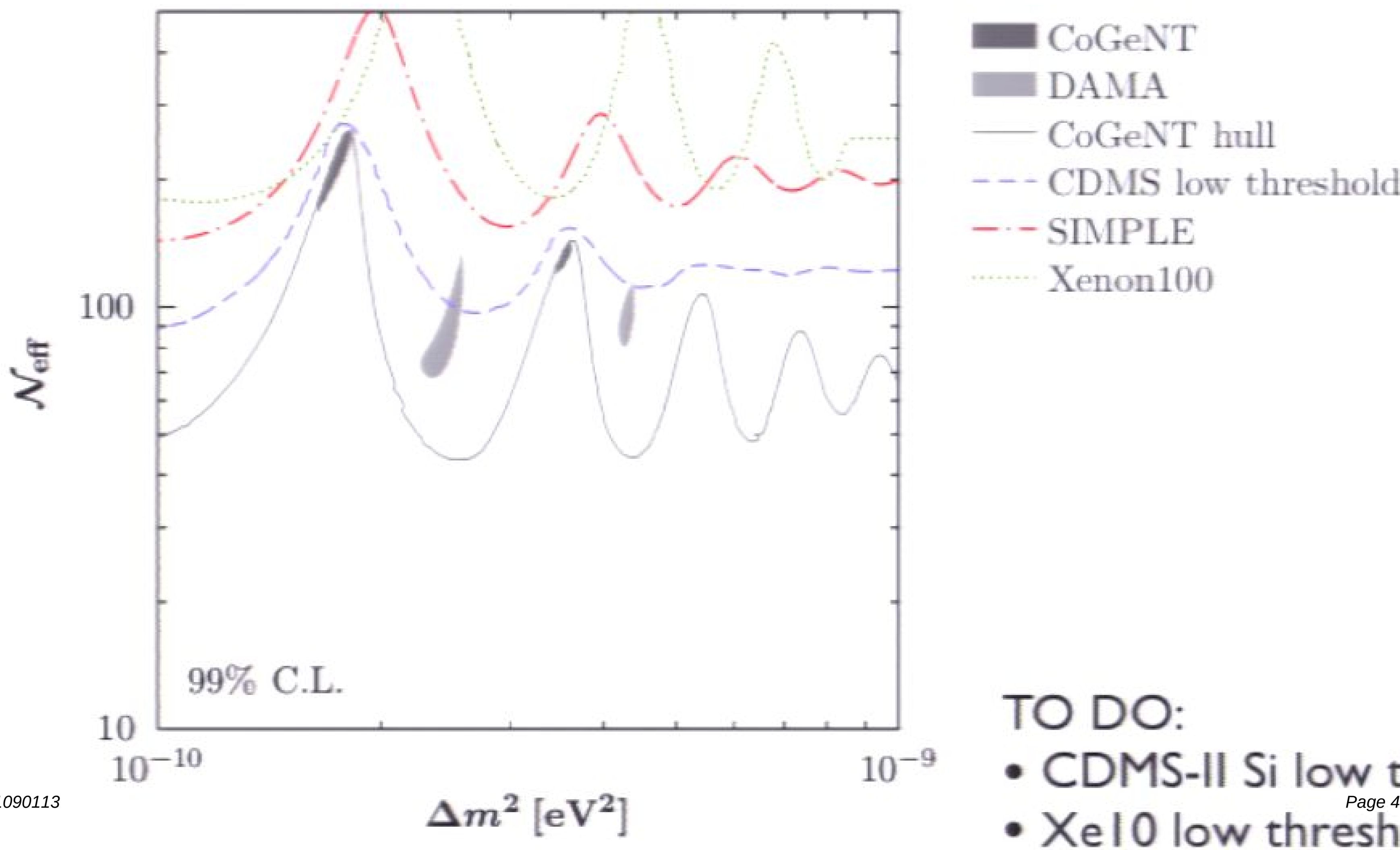
# constraints: SIMPLE




- superheated droplets from $C_2ClF_5$ (total active mass ~0.2kg)
- light target! use exposure 14.8 kg days (Stage I of Phase II)
- threshold ~ 8 keV
- observed: 9 events; expected (neutron) background ~12
- include heat transfer and bubble nucleation efficiency
- we use simple Poisson on Stage I including bkg.

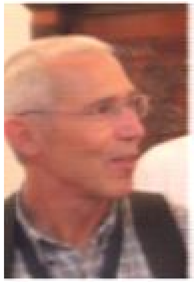
[Felizardo et al, 2011]

# constraints from 'null' searches




TO DO:

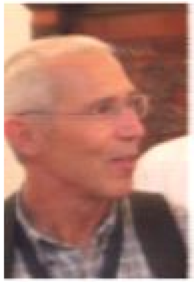
- CDMS-II Si low thr.
- Xe10 low threshold



# Results from 730 kg days of the CRESST-II Dark Matter Search

G. Angloher[1], M. Bauer[2], I. Bavykina[1], A. Bento[1,5], C. Bucci[3], C. Ciemniak[4], G. Deuter[2], F. von Feilitzsch[4], D. Hauff[1], P. Huff[1], C. Isaila[4], J. Jochum[2], M. Kiefer[1], M. Kimmerle[2], J.-C. Lanfranchi[4], F. Petricca[1], S. Pfister[4], W. Potzel[4], F. Pröbst[1a], F. Reindl[1], S. Roth[4], K. Rottler[2], C. Sailer[2], K. Schäffner[1], J. Schmaler[1b], S. Scholl[2], W. Seidel[1], M. v. Sivers[4], L. Stodolsky[1], C. Strandhagen[2], R. Strauß[4], A. Tanzke[1], I. Usherov[2], S. Wawoczny[4], M. Willers[4], and A. Zöller[4]

arXiv:1109.0702



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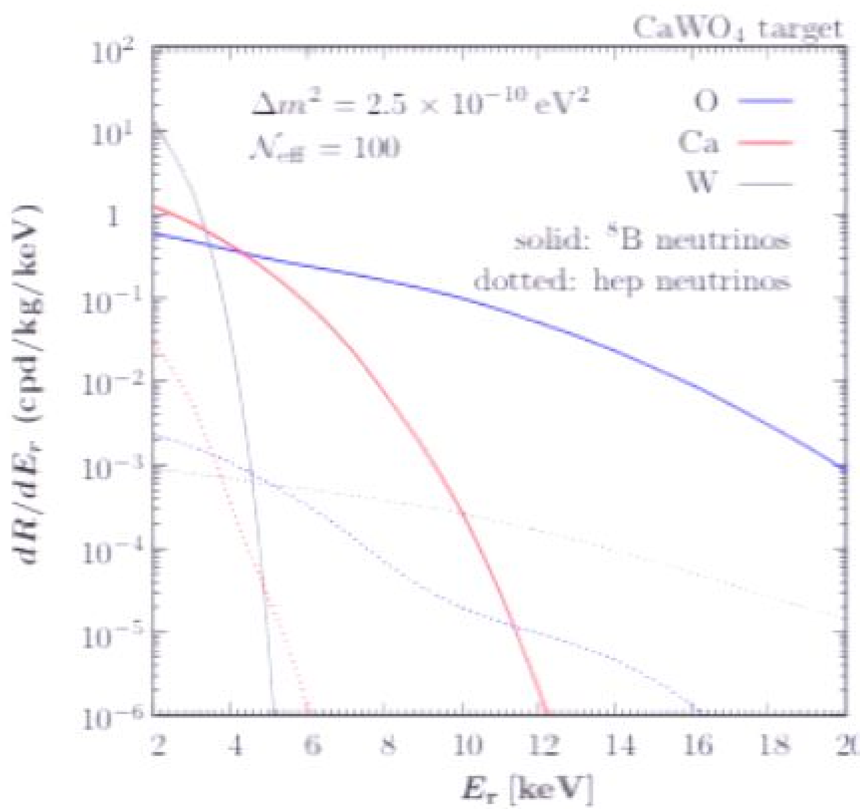
# CRESST --- a neutrino$_b$ observatory?



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arXiv:1109.0702

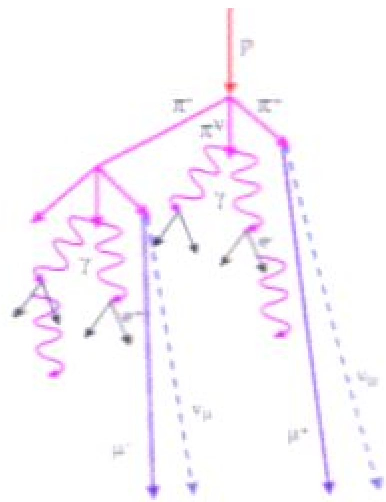
# CRESST --- a neutrino$_b$ observatory?

- in the first place CRESST is an observatory for murky backgrounds.
- 8 $CaWO_4$ crystals, total of 730 kg days effective exposure
- measure scintillation light and phonons from nuclear recoil
- in a nutshell: 67 events in acceptance region; only half of which they can attribute to backgrounds.

=> assess the viability of a signal we have to deal with the backgrounds (at least in some minimal way)

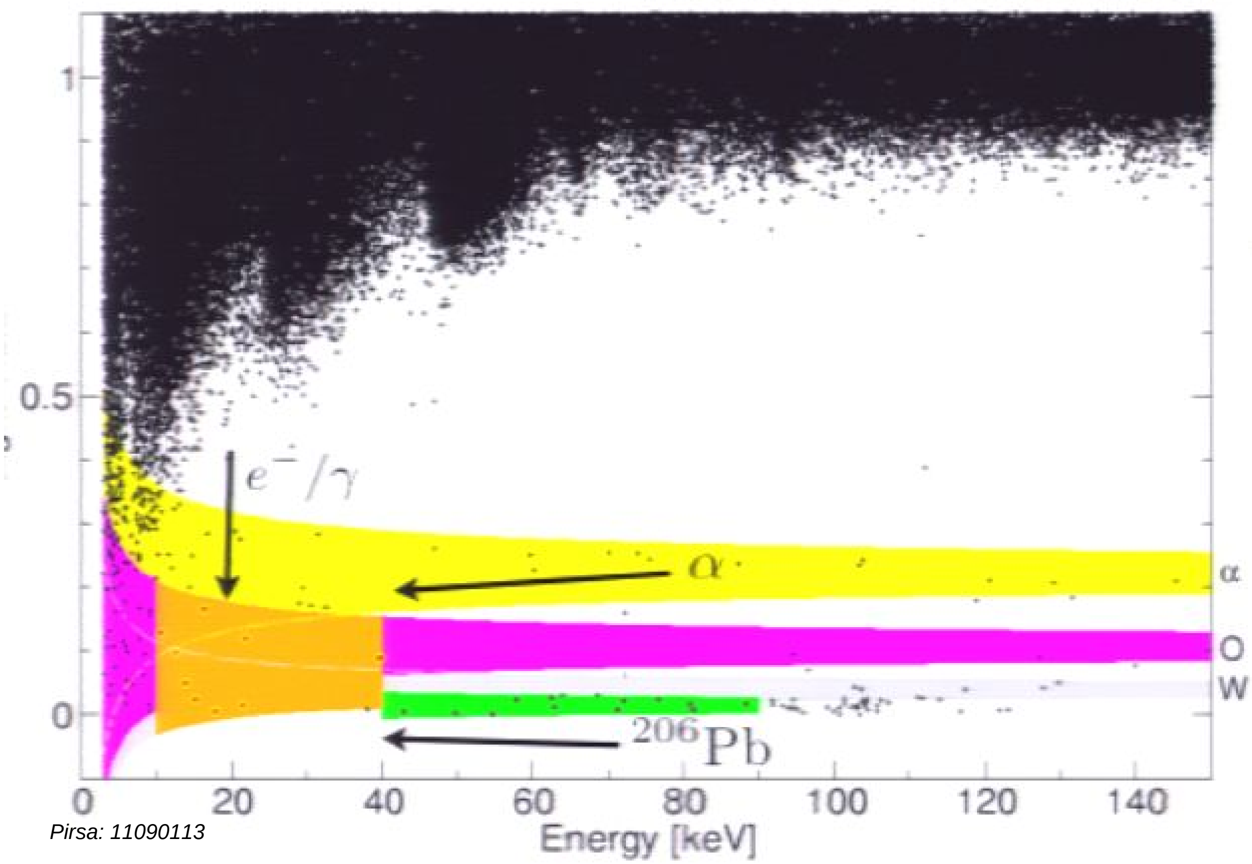
# CRESST

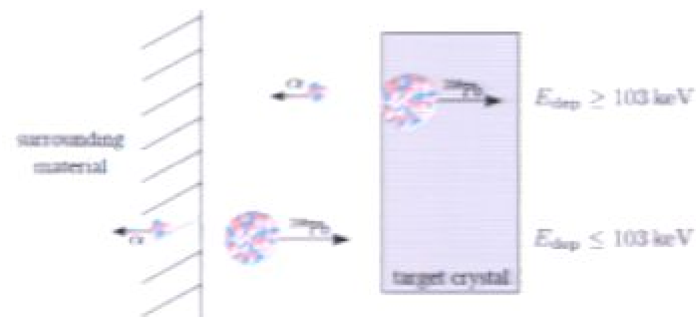
backgrounds




$n$

(one of 8 detector modules)




$$^{210}\mathrm{Po} \rightarrow {}^{206}\mathrm{Pb} + \alpha$$

in or on the surface of the clamps holding the crytals

# CRESST

## backgrounds


this is what
they need

# CRESST

backgrounds


this is what
they need

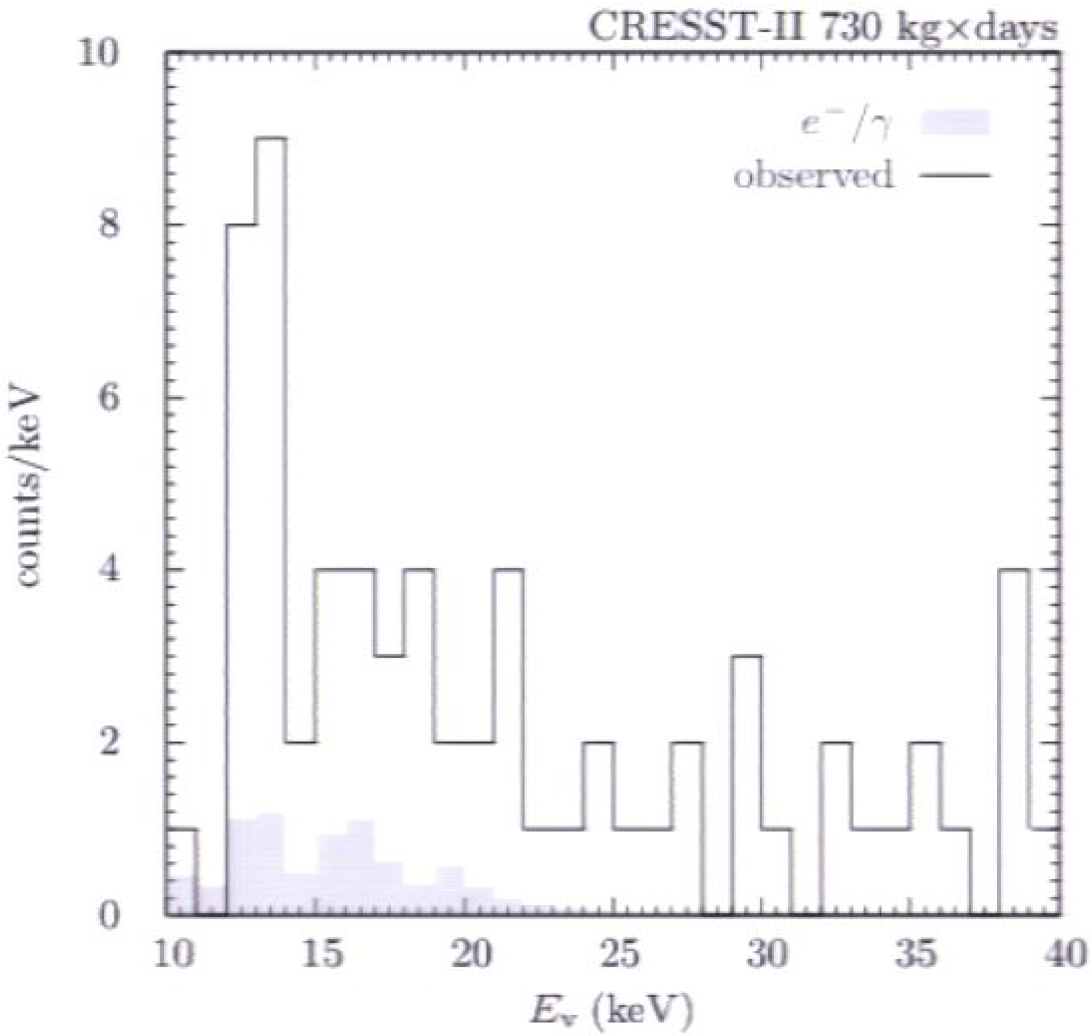
\+  better brackets

# CRESST

fits

- we follow CRESST in their modelling of backgrounds

=> e/gamma events known
=> others essentially flat distributed!!



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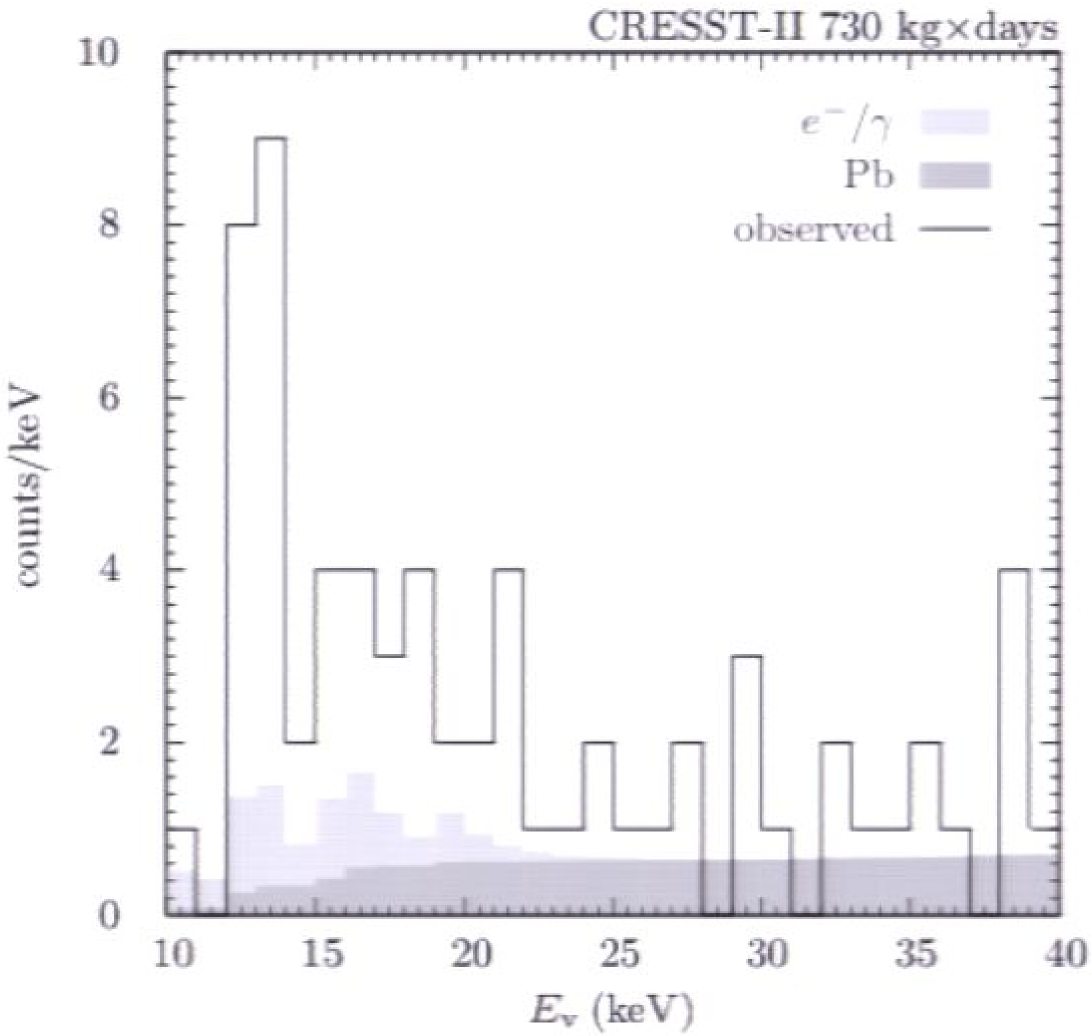

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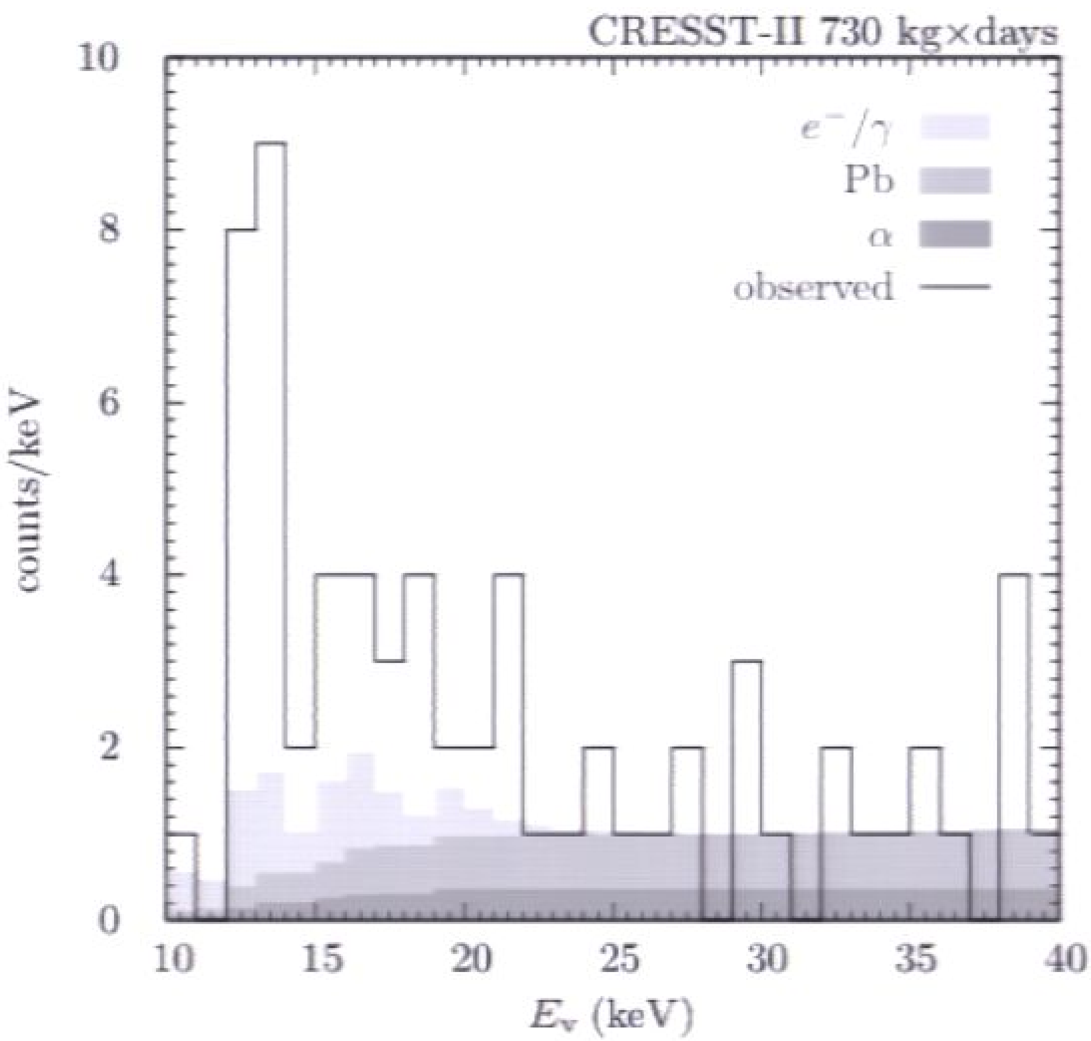

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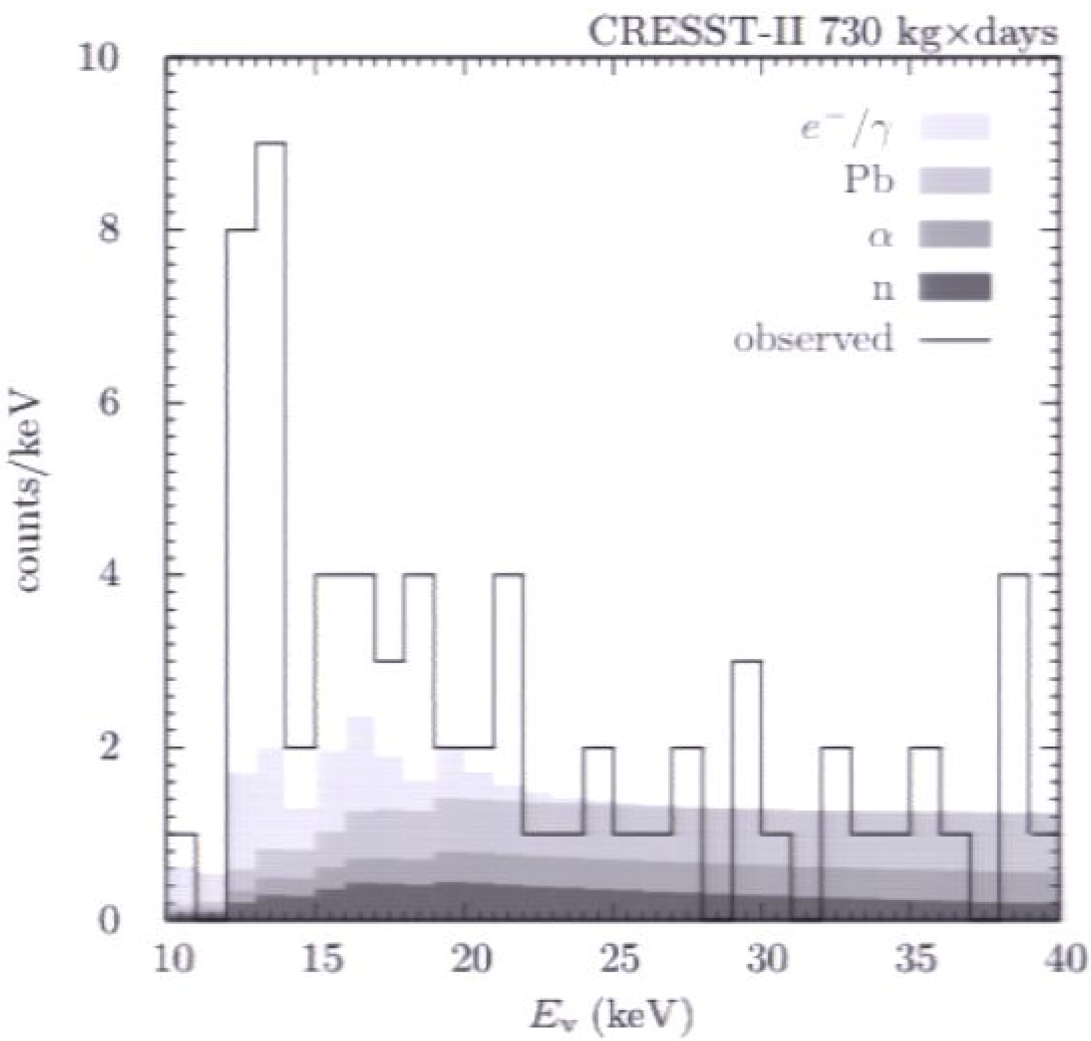


# CRESST

fits

- we follow CRESST in their modelling of backgrounds

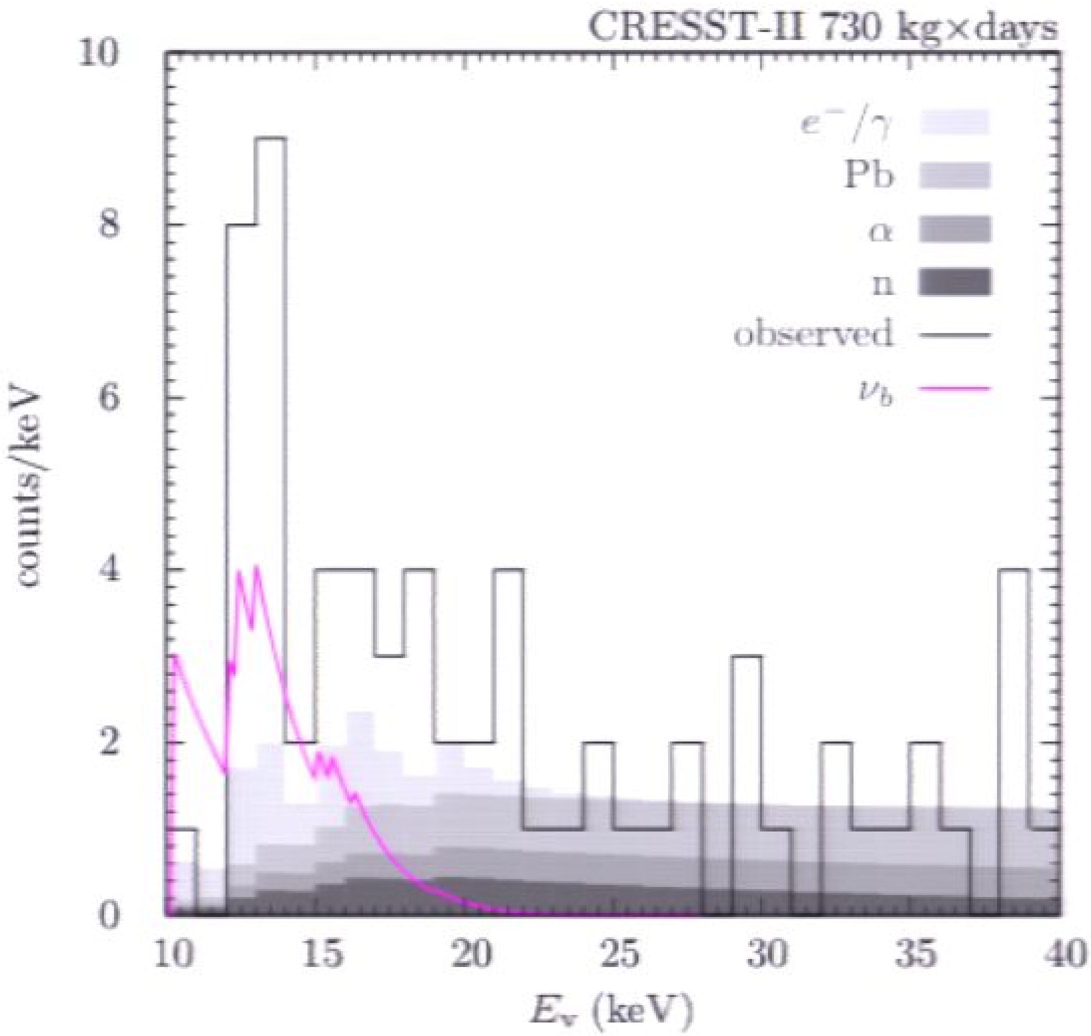
  => e/gamma events known
  => others essentially flat distributed!!

- use Poisson log-Likelihood to fit $\nu_b$

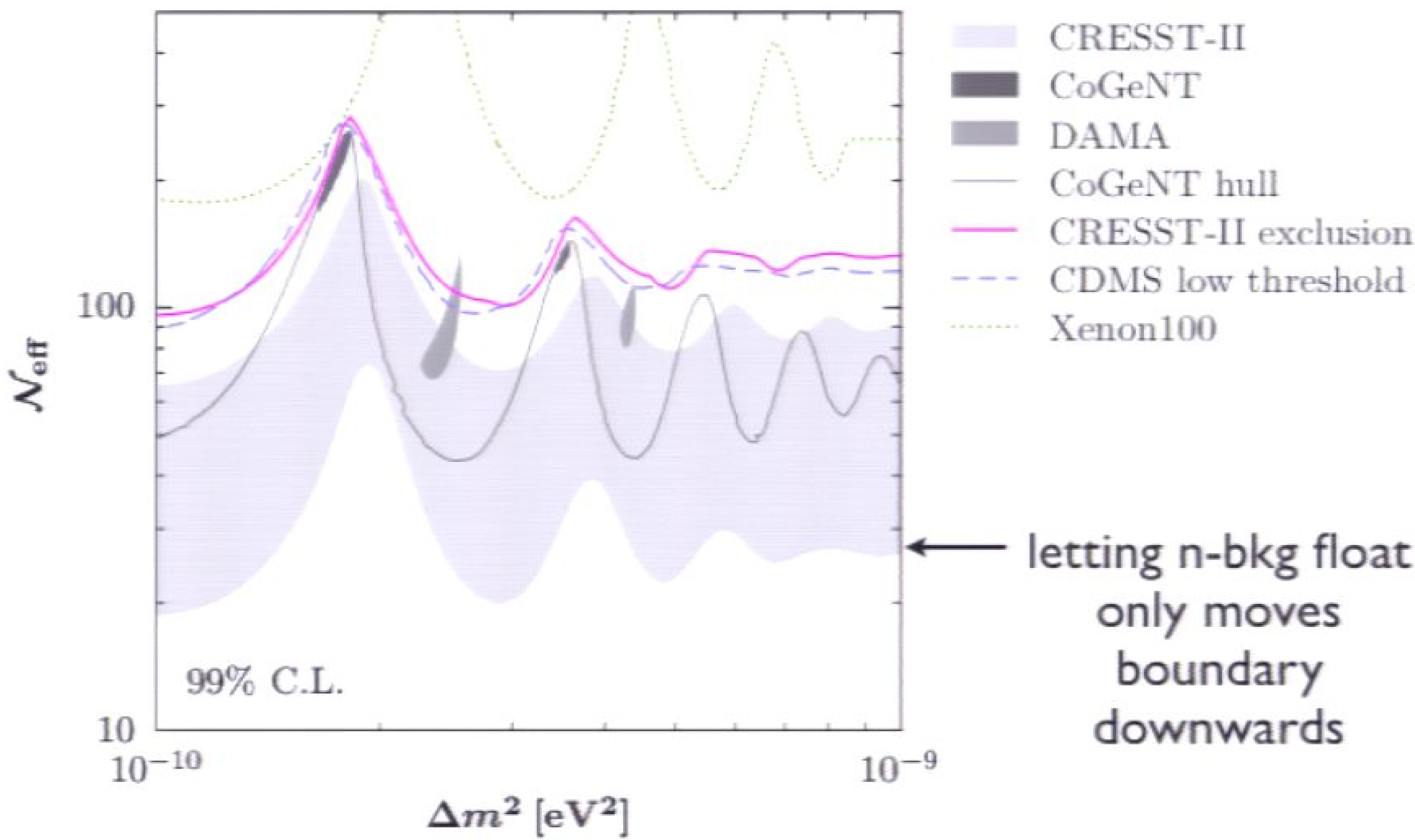
$$\chi_P^2 = 2\sum_i \left[ y_i - n_i + n_i \ln\left(\frac{n_i}{y_i}\right)\right]$$

- best fit yields

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



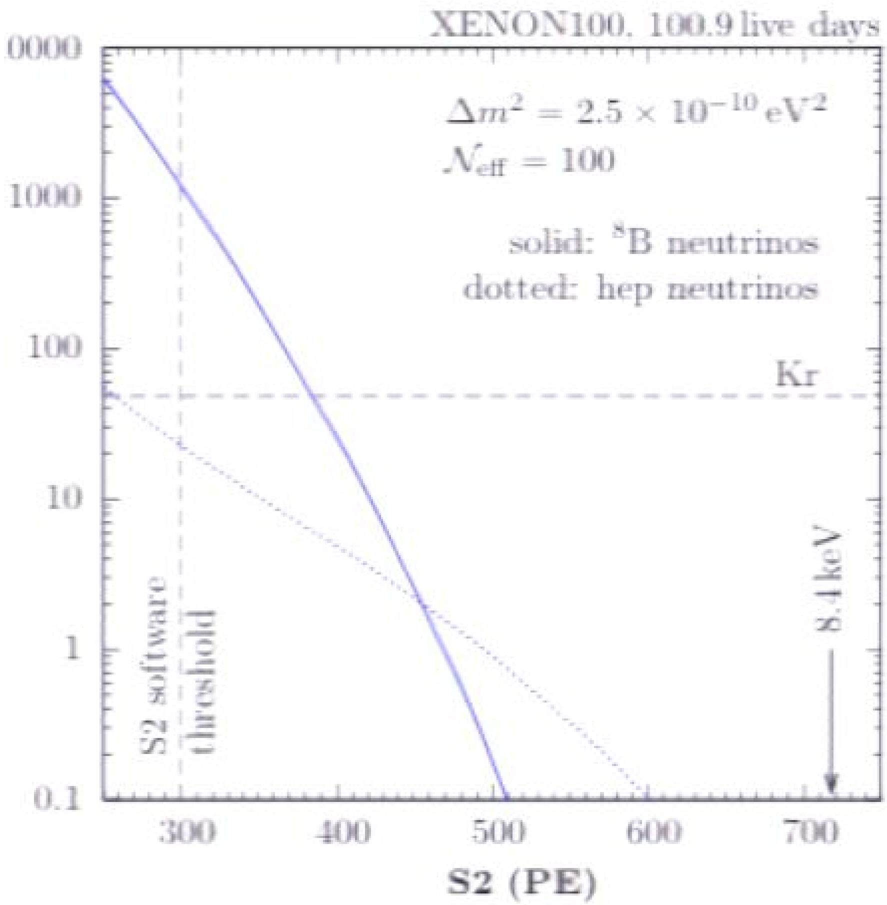
# putting it all together



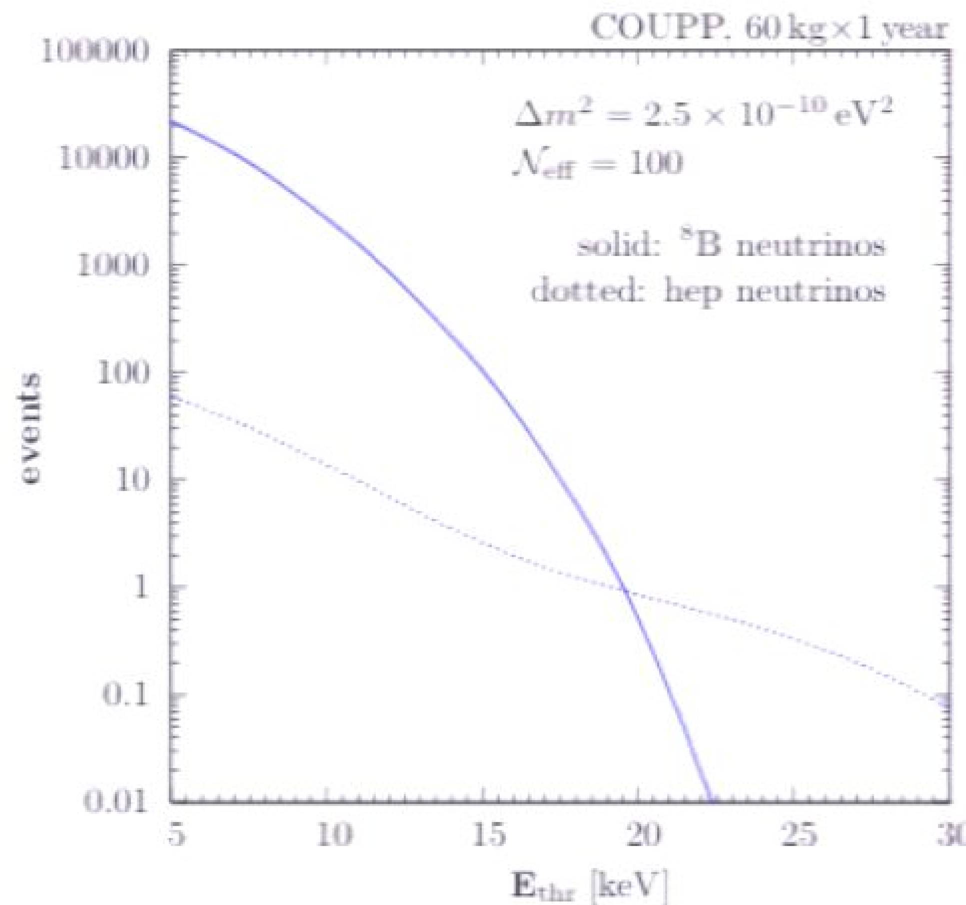

letting n-bkg float only moves boundary downwards

# outlook

--this model is testable--




prediction for Xenon100
low-threshold analysis




prediction for COUPP
bubble chamber ($CF_3I$)

(Xe10 low threshold may be very constraining => in the works)

# outlook

--this model is testable--

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

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

- 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)

(stay tuned for Dan McKinsey's talk tomorrow)

# Conclusions

- "baryonic" neutrinos can be fitted to (unmodulated) CoGeNT and CRESST data --- seems challenged by other searches

- DAMA modulation amplitude can be fitted nicely;
  phase is off by a few weeks

- upcoming experimental results may significantly cut on the parameter space or even exclude the most interesting parameter space of the model