New signals and old backgrounds in dark matter direct detection

Josef Pradler

Perimeter Institute

with **Spencer Chang** and **Itay Yavin**, Phys.Rev.D 85 063505 (2012)

with **Maxim Pospelov**, arXiv:1203.0545

CERN, March 16, 2012

PLAN

Part I

- signal modulation in dark matter direct detection experiments
- DAMA & CoGeNT and the "muon-hypothesis"
- new signatures from dark matter modulation

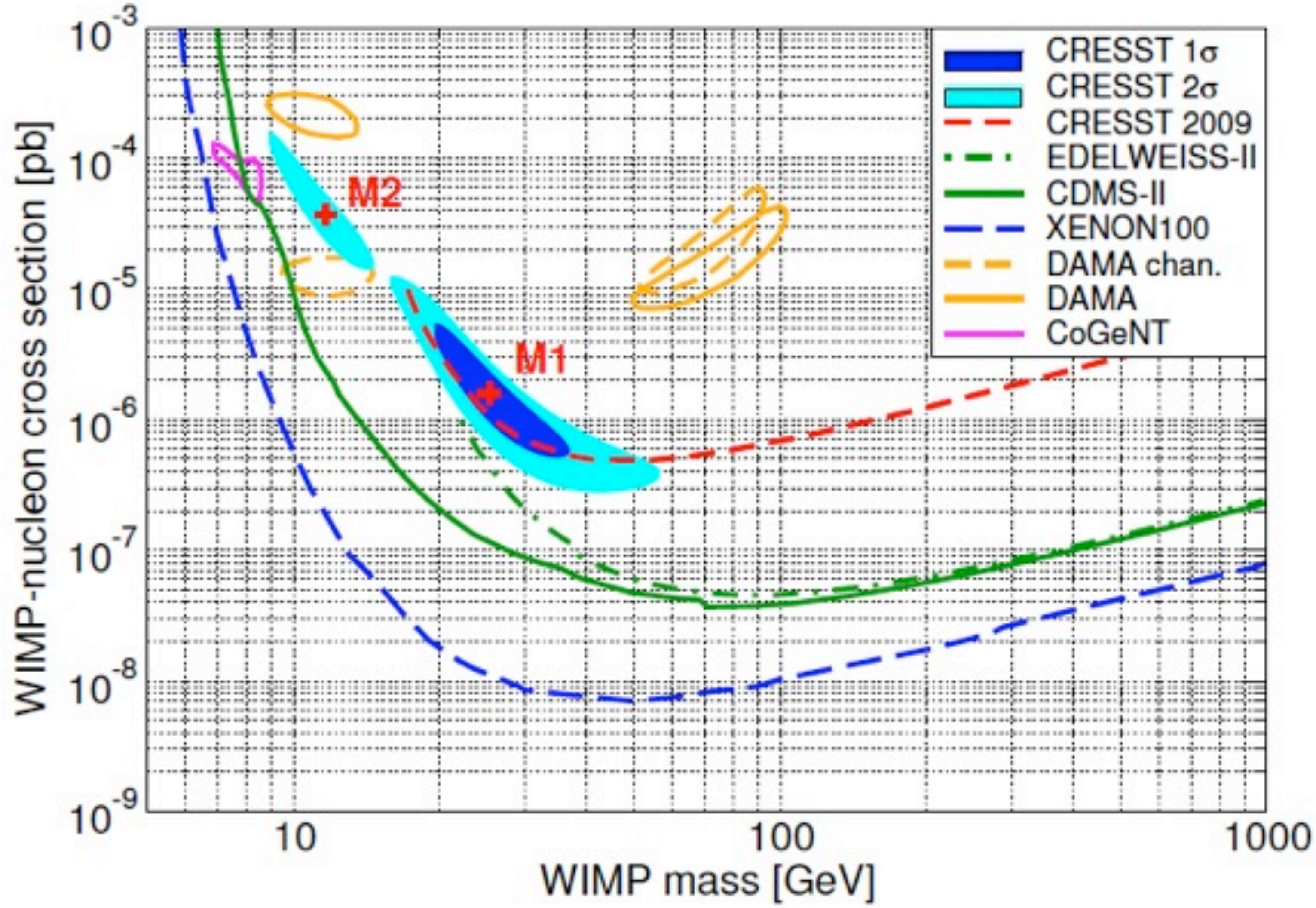
Part II

- dark matter vs. neutrinos from the sun
- "baryonic" neutrinos ν_b
- direct detection experiments as ν_b observatories?

one species - three signals?

- **DAMA**: 250 kg of scintillating NaI crystals, running since 1995, exposure in excess of 1 ton x year, no discrimination
- **CoGeNT**: 440 g Ge crystal, 442 live days; ionization only, no discrimination
- **CRESST**: scintillation and phonons; 730 kg days, multi-target

one species - three signals?



[Angloher et al., 2011]

- **DAMA**: 250 kg of scintillating NaI crystals, running since 1995, exposure in excess of 1 ton x year, no discrimination
- **CoGeNT**: 440 g Ge crystal, 442 live days; ionization only, no discrimination
- **CRESST**: scintillation and phonons; 730 kg days, multi-target

Part I

"take away message"

- cosmic muons as origin for DAMA modulation strongly disfavoured

  - different in phase
  - different in correlation
  - possibly different in power
  - possibly different in amplitude

- similar conclusions hold for CoGeNT modulation

- there is more than "one modulation"

signal modulation in direct detection

$$\frac{dR}{dE_R} = N_T \, n_{\rm DM} \int_{v \geq v_{min}} d^3\mathbf{v} \, v f_{\rm LAB}(\mathbf{v}) \frac{d\sigma}{dE_R} \qquad [\text{cpd/kg/keV}]$$

$$\downarrow$$

$$f_{\rm GAL}(\mathbf{v}_{\rm obs} + \mathbf{v})$$

see e.g. [Druiker et al, 1986; Freese et al, 1988; Savage et al, 2009]

signal modulation in direct detection

$$\frac{dR}{dE_R} = N_T\, n_{\rm DM} \int_{v \geq v_{min}} d^3\mathbf{v}\, v\, f_{\rm LAB}(\mathbf{v}) \frac{d\sigma}{dE_R} \qquad [\text{cpd/kg/keV}]$$

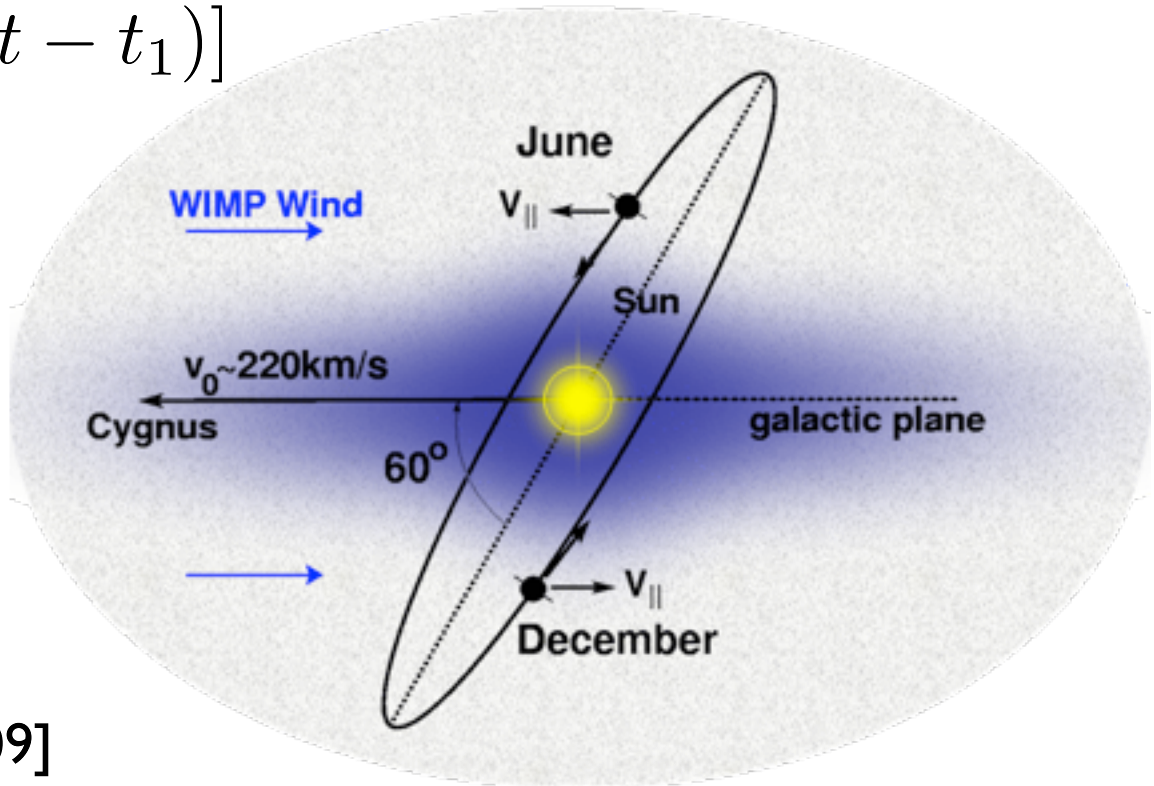
$$\downarrow$$

$$f_{\rm GAL}(\mathbf{v}_{\rm obs} + \mathbf{v})$$

$$\mathbf{v}_{\rm obs} = \mathbf{v}_\odot + V_\oplus \left[\varepsilon_1 \cos\omega\,(t - t_1) + \varepsilon_2 \sin\omega\,(t - t_1)\right]$$

$$|\mathbf{v}_{\rm obs}| = |\mathbf{v}_\odot| + \frac{1}{2} V_\oplus \cos\omega(t - t_0)$$

$t_0 \simeq 152\,\text{days} \quad (\text{June 2nd})$



see e.g. [Druiker et al, 1986; Freese et al, 1988; Savage et al, 2009]

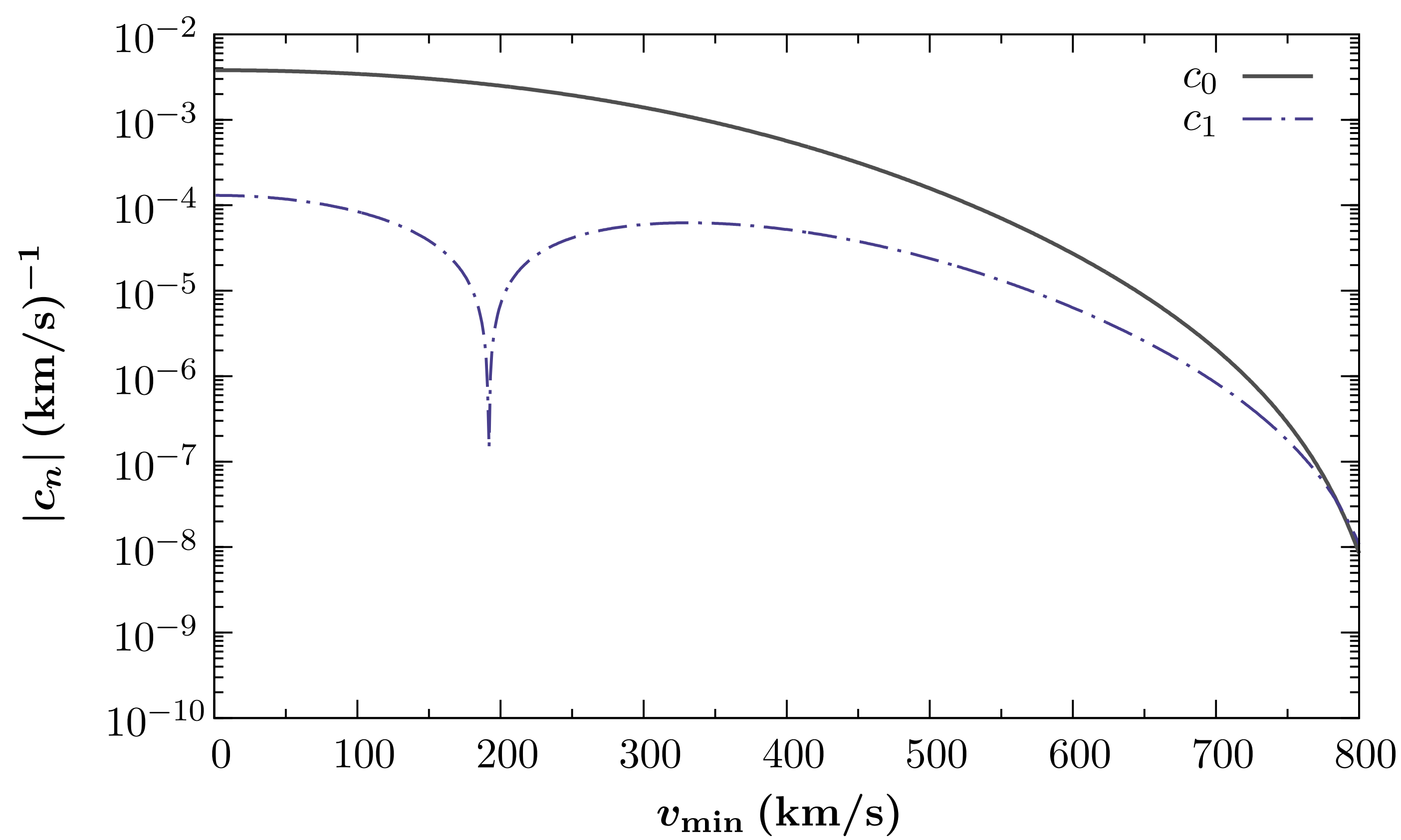
signal modulation in direct detection

annual modulation

$$\frac{dR(t)}{dE_R} \propto \int_{v_{min}}^{\infty} \frac{f(v)}{v} dv \simeq c_0(v_{min}) + c_1(v_{min}) \cos\left[\omega(t - t_0)\right]$$

$$v_{min} = \frac{1}{\sqrt{2m_N E_R}} \left(\frac{m_N E_R}{\mu_{N\chi}} + \delta \right)$$

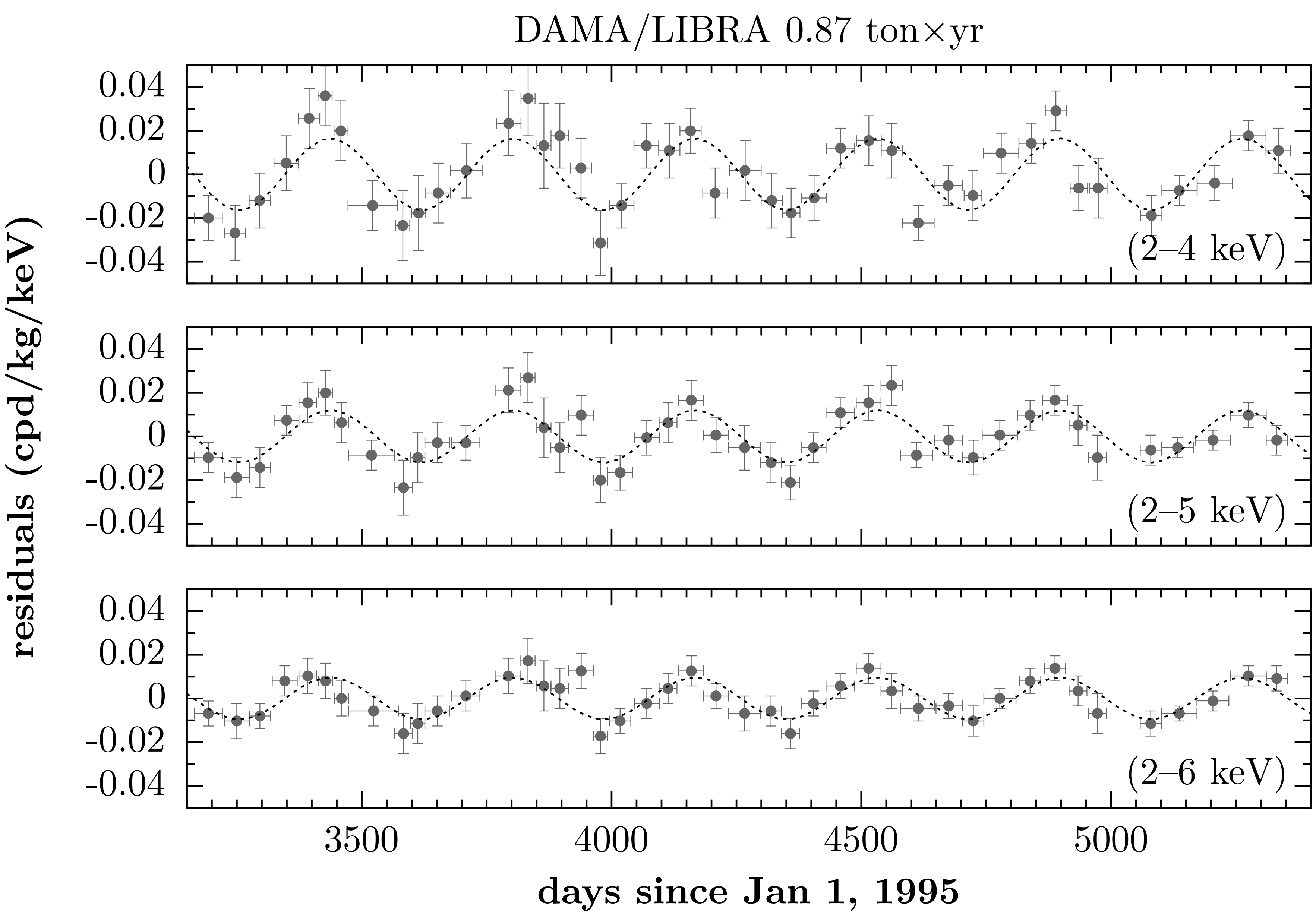
$t_0 \simeq 152\,\text{days} \quad \text{(June 2nd)}$



[using f(v) from Lisanti et al, 2010]

$\sim 3\%$

DAMA/LIBRA

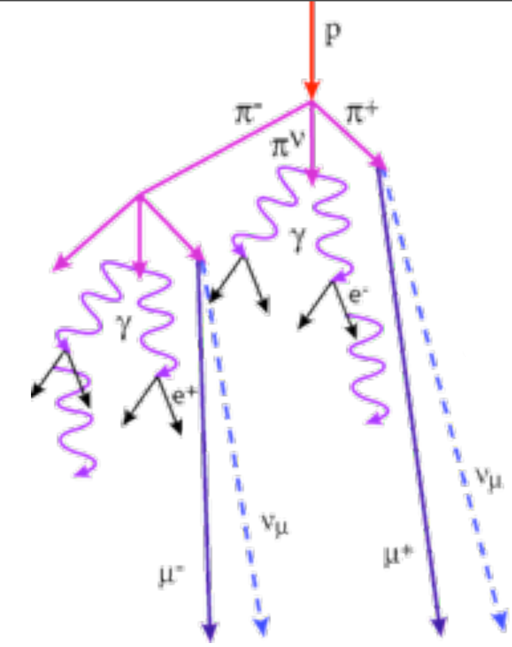


- scintillation from NaI-crystals
- 8σ+ modulation
- phase consistent as expected from WIMPs

$$t_0 \simeq 2\ \text{June}$$
$$= 152.5\ \text{days}$$

[Bernabei et al. 2010]

Muon Flux underground



--- modulates too ---

- underground flux sourced mainly by primary meson decays (pions, kaons,...) => muons need to be TeV-like to reach underground

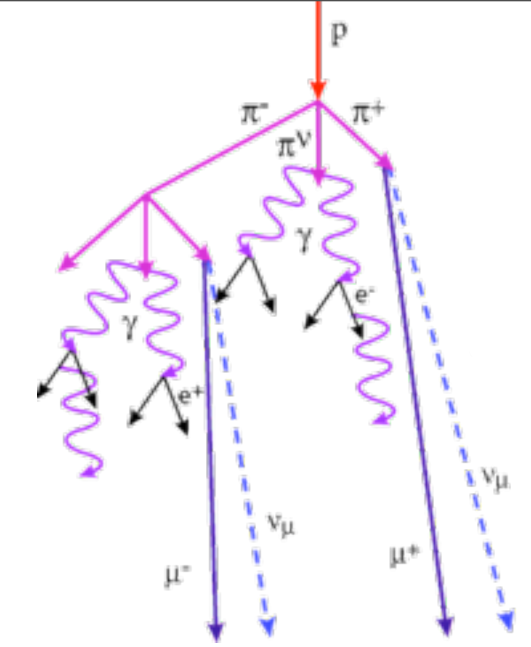
- competition between secondary meson interactions vs. decay depends on air-density

  => muon flux correlated with temperature

$$\frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T_{\rm eff}}{T_{\rm eff}} \qquad\qquad T_{\rm eff} = \int_0^\infty dX\, T(X) W(X)$$

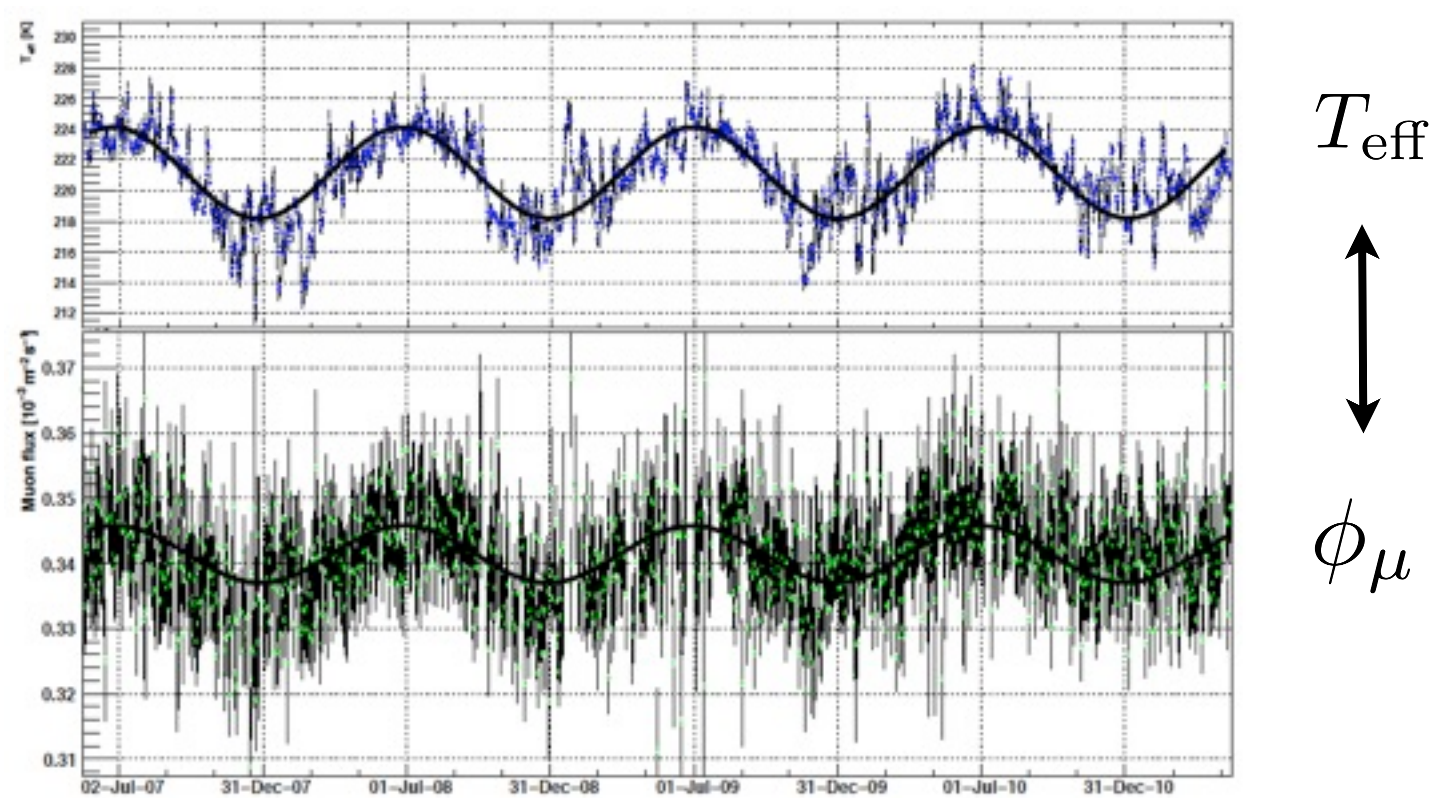
- flux peaks in Summer (on northern hemisphere)

Muon Flux underground



- many measurements available, correlation with $T_{\rm eff}$ firmly established

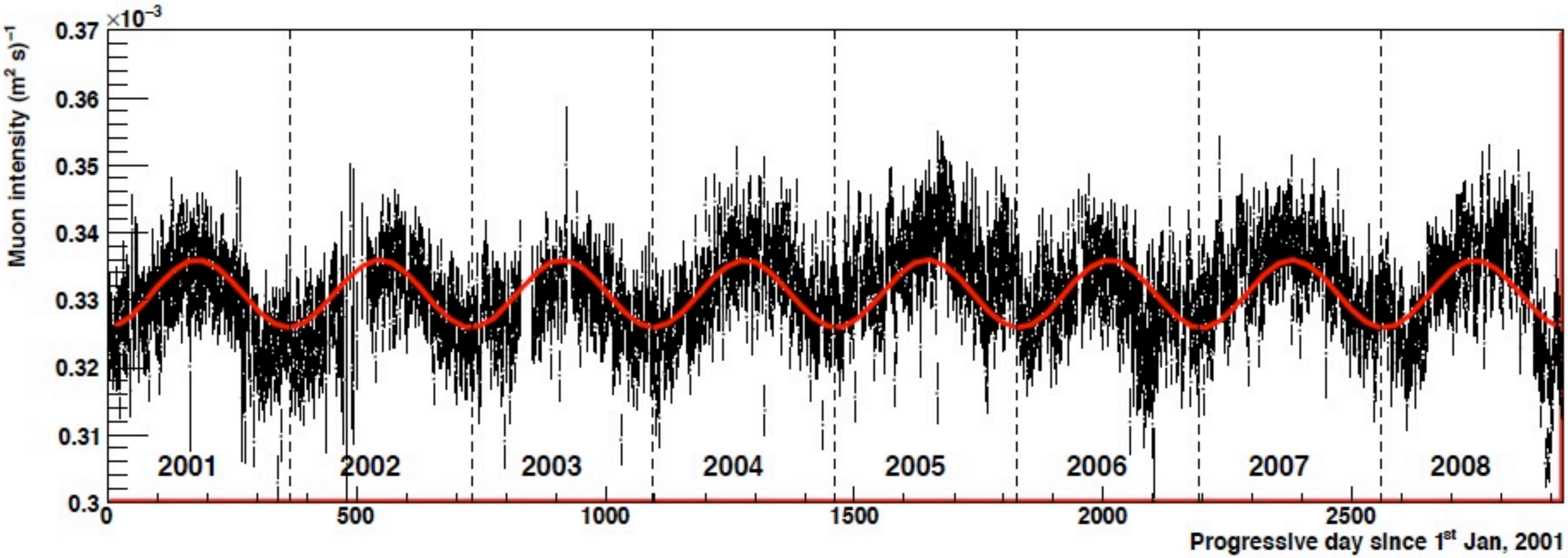
  - LNGS: Macro, LVD, Borexino (DAMA location)
  - Soudan Mine: MINOS (CoGeNT location)
  - South Pole: Amanda, Icecube



[Borexino 2011]

LVD and DAMA

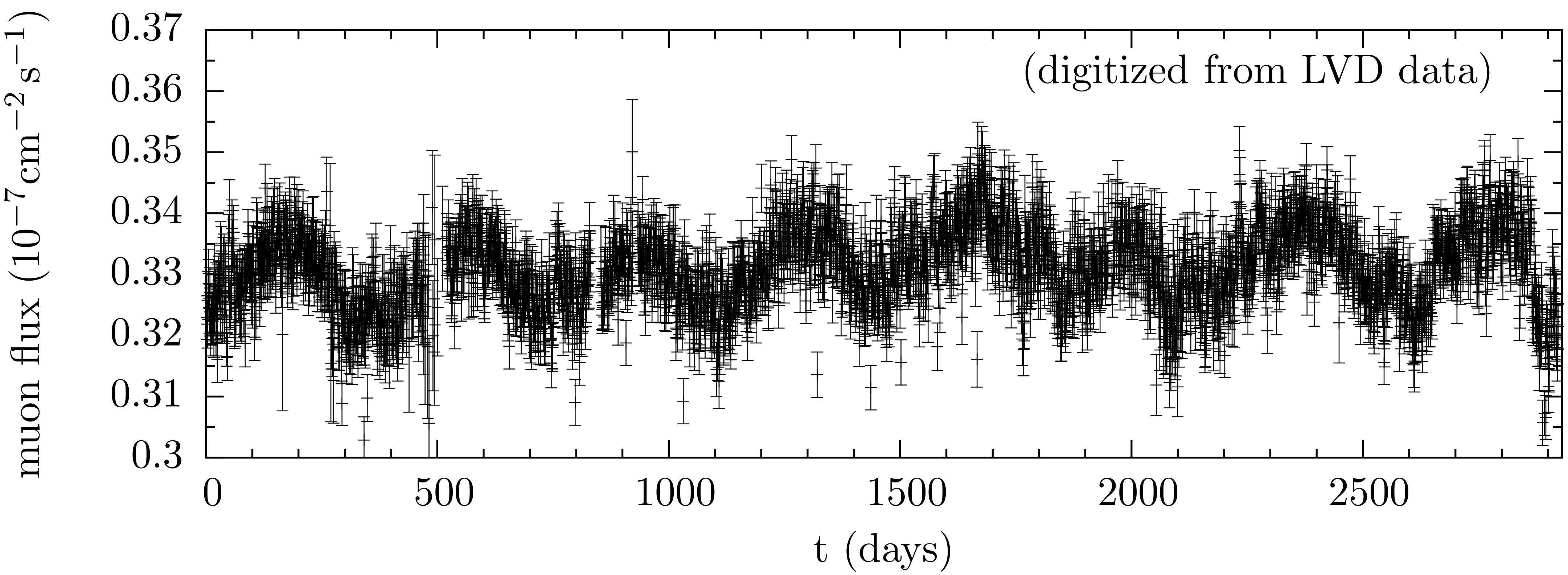
- Large Volume liquid scintillator Detector (LVD) reports underground muon-flux at LNGS => temporal overlap with DAMA data



$\overline{I}_{\mu} \sim 30/\mathrm{day}/\mathrm{m}^2$ @ DAMA site

[Selvi, 2009]

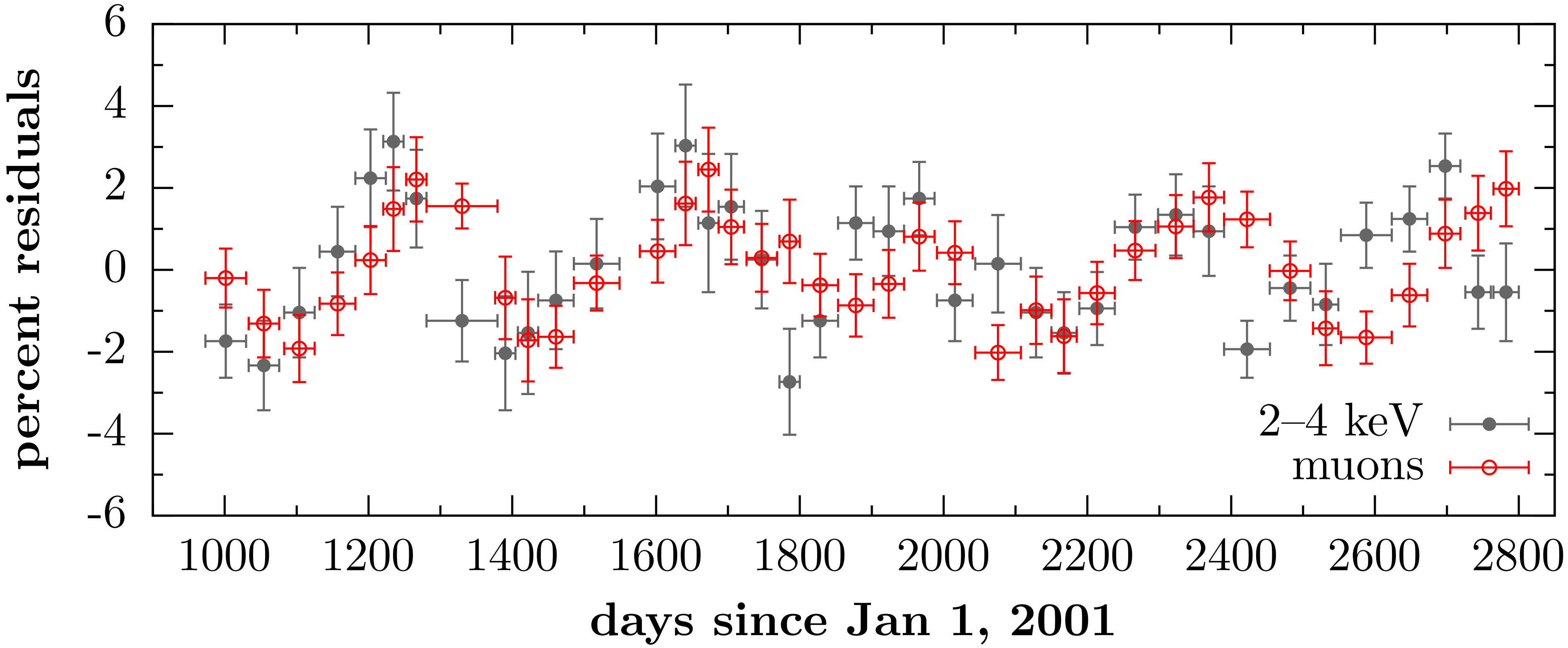
LVD and DAMA



- renewed interest in muons as DAMA background, see e.g. [Ralston, 2010], [Nygren, 2011], [Blum, 2011]

- very recent response by DAMA [Bernabei, 2012]

LVD and DAMA



- renewed interest in muons as DAMA background, see e.g. [Ralston, 2010], [Nygren, 2011], [Blum, 2011]

- very recent response by DAMA [Bernabei, 2012]

LVD and DAMA

- muons can either directly hit the detector or indirectly, by spallation of nuclei which leads to neutron flux

  => guaranteed source of background (especially if un-vetoed)

- in this talk we will base our analysis exclusively on the time-series of events in both data sets

  => we are ignorant to how the signal formation process concretely happens

  => but if we can make firm statements already it means that this approach is very model-independent and thus conservative

detecting periodicities

- evenly spaced data $d_i = d(t_i)$ discrete FT

$$P(\omega) \propto \left| \sum_i d_i \exp(-i\omega t_i) \right|^2 = \left[\left(\sum_i d_i \cos(\omega t_i) \right)^2 + \left(\sum_i d_i \sin(\omega t_i) \right)^2 \right]$$

- unevenly spaced data: Lomb-Scargle Periodogram

$$\mathrm{LS}(\omega) = \frac{1}{2} \left\{ \frac{1}{\sum_i \cos^2(\omega \tilde{t}_i)} \left[\sum_i d_i \cos(\omega \tilde{t}_i) \right]^2 + \frac{1}{\sum_i \sin^2(\omega \tilde{t}_i)} \left[\sum_i d_i \sin(\omega \tilde{t}_i) \right]^2 \right\}$$

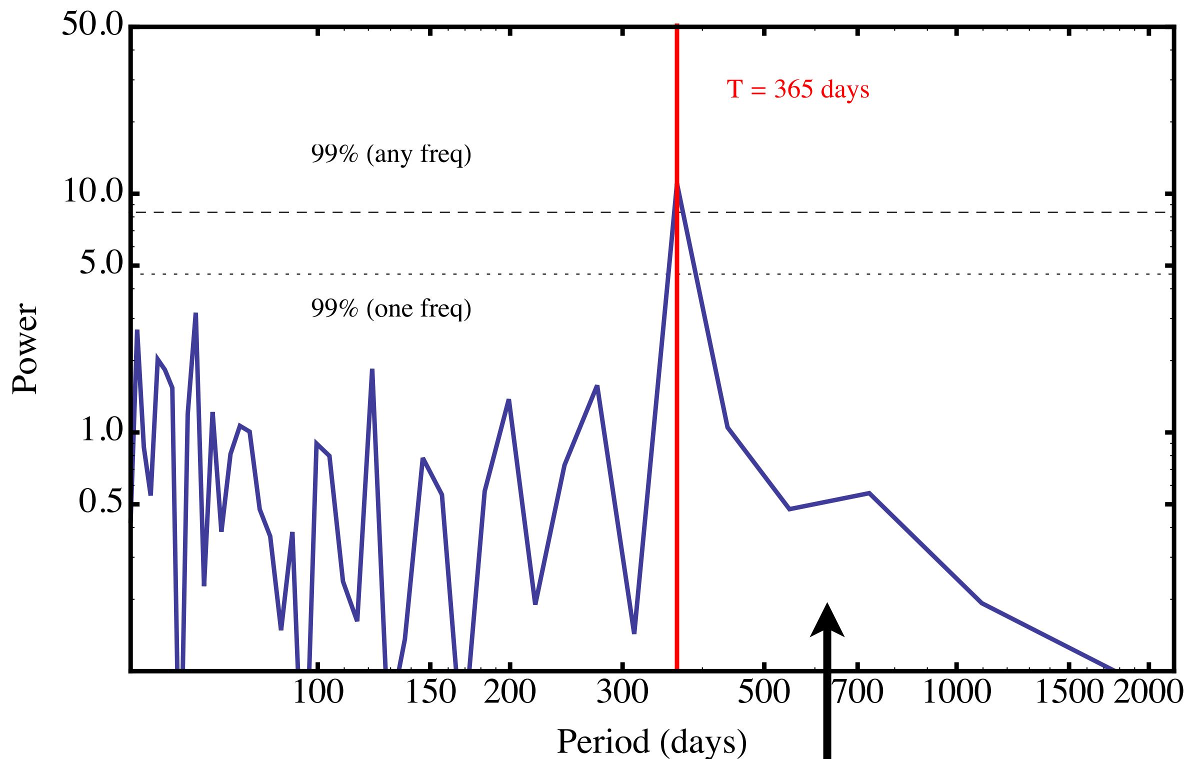
$$\tilde{t}_i \equiv t_i - \tau$$

- invariant to shifts in time origin
- if d_i is pure noise (with unit variance)

$$\Pr(P > p) = e^{-p}$$

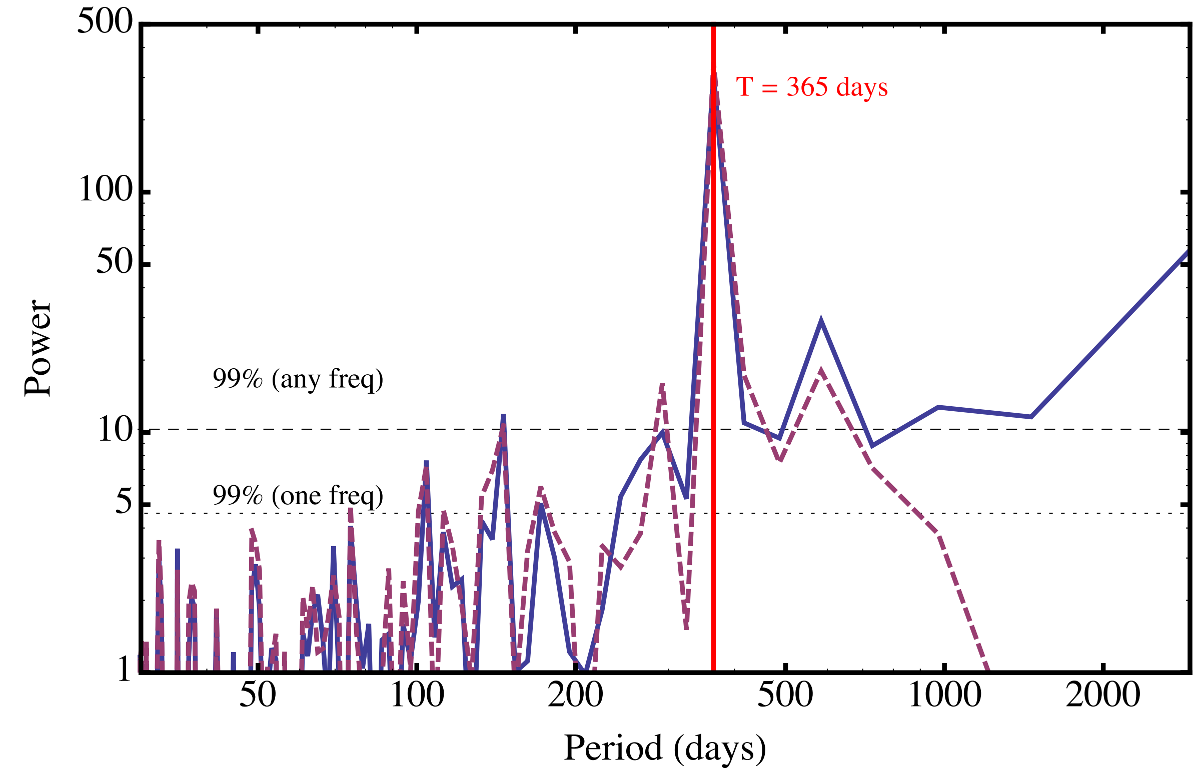
detecting periodicities

DAMA/LIBRA



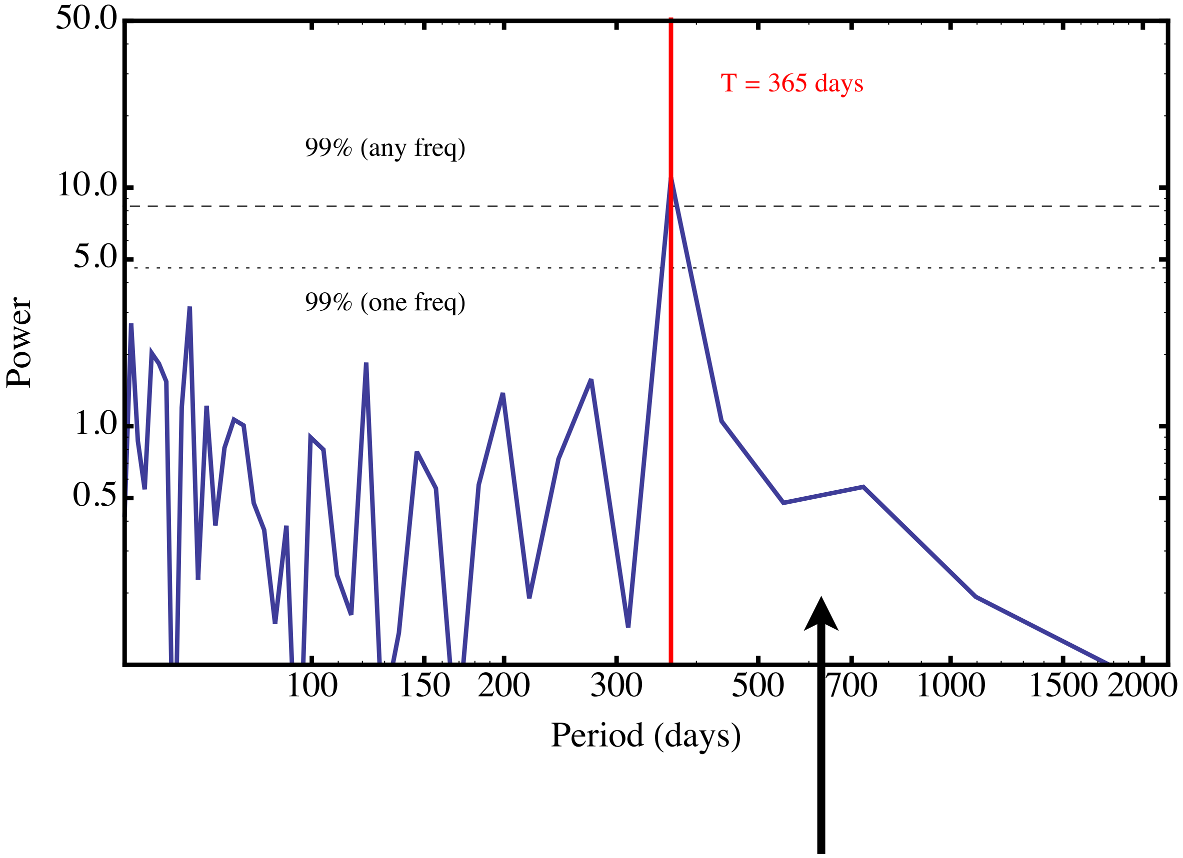
no power on timescales > 1yr

LVD muons



detecting periodicities

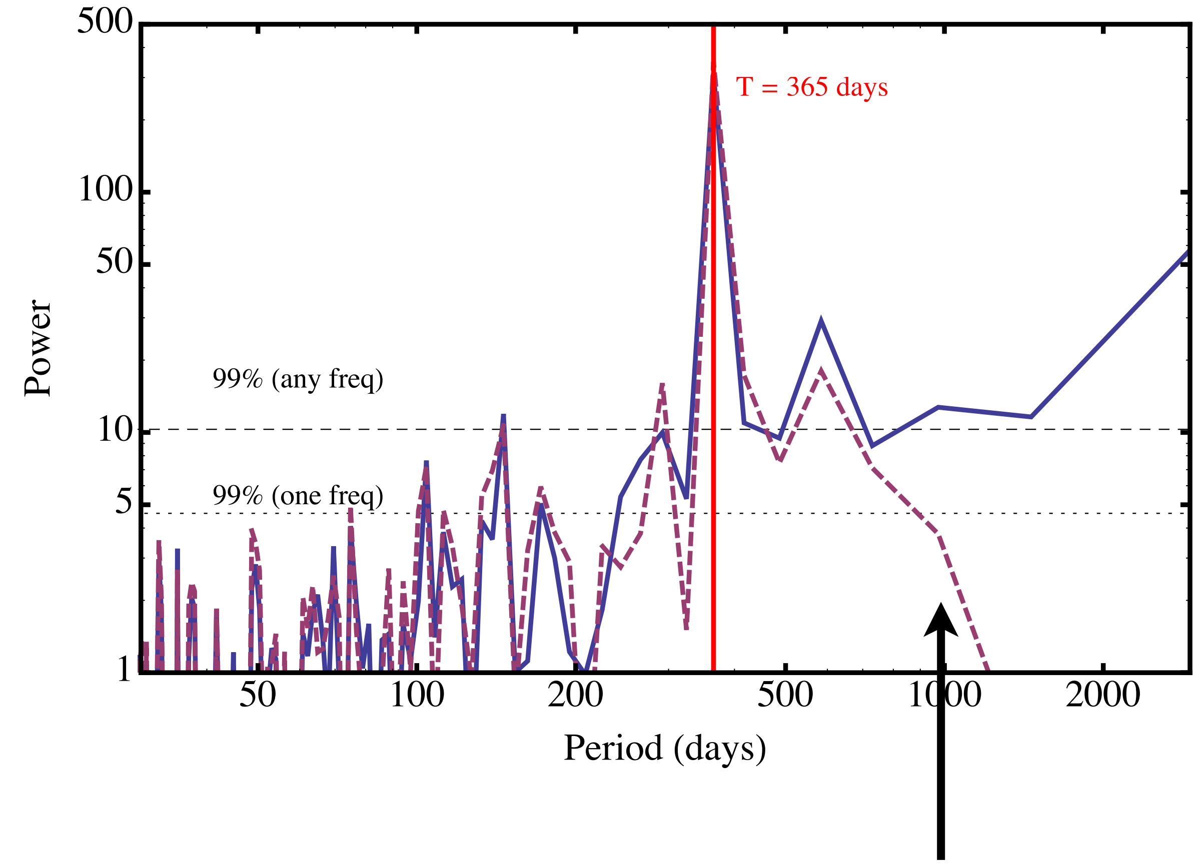
DAMA/LIBRA



no power on timescales > 1yr

BUT

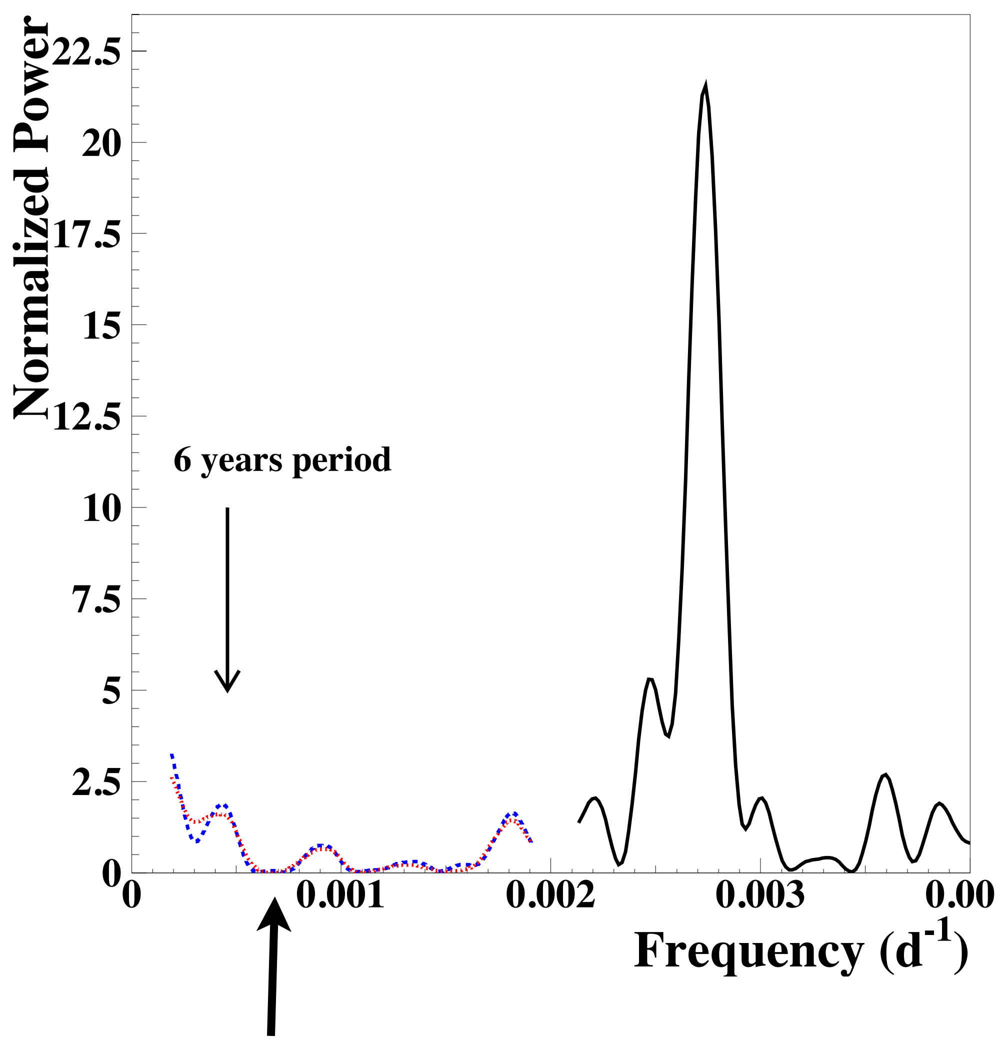
LVD muons



adopting DAMA's procedure of subtracting baseline on each cycle suppresses power on timescales longer than 1 yr (see also Blum, 2011)

detecting periodicities

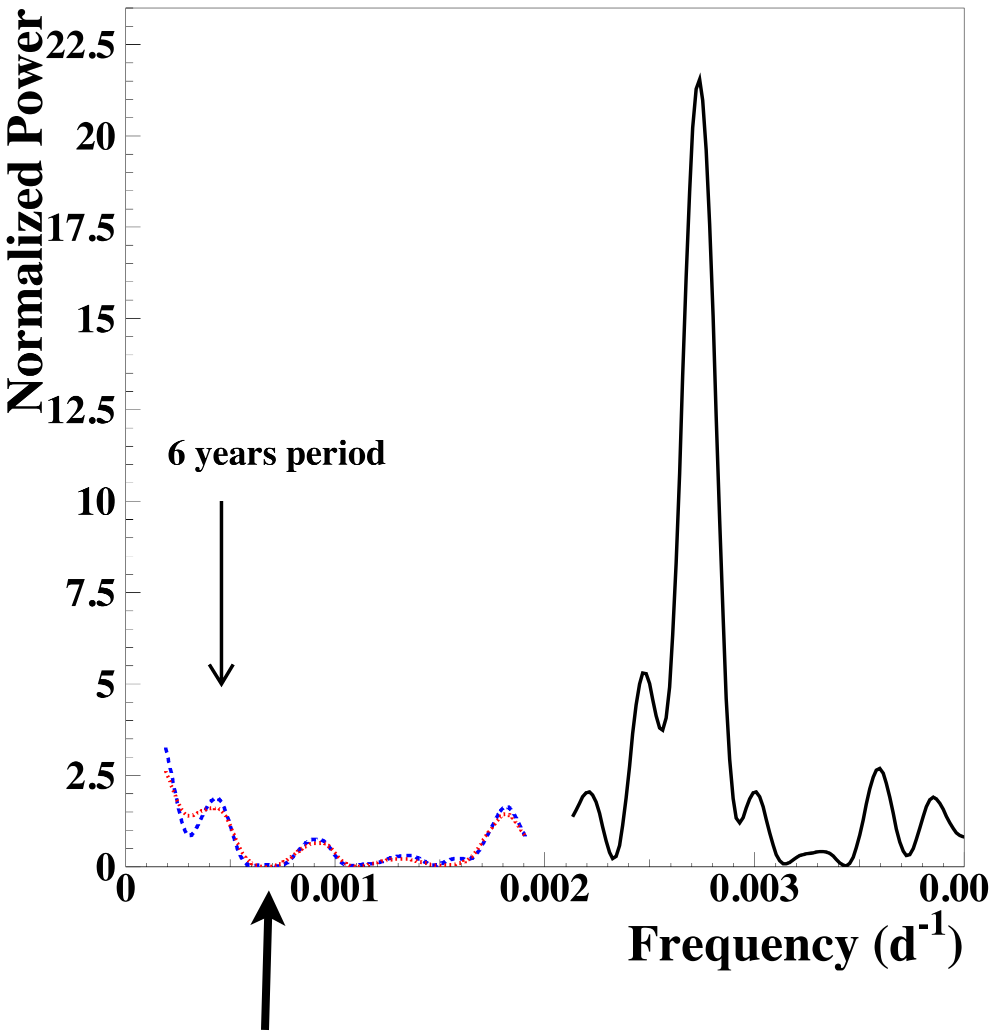
DAMA/LIBRA, 2012



LS of baselines
O(10) data points, no significant power!

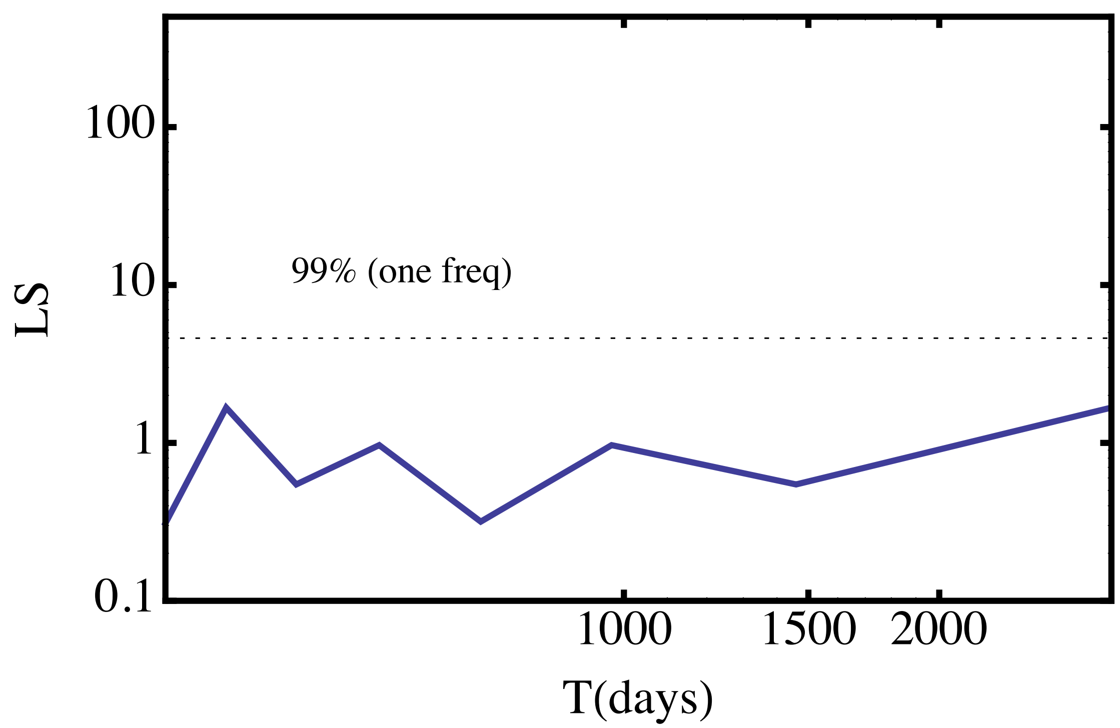
detecting periodicities

DAMA/LIBRA, 2012



LS of baselines
O(10) data points, no
significant power!

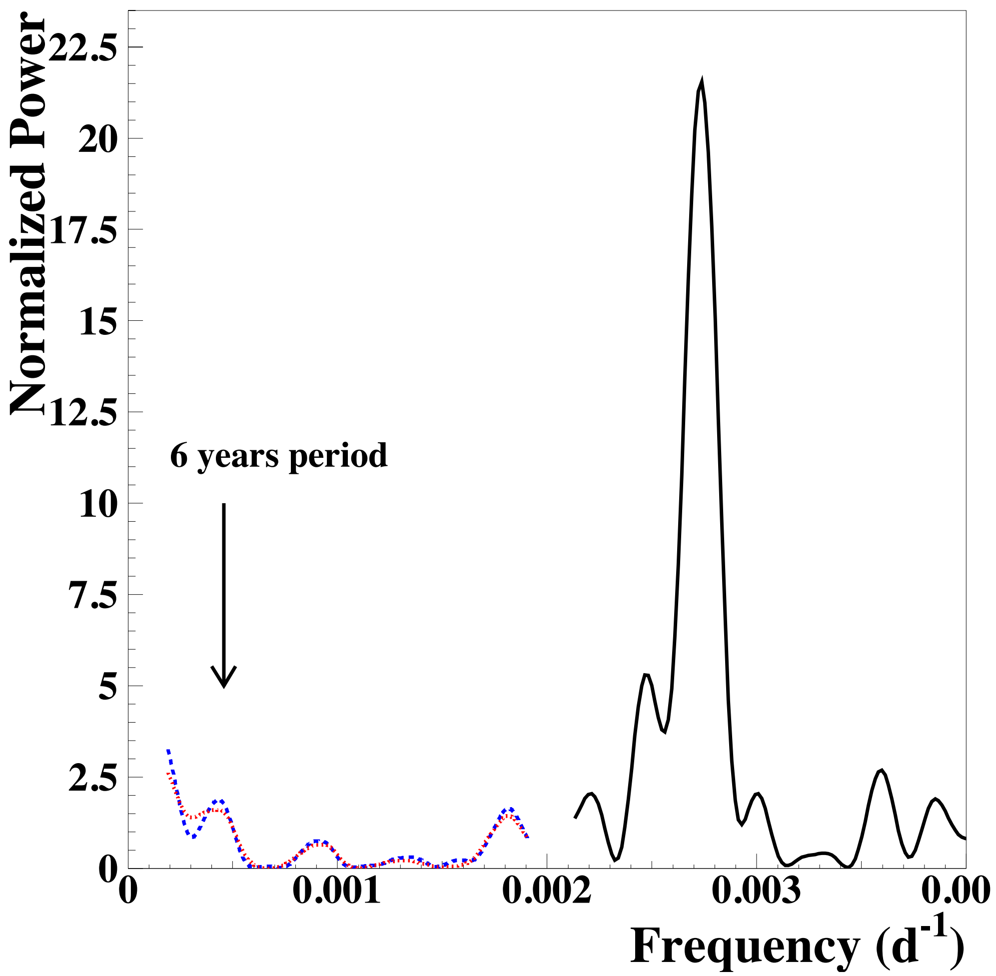
LVD muons



LS of muon baselines
O(10) data points
no significant power neither!

detecting periodicities

DAMA/LIBRA, 2012



- with a small dataset it is hard to achieve statistical significance

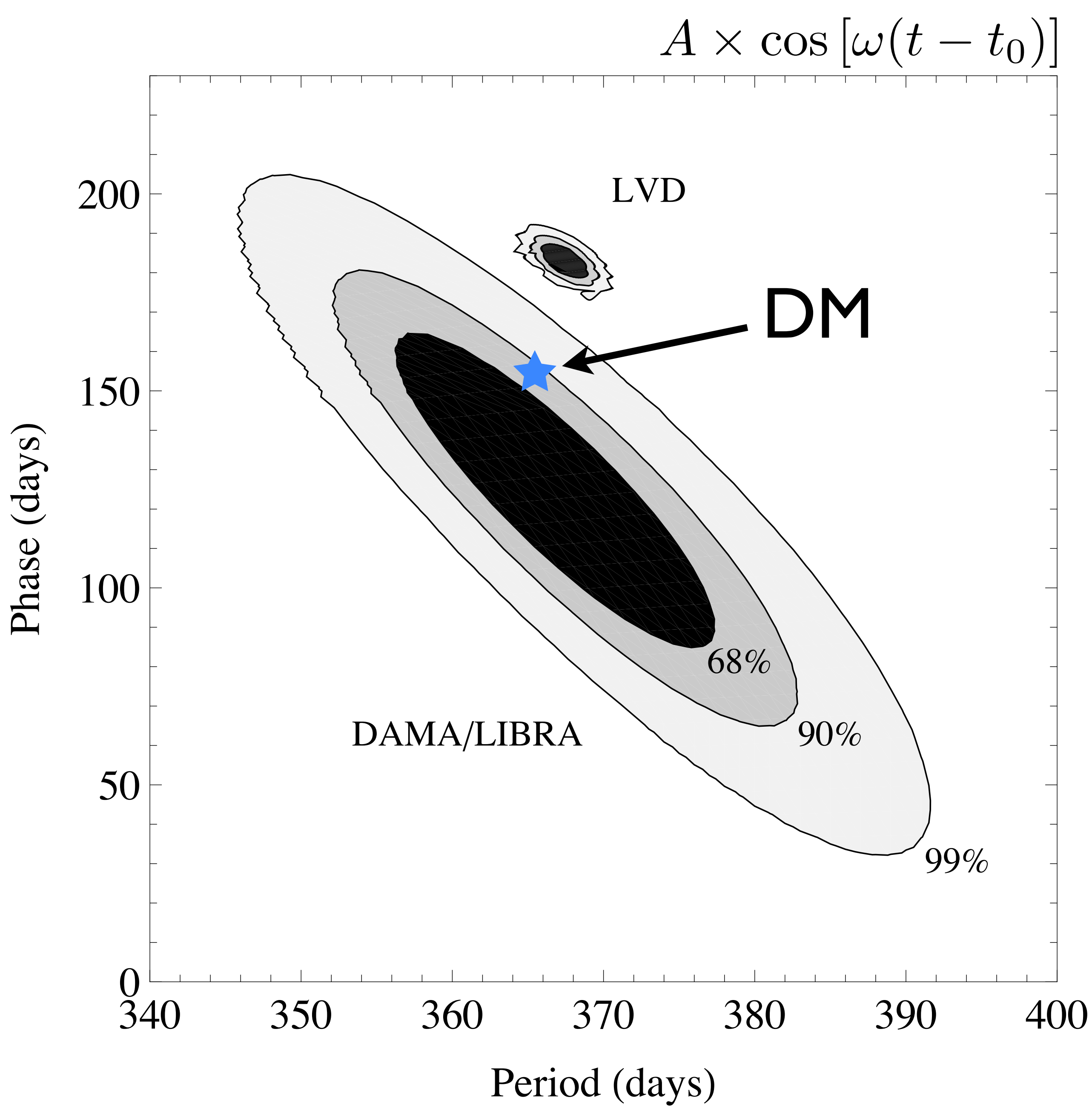
  => normalized power

  $$P(\omega) = LS(\omega)/\sigma^2$$

- power spectrum of baselines alone does NOT convincingly show that there is indeed no long term modulation in DAMA

=> DAMA should provide baseline rates

The phase of DAMA vs the "phase" of LVD



- interpret data as sinusoidal variations
- phase of DAMA/LIBRA incompatible with muons

@ $\omega = 2\pi/1\text{yr}$:

$$t_0(\text{DAMA}) = (131 \pm 13)\,\text{days}$$

$$t_0(\text{LVD}) = (187 \pm 2)\,\text{days}$$

The phase of DAMA
vs
the "phase" of LVD

- two studies suggest that phase can potentially in agreement

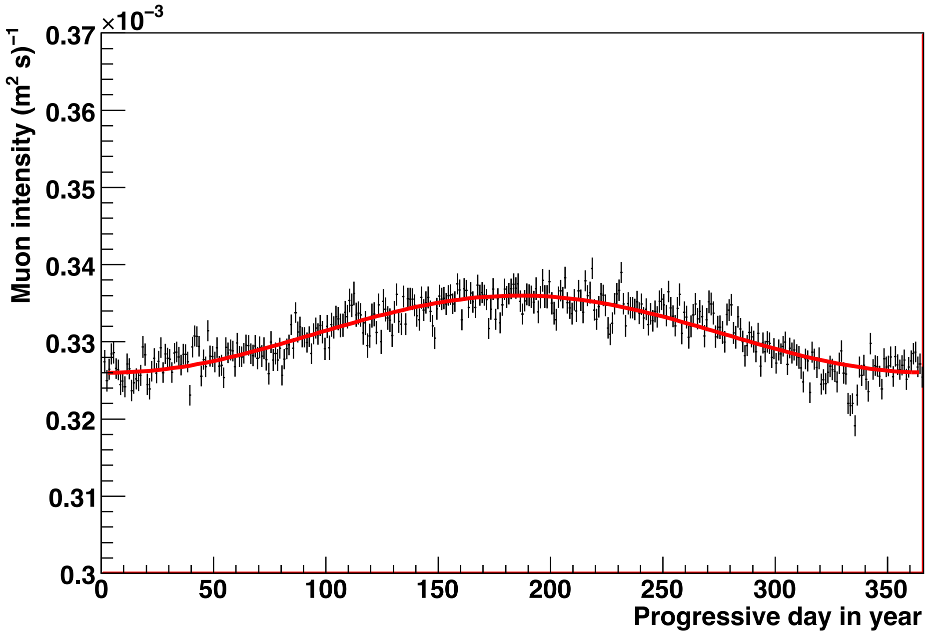
1. Selvi for LVD collaboration finds

$$t_0(\mathrm{LVD})_{\mathrm{LVD-collab}} = (185 \pm 15)\,\mathrm{days}$$

$$\chi^2/dof = 577/362$$

adopting this procedure we find

$$t_0(\mathrm{LVD}) = (186 \pm 2)\,\mathrm{days}\,!$$



[Selvi for LVD, 2009]

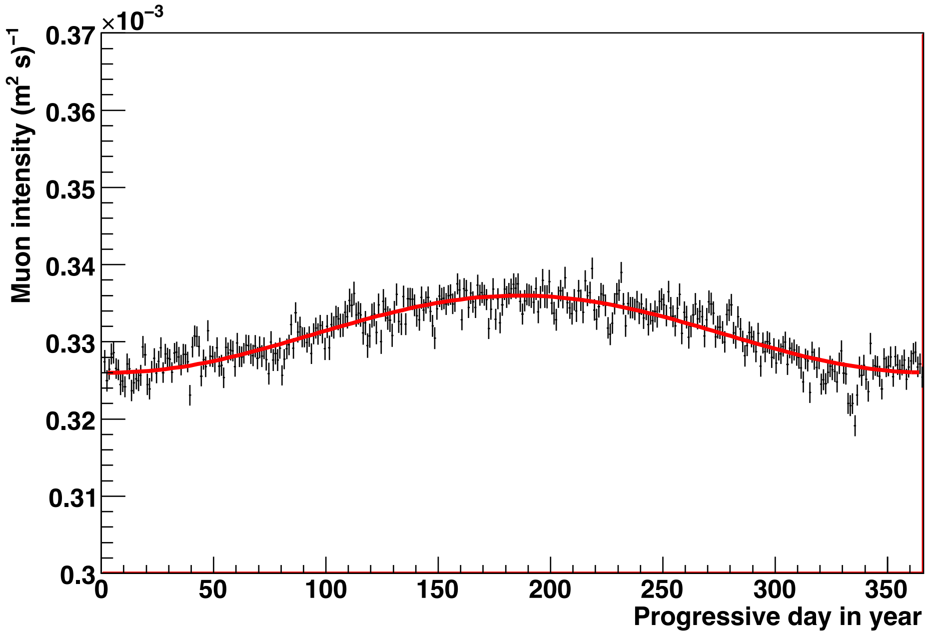
The phase of DAMA
vs
the "phase" of LVD

- two studies suggest that phase can potentially in agreement

1. Selvi for LVD collaboration finds

$$t_0(\mathrm{LVD})_{\mathrm{LVD-collab}} = (185 \pm 15)\,\mathrm{days}$$

$$\chi^2/dof = 577/362$$



adopting this procedure we find

$$t_0(\mathrm{LVD}) = (186 \pm 2)\,\mathrm{days}\,!$$

[Selvi for LVD, 2009]

suspecting that Selvi used reduced χ^2 for construction of confidence region => confidence interval overestimated

The phase of DAMA vs the "phase" of LVD

- two studies suggest that phase can potentially in agreement

2. Blum, 2011:
nice observation that *direct* hits by muons induce produce too large spread in signal, BUT

$$s_i = \frac{y N_{\mu,i}}{M \Delta E \epsilon_i t_i}$$ ⟵ count rate in DAMA bin i

y = signal counts / muon

$$\langle N_{\mu,i} \rangle = A_{\text{eff}} I_{\mu,i} \epsilon_i t_i$$ ⟵ mean of Poisson distributed $N_{\mu,i}$

=> used to generate DAMA mock data

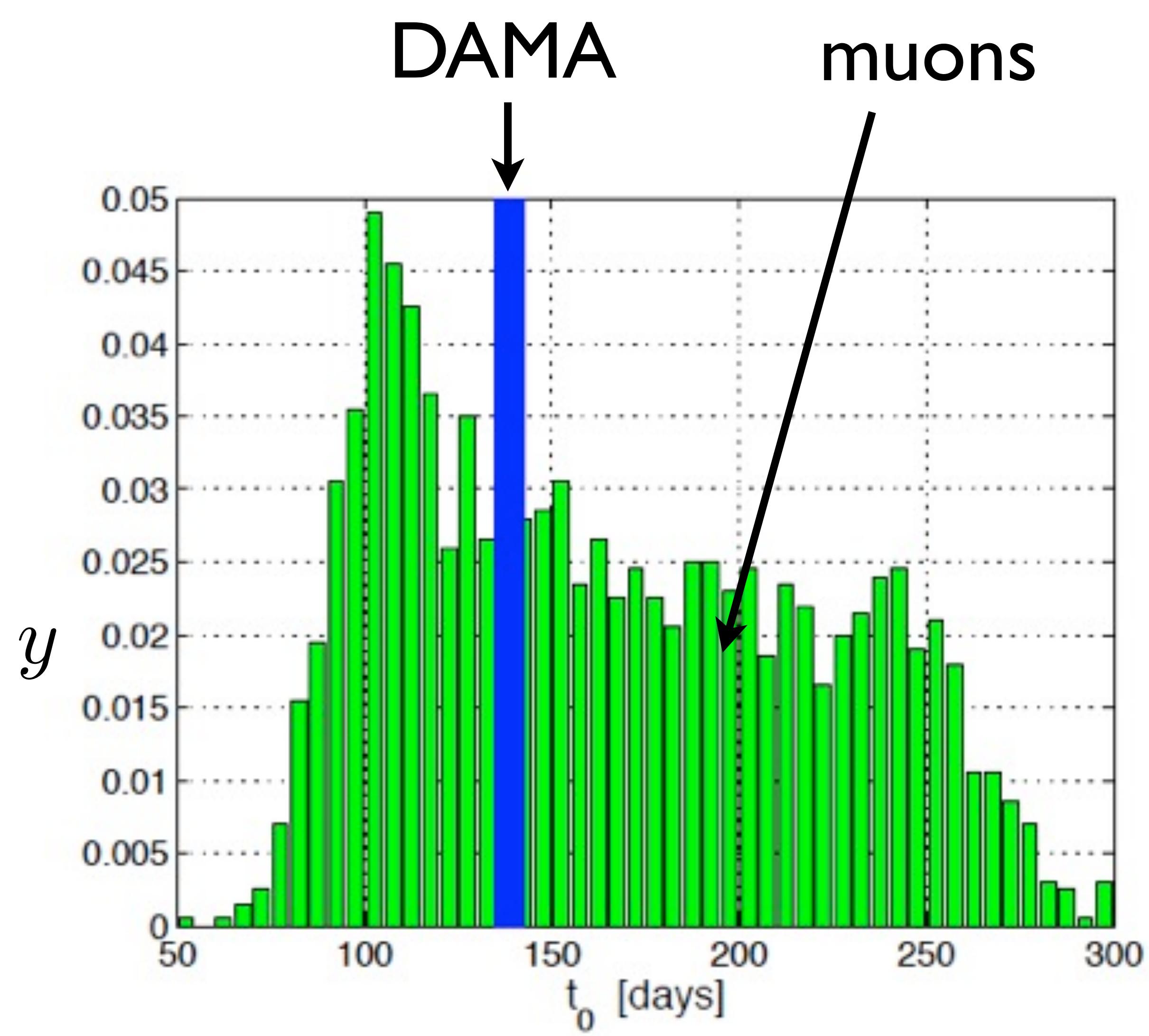
The phase of DAMA vs the "phase" of LVD

- two studies suggest that phase can potentially in agreement

2. Blum, 2011:
nice observation that *direct* hits by muons induce produce too large spread in signal, BUT

$$s_i = \frac{y N_{\mu,i}}{M \Delta E \epsilon_i t_i}$$

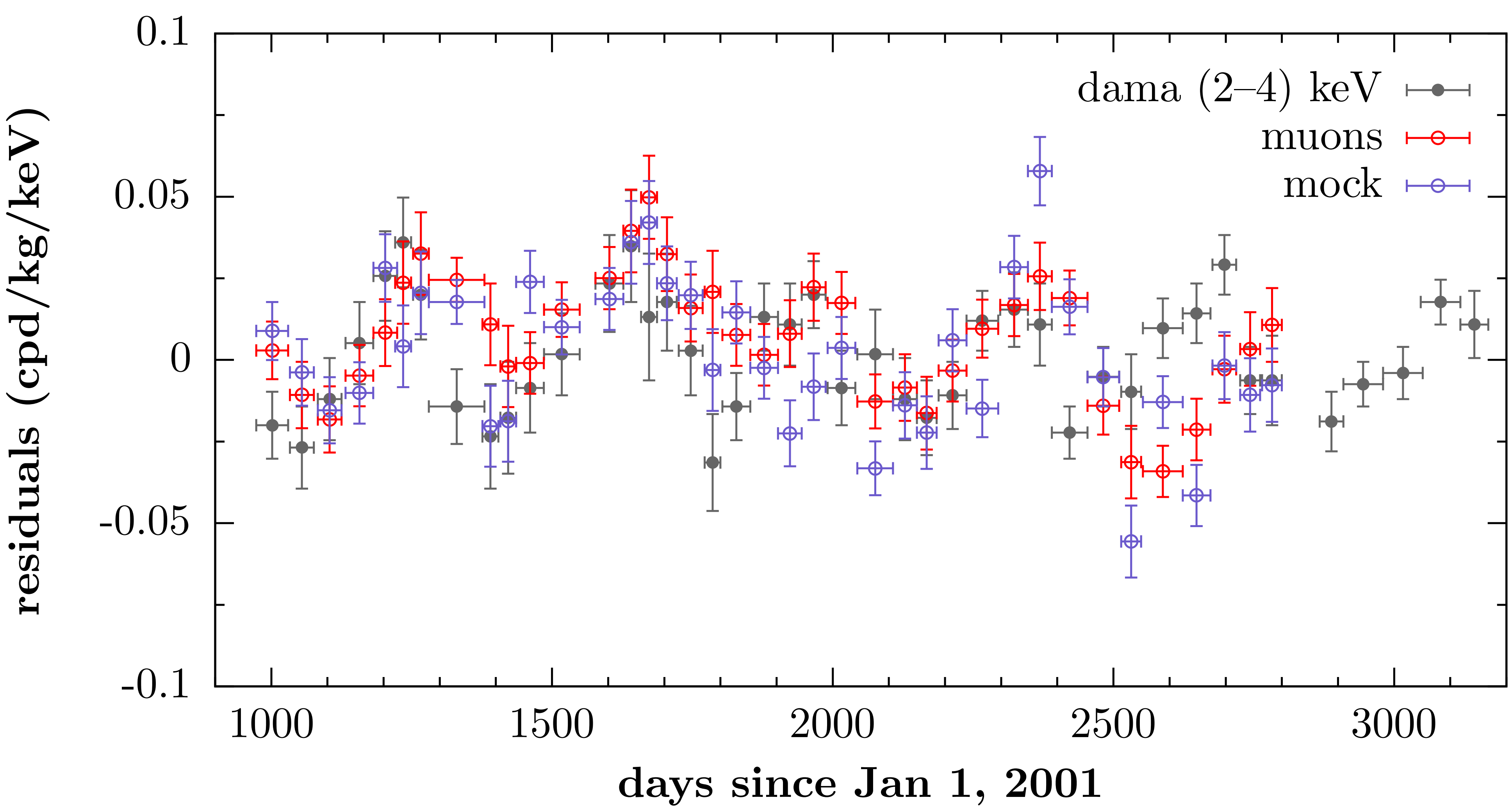
$$\langle N_{\mu,i} \rangle = A_{\text{eff}} I_{\mu,i} \epsilon_i t_i$$



=> used to generate DAMA mock data

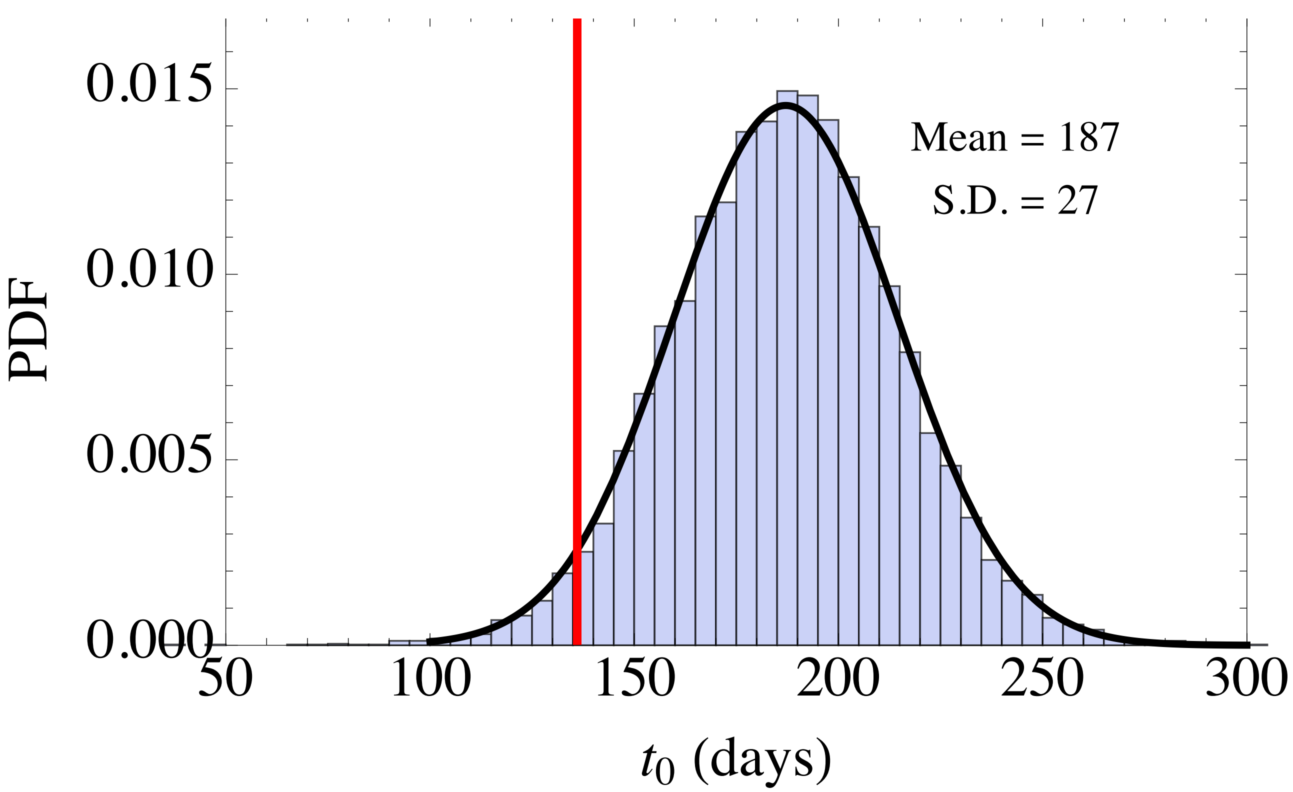
The phase of DAMA vs the "phase" of LVD

=> redo Blum's analysis:

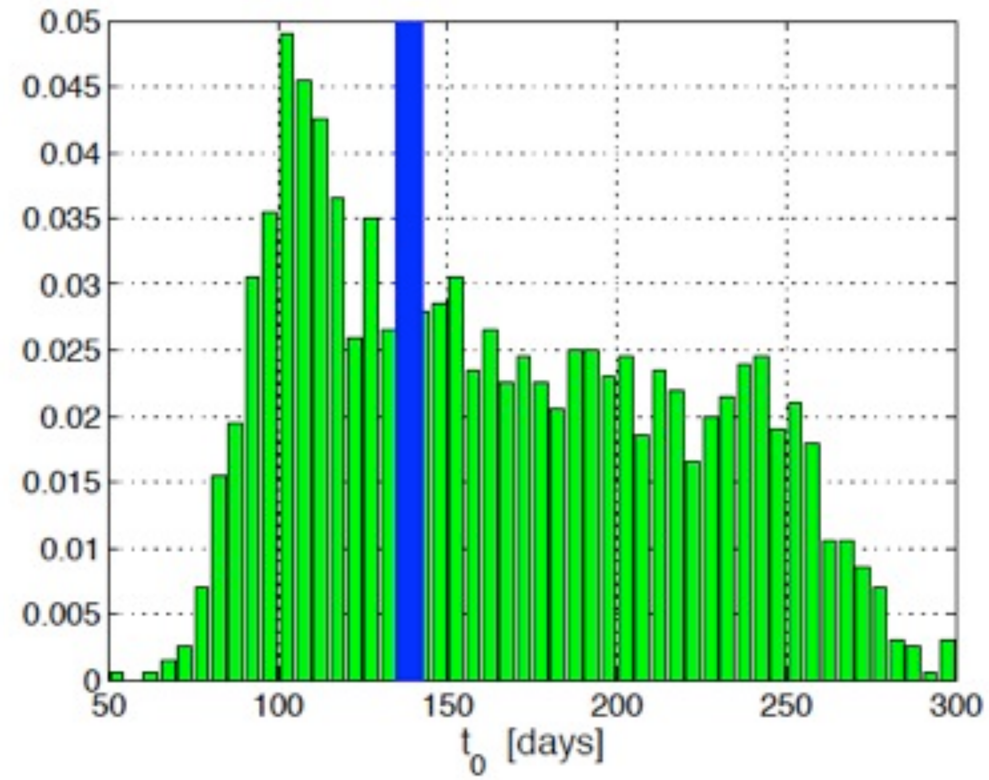


(one representative out of a sample of 10k)

The phase of DAMA
vs
the "phase" of LVD



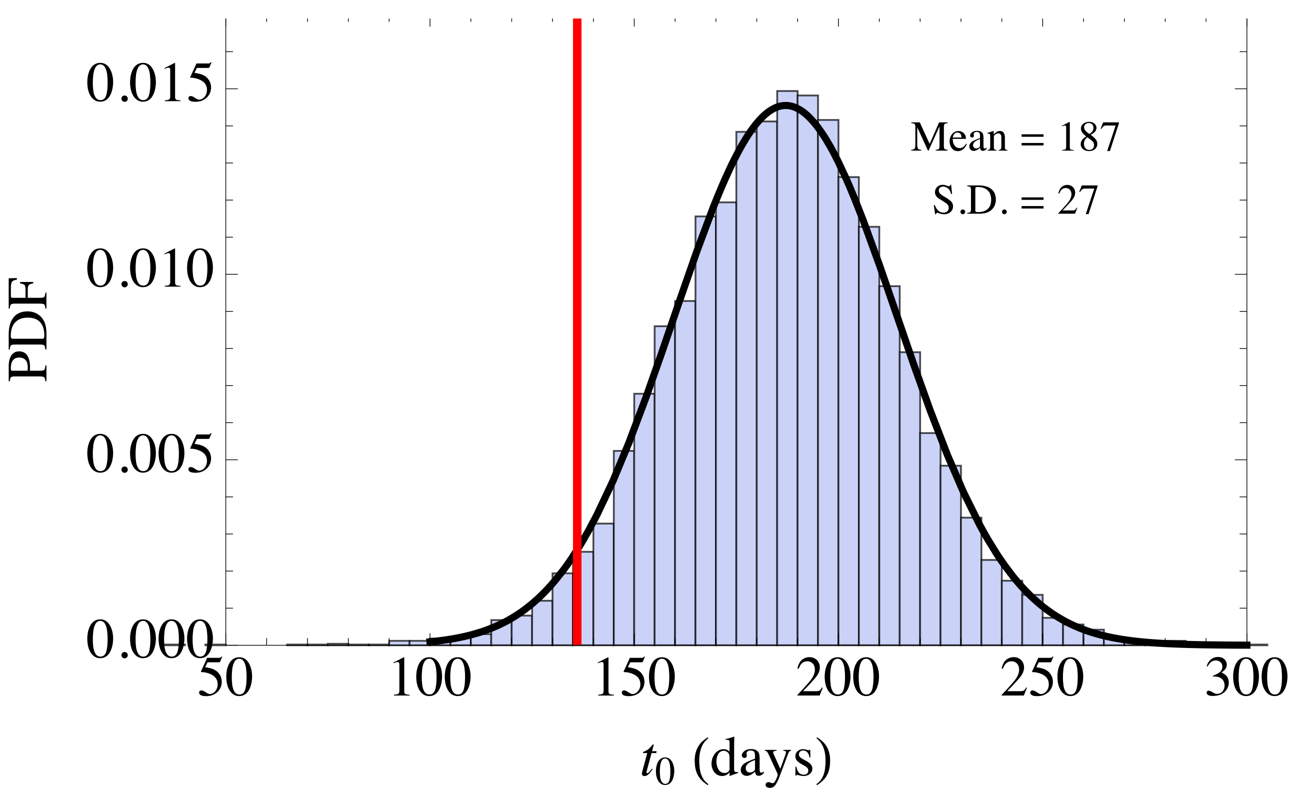
vs.



[Blum, arXiv:1110.0857]

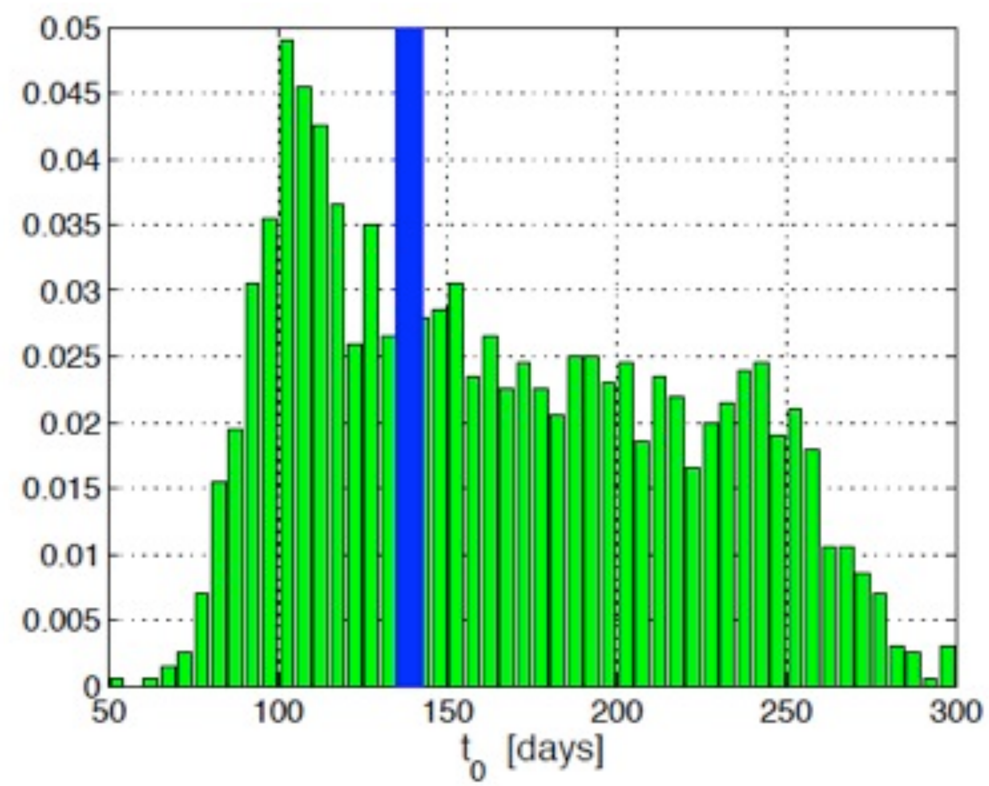
The phase of DAMA
vs
the "phase" of LVD

t_0 from Jan 1, 2003



vs.

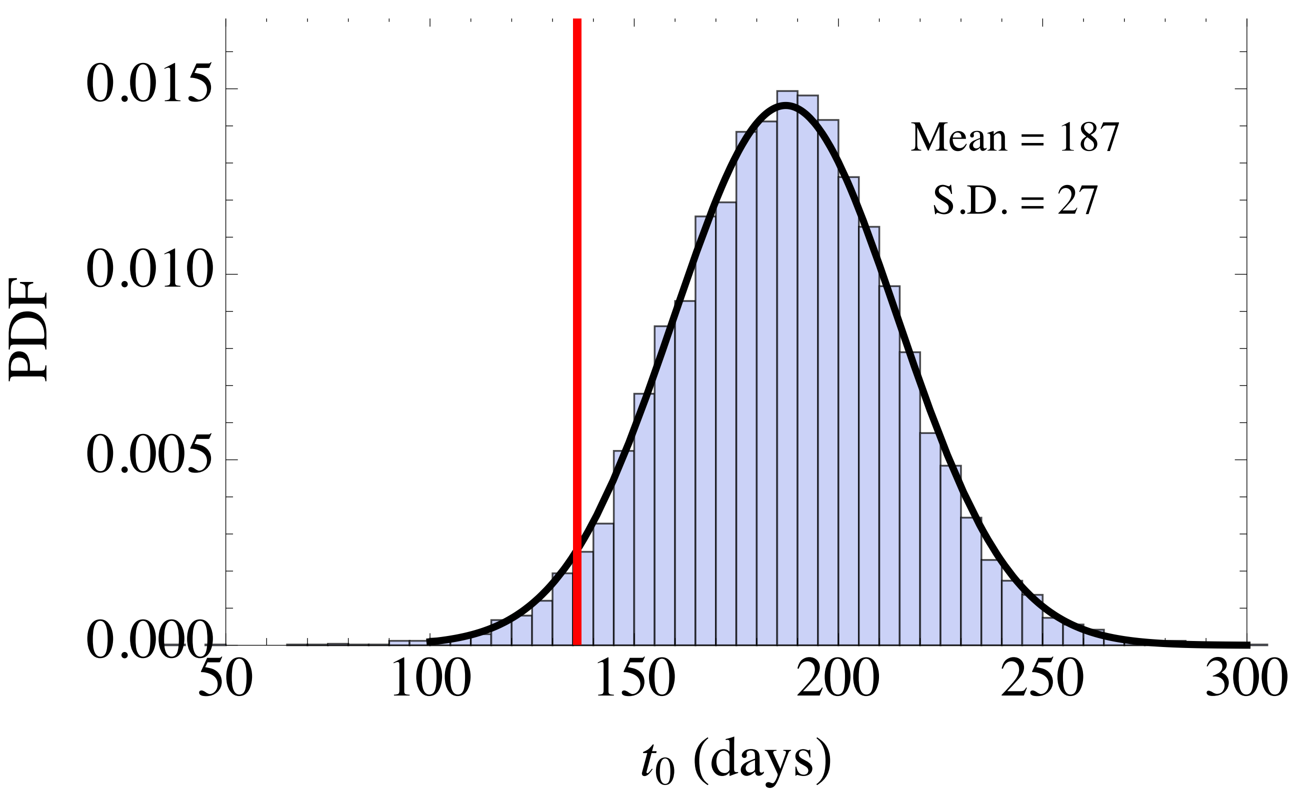
t_0 from Jan 1,1995



[Blum, arXiv:1110.0857]

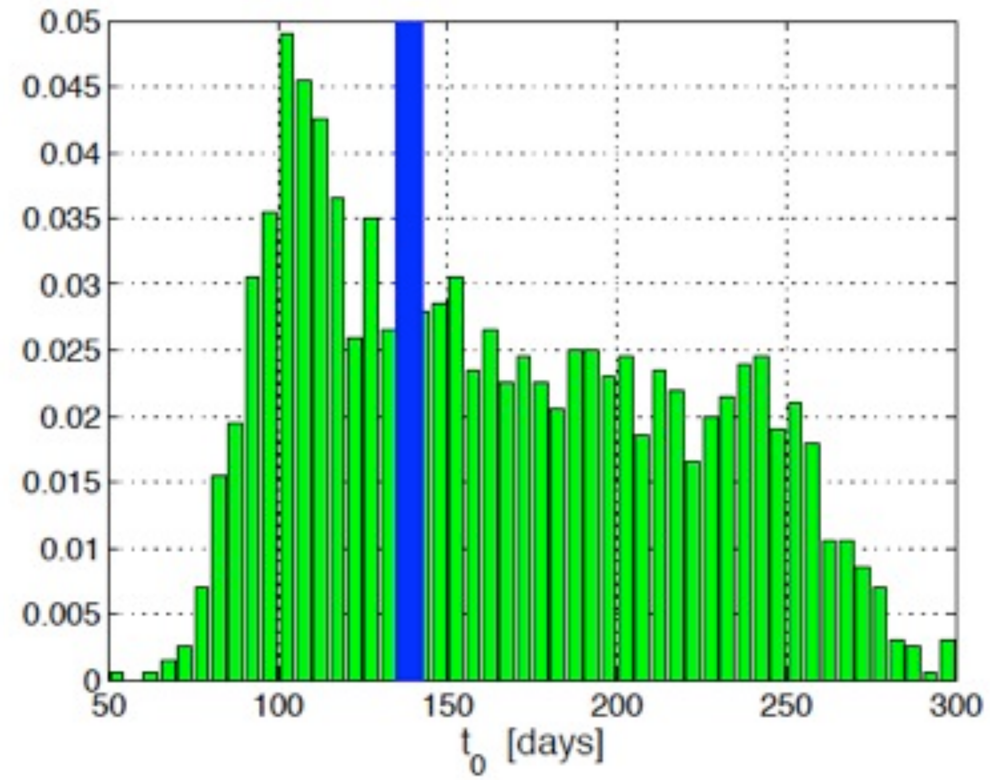
The phase of DAMA
vs
the "phase" of LVD

t_0 from Jan 1, 2003



vs.

t_0 from Jan 1,1995



[Blum, arXiv:1110.0857]

since period floats in fit => t_0 **looses its absolute meaning**!

lessons learned

1. distribution in t_0 depends on time origin

   => frequentist fits to mock-data do not define a good test statistic

2. we need better ways to quantify agreement/disagreement of DAMA with the Muon hypothesis

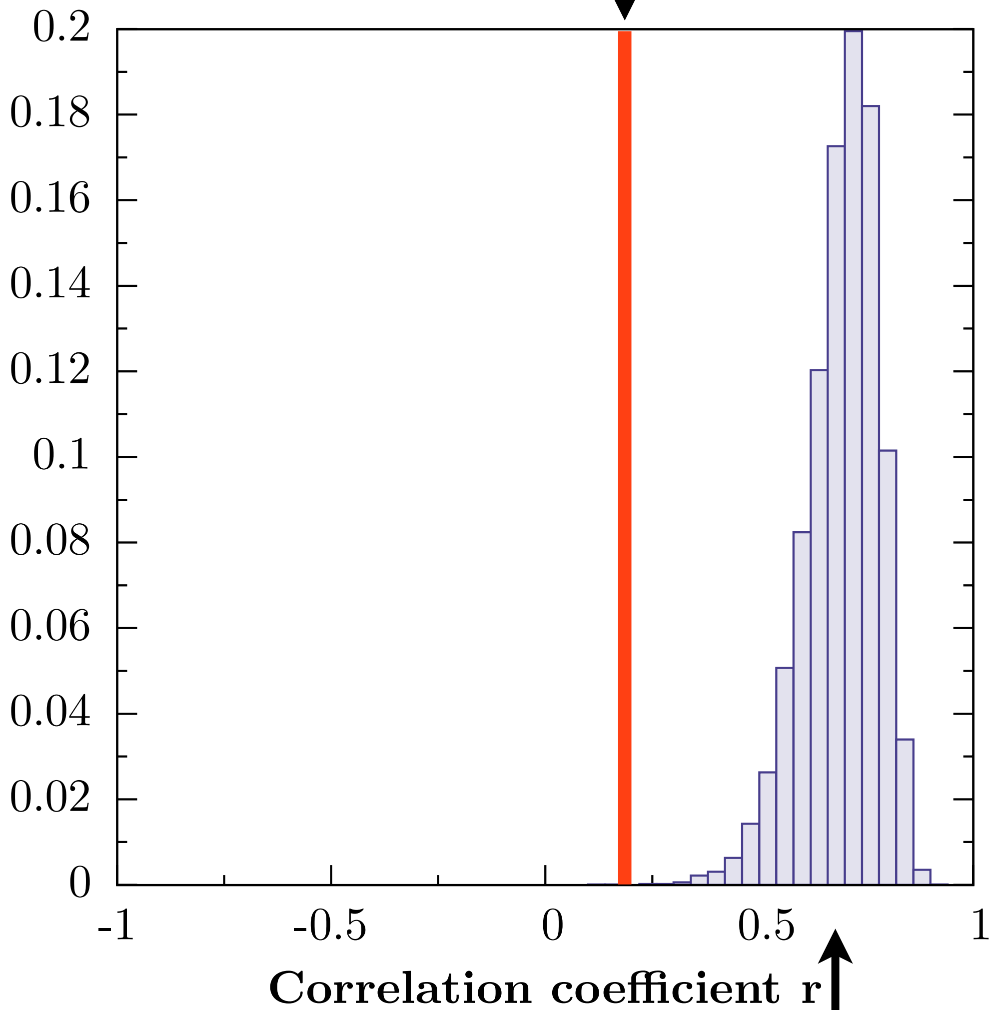
   => preferentially without reliance on sinusoidal function

   => look at the correlation coefficient $r \in [-1, 1]$

$$r_{XY} = \frac{\sum_i (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_i (X_i - \bar{X})^2}\sqrt{\sum_i (Y_i - \bar{Y})^2}}$$

correlation study

correlation
r(muon,mock=DAMA)

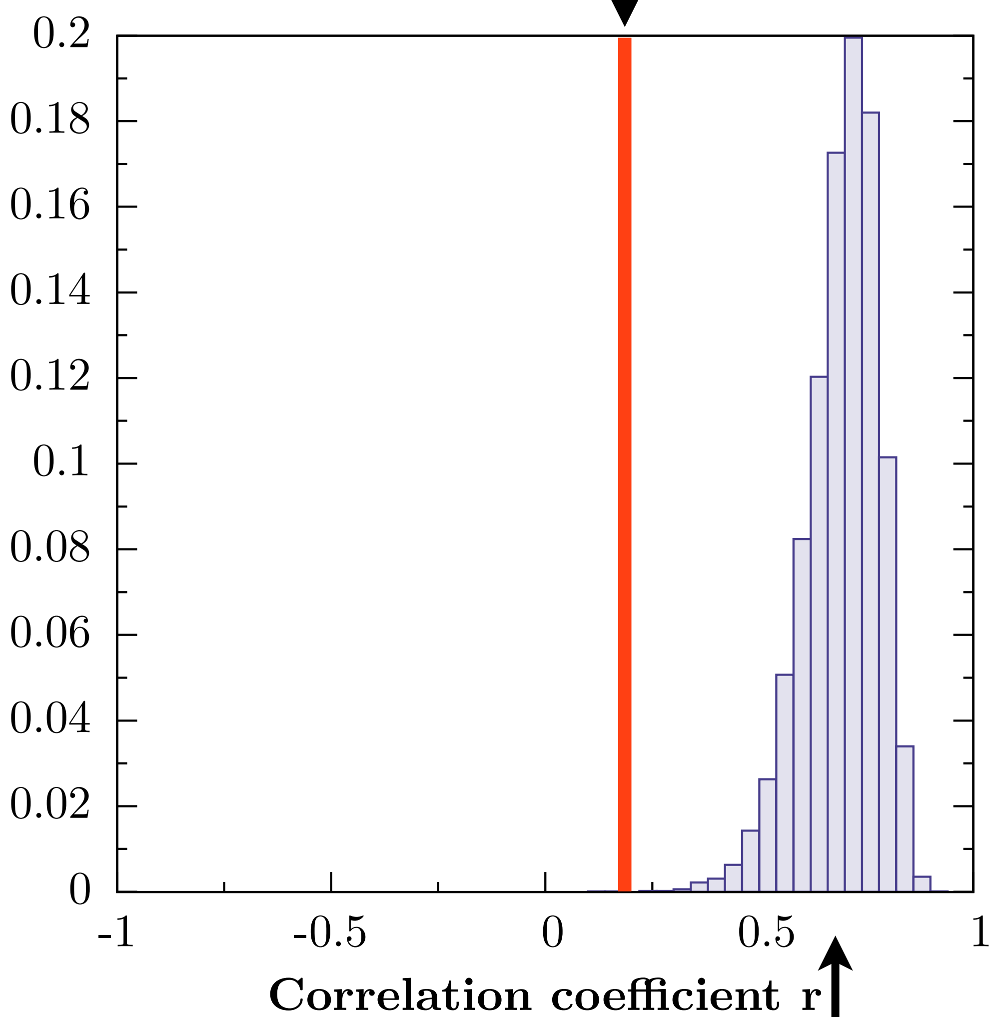


correlation
r(muon,mock)

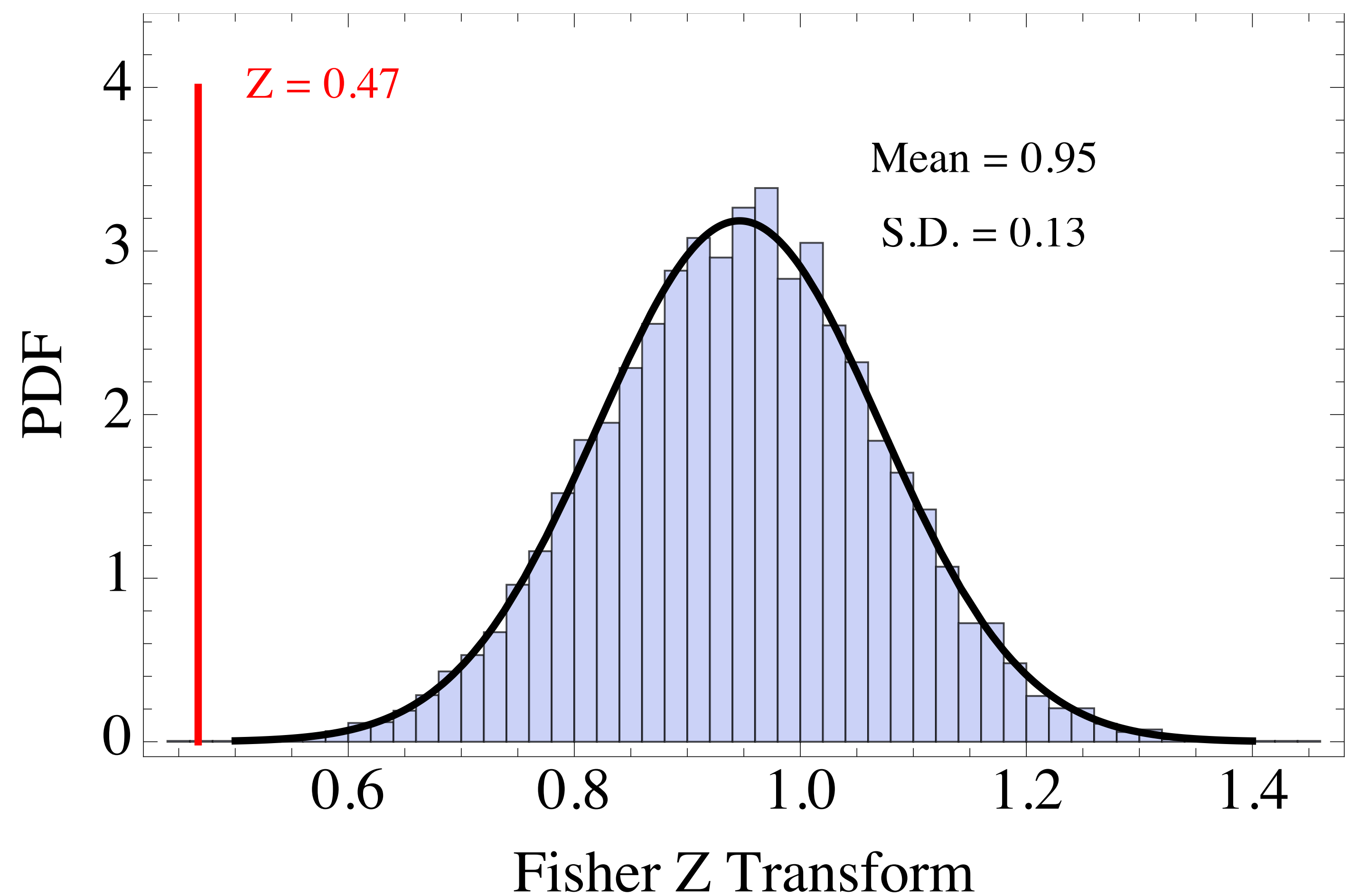
Q: how significant is the difference between these two?

correlation study

correlation
r(muon,mock=DAMA)



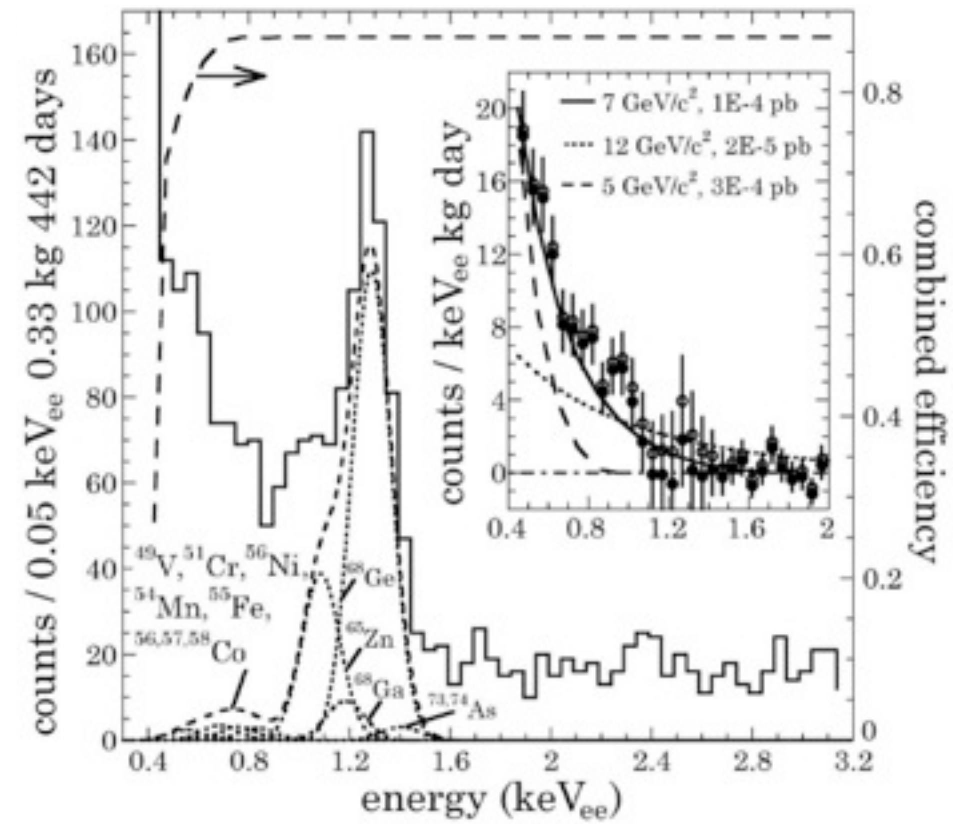
correlation
r(muon,mock)

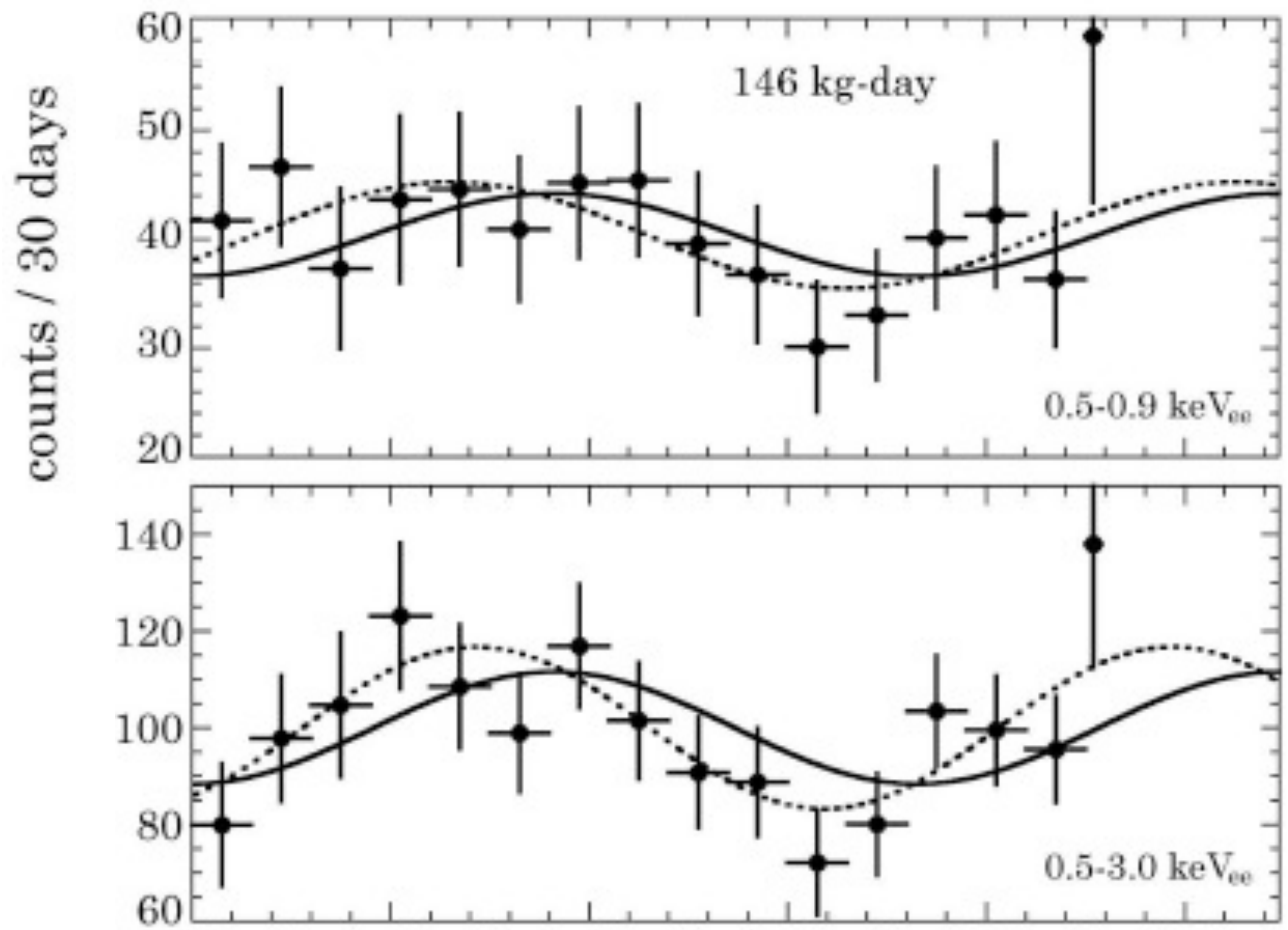


Model excluded $\gtrsim 99\%$ C.L.

CoGeNT

- 442 kg live-days
- Ge-target, ionization
- potential exponential rise toward low energies
- cosmogenic peaks
- modulation too

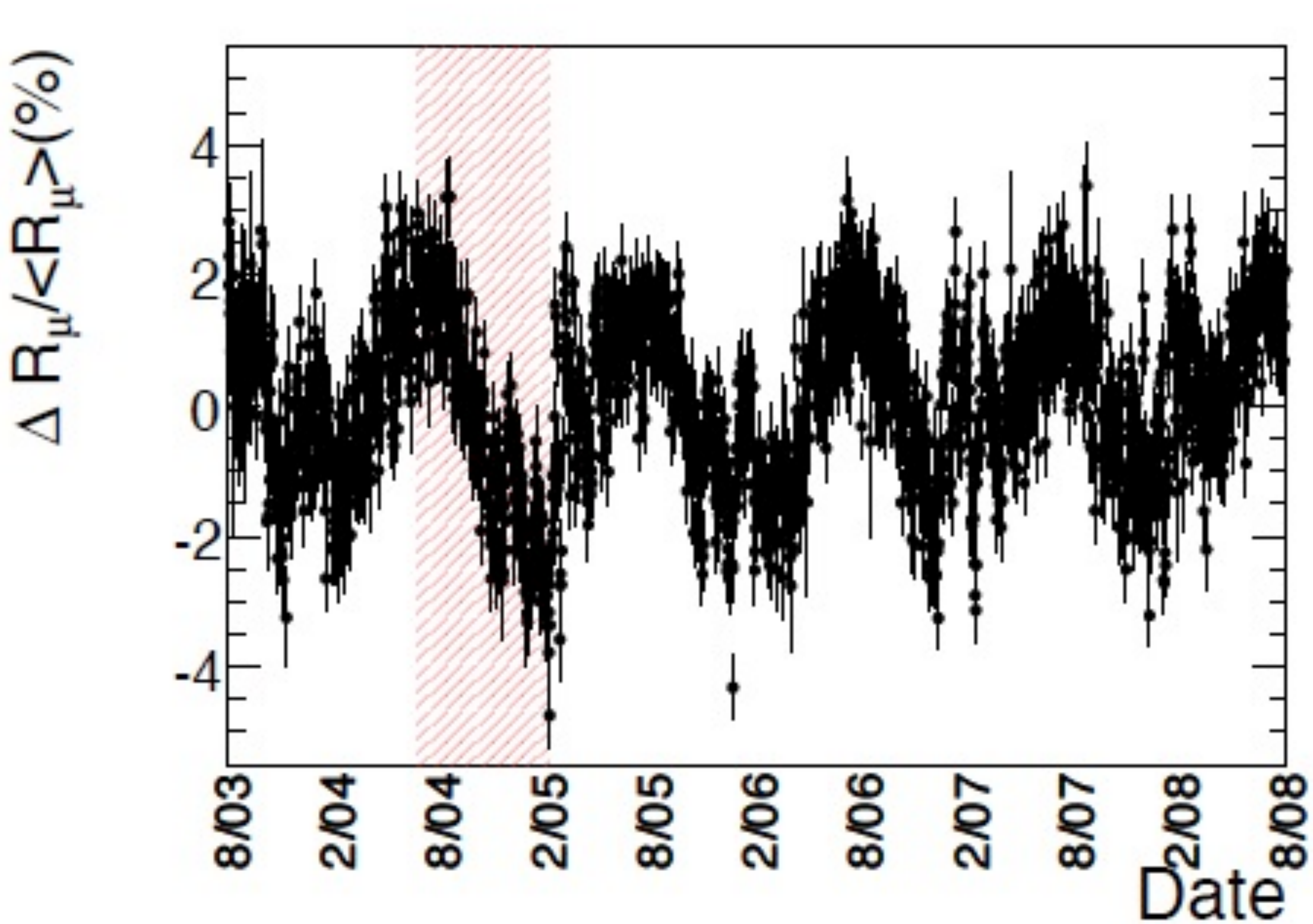




[Aalseth et al, 2011]

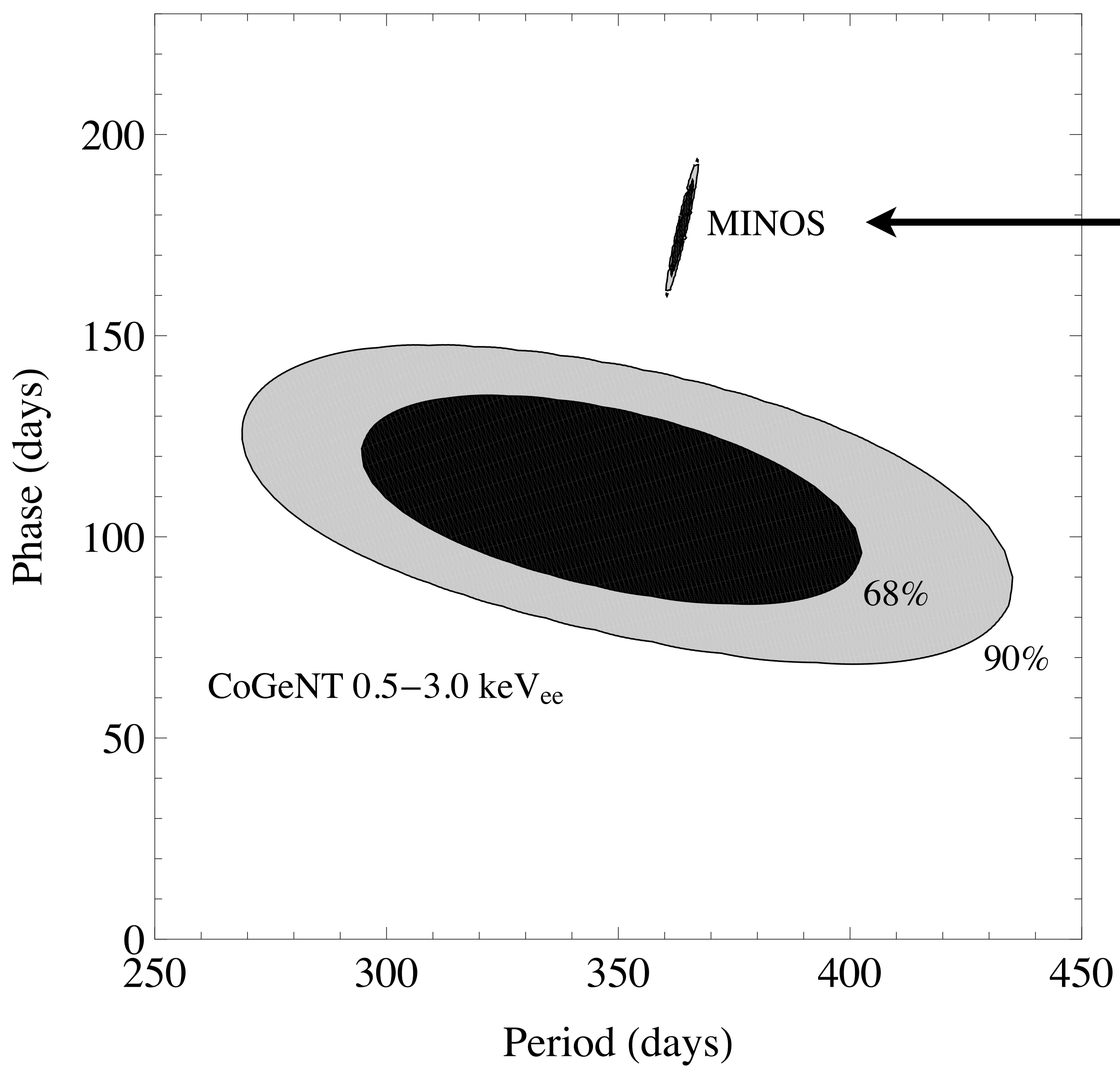
CoGeNT

- muon measurements at CoGeNT site (Soudan Mine, MN) from MINOS experiment exist



[Adamson et al, 2010]

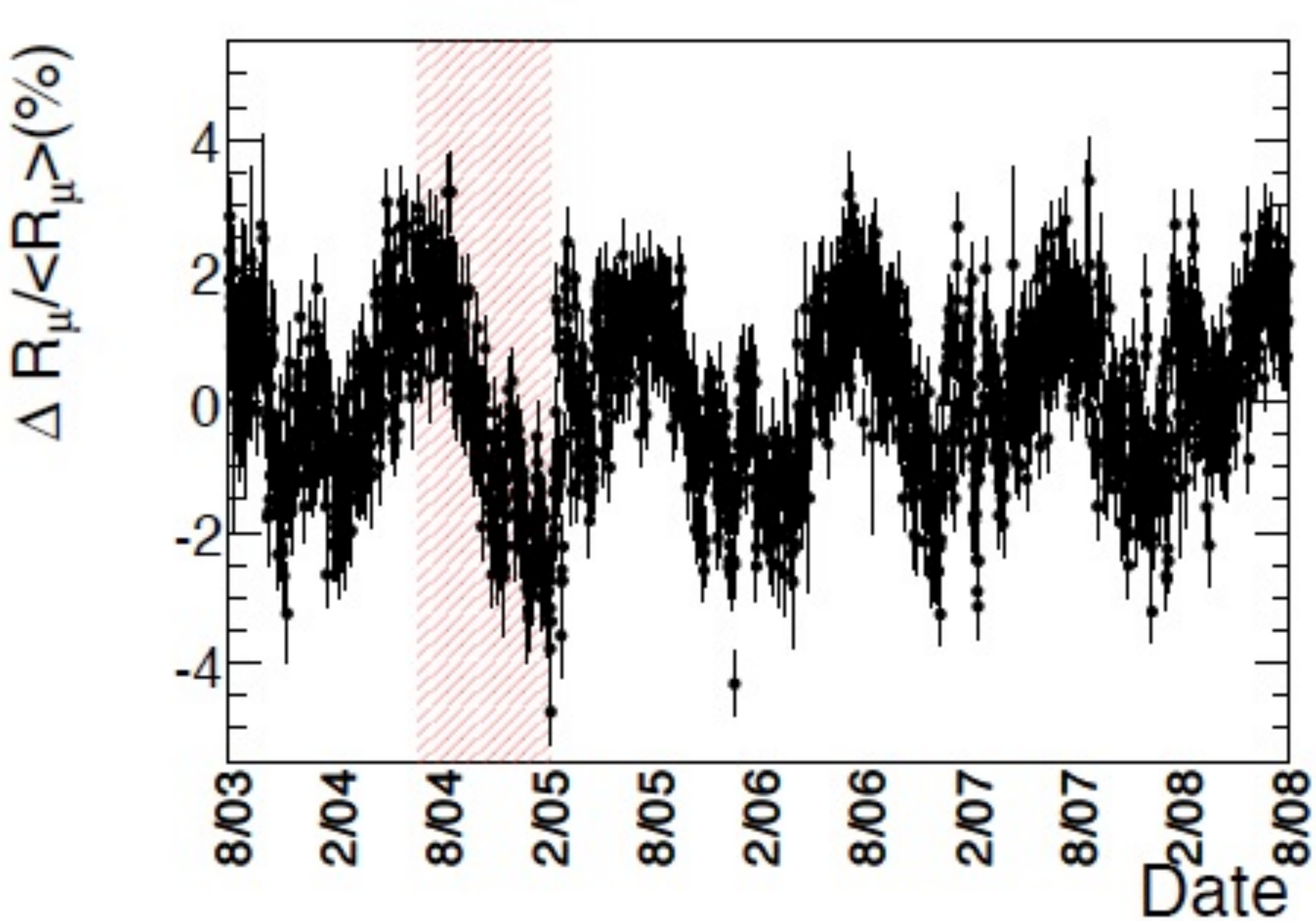
phase analysis for CoGeNT



Data has no temporal overlap!

CoGeNT

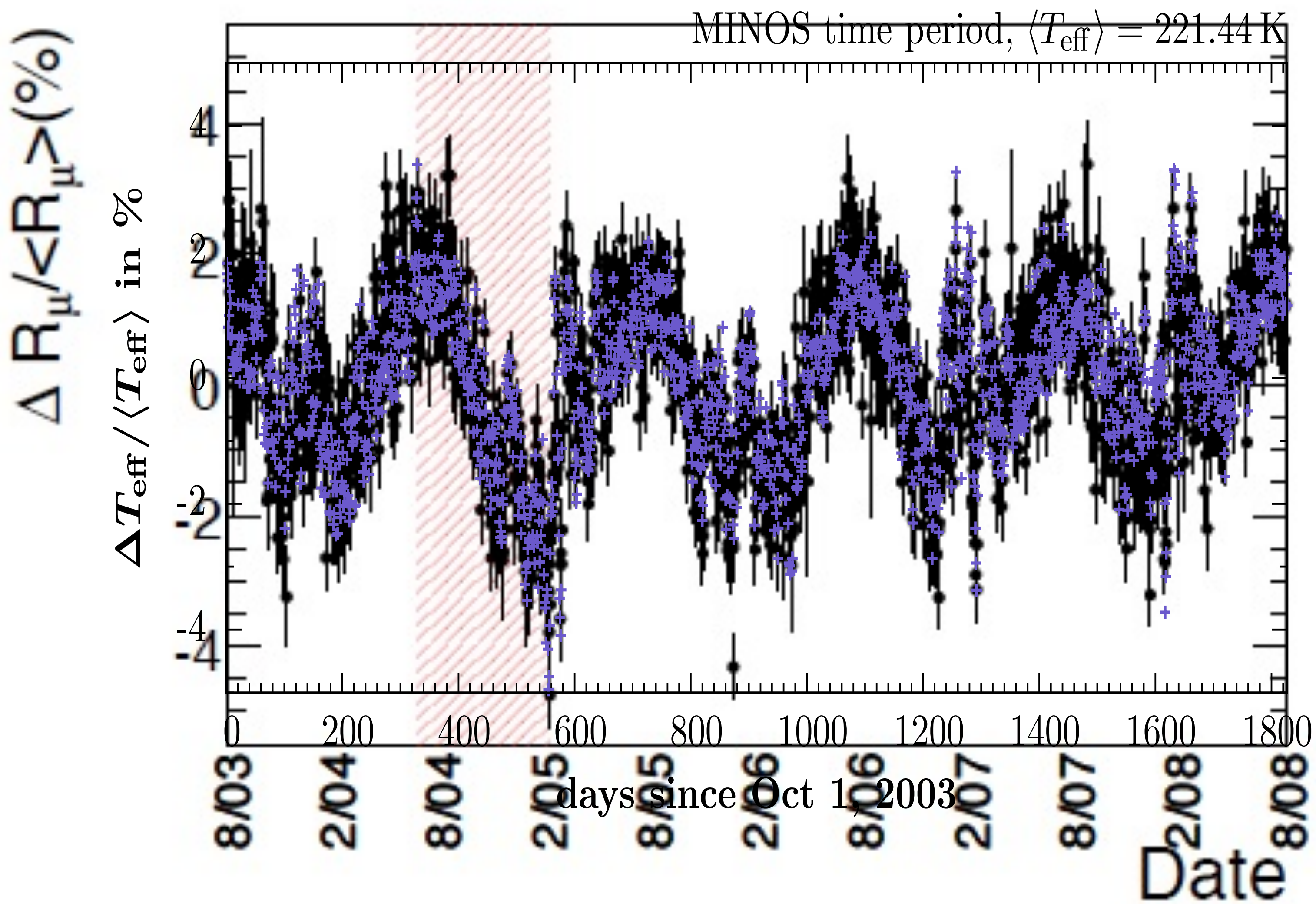
- muon measurements at CoGeNT site (Soudan Mine, MN) from MINOS experiment exist - but no temporal overlap



[Adamson et al, 2010]

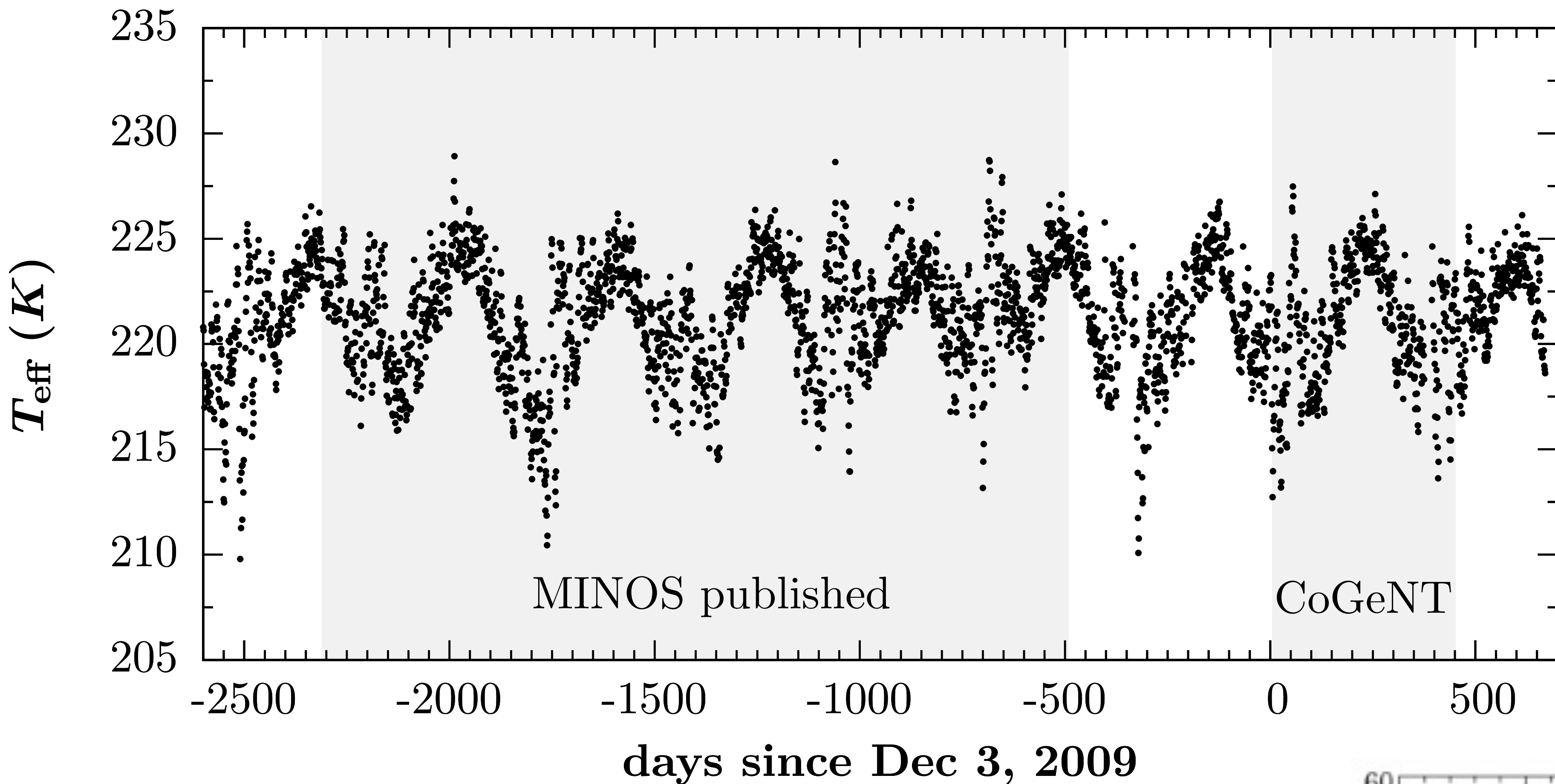
- muon measurements at CoGeNT site (Soudan Mine, MN) from MINOS experiment exist - but no temporal overlap

=> use available climate data to predict muon flux!



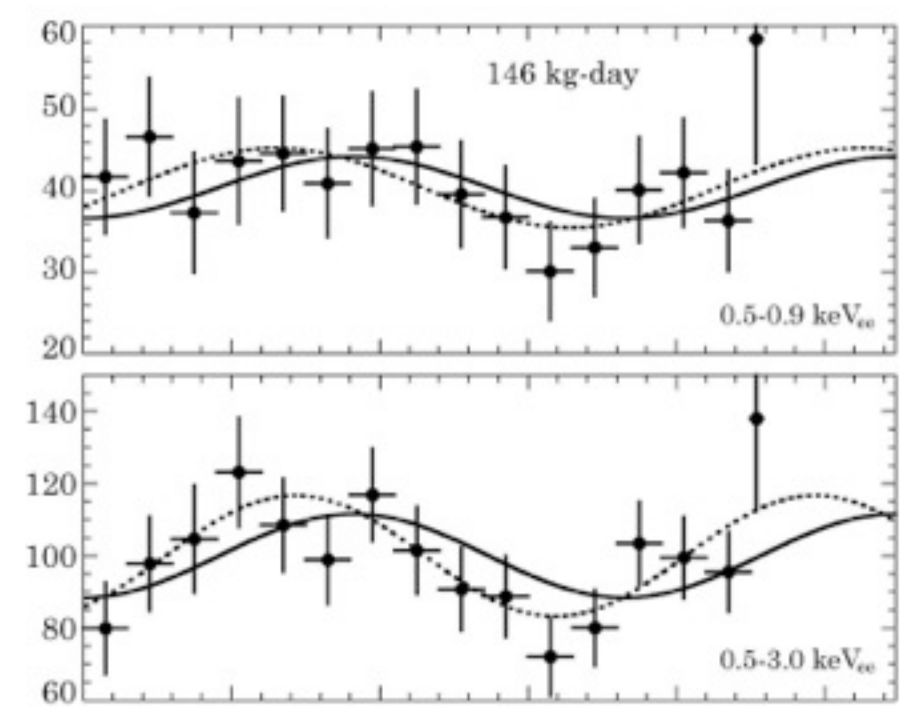
[Adamson et al, 2010]

CoGeNT

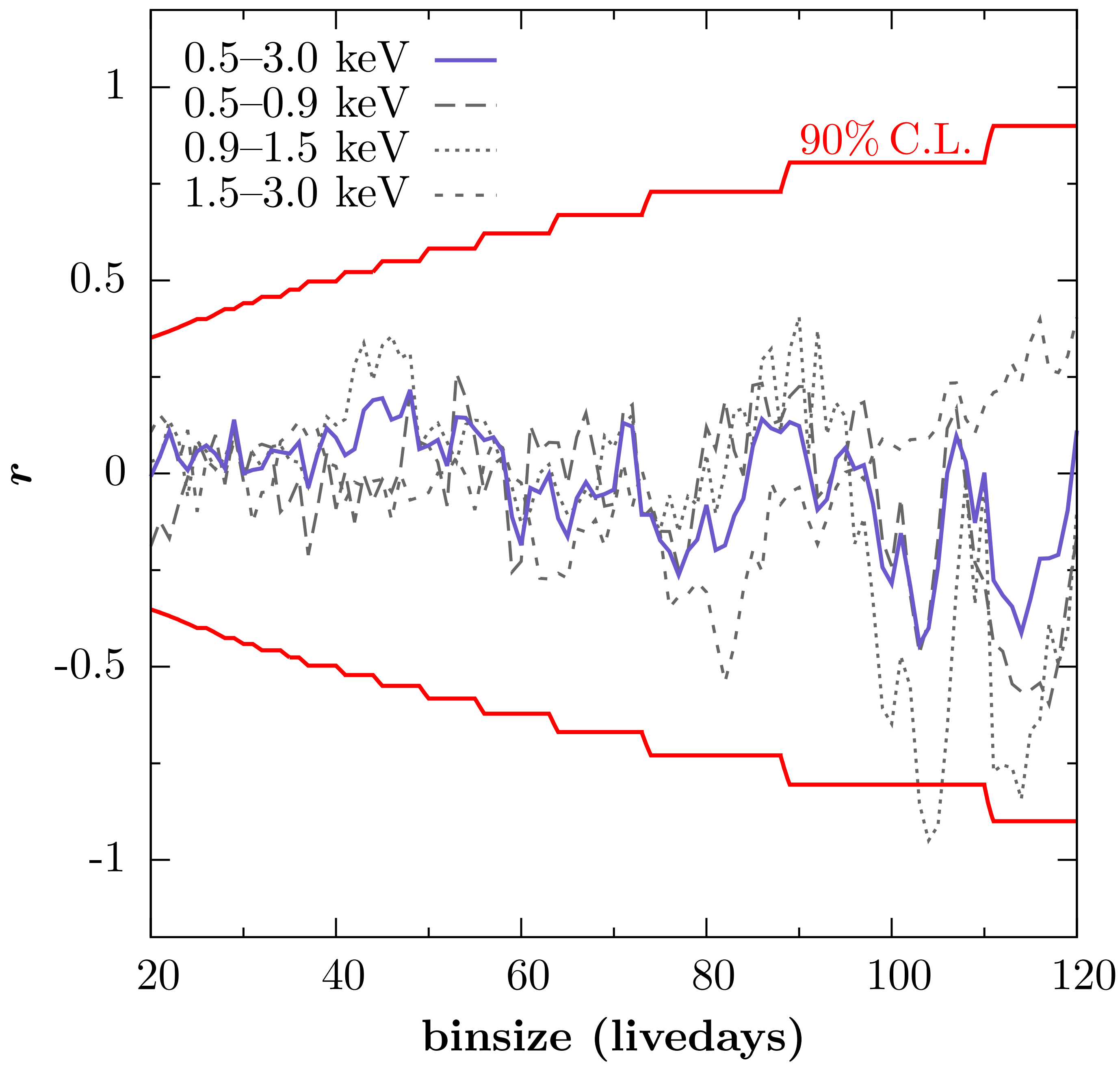


“International Falls, MN” balloon data

vs.



CoGeNT correlation study



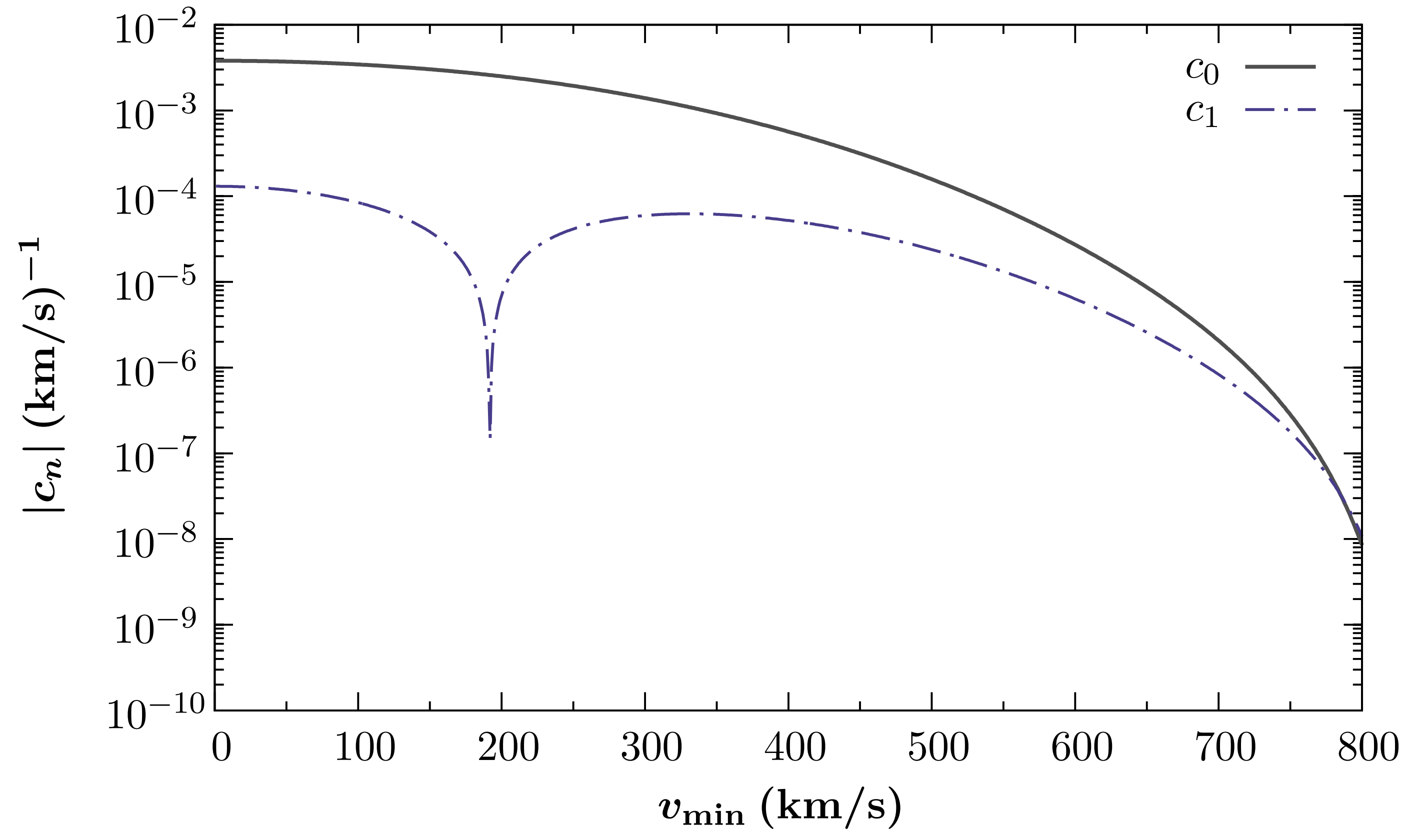
no correlation
with high significance!

=> CoGeNT's
modulation
not muon-induced

higher harmonics in DM modulation

$$\frac{dR(t)}{dE_R} \propto \int_{v_{min}}^{\infty} \frac{f(v)}{v} dv \simeq c_0(v_{min}) + c_1(v_{min}) \cos\left[\omega(t - t_0)\right]$$

$$v_{min} = \frac{1}{\sqrt{2 m_N E_R}} \left(\frac{m_N E_R}{\mu_{N\chi}} + \delta \right)$$



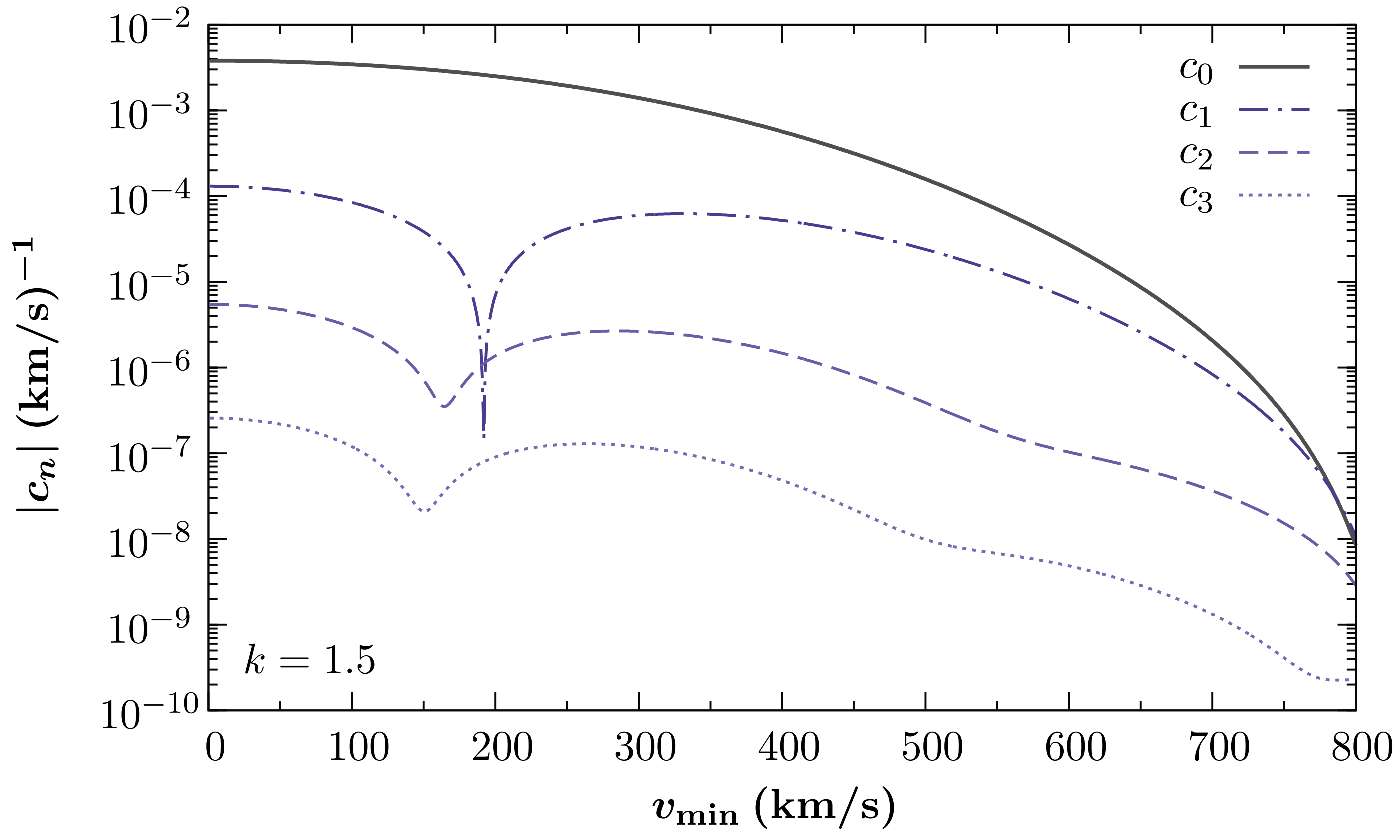
[using f(v) from Lisanti et al, 2010]

higher harmonics in DM modulation

$$\frac{dR(t)}{dE_R} \propto \int_{v_{min}}^{\infty} \frac{f(v)}{v} dv = \sum_{n=0,1,\ldots} c_n(v_{min}) \cos\left[n\omega(t - t_n)\right]$$

$$v_{min} = \frac{1}{\sqrt{2 m_N E_R}} \left(\frac{m_N E_R}{\mu_{N\chi}} + \delta \right)$$

- biannual mode
- triannual mode
- ...



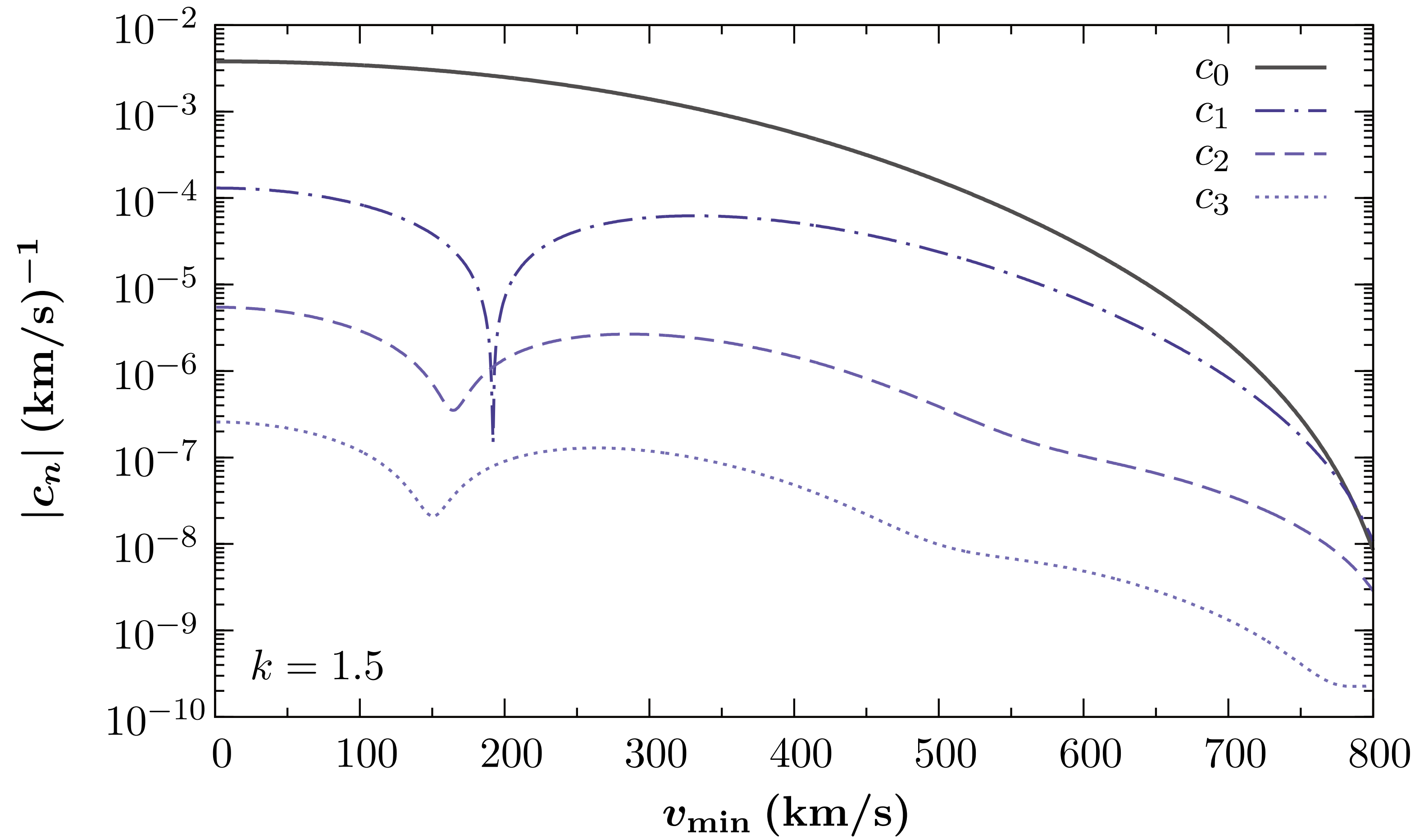
[using f(v) from Lisanti et al, 2010]

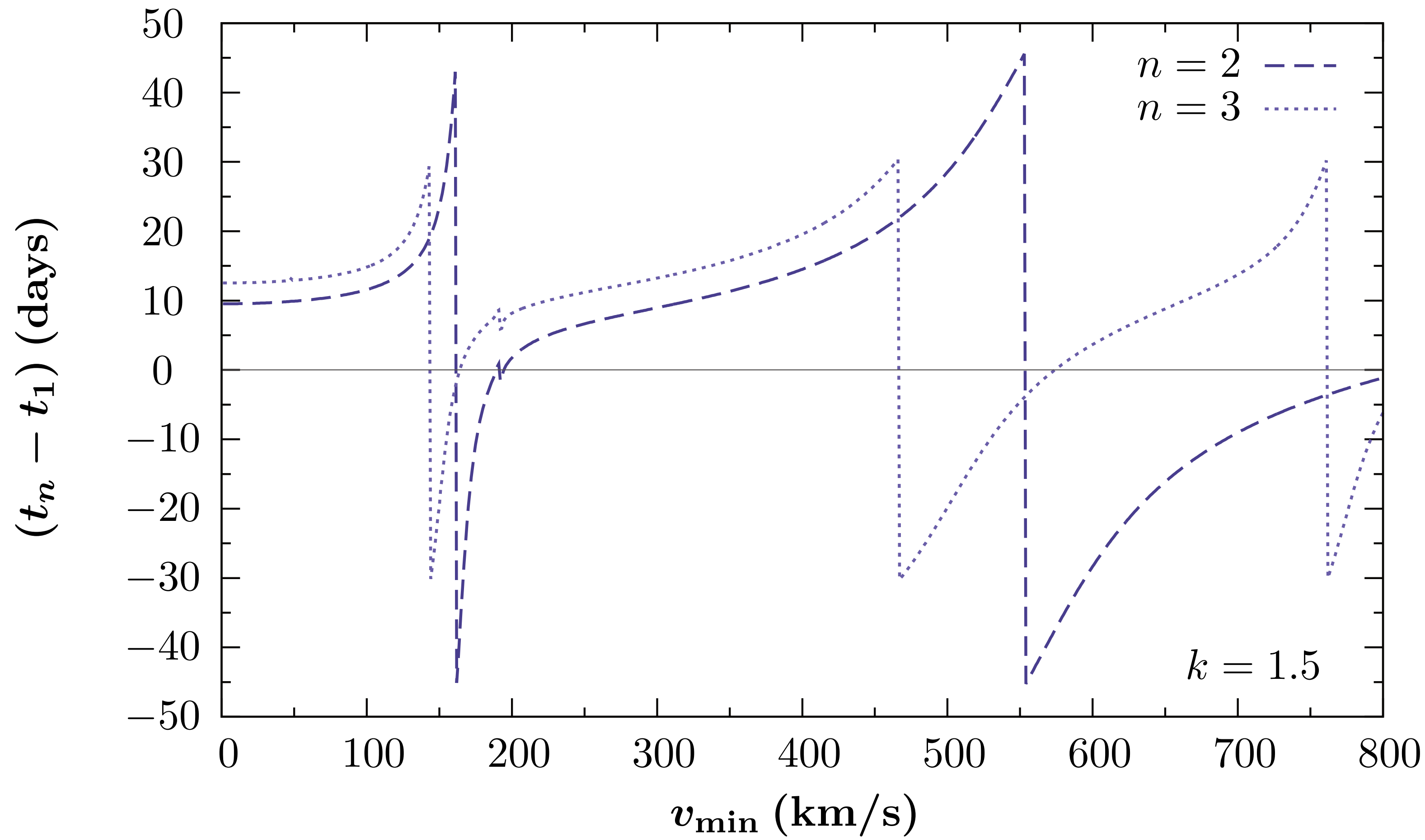
higher harmonics in DM modulation

- can be thought of as an expansion in $V_\oplus/v_\odot$
- once ellipticity of earth's orbit is included

  => phase shifts between different harmonics

  => new signature
- detection is likely to require large exposure



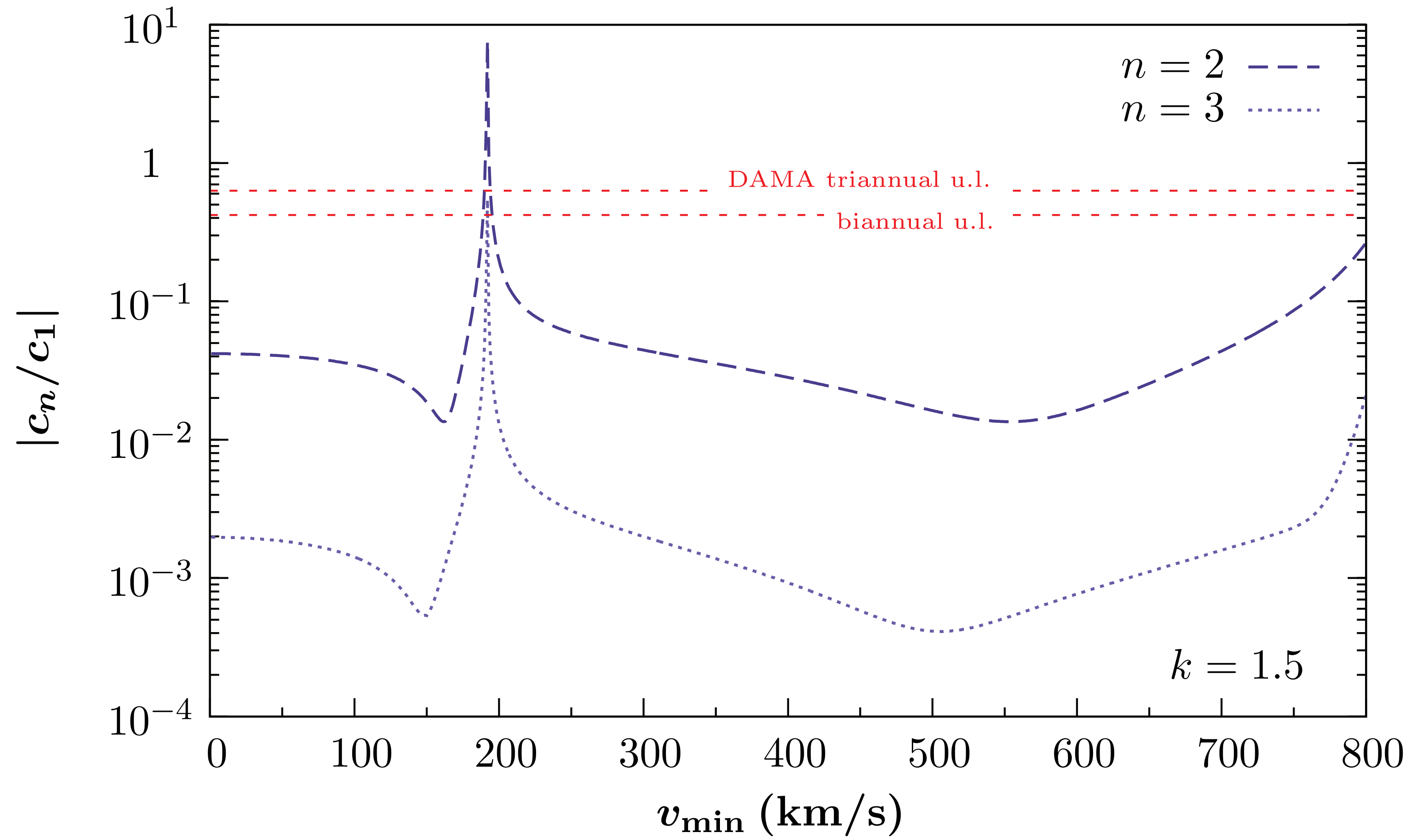


higher harmonics in DM modulation

- can be thought of as an expansion in $V_\oplus / v_\odot$
- once ellipticity of earth's orbit is included

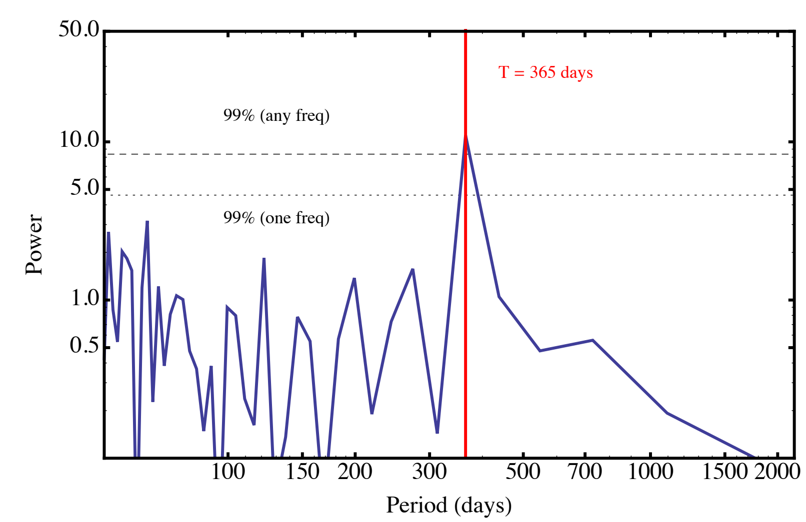
  => phase shifts between different harmonics

  => new signature
- detection is likely to require large exposure



DAMA/LIBRA:

$$P_{\rm obs}(\text{biann}) = 0.57$$
$$P_{\rm obs}(\text{triann}) = 1.8$$



Part II

"moral"

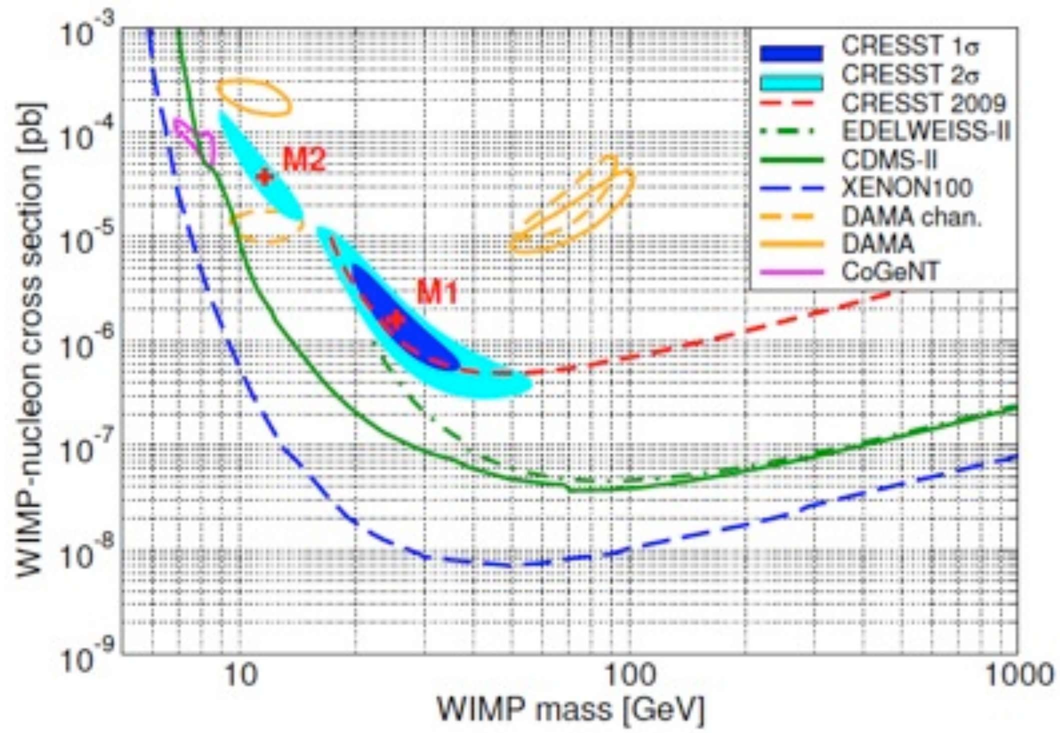
- there can be alternatives to the "**light WIMP paradigm**" in explaining direct detection anomalies/signals

=> diversifying physics output of direct detection experiments [see e.g. also Harnik, Kopp, Machado 2012]

Part II

"moral"

- there can be alternatives to the "**light WIMP paradigm**" in explaining direct detection anomalies/signals



[Angloher et al., 2011]

=> diversifying physics output of direct detection experiments [see e.g. also Harnik, Kopp, Machado 2012]

Leo 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

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

(this process has not yet been observed)

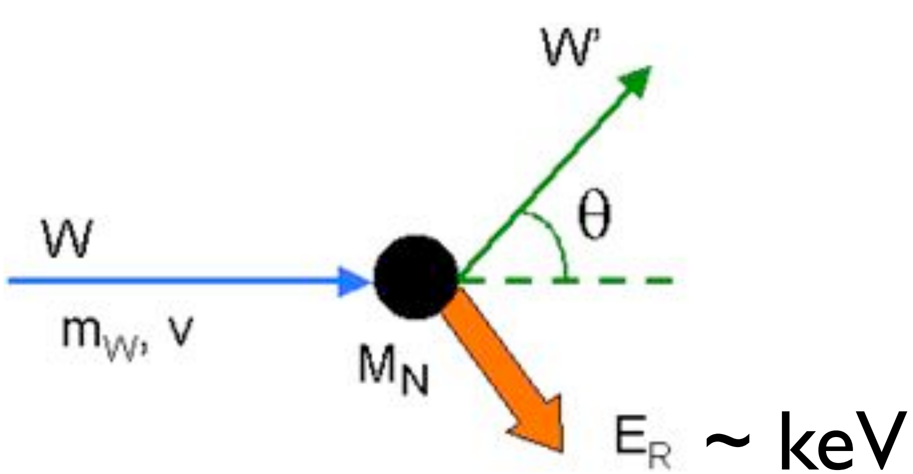
=> direct DM detection

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)

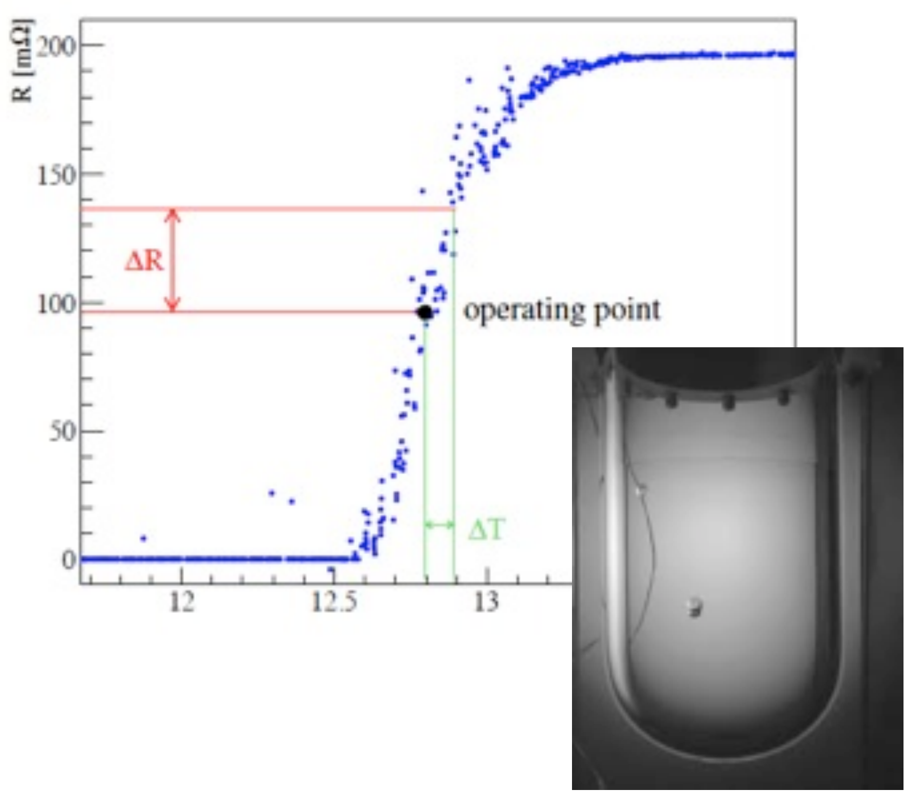
We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and 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.



Witten 1985

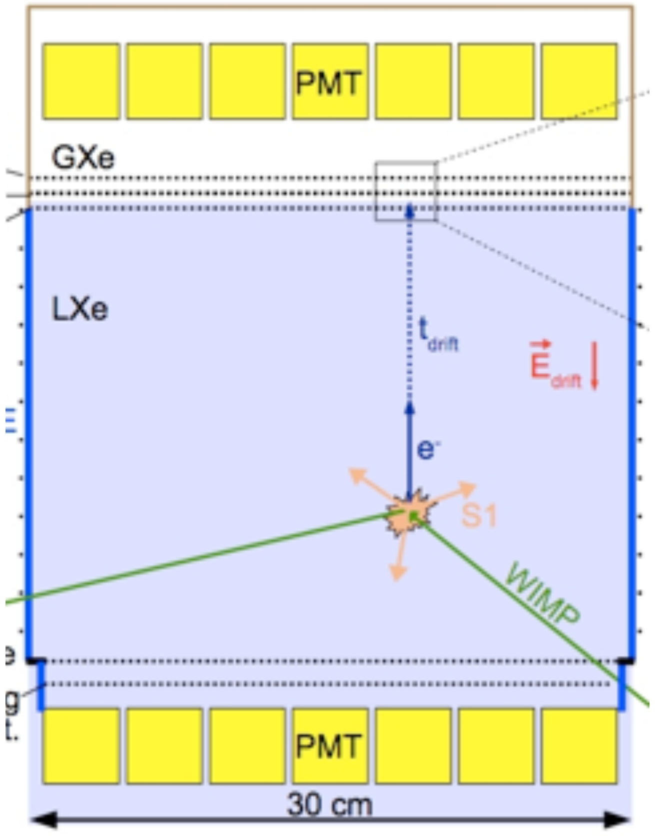
=> direct DM detection

- 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

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

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

solar ν 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 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$_{\nu_b}$

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 :

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

“baryonic” neutrinos$_{\nu_b}$

M. Pospelov arXiv:1103.3261

- baryonic neutrino can get mass from ν_R

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

- neutrinos talk via mass mixing => “sterile-active” oscillations

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

"baryonic" neutrinos$_{\nu_b}$

M. Pospelov arXiv:1103.3261

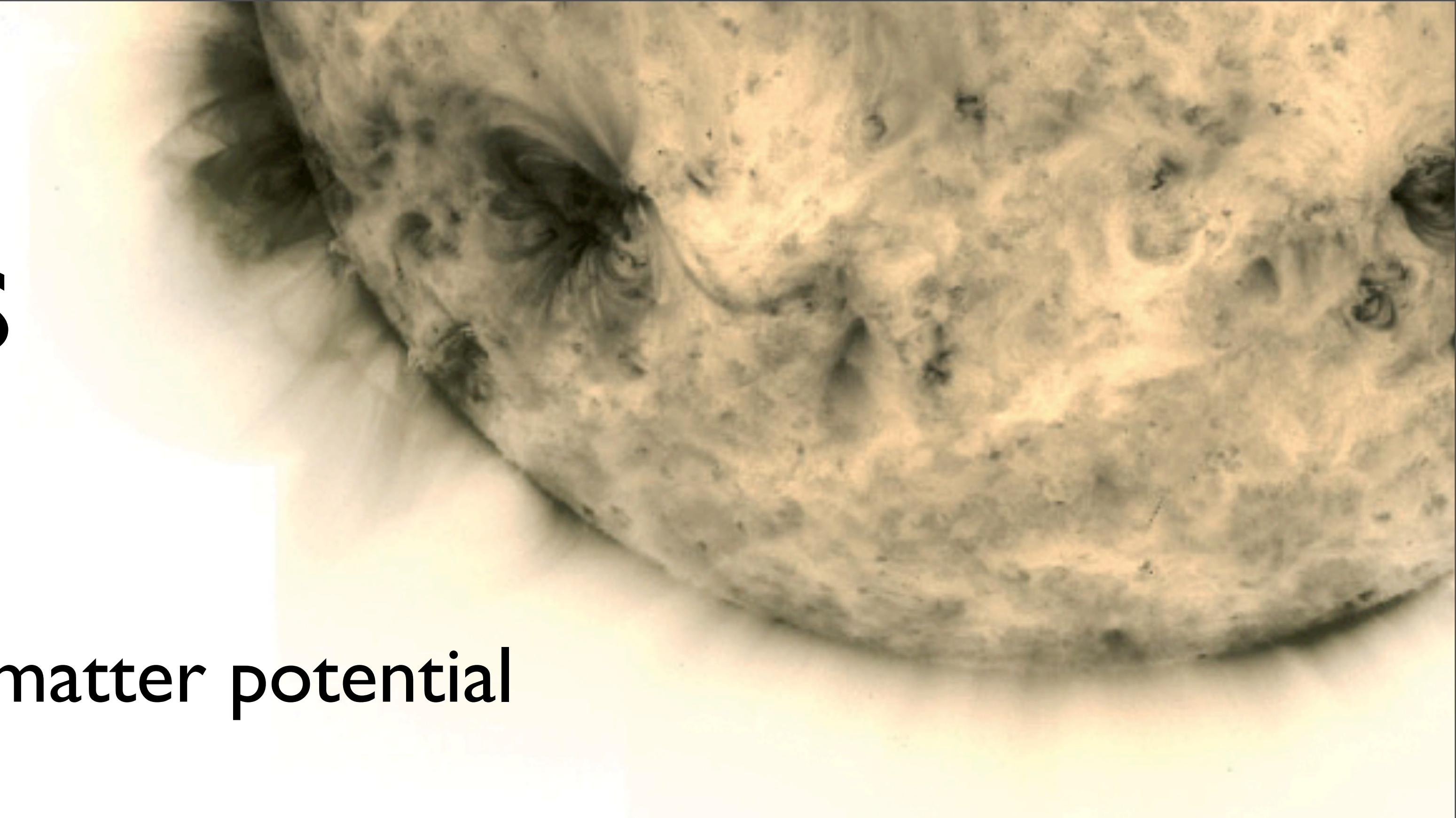
- **crucial insight:**

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

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

- deuteron breakup in SNO does not constrain scenario

matter effects



- forward scattering induces matter potential

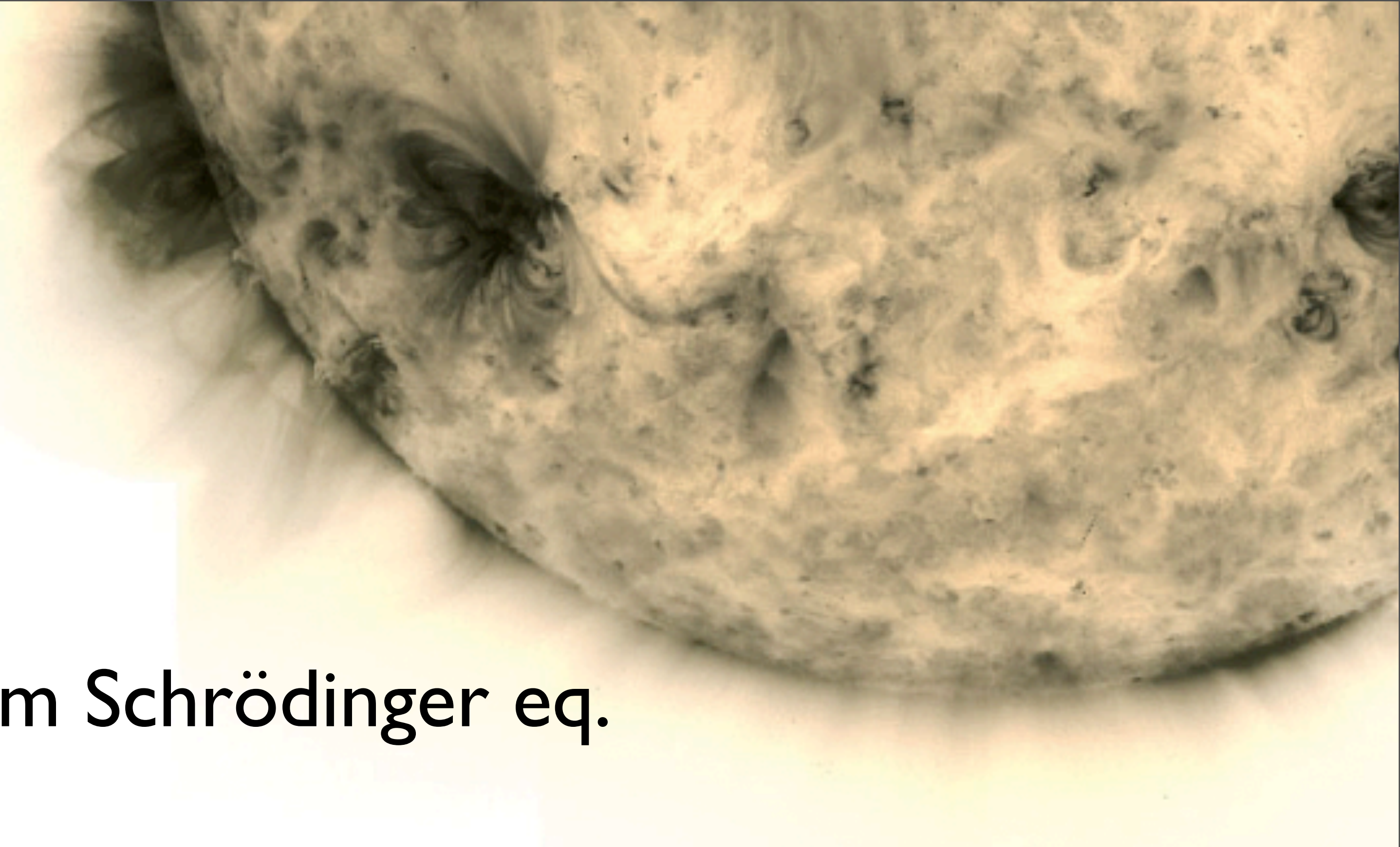
$$V_{NCB} = \pm q_b \mathcal{N} G_F n_B \left(Y_N + 2Y_{\nu_b}\right), \qquad Y_f = \frac{n_f - n_{\overline{f}}}{n_B},$$

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

$X_p =$ mass fraction of protons

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

matter effects



- flavor transition amplitudes from Schrödinger eq.

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

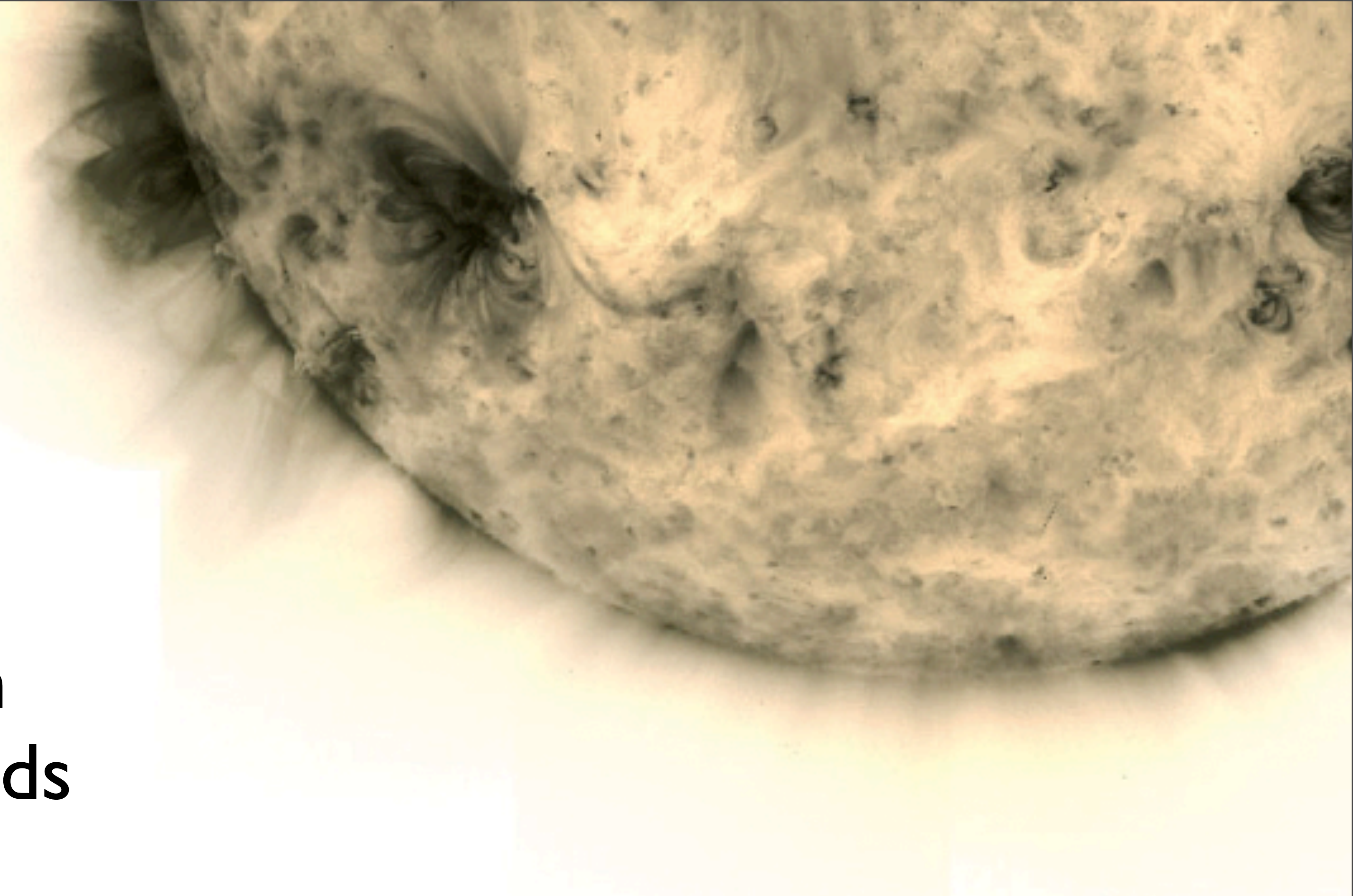
$$\tan 2\theta_M = \frac{\tan 2\theta_b}{1 + 2EV_{NCB}/(\Delta m_b^2 \cos 2\theta_b)}$$

matter mixing angle

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

=> mixing angle in matter suppressed

matter effects



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

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

$$\downarrow$$

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

(from a tribimaximal ansatz assuming mixing to ν_2)

[see arXiv:1103.3261]

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

direct detection of ν_b

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

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

overall flux modulation

average over neutrino spectrum i

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

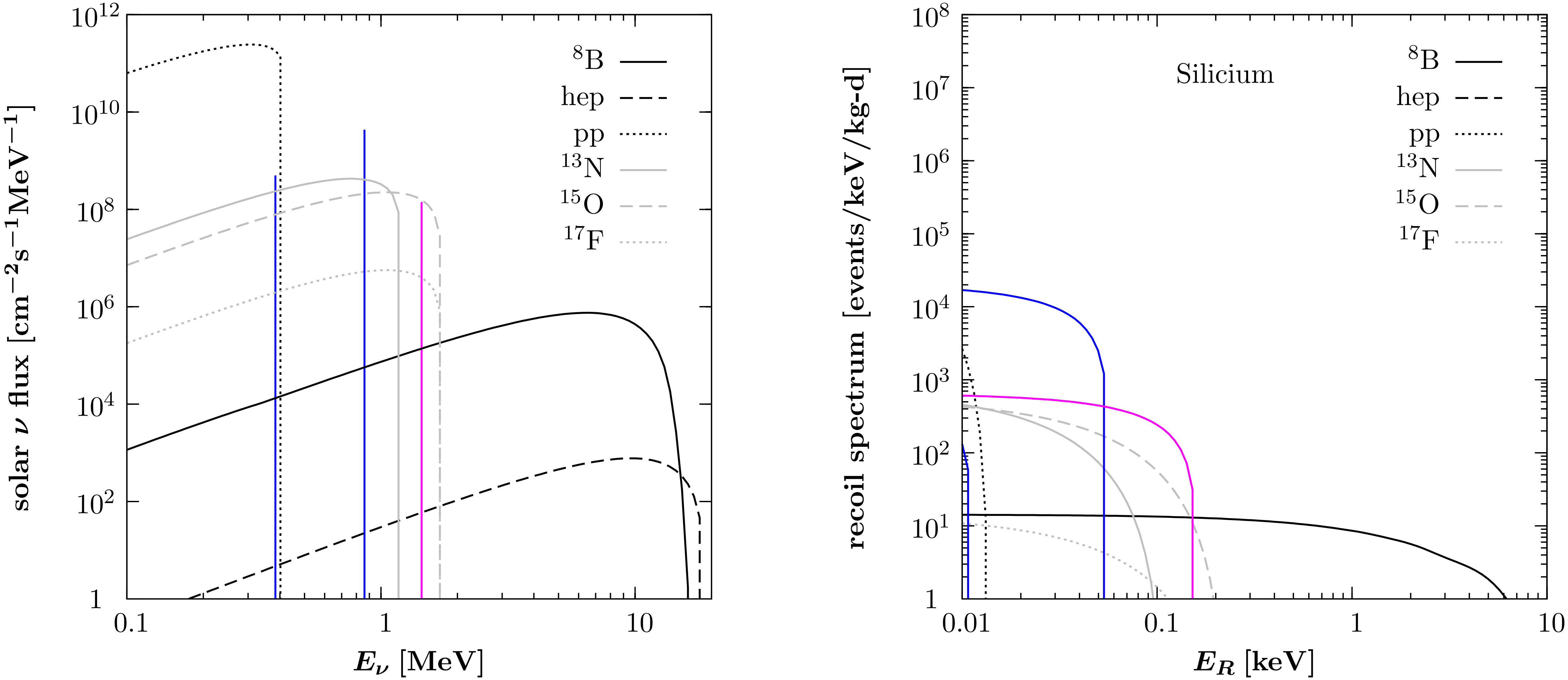
$$L_0 = 1\,\mathrm{AU}$$

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

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

direct detection of ν_b

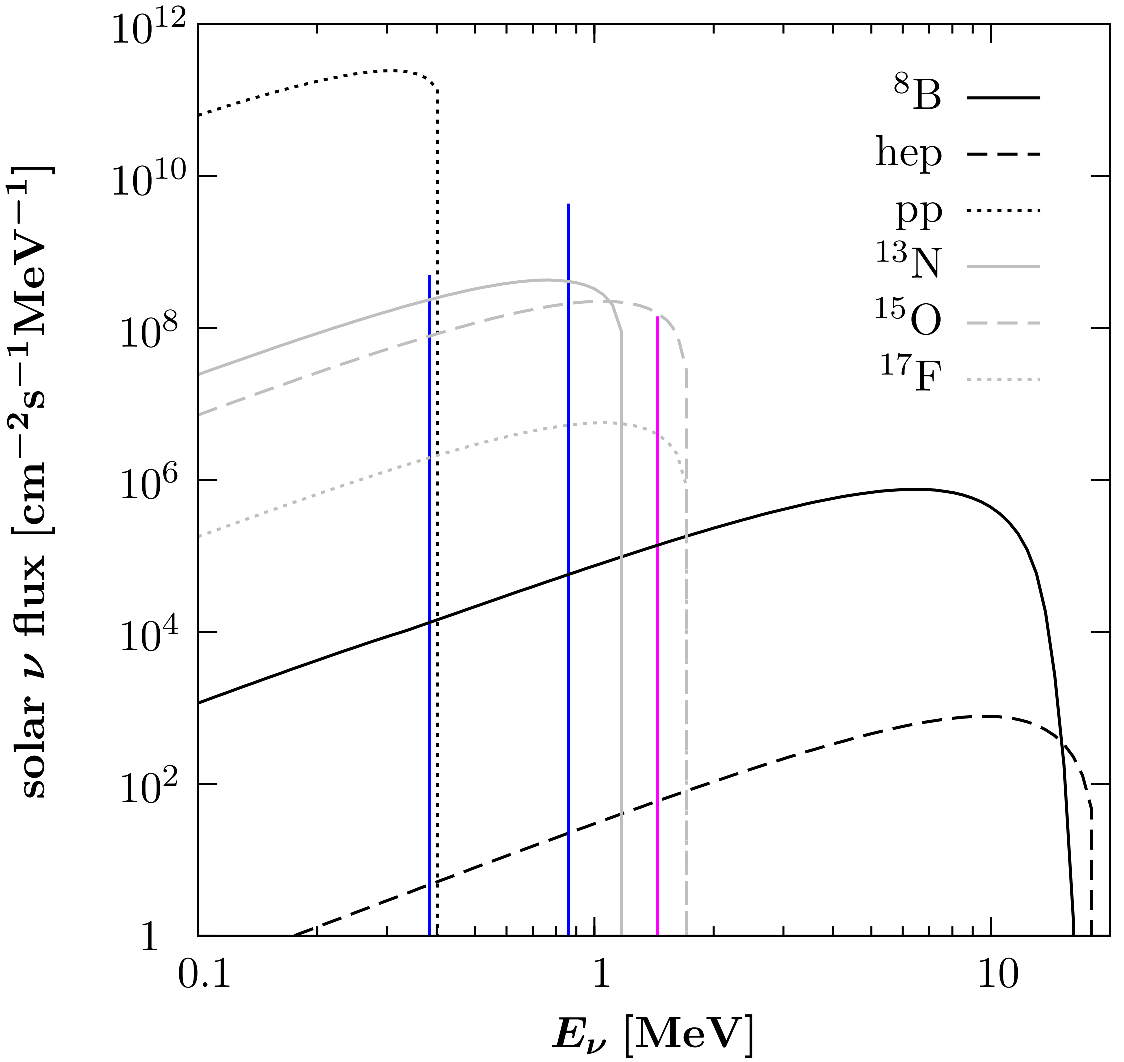
$A_{\mathrm{Si}} = 28$



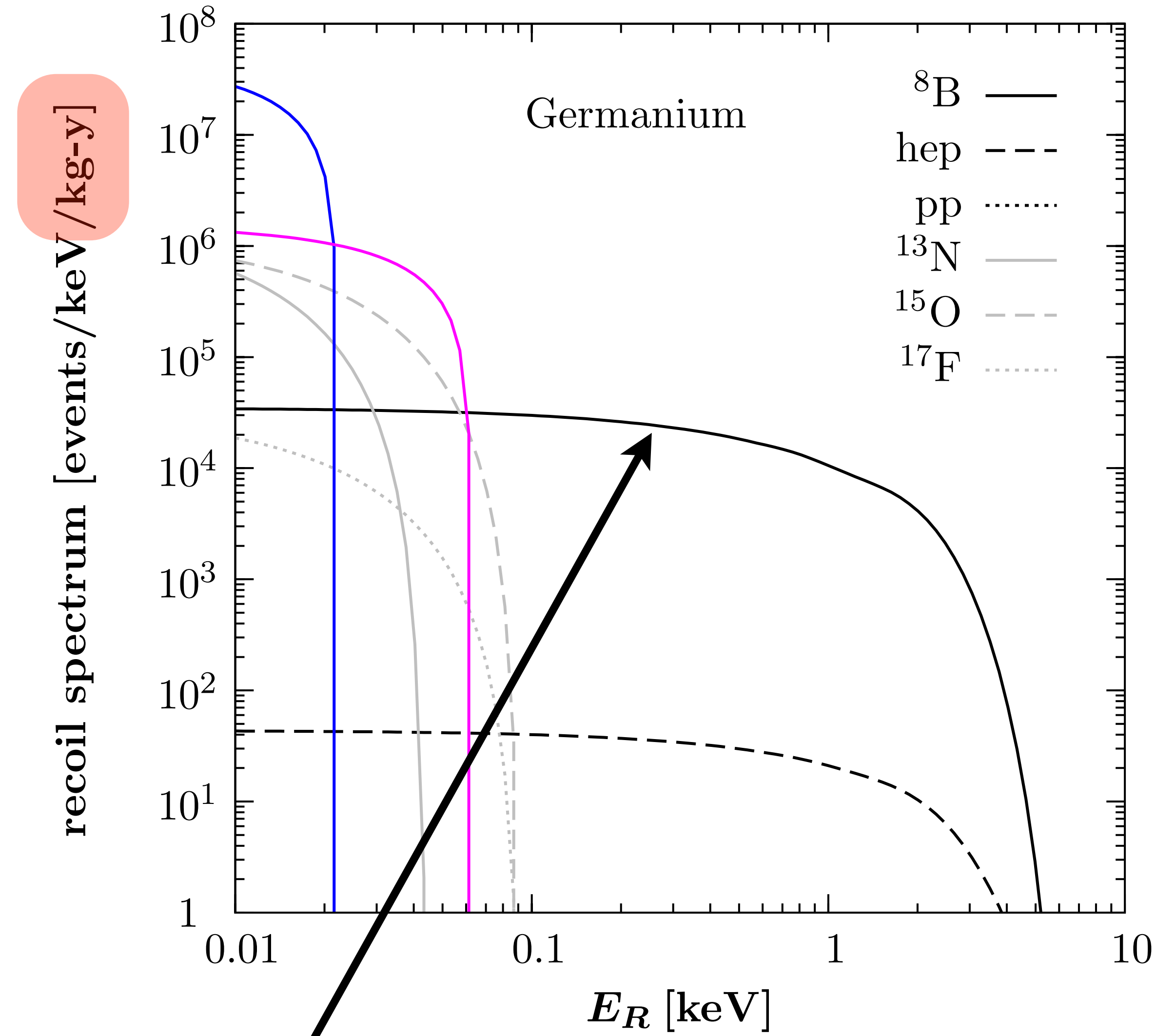
$N_{\mathrm{eff}} = 100$

(perfect detector)

direct detection of ν_b



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



^{8}B

$N_{\rm eff} = 100$

(perfect detector)

direct detection of ν_b

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

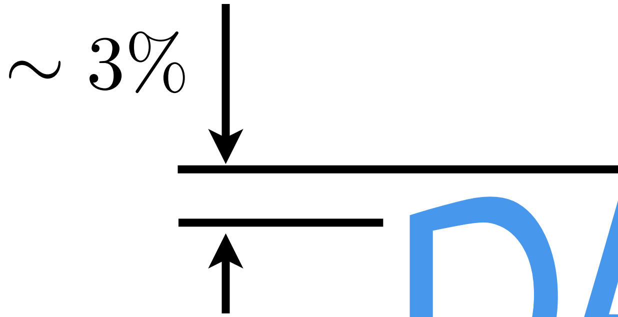
↑

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? **explain DAMA**?



DAMA/LIBRA

- DAMA signal conveniently expressed in terms modulation amplitude S_m

$$S = S_0 + S_m \cos\left[\omega(t - t_0)\right]$$

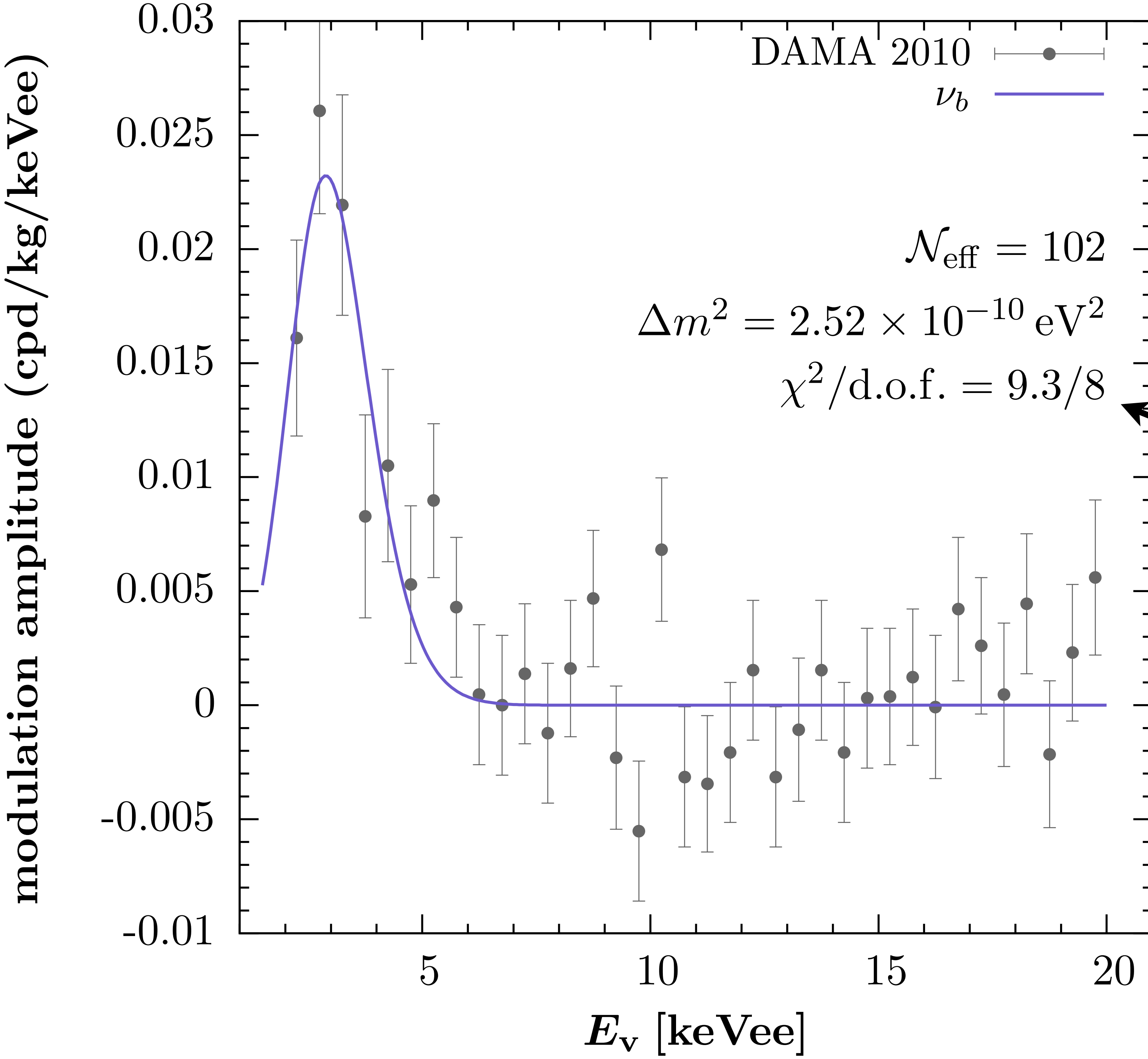
$$S_m = \frac{1}{2}\left(\left.\frac{dR}{dE_{\mathrm{v}}}\right|_{\mathrm{max}} - \left.\frac{dR}{dE_{\mathrm{v}}}\right|_{\mathrm{min}} \right)$$

$S_0 \sim 1\,\mathrm{cpd/kg/keV}$ **(baseline)**

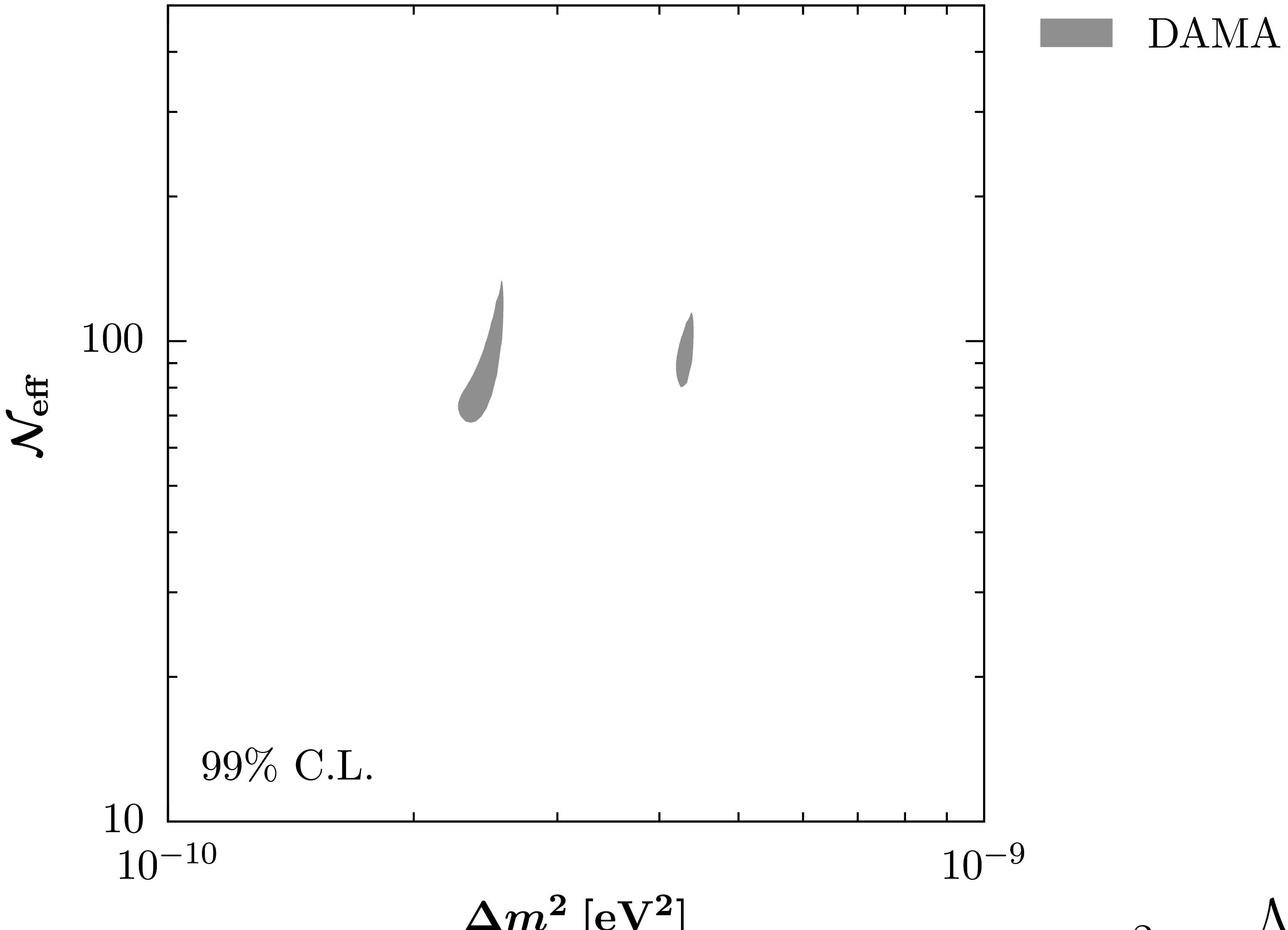
$$S_m / S_0 \sim 3\%$$

$\sim 3\%$

DAMA/LIBRA



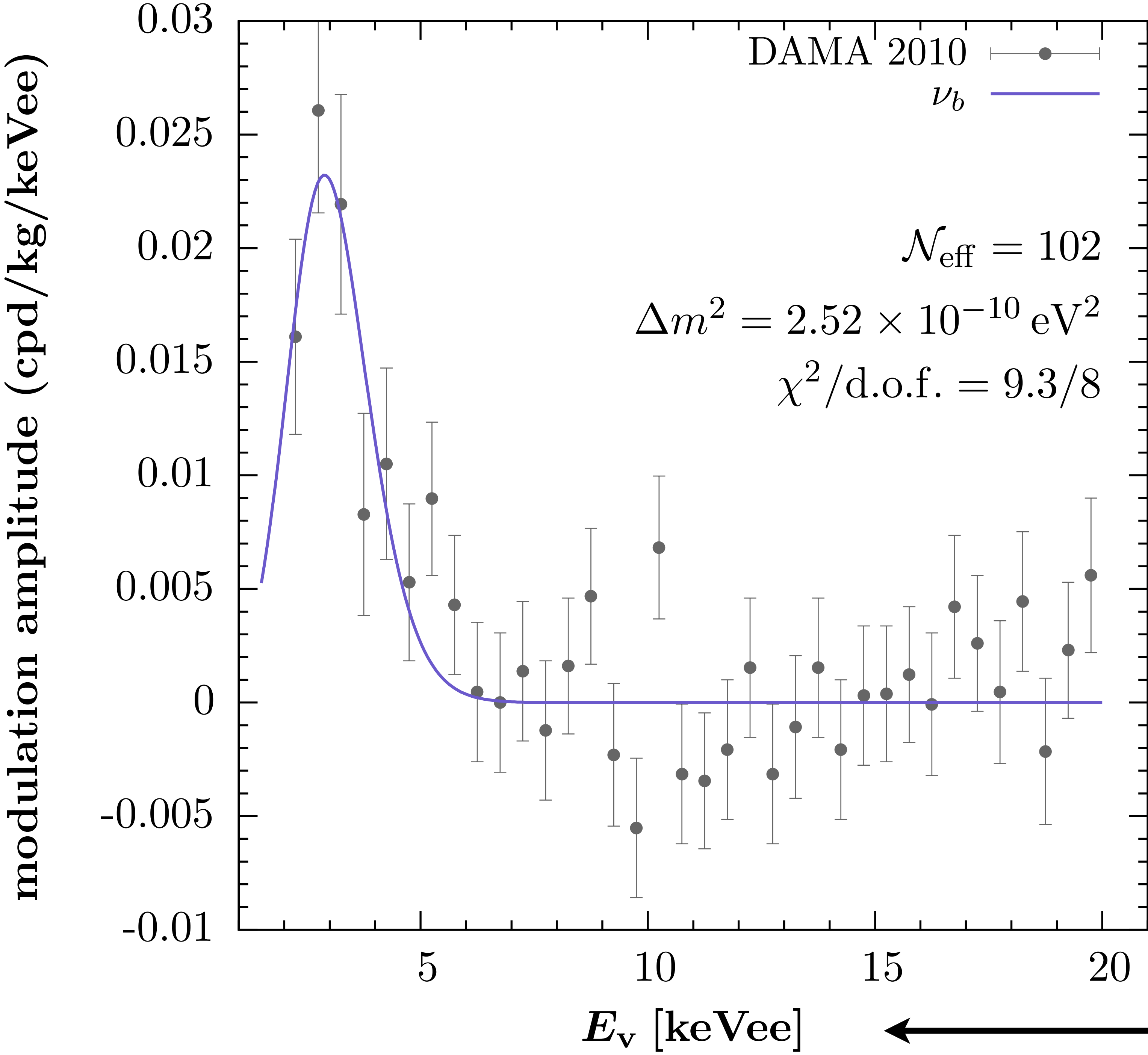
fit only first 10 bins



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

$\sim 3\%$

DAMA/LIBRA



used Q = 0.3

- Q = quenching factor

$$\frac{dL}{dx} = \frac{A dE/dx}{1 + k_B dE/dx}$$

(Birk's formula)

scintillation light (L) output depends on the stopping power of the scattered nucleus

$$L \sim \frac{A}{1 + k_B \langle dE/dx \rangle} \int_0^{E_R} dE$$

↓

$$E_{\mathrm{v}}(\mathrm{keVee}) = Q \times E_R(\mathrm{keV})$$

(Q can be energy dependent)

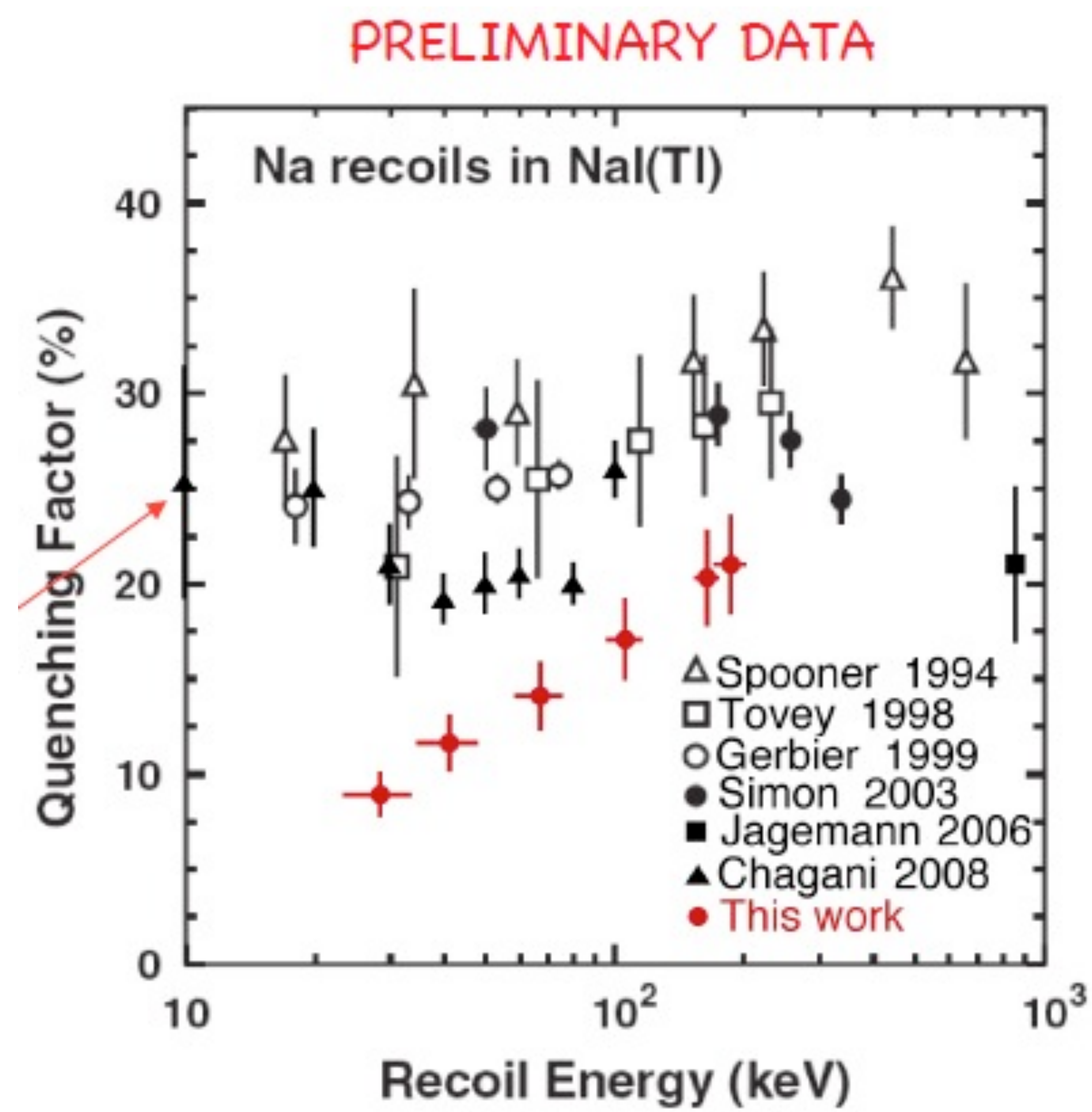
$\sim 3\%$

DAMA/LIBRA

- new quenching factor measurements indicate smaller values

  => higher nuclear recoil energy necessary to produce same observed signal in scintillation

  (for DM this means larger WIMP masses; moves light-DM DAMA region deeper into “forbidden” zone)



[Collar, TAUP talk 2011]

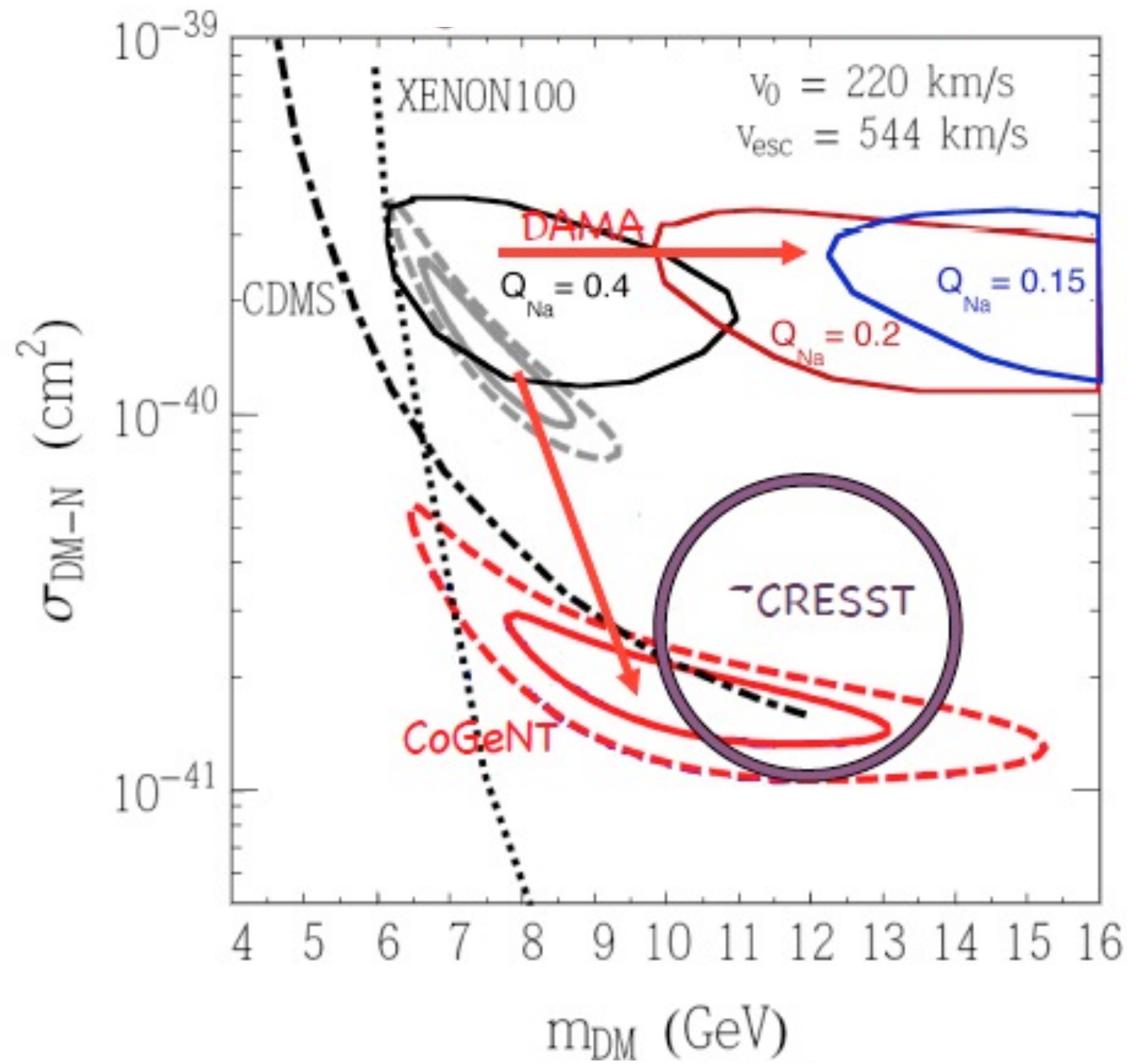
$\sim 3\%$

DAMA/LIBRA

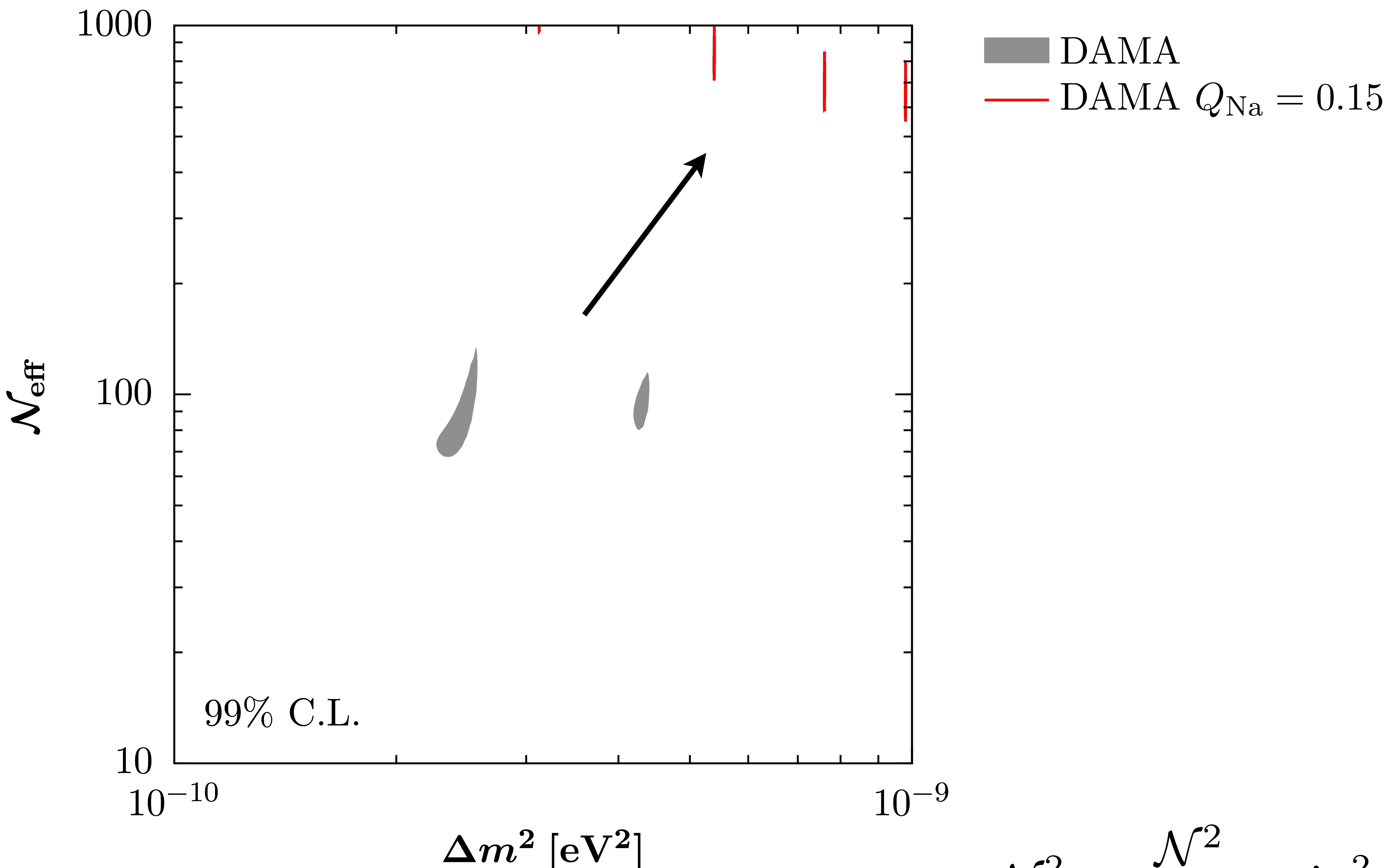
- new quenching factor measurements indicate smaller values

  => higher nuclear recoil energy necessary to produce same observed signal in scintillation

  (for DM this means larger WIMP masses; moves light-DM DAMA region deeper into "forbidden" zone)



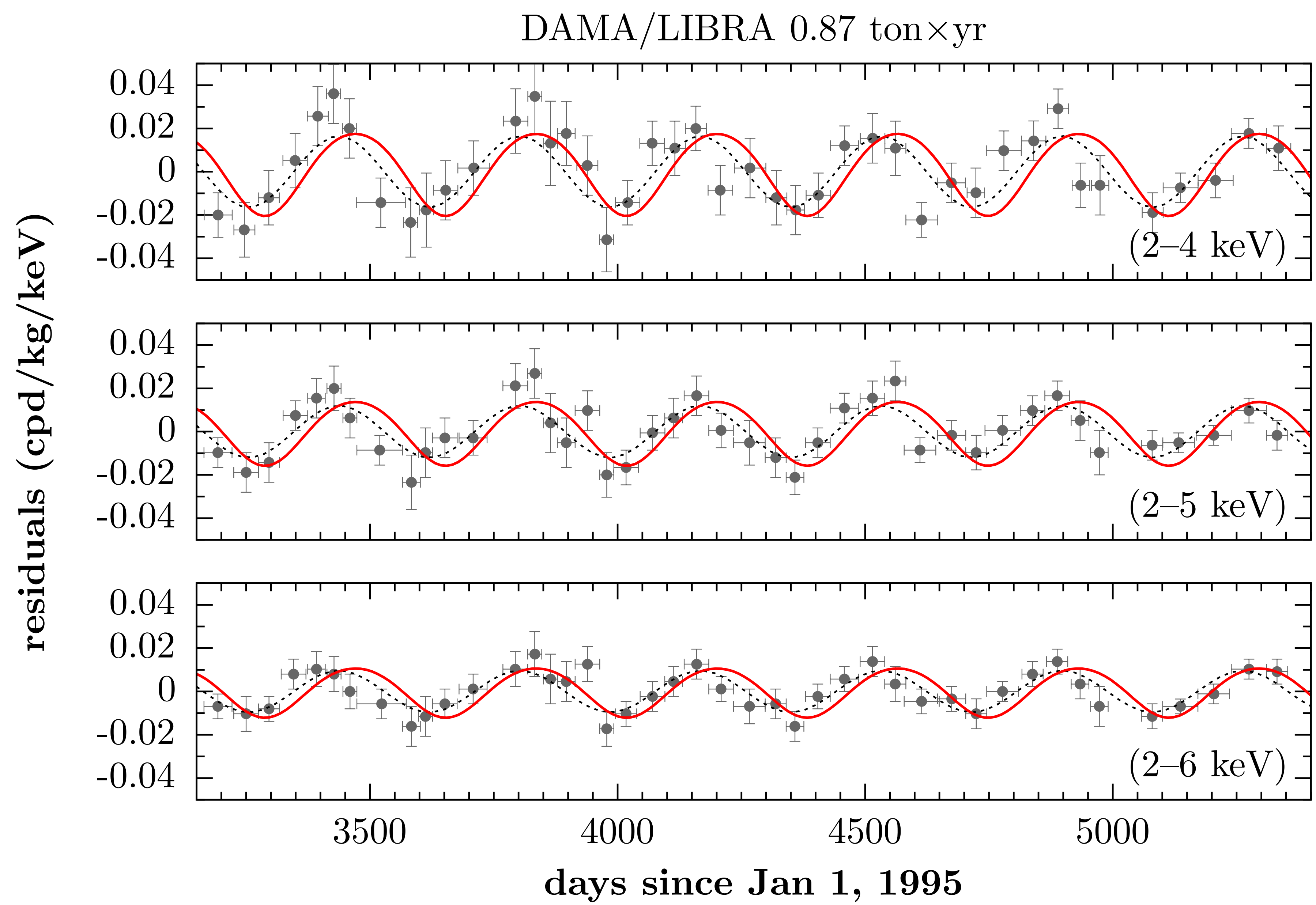
[Collar, TAUP talk 2011]



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

$\sim 3\%$

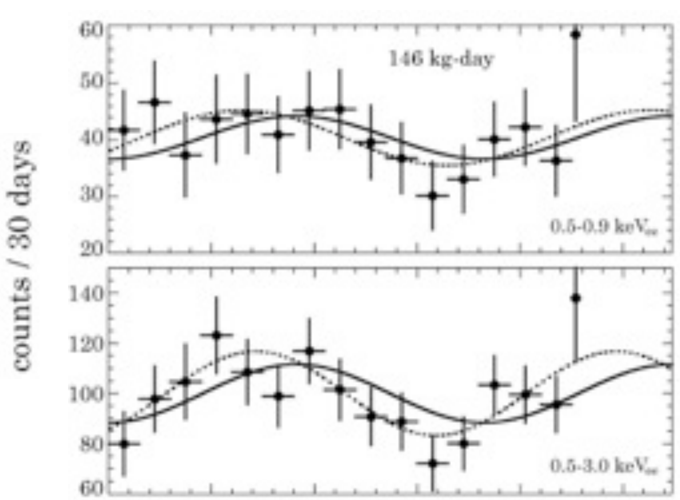
DAMA/LIBRA

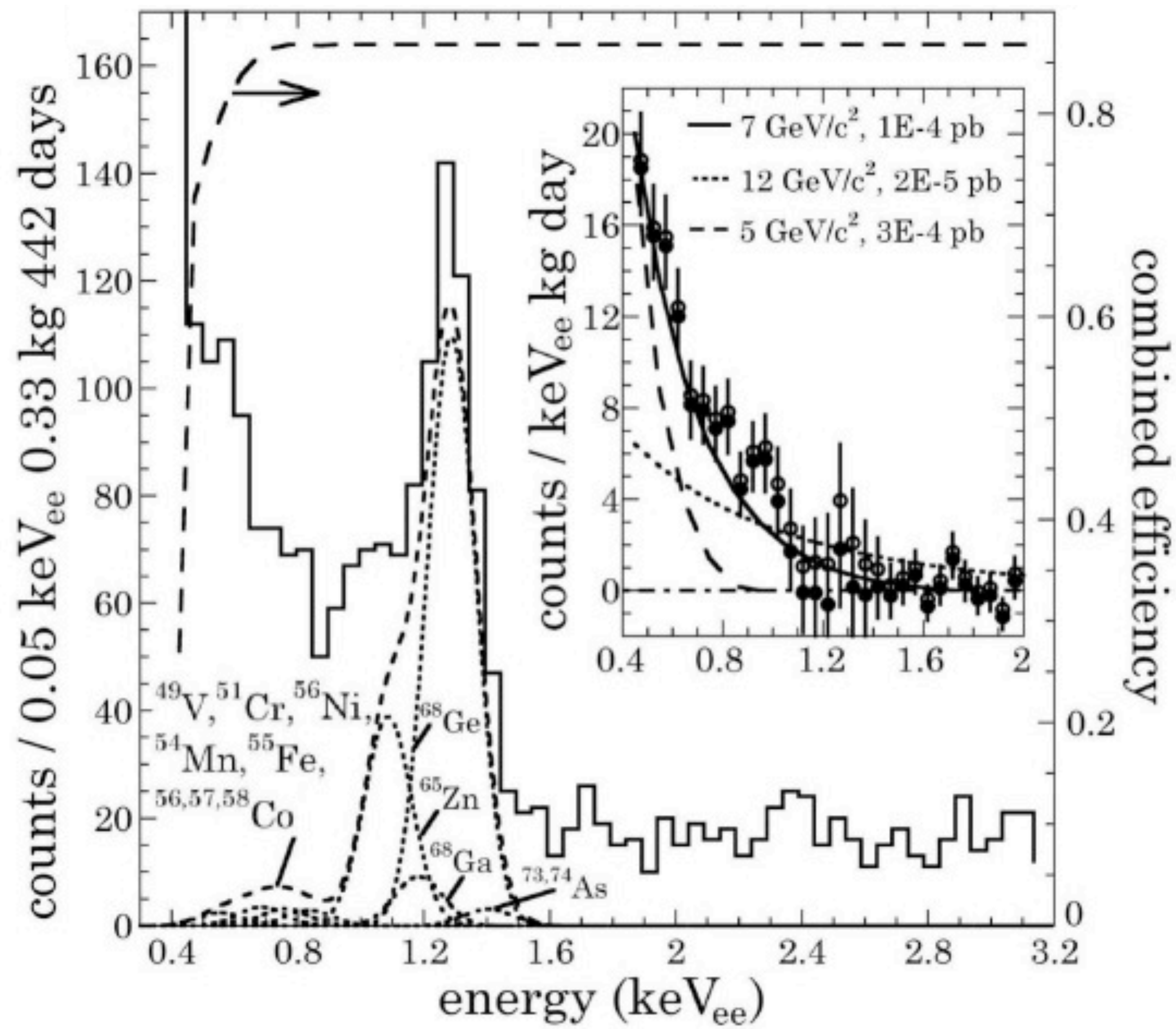


phase off by ~month!

CoGeNT

- 442 kg live-days
- Ge-target, ionization
- exponential rise toward low energies!
- cosmogenic peaks
- indication of modulation

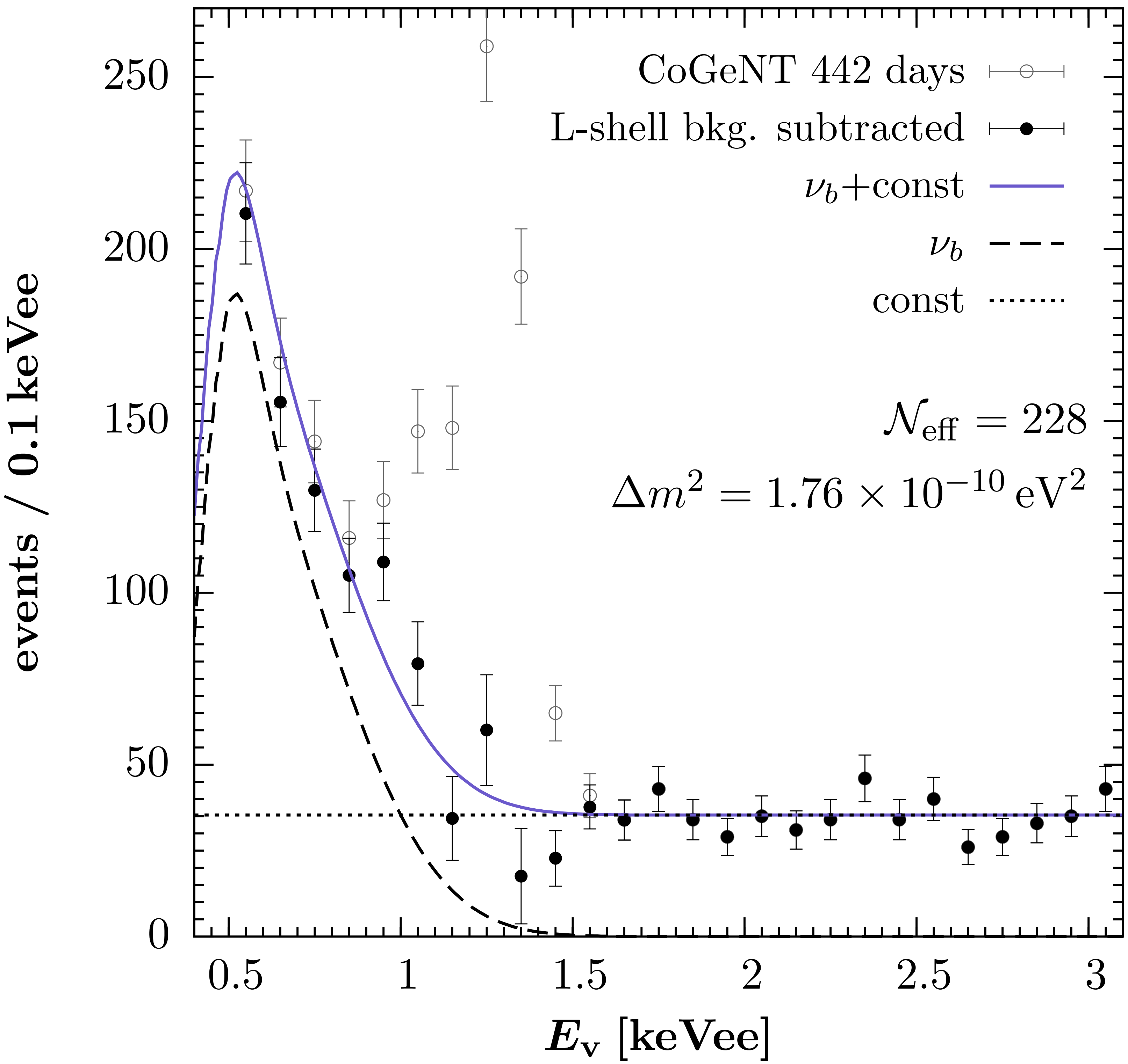


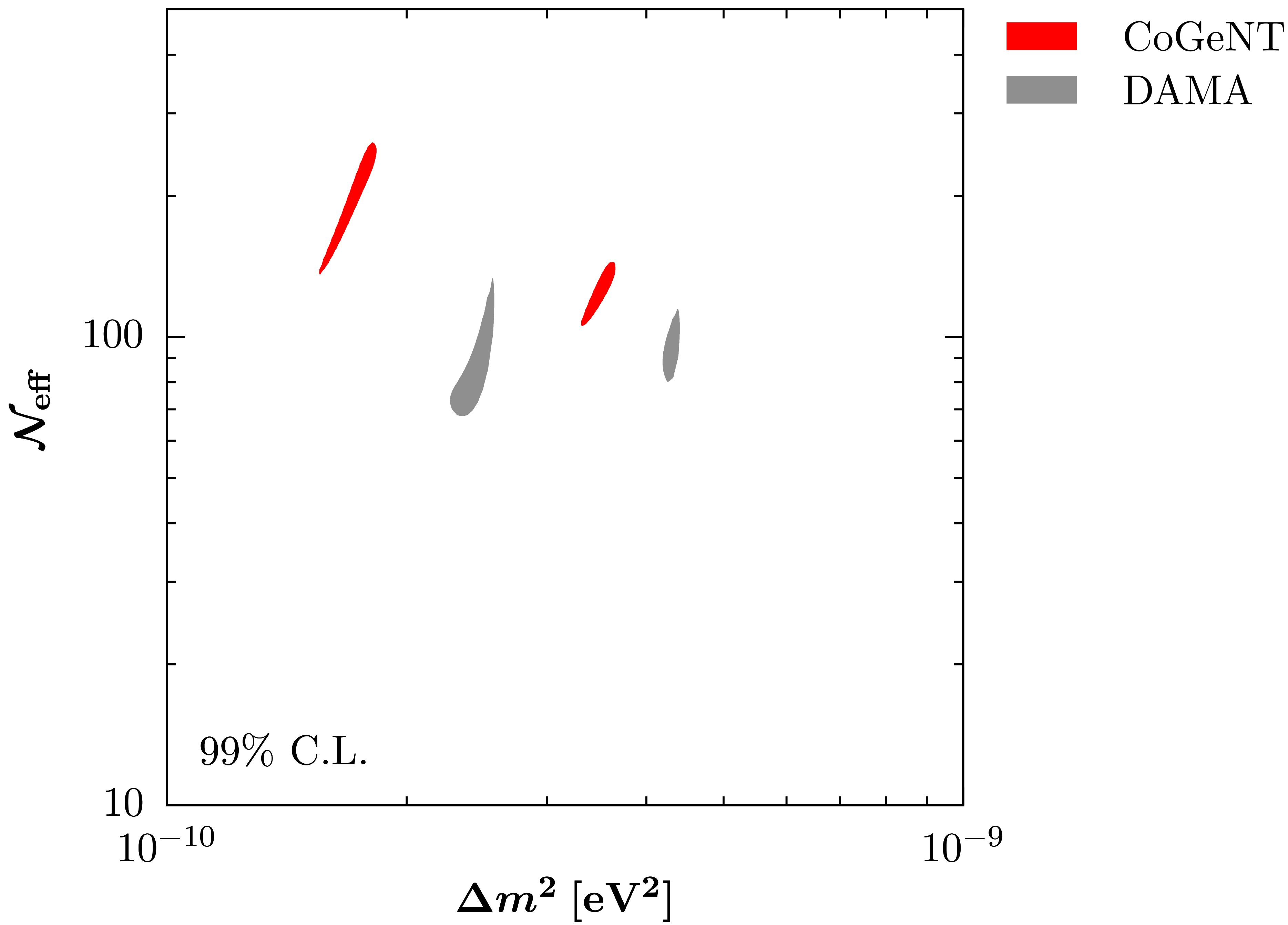


[Aalseth et al, 2011]

CoGeNT

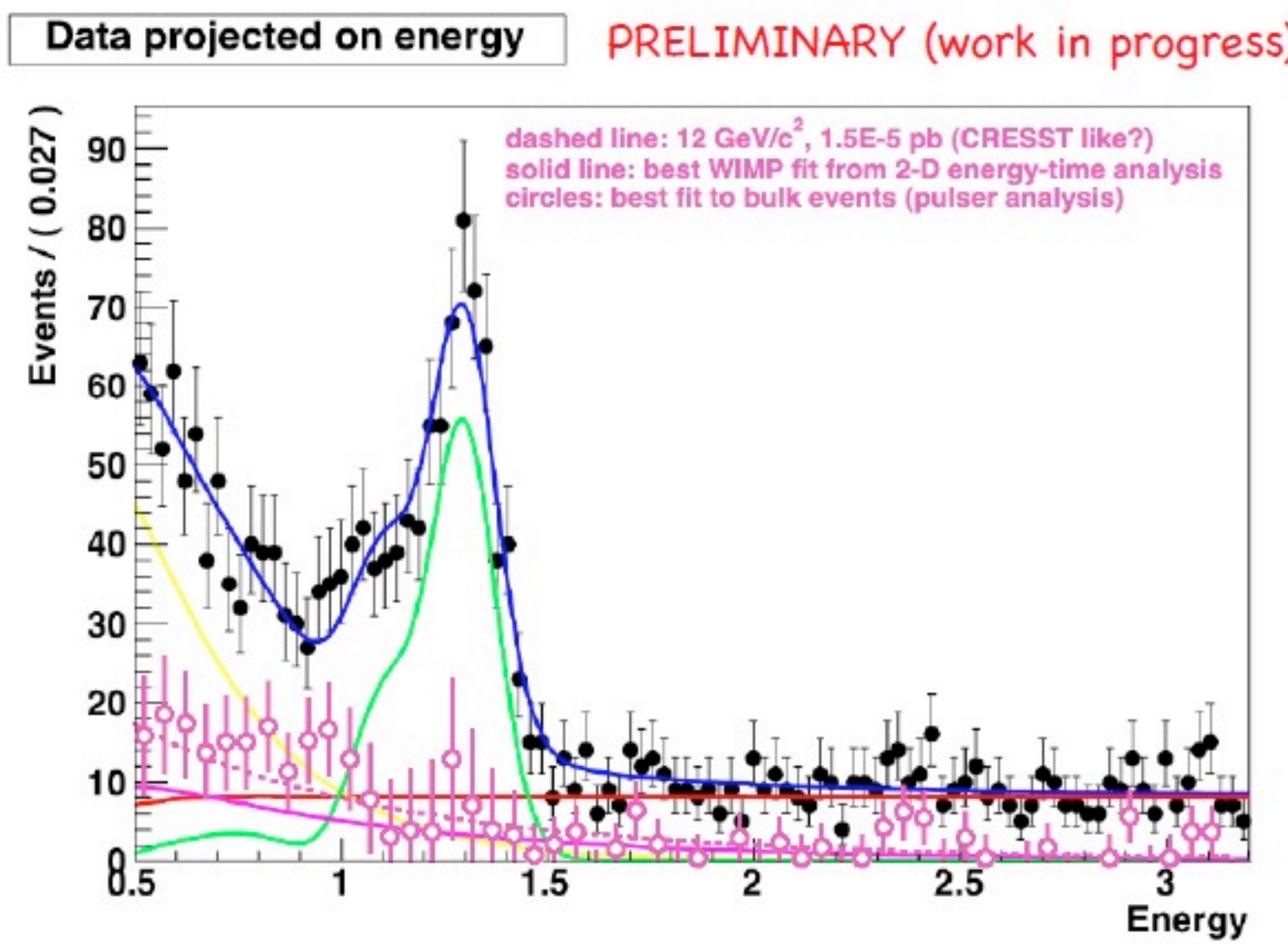
- 442 kg live-days
- Ge-target, ionization
- exponential rise toward low energies
- cosmogenic peaks subtracted
- will not address modulation here!




CoGeNT
DAMA
100
10
$\mathcal{N}_{\mathrm{eff}}$
99% C.L.
10^{-10}
10^{-9}
Δm^2 [eV^2]

CoGeNT

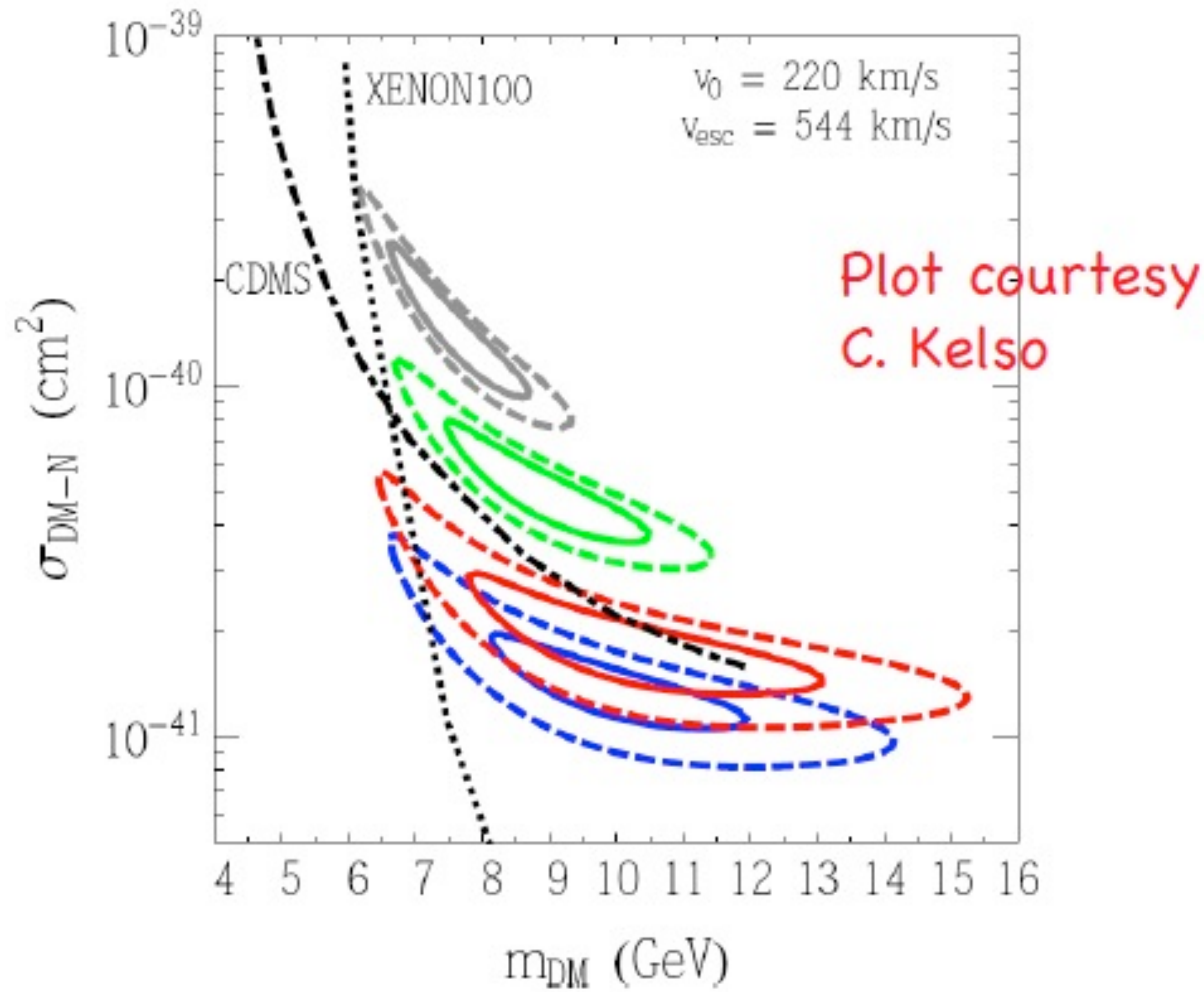
- additional surface background
- rise at lowest recoil energies near threshold will be revised
- for DM this means smaller cross sections



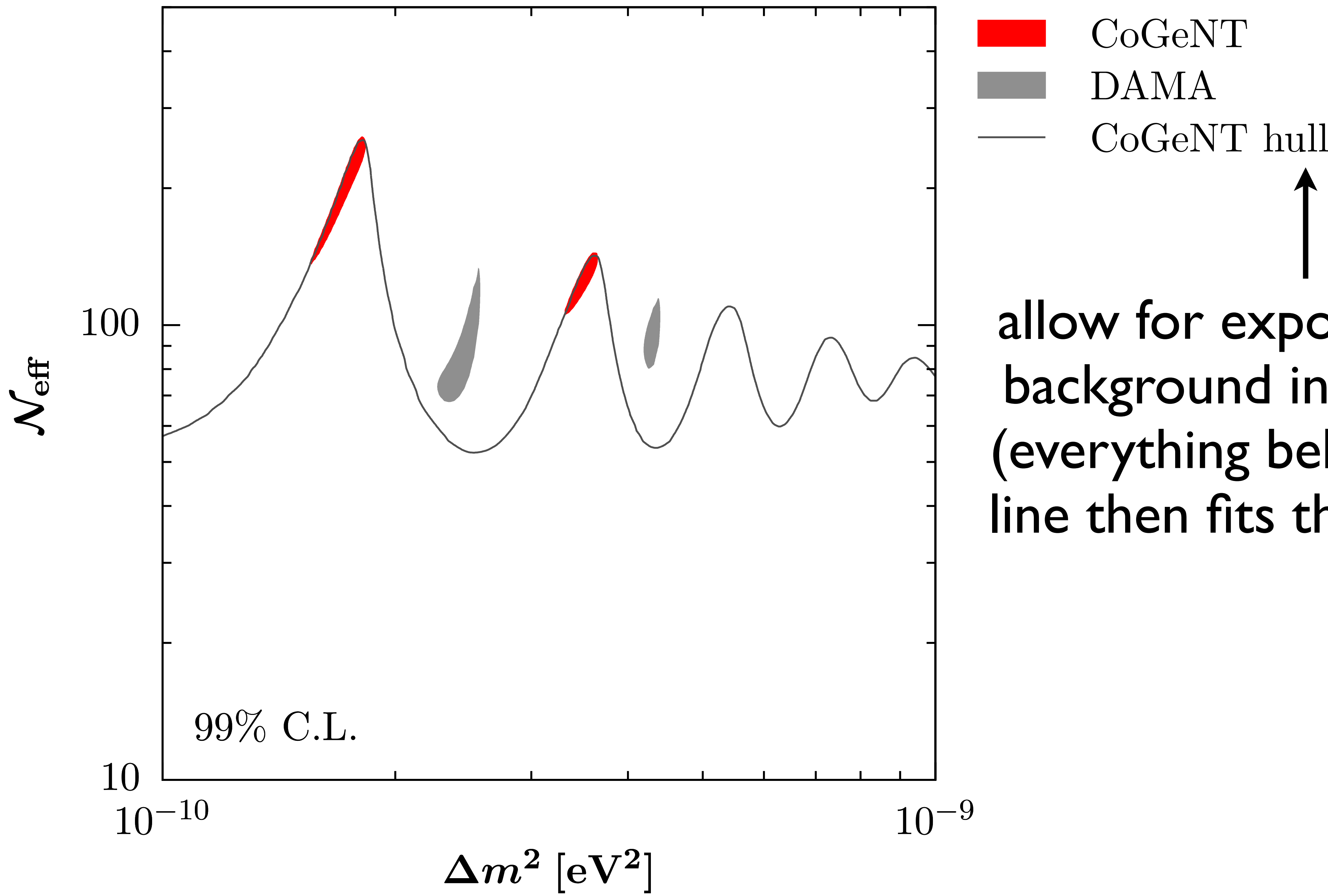
[Collar, TAUP talk 2011]

CoGeNT

- additional surface background
- rise at lowest recoil energies near threshold will be revised
- for DM this means smaller cross sections



CoGeNT

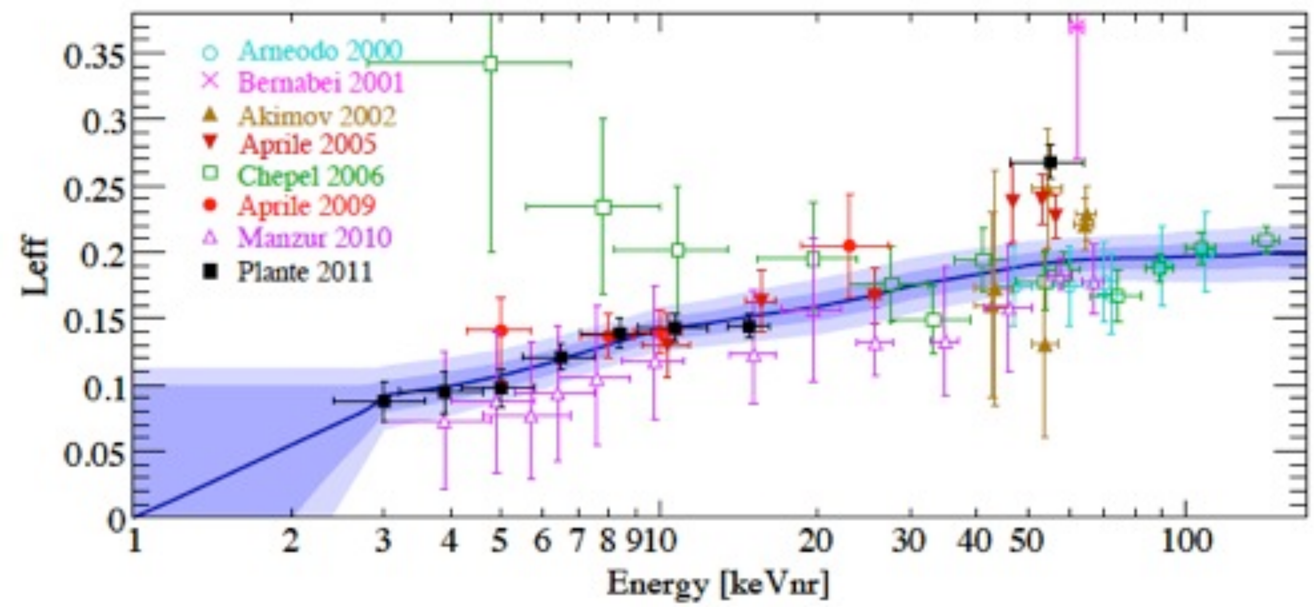


allow for exponential background in the fit (everything below the line then fits the data)

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]

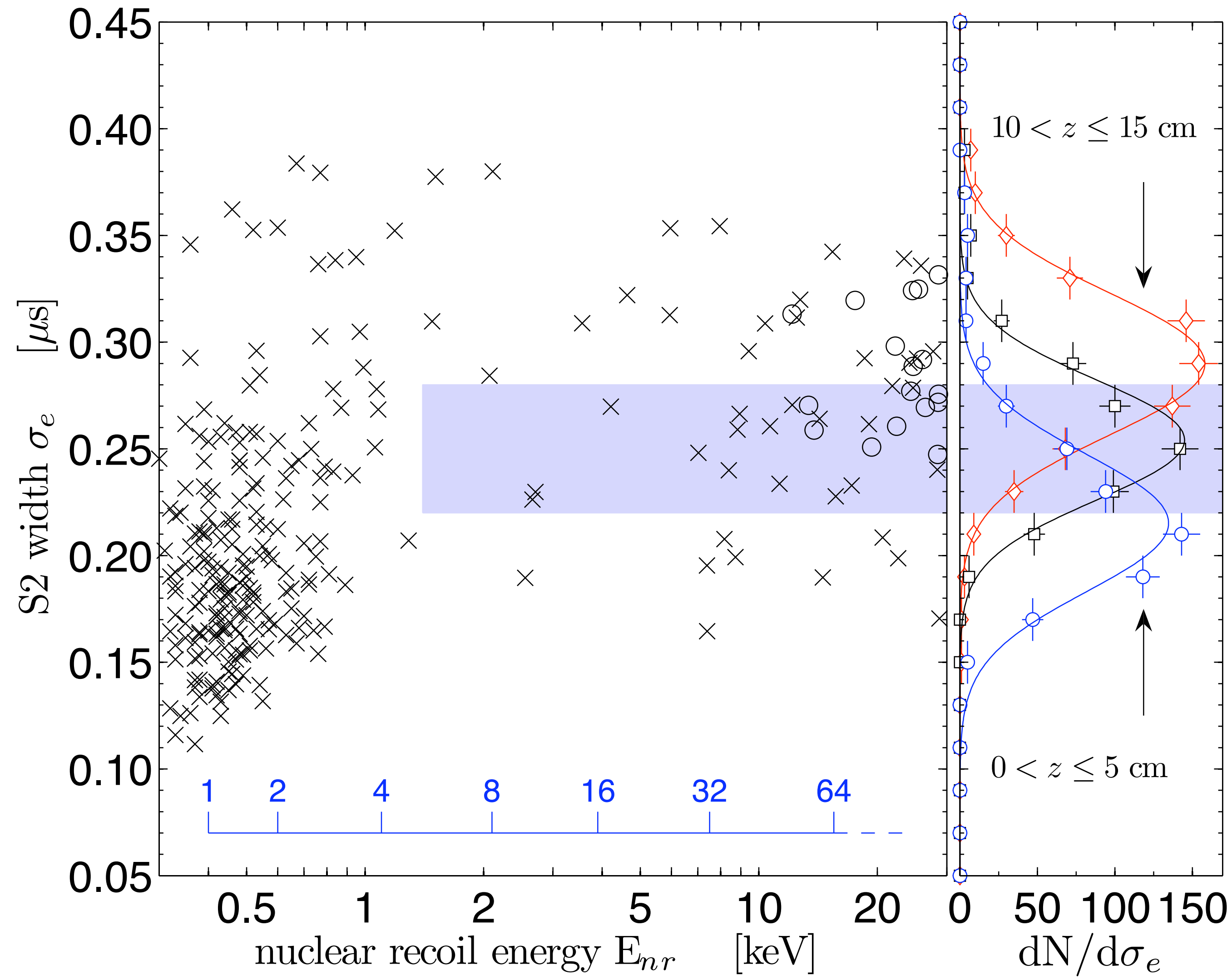
constraints: XENON10 low thr.

- discard scintillation signal => buys e-background, wins lower threshold
- ionization only (S2)
- use $E_{\min} = 1.4\,\mathrm{keV}$
- include Poisson

$$\mathrm{S2} = \underbrace{Q_y E_R}_{n_e} \zeta$$

(large uncertainty in number of ionized electrons [Collar, 2011])

=> resulting bounds uncertain



[Aprile et al. 2011]

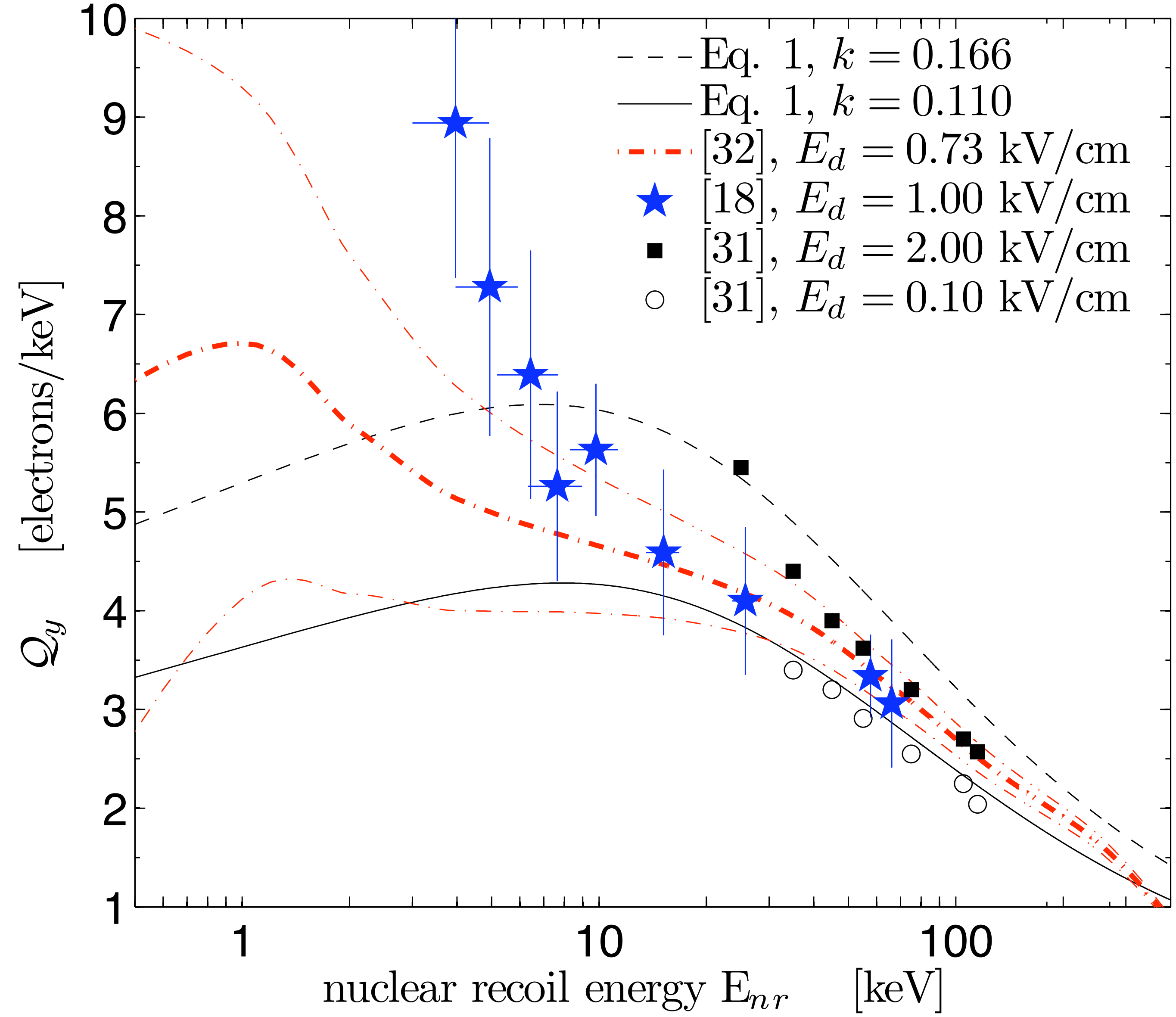
constraints: XENON10 low thr.

- discard scintillation signal => buys e-background, wins lower threshold
- ionization only (S2)
- use $E_{\min} = 1.4\,\mathrm{keV}$
- include Poisson

$$\mathrm{S2} = \underbrace{Q_y E_R}_{n_e} \zeta$$

(large uncertainty in number of ionized electrons [Collar, 2011])

=> resulting bounds uncertain



[Aprile et al. 2011]

constraints: CDMS-II low thresh.

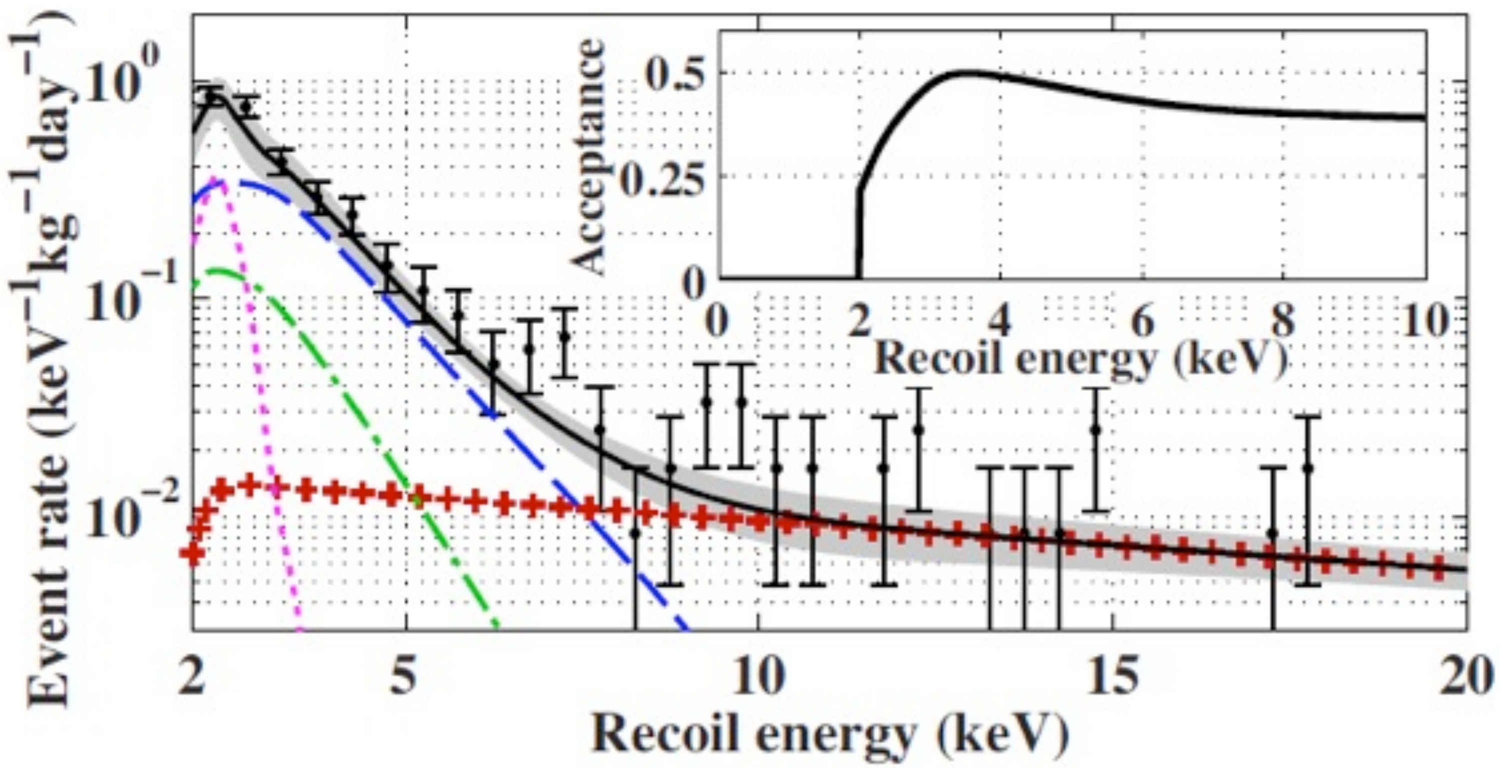
- use data from Ge-detectors (same target as CoGeNT)
- "binned Poisson" technique

⟷ sensitivity to ν_b

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

↑

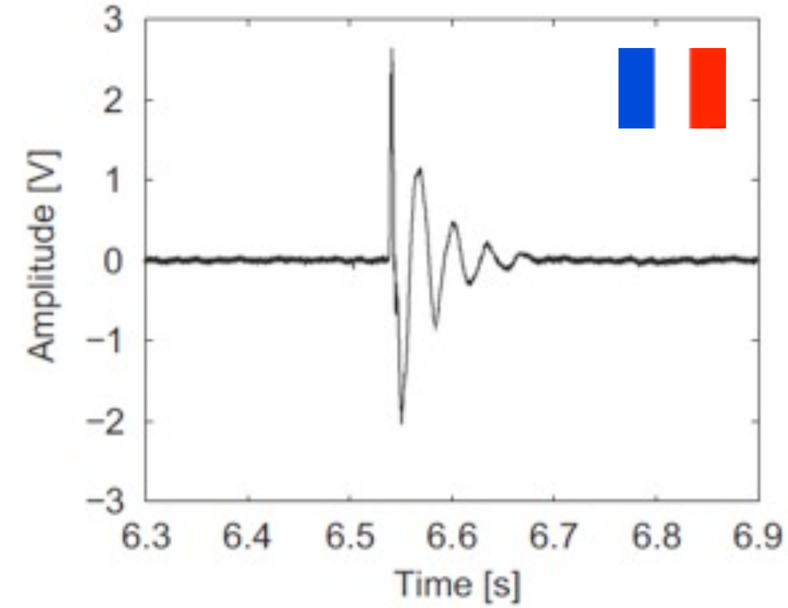
probability to see as few events as observed in one bin



[Z. Ahmed et al, 2010]

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

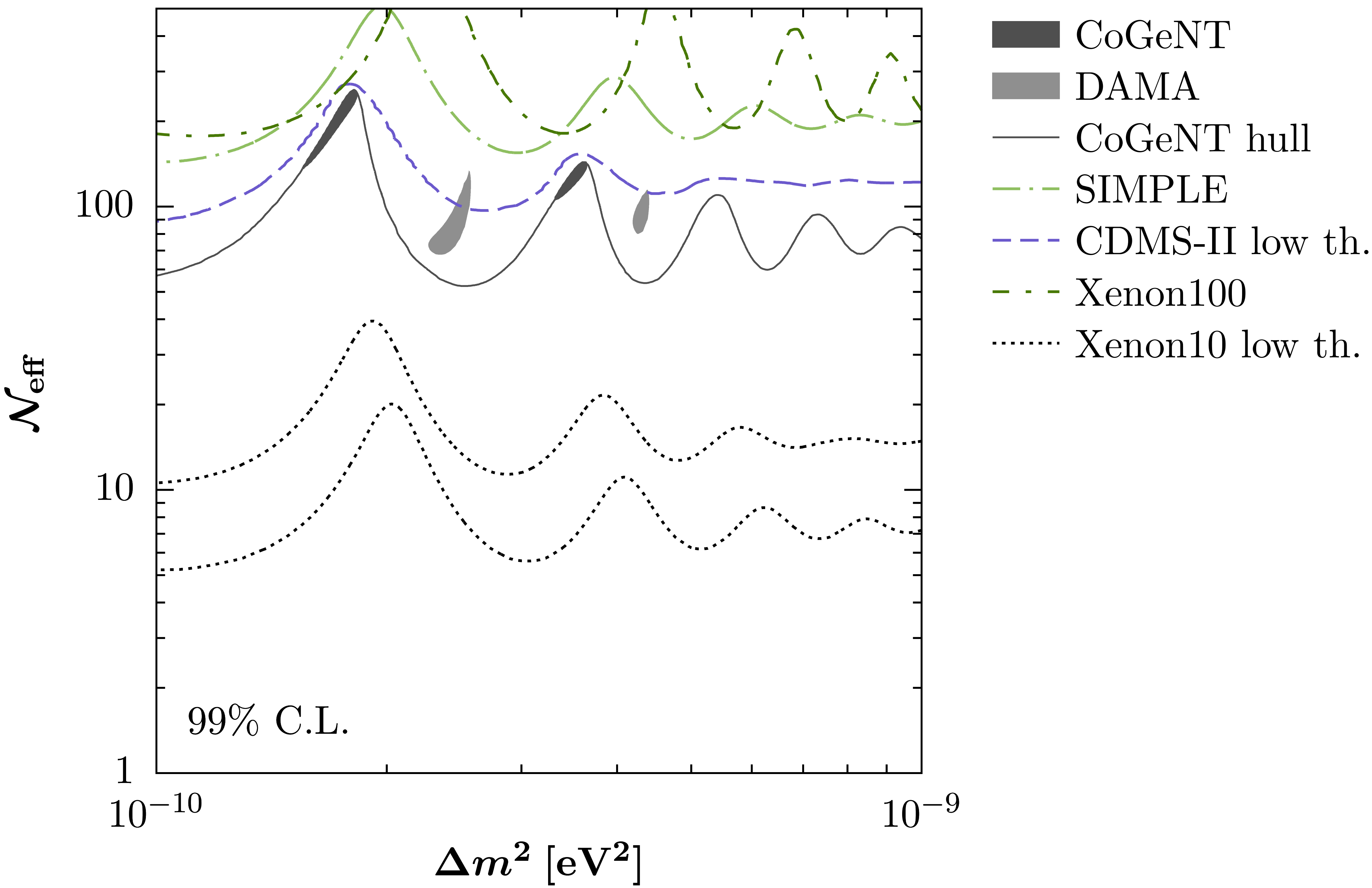
constraints: SIMPLE



- superheated droplets from $\mathrm{C_2\,Cl\,F_5}$ (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



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]

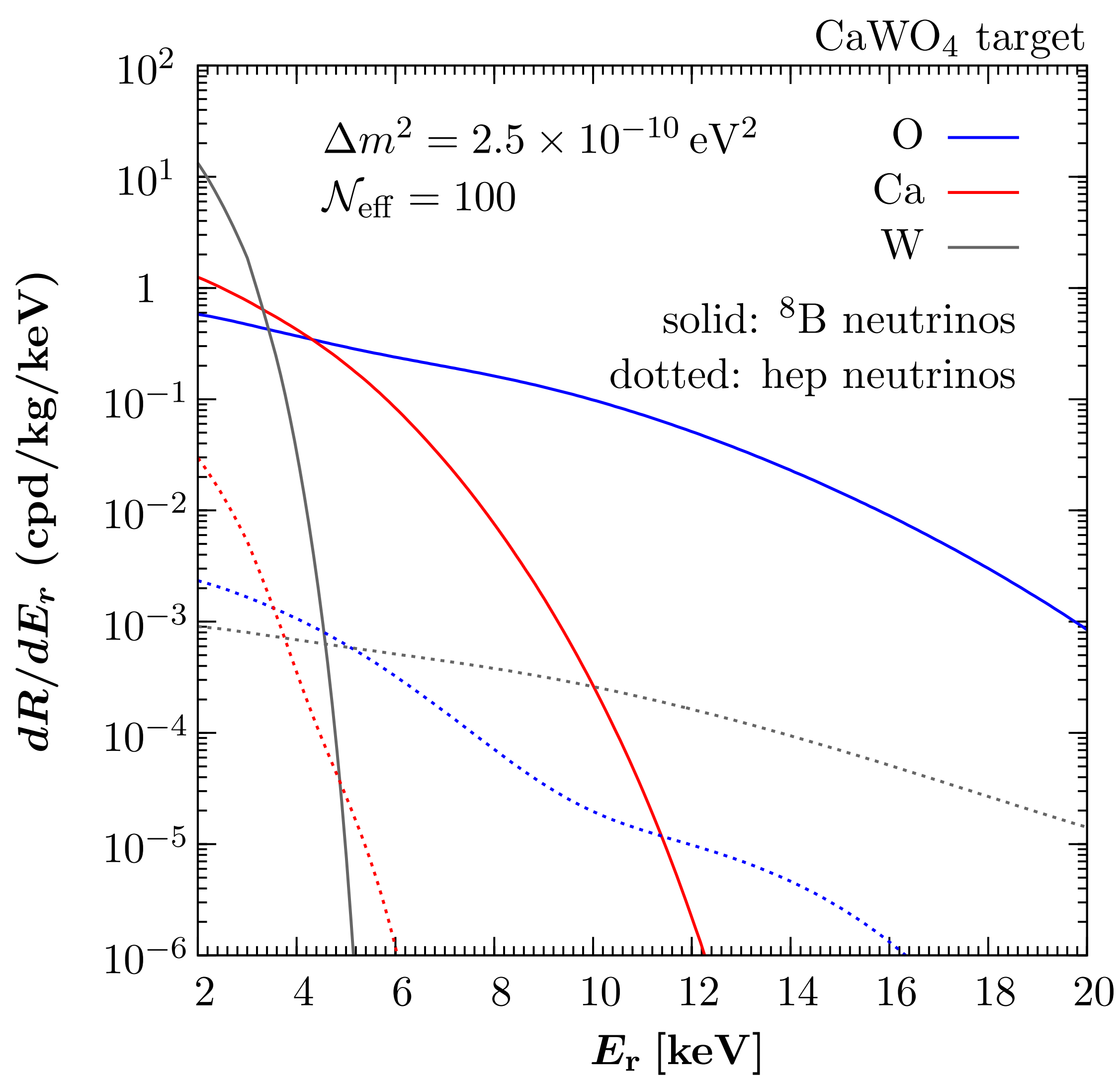
arXiv:1109.0702

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

CRESST-II, a neutrino$_b$ observatory?



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

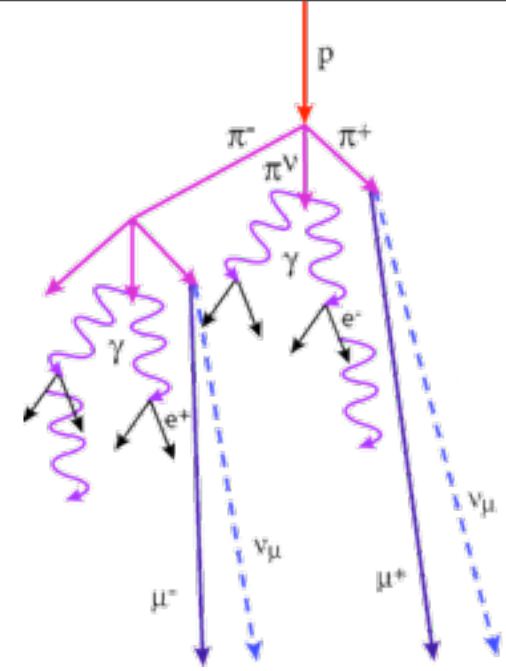
CRESST-II, a neutrino$_b$ observatory?

- 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 can (currently) be attributed to backgrounds.

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

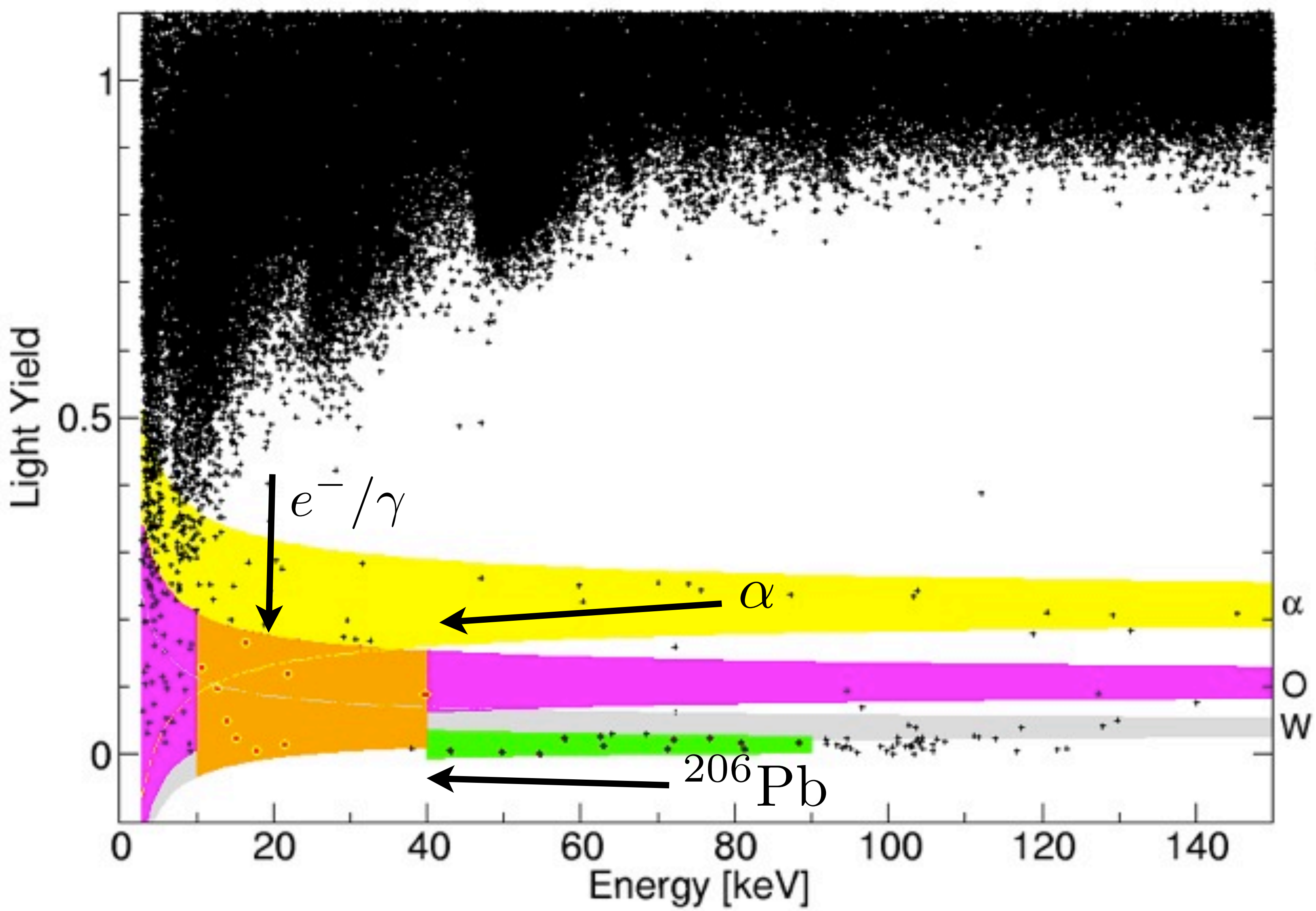
CRESST

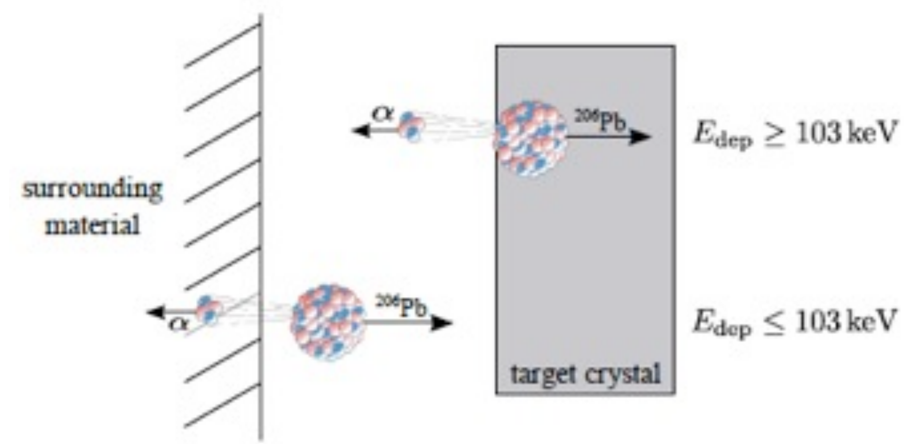
backgrounds



n

(one of 8 detector modules)





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

in or on the surface of the clamps holding the crystals

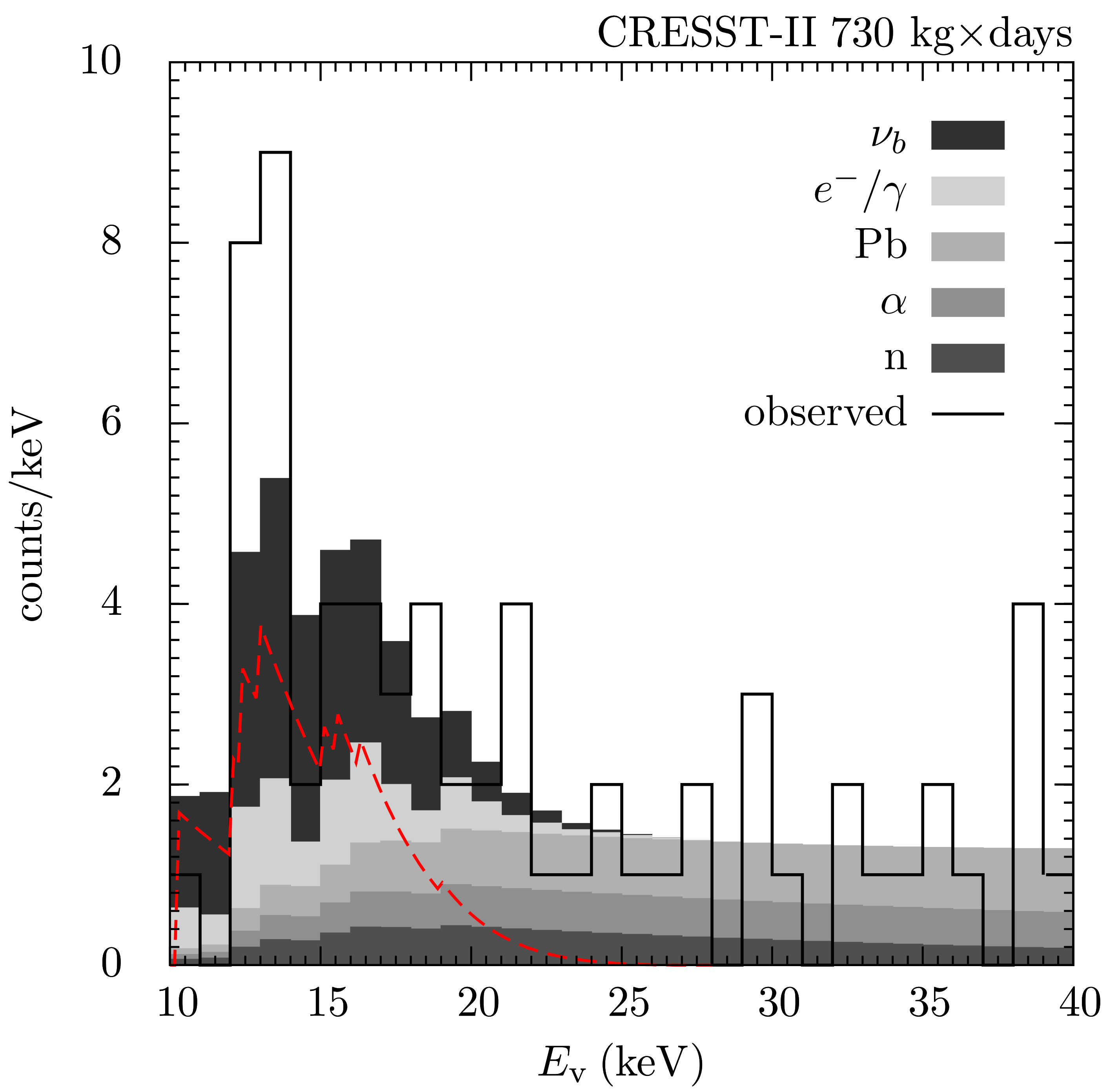
CRESST

fits

- we follow CRESST in their modelling of backgrounds

  => e/gamma events known

  => others essentially flat distributed



CRESST

fits

- we follow CRESST in their modelling of backgrounds

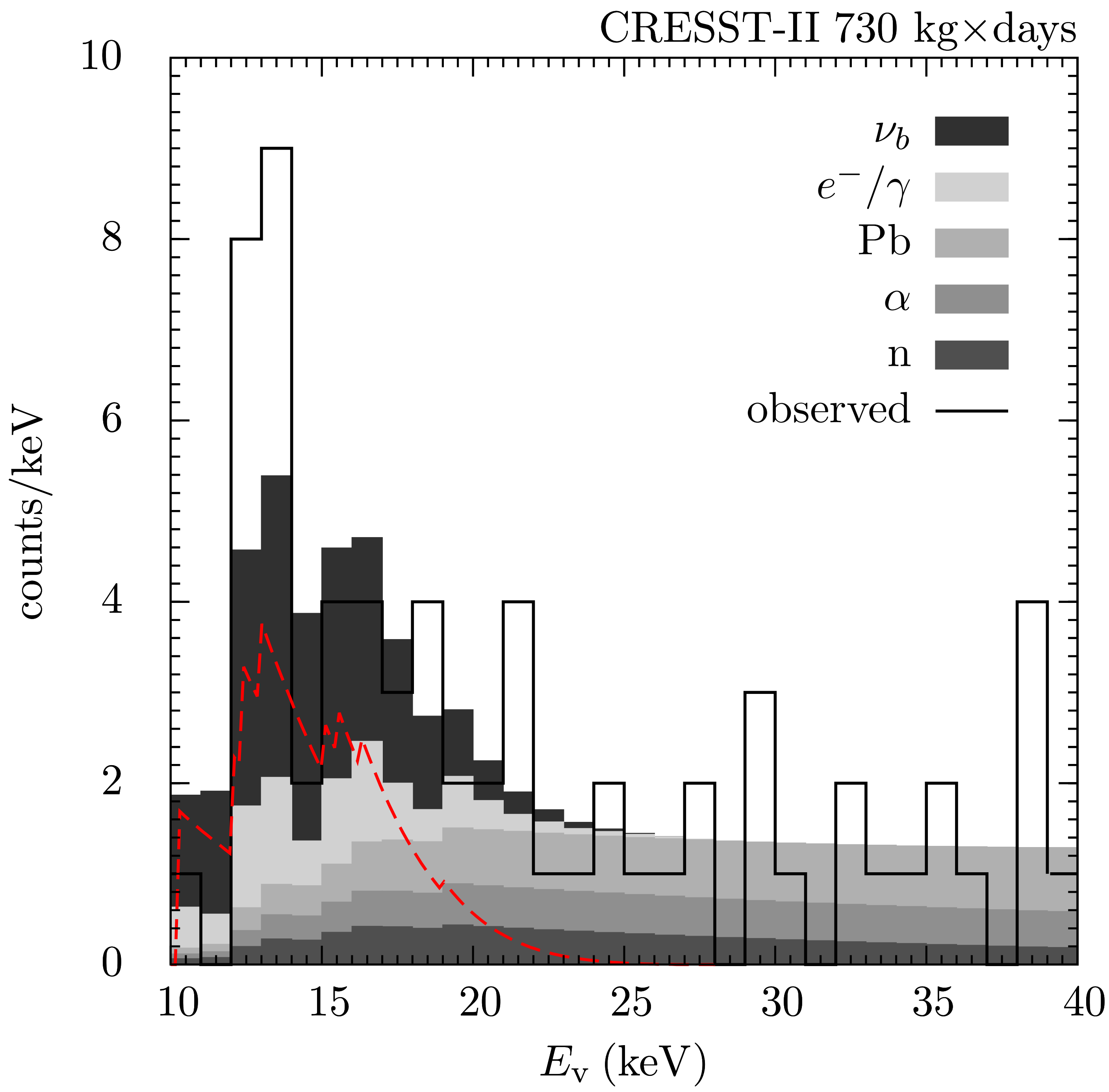
  => e/gamma events known
  => others essentially flat distributed

- use Poisson log-Likelihood to fit ν_b

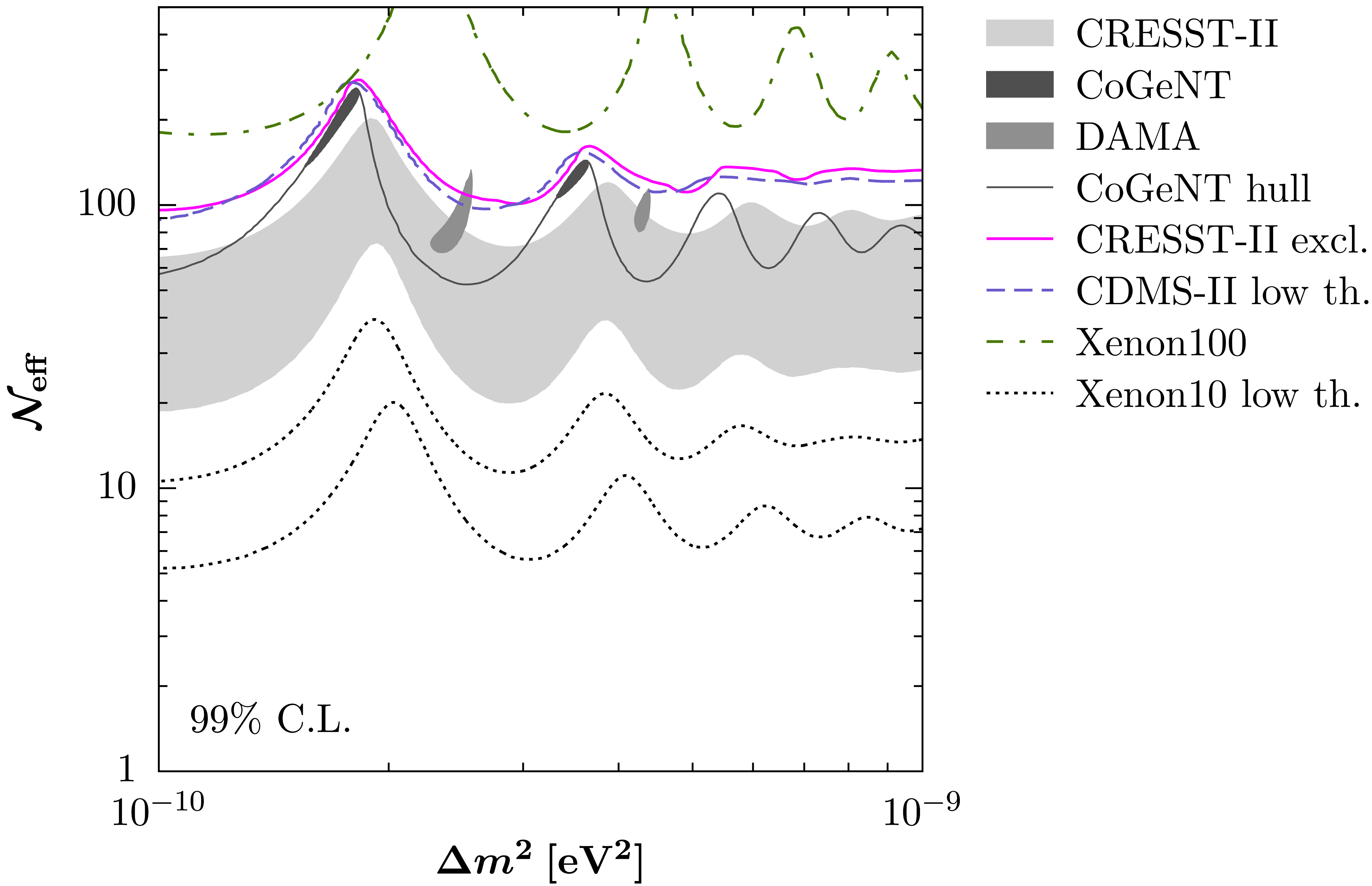
$$\chi^2_P = 2\sum_i \left[y_i - n_i + n_i \ln\left(\frac{n_i}{y_i}\right)\right]$$

- best fit yields

$\chi^2_P/\text{d.o.f.} = 27.8/28$ (recoil spectrum only)

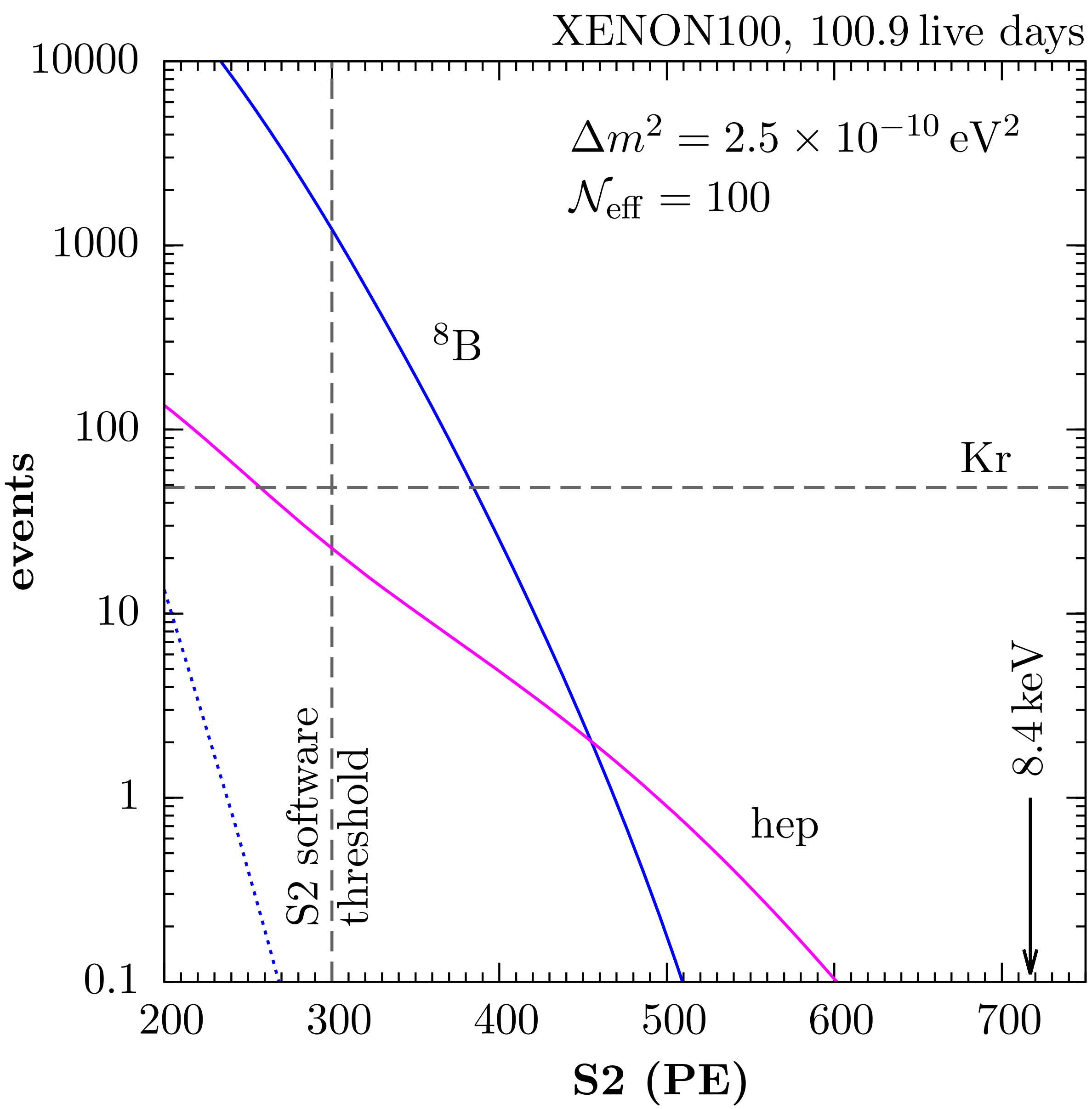


putting it all together

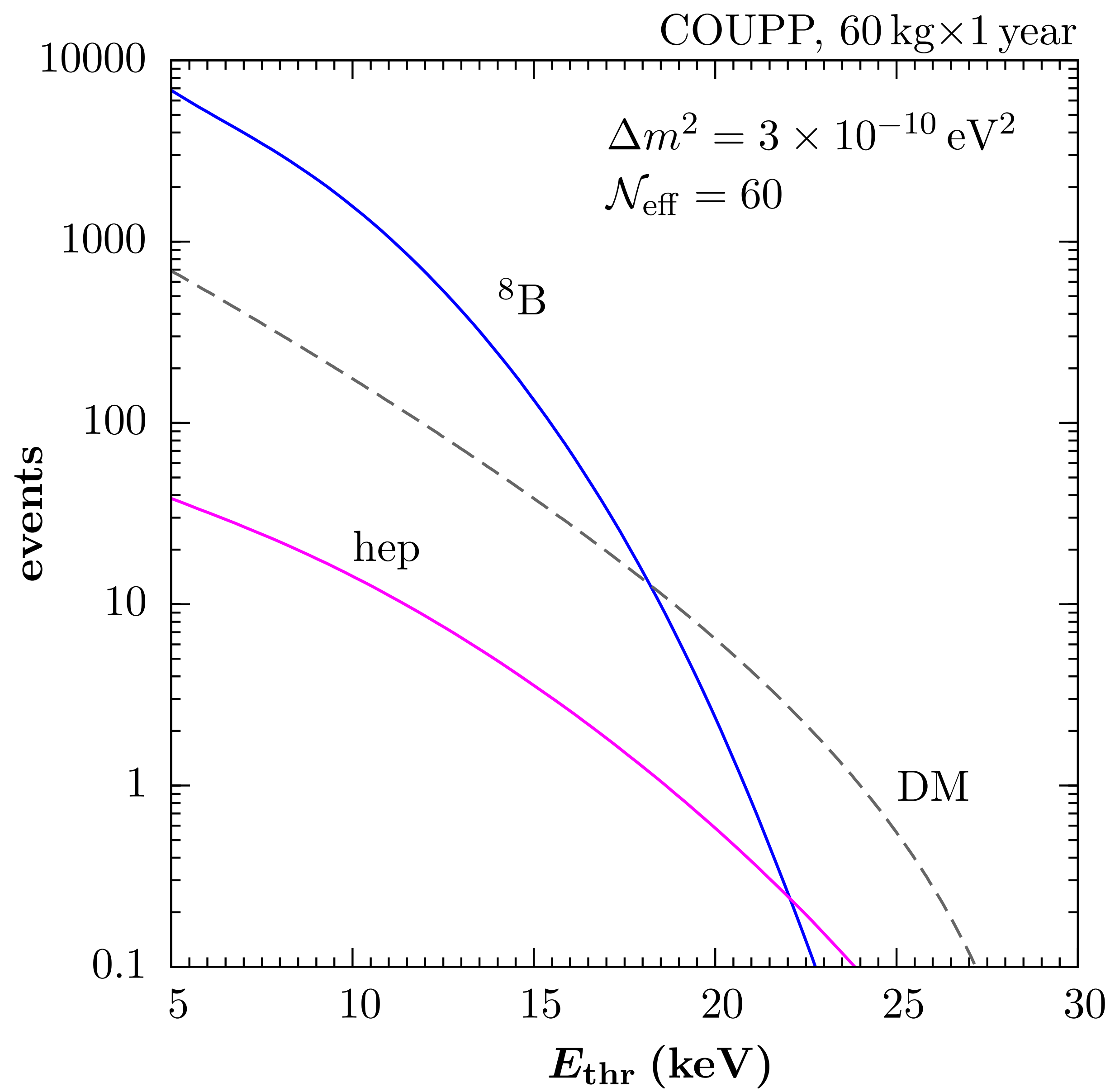


outlook

--this model is (very) testable--



prediction for Xenon100
low-threshold analysis

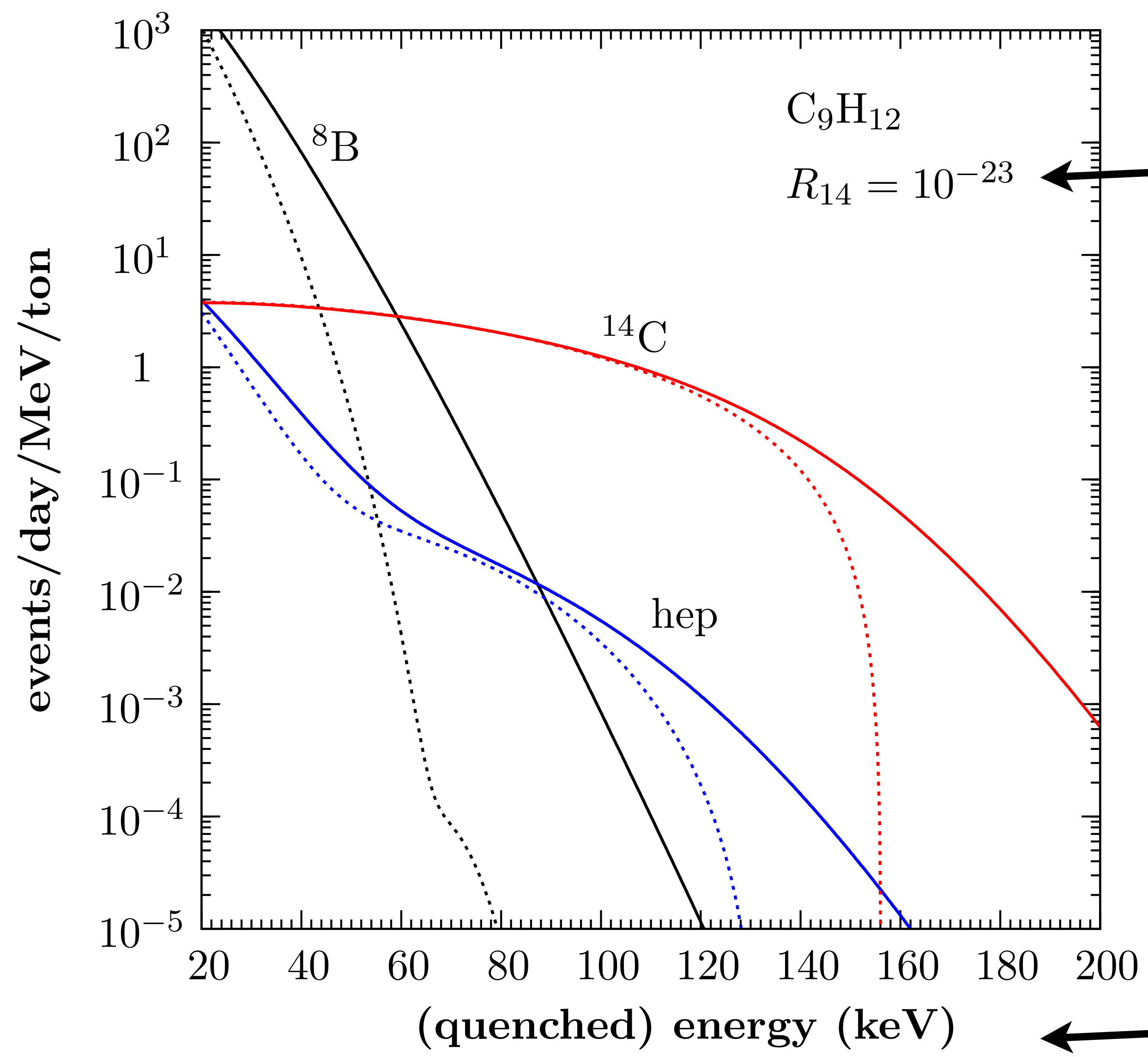


prediction for COUPP
bubble chamber (CF_3I)

outlook II

neutrino searches?

- elastic scattering off scintillating mineral oil
[Borexino is the best candidate experiment]



however,
Borexino has C14 contamination of
10^{-18}

mainly proton recoils (we used SRIM)

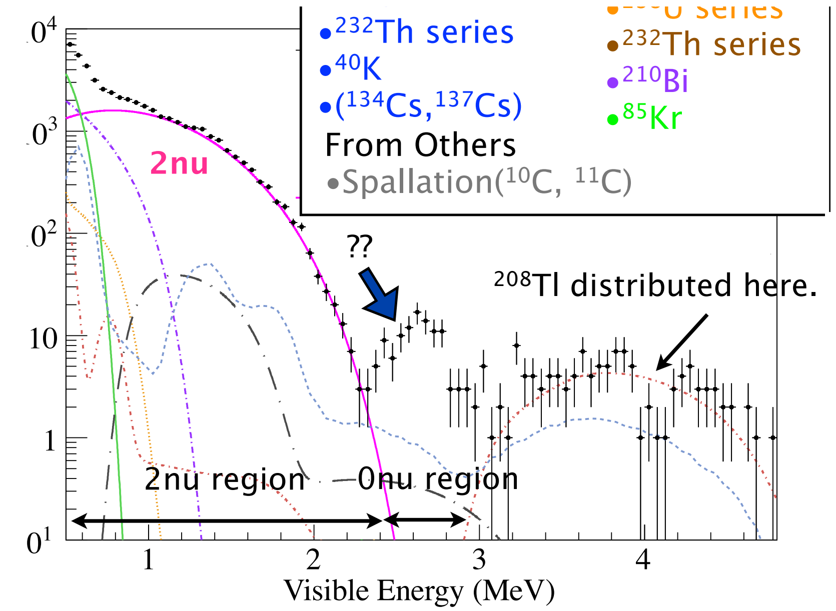
outlook III

- inelastic processes ?

  => ^{12}C excitation in neutrino searches (4.4 MeV gamma)

  => more generally, look for nuclear excitations

  e.g. "Kamland-Zen bump" →



[Azusa GANDO, Moriond 2012]

- astrophysical consequences

  => stellar cooling constraints

  => CMB Neff = 4 ?

  => SN: nearby / dynamics of explosions / sensitivity to tiny mass splittings

conclusions

- "Old Backgrounds"

  => cosmic ray muon flux unlikely source for the modulation signals in DAMA and CoGeNT

  => DAMA can do better in convincing us that the above is true

- "New Signals"

  => periodic signals contain higher harmonics which may provide further discriminating power in telling background from signal

  => entertained a model of neutrinos which can give similar "DM-like" signals in DM direct detection experiments