# DAMA and CoGeNT - muon background and higher harmonics

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*with Spencer Chang and Itay Yavin*

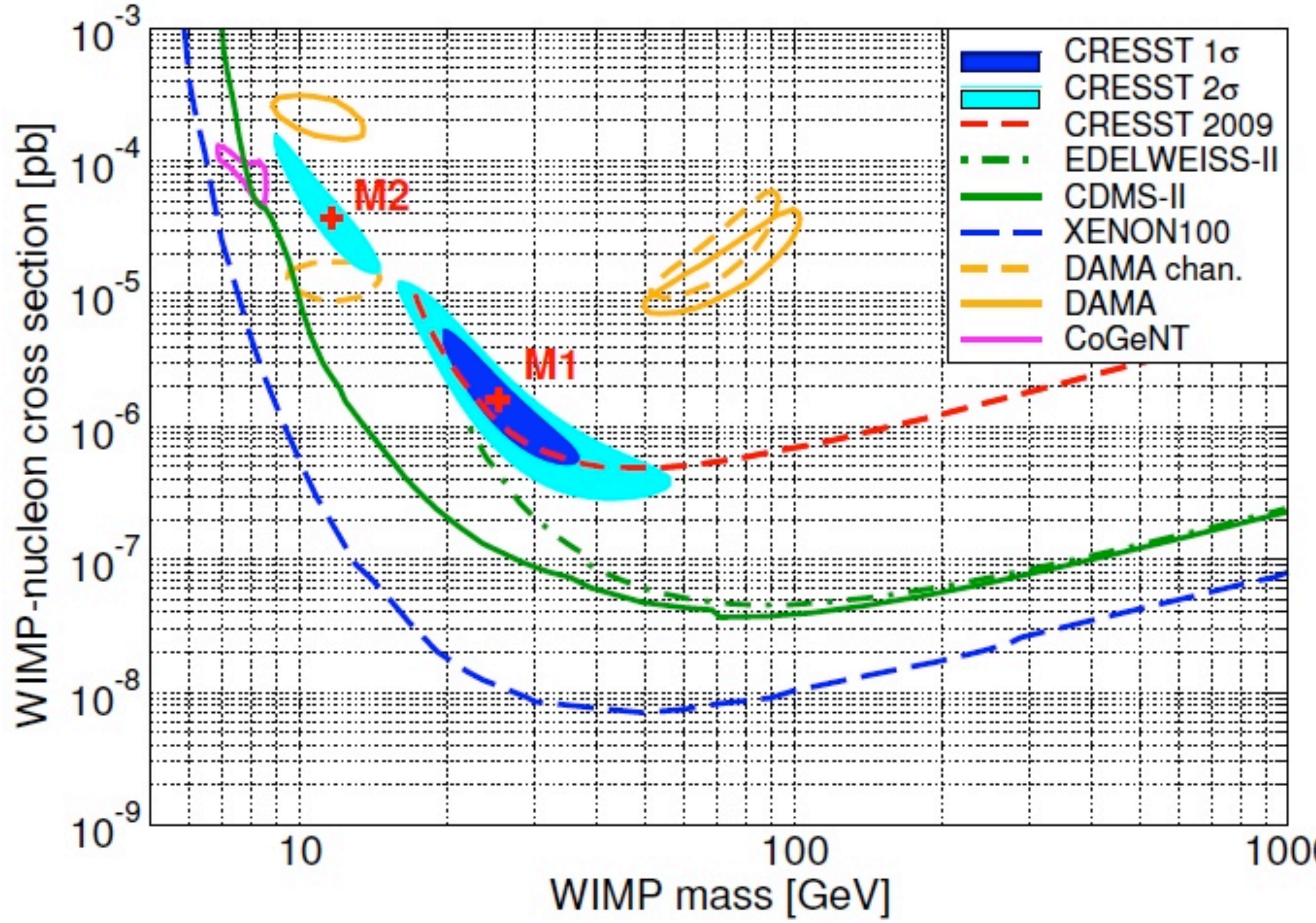
*arXiv: 1111.4222 (PRD, to appear)*

*Moriond EW, March 5, 2012*

one
species
-
three
signals?

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

# “take home 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

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

$$\downarrow$$

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

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

# signal modulation in direct detection

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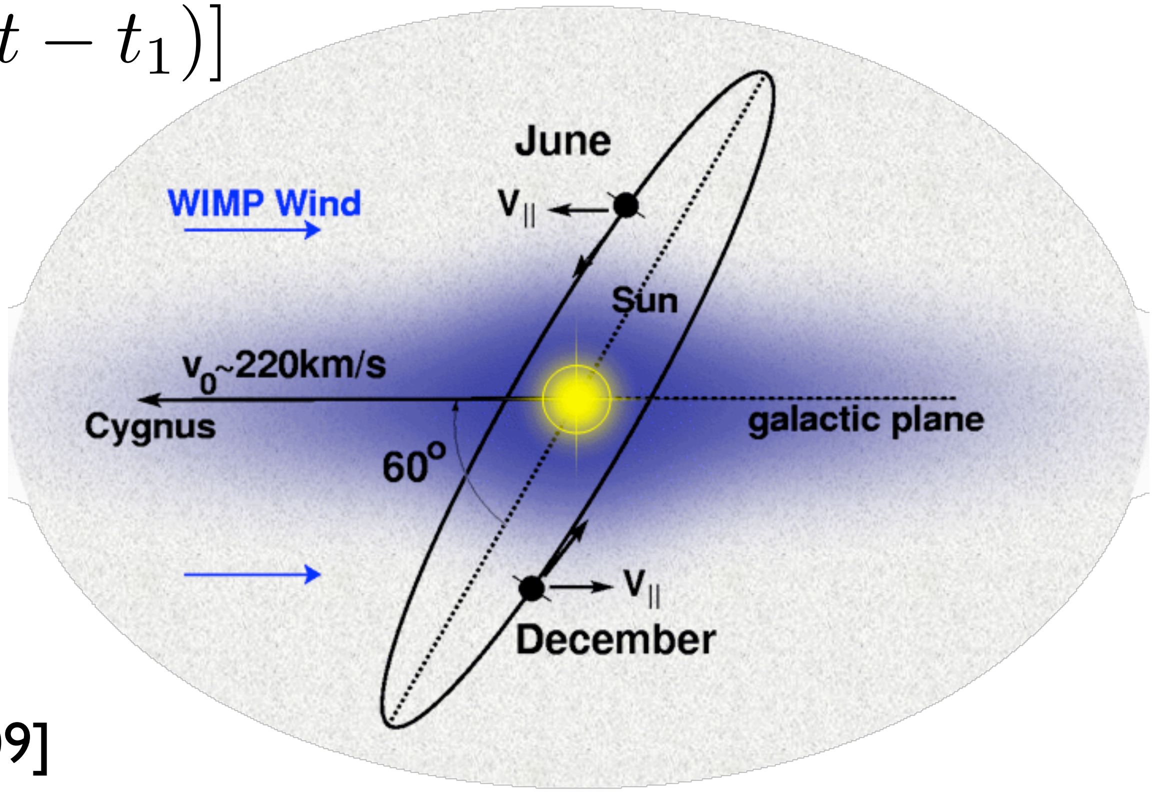
$$\downarrow$$

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

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

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

$t_0 \simeq 152\,\rm days \quad (June\ 2nd)$



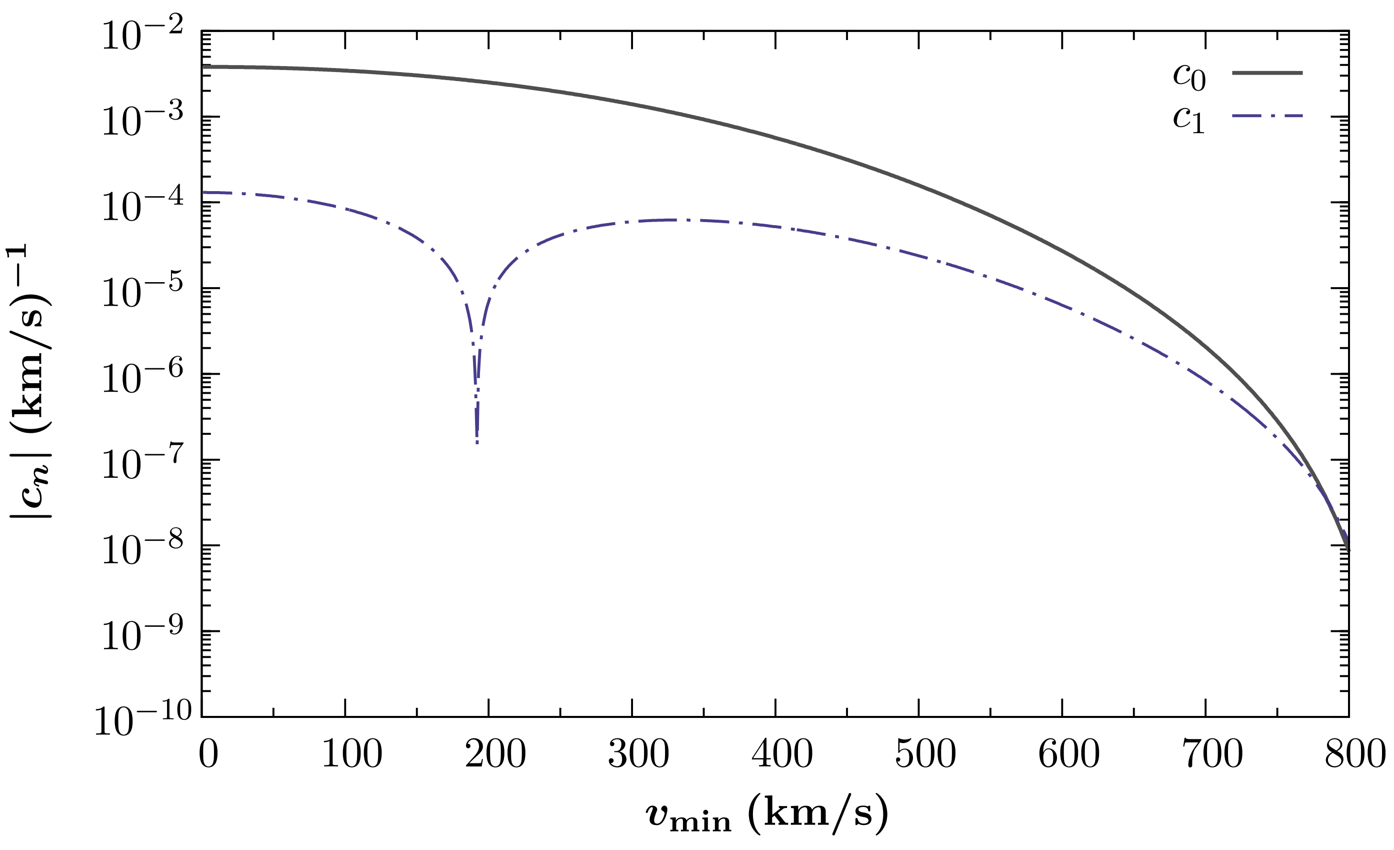

see e.g. [Druiker et al, 1986; Freese et al, 1988; Savage et al, 2009]

# signal modulation in direct detection

annual modulation

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

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

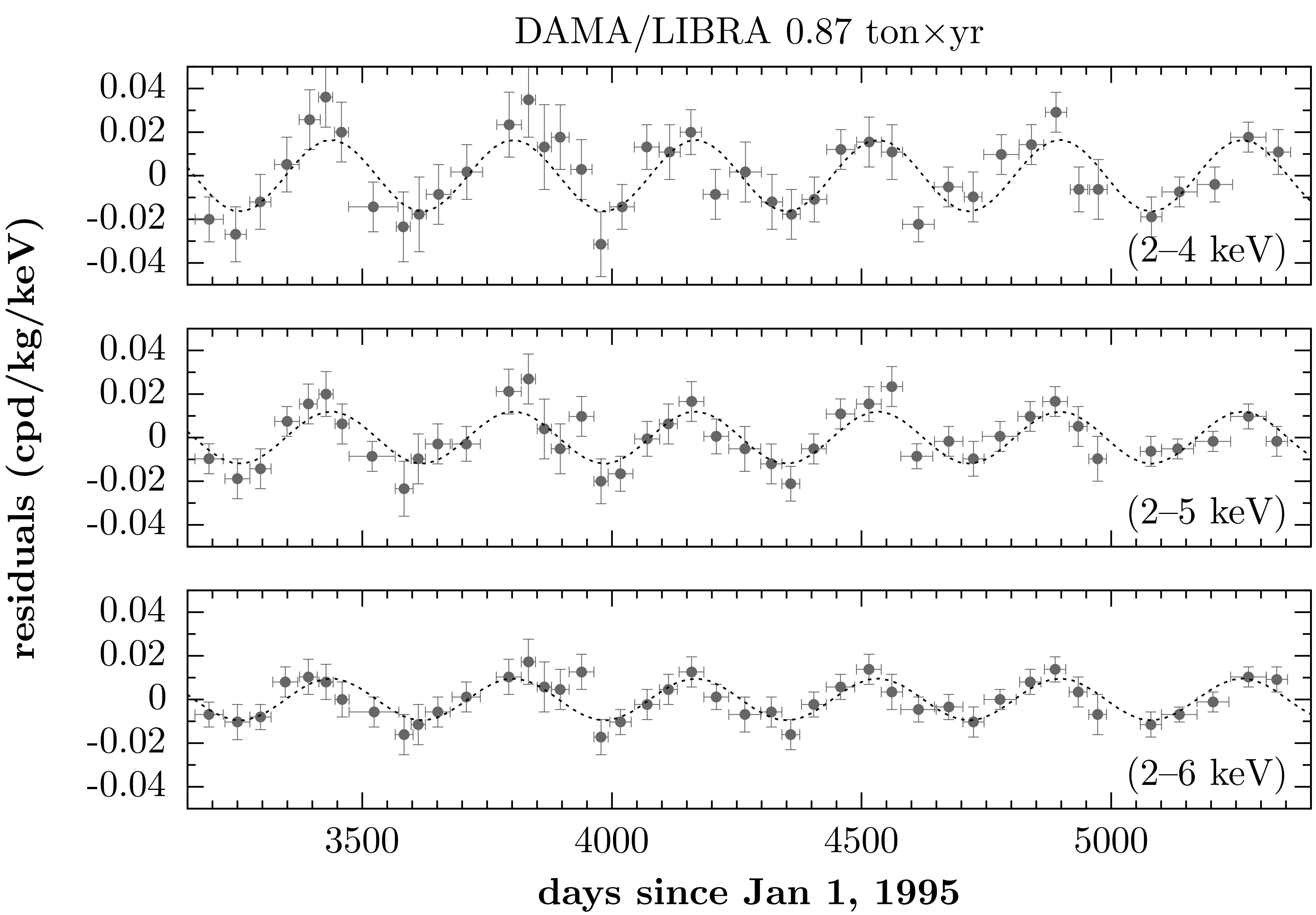



$t_0 \simeq 152\,\text{days} \quad (\text{June 2nd})$

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

$\sim 3\%$

# DAMA/LIBRA



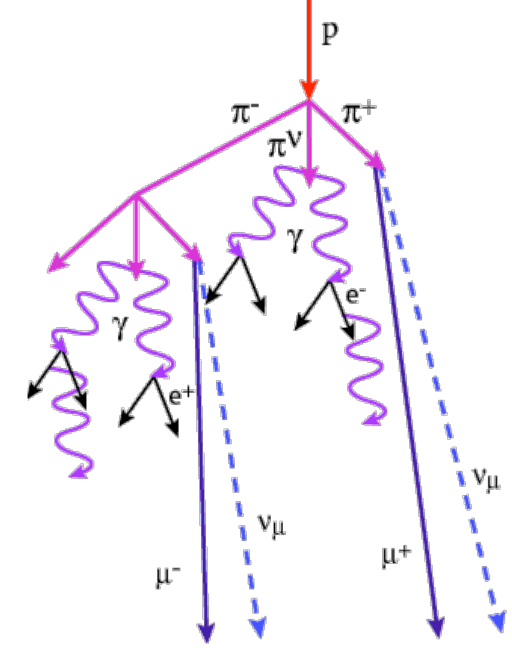

- scintillation from NaI-crystals
- 8σ+ modulation
- phase consistent as expected from WIMPs

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

[Bernabei et al. 2010]

# Muon Flux underground

## --- modulates too ---



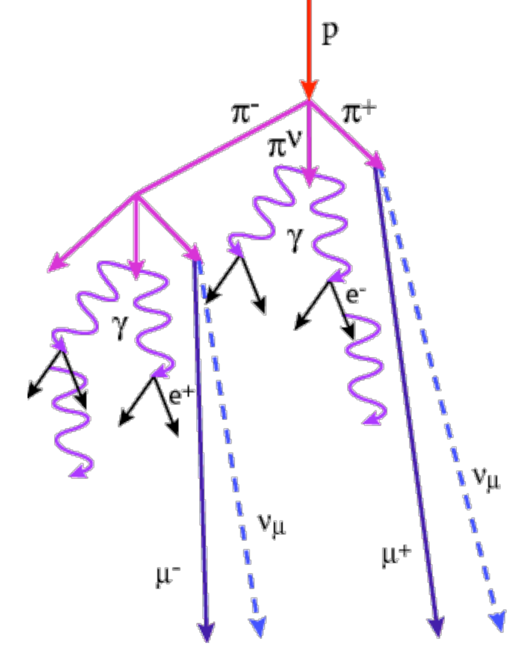

- underground flux sourced mainly by primary meson decays (pions, kaons,...) => muons need to be TeV-like to reach underground
- competition between secondary meson interactions vs. decay depends on air-density

  => muon flux correlated with temperature

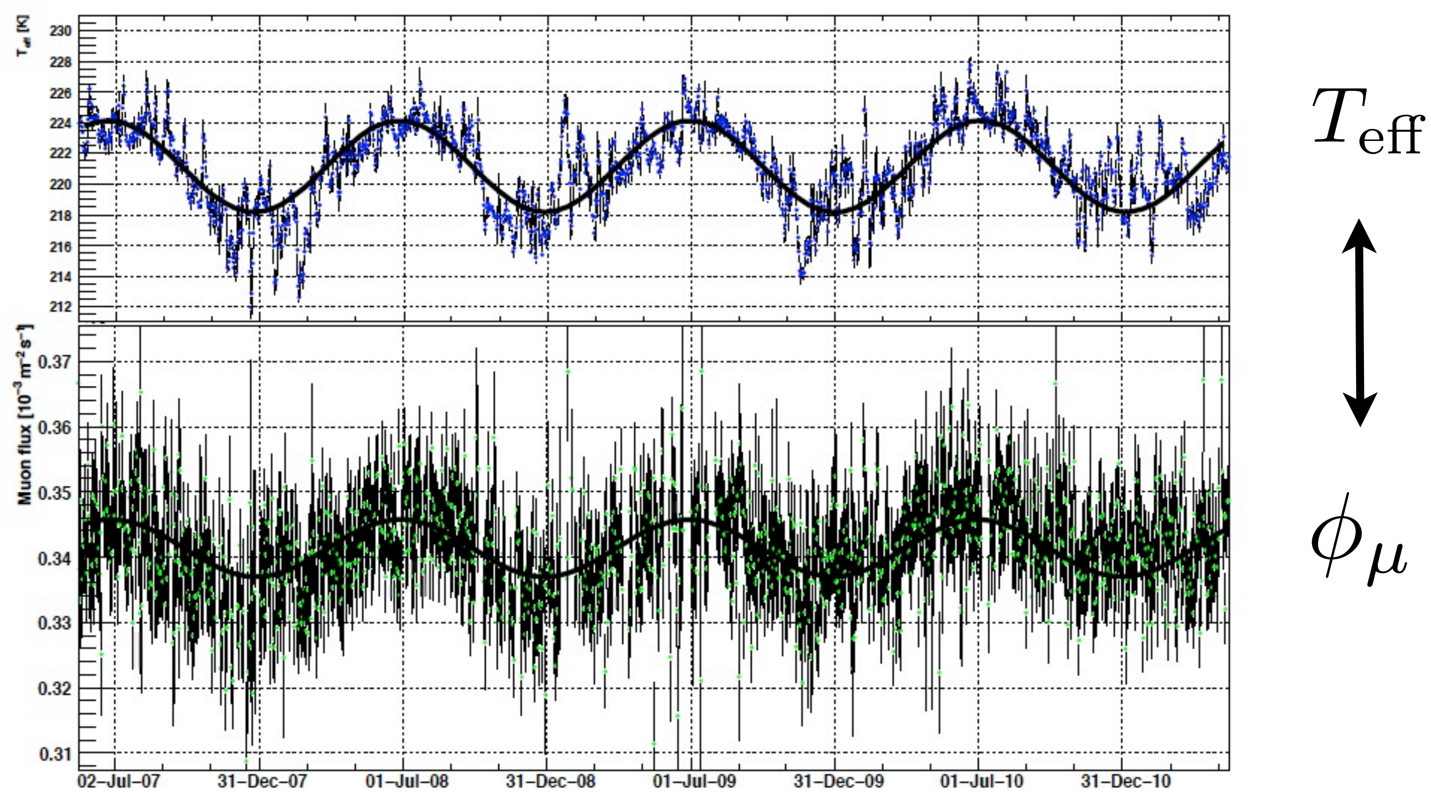
$$\frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T_{\text{eff}}}{T_{\text{eff}}} \qquad T_{\text{eff}} = \int_0^\infty dX\, T(X) W(X)$$

- flux peaks in Summer (on northern hemisphere)

# Muon Flux underground




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

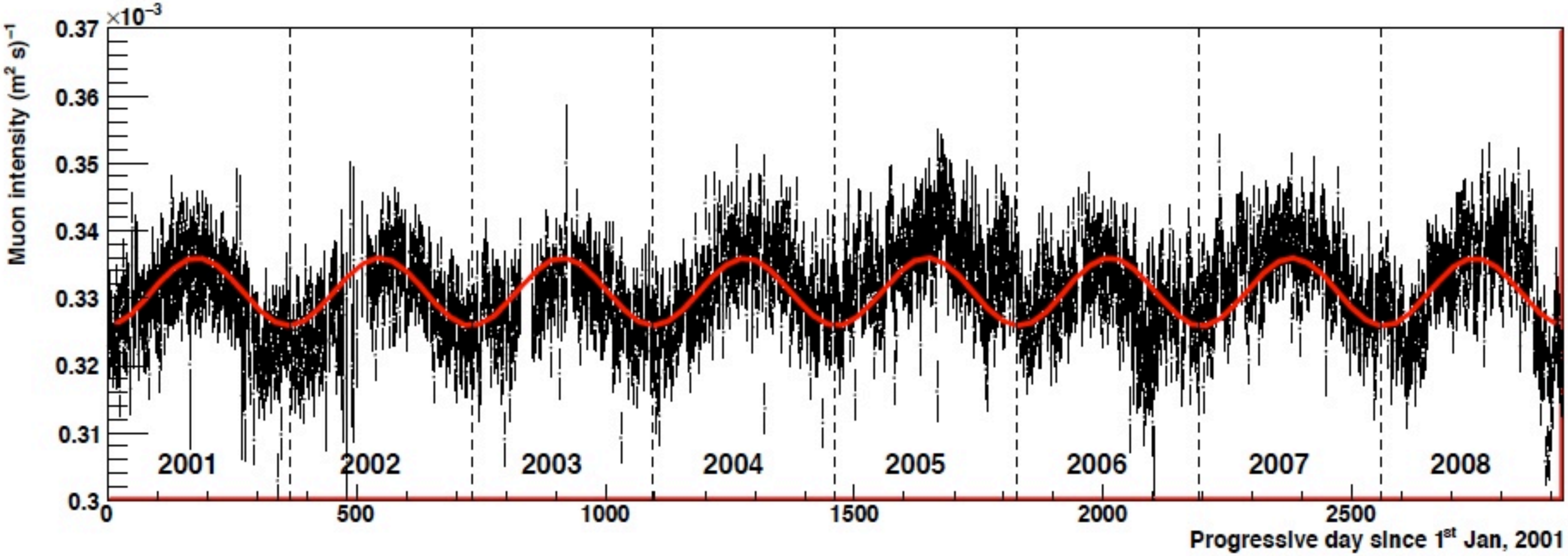



[Borexino 2011]

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

# LVD and DAMA

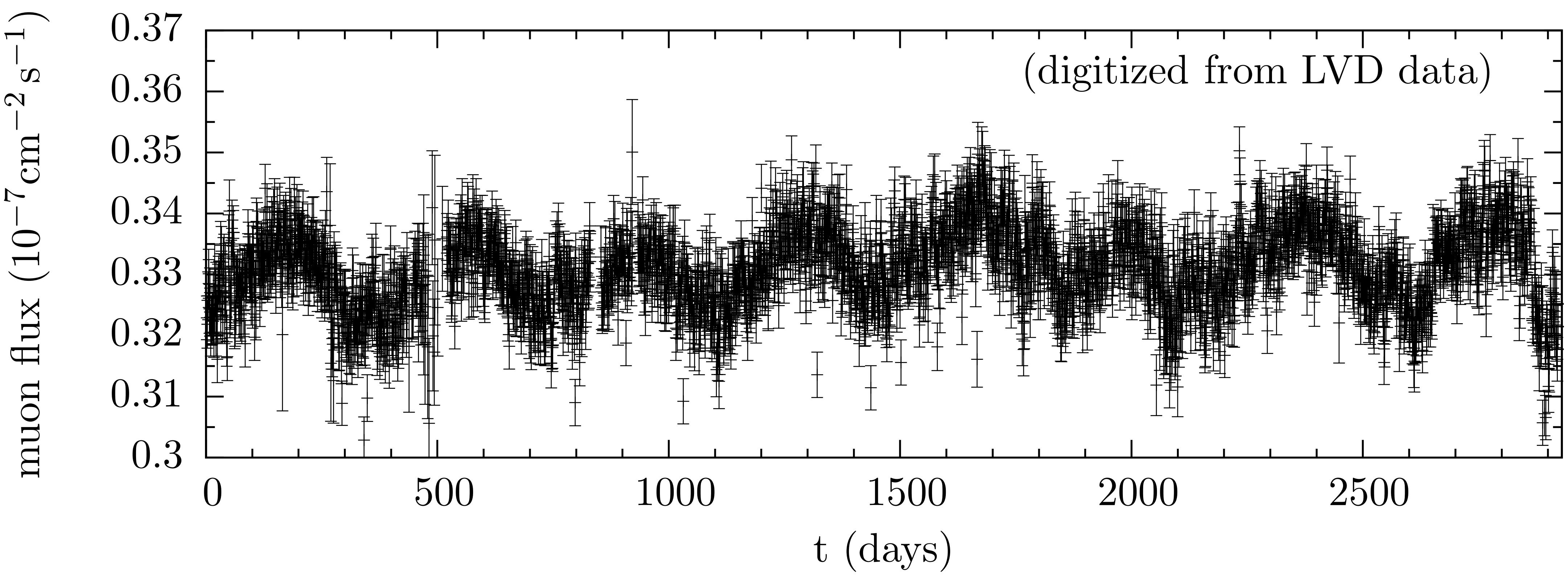
- Large Volume liquid scintillator Detector (LVD) reports underground muon-flux at LNGS => temporal overlap with DAMA data




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

[Selvi, 2009]

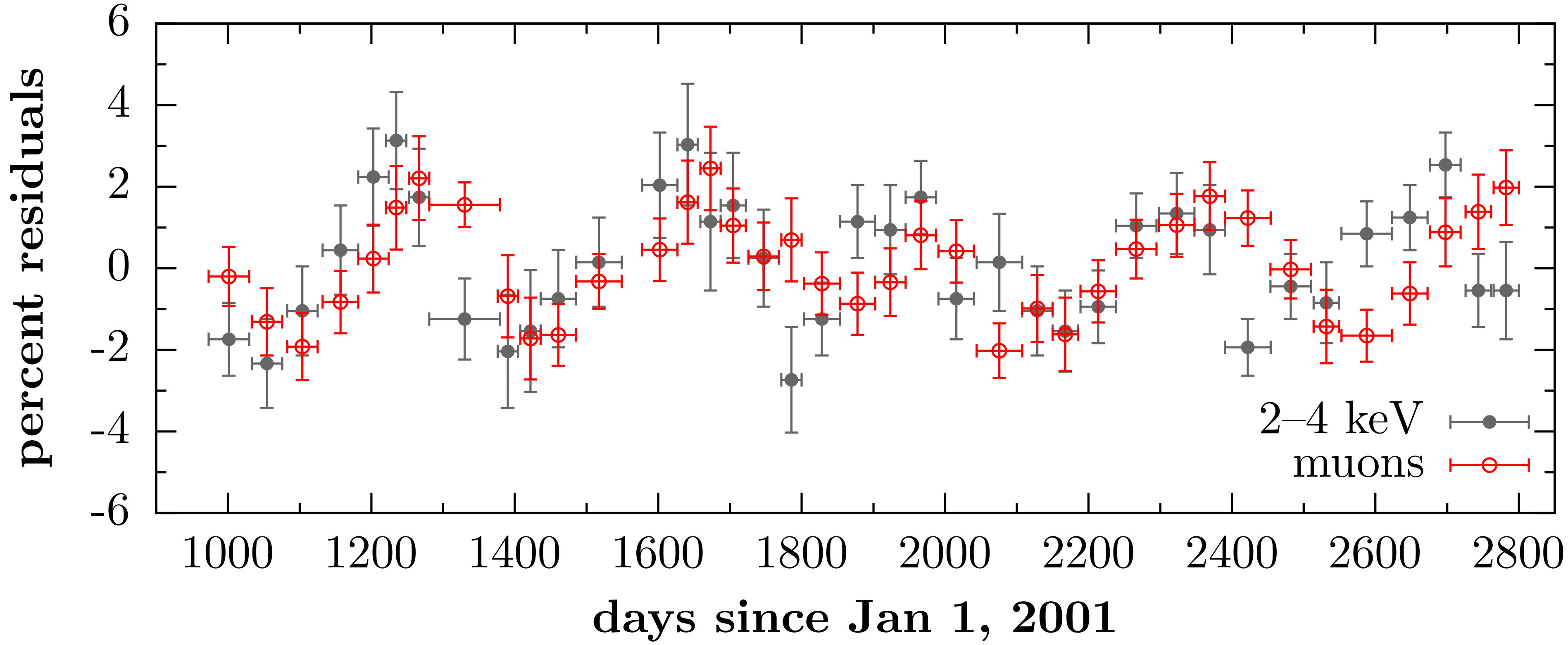
# LVD and DAMA




- recent 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




- recent 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

- 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

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

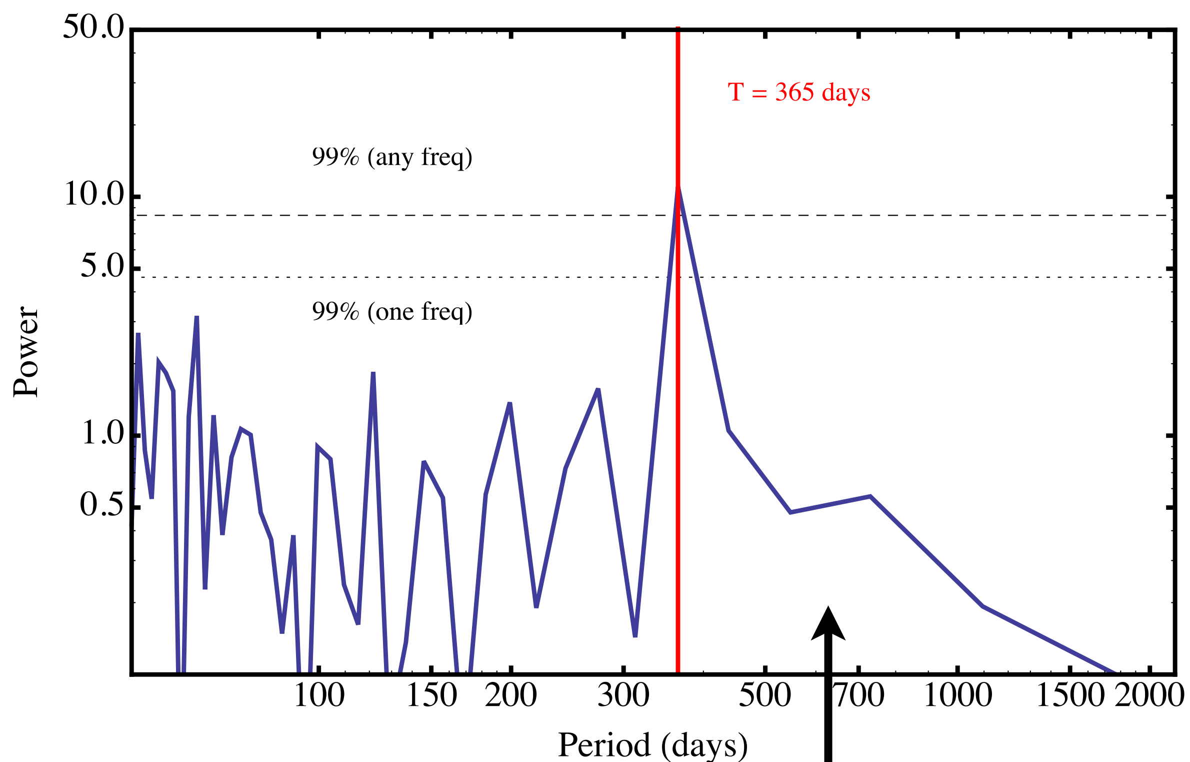
$$\tilde{t}_i \equiv t_i - \tau$$

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

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

# detecting periodicities

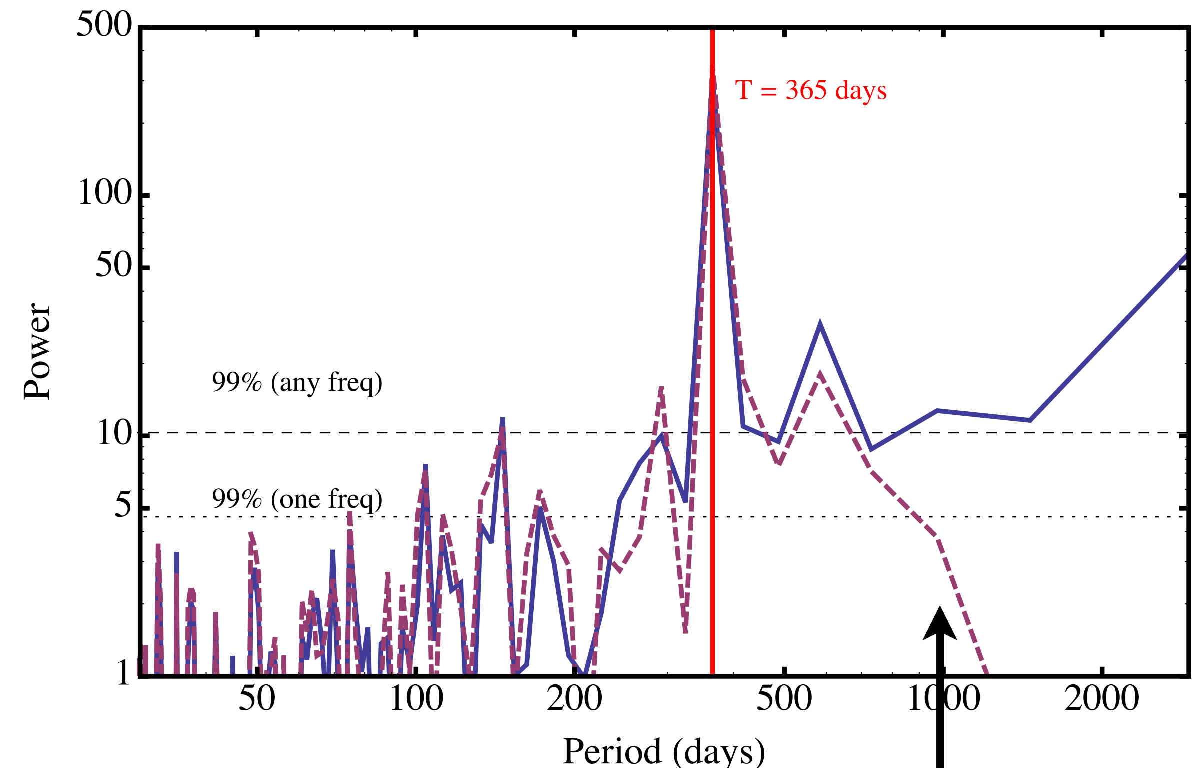
## DAMA/LIBRA




no power on timescales > 1yr

BUT

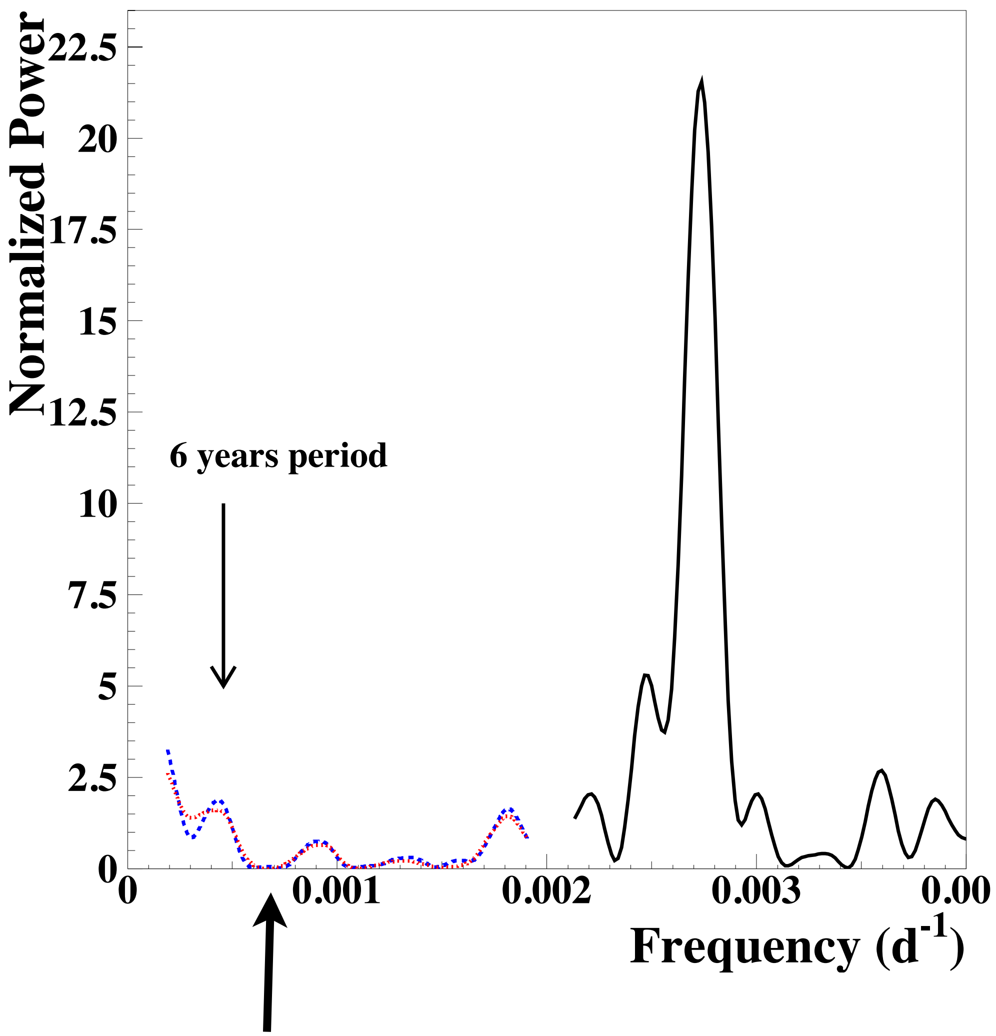
## LVD muons




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

# detecting periodicities

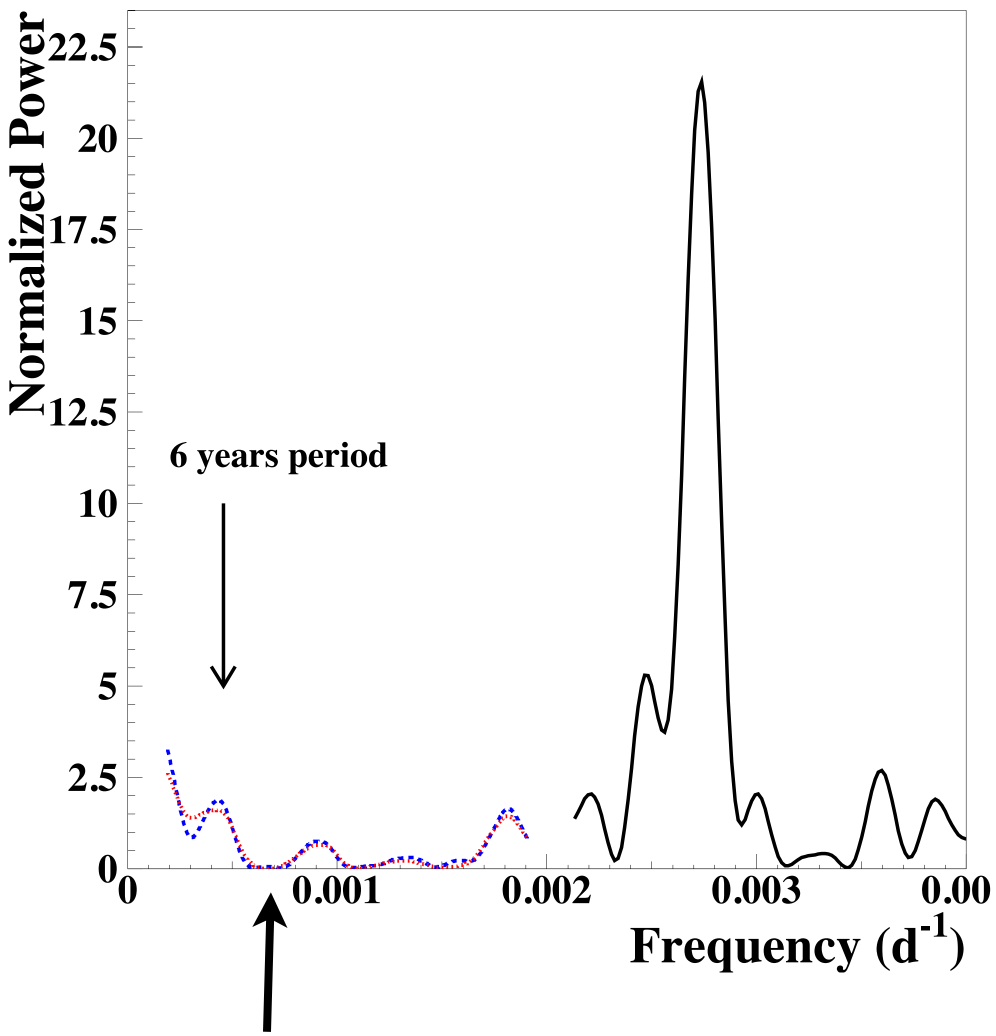
## DAMA/LIBRA, 2012




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

# detecting periodicities

## DAMA/LIBRA, 2012

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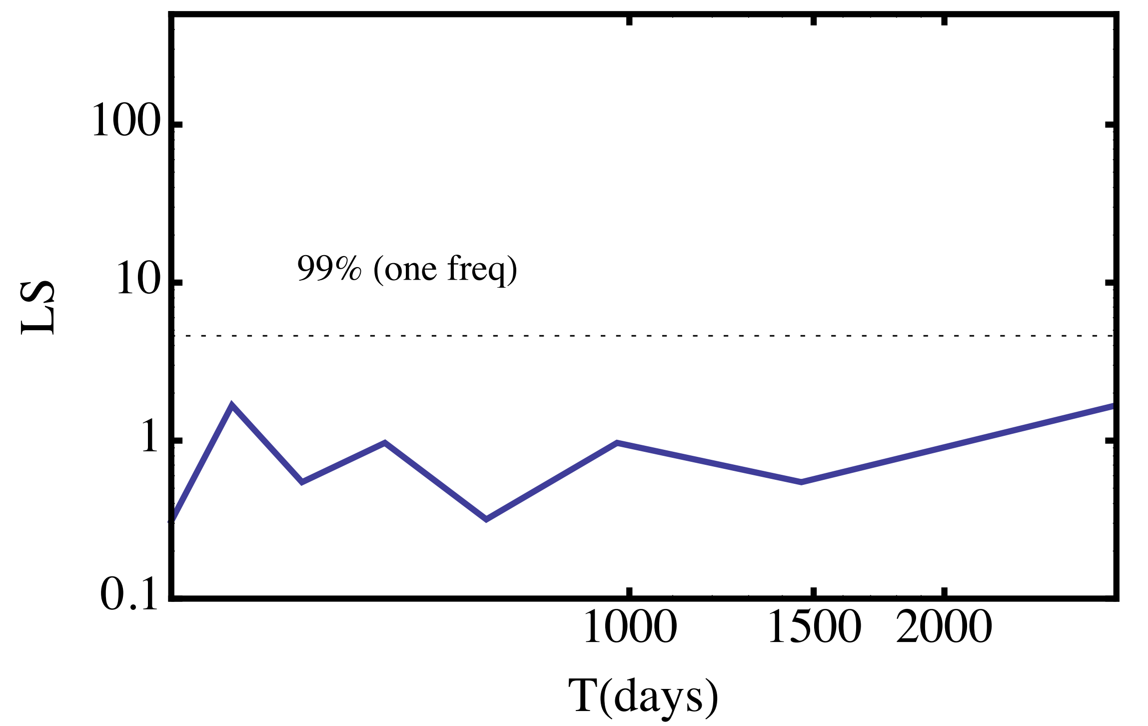
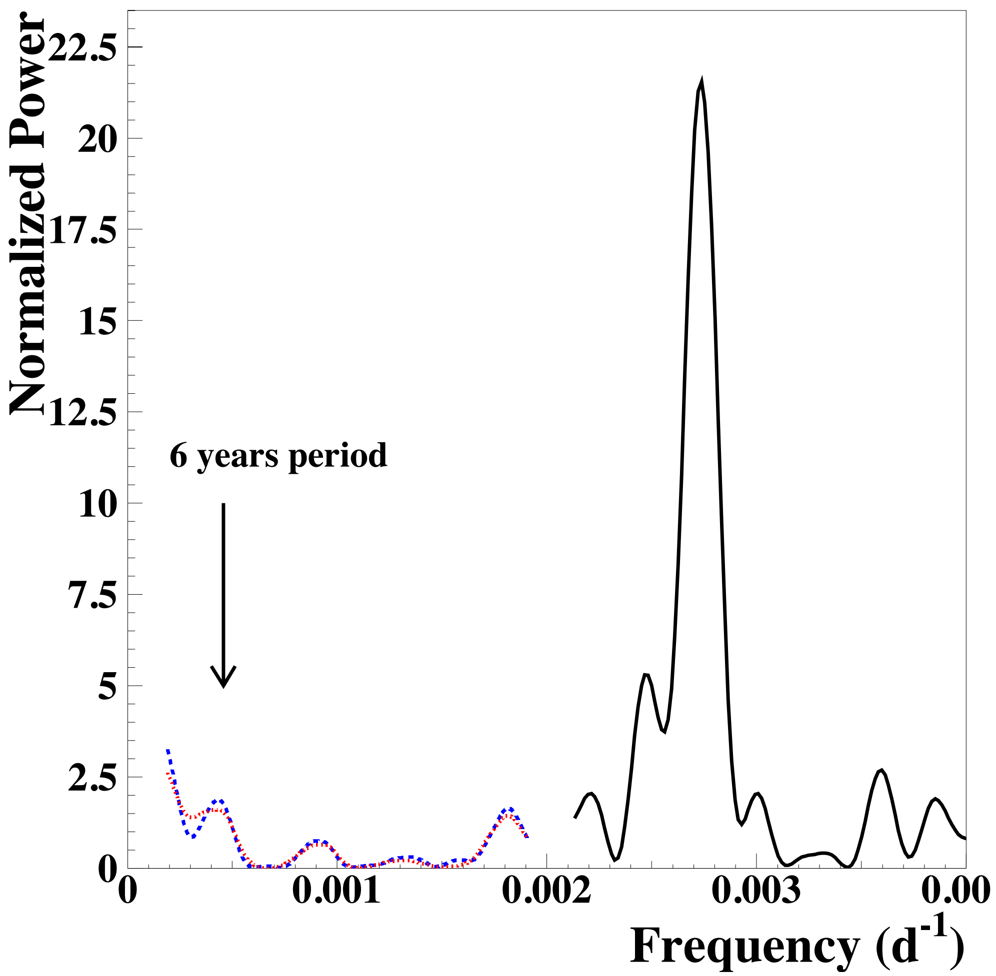
## LVD muons




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

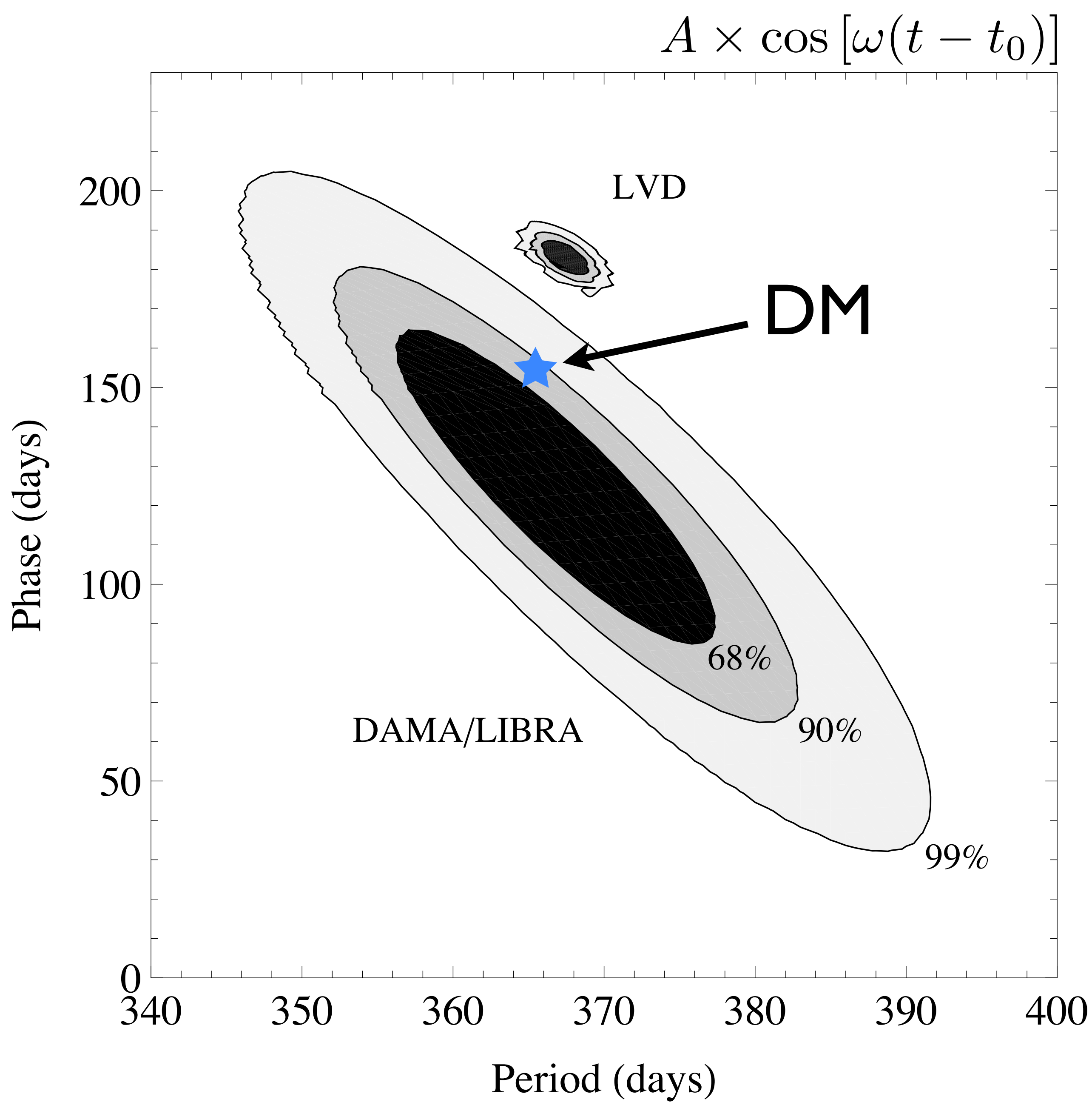
  => normalized power

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

- 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

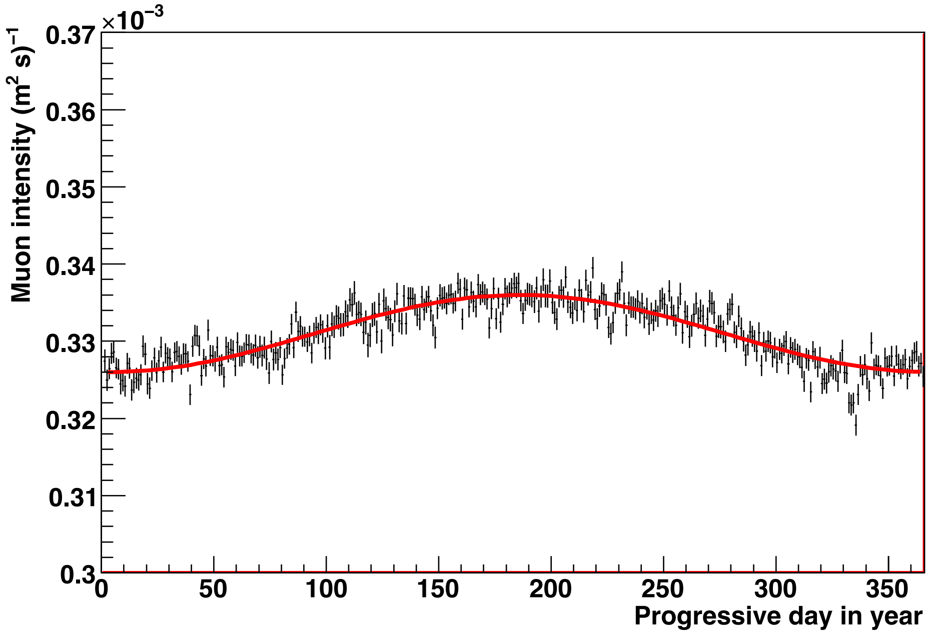
1. Selvi for LVD collaboration finds

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

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

adopting this procedure we find

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




[Selvi for LVD, 2009]

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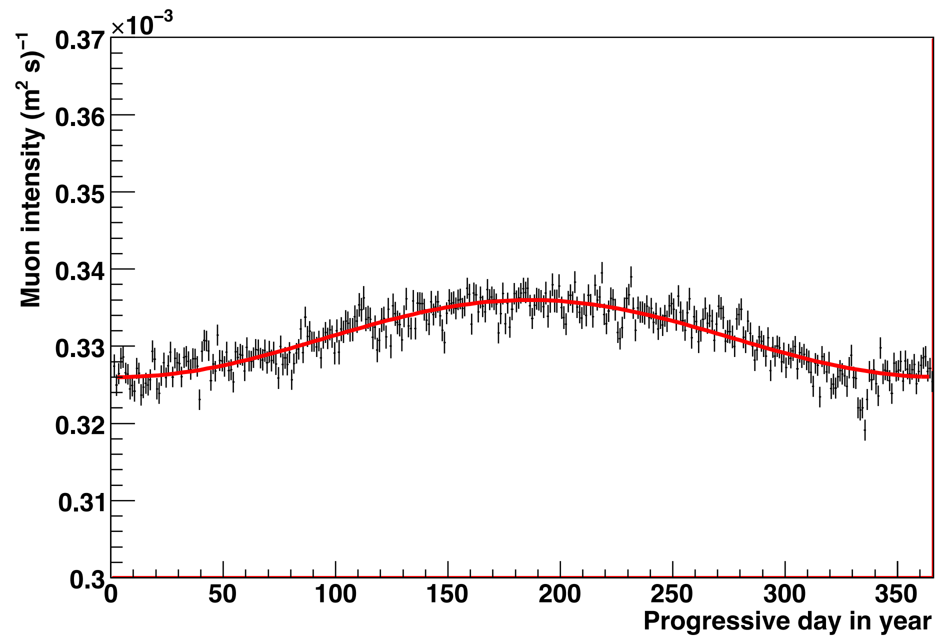


[Selvi for LVD, 2009]

adopting this procedure we find

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

suspecting that Selvi used reduced $\chi^2$ 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

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

=> used to generate DAMA mock data

# The phase of DAMA
# vs
# the "phase" of LVD

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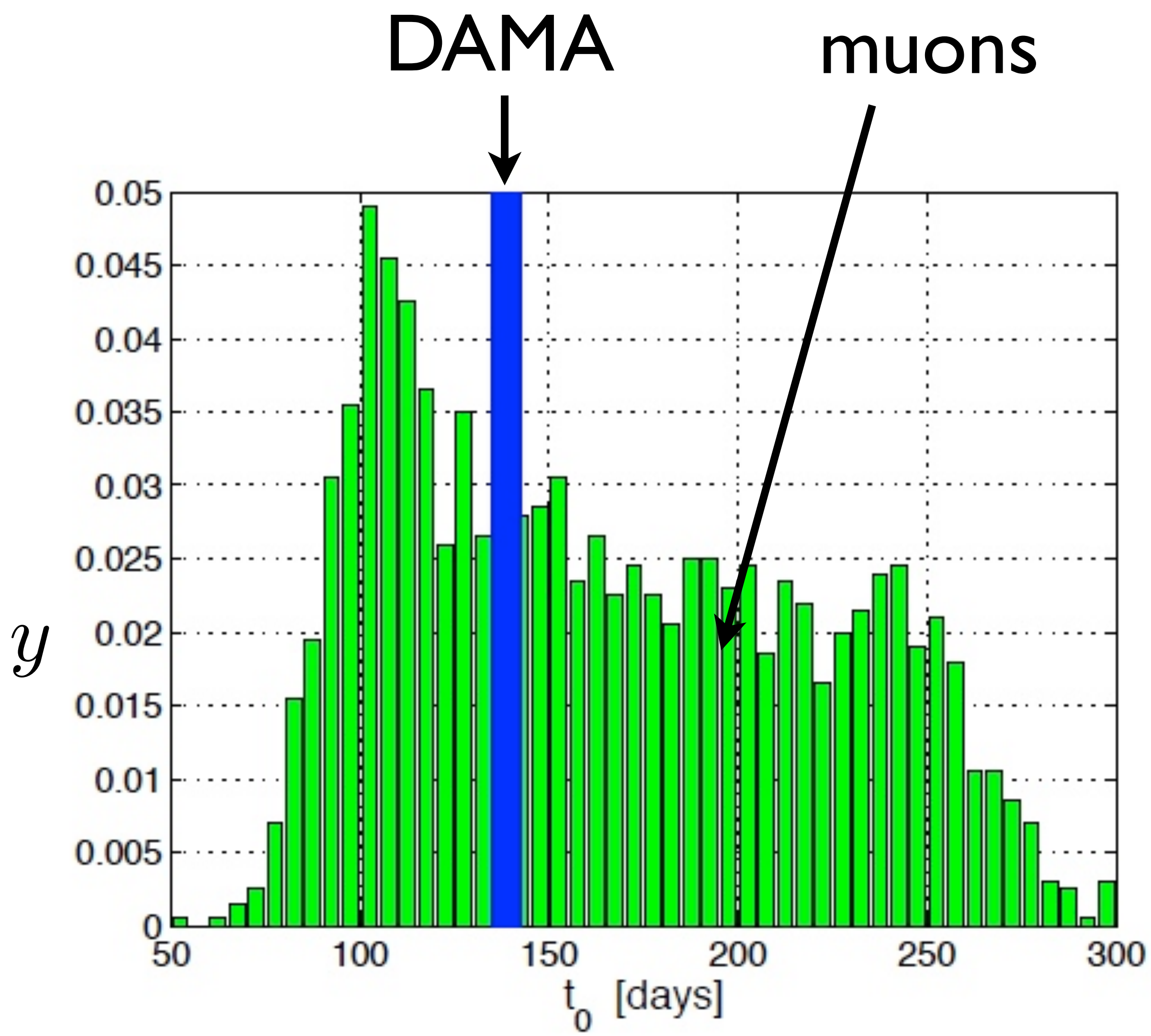
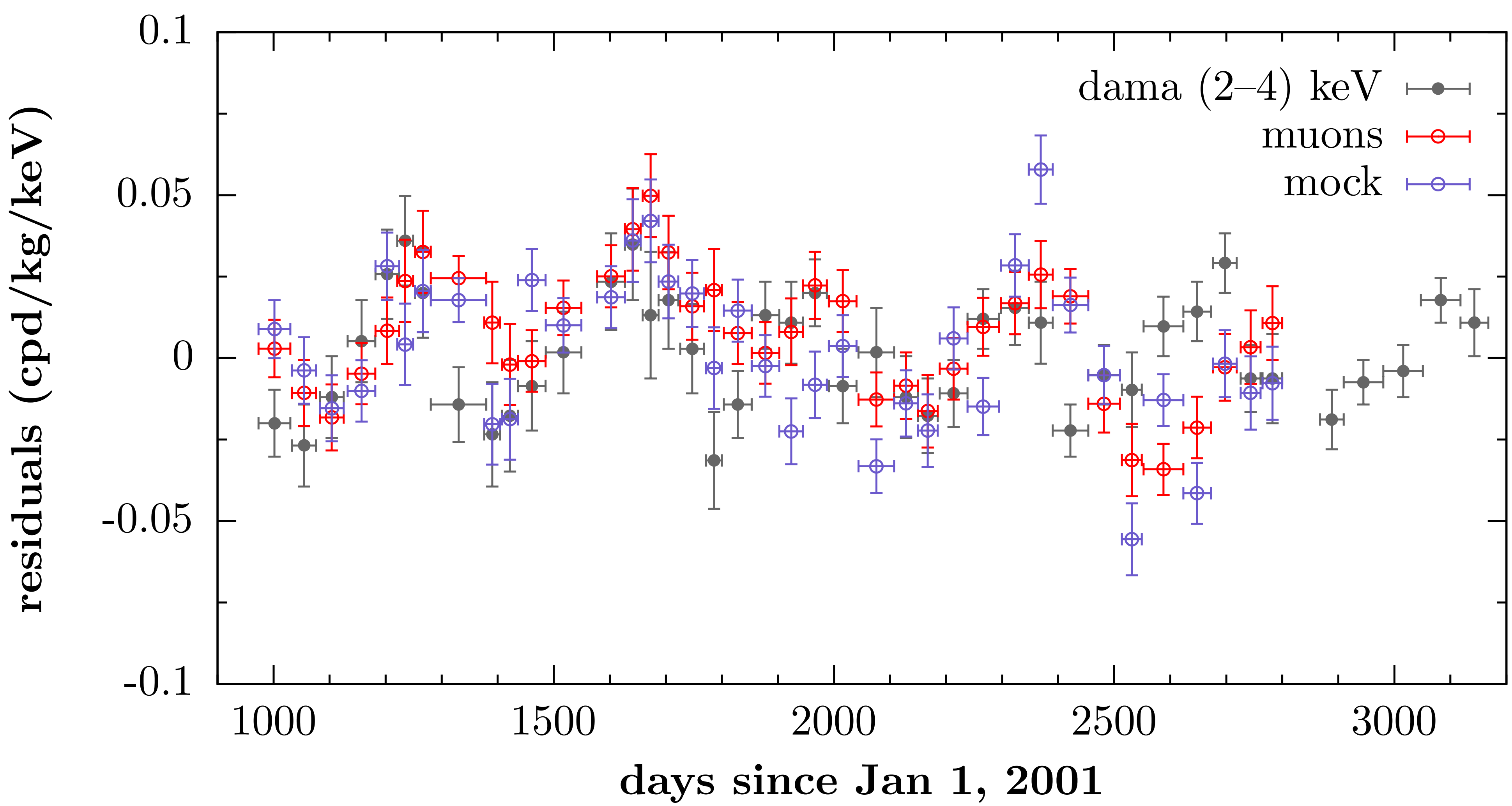



=> used to generate DAMA mock data

# The phase of DAMA
# vs
# the “phase” of LVD

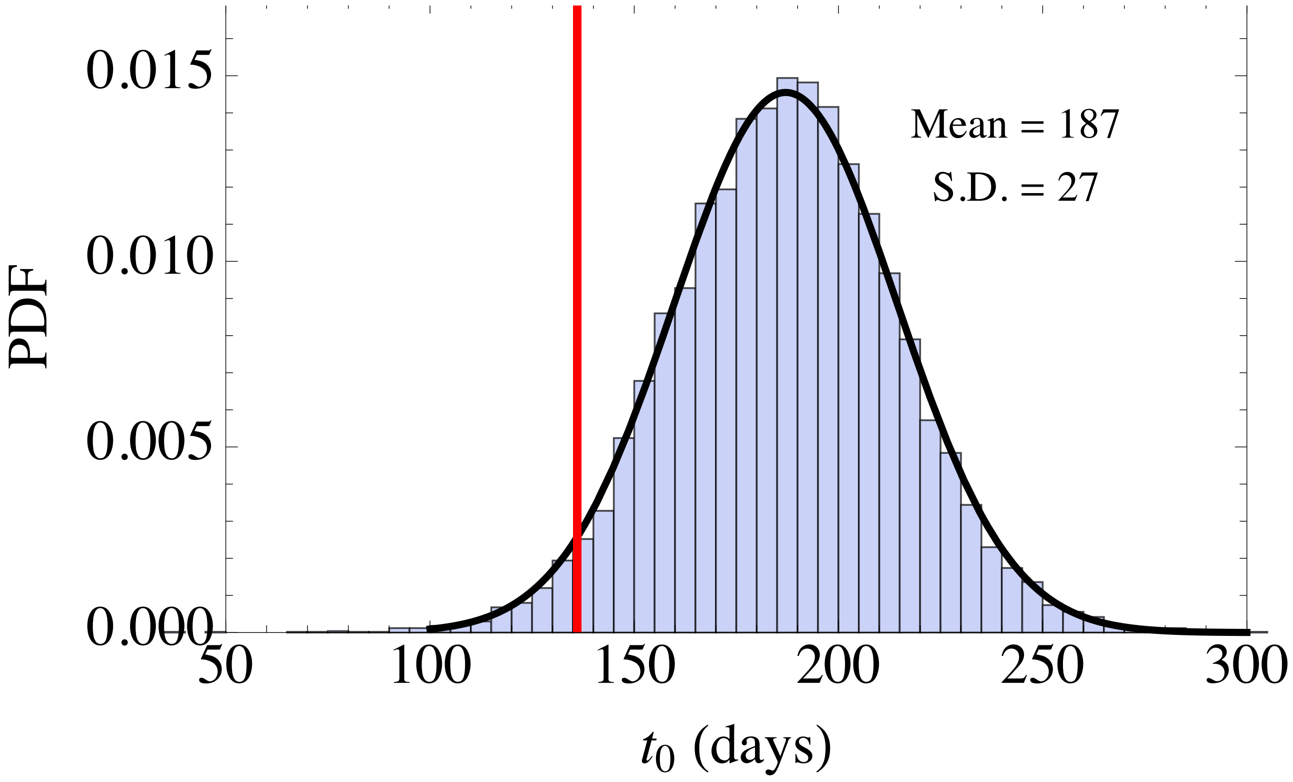
=> redo Blum’s analysis:




(one representative out of a sample of 10k)

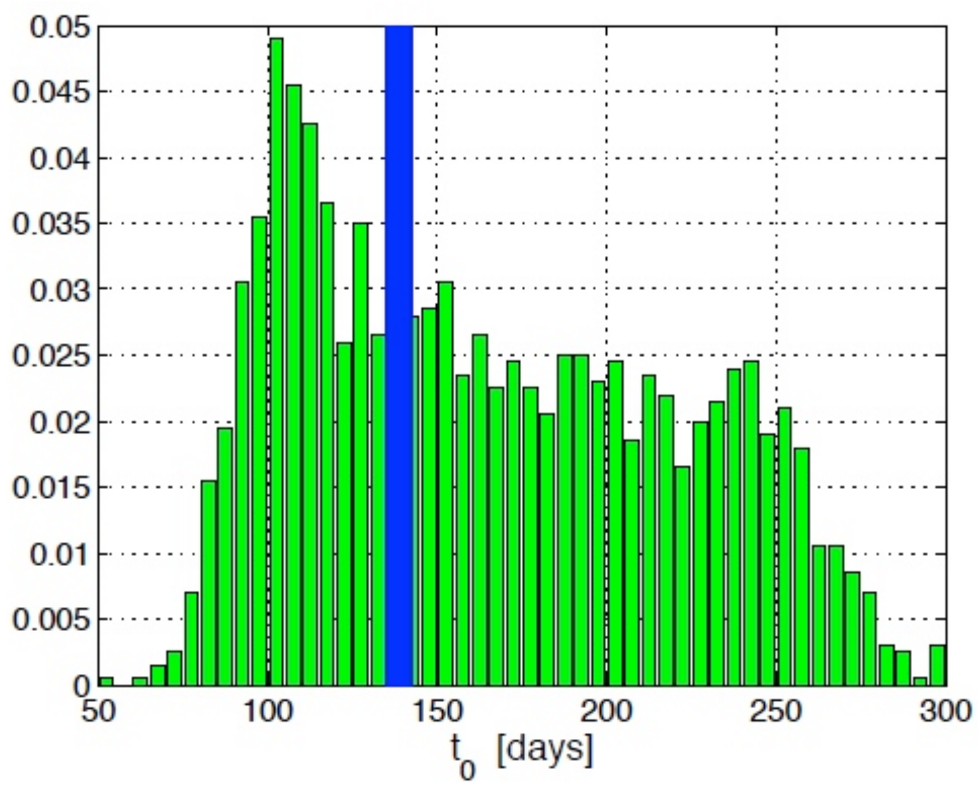
# The phase of DAMA
# vs
# the "phase" of LVD

$t_0$ 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

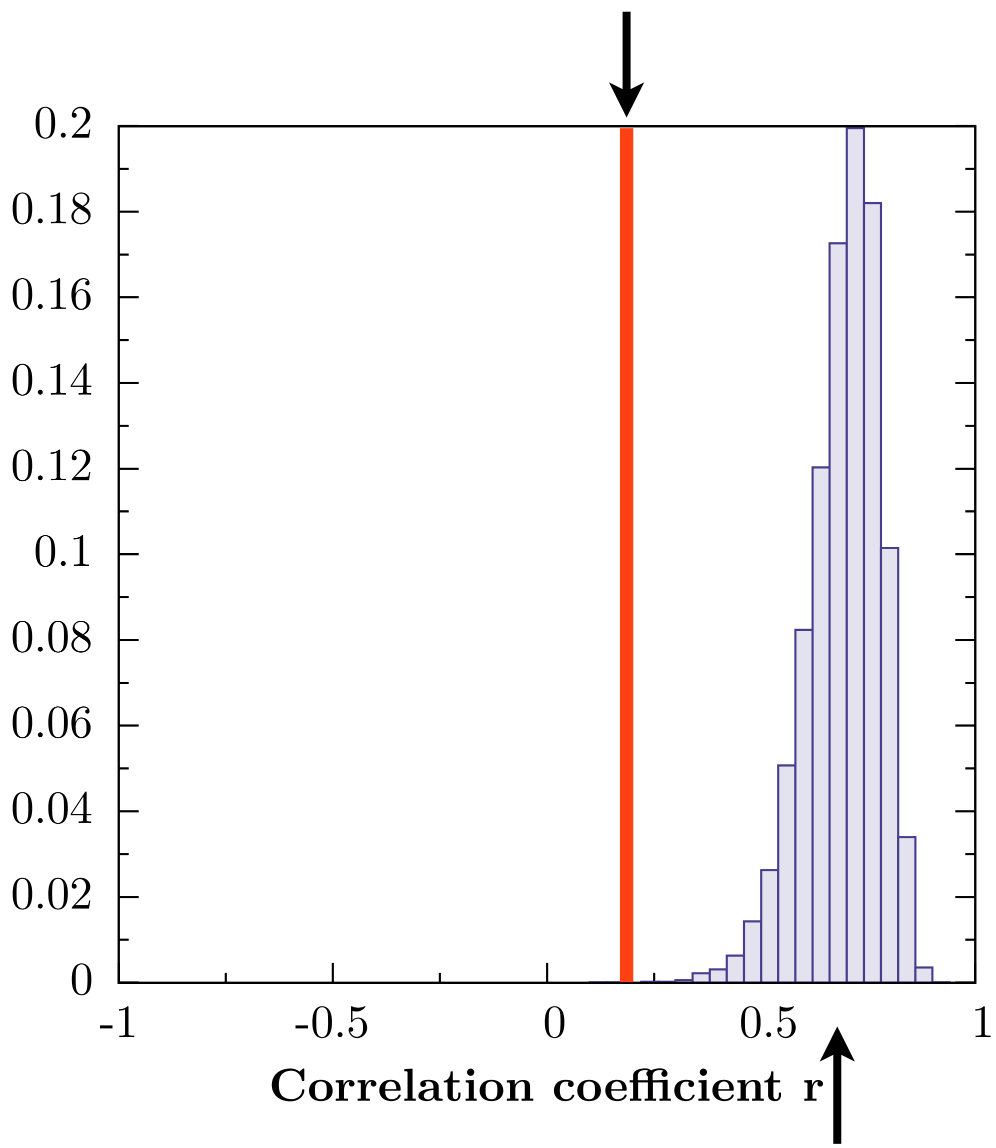
   => preferentially without reliance on sinusoidal function

   => 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)

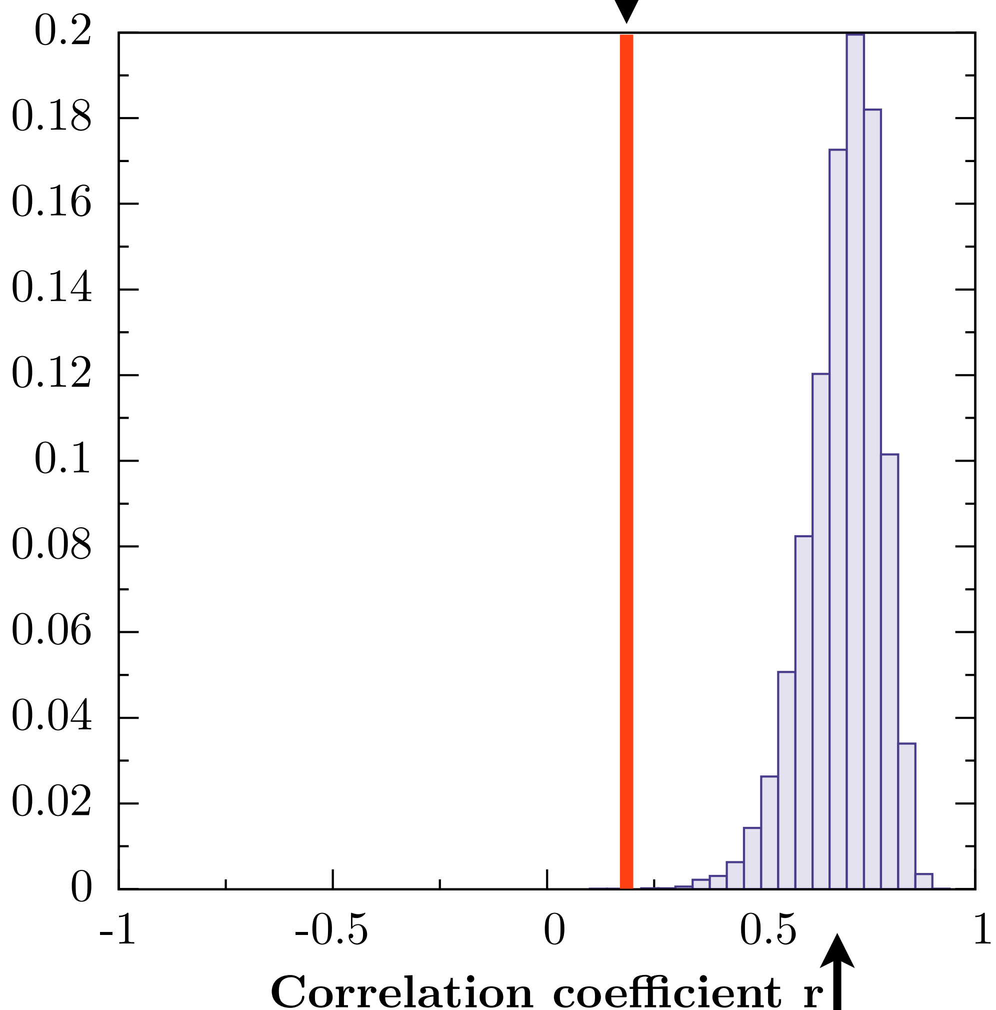



correlation
r(muon,mock)

Q: how significant is the difference between these two?

# correlation study

correlation
r(muon,mock=DAMA)

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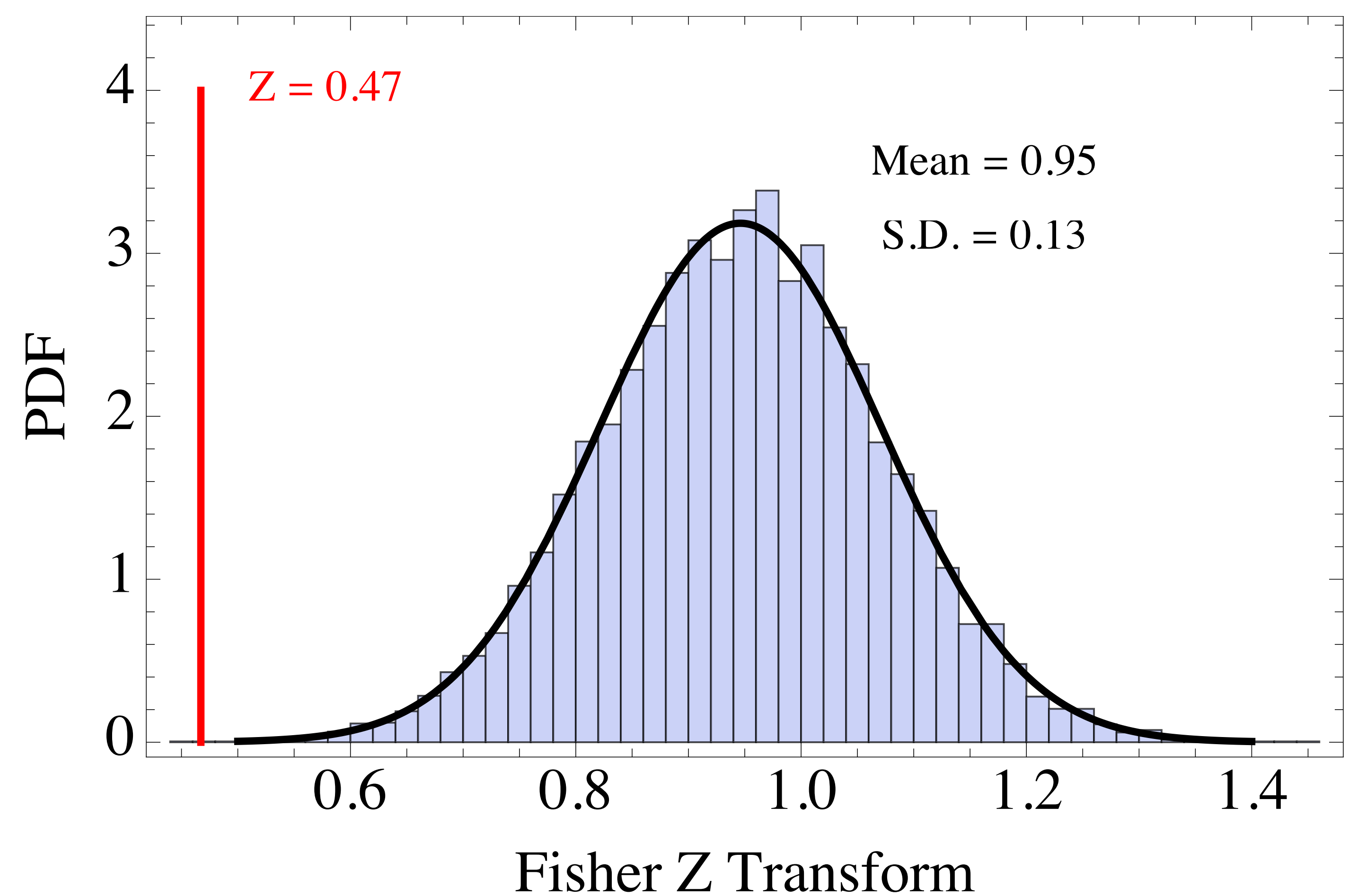
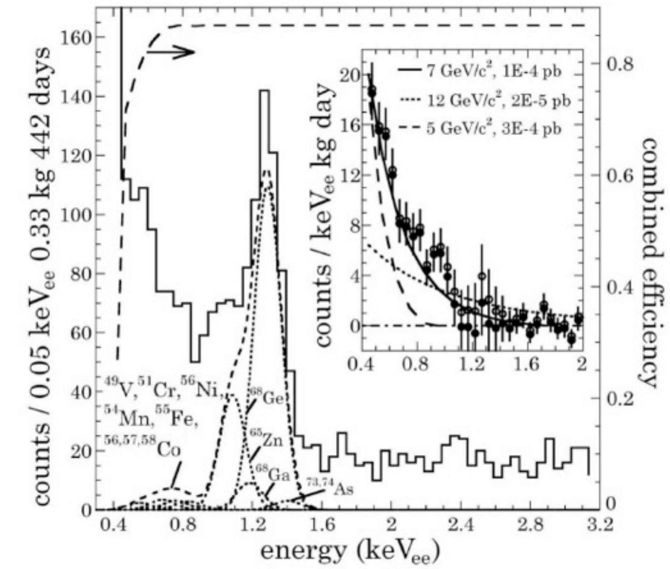
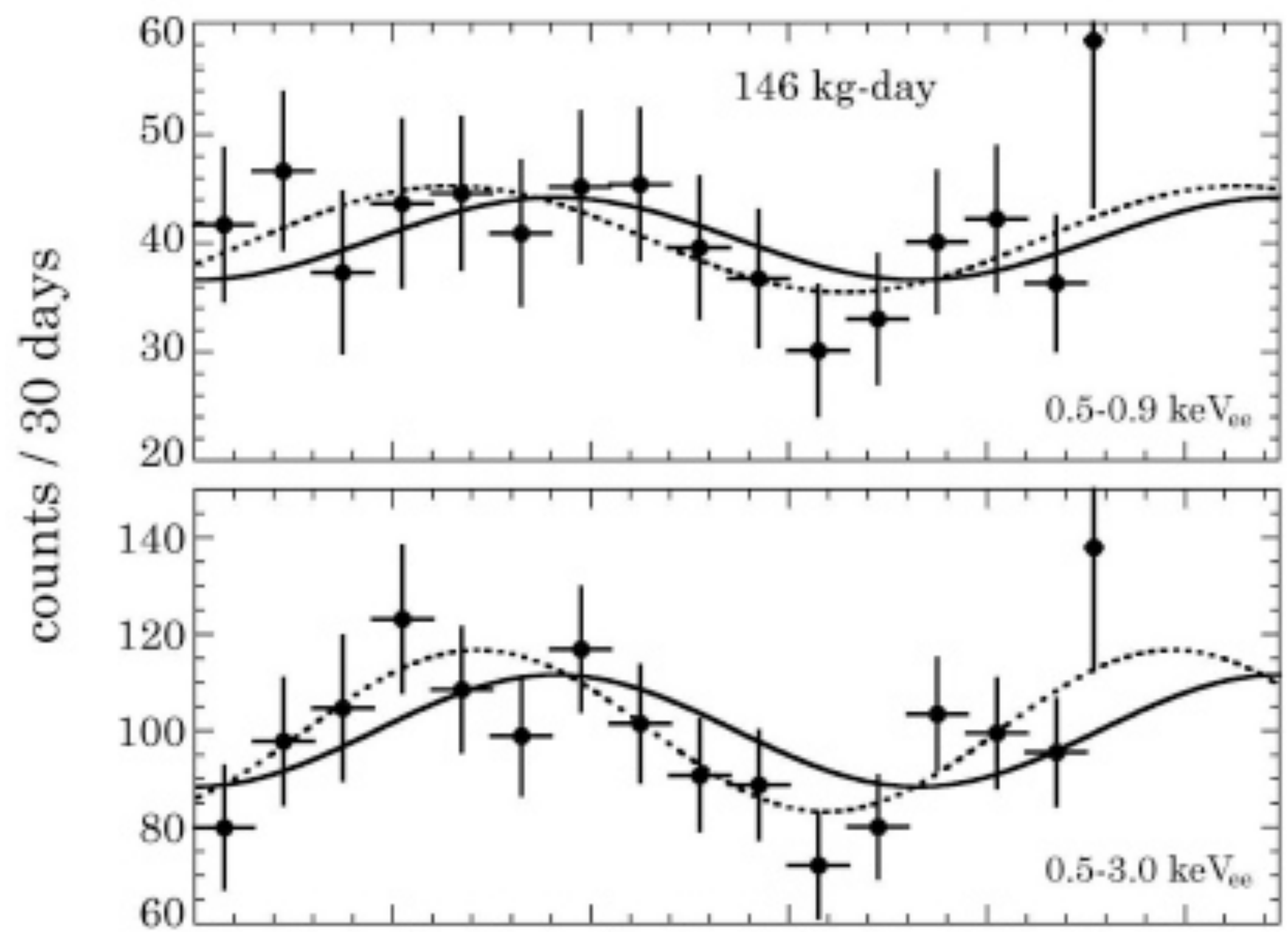



Model excluded $\gtrsim 99\%$ C.L.

# CoGeNT



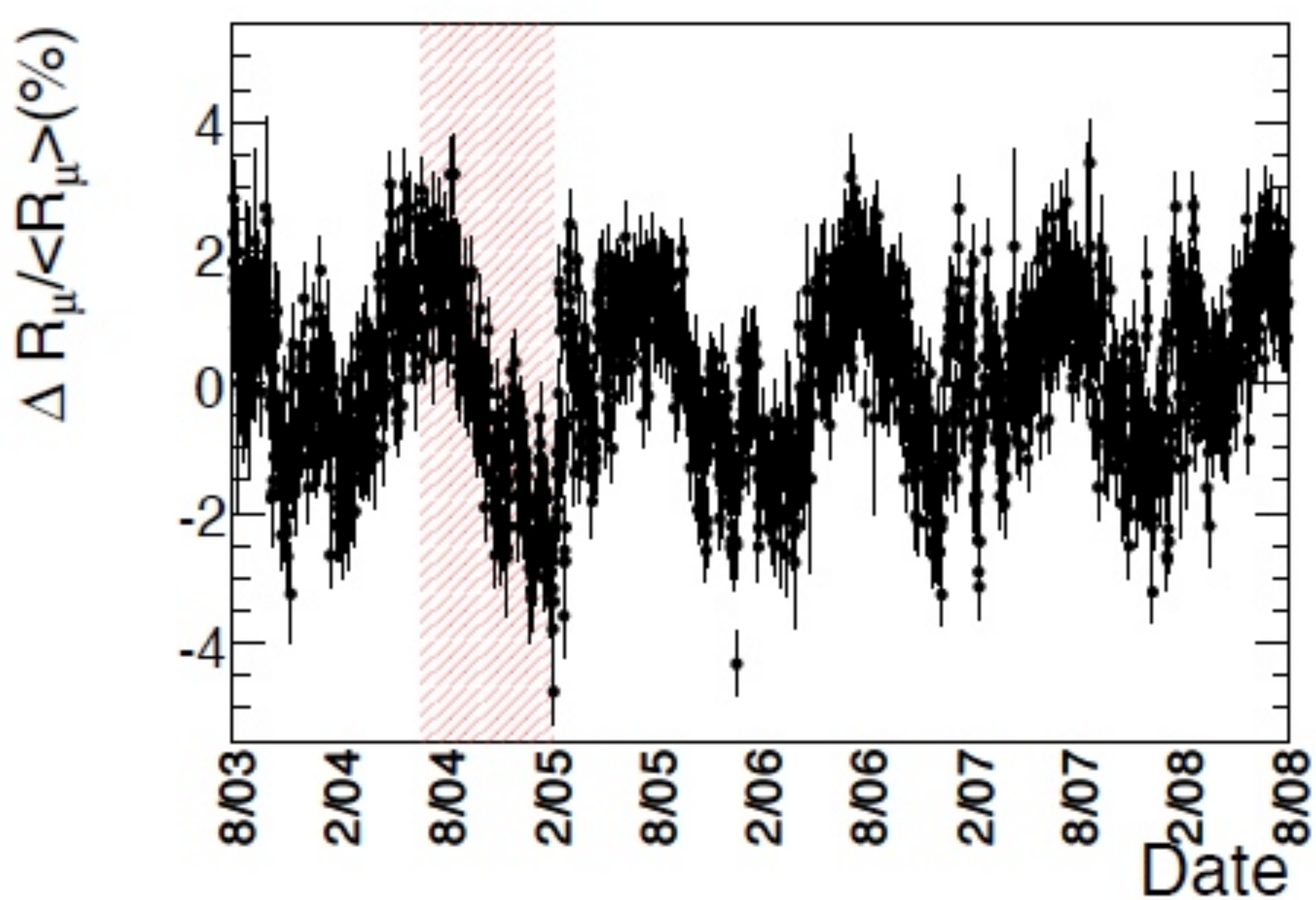

- 442 kg live-days
- Ge-target, ionization
- potential exponential rise toward low energies
- cosmogenic peaks
- modulation too




[Aalseth et al, 2011]

# CoGeNT

- muon measurements at CoGeNT site (Soudan Mine, MN) from MINOS experiment exist---but only for earlier time period




[Adamson et al, 2010]

CoGeNT

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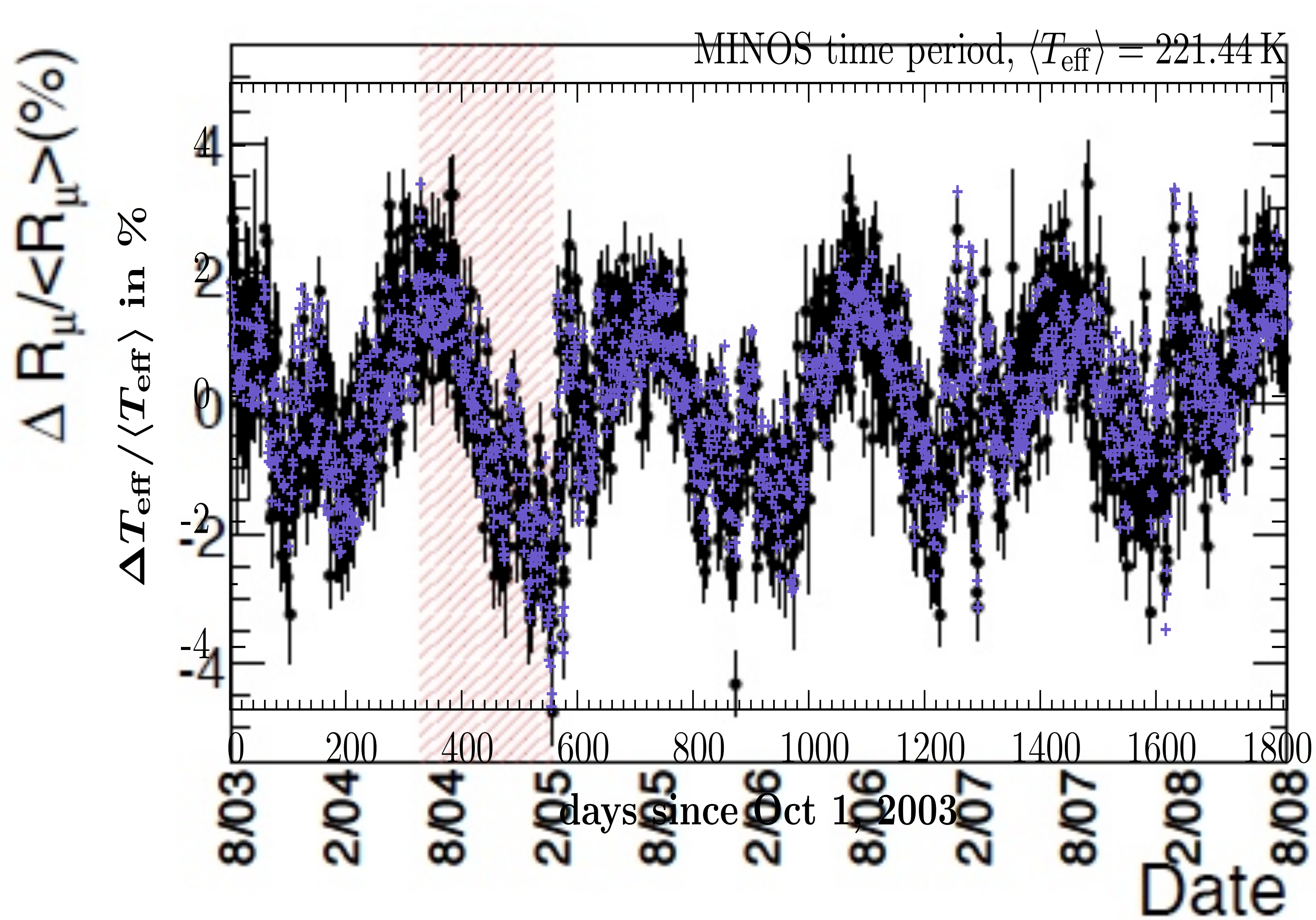
=> use available climate data to predict muon flux!




[Adamson et al, 2010]

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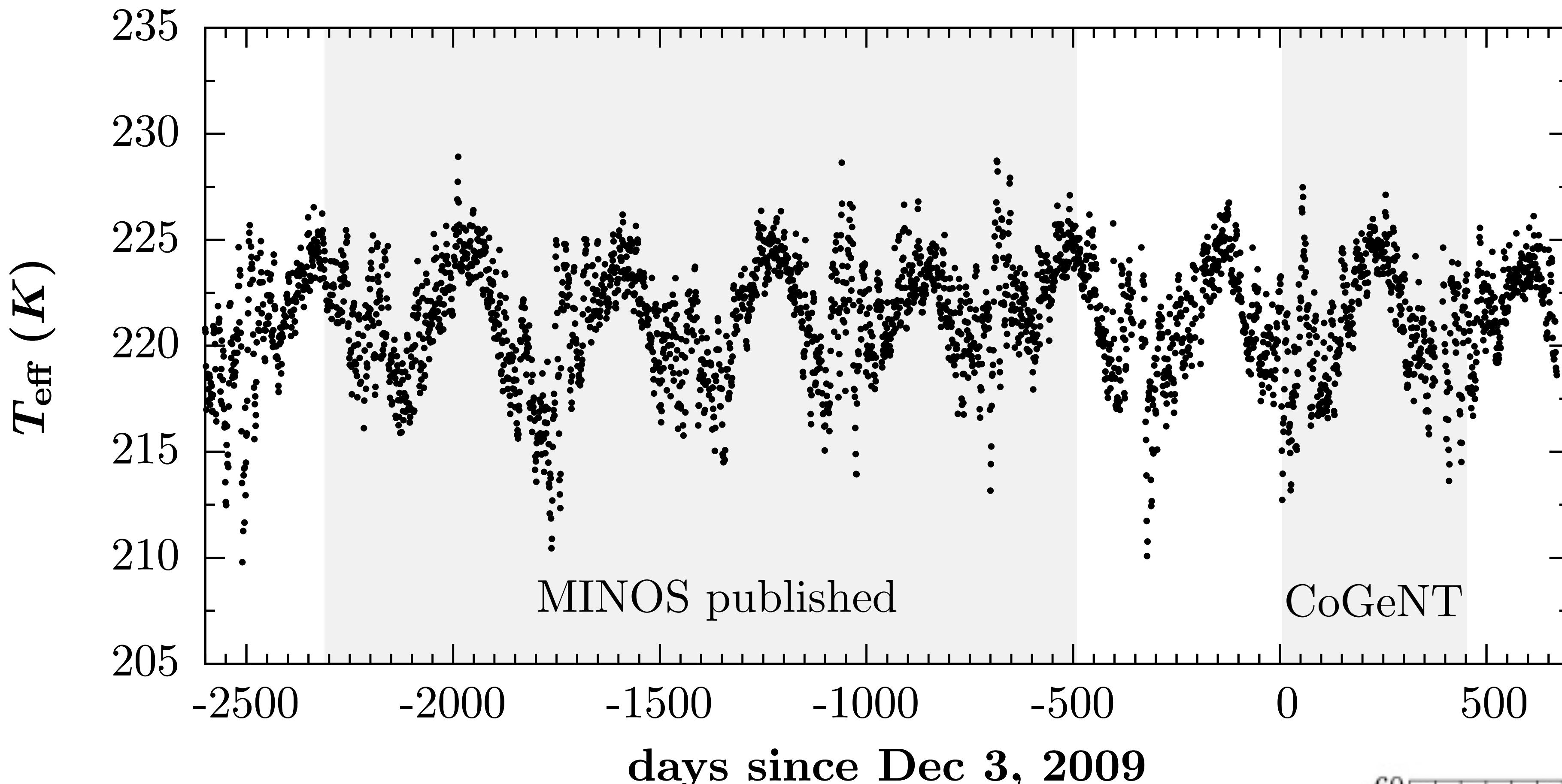
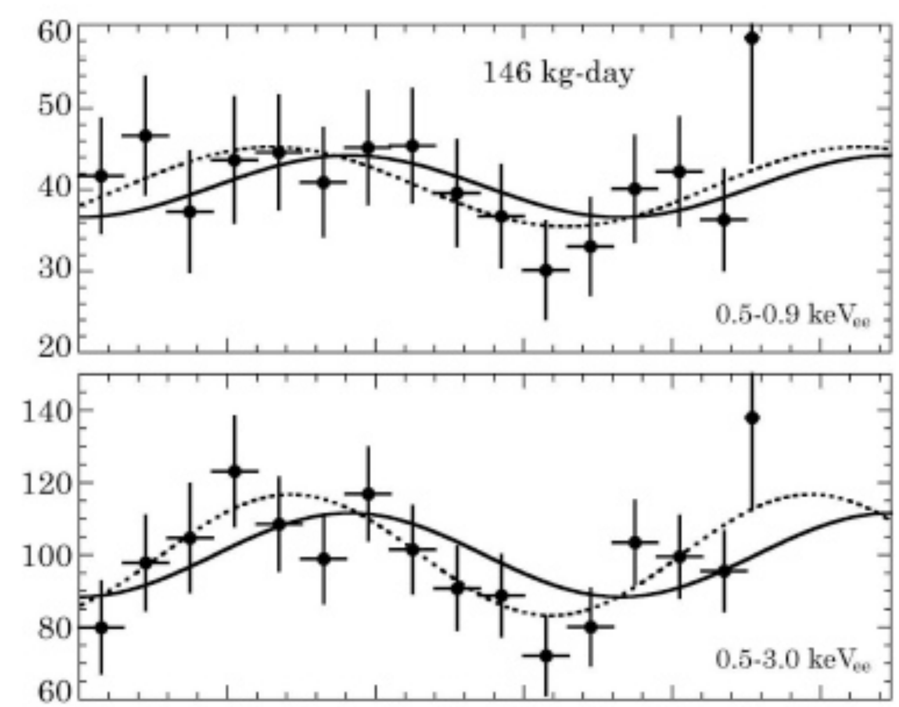


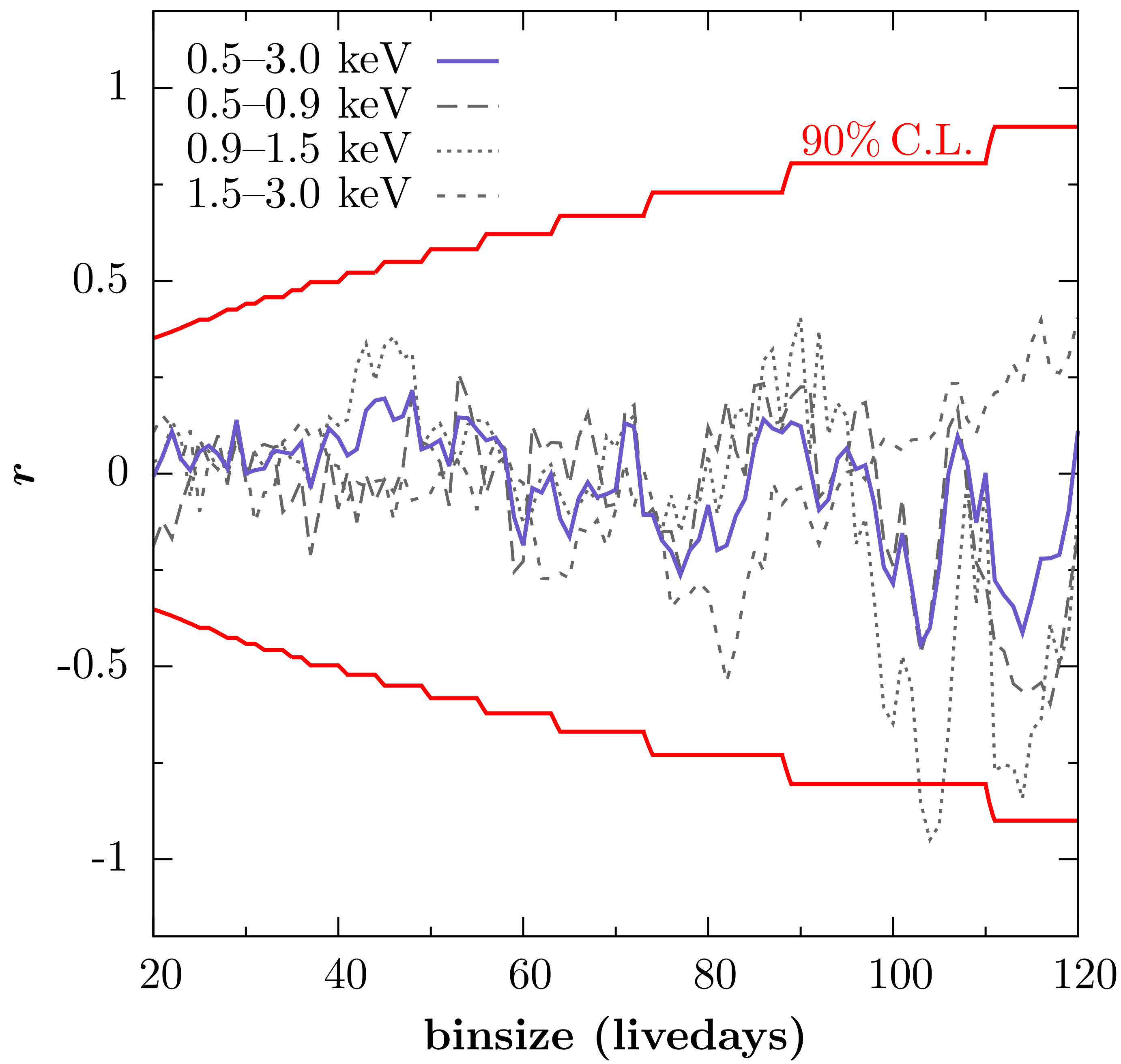
235
230
225
220
215
210
205
$T_{\text{eff}}$ ($K$)
MINOS published
CoGeNT
-2500
-2000
-1500
-1000
-500
0
500
days since Dec 3, 2009


vs.



146 kg-day
0.5-0.9 keV$_{ee}$
0.5-3.0 keV$_{ee}$
60
50
40
30
20
140
120
100
80
60

# correlation study



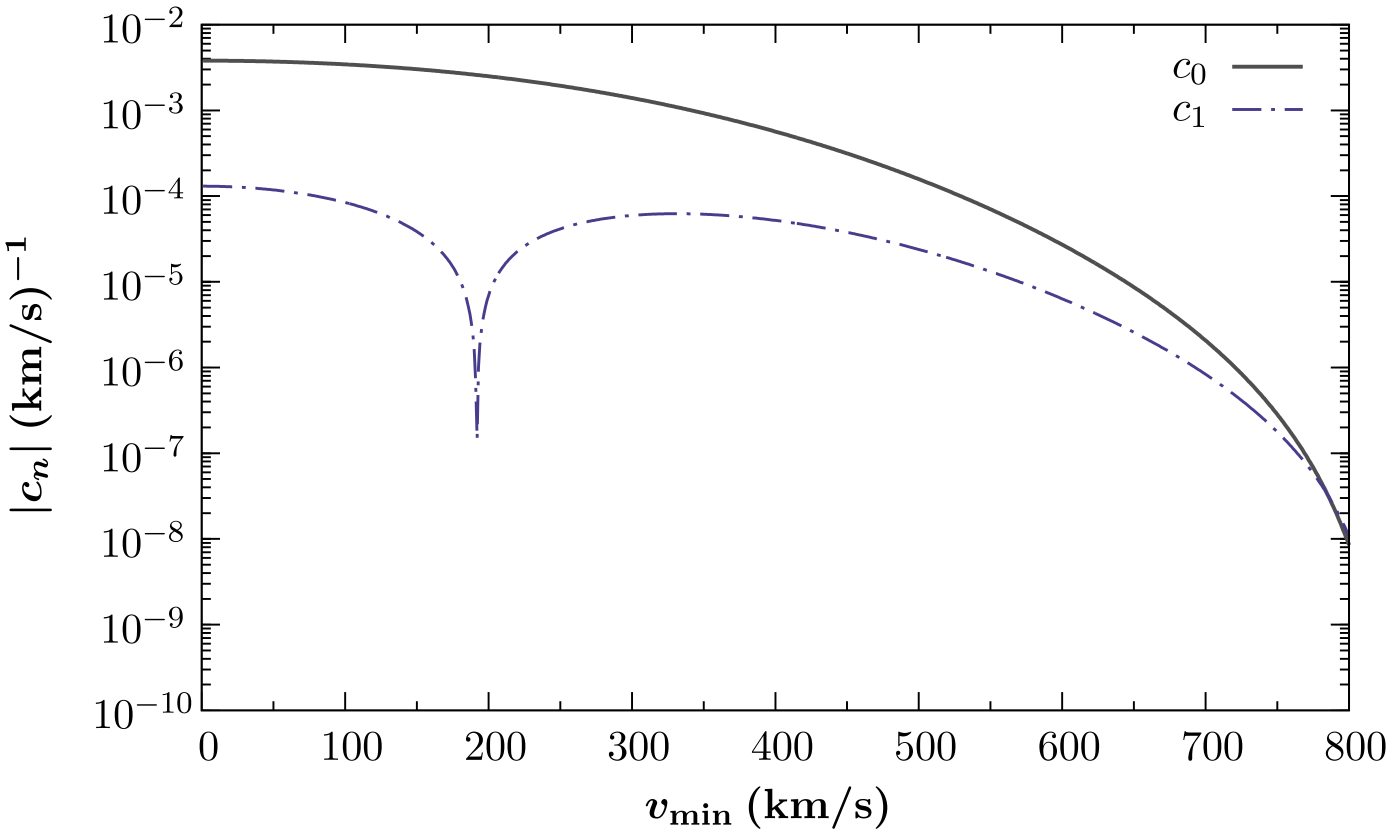

no correlation
with high significance!

=> CoGeNT's
modulation
not muon-induced

# higher harmonics in DM modulation

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

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



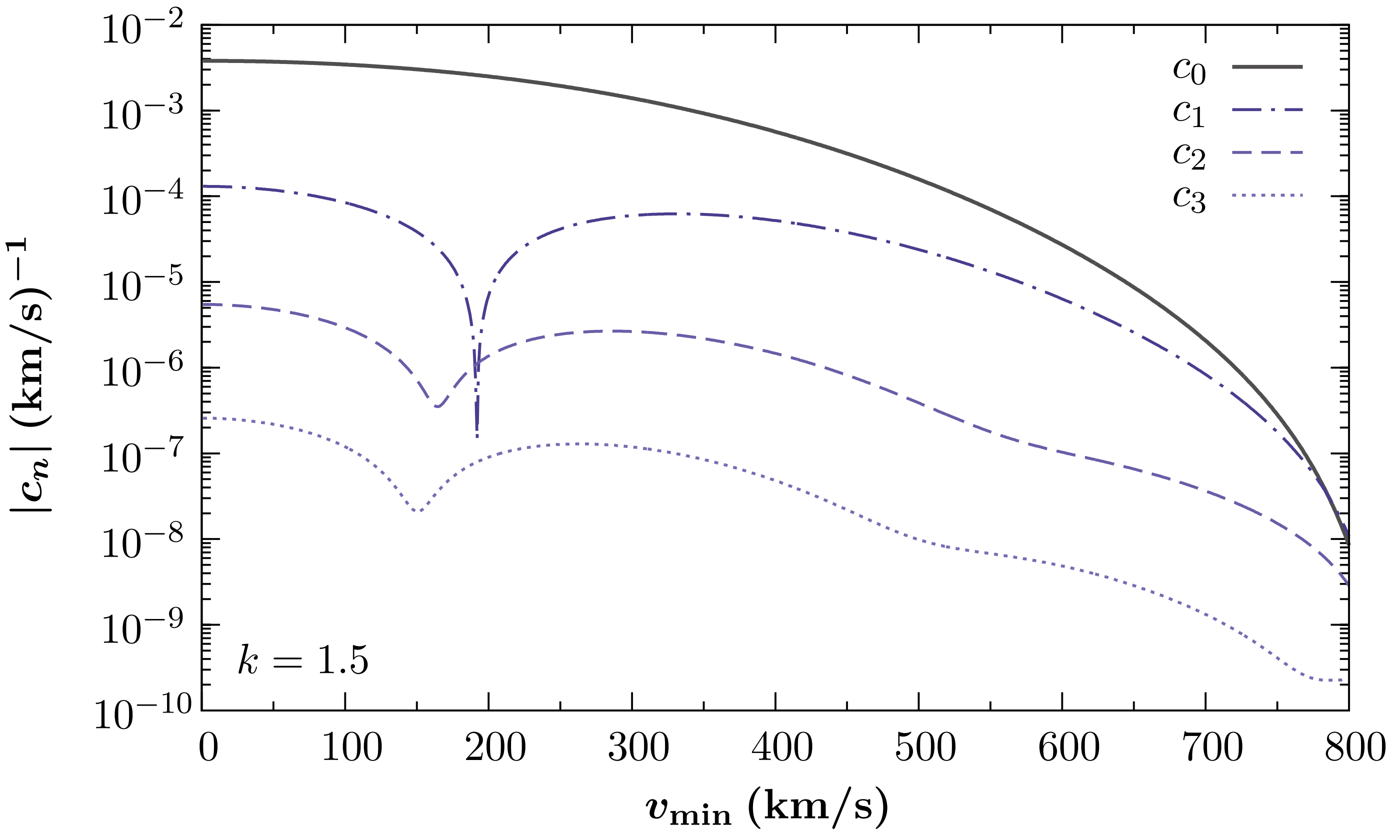

[using f(v) from Lisanti et al, 2010]

# 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
- ...



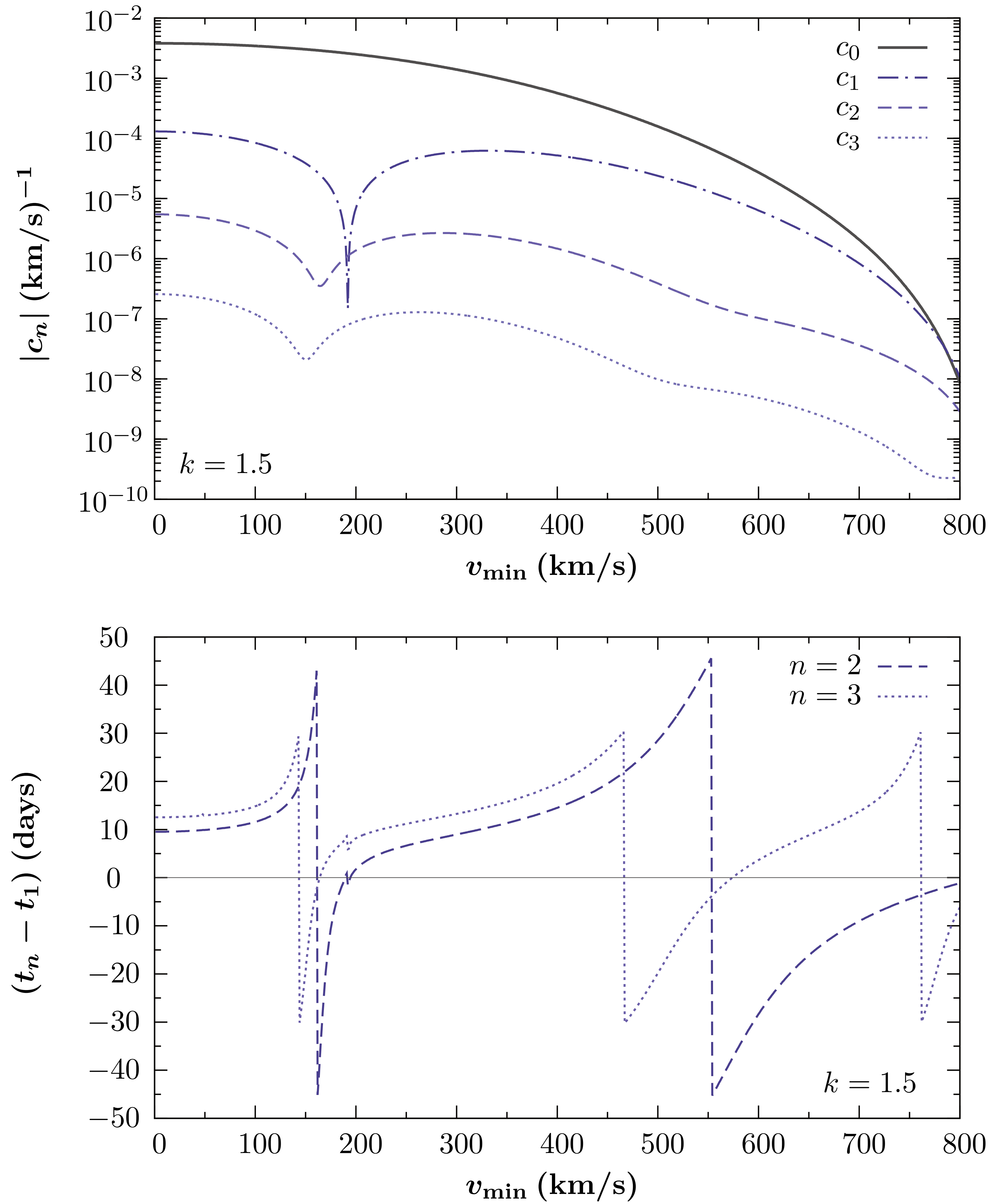

[using f(v) from Lisanti et al, 2010]

# 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



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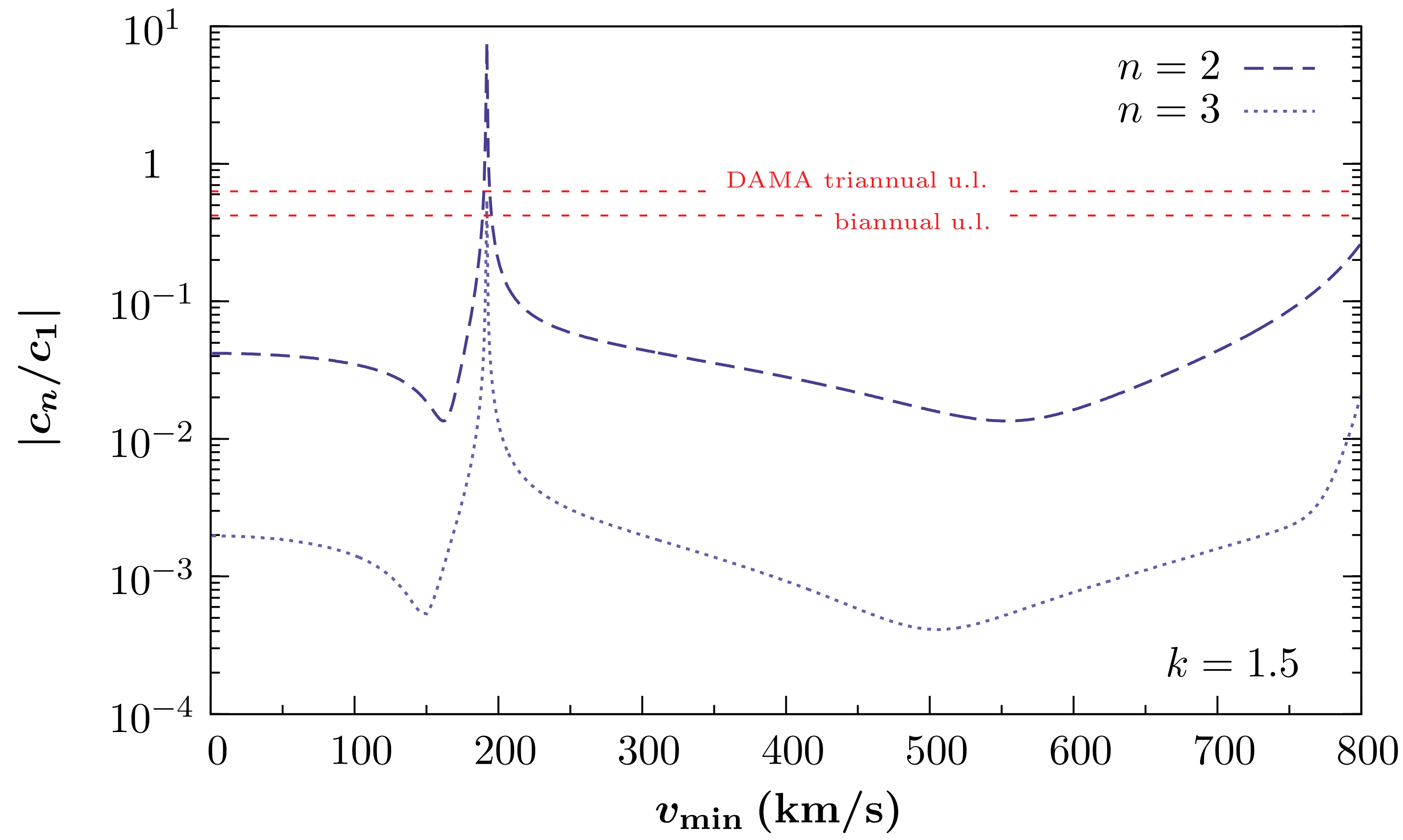


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  => phase shifts between different harmonics

  => new signature
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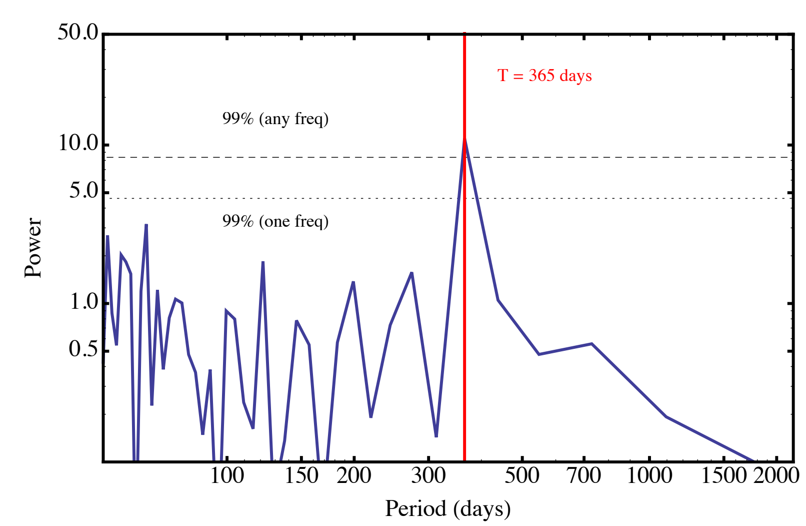
DAMA/LIBRA:

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



# conclusions

- 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

- higher harmonics in the modulation signal may provide additional handles in discriminating signal from background