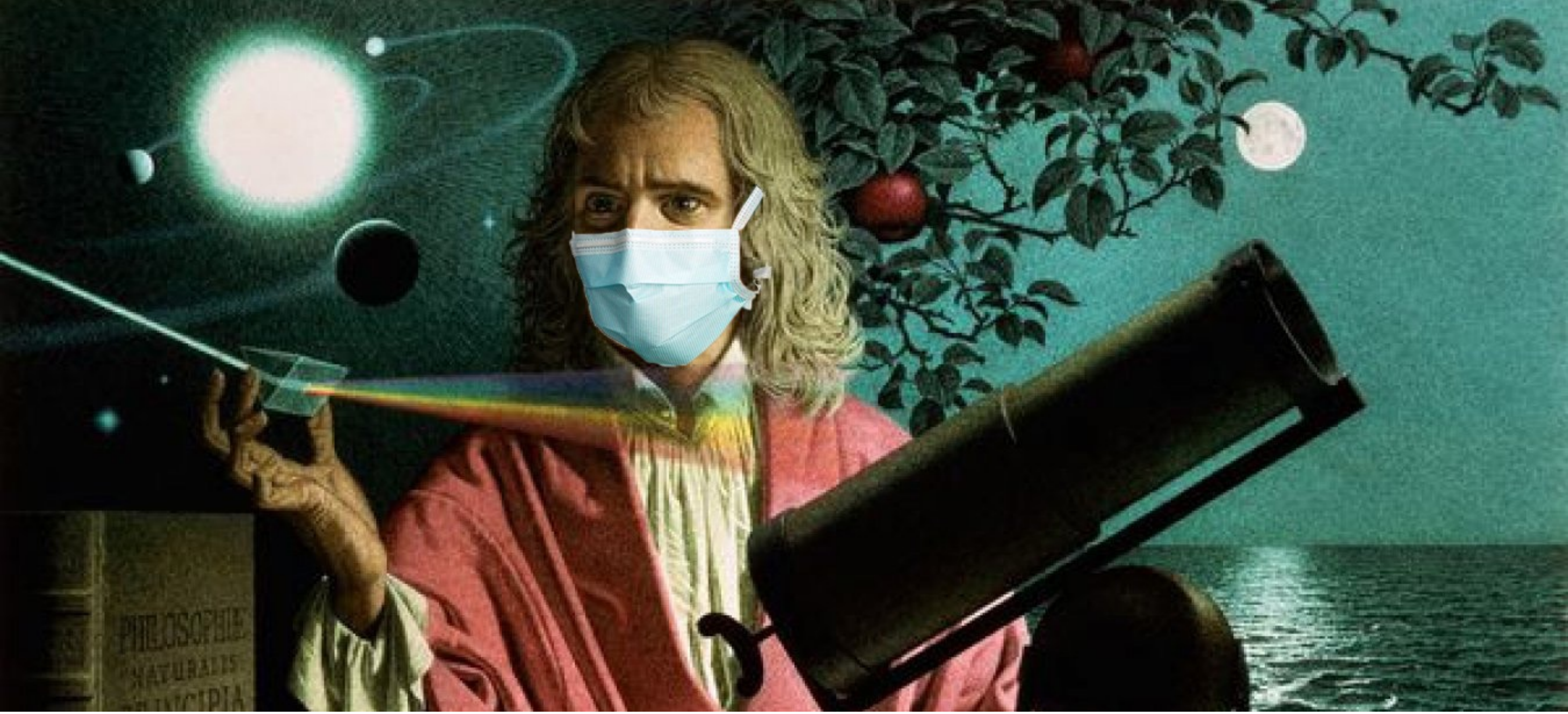


Annual modulations from secular variations: Relaxing DAMA?

Dario Buttazzo

based on 2002.00459 with P. Panci, N. Rossi, A. Strumia

INFN
Istituto Nazionale di Fisica Nucleare

“Newton 1665” on-line seminar — 27.03.2020

Disclaimer

Warning

The content of this talk is based on arXiv:2002:00459

The assumptions in arXiv:2002.00459 are **untenable** and the conclusions are **valueless**.

(P. Belli, talk at CNNP2020)

By connecting to this meeting you declare to be aware of the content that is going to be presented, and implicitly accept any potential consequence of this action at your own risk.

Status of Dark Matter experiments

The year is 2020 AD.

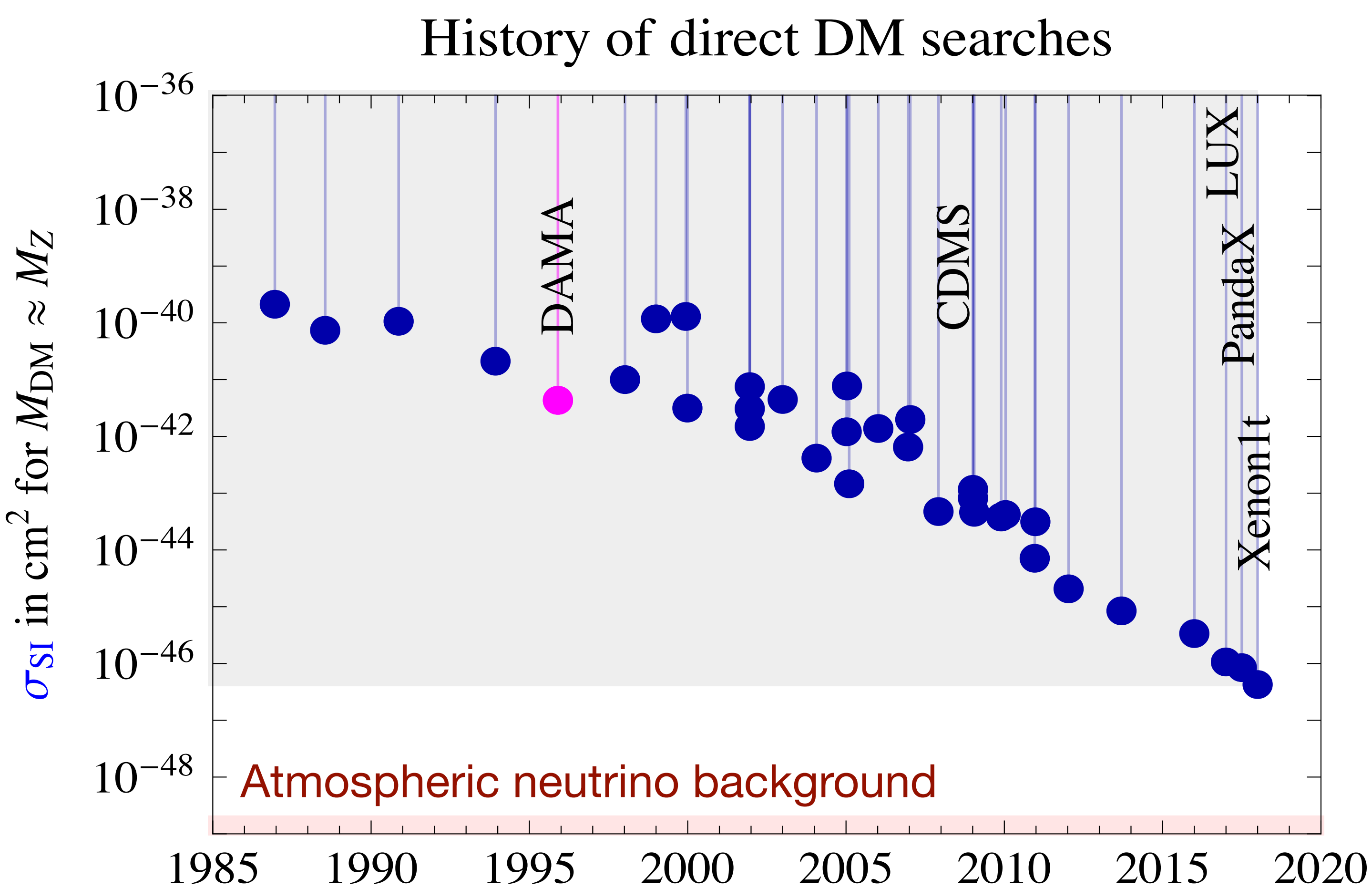
WIMP Dark Matter is entirely ruled out by Direct Detection experiments.

Entirely? Well, not quite entirely…

One small indomitable Dark Matter experiment still holds out against the invaders.

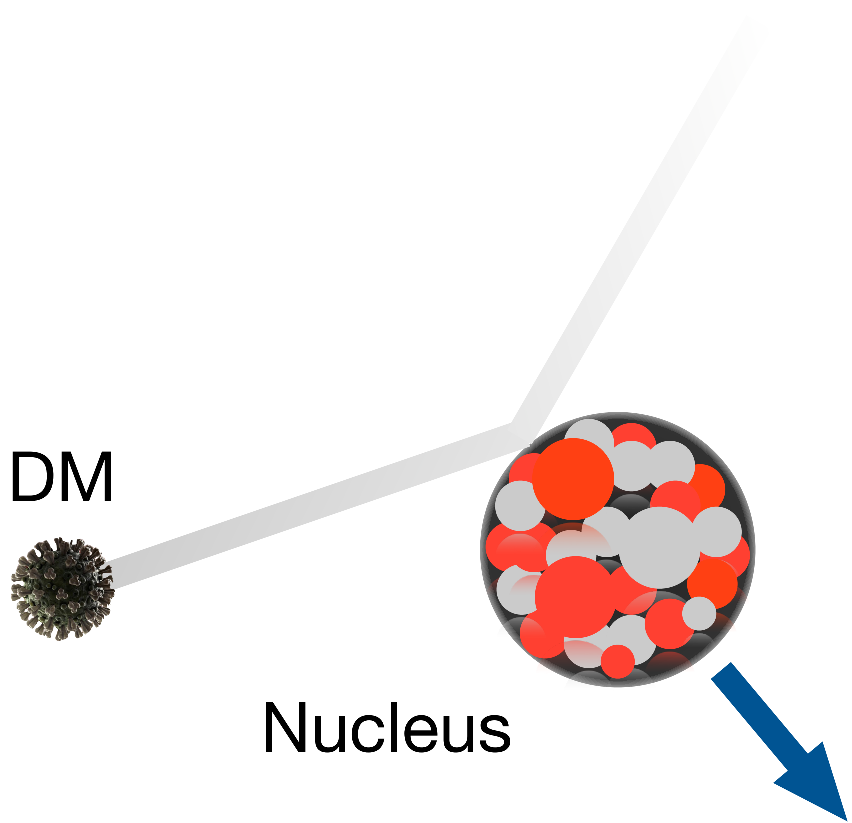
And life is not easy for the theorists who garrison the fortified camps nearby…

Dark Matter direct detection



- ✦ DM scatterings are very rare events
- ✦ Not easy to fully understand backgrounds at low recoil energy
- ➡ most experiments aim at reducing backgrounds as much as possible

No evidence for DM found until now



Rate for contact interactions:

DM velocity distribution

$$\frac{dR}{dE_{\rm rec}} = ({\rm mass}) \times \frac{\sigma_0 F(q)^2}{2\mu^2 m_{\rm DM}} \rho_{\rm DM} \int_{v_{\rm min}}^{v_{\rm esc}} d^3v \, \frac{f(\mathbf{v},t)}{v}$$

$$v_{\rm min} = \sqrt{M_{\rm nucl} E_{\rm rec}/2\mu^2}$$

for elastic scattering

Dark Matter direct detection: annual modulation

DM velocity distribution in Earth's rest frame:

$$f_{\oplus}(\mathbf{v}, t) = f_{\rm MW}(\mathbf{v} + \mathbf{v}_{\odot} + \mathbf{v}_{\oplus}(t)), \qquad f_{\rm MW}(\mathbf{v}) \approx \exp\left(-v^2/v_0^2\right)\Theta(v_{\rm esc} - v)$$

Component along galactic plane: $v_{\oplus}(t) = v_{\odot} + v_{\rm orb}\cos\gamma\cos\left[2\pi(t - t_0)/{\rm yr}\right]$

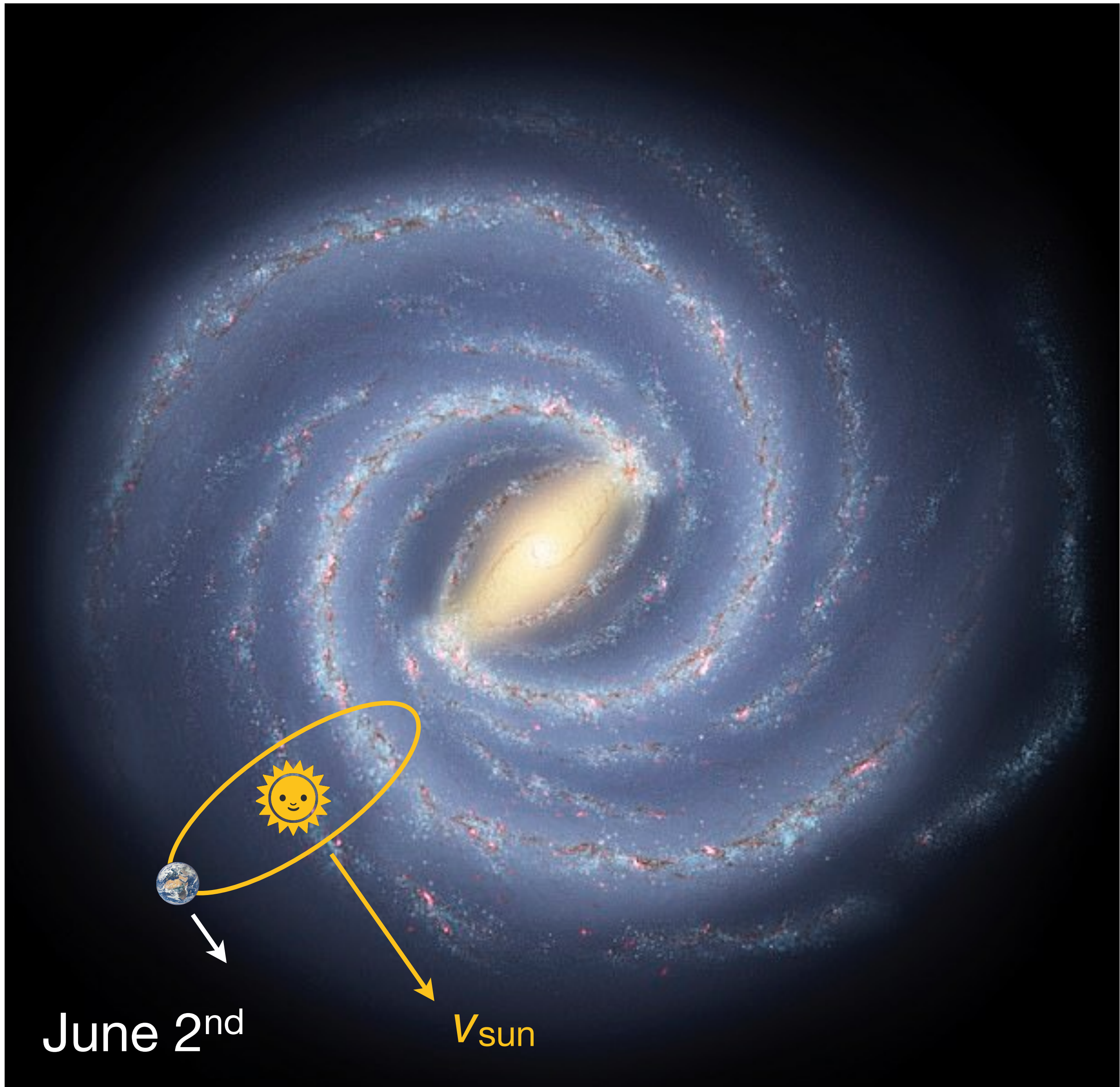
$$\cos\gamma \approx 0.49, \qquad t_0 \approx \text{June, } 2^{\rm nd}$$

$$\text{Rate} \propto \int_{v_{\rm min}}^{v_{\rm esc}} d^3v \frac{f(\mathbf{v}, t)}{v}$$

is modulated, with a maximum around June, 2nd

$$v_{\odot} \approx 220\,{\rm km/s}, \quad v_{\rm orb} \approx 30\,{\rm km/s} \quad \Rightarrow \quad \Delta v/v \approx 5\%$$

A small effect! Looking for the modulation is hard.



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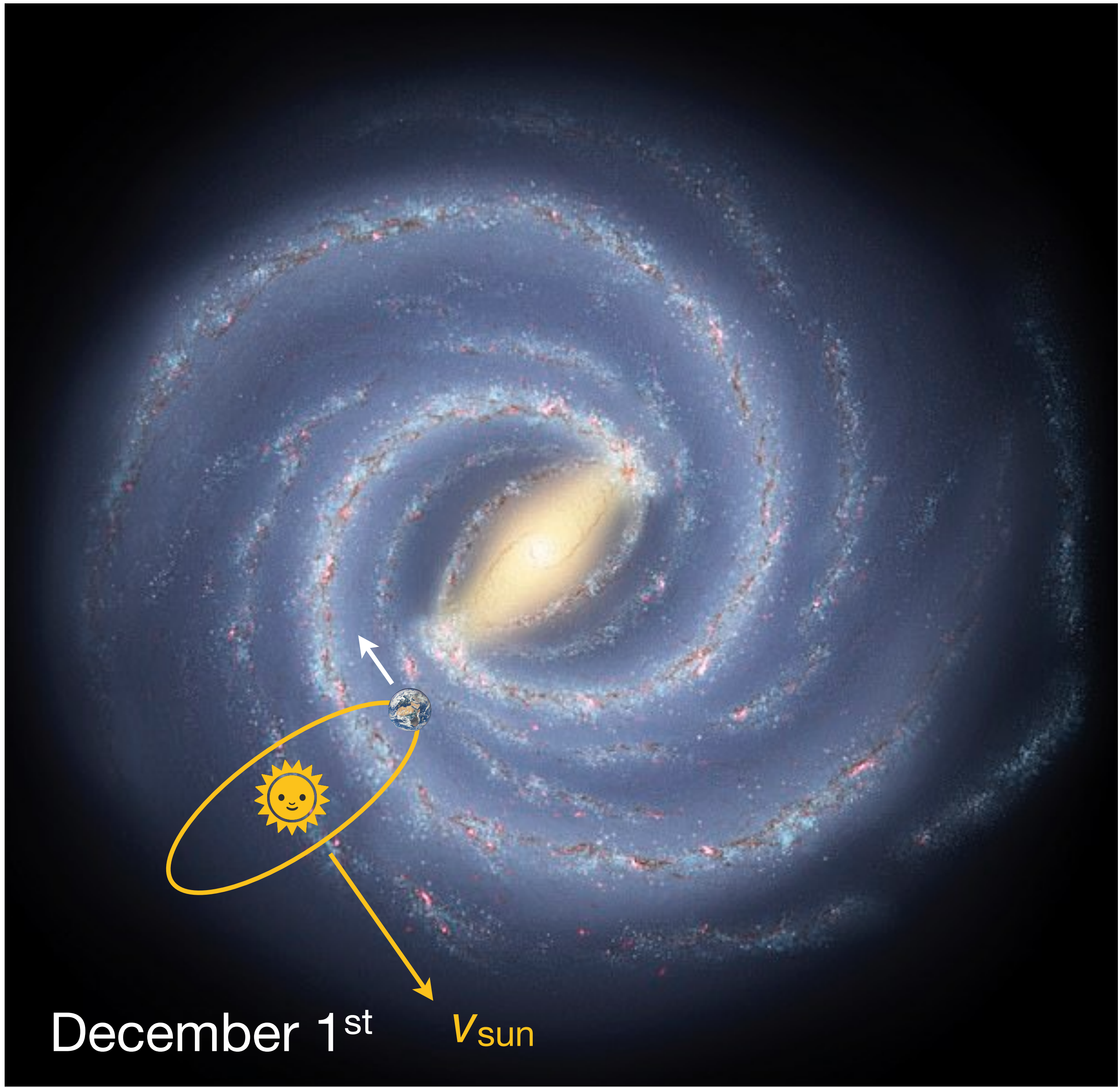
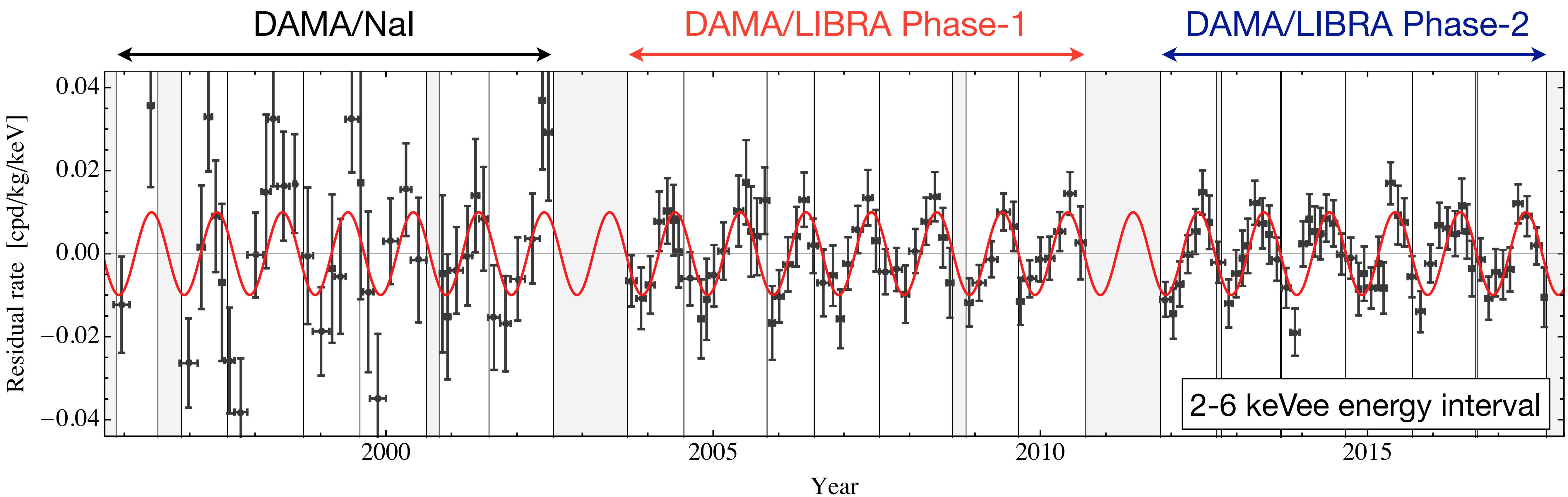


The DAMA results

DAMA observes a modulation in single-hit scintillation events in NaI crystals



- ➡ Most recent results from 2018: 12.9 σ evidence for modulation

  Amplitude = (0.0103 ± 0.0008) c.p.d./kg/keVee

  Period = (0.9987 ± 0.0008) years

  Phase = May 26th ± 5 days

DAMA collaboration, ЯДЕРНА ФІЗИКА ТА ЕНЕРГЕТИКА **19** (2018) 4.

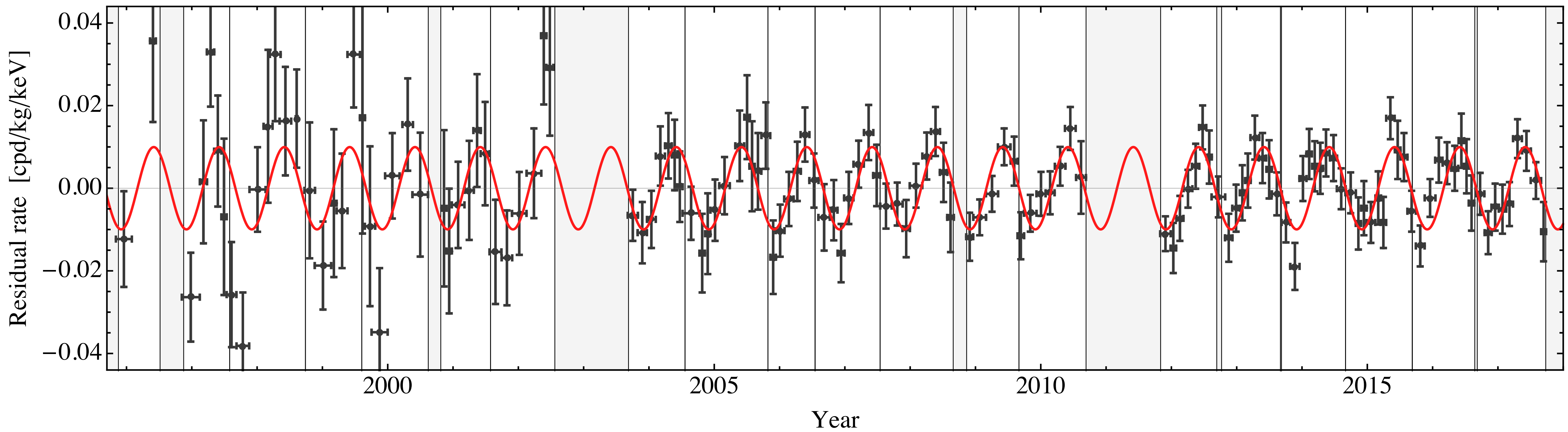
Motivations

- Many experiments rule out simple DM interpretations of the DAMA signal
  - ➡ However, as long as no convincing explanation is found, the DAMA result remains an open issue
  - ➡ DM physics might be more complex and reconcile the results (unlikely…)
- Several explanations in terms of oscillating backgrounds have been proposed

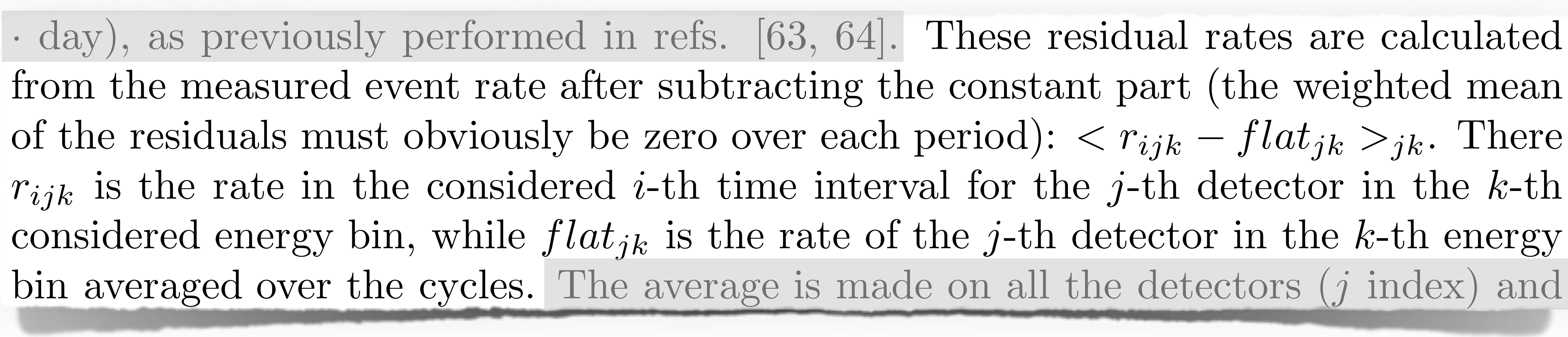
  0912.2983, 1006.5255, 1101.5205, 1102.0815, …
  - ➡ Amplitude, time-dependence, and event distribution in the detector array are difficult to explain with modulated backgrounds, see e.g. 0804.2741
  - ➡ Peak of the modulation close to June 2nd is a strong argument in favor of the DM interpretation.
- Experimentalists have been killing models since decades. I was hoping to take my revenge trying to kill an experiment… 🙃

The DAMA residuals

- DAMA never published the event rate as a function of time



- Only the residuals were published, after subtracting the yearly average:



· day), as previously performed in refs. [63, 64]. These residual rates are calculated from the measured event rate after subtracting the constant part (the weighted mean of the residuals must obviously be zero over each period): $< r_{ijk} - flat_{jk} >_{jk}$. There r_{ijk} is the rate in the considered i-th time interval for the j-th detector in the k-th considered energy bin, while $flat_{jk}$ is the rate of the j-th detector in the k-th energy bin averaged over the cycles. The average is made on all the detectors (j index) and

1805.10486 and other DAMA papers

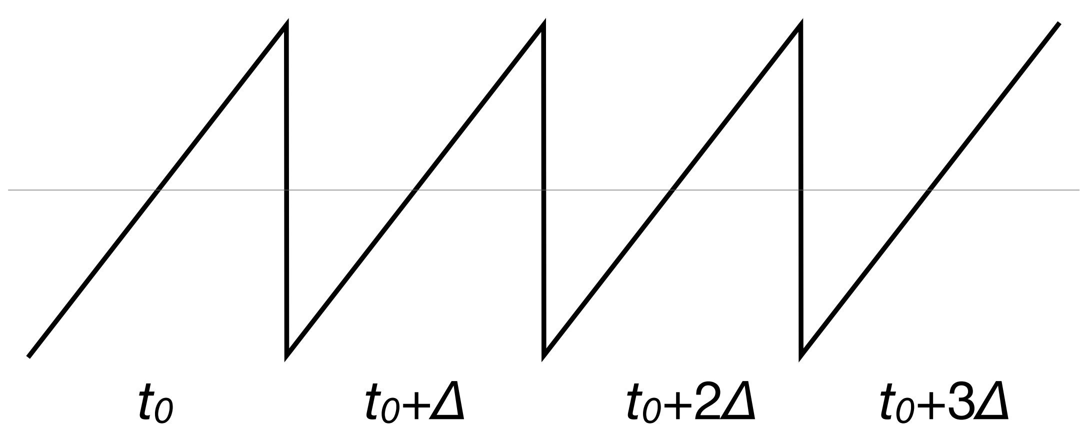
NB: residuals are very useful at low statistics, when one needs to combine data from different cycles to get a significant signal!

Annual modulation vs secular variation

Signal on top of a background rate $R(t) = R_0(t) + \mathcal{A}\cos\left(\frac{2\pi t}{T} - \phi\right)$

- If $R_0 = C$ is constant, $\mathcal{A}\cos\left(\frac{2\pi}{T}t - \phi\right) = R(t) - \mathcal{C} = R(t) - \langle R(t)\rangle$
  the "DAMA method" correctly subtracts the background

- If R_0 is not constant, a bias is introduced.
  Consider $R_0(t) = C + B\,t$: the residuals in each interval Δ are $B(t - t_0)$



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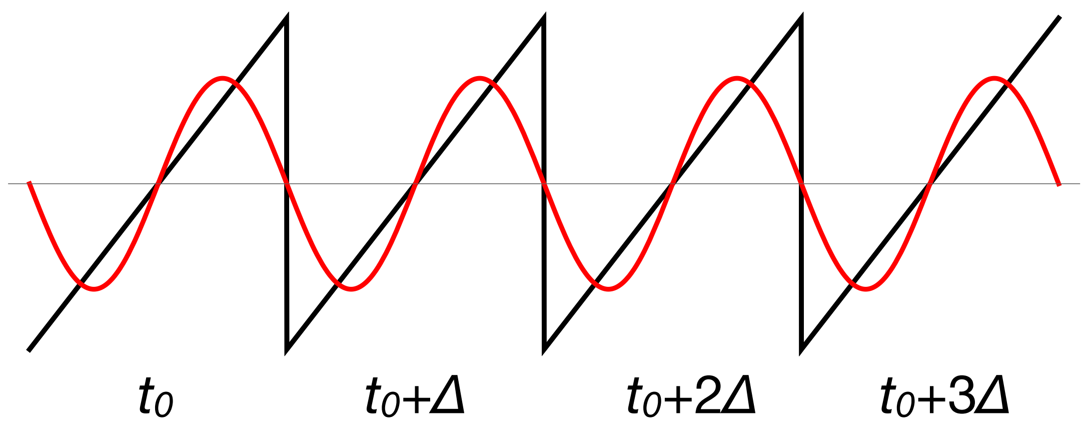
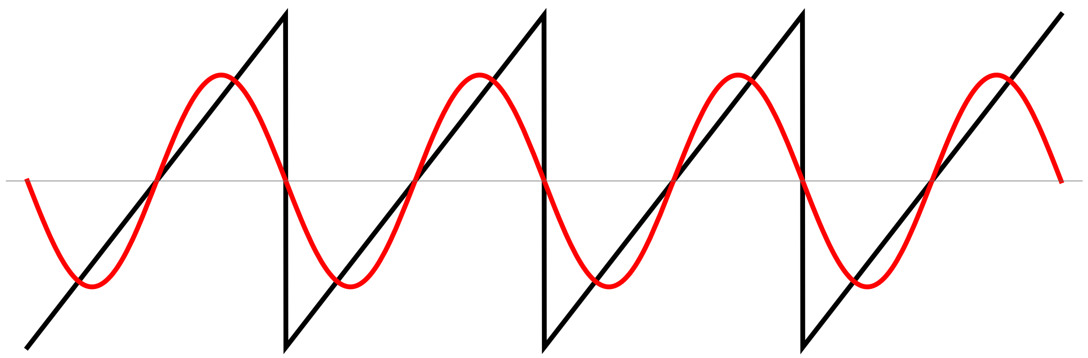


With experimental errors, it can be fitted with a sinusoid

Annual modulation vs secular variation

Fitting a function with a sinusoid is equivalent to taking its Fourier series:



$$\mathcal{B}(t-t_0) = \frac{\mathcal{B}\Delta}{\pi}\sin\left(\frac{2\pi}{\Delta}(t-t_0)\right)$$

+ higher modes

- A linearly varying rate $R_0(t) = C + B\,t$ gives an apparent modulation with

$$T = \Delta, \qquad \mathcal{A} = \frac{\mathcal{B}\Delta}{\pi}, \qquad \phi = \frac{\pi}{2} + \frac{2\pi t_0}{\Delta}.$$

The minimum (if B > 0) or maximum (if B < 0) is a quarter of a period after the start of the cycle (3 months).

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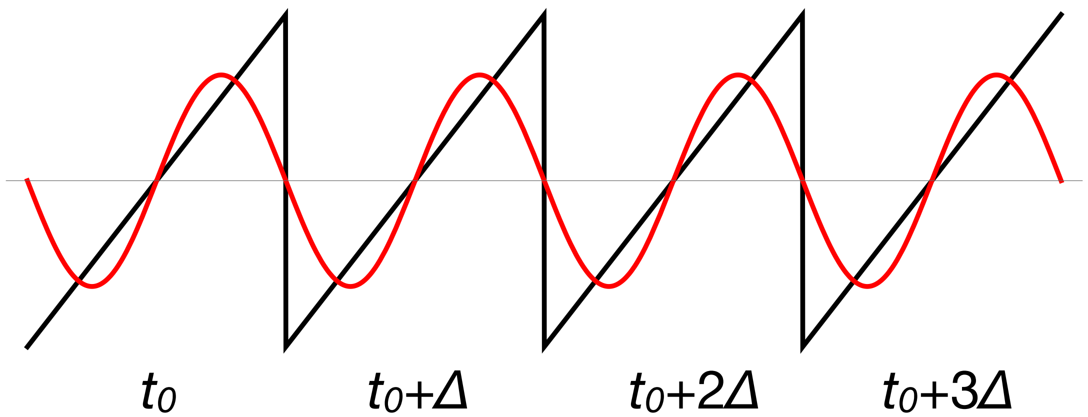

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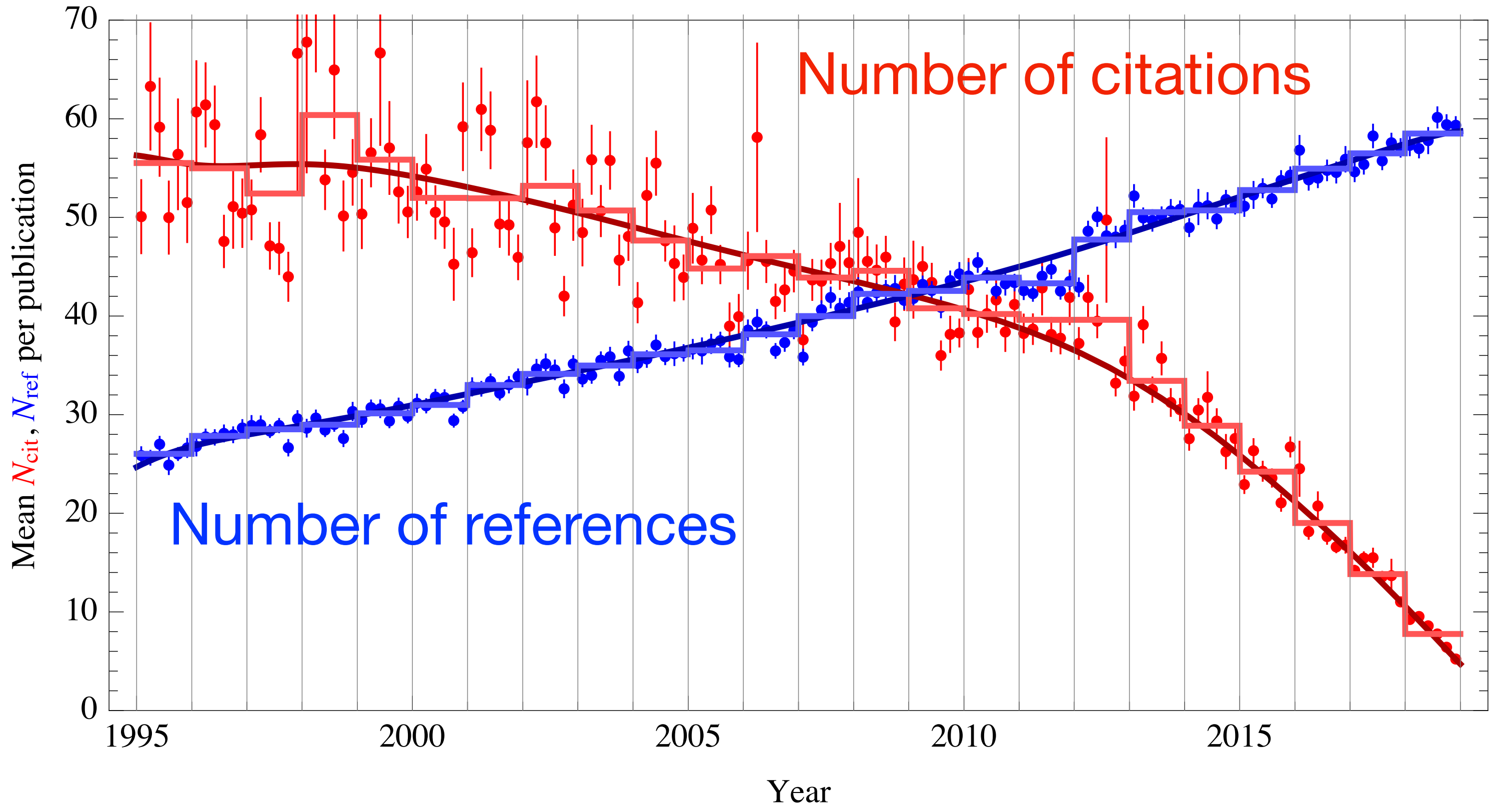
The minimum (if B > 0) or maximum (if B < 0) is a quarter of a period after the start of the cycle (3 months).

- If a true modulation is present, the extraction of the signal is biased

$$\mathcal{A}^2_{\rm fit} = \mathcal{A}^2 + \frac{\mathcal{B}^2 T^2}{\pi^2} + 2\frac{\mathcal{A}\mathcal{B}T}{\pi}\sin\left(\phi - \frac{2\pi t_0}{T}\right), \quad \tan\phi_{\rm fit} = \frac{\mathcal{A}\sin\phi + (\mathcal{B}T/\pi)\cos(2\pi t_0/T)}{\mathcal{A}\cos\phi - (\mathcal{B}T/\pi)\sin(2\pi t_0/T)}.$$

(An example without Dark Matter)

Consider the papers published in HEP after 1995 (from inspirehep.net)

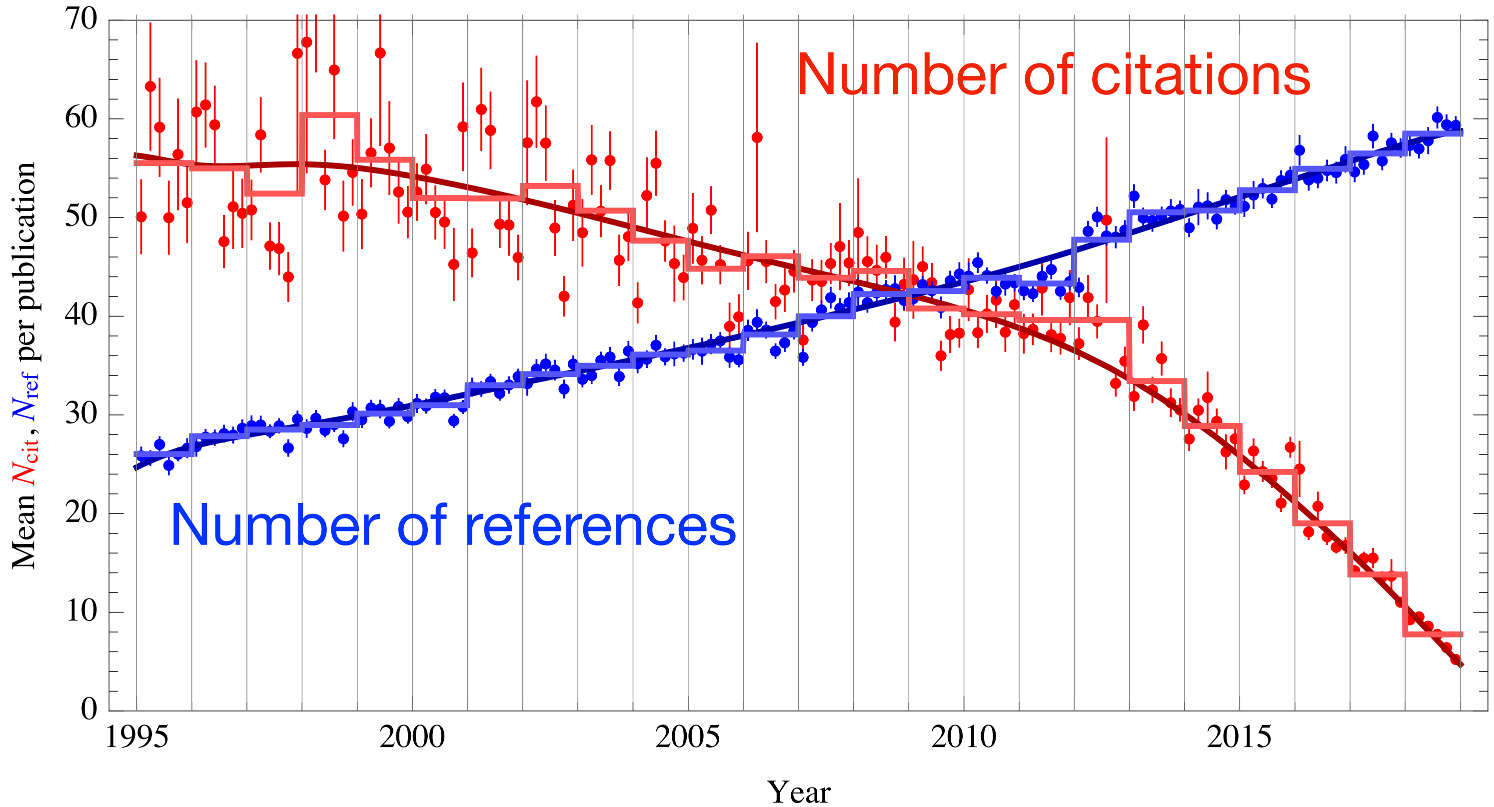


- References increase with time because the field expands.
- Citations decrease with time because more recent papers have not yet been cited.

Do you see a modulation?

(An example without Dark Matter)

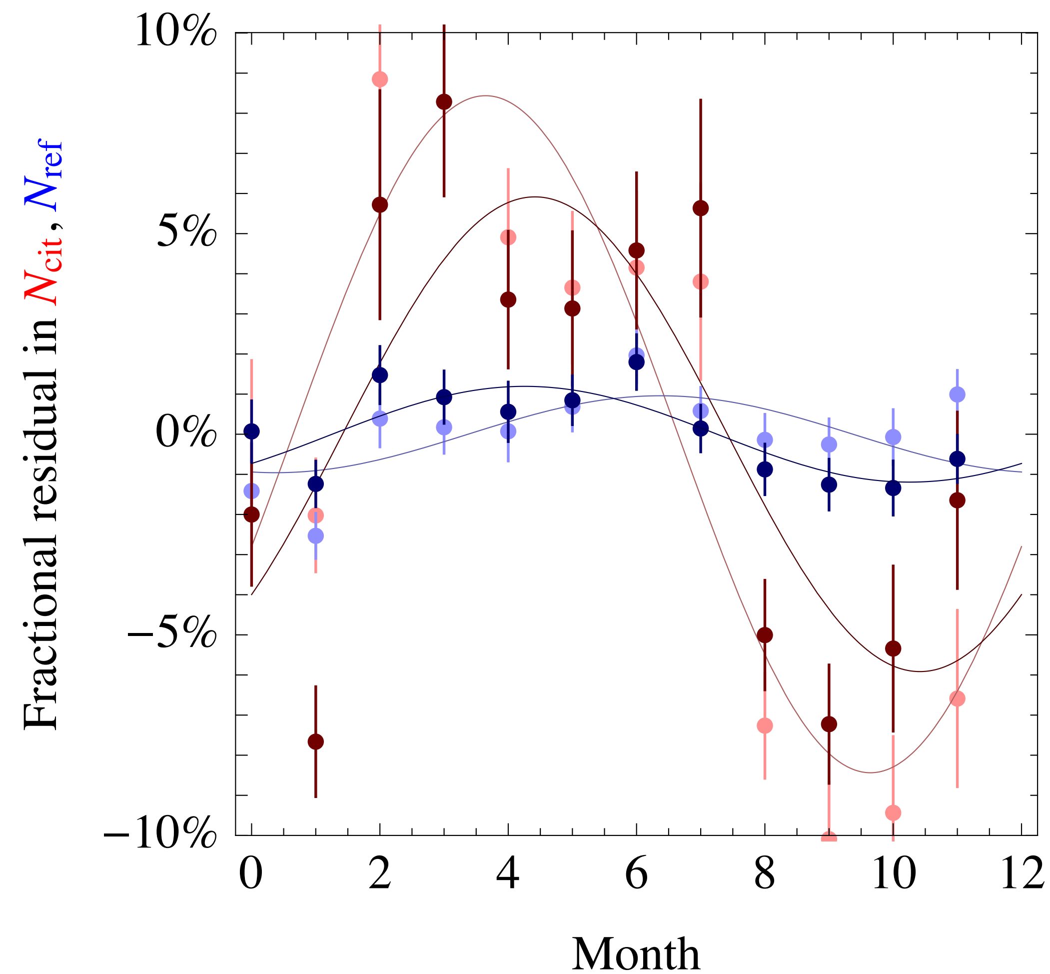
Consider the papers published in HEP after 1995 (from inspirehep.net)



- References increase with time because the field expands.
- Citations decrease with time because more recent papers have not yet been cited.

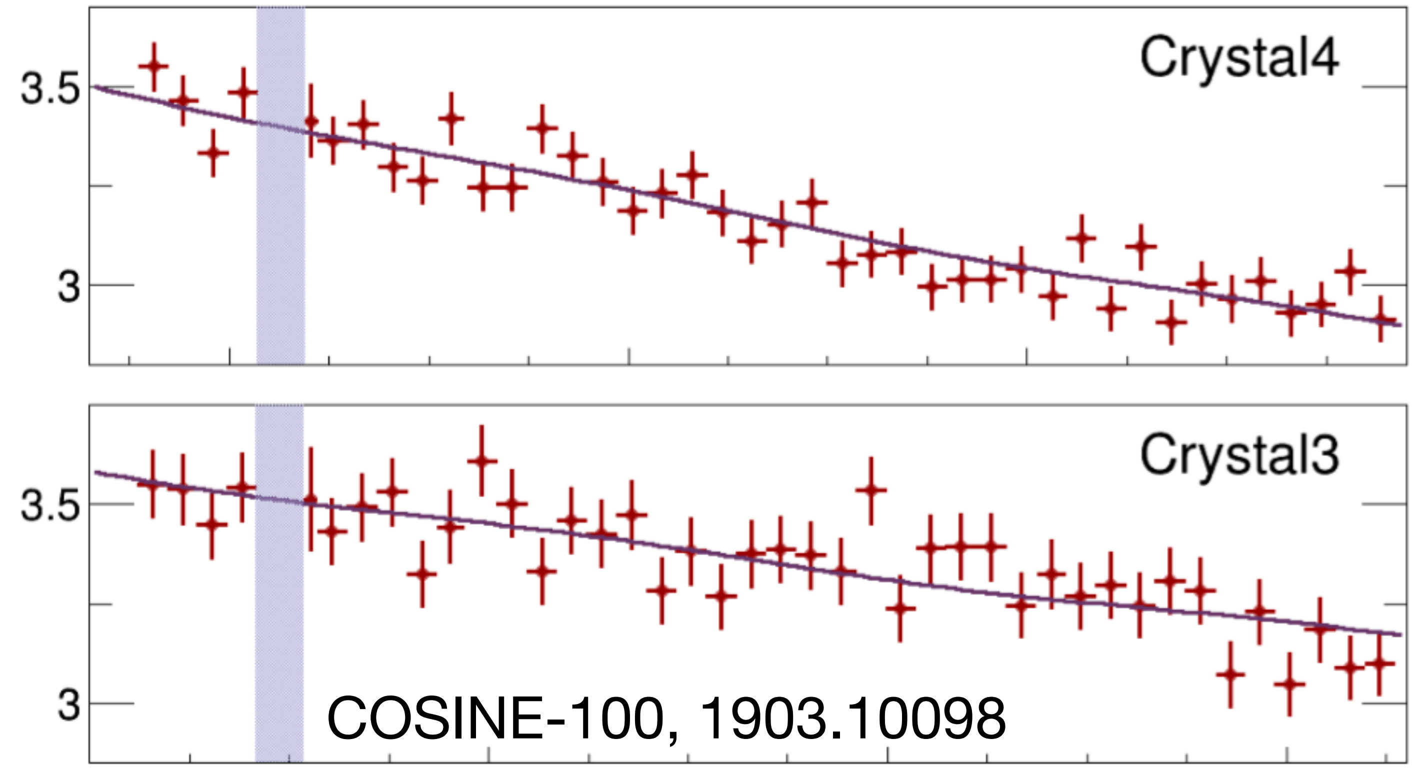
Need to compute residuals and combine the events from different years

- Lighter colors: subtracting yearly averages the amplitude and phase get biased
- Darker colors: subtracting a smooth function one gets the correct result: both quantities peak in spring

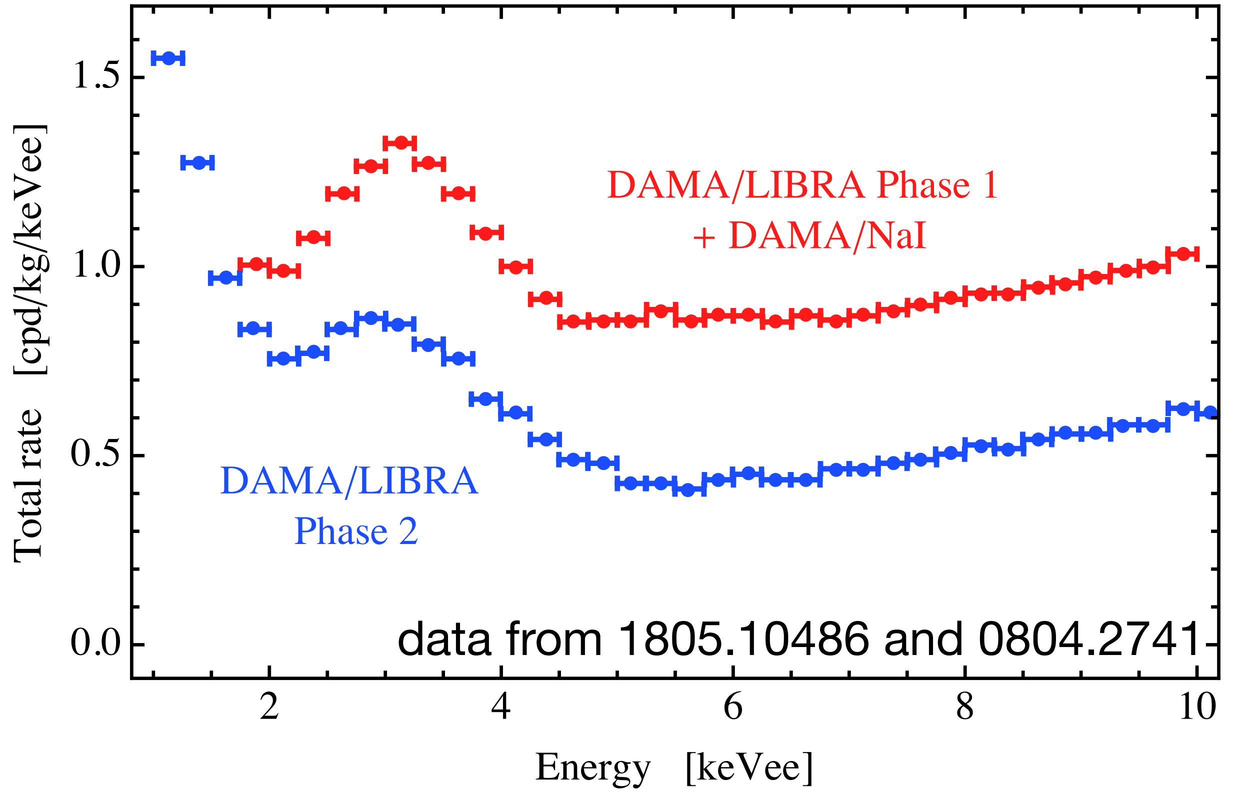


What about Dark Matter…?

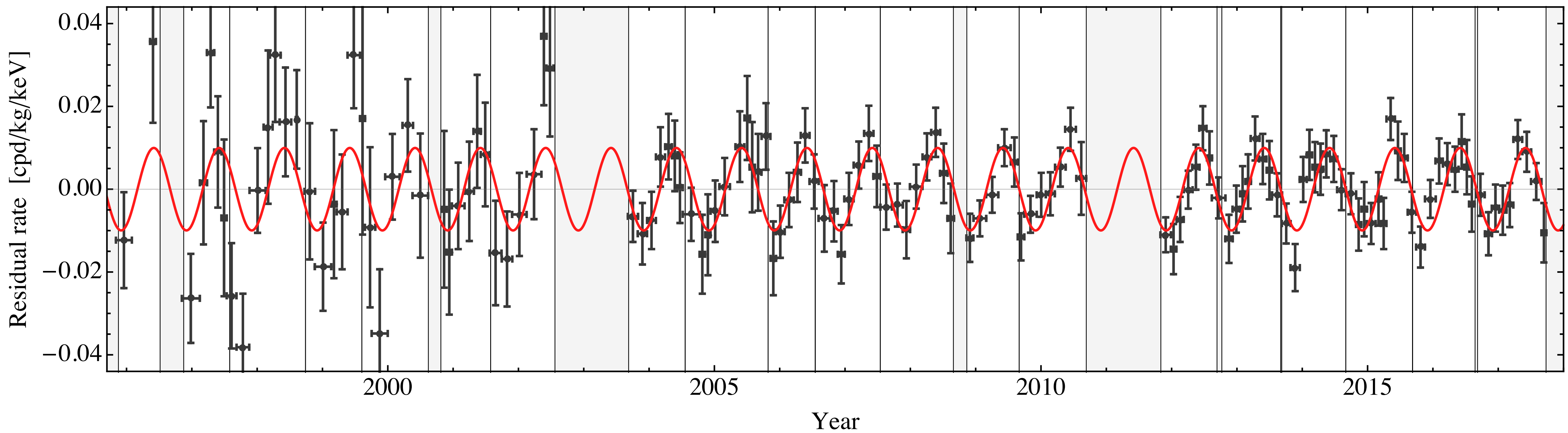
- COSINE-100 and ANAIS: two experiments aiming at a verification of the DAMA signal (also based on NaI crystals). *They publish their total rates: they vary with time*



- DAMA has published the total rate, averaged over the entire data-taking periods, at two different points in time: *it changes…*



The DAMA cycles



All the DAMA cycles last about one year, and start around September:

Sept. - 3 months
= June

1805.10486

DAMA/LIBRA–phase2 annual cycle	Period	Mass (kg)	Exposure (kg×day)
1	Dec. 23, 2010 – Sept. 9, 2011	commissioning of phase2	
2	Nov. 2, 2011 – Sept. 11, 2012	242.5	62917
3	Oct. 8, 2012 – Sept. 2, 2013	242.5	60586
4	Sept. 8, 2013 – Sept. 1, 2014	242.5	73792
5	Sept. 1, 2014 – Sept. 9, 2015	242.5	71180
6	Sept. 10, 2015 – Aug. 24, 2016	242.5	67527
7	Sept. 7, 2016 – Sept. 25, 2017	242.5	75135

A rate that grows by a few percent each year, will generate an apparent modulation with period of 1 year and peaked at the beginning of June!

Monte Carlo simulation

We perform a simulation with a setup similar to the DAMA/LIBRA detector.

- Events simulated for each day following a Poisson distribution with mean

$$N(t) = \text{efficiency} \times \text{mass} \times \Delta E \times R_0(t), \qquad R_0(t) = \mathcal{C} + \mathcal{B}t$$

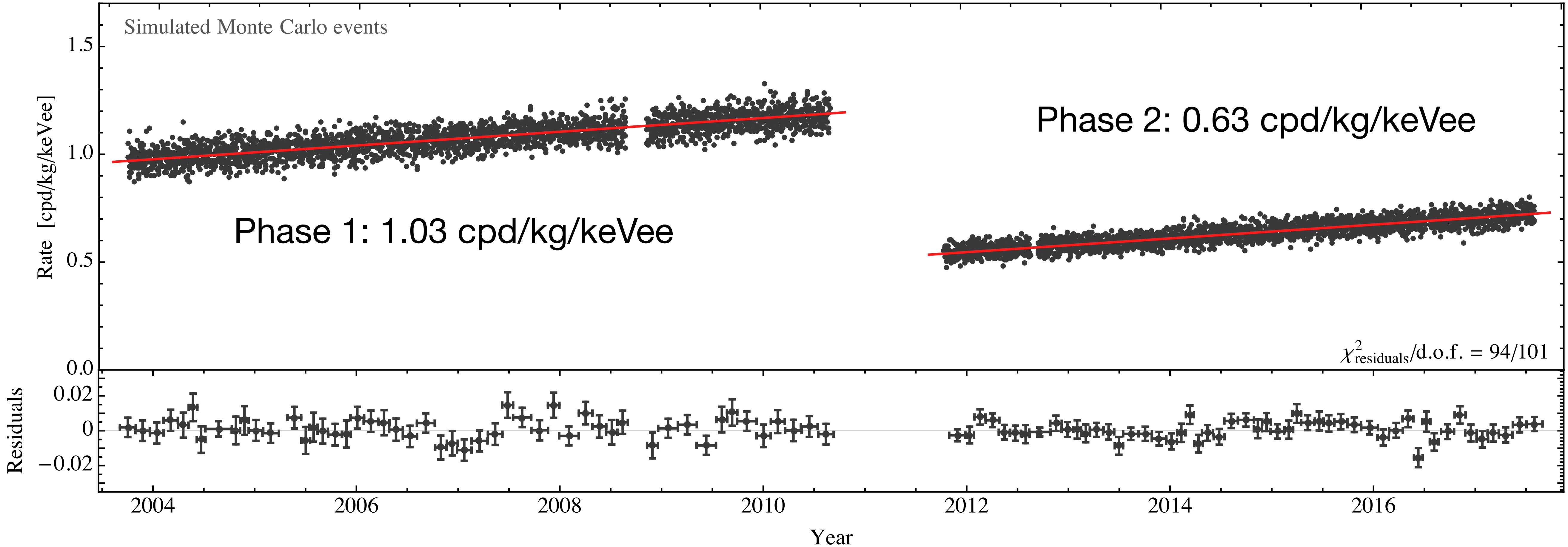
efficiency → 60% - 80%

mass → 242.5 kg of NaI

ΔE → 2-6 keV

$\mathcal{B} = 0.01 \cdot \pi \ \text{cpd/kg/keVee/yr}$

$\mathscr{C}$ fixed by average rate



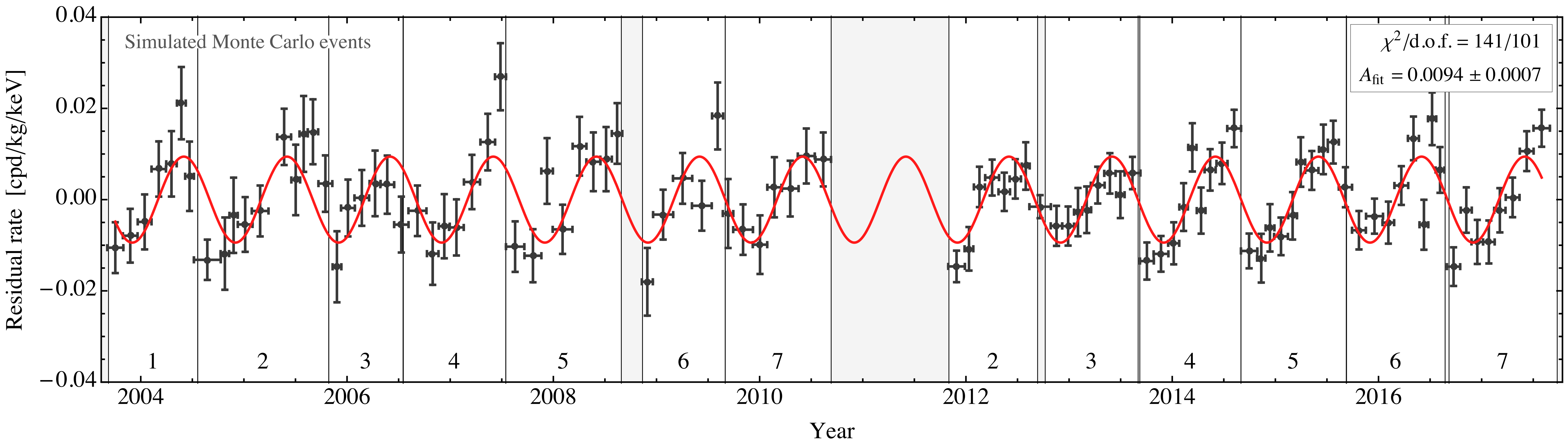
Monte Carlo simulation

- Consider the same cycles as DAMA (which do not last exactly one year)
- Calculate the residuals subtracting the averages over each cycle *k*: the events follow an irregular sawtooth

$$\mathcal{S}(t) = \zeta M \Delta E\, S_0(t) \qquad \text{with} \qquad S_0(t) = \mathcal{B}\left(t - \frac{t_{i,k} + t_{f,k}}{2}\right) \qquad \text{for } t_{i,k} < t < t_{f,k}\,,$$

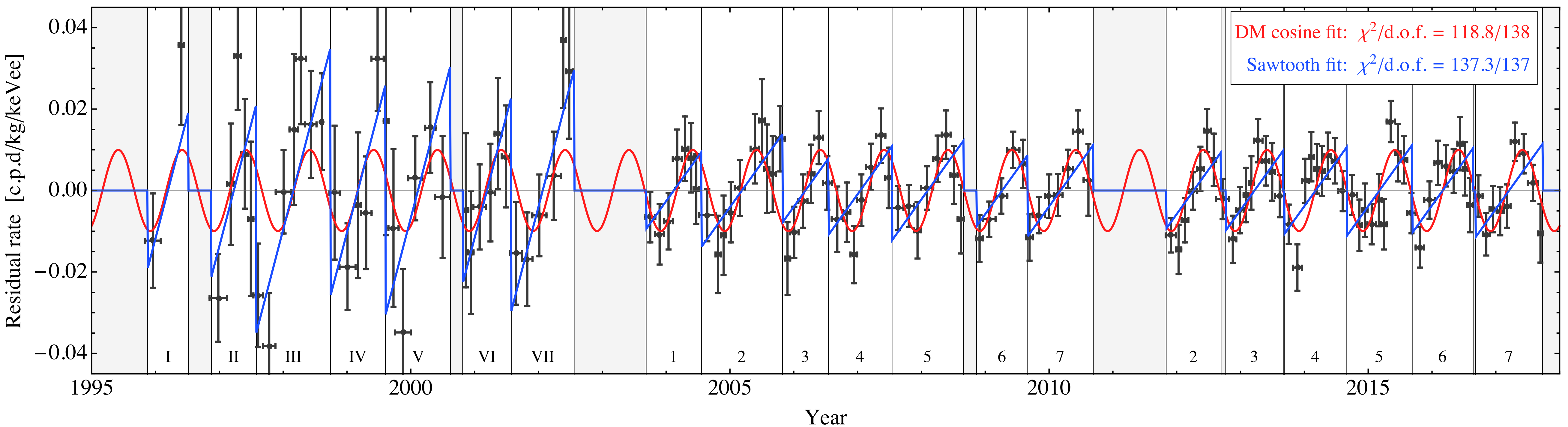
- Fitting the residuals with a cosine of period T = 1 yr, peaked on June 2nd:

$\mathcal{A} = (0.0094 \pm 0.0007)\,\text{cpd/kg/keVee}$ 12.7 σ evidence for non-zero modulation



The DAMA data

- Time dependence of the total rate is not public ☹
  we can only look at the residuals:



- Fit to irregular sawtooth following the DAMA cycles: $\chi^2/\mathrm{dof} = 137/137$

$$\mathcal{B}_{\mathrm{NaI}} = (0.060 \pm 0.009)\,\mathrm{cpd/kg/keVee/yr}\,,$$
$$\mathcal{B}_{\mathrm{LIBRA}} = (0.022 \pm 0.003)\,\mathrm{cpd/kg/keVee/yr}\,,$$

Modulation could be due by a yearly few percent growth of the rate.

- A cosine (over-)fits better, especially for the more recent Phase-2 data.

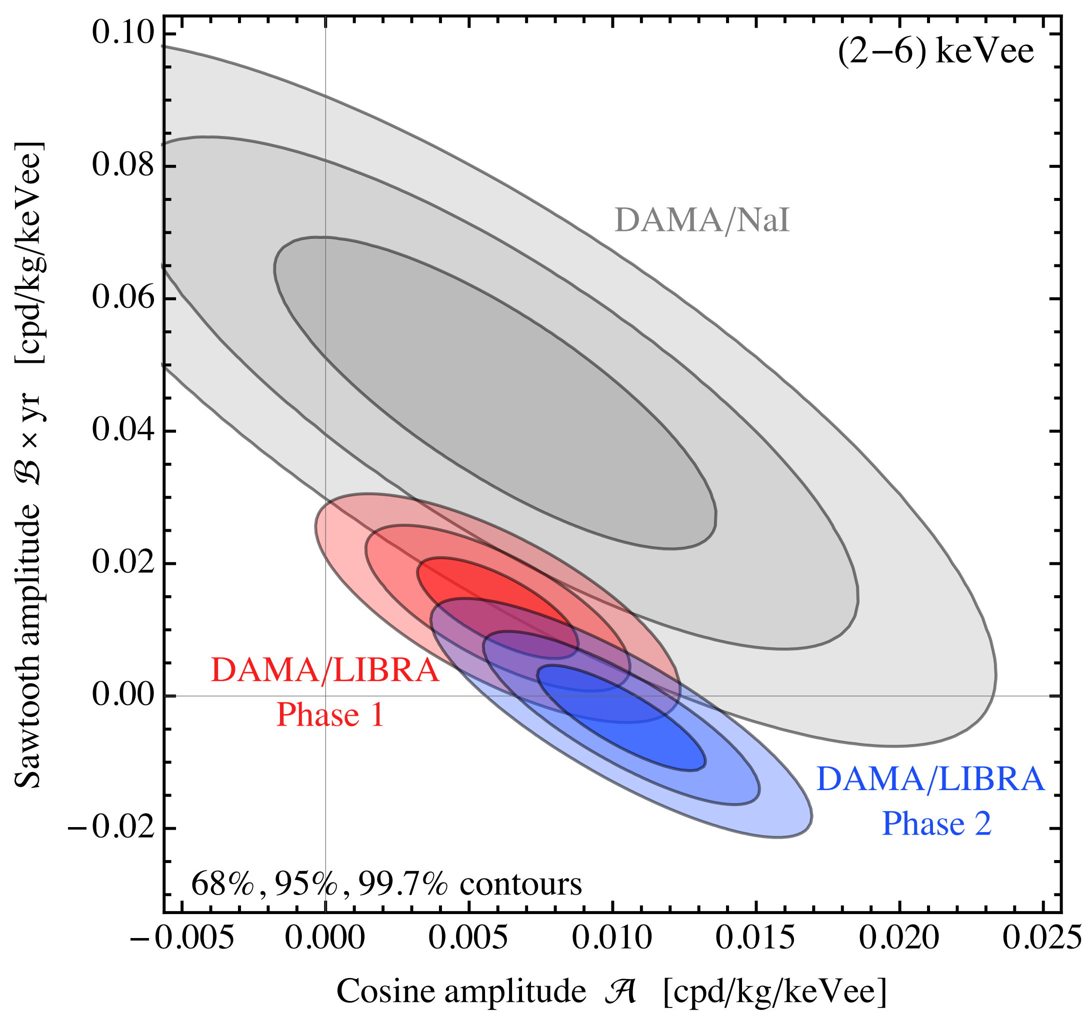
The DAMA data

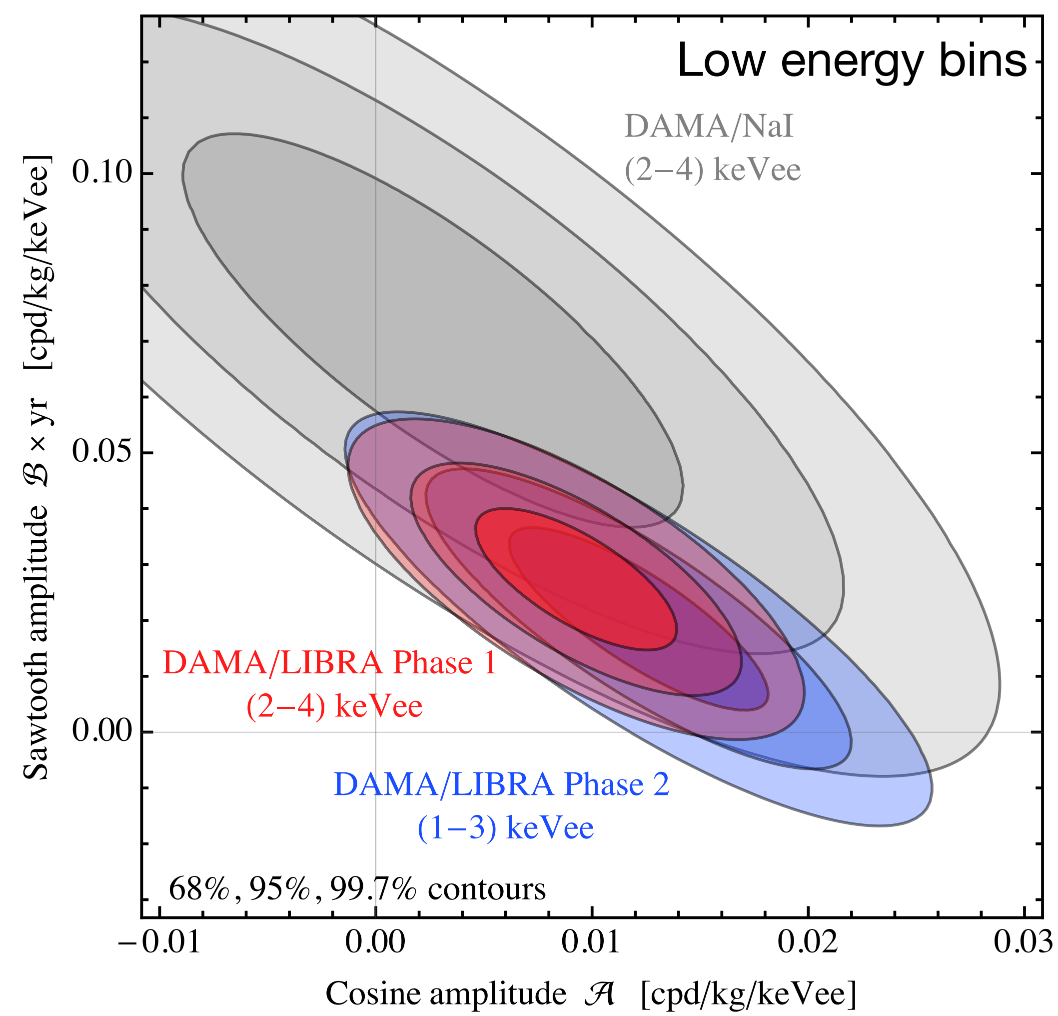
We performed fits for all energy bins available in the various phases

Fitted data	Fit to a cosine modulation		Fit to a secular variation	
	$\mathcal{A}$ [cpd/kg/keVee]	$\chi^2_{\rm cos}$/d.o.f.	$\mathcal{B}$ [cpd/kg/keVee/yr]	$\chi^2_{\rm saw}$/d.o.f.
DAMA/NaI				
(2-4) keVee	0.0214 ± 0.0046	36.3/36	0.0783 ± 0.0141	26.9/36
(2-5) keVee	0.0200 ± 0.0037	24.1/36	0.0605 ± 0.0113	24.7/36
(2-6) keVee	0.0178 ± 0.0031	36.9/36	0.0602 ± 0.0094	29.6/36
LIBRA Phase I				
(2-4) keVee	0.0164 ± 0.0022	53.5/49	0.0452 ± 0.0059	51.9/49
(2-5) keVee	0.0120 ± 0.0016	42.8/49	0.0302 ± 0.0044	50.5/49
(2-6) keVee	0.0095 ± 0.0013	30.0/49	0.0249 ± 0.0035	33.6/49
LIBRA Phase II				
(1-3) keVee	0.0182 ± 0.0023	61.2/51	0.0475 ± 0.0062	67.1/51
(1-6) keVee	0.0103 ± 0.0011	52.0/51	0.0230 ± 0.0029	83.7/51
(2-6) keVee	0.0093 ± 0.0011	44.8/51	0.0197 ± 0.0030	72.9/51
LIBRA I and II				
(2-6) keVee	0.0094 ± 0.0008	74.8/101	0.0219 ± 0.0026	107.7/101
DAMA combined				
(2-6) keVee	0.0100 ± 0.0008	118.8/138	0.0240 ± 0.0022	152.9/138

The DAMA data: sawtooth vs cosine

- Both models fit the data reasonably well. To discriminate between them we perform a likelihood-ratio test, $\mathscr{L}/\mathscr{L}_0 = \exp(-\Delta\chi^2/2)$ see also 2003.03340





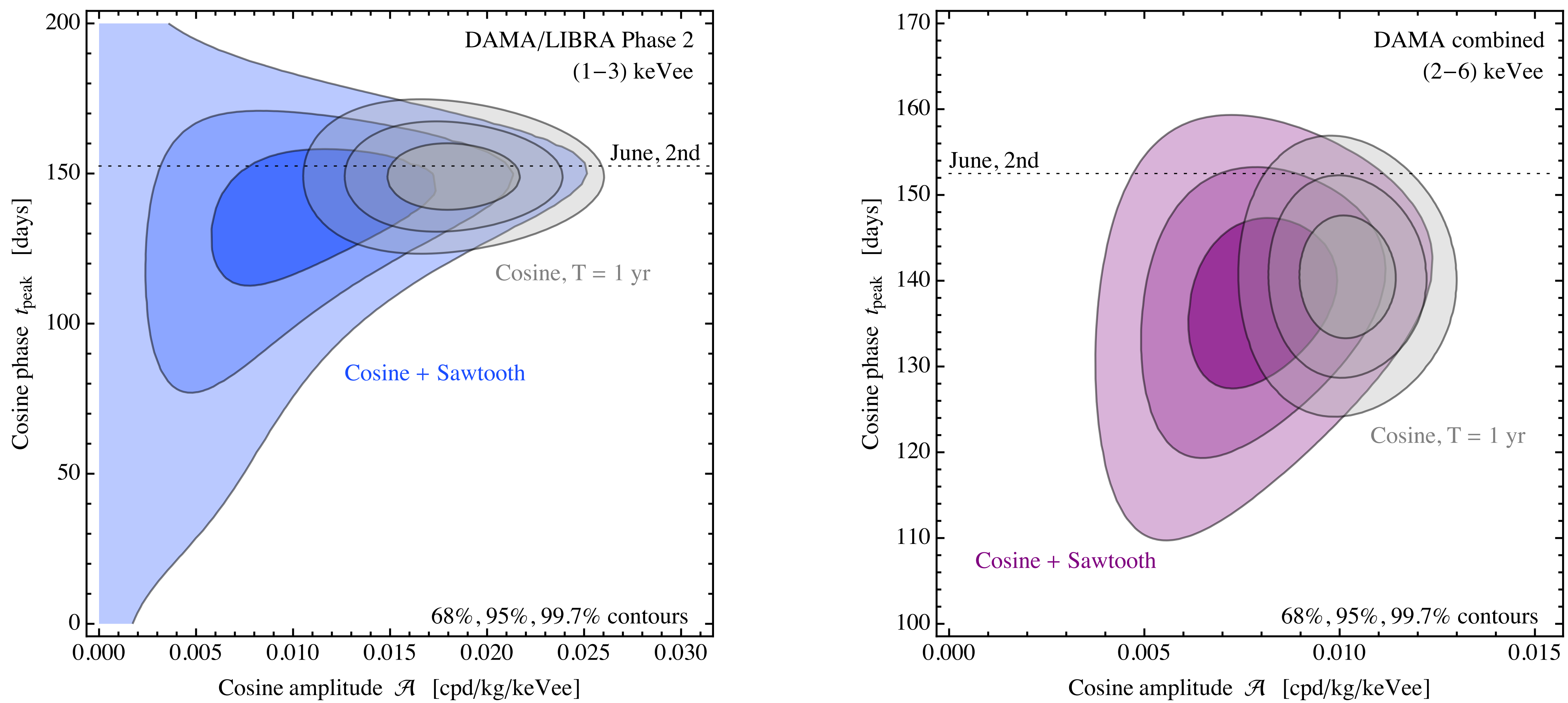
- In general, the sawtooth is allowed in the low energy bins where the signal is larger, and for Phase-1 & NaI.
- A cosine is favored by more recent Phase-2 data in the 2-6 keV bin.

Impact on the signal

- In presence of both a signal + a time-varying background, the signal extraction is biased:

$$\mathcal{A}_{\rm fit}^2 = \mathcal{A}^2 + \frac{\mathcal{B}^2 T^2}{\pi^2} + 2\frac{\mathcal{A}\mathcal{B}T}{\pi}\sin\left(\phi - \frac{2\pi t_0}{T}\right), \quad \tan\phi_{\rm fit} = \frac{\mathcal{A}\sin\phi + (\mathcal{B}T/\pi)\cos(2\pi t_0/T)}{\mathcal{A}\cos\phi - (\mathcal{B}T/\pi)\sin(2\pi t_0/T)}.$$

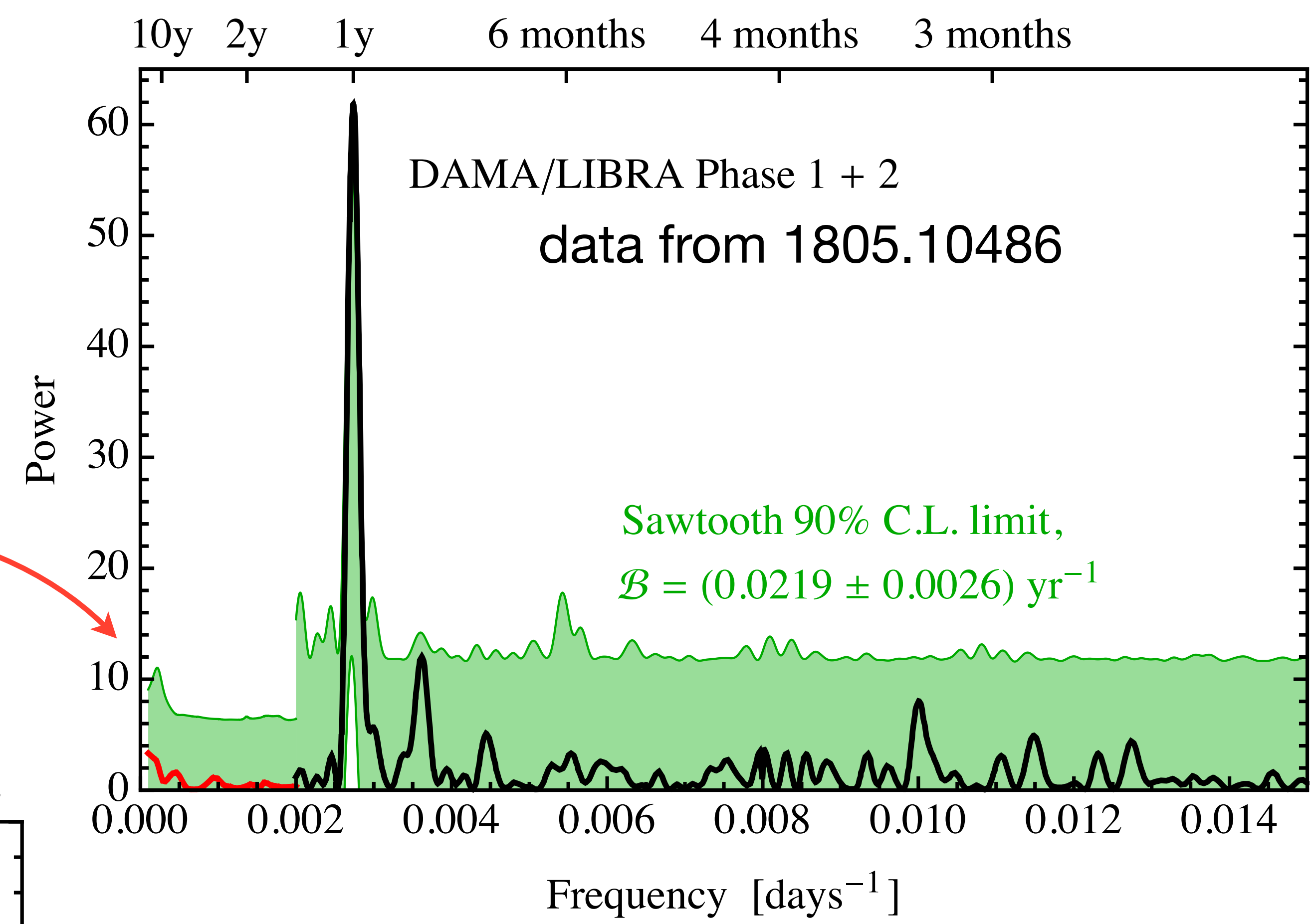
- In particular, the phase gets shifted, and can deviate more from June 2nd

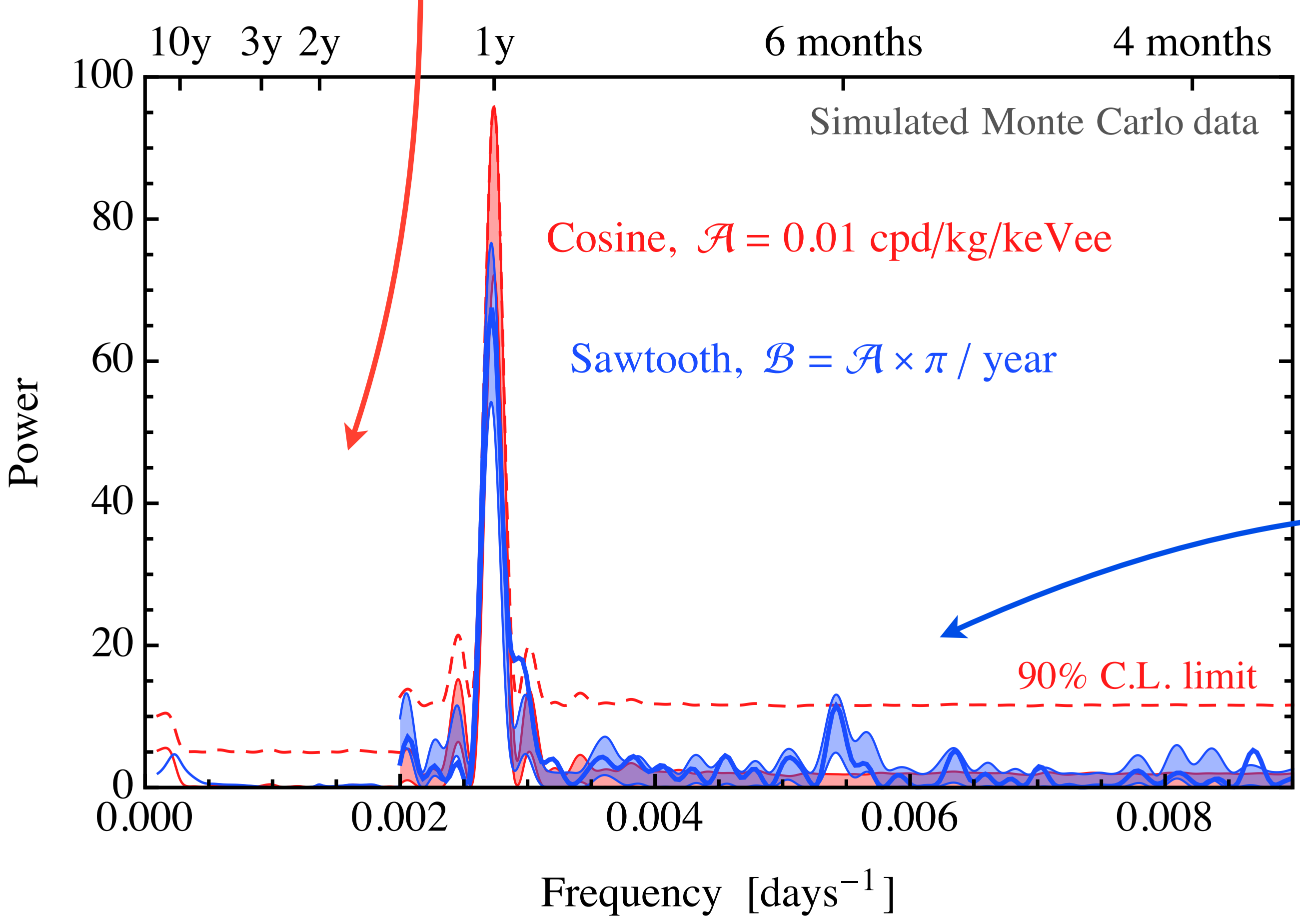


Frequency analysis

A spectral analysis of the residual rate has also been provided

- Power spectrum consistent with sawtooth or cosine
- No significant peak at low frequencies (1 year bins, only few data points)



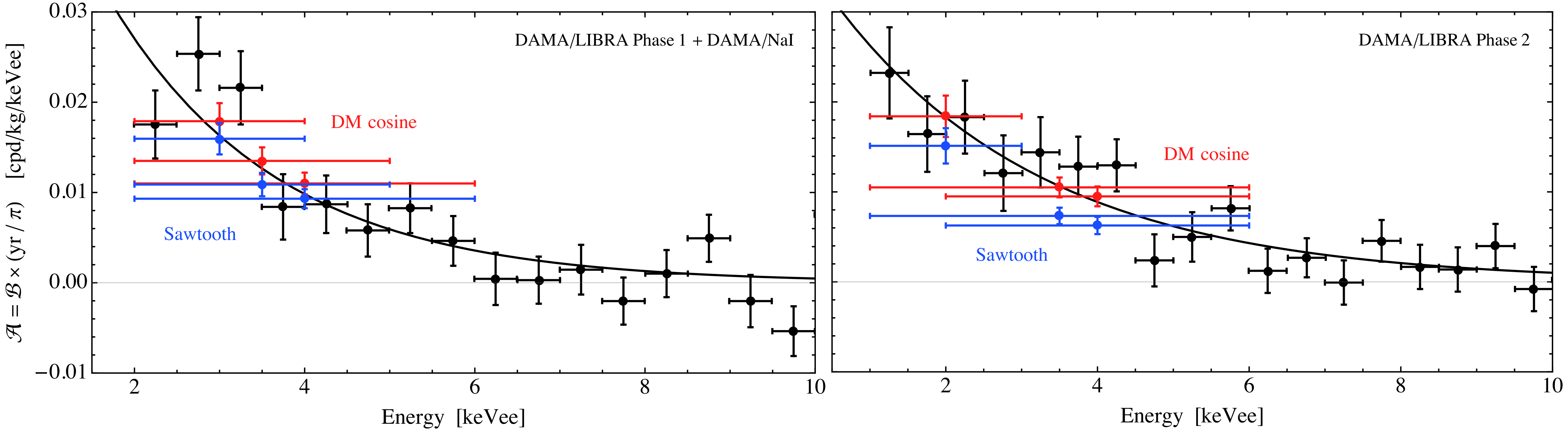


- Higher modes suppressed as $1/n^2$

$$\mathcal{B}t = \mathcal{B} \cdot T \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n\pi} \sin\left(\frac{2\pi n}{T} t\right)$$

… and smeared by non-constant duration of cycles

Energy spectrum



- We can fit the data only in the bins for which the time series is provided: for other energies, assume that B ~ A π / yr holds.

- The energy spectrum of the modulated signal is peaked at low energies:

    shape consistent with the DM interpretation (exp(-E/E_0)),
    but also reasonable for a background

Time-varying backgrounds?

Backgrounds that increase with time are not a crazy possibility, in general.

Few examples (not necessarily relevant to the DAMA rate) include:

- Out-of-equilibrium physical effects.
  - broken equilibrium in a decay chain (e.g. Pb → Bi → Po)
  - diffusion of contaminants from the surface into the crystals
- Instrumental effects.
  - contamination of PMT glass causing fake events
  - electronic noise
- Apparent increase due to degradation of detector resolution.

Backgrounds that decrease with time can be due e.g. to decays of contaminants with life-time of ~ 10 years.

Conclusions

1. A scintillation rate that varies with time can induce a fake modulation signal in the DAMA detector.

   - If the rate grows with time, the induced modulation is peaked in June and could be consistent with the observed signal.

   - If the rate decreases with time, the modulation has a minimum around June, and the true signal would be larger.

   - In any case, a slowly varying rate would bias the extraction of the signal. In particular, the peak can be shifted away from June 2nd.

2. The DAMA data are consistent with being generated from a slowly varying rate. However DAMA/LIBRA phase 2 data in the 2 - 6 keV energy bin prefer a cosine over a sawtooth.

The only (easy!) way to settle the question is to look at the time-dependence of the total rate.

Comments

- We do not make claims about the presence or absence of any particular background in DAMA: we do not have the relevant information
- Fact: the current analysis is *not robust* against a non-constant rate. Either change the analysis (no residuals, no yearly cycles), or show that the total rate is constant.
- Some ancillary analyses have been presented by DAMA:
  - A direct fit of signal + constant background to the data, without using residuals, but still done cycle by cycle (1805.10486): equivalent to residuals method
  - A similar fit, with non-constant background, was presented as a response to our paper (P. Belli, talk at CNNP2020). Similar results. Still done cycle by cycle: why?
- The time-dependence of the event rate can *only* be determined by…
  … the time-dependence of the event rate!

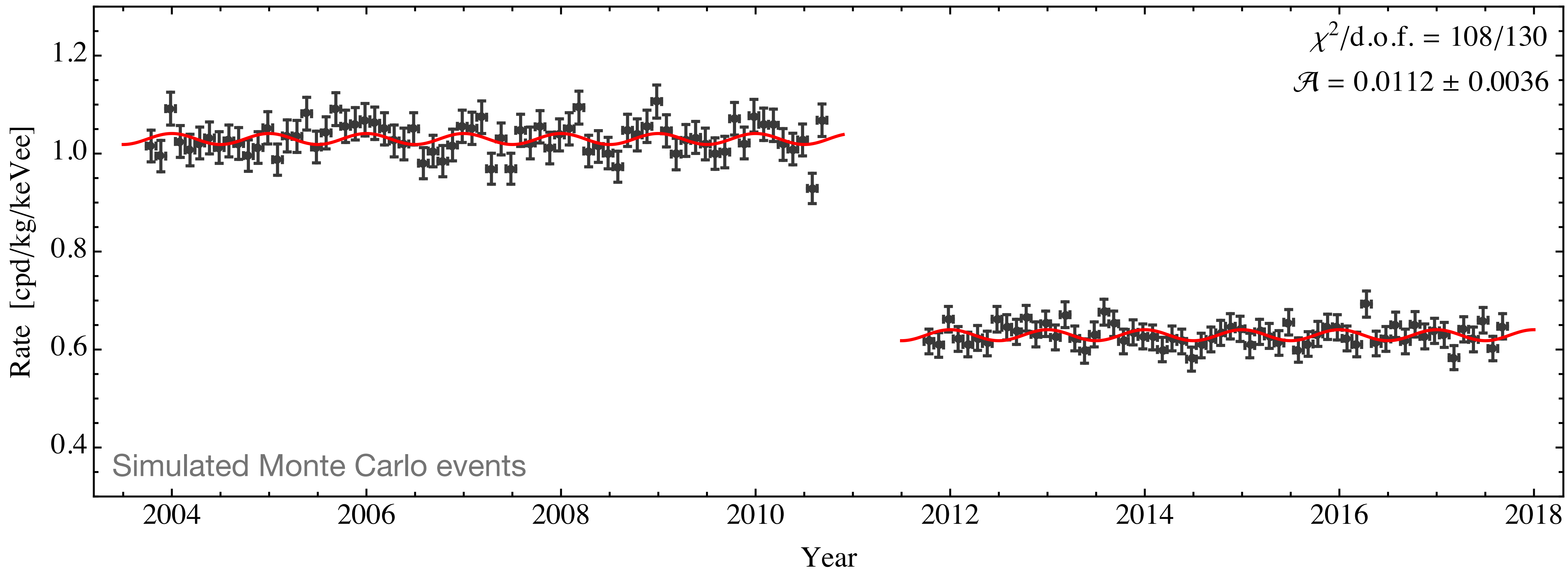
  Information about the various individual backgrounds that contribute to the rate (e.g. time-dependence of the contaminants) is not enough:

$$\text{Rate}(t) \neq \text{Sum[backgrounds]}$$

Backup

Fitting the total rate

With the current statistical precision, assuming an amplitude of 0.01 cpd/kg/keVee, it is possible to fit the modulated signal directly from the total rate, without doing residuals (even visible by eye):



Energy spectrum of the total rate

The average rate has changed between Phase 1 and Phase 2 (probably due to improvements in the detector).

Seems a constant shift above ~ 5 keV.

If a growing component is added, with spectrum as the modulated signal, the change between Phase 1 and Phase 2 is shown in green.