Strongly interacting dark matter doesn't explain the DAMA signal

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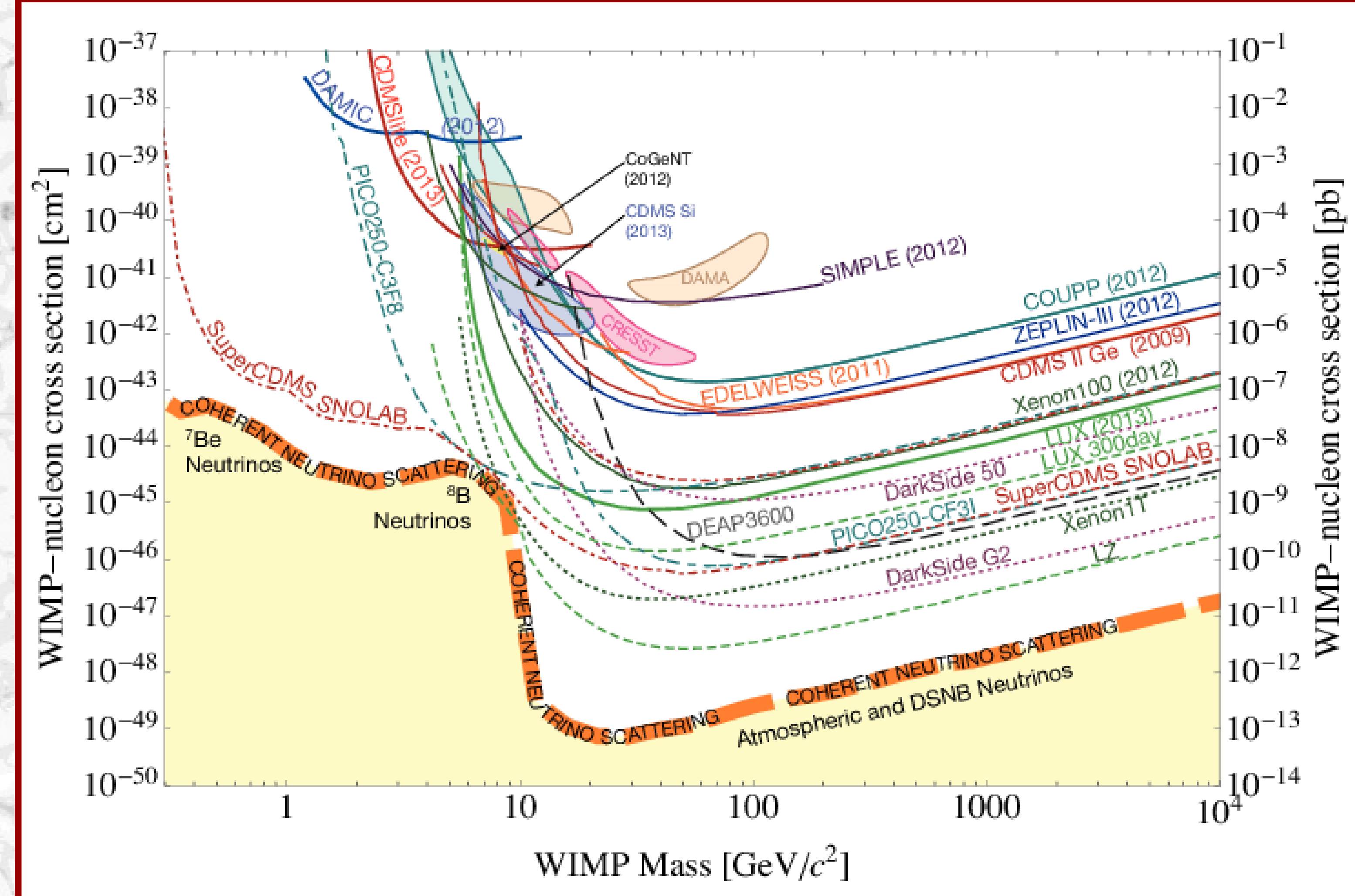
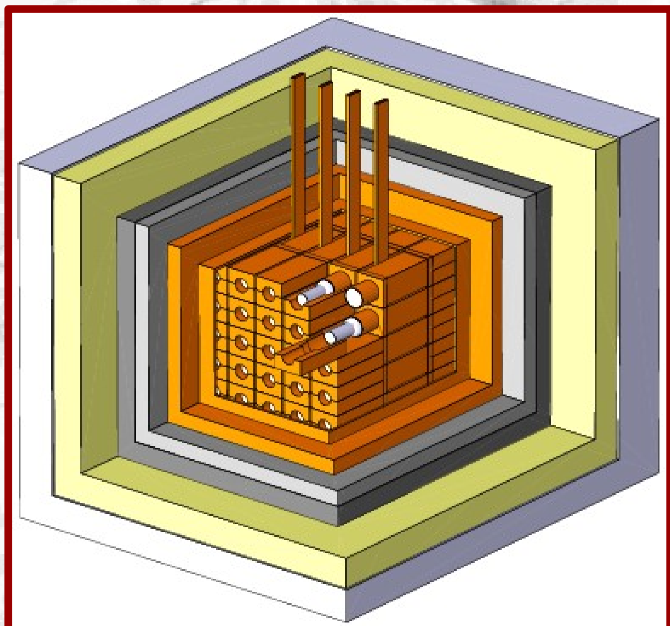
Direct detection puzzle

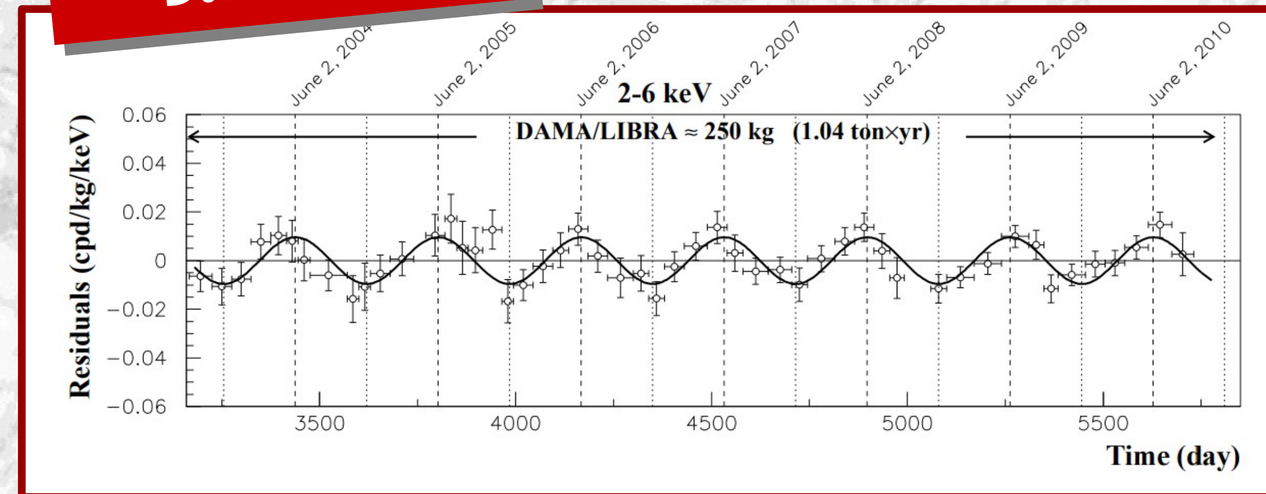


J. Cooley, Phys.Dark Univ. 4, 2014

DAMA Experiment

9.3 σ C.L.





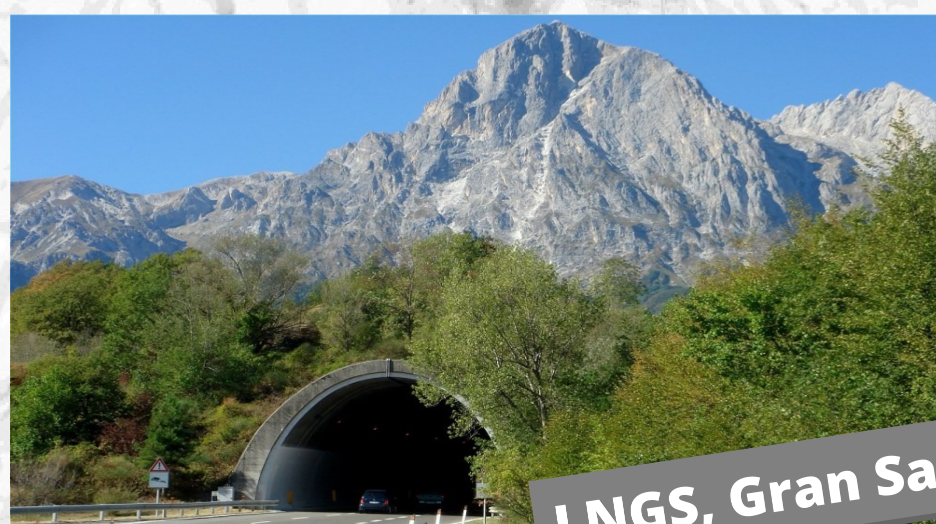
Annual modulation of the signal

DAMA/LIBRA

250 kg NaI(Tl)

1.33 ton*yr

~ 10^3 counts per day



LNGS, Gran Sasso

Explanations

- **Background neutrons**
- **Muon-induced neutrons**
- **Neutrino-induced neutrons**

However, these explanations don’t work

- “No role for neutrons, muons and solar neutrinos in the DAMA annual modulation results”, *Bernabei et al., Eur.Phys.J., 2014*
- “Comment on "Fitting the annual modulation in DAMA with neutrons from muons and neutrinos"”, *Barbeau et al., Phys.Rev.Lett., 2014*
- “Can muon-induced backgrounds explain the DAMA data?”, *Klinger and Kudryavtsev, J.Phys.Conf.Ser., 2016*

Any room for dark matter?

Yes, but not for simple WIMPs

- Resonant Dark Matter, *Yang Bai, Patrick J. Fox (Fermilab) JHEP 0911 (2009) 052*
- Mirror dark matter interpretations of the DAMA, CoGeNT and CRESST-II data, *R. Foot Phys.Rev. D86, 2012*
- Inelastic dark matter with spin-dependent couplings to protons and large modulation fractions in DAMA, *Stefano Scopel, Kook-Hyun Yoon, JCAP 1602, 2016*

Essentially, all these models assume that DAMA detector is somehow "special", so that there is no signal in other detectors

Composite dark matter

- Significant elastic cross sections (~ 10^{-26} cm^2)
- Tiny recoil energies (slow down before the detector)
- Produce the signal due to inelastic processes on some special component of DAMA

- Composite Dark Matter and Puzzles of Dark Matter Searches, *M. Khlopov, A. Mayorov, E. Soldatov, Int.J.Mod.Phys. D19 (2010)*
- Milli-interacting dark matter, *Q. Wallemacq, Phys. Rev. D 88 (2013)*
- Dark antiatoms explain DAMA, *J.R. Cudell, Q. Wallemacq, JCAP 2015*

Slowdown in the ground

DM looses energy after multiple collisions on terrestrial nuclei (mainly Si and O) and acquires the surrounding temperature (thermalizes)

The recoil energy on nuclei is tiny

$$E_{\rm rec} = \left(\frac{M v_{\rm th}^2}{2}\right) \frac{2mM}{(m+M)^2} \approx 1\,{\rm meV}$$

Thermalization depth

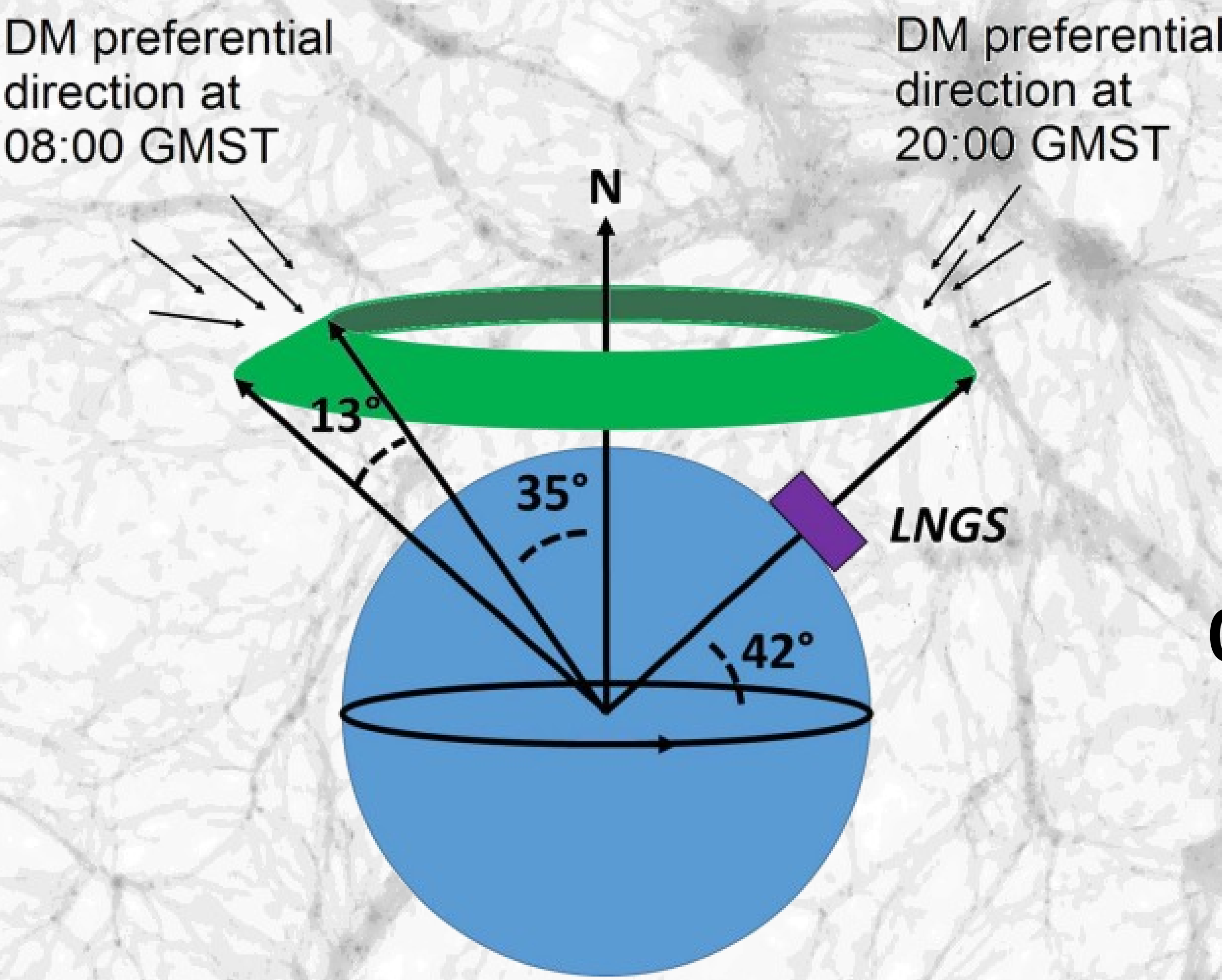
$$l_{\rm th} = \frac{M\lambda}{m} \log\left(\frac{v_{\rm in}}{v_{\rm th}}\right)$$

Mean free path length

$$\lambda = \frac{1}{n\sigma}$$

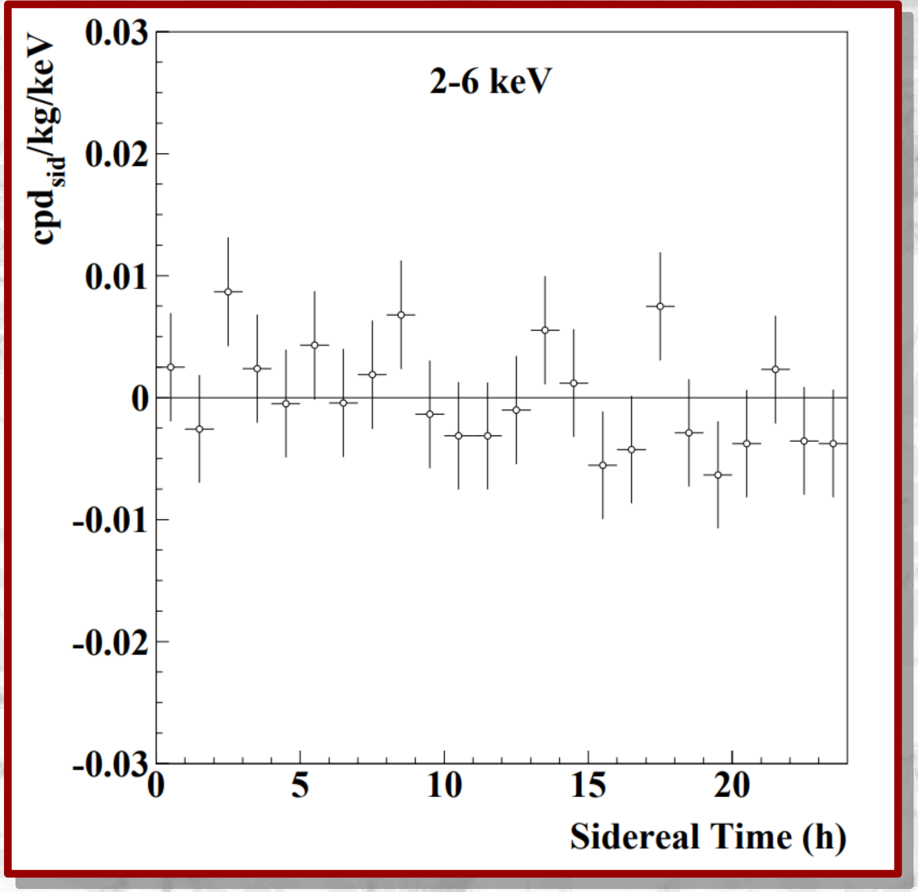
Number density of the medium (rock)

Diurnal modulation

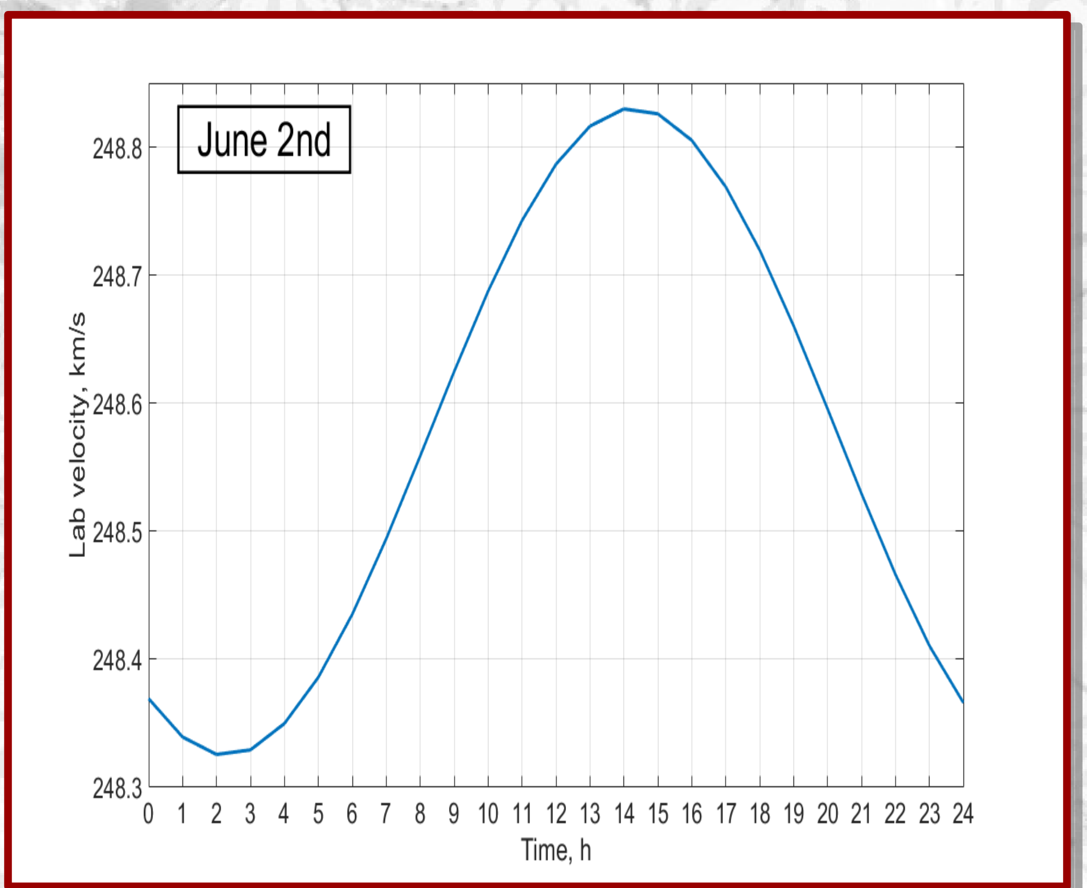


One expects diurnal modulation for SIMPs

Diurnal modulation

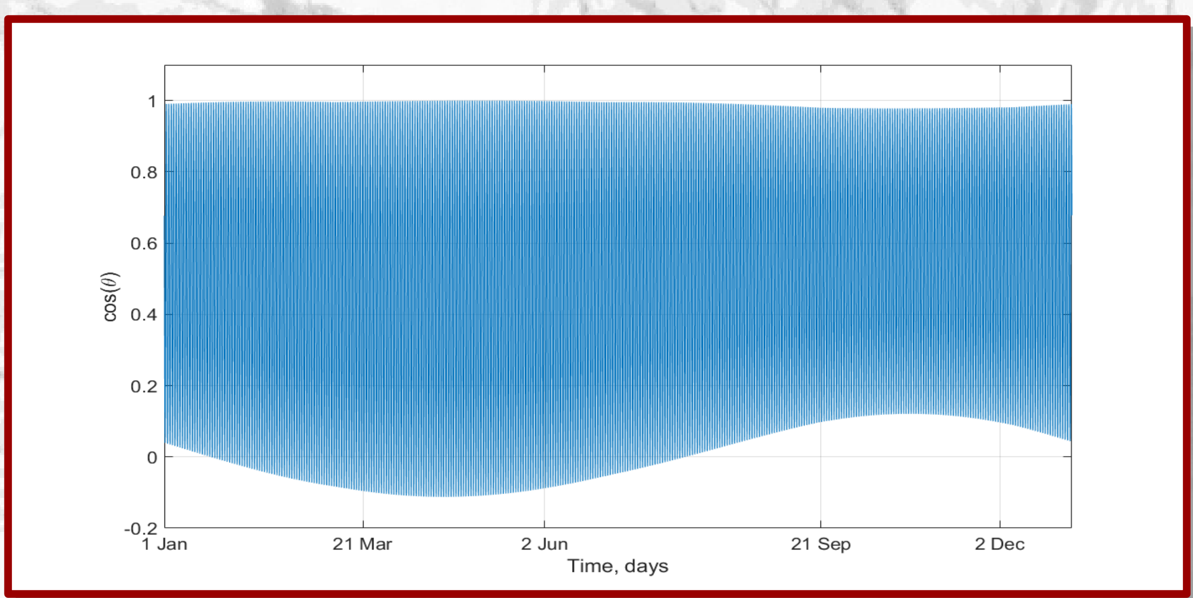


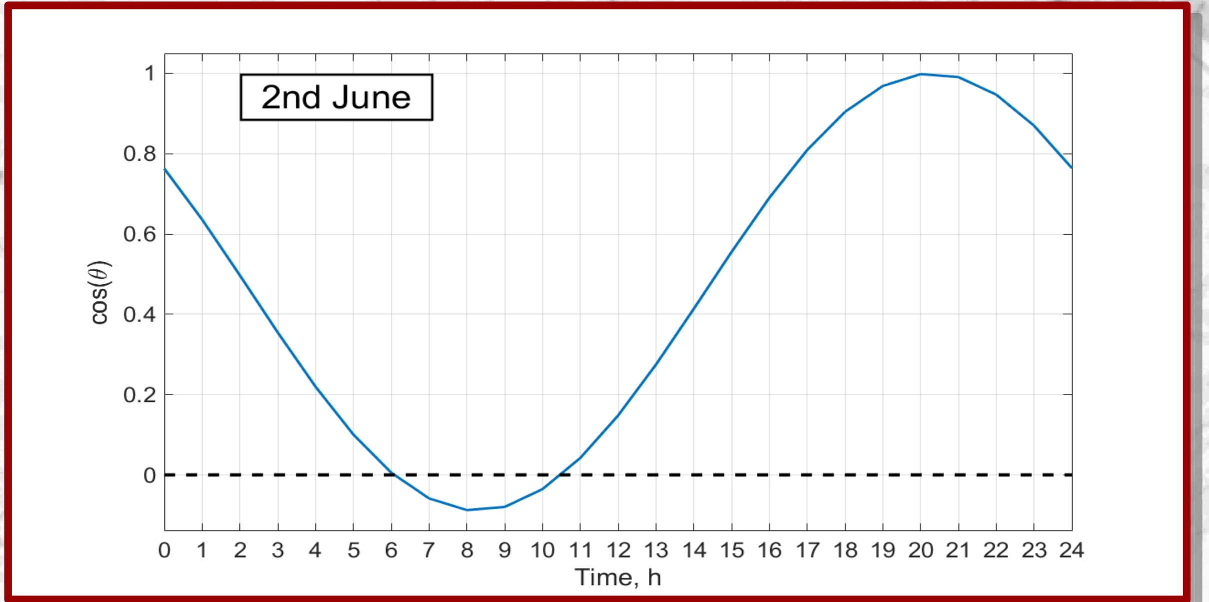
DAMA data

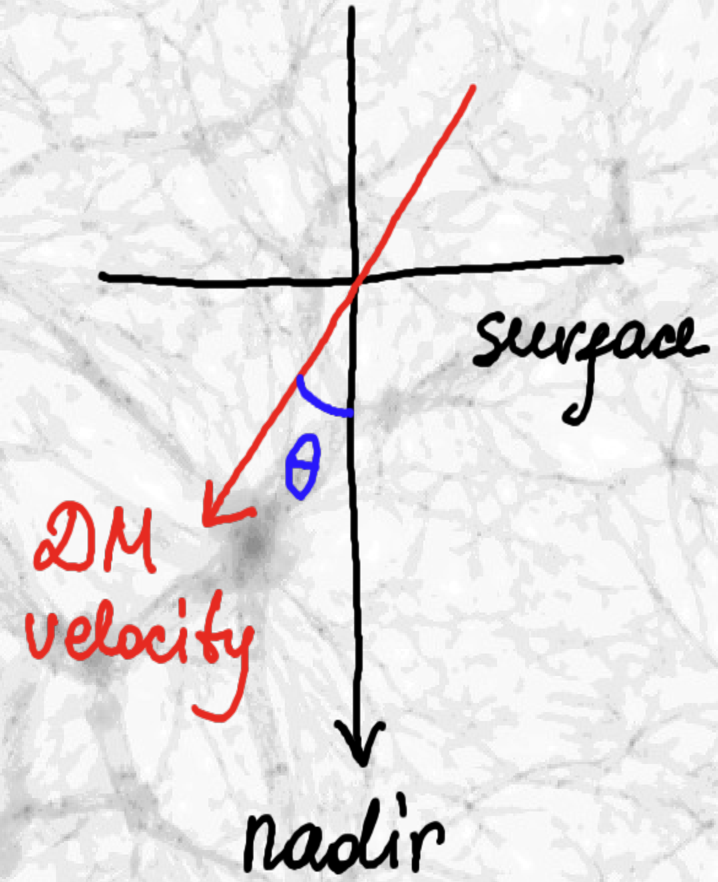


Expected for WIMPs

Diurnal modulation







Propagation in the ground

The propagation can be described as diffusion with a drift due to gravity

$$\frac{\partial N(\vec{x},t)}{\partial t} = D\Delta N(\vec{x},t) - v_d \frac{\partial N(\vec{x},t)}{\partial z} + f(\vec{x},t)$$

Particle number density

Diffusion coefficient

Drift velocity

Source function

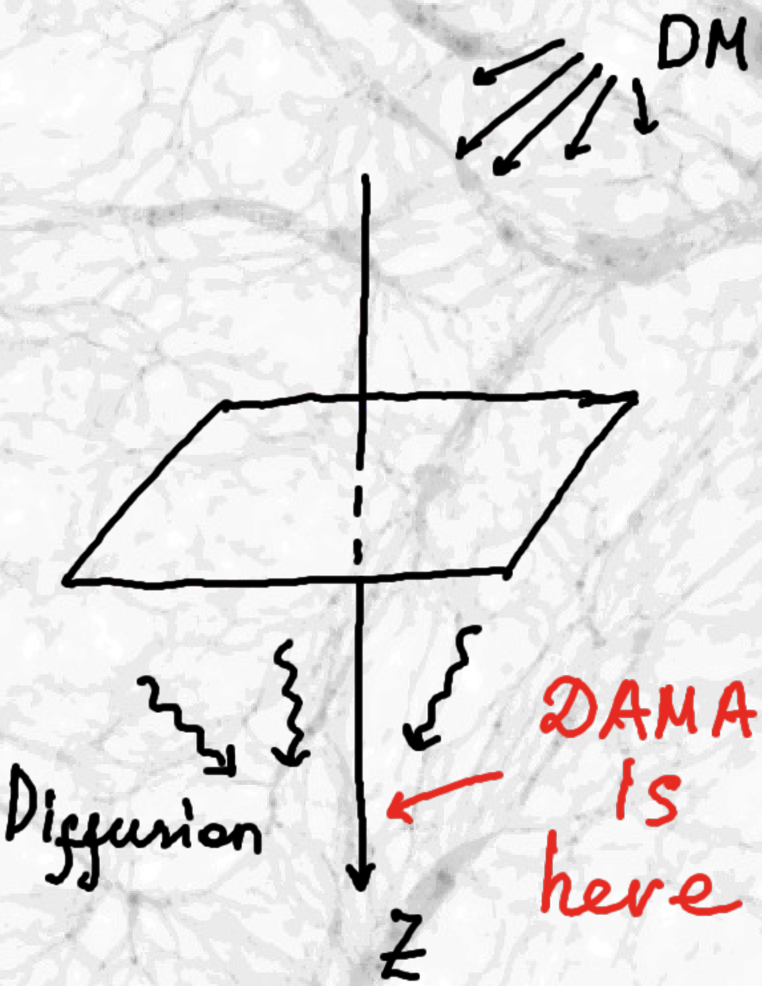
Diffusion coefficient

$$D = \sqrt{\frac{\pi k T}{8M}} \frac{m+M}{mn\sigma}$$

Drift velocity (related to the diffusion coefficient via Einstein relation)

$$v_d = \frac{MgD}{kT}$$

"Flat-Earth" approximation



All the points on the surface are equal, so the only dimension that matters is Z

⬇

1D diffusion equation

Slow diffusion only takes place below the surface
Above the surface the diffusion coefficient is 0

Density in the detector

General solution of the diffusion equation in the unbounded space

$$N(t) = \frac{1}{\sqrt{4\pi D}} \int_0^t \frac{d\tau}{\sqrt{t-\tau}} \iiint_{-\infty}^{\infty} d\vec{l}\, \omega_l(\vec{l},\tau)\, f(\vec{l},\tau)\, G(\vec{l},\tau,t)$$

Depth distribution

with the Green's function

$$G(\vec{l},\tau,t) = \exp\left(\frac{v_d(z_{\rm det}-l_z)}{2D} - \frac{v_d^2 t}{4D}\right)\left[\exp\left(-\frac{(z_{\rm det}-l_z)^2}{4Dt}\right) - \exp\left(-\frac{(z_{\rm det}+l_z)^2}{4Dt}\right)\right]$$

Drift factor

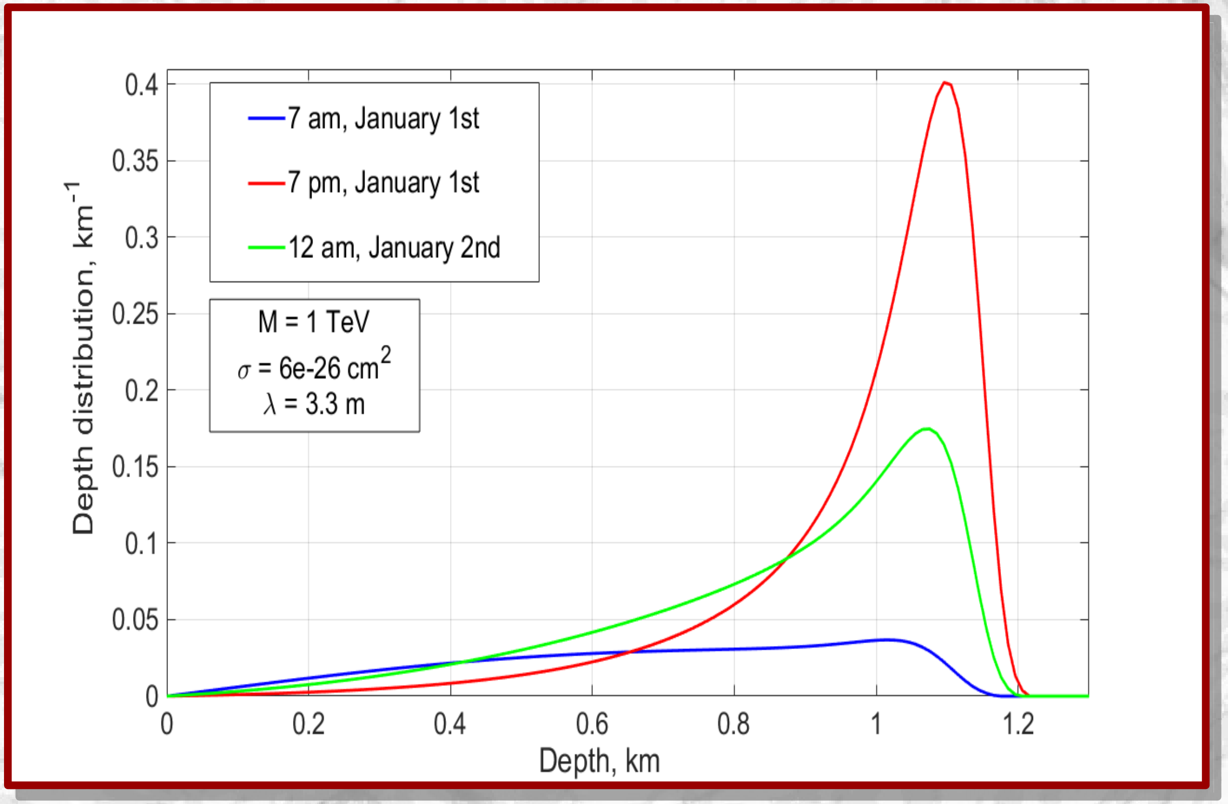
"Mirror" sink term describes the leakage of particles into the air

$$f(\vec{l},\tau) = \frac{\rho_{\rm loc}\cdot 1\%}{M} v(\vec{l})\cos(\theta)$$

Velocity distribution

Dark matter thermal velocity distribution

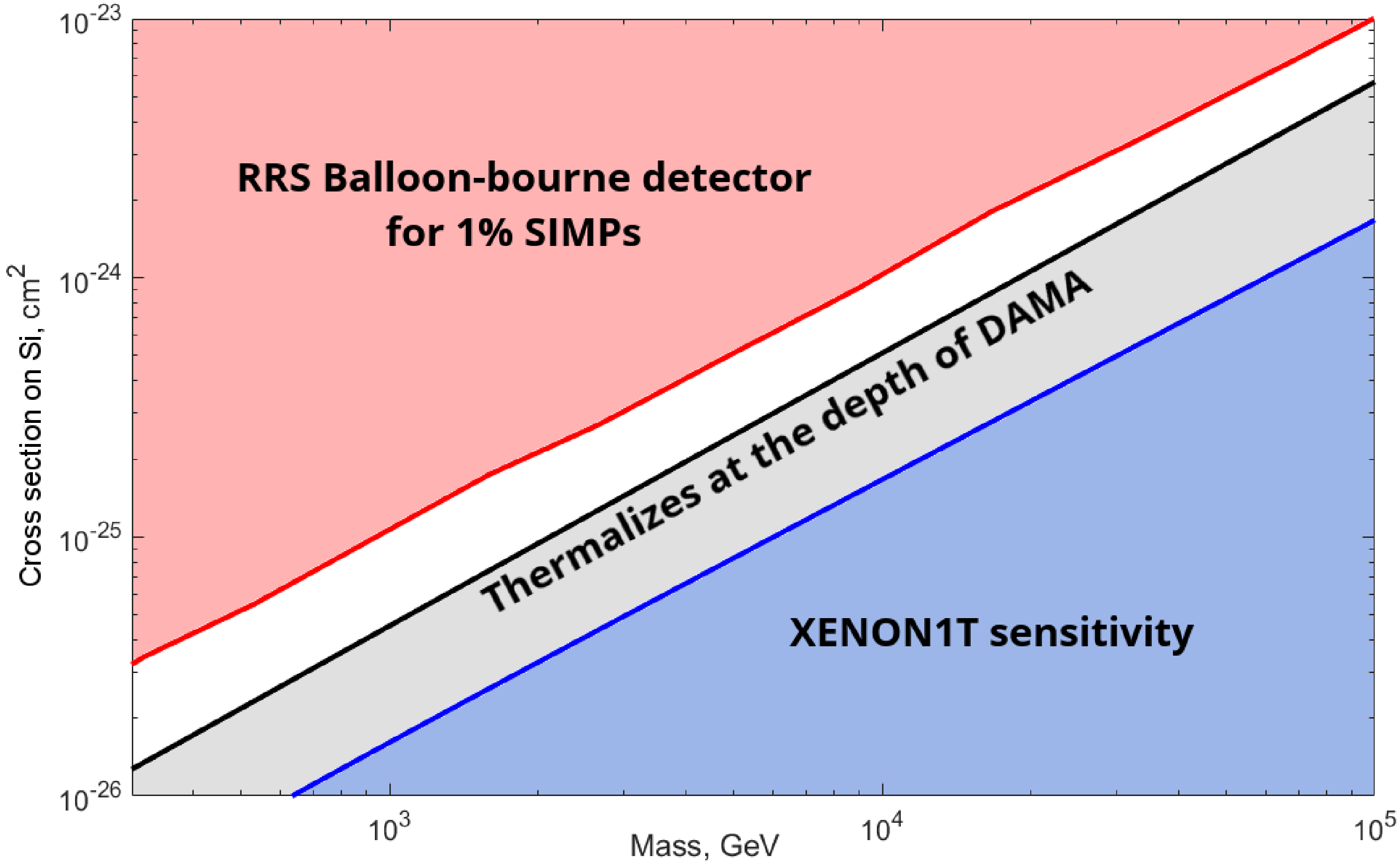
$$\omega_v(\vec{v}) = N \exp\left(\frac{(\vec{v} - \vec{v_{\rm lab}})^2}{v_{\rm o}^2}\right) \Theta\left(\vec{v_{\rm esc}} - |\vec{v} - \vec{v_{\rm lab}}|\right)$$



Can be translated into the depth distribution

$$\omega_l(\vec{l}) = \frac{mv}{M\lambda l^2}\omega_v(\vec{l})$$

Constraints

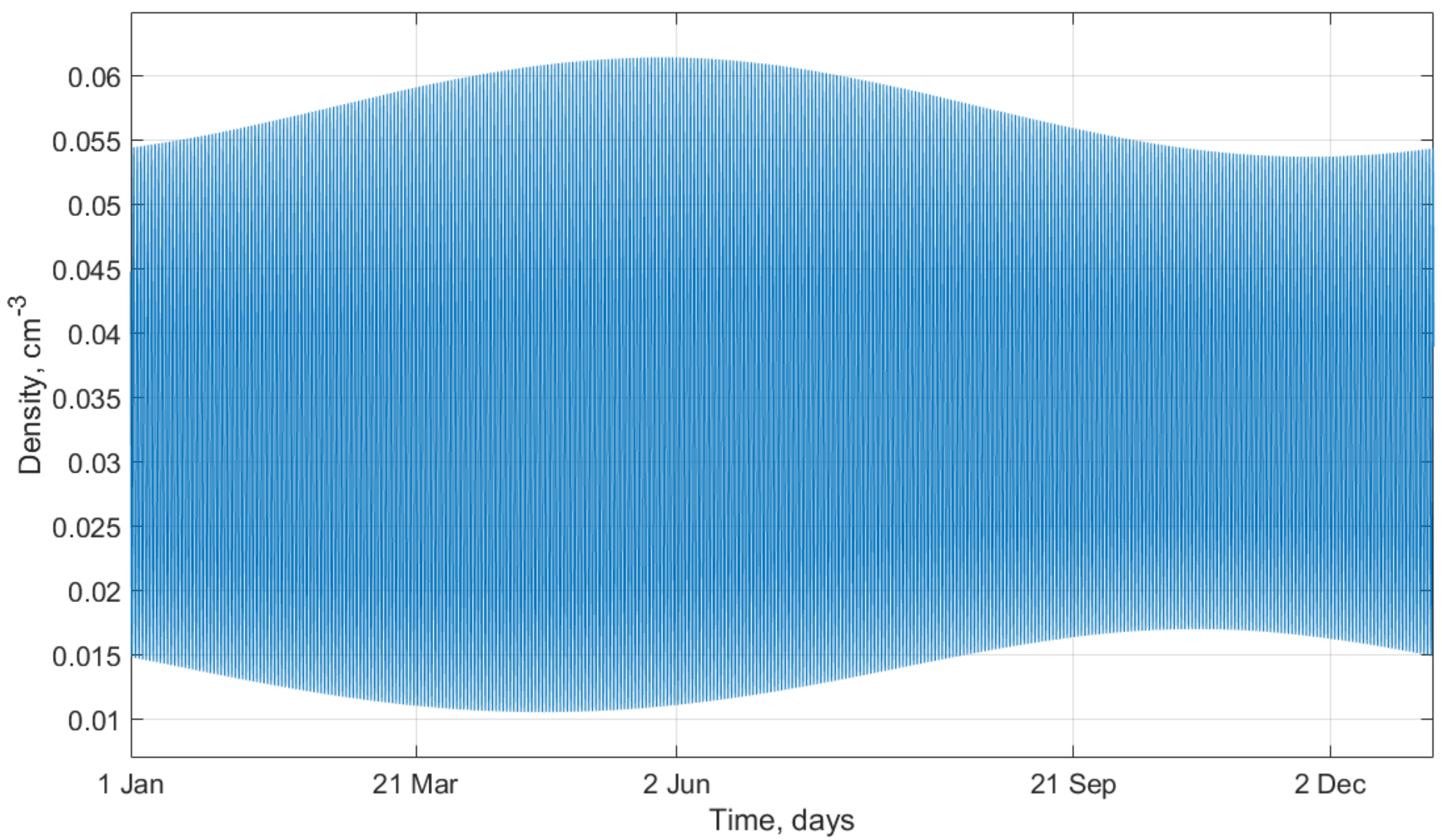


Let's study a particular set of parameters,

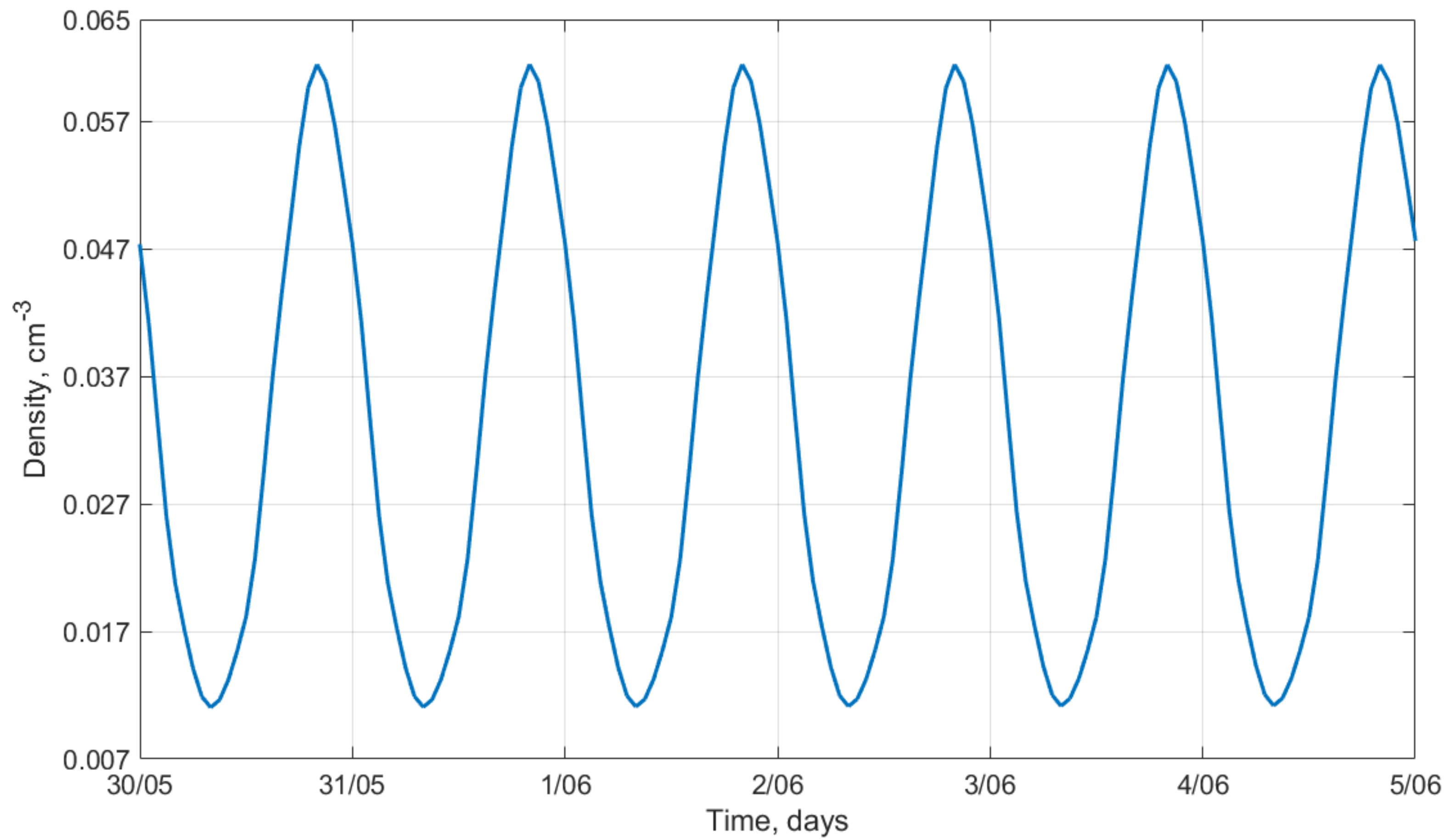
M = 1 TeV

$\sigma = 10^{-26}\ \mathrm{cm}^2$

Density inside the detector



Density inside the detector



Reconstructing the signal

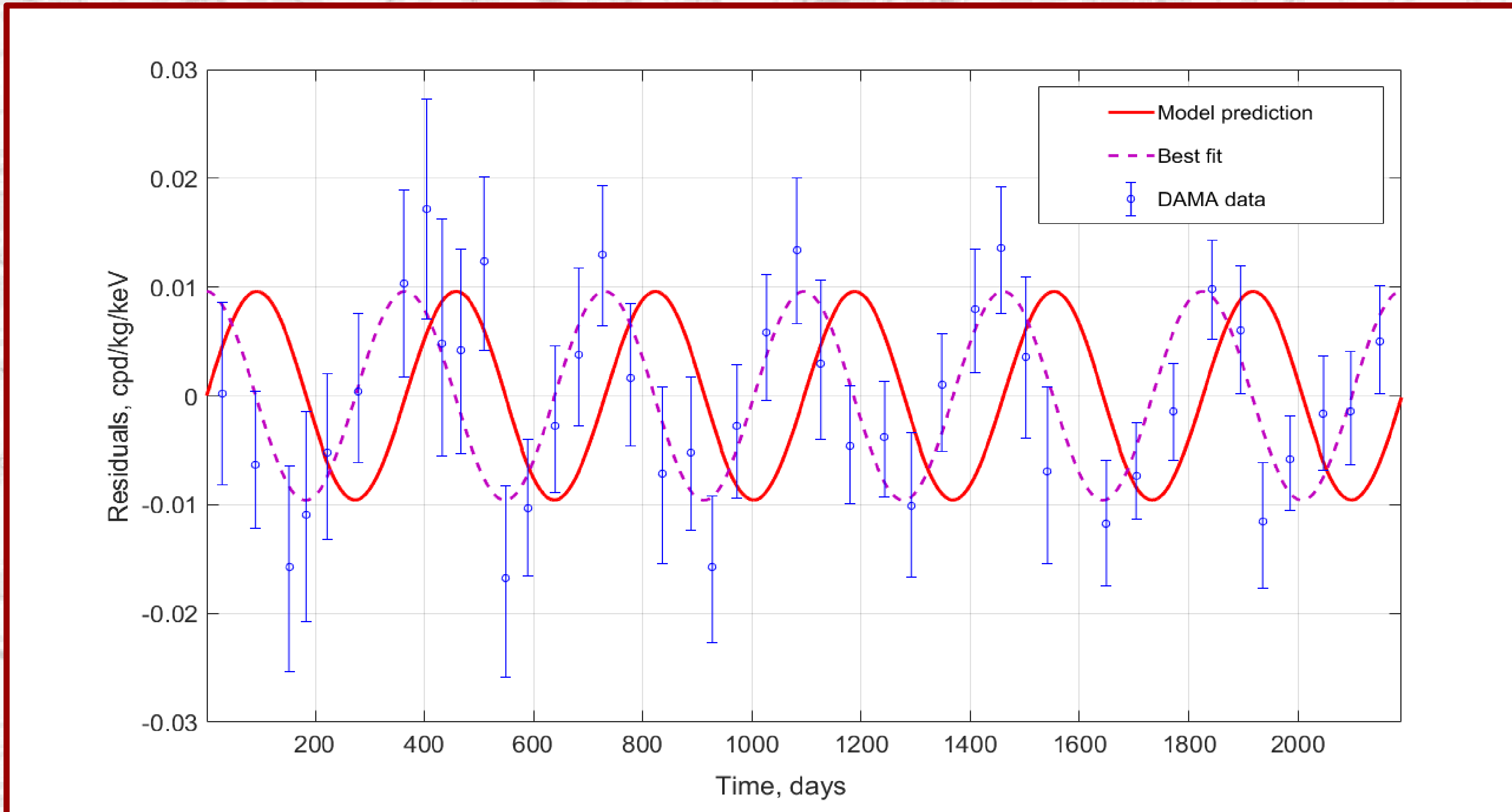
Inelastic cross section - additional parameter that we use to normalize the signal

$$\Gamma(t) = \frac{N(t)\sigma_{\rm in}}{m_{\rm NaI}} \left(\frac{n_{\rm Tl}}{n_{\rm NaI}}\right) \sqrt{\frac{\pi k T}{8M}}$$

~ 10^{-3}

The rate is than averaged over every day and the yearly average of the signal (background) is subtracted

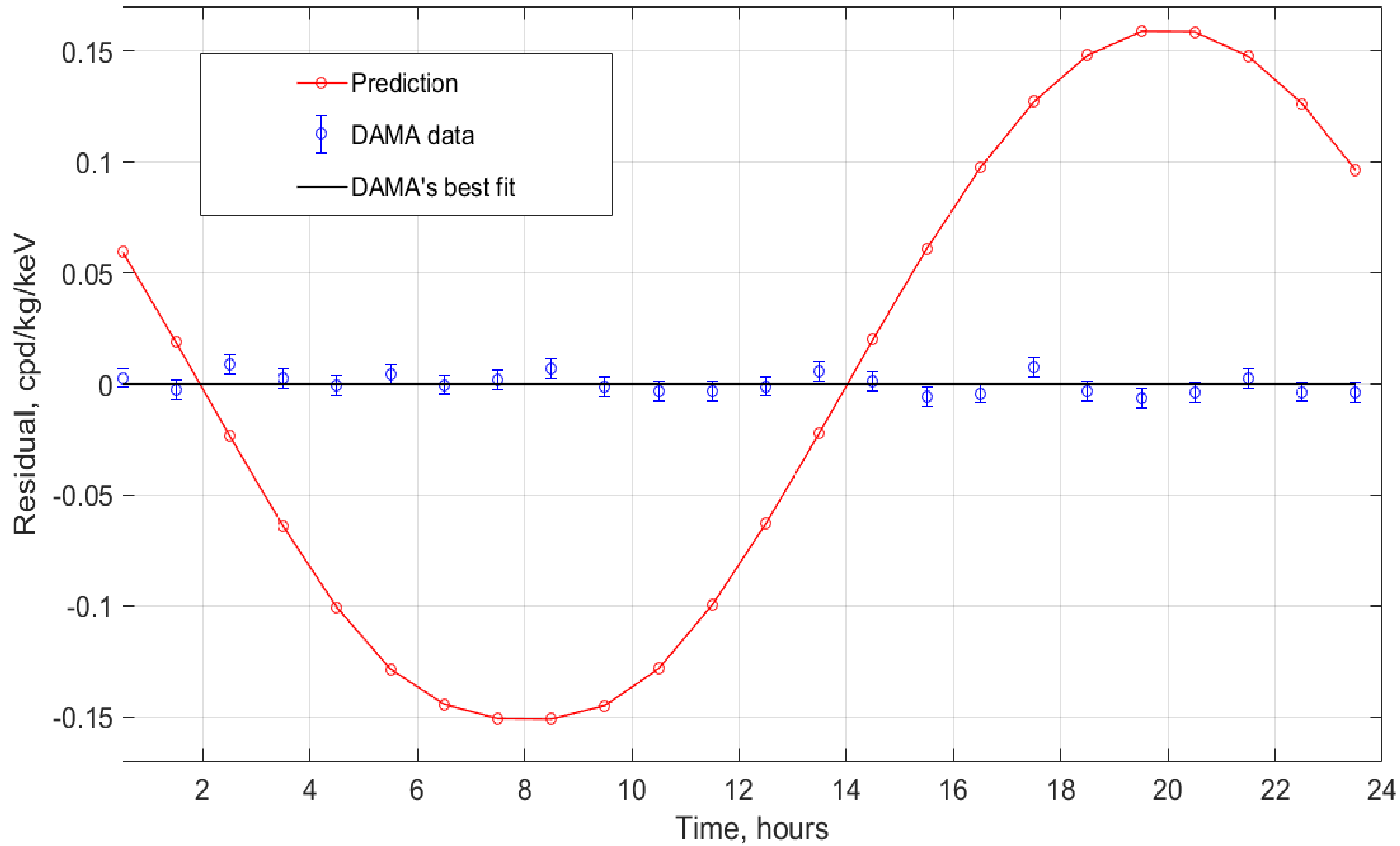
Annual modulation



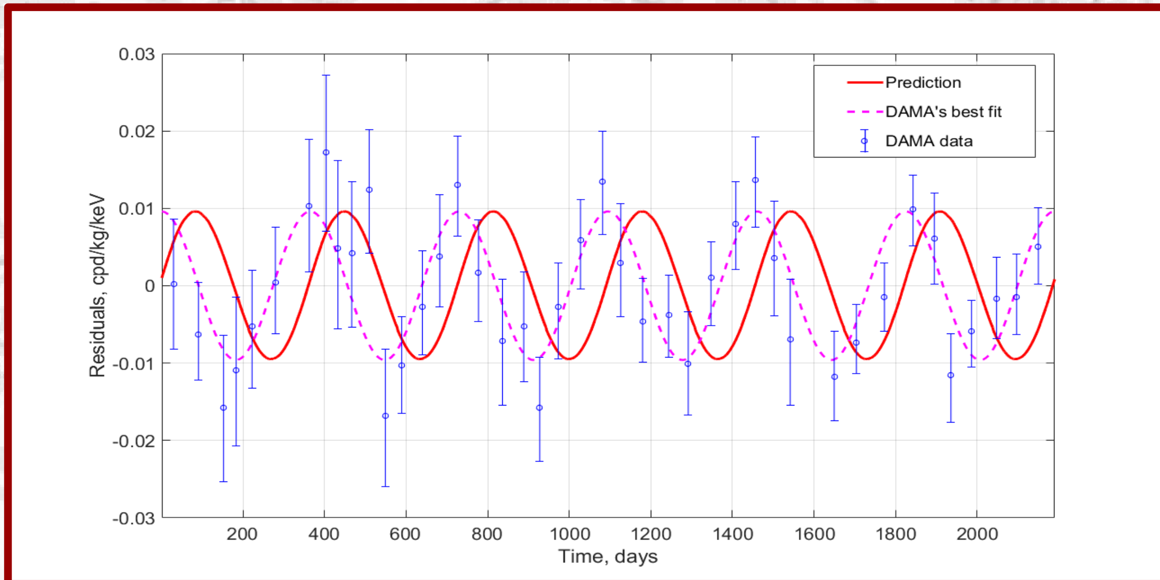
$$\frac{\chi^2}{\text{d.o.f}} = 3.38$$

~ 100 days shift

Diurnal modulation



Other parameter values

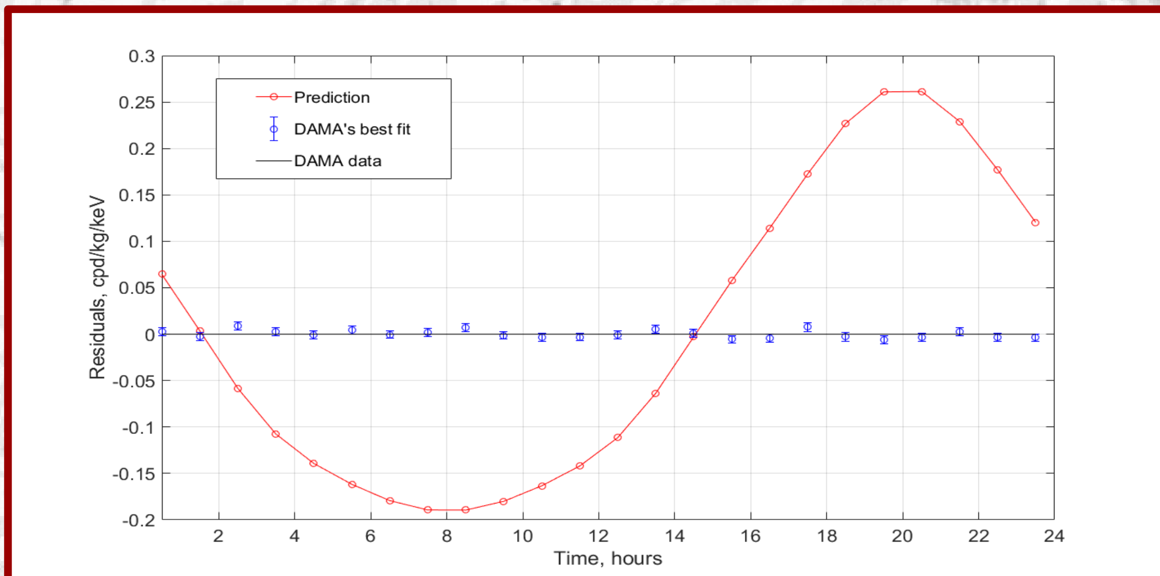


M = 100 GeV

$\sigma = 10^{-26}$ cm^2

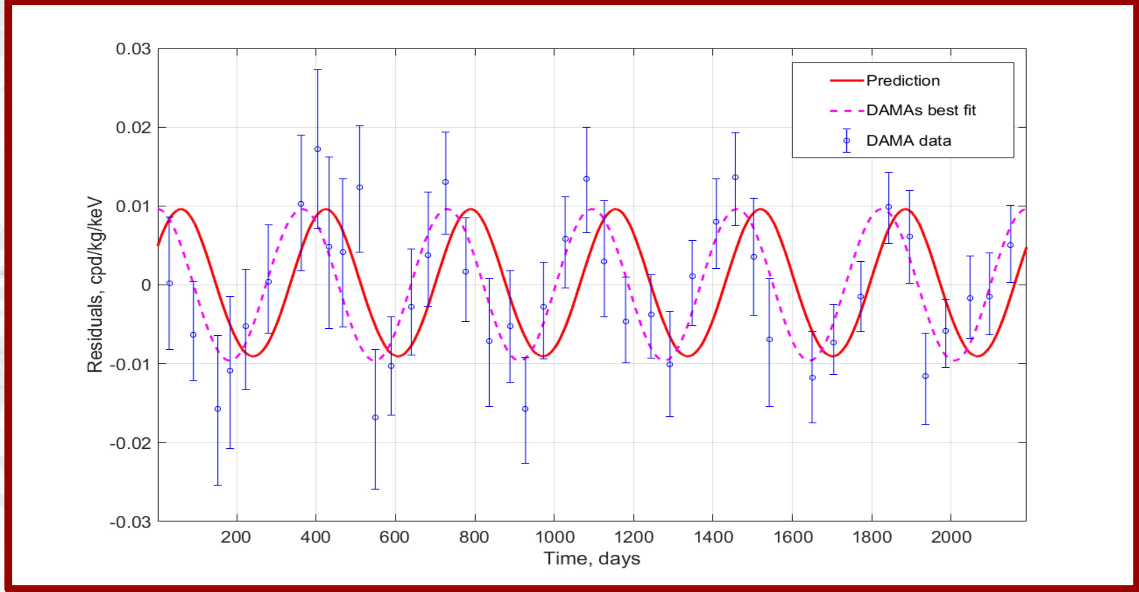
~ 90 days shift

Annual modulation



Diurnal modulation

Other parameter values

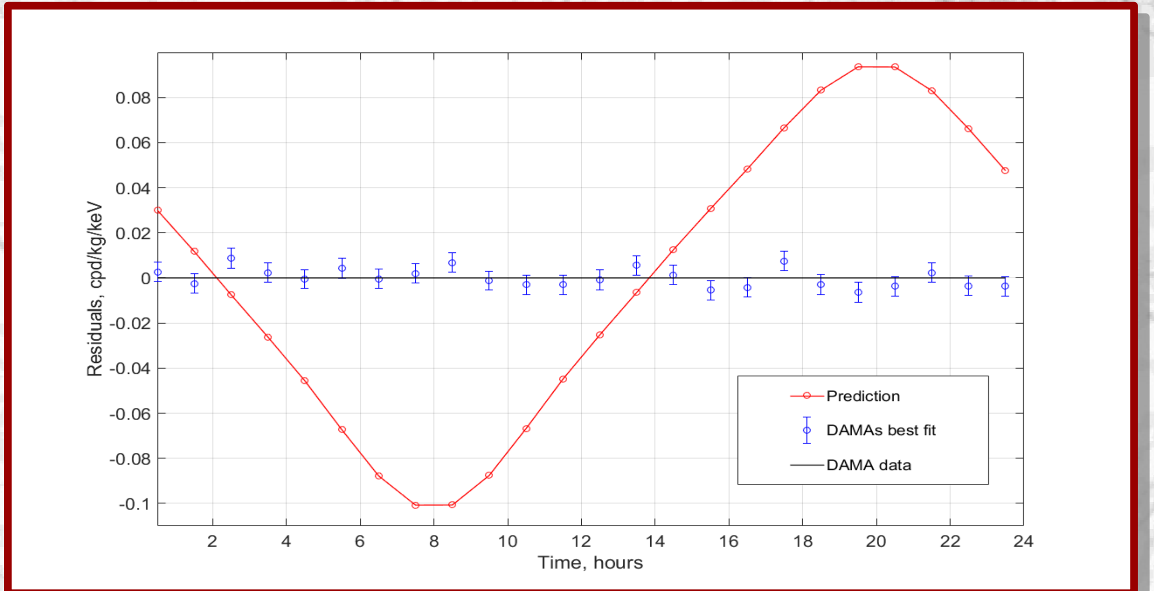


M = 100 TeV

$\sigma = 6\ 10^{-24}\ cm^2$

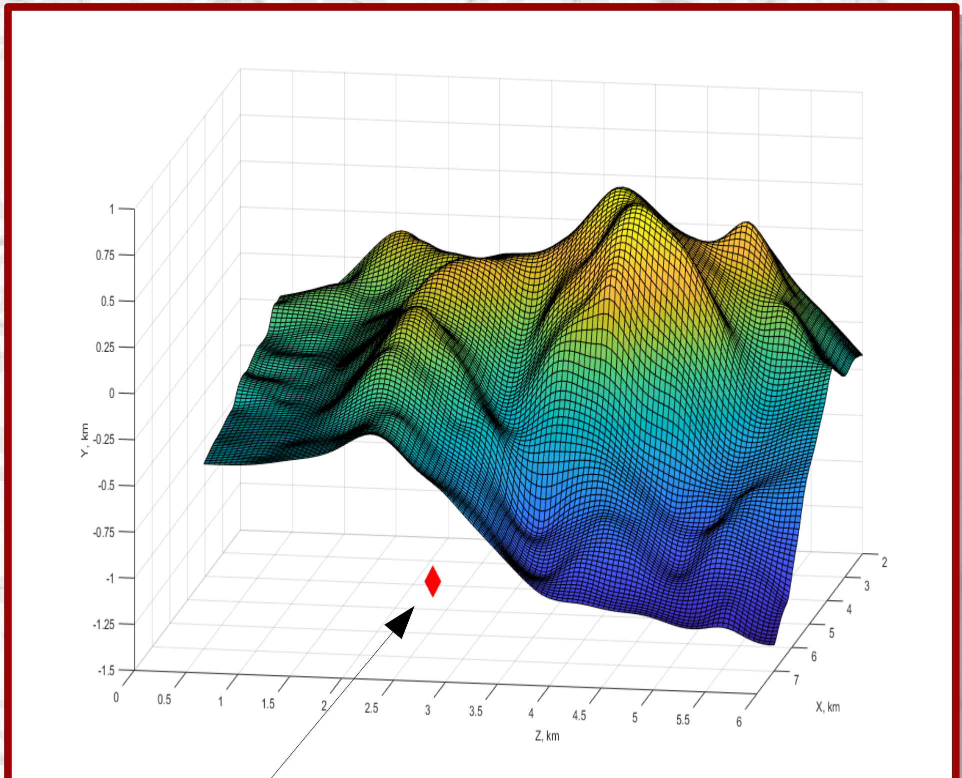
~ 60 days shift

Annual modulation



Diurnal modulation

Realistic surface

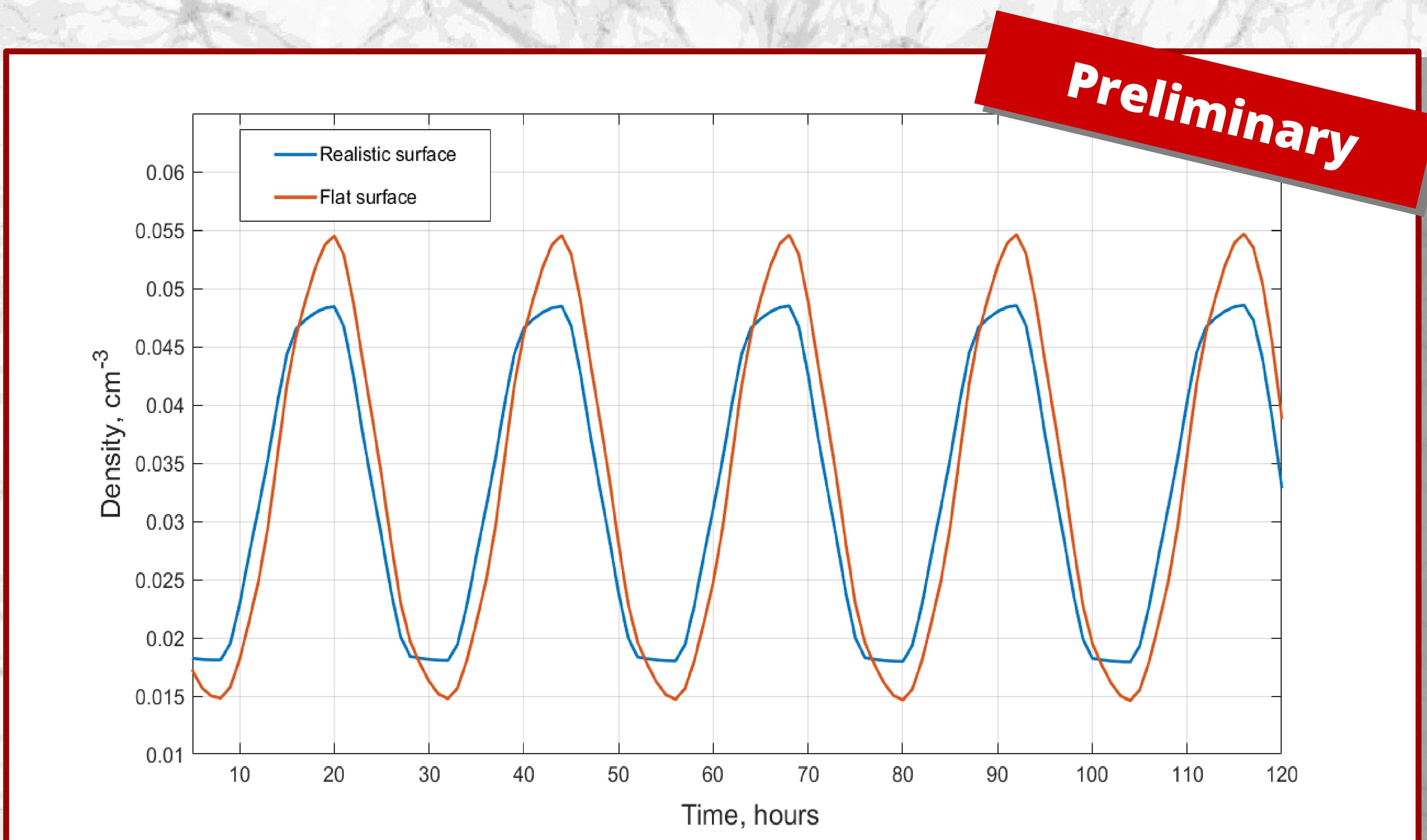


DAMA is here

Gran Sasso mountain (Google Earth)

A more detailed picture includes a complex realistic surface

Realistic surface



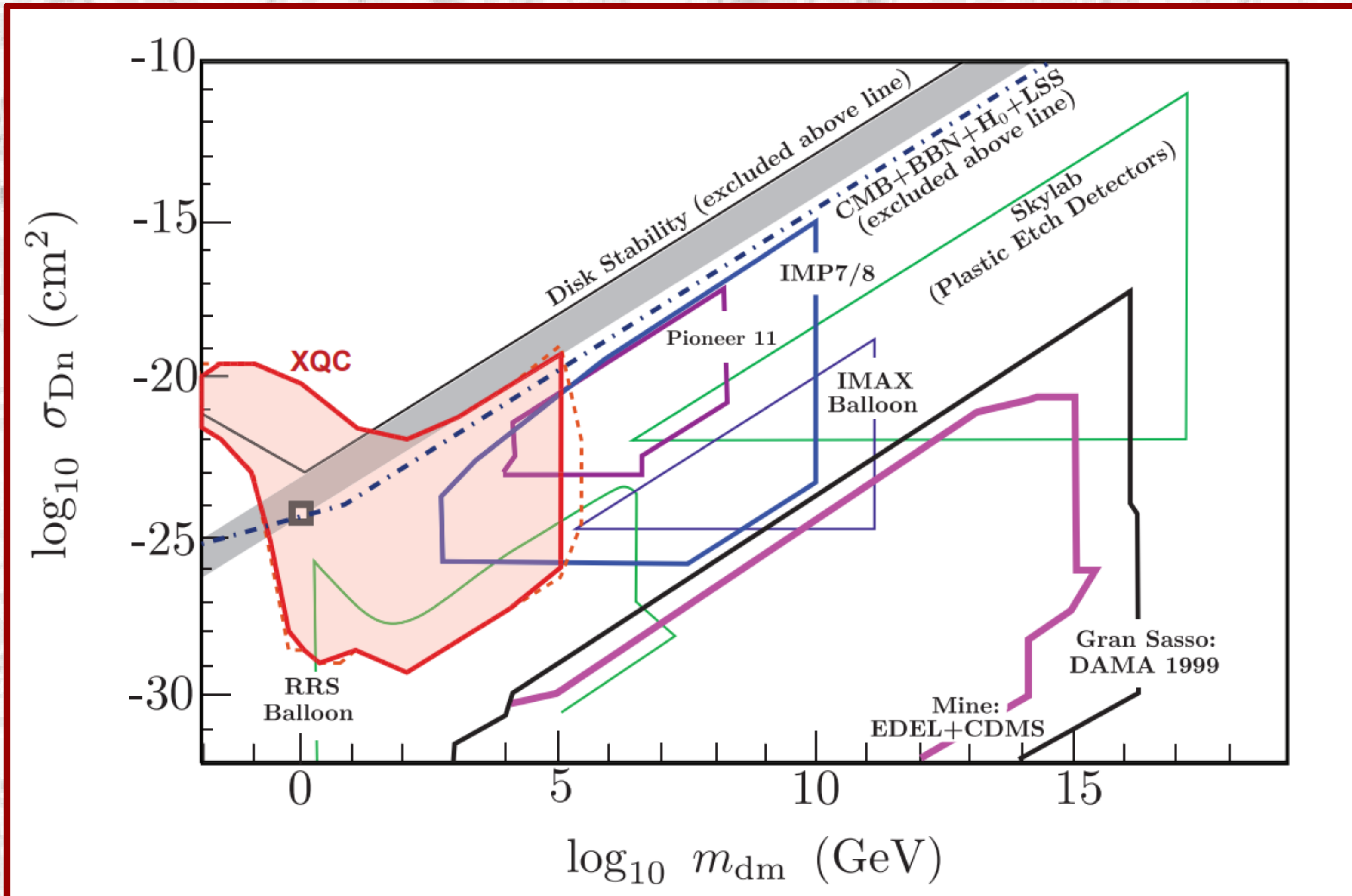
Conclusions

- The effects of propagation rule out some dark matter models explaining the DAMA results with strongly interacting massive particles;
- Both annual and diurnal modulations cannot be reproduced;
- The effects of "bouncing" particles needs to be studied, however a significant improvement of the fit is not expected;
- DAMA results will be tested in a series of experiments: ANAIS, COSINE-100, SABRE, COSINUS and so on.

Thank you for attention!

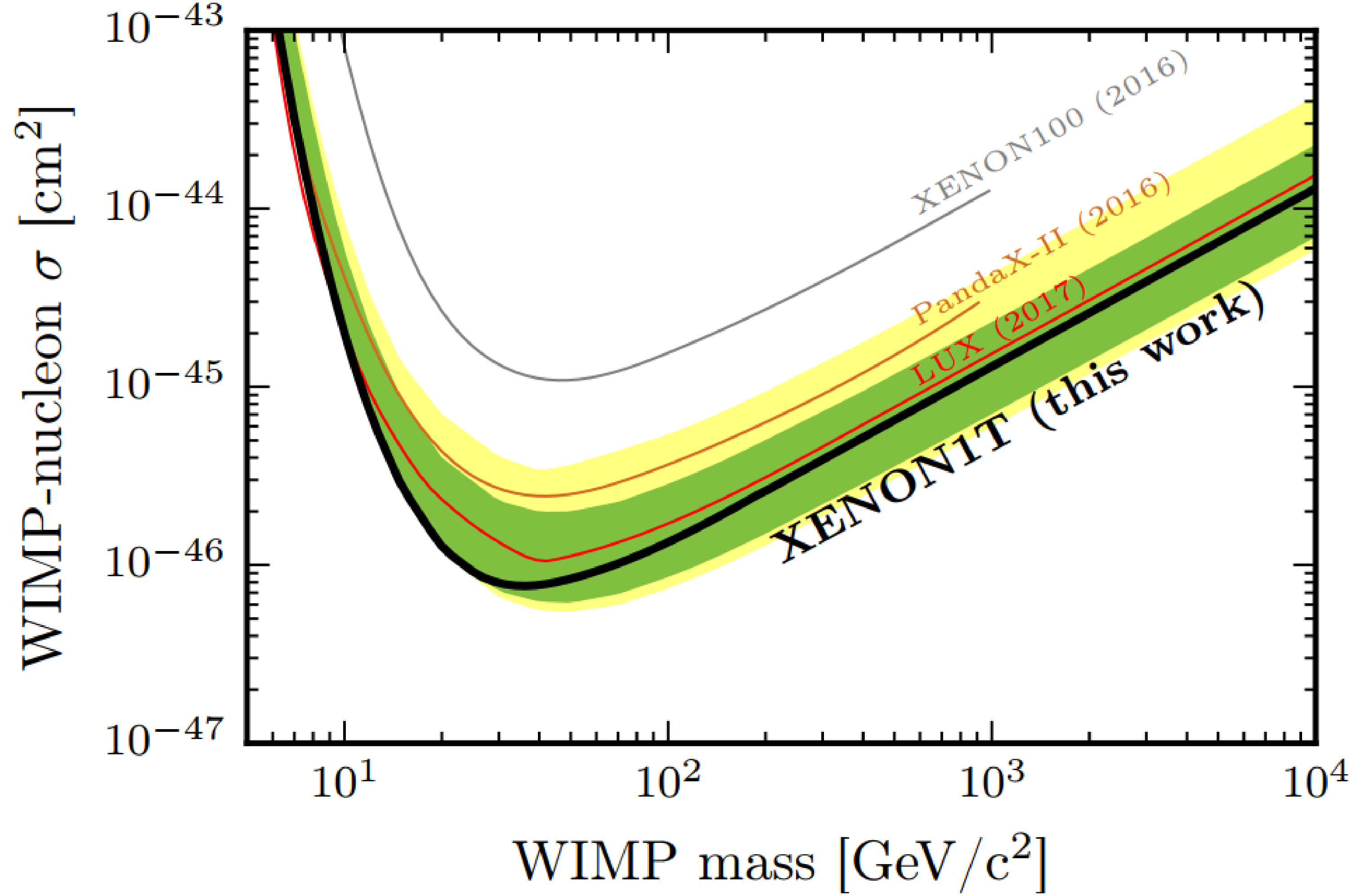
Backup

Constraints on SIMPs

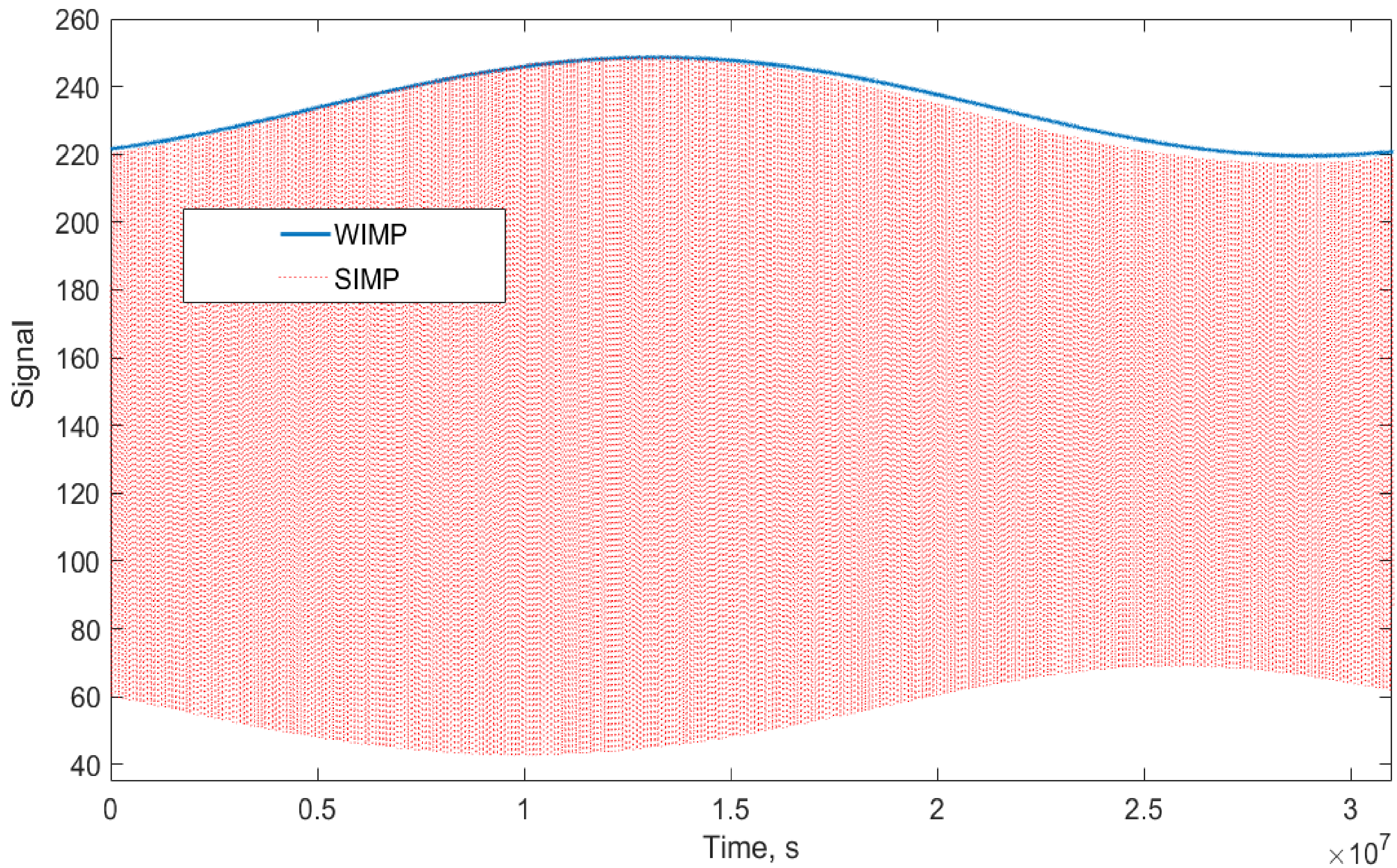


Erickcek+, Phys. Rev. D 2007, 0704.0794

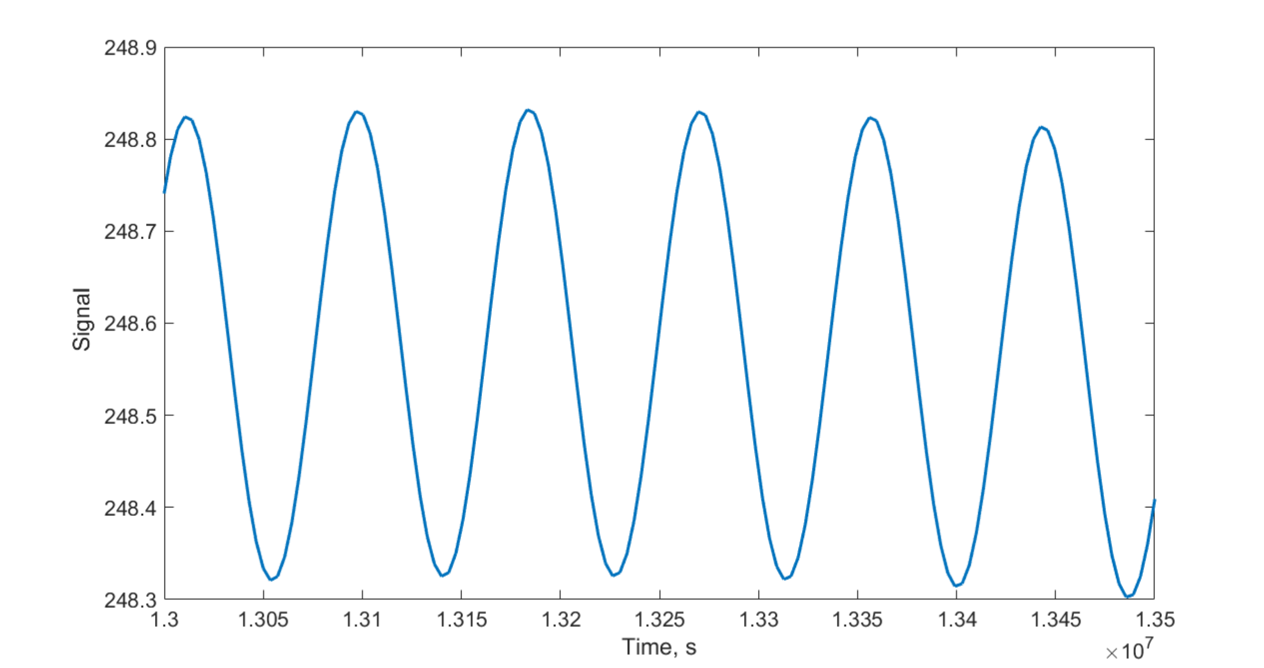
XENON1T (2017)



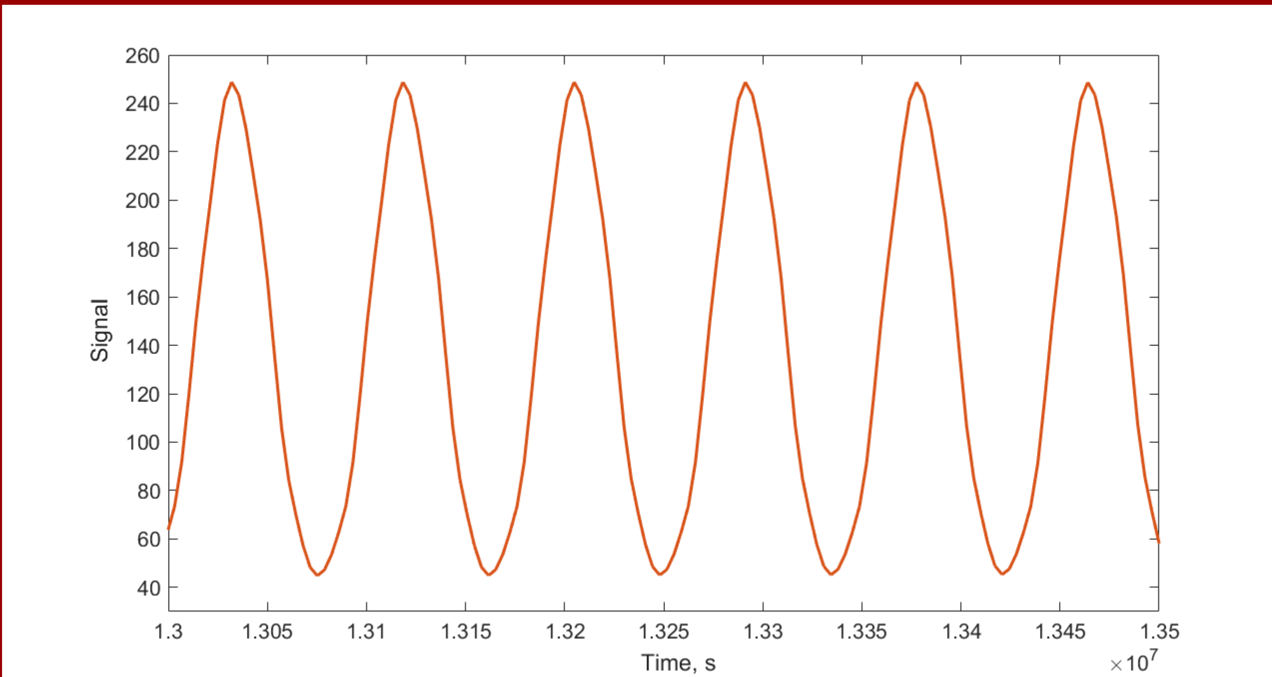
Signal comparison



WIMP Signal around annual maximum



SIMP Signal around annual maximum



Signal reconstruction

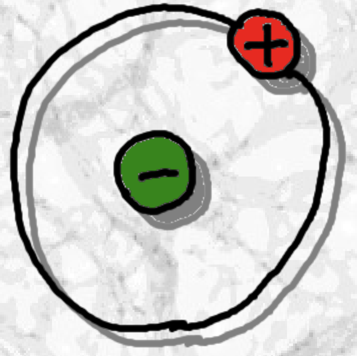
$$\Gamma^i_{\rm Res}(t) = \langle \Gamma(t) \rangle^i - \langle \langle \Gamma(t) \rangle \rangle$$

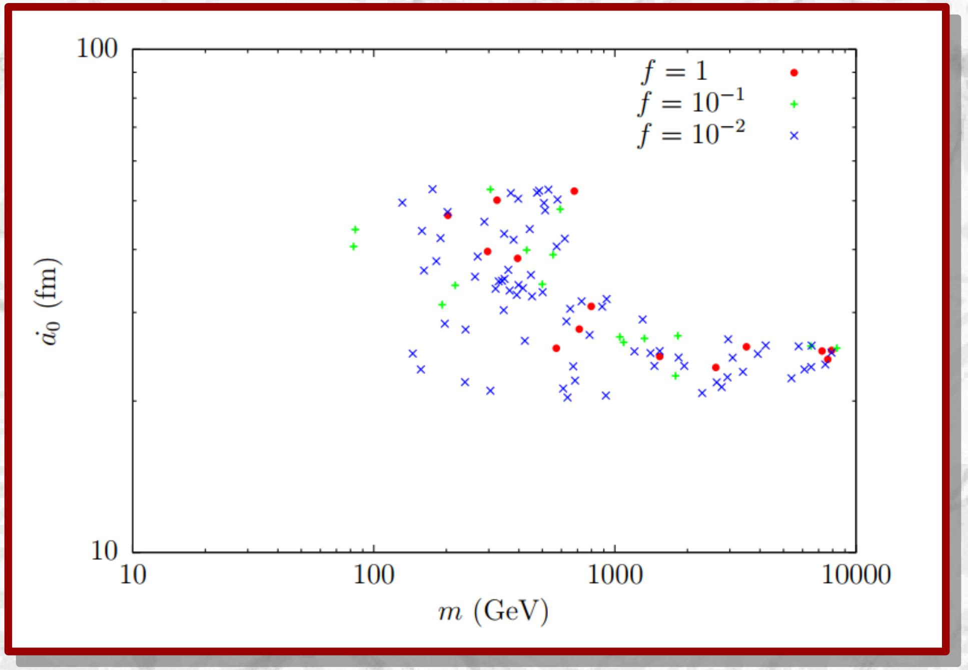
Averaged over each day (annual modulation) or each hour of every day during the year (diurnal modulation)

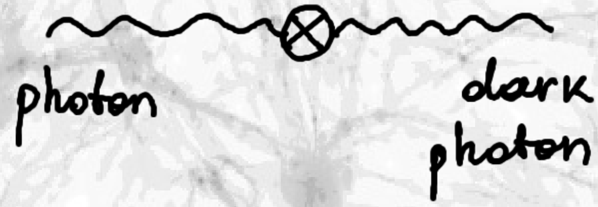
Averaged over the year

Dark antiatoms

- Dark antiproton and dark positron
- Dark photon can "convert" to ordinary photon
- Interacts strongly with "our world"
- Couple to heavy elements (Thalium in DAMA)
- Emit X-rays, which produce electron recoils

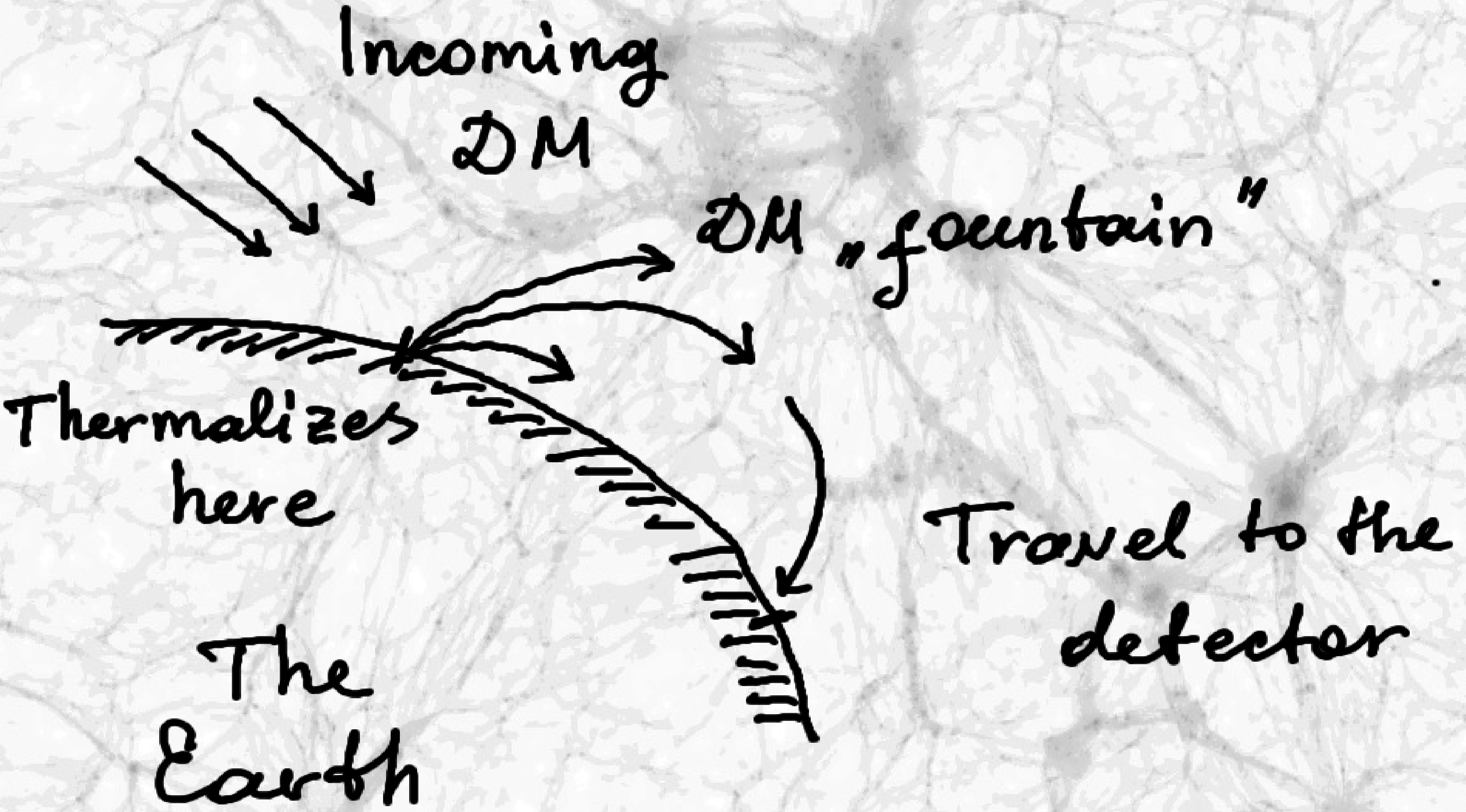






J.R. Cudell, Q. Wallemacq, JCAP 2015

"Bouncing" SIMPs



However, we do not expect this to drastically change our conclusion