A WIMP halo around the Sun and prospects for gamma ray detection

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Alternative title

Is the WIMP halo around the Sun detectable in gamma rays?

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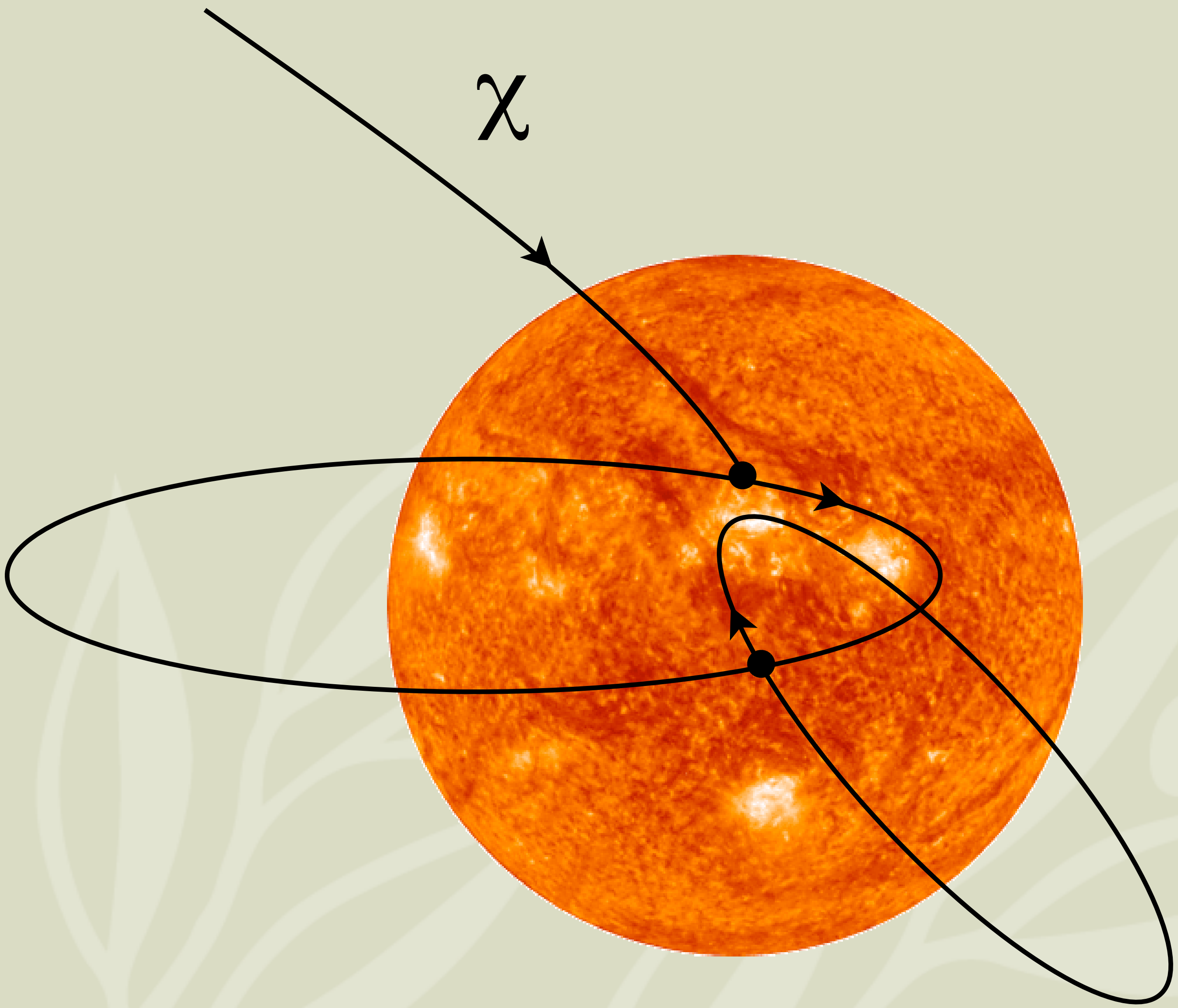
Basic idea



- WIMPs in the process of being captured will constitute a halo of WIMPs around the Sun
- Annihilations of these WIMPs in the halo could produce e.g. gamma rays
- Maybe these can be seen?

Earlier work

- Early estimates by Strausz ('98) showed that gamma ray fluxes could be detectable Phys. Rev. **D59**, 023504 (1999)
- Hooper ('01) revisited the problem and found much lower gamma ray fluxes (by many orders of magnitude) arXiv:hep-ph/0103277 (2001)
- Both of these calculations use rather simple approximative calculations
- Fleysher ('03) performed calculations and found even higher rates than Strausz arXiv: astro-ph/0305056
- MILAGRO has searched for this gamma-ray signal without success Phys. Rev. **D70**, 083516 (2004)
- We here want to revisit the problem with a more careful 3D calculation to settle the issue – can these gamma rays be observed or not?

Outline of calculation

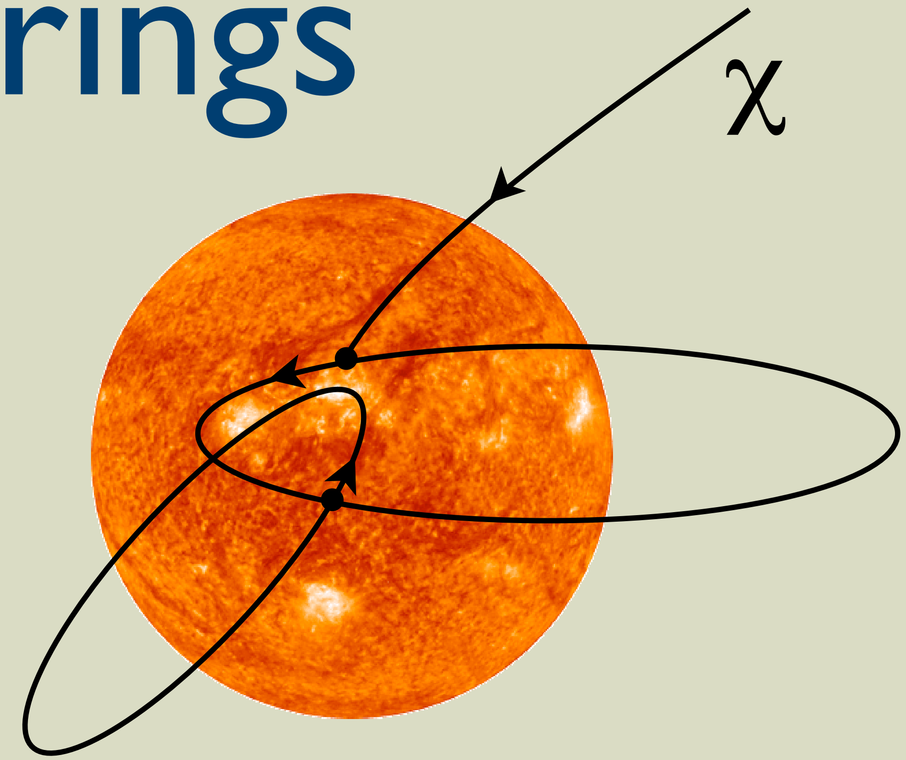
(done as a Monte Carlo)

- Let WIMPs from the Milky Way halo interact with elements in the Sun
- Calculate the energy loss in the interaction and put the WIMP on a new (almost) Keplerian orbit
- Calculate lifetime of this orbit and its contribution to the WIMP density outside the Sun
- Continue with subsequent scatterings until the WIMP is entirely inside the Sun

The WIMP Milky Way halo

- We here assume a ‘standard’ Maxwell-Boltzmann velocity distribution of WIMPs in the halo
- As the WIMPs approach the (moving) Sun, they will be gravitationally focused and have increased their velocity due to the Sun’s gravitation

WIMP scatterings



- The WIMPs scatter either via spin-dependent scattering (Hydrogen only) or via spin-independent scattering on Hydrogen and heavier elements (exponential form factors used for these).
- We have included all major elements with distributions inside the Sun given by the solar model of Bahcall et al. ('01) and with heavier elements from Grevesse and Sauval ('98)
- After each scatter, we calculate the actual orbit for each WIMP (elliptical outside the Sun, and a perturbed elliptical inside)
- We calculate the lifetime of the WIMP given the amount of material traversed through the Sun and the cross sections and then let it interact again and again until it is completely inside the Sun.

More on WIMP scattering

- As the WIMPs scatter, we kill the process of scatterings if the lifetime would be more than the age of the solar system.
- Given the lifetime of each WIMP orbit, we can calculate its contribution to the WIMP halo density around the Sun (as we know how much time it spends at different radii).
- Example: For scattering only on Hydrogen, for a 100 GeV WIMP, about 40 scatters are needed before complete entrapment within the Sun.

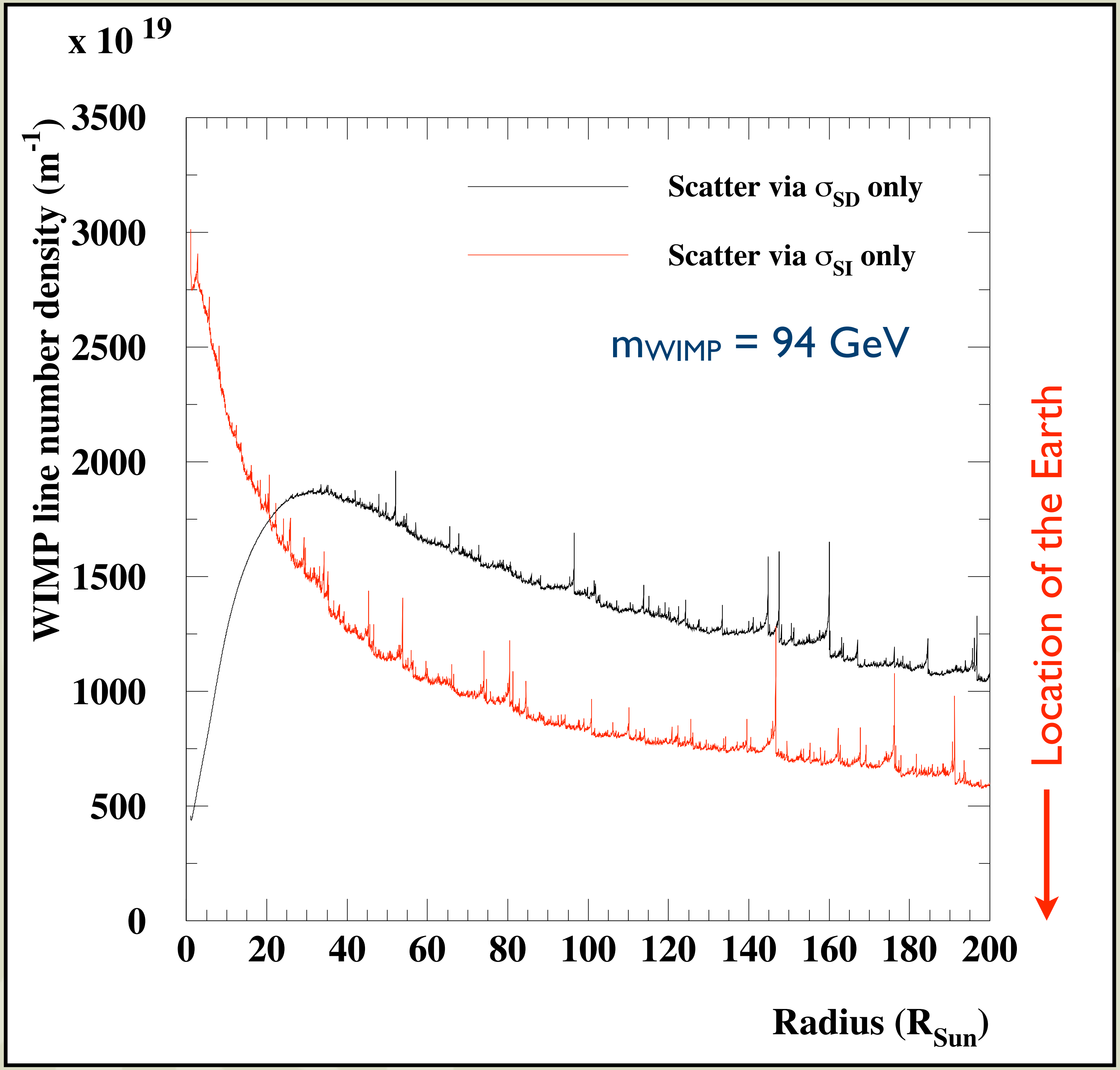
Monte Carlo setup

- We do this calculation with a Monte Carlo
  - choosing WIMPs from the halo velocity distribution, and
  - picking scattering energy losses, interaction places etc according to their probability distributions

Base parameters

- As a base set of parameters, we have chosen:
  - m_{WIMP} = 100, 300, 1000, 3000, 10000 GeV
  - $\sigma_{SI} = 10^{-5}$ pb
  - $\sigma_{SD} = 10^{-3}$ pb
- but results do not depend (much) on the cross sections.
- Lower cross sections means that the probability for the first scatter is lower. However, the lifetime of the orbits (and hence the contribution to the density) are then higher. These two effects exactly cancel (unless if the lifetime > age of the solar system)

Line number density after **one** scatter



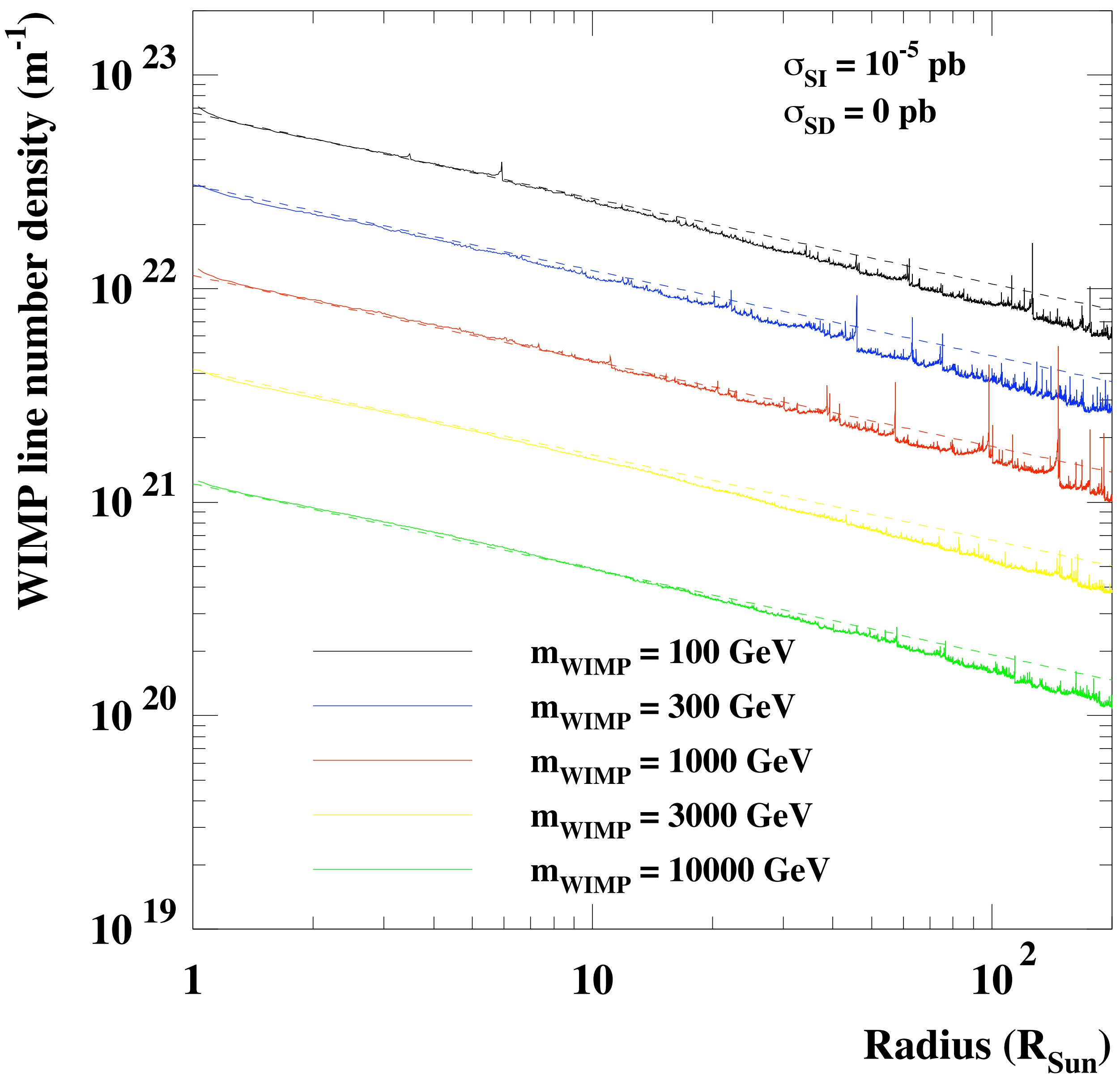
- The line number density, N, is the density of WIMPs (summing up all WIMPs on a given radius).
- The 3D number density, n, is given by

$$n(r) = \frac{N}{4\pi r^2}$$

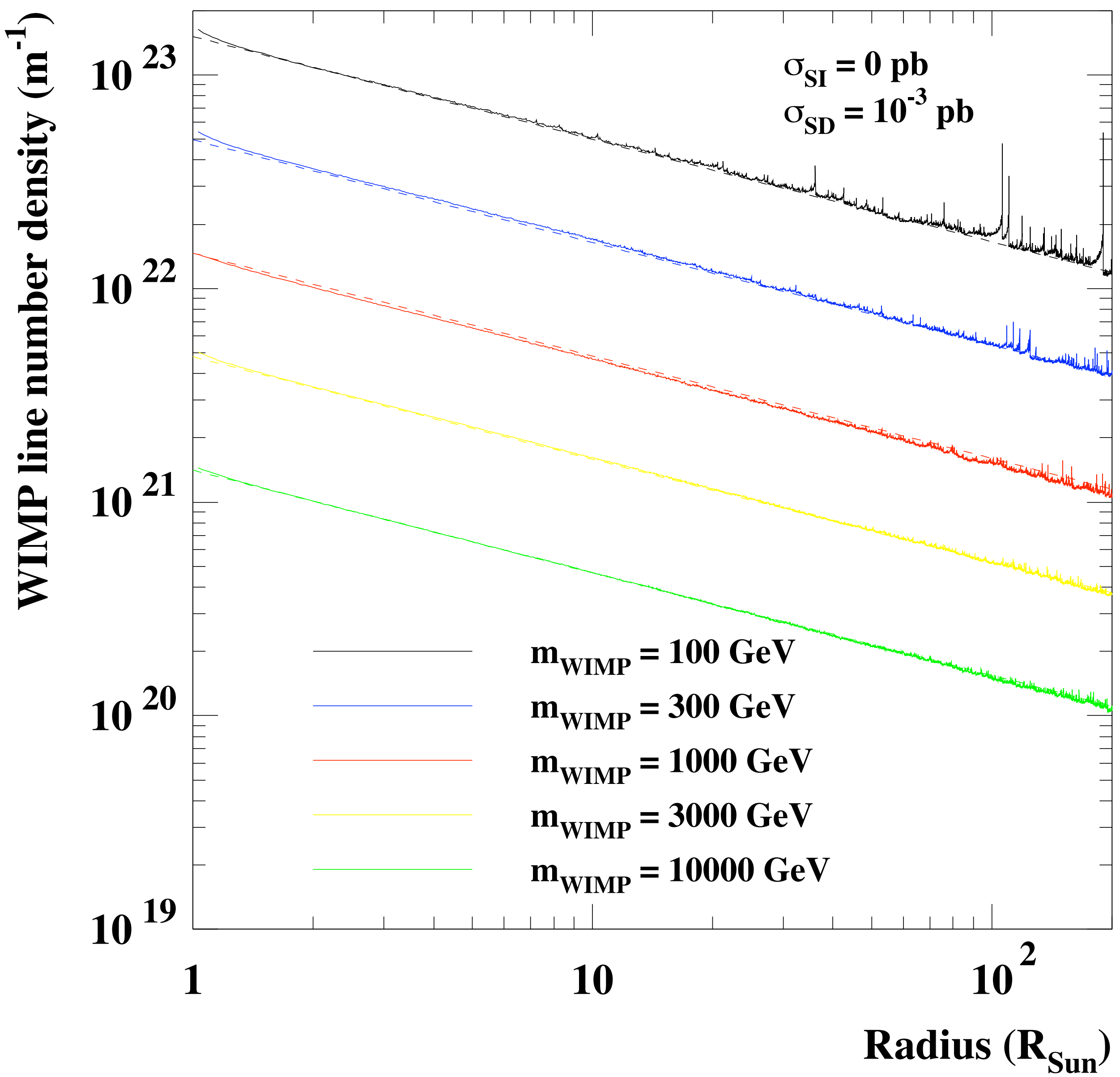
Peaks are due to long lifetime of improbable orbits (low statistics in the Monte Carlo)

Line density around the Sun

Spin-independent



Spin-dependent



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Fits to the line densities

- We can fit the line densities (the fit is optimized for low radii, where the density is the highest)

$$
\begin{aligned}
n^{SD} &= 10^{25.21-1.015x}\left(\frac{r}{r_\odot}\right)^{-0.48} \quad \mathrm{m}^{-1} \\
n^{SI} &= 10^{23.71-0.2332x-0.1056x^2}\left(\frac{r}{r_\odot}\right)^{-0.40} \quad \mathrm{m}^{-1} \\
\text{with } x &= \log_{10}\left(\frac{M}{1\ \mathrm{GeV}}\right).
\end{aligned}
$$

- The fit does not depend on the cross sections (unless for extremeley low cross sections).

Gamma ray production

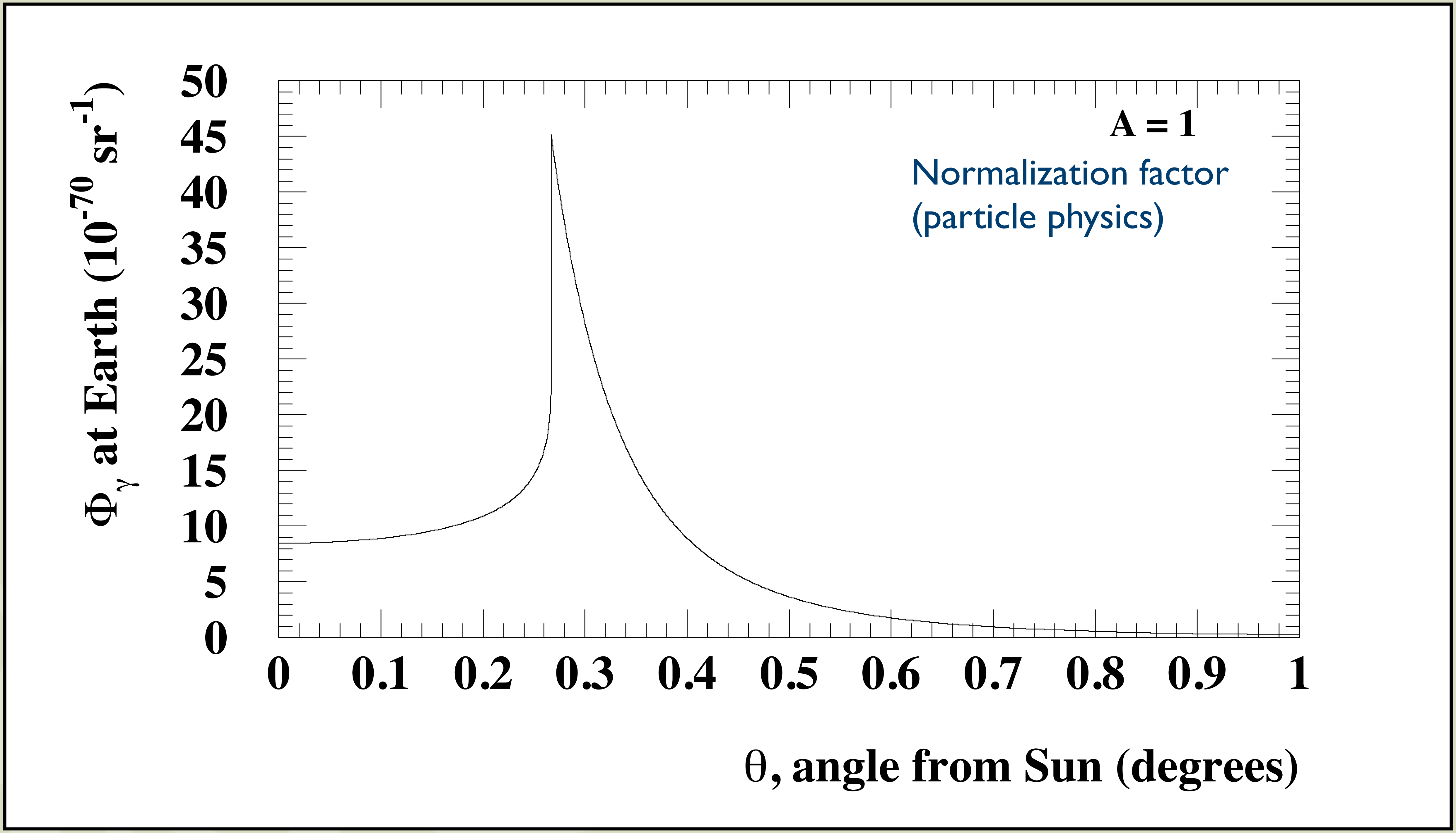
- Knowing the density of WIMPs around the Sun, we can write the flux of gamma rays at Earth as

Number of photons / annihilation

$$\frac{d\Phi_\gamma}{d\Omega} = \frac{1}{8\pi}\sigma v N_\gamma \int n^2(r)\, dl$$

where we just have to evaluate the line of sight integral for our given densities

Gamma ray fluxes



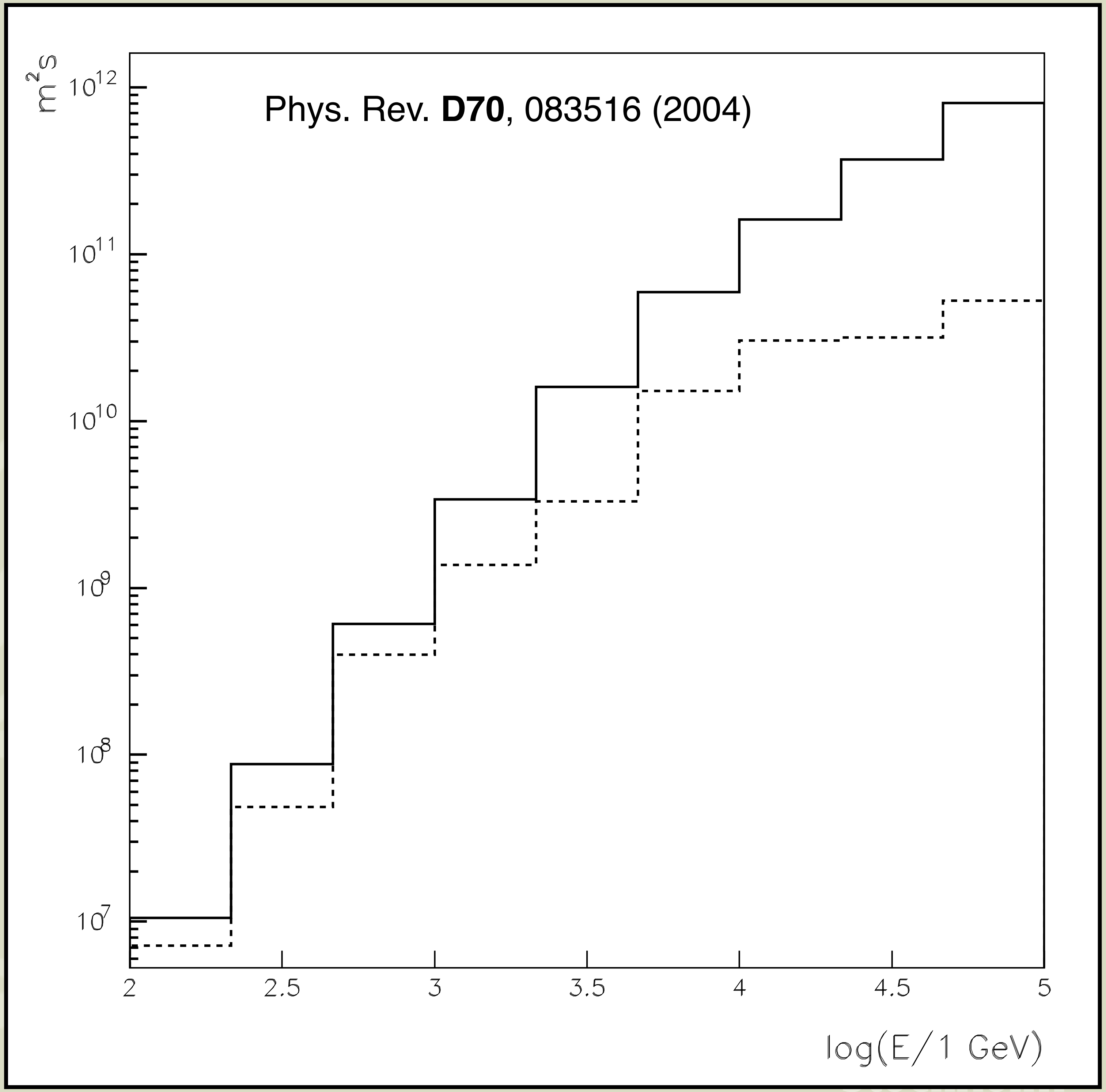
Putting in the numbers

- Now put in some typical numbers
  - $\sigma v = 10^{-26}$ cm^3/s
  - $N_\gamma = 20$
- We then get the following fluxes (m^{-2} s^{-1})

	$M = 100$ GeV	$M = 1$ TeV	$M = 10$ TeV
$\sigma_{sd} = 10^{-3}$ pb, $\sigma_{si} = 0$	$5.3 \cdot 10^{-19}$	$6.8 \cdot 10^{-21}$	$3.2 \cdot 10^{-23}$
$\sigma_{sd} = 0$, $\sigma_{si} = 10^{-5}$ pb	$1.1 \cdot 10^{-19}$	$3.7 \cdot 10^{-21}$	$5.5 \cdot 10^{-23}$

What about MILAGRO?

- Effective area for MILAGRO search (2004) for excess gamma events around the Sun
- Use this to convert our fluxes to events passing the MILAGRO search cuts



Absolute events

- Total number of events expected in the MILAGO search (2004).

Case \ Mass	100 GeV	1 TeV	10 TeV
$\sigma_{SD} = 10^{-3}$ pb $\sigma_{SI} = 0$	$5.3 \cdot 10^{-12}$	$4.1 \cdot 10^{-12}$	$1.9 \cdot 10^{-12}$
$\sigma_{SD} = 0$ $\sigma_{SI} = 10^{-5}$ pb	$1.1 \cdot 10^{-12}$	$2.2 \cdot 10^{-12}$	$3.3 \cdot 10^{-12}$

- Kind of hopeless...

Comparison with other work

- Let's calculate the fraction of annihilations in the Sun that occur outside the Sun (as compared to inside after complete capture)

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Our work	$f_{out} \sim 10^{-21} – 10^{-19}$

Tests done to check our code

- We have performed several tests to check our calculation:
  - with our Monte Carlo, we can calculate the total capture rate and compare with e.g. the formulae by Gould. They agree very well
  - We have also checked partial results to see that we retrieve the probability distributions we should
  - We have also made simplified semi-analytical calculations to get upper bounds on the annihilation in the WIMP halo around the Sun. They give results a few orders of magnitude higher than our full Monte Carlo, i.e. consistent with our results.

Possible effect of Jupiter

- In our setup, we treat the WIMP-Sun system as an isolated 2-body system
- This is clearly an approximation as the planets can perturb the WIMP orbits
- According to Annika Peter that has performed recent detailed simulations of WIMP diffusion in the solar system, Jupiter will perturb orbits that reach out to it:
  - on a timescale ~10^4 years, orbits intersecting the Sun, will be moved outside the Sun
  - on a timescale ~10^6 years, orbits will be thrown out of the solar system
- The first effect means that we could have underestimated the lifetime of some orbits by a factor of up to 100.
- The second effect means that we could have overestimated the contribution from some orbits by (as we have the age of the solar system as cut-off, not 10^6 years)
- Preliminary results show that the effect seems to be very small, and in either case, it cannot give us the many, many orders of magnitude needed to see a signal.

Conclusions

- We have performed a careful 3D Monte Carlo simulation of the WIMP halo around the Sun to estimate the possible gamma ray signal from it
- The gamma ray signal is very, very small and hopeless to detect with e.g. Milagro.