

ReD – Recoil Directionality Studies in Two-Phase Liquid Argon TPC Detectors

The background of the slide is a dark blue-grey color with a faint, light-colored constellation map of Orion. The map shows the Orion constellation with its characteristic belt and sword. Several stars are labeled with white text: 'Deneb' is located near the top left, 'Vega' is near the top center, and 'Altair' is near the bottom center. The constellation lines are thin and light-colored, creating a subtle pattern across the slide.

Matteo Cadeddu on behalf of the ReD collaboration

ICNFP2016, 5th International Conference on New Frontiers in Physics
6-14 July 2016

The RED Collaboration

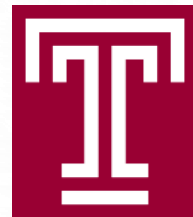
Italy (INFN):

University of Napoli Federico II,
University of Roma, University of Cagliari,
University of Genova, University of Pisa, LNGS, LNS, TIFPA



International Collaborators:

APC-IN2p3, Princeton University, Temple, UCLA



Facing the problems of past and future WIMP detection

Upcoming direct dark matter detection experiments will have sensitivity to detect neutrinos from several astrophysical sources (Sun, atmosphere, and diffuse Supernovae).

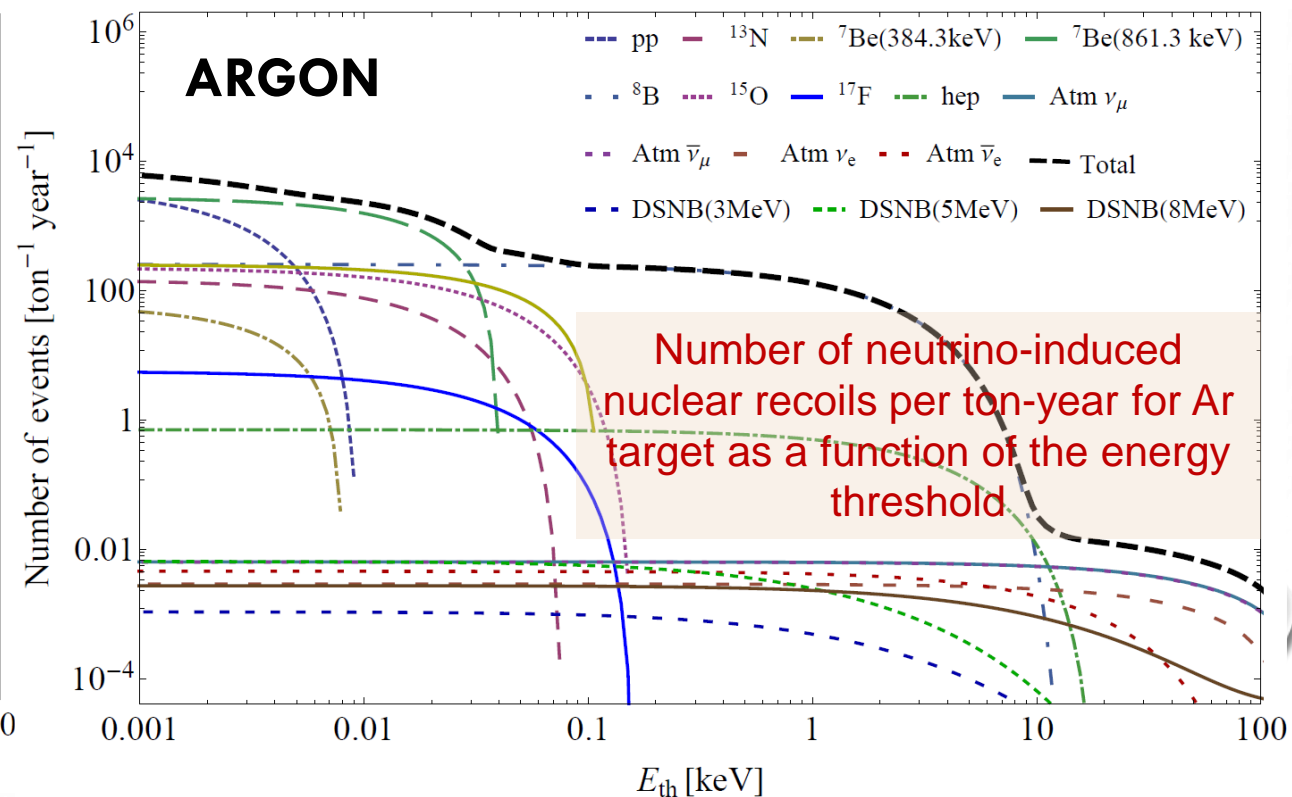
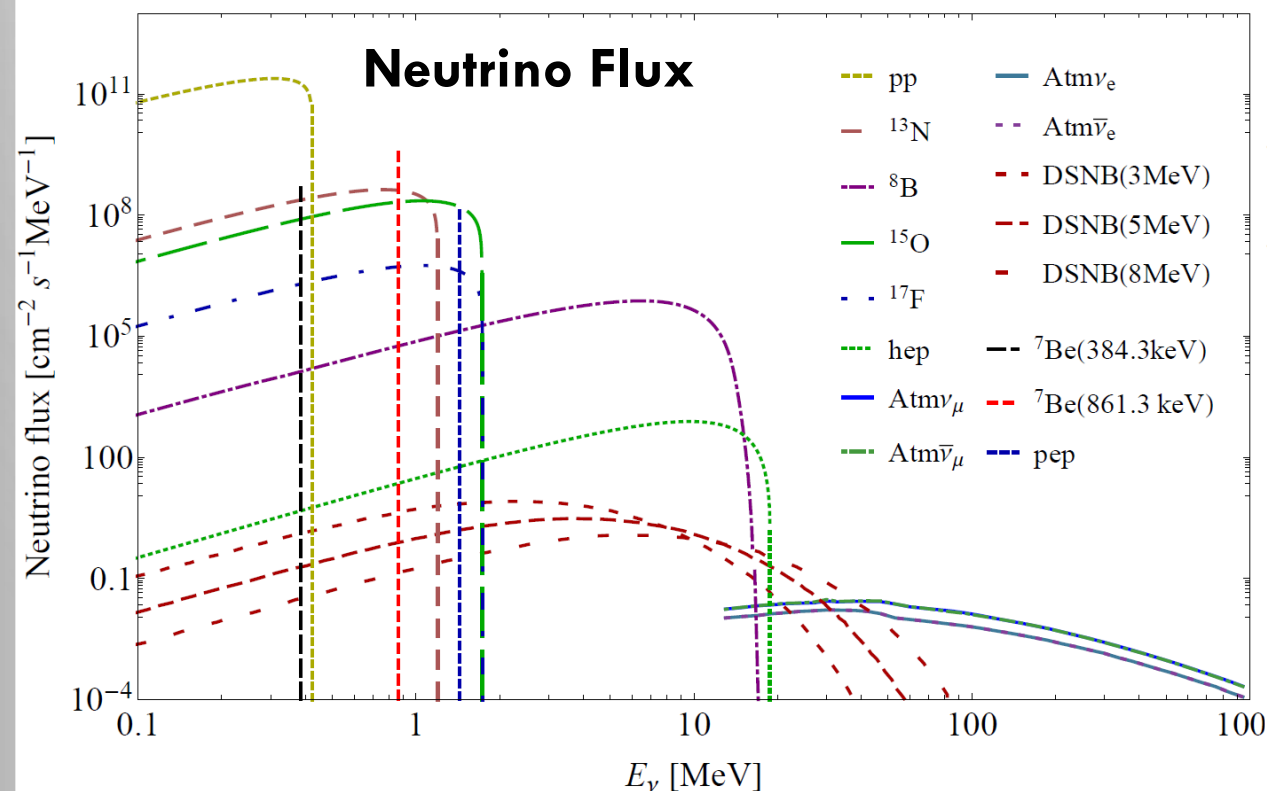
Coherent neutrino scattering on Nucleus (CNS)

$$\nu_x + (A, Z) \rightarrow \nu_x + (A, Z)$$

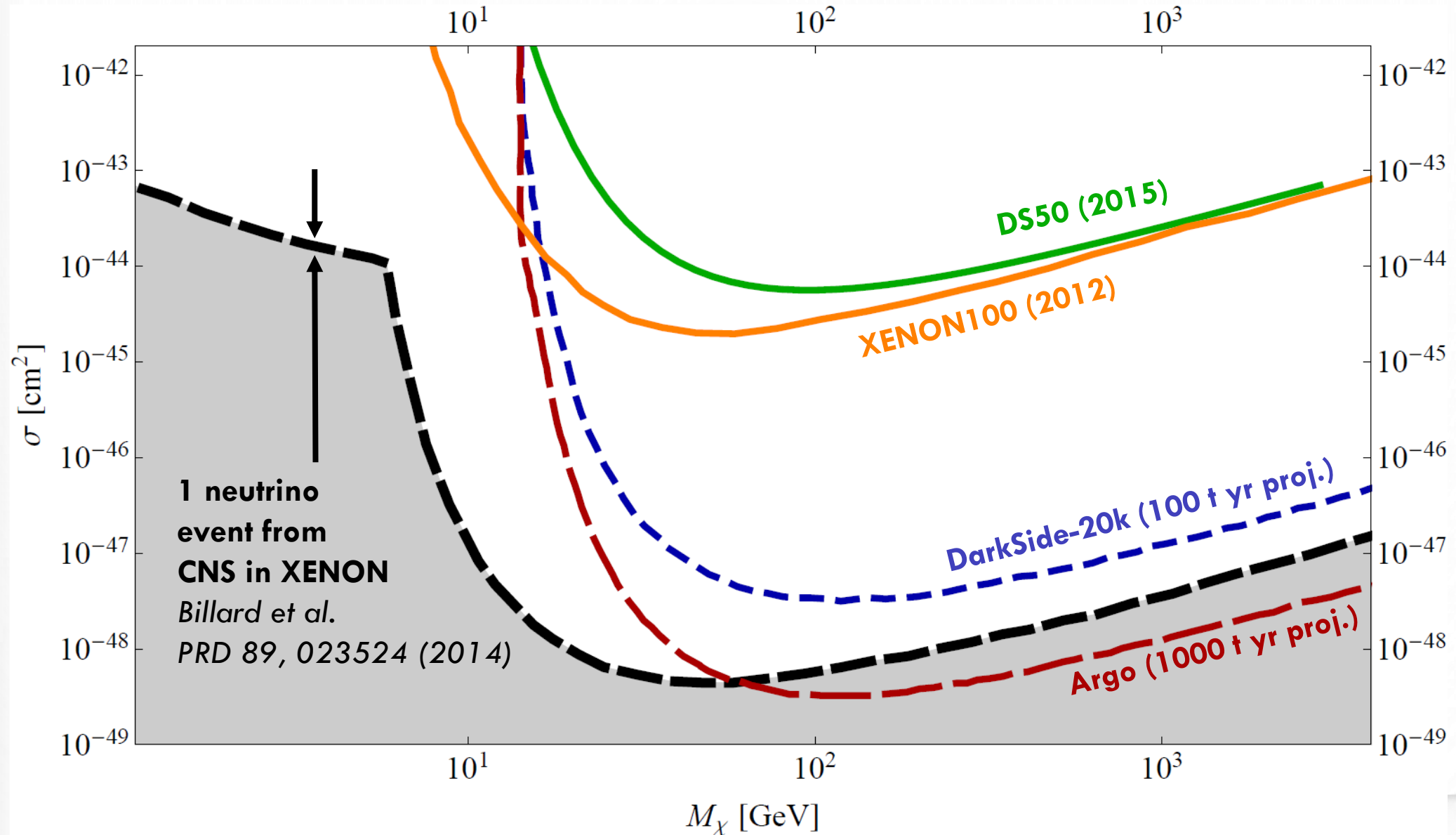
$$\frac{d\sigma^{CNS}(E_\nu, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_w^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F^2(E_r)$$

$$Q_w = N - (1 - 4\sin^2 \theta_W)Z$$

$$E_r^{max} = \frac{2E_\nu^2}{m_N + 2E_\nu}$$



The neutrino floor (Neutrinos as a background)



Searching for the Wimp wind

- **Non rotating Wimp Halo + Barionic matter rotation**



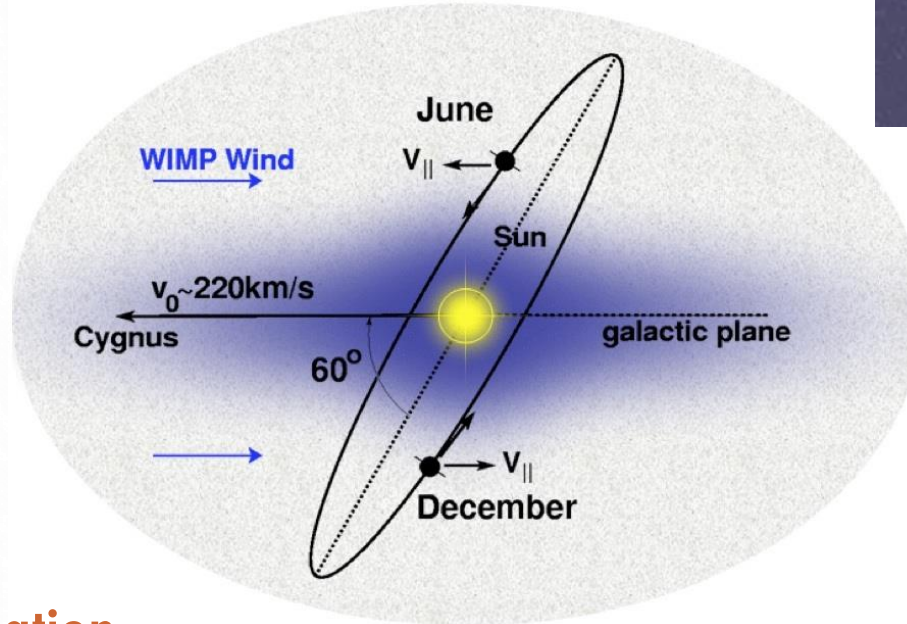
Apparent Wimp wind

Solar System orbit at $v_0 \sim 220$ km/s around the galactic center

Standard technique:

- **Annual rate modulation**

Earth orbits at $v_E \cong \pm 30$ km/s
(few % effect)



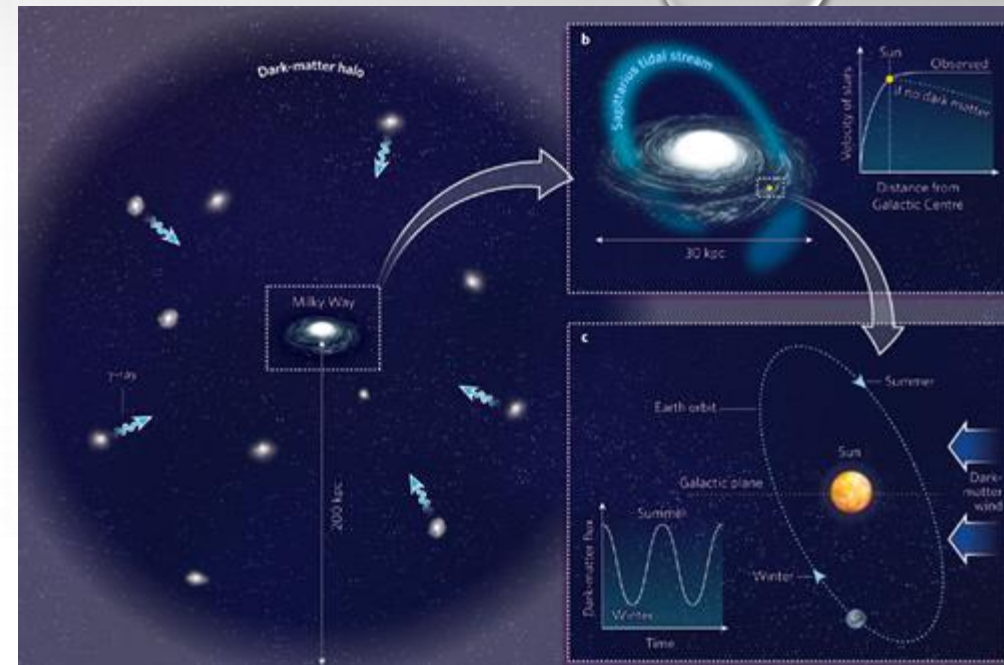
Innovative technique:

- **Sidereal direction modulation**

Measuring the angle between WIMP and Earth gives a directionality signature unique to WIMPs.



Directionality may be the most robust signature of the WIMP nature of DM



BUT: Background may be also annual modulated!

The standard WIMP recoil spectrum

Standard **non-directional recoil spectrum**, i.e. differential event rate **per unit detector mass**:

$$\frac{dR}{dE_r} =$$

$$\frac{\sigma_{w-n}}{2M_w \mu_n^2}$$

\times

$$A^2 F^2 (E_r)$$

\times

$$\rho \int_{v>v_n} \frac{f(v)}{v} d^3v$$

Physics

$\sigma_{w-n} \rightarrow$ WIMP-nucleon cross section

$M_w \rightarrow$ WIMP mass

$\mu_n \rightarrow$ WIMP-nucleon reduced mass

Detector

$A \rightarrow$ atomic mass of target material

$F(E_r) \rightarrow$ The finite size of the nucleus is implemented with **Helm form Factor**

Astrophysics (DM halo properties)

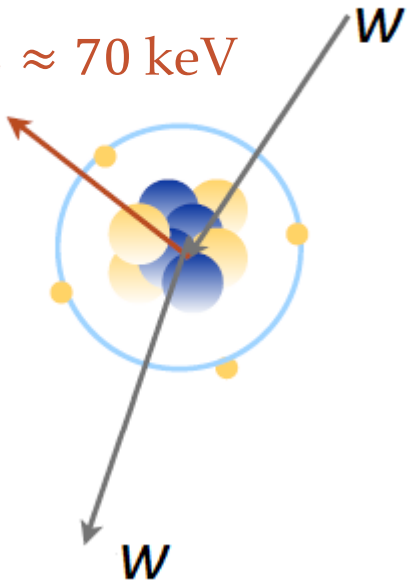
$\rho \rightarrow$ WIMP mass density

$f(v) \rightarrow$ WIMP velocity distribution

$v_n \rightarrow$ minimum WIMP speed required to transfer an energy E_r to the nucleus of mass M_n in the detector.

Recoiling nucleus

$E_r \approx 70 \text{ keV}$

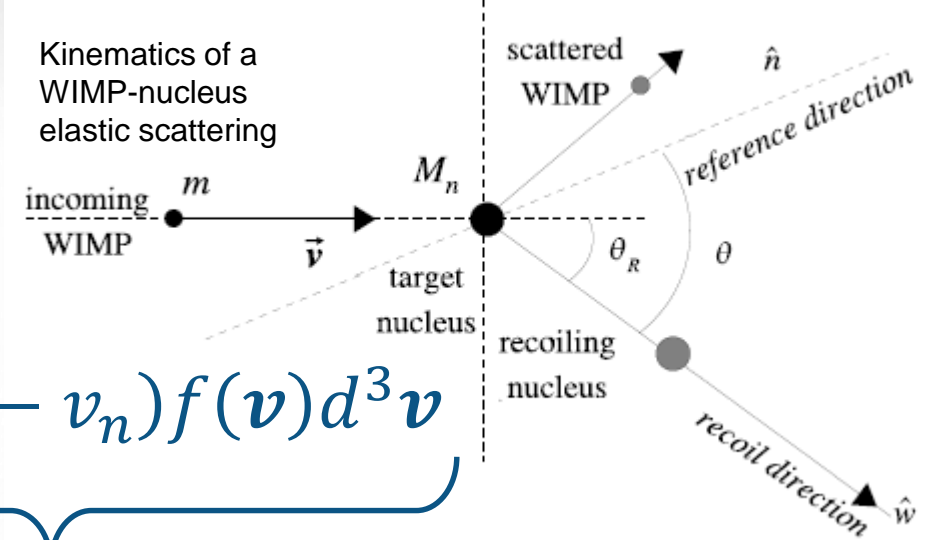


$E_r \rightarrow$ Recoiling nucleus energy

A closer look to directionality

Double differential directional recoil spectrum:

$$\frac{dR}{dE_r d\Omega(\theta, \phi)} = \frac{\sigma_{w-n}}{4\pi M_w \mu_n^2} A^2 F^2(E_r) \rho \underbrace{\int \delta(\mathbf{v} \cdot \mathbf{w} - v_n) f(\mathbf{v}) d^3\mathbf{v}}_{\text{Radon transform}} \quad \text{Kinematics of a WIMP-nucleus elastic scattering}$$



Radon transform $\equiv \hat{f}(v_n, \mathbf{w})$

$$\Rightarrow \hat{f}(v_n, \mathbf{w}) = \frac{1}{\sqrt{2\pi\sigma_v^2}} \exp \left[-\frac{1}{2} \frac{(v_n - \mathbf{w} \cdot \mathbf{V})^2}{\sigma_v^2} \right]$$

If we assume the **Standard Halo Model (SHM)**, i.e., an **isotropic Maxwell-Boltzmann** WIMP velocity distribution of width σ_v in a inertial reference frame at rest with respect to the Galactic center.

Here \mathbf{V} is the average velocity of the WIMPs with respect to the detector:

$$\mathbf{V} = -\mathbf{V}_{SG} - \mathbf{V}_{ES}$$

- \mathbf{V}_{SG} : velocity of the **Sun relative to the Galactic center**.
- \mathbf{V}_{ES} : velocity of the **center of mass of the Earth relative to the Sun**

To evaluate the Radon transform we had to calculate explicitly the scalar products $\mathbf{w} \cdot \mathbf{V}_{ES}$ and $\mathbf{w} \cdot \mathbf{V}_{SG}$ in a defined **reference frame**.

Assumptions and choice of parameters

Astrophysics:

$$\rho = 0.3 \text{ GeV } c^{-2} \text{ cm}^{-3} \text{ (Dark Matter density) ;}$$
$$v_0 = 220 \text{ km } s^{-1};$$

Physics:

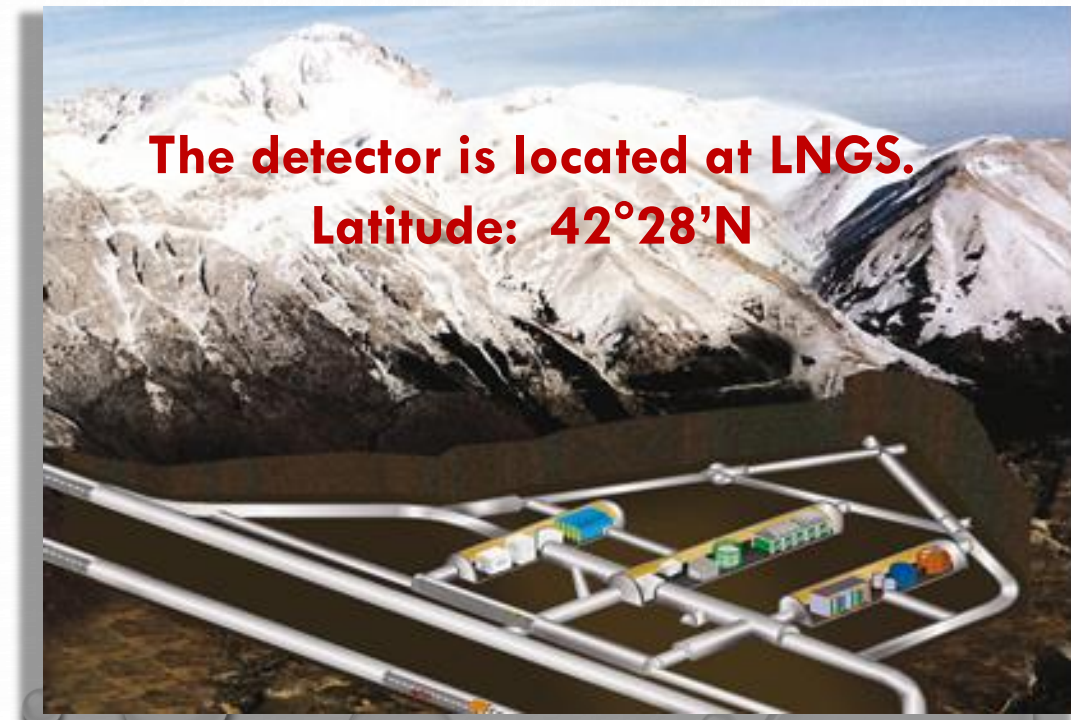
$$\sigma_{W-n} = 10^{-46} \text{ cm}^2 \text{ (Wimp-nucleon cross section) ;}$$
$$M_W = 200 \text{ GeV } c^{-2} \text{ (Wimp mass) ;}$$

Detector:

$$E_{min}^{th} = 50 \text{ keV (Minimum threshold Energy) ;}$$

$$E_{max}^{th} = 200 \text{ keV (Maximum Energy) ;}$$

$$\text{Exposure} = 100 \text{ tonne year ;}$$



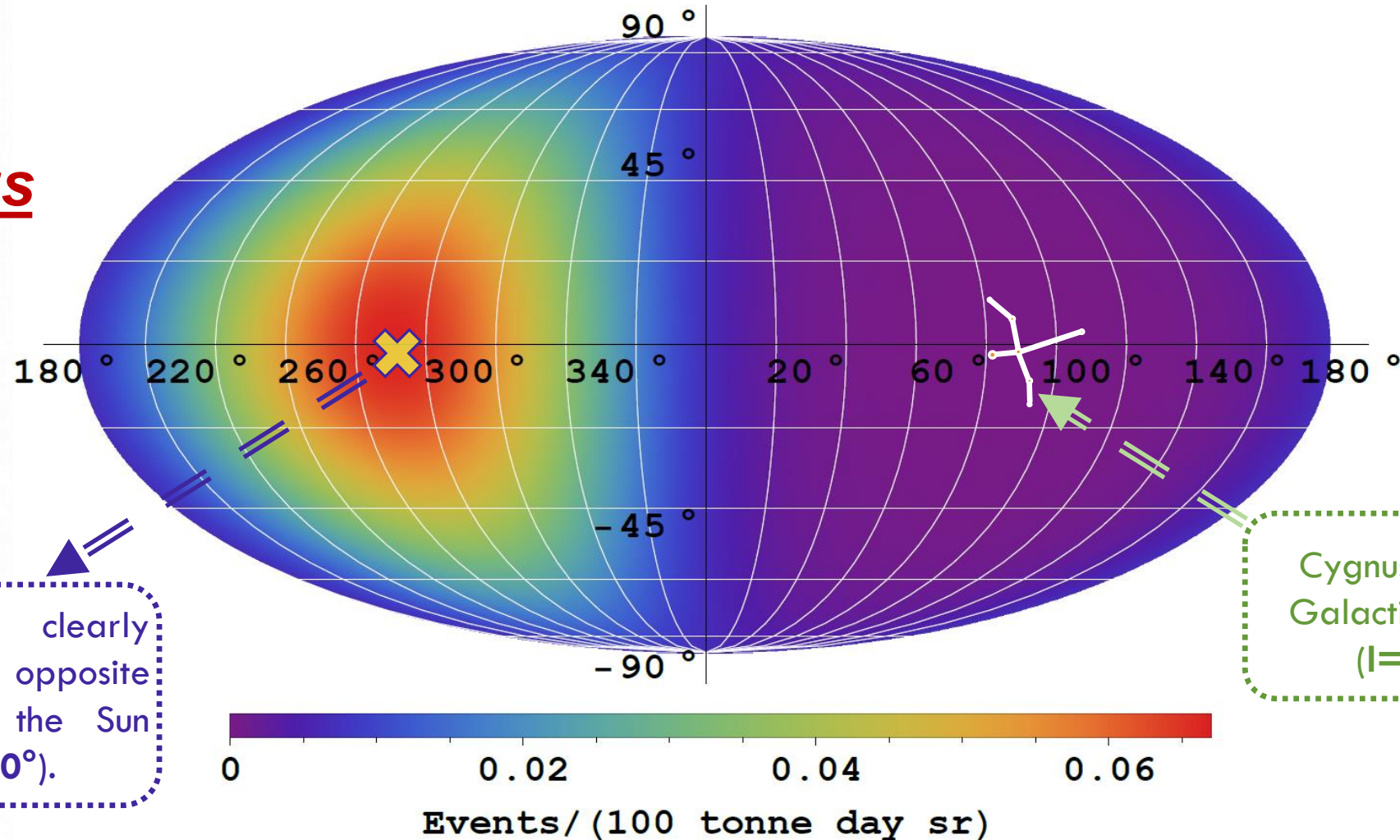
The detector is located at LNGS.
Latitude: 42°28'N

Wimp directionality in Galactic frame

$$\frac{dR}{d \cos \vartheta d\varphi} = \int_{50 \text{ keV}}^{200 \text{ keV}} \frac{dR}{dE_r d \cos \vartheta d\varphi} dE_r$$

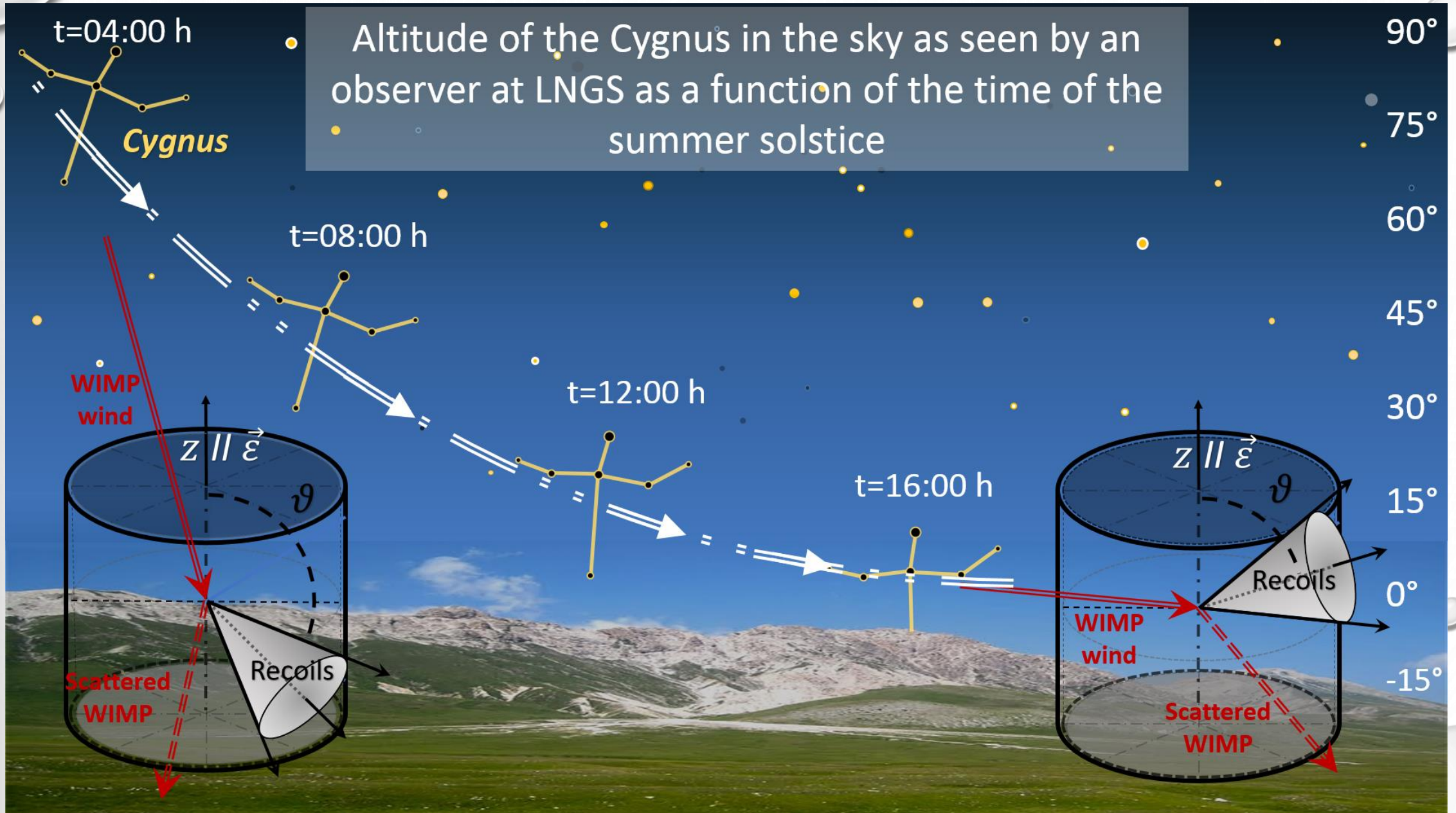
In the Galactic coordinate system x points from the Sun towards the Galactic center, y in the direction of the Solar motion and z towards the Galactic north pole; therefore, $\mathbf{V} = \mathbf{V}_{\text{SG}} \mathbf{y}$.

**Unambiguous
difference
between
WIMP and
background!**



The recoil rate is clearly anisotropic and points opposite to the direction of the Sun motion ($l = 270^\circ; b = 0^\circ$).

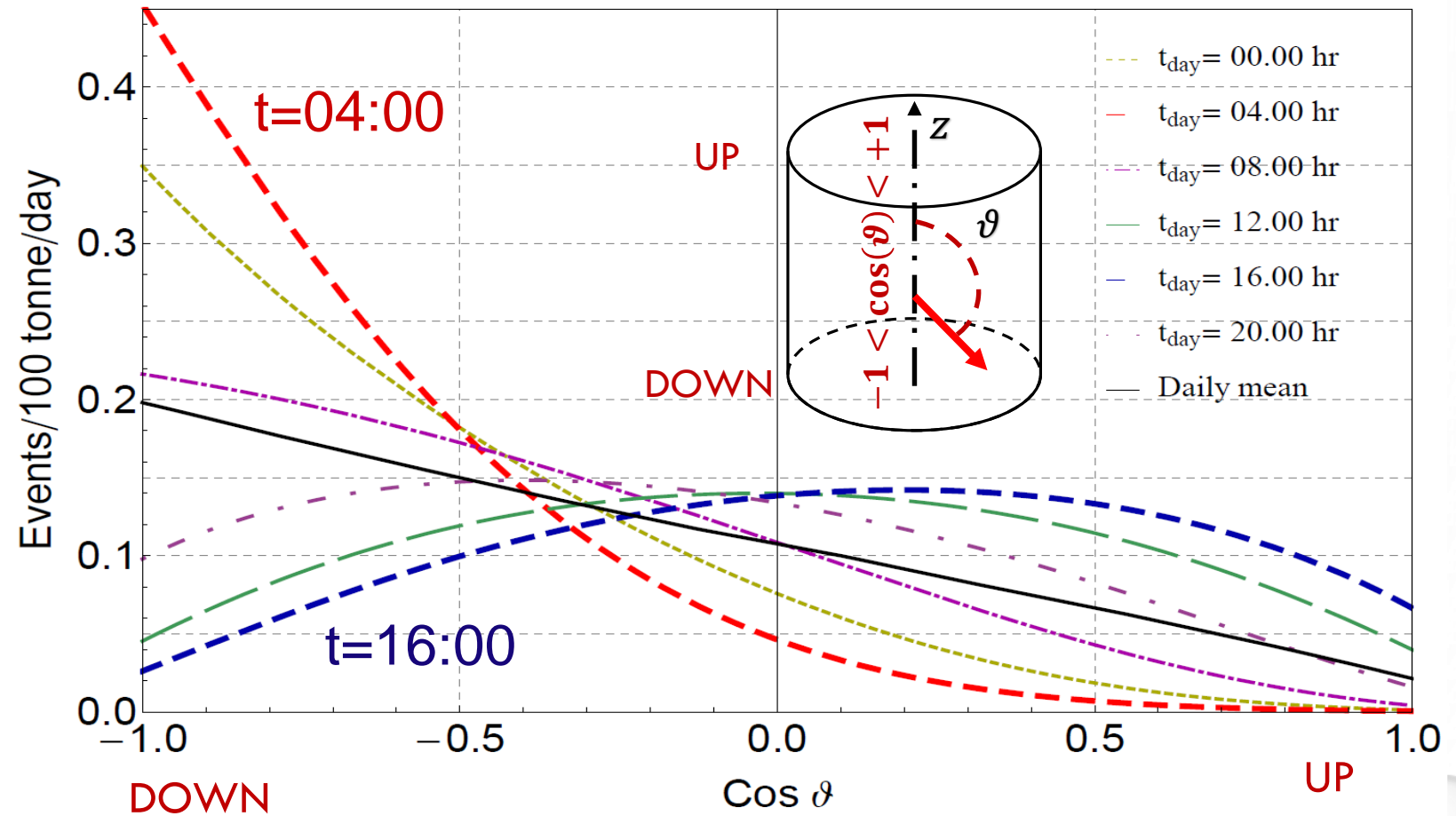
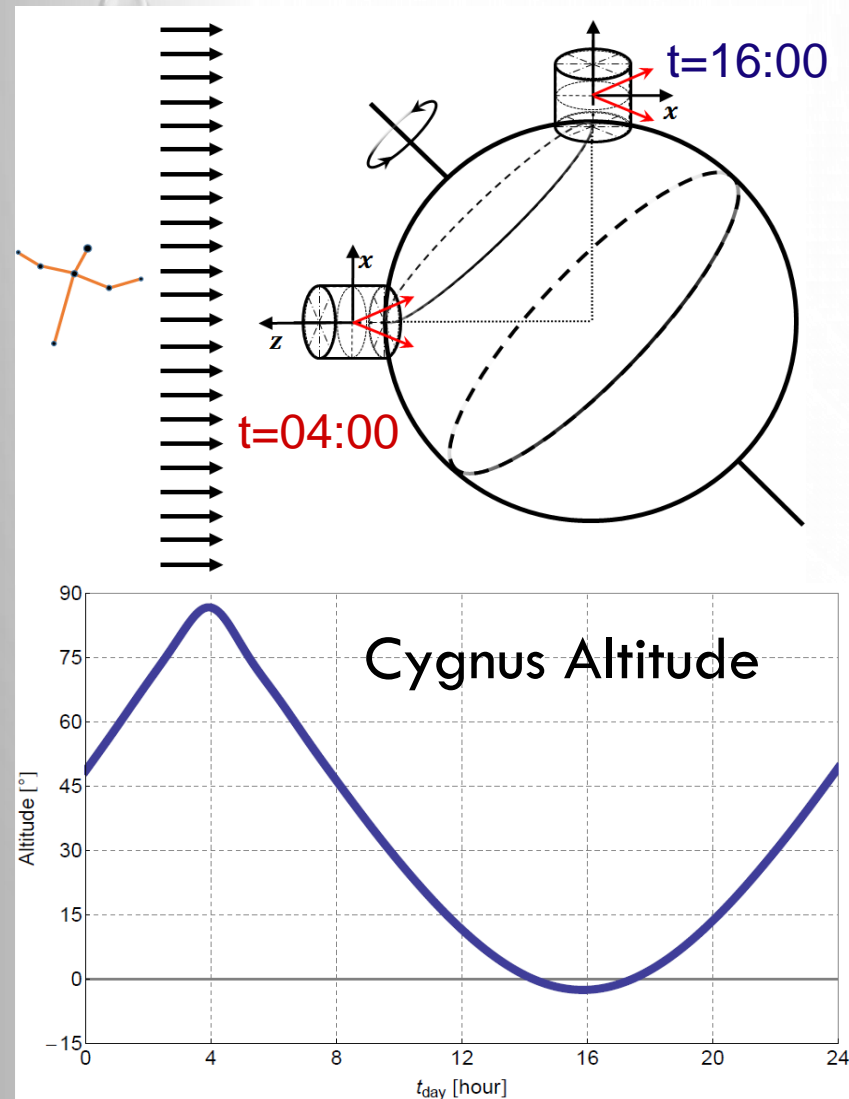
As seen in a Earth-bound detector (@LNGS)



As seen in the laboratory (LNGS)

*The azimuthal ϕ angle is integrate $[0, 2\pi]$

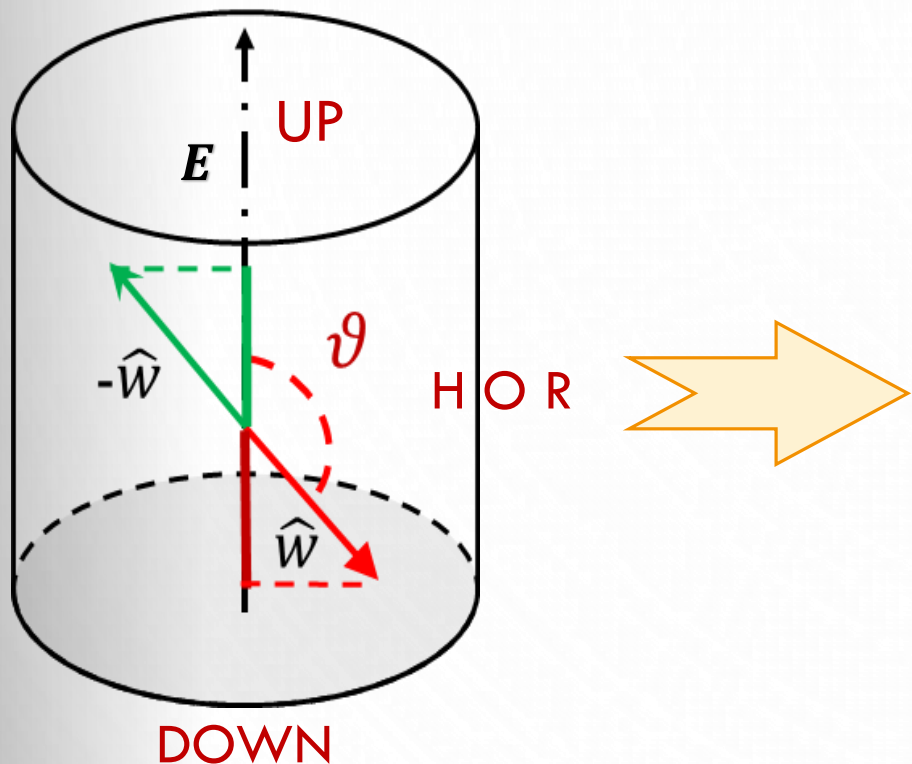
For an Earth-bound laboratory the velocity \mathbf{V} can be decomposed as $\mathbf{V} = -\mathbf{V}_{\text{SG}} - \mathbf{V}_{\text{ES}}$, where \mathbf{V}_{ES} is the Earth velocity relative to the Sun, $|\mathbf{V}_{\text{ES}}| \cong 29.8 \text{ km/s}$. The detector is a rotating reference frame.



Strong angular dependence of the event rate with respect to the z-axis of the detector as a function of the time of the day. The dependence remains also when it is mediated over the full day (black line: "Daily average").

Columnar recombination detector

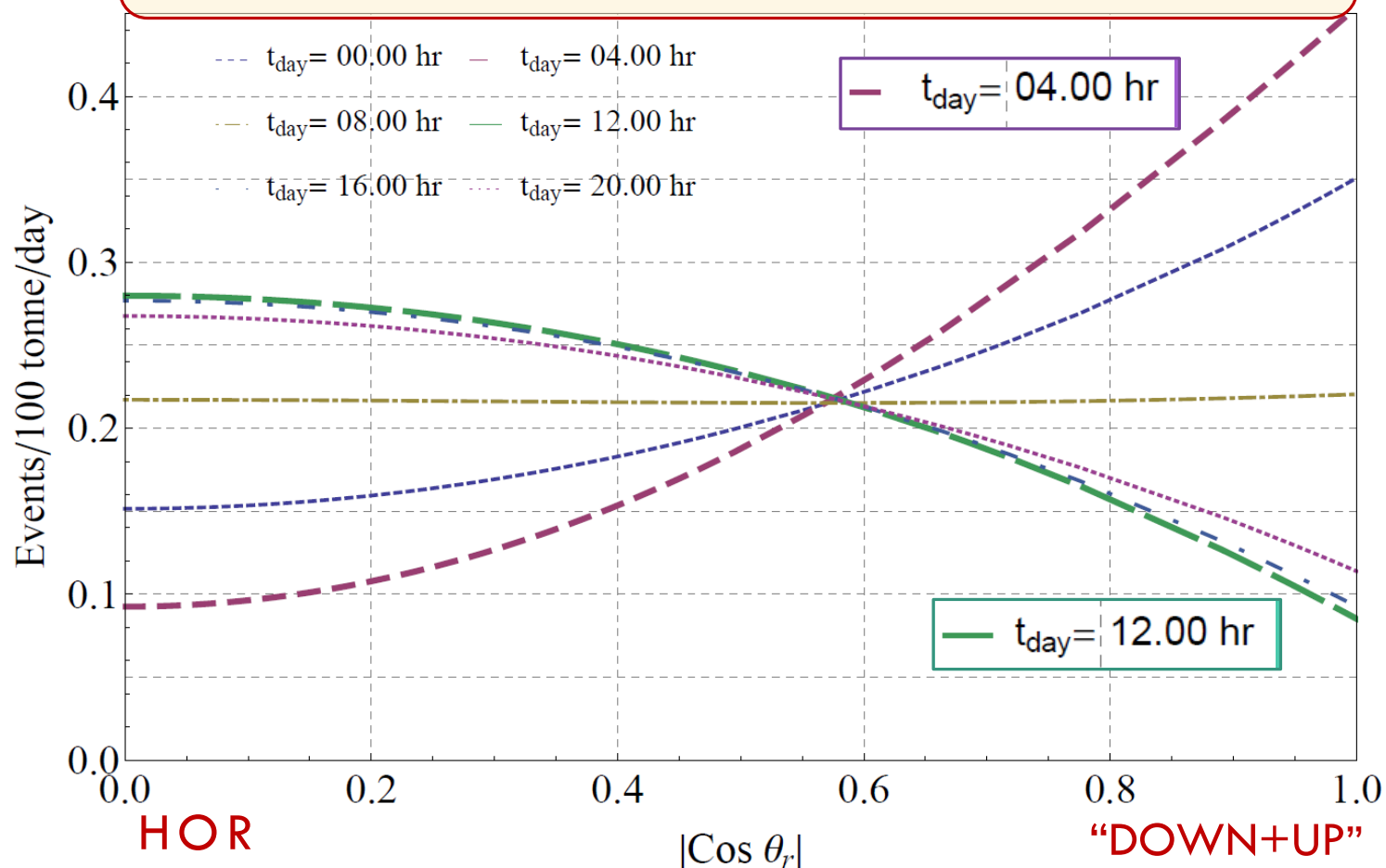
Recoils at 180° give the same signal in detectors based on **CR**



Columnar Recombination may display a sensitivity to the angle between nuclear recoil direction and drift field E in a LAr TPC.

We introduce a **"folded"** recoil rate:

$$\frac{dR_F(|\cos \vartheta|)}{d \cos \vartheta} \equiv \frac{dR(\cos \vartheta)}{d \cos \vartheta} + \frac{dR(-\cos \vartheta)}{d \cos \vartheta}$$



Strong angular dependence of the event rate with respect to the z-axis of the detector as a function of the time of the day

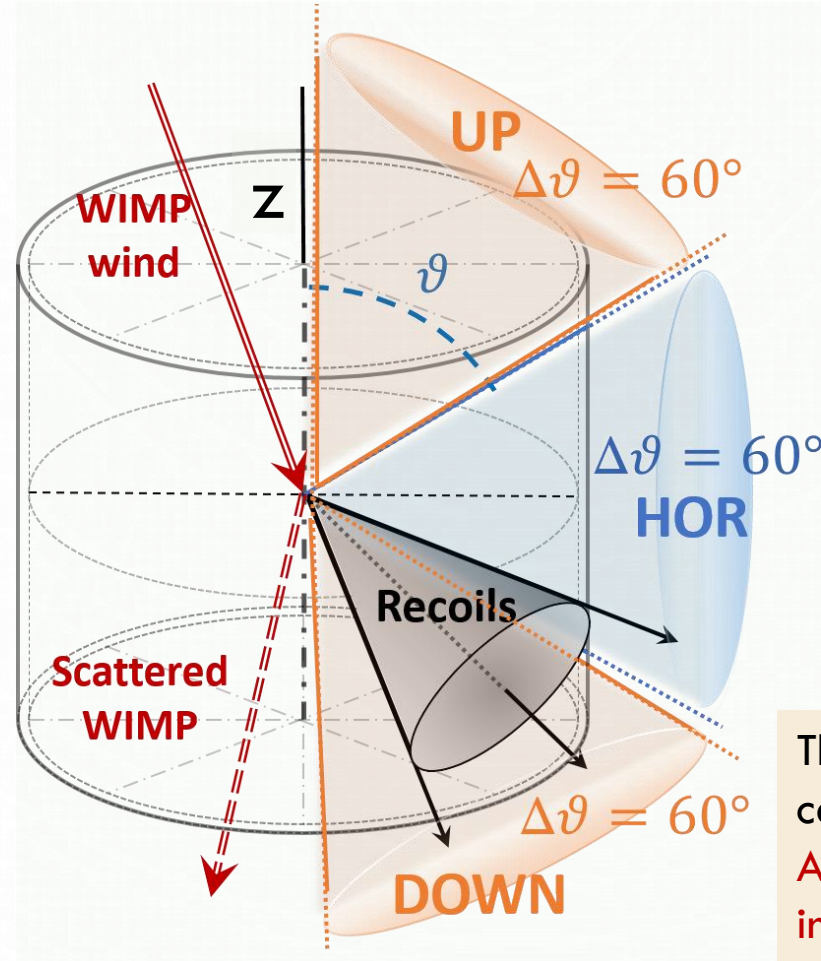
The division of the events

In case of minimal angular resolution

A way to categorize the events is to introduce the **UP** events corresponding to $(\vartheta < 120^\circ)$.

The **horizontal events (HOR)**, corresponding to $|\cos \vartheta| < 0.5$ ($60^\circ < \vartheta < 120^\circ$) and **DOWN** events ($\vartheta > 120^\circ$).

A **CR** based detector should be unable to discriminate between **UP** and **DOWN**. We introduce the **vertical events (VER)**, corresponding to $|\cos \vartheta| > 0.5$ ($\vartheta < 60^\circ$ and $\vartheta > 120^\circ$).



Ratio HOR/VER

From an experimental point of view, ratios of event rates are useful quantities in order to keep the systematic uncertainties budget under control.

An interesting observable is the ratio between HOR and VER events

$$R = \frac{HOR}{UP + DOWN} = \frac{HOR}{VERTICAL}$$

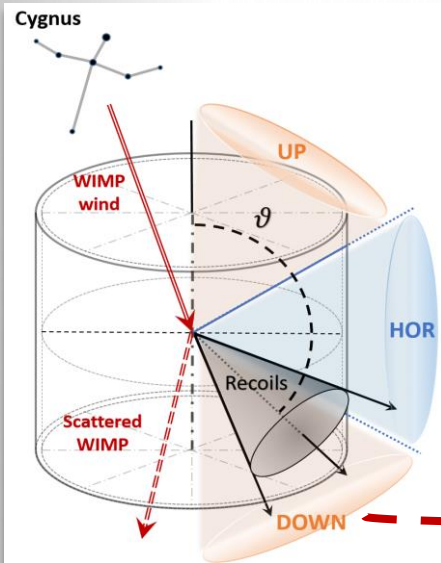
This **ratio** should be exactly equal to one in the case of isotropic signal.

Any significant deviation would be a strong indication in favor of a genuine WIMP signal.

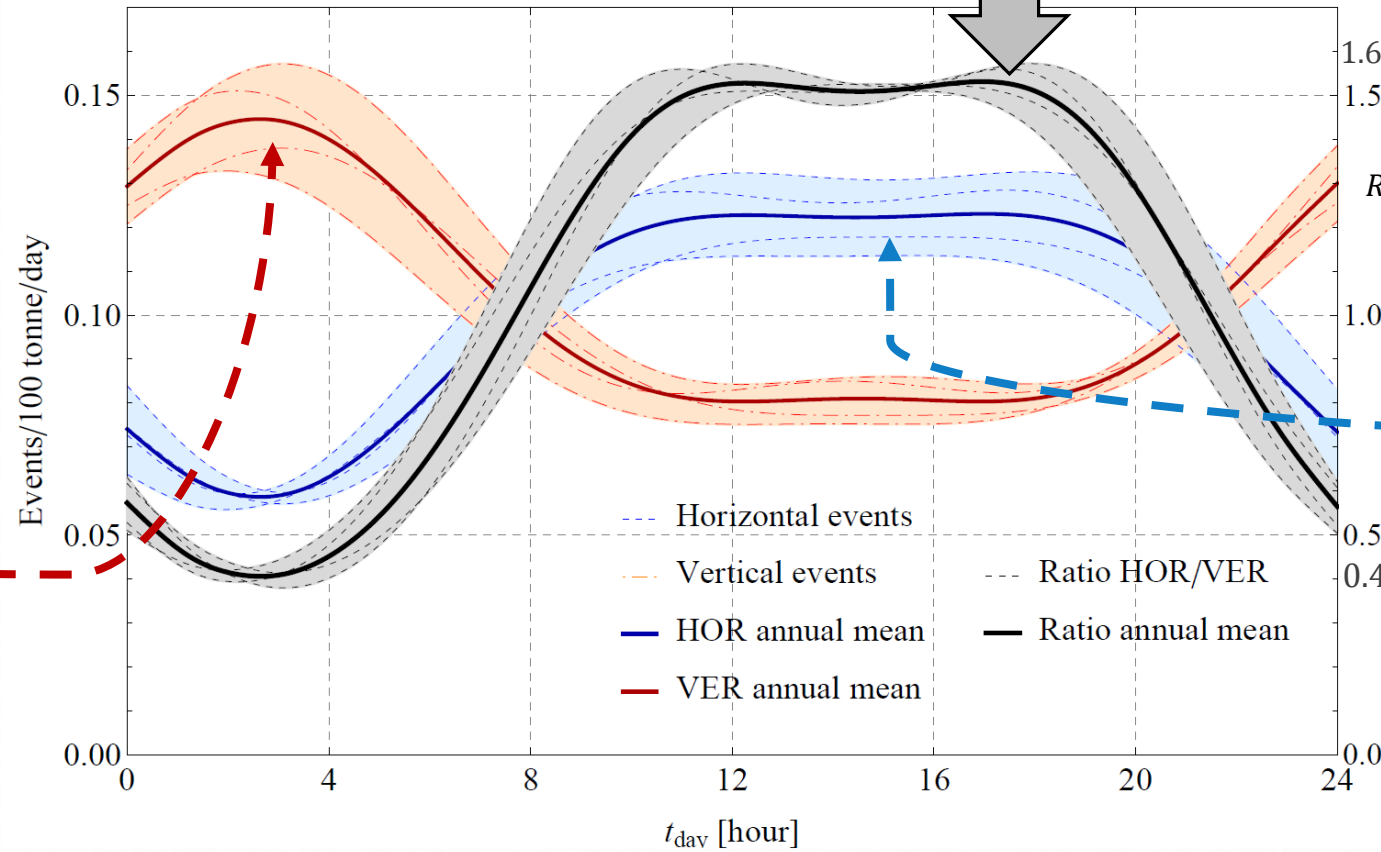
Event ratio Horizontal/Vertical

$$R = \frac{HOR}{UP + DOWN} = \frac{HOR}{VERTICAL}$$

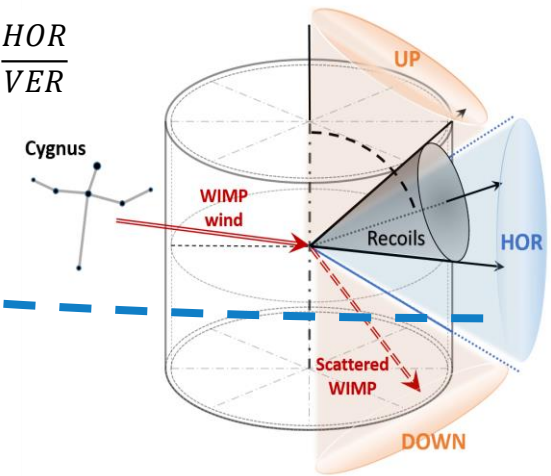
The ratio of **horizontal** to **vertical** events is shown by the black line. It exhibits a huge variation of **a factor 4** during the day.



Cygnus close to the zenith:
vertical events are greater than **horizontal** ones at the beginning of the day, until 8:00 a.m.



The single **horizontal** (**vertical**) component shows a huge variation within a sidereal day, more precisely a **38%** (**30%**) effect with respect to the average.

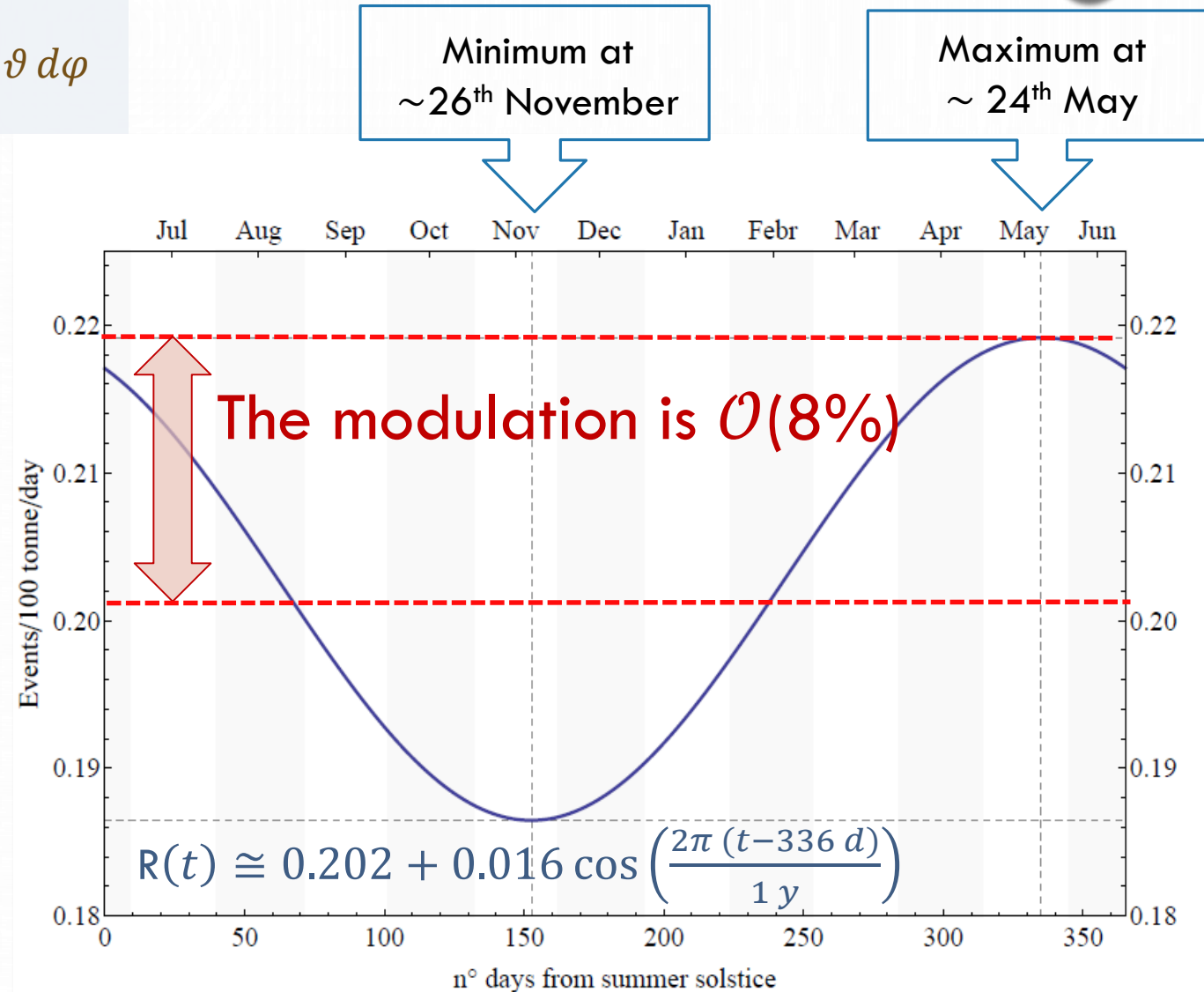
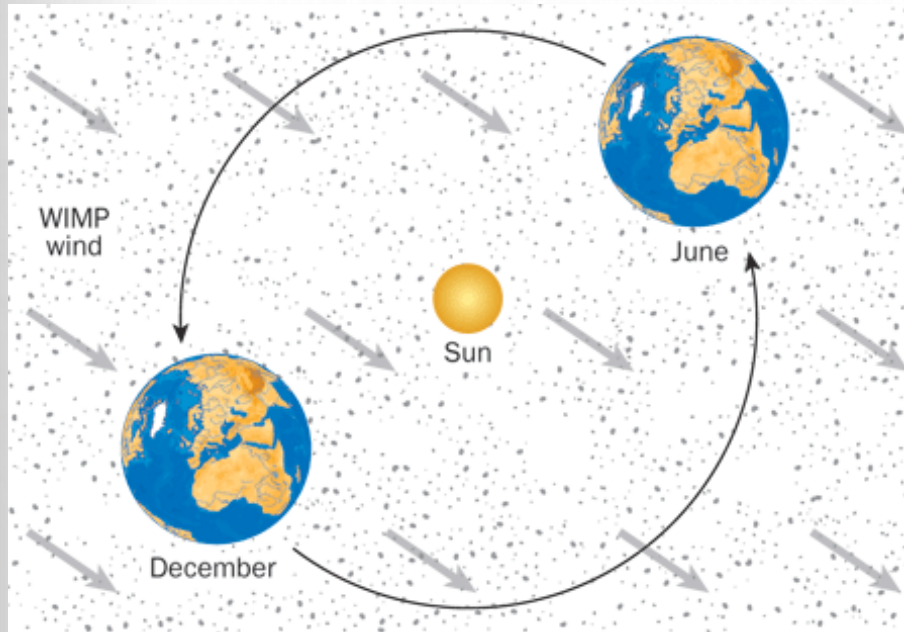


Cygnus close to the horizon:
horizontal events are greater than **vertical** ones in the middle of the day, after 8:00 a.m.

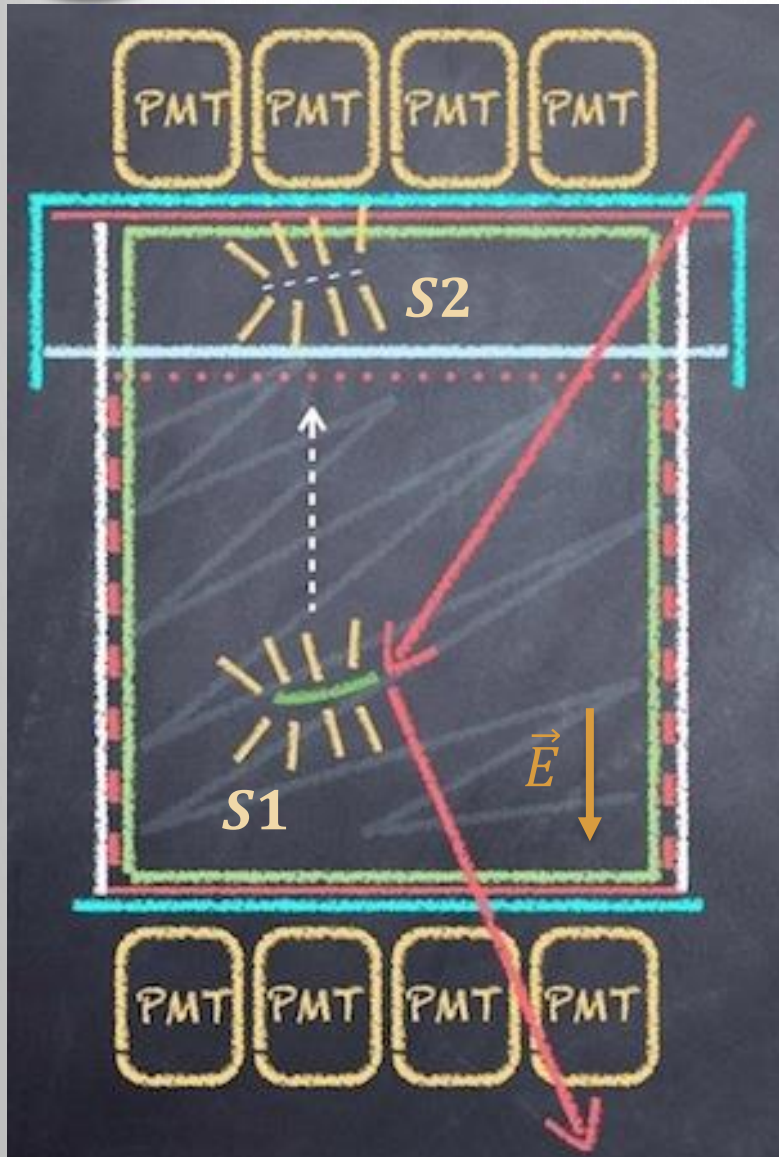
Annual rate modulation without directionality

$$R(t) = \int_0^{2\pi} \int_{-1}^1 \int_{E_{th}=50 \text{ keV}}^{E_{th}=200 \text{ keV}} \frac{dR}{dE_r d \cos \vartheta d\varphi} dE_r d \cos \vartheta d\varphi$$

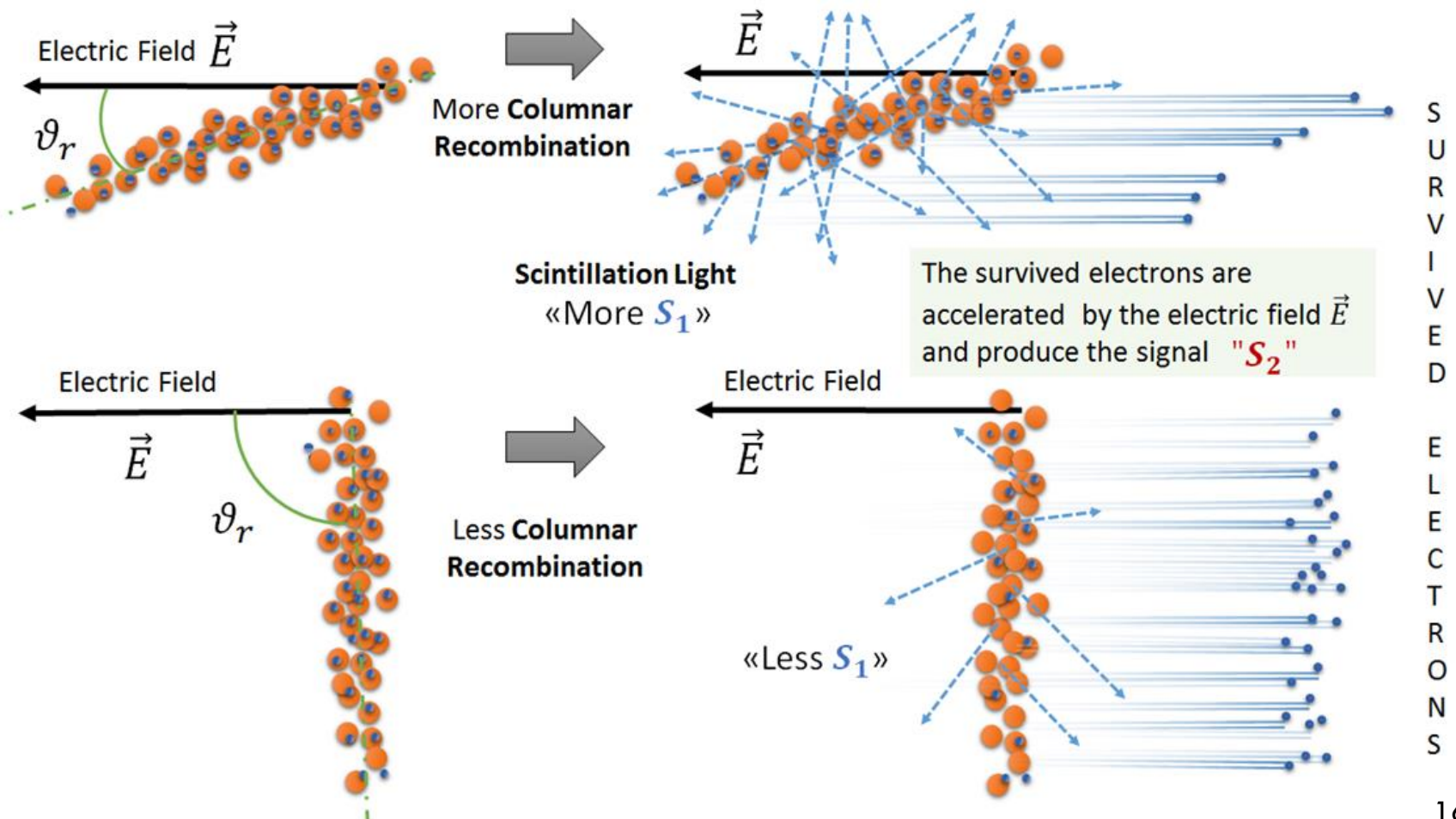
The amplitude of the modulation is small and, up to the first approximation, the event rate can be written as a Taylor series $R(t) \cong R_0 + R_m \cos\left(\frac{2\pi(t-t_0)}{T}\right)$; with the condition that $|R_m| \ll R_0$



Two-phase LAr detector: S1 and S2 signal

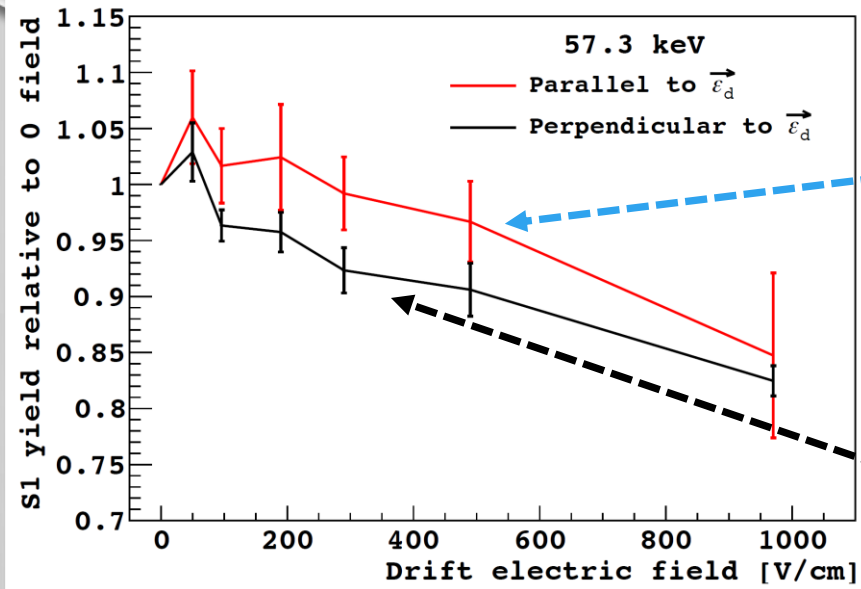


The basic idea of Columnar Recombination: When a nuclear recoil is *parallel* to the electric field, there will be *more electron-ion recombination* since the electrons pass more ions as they drift through the chamber.

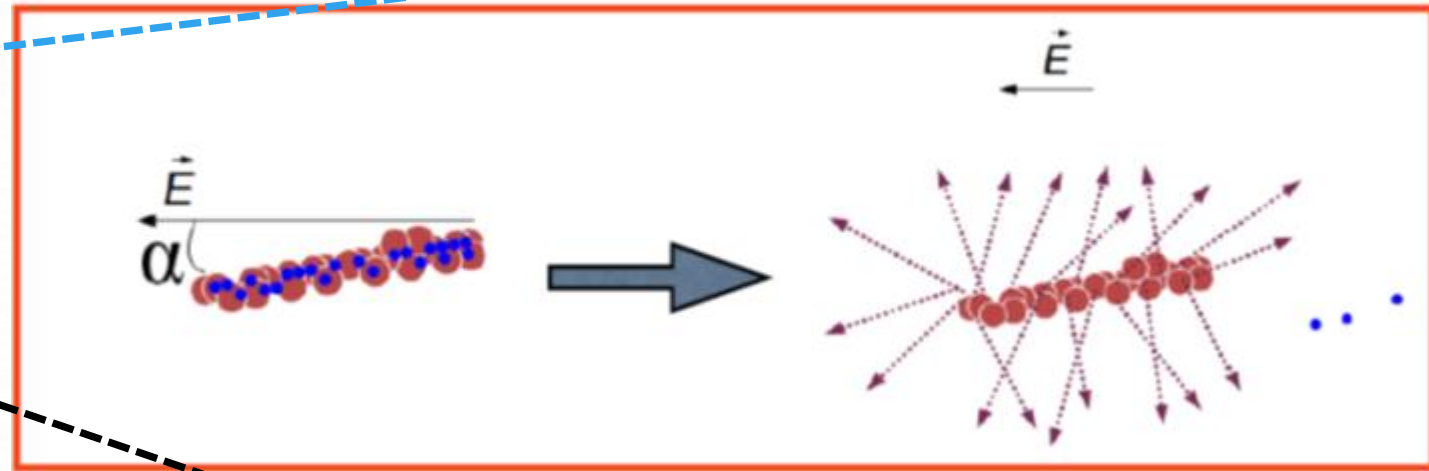


Moving from theory to experiment (SCENE experiment)

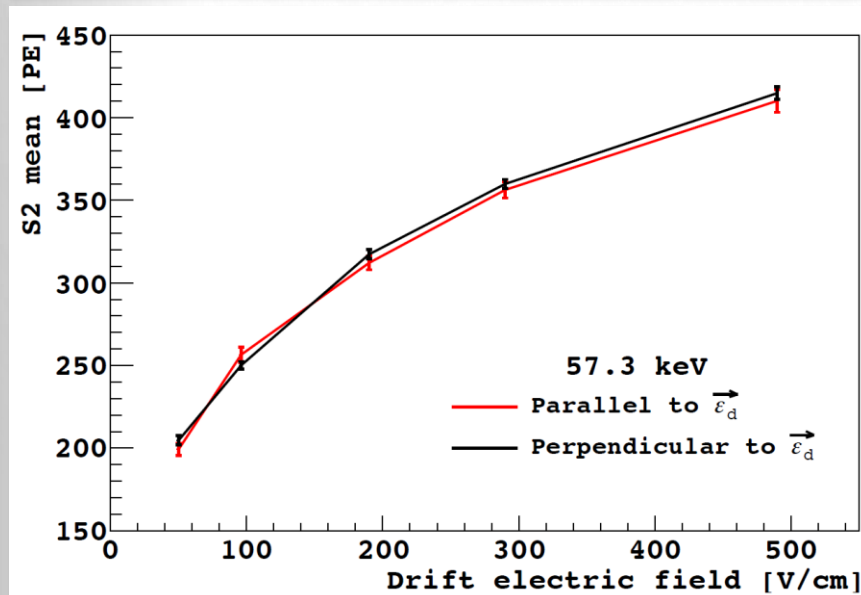
Scintillation



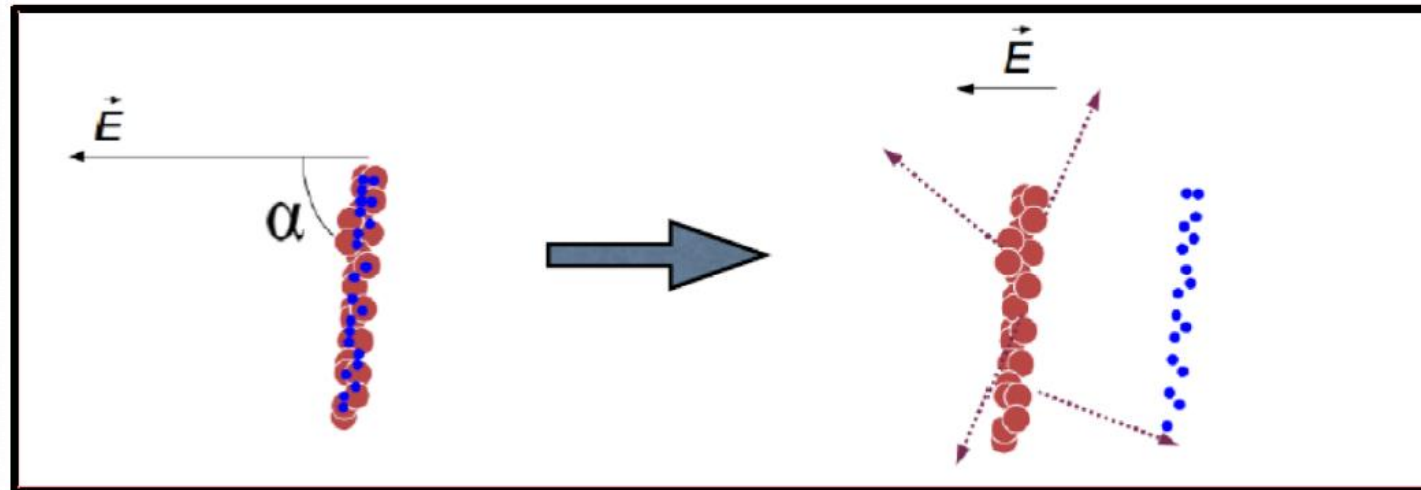
Substantial CR: more light (S1), less charge (S2)



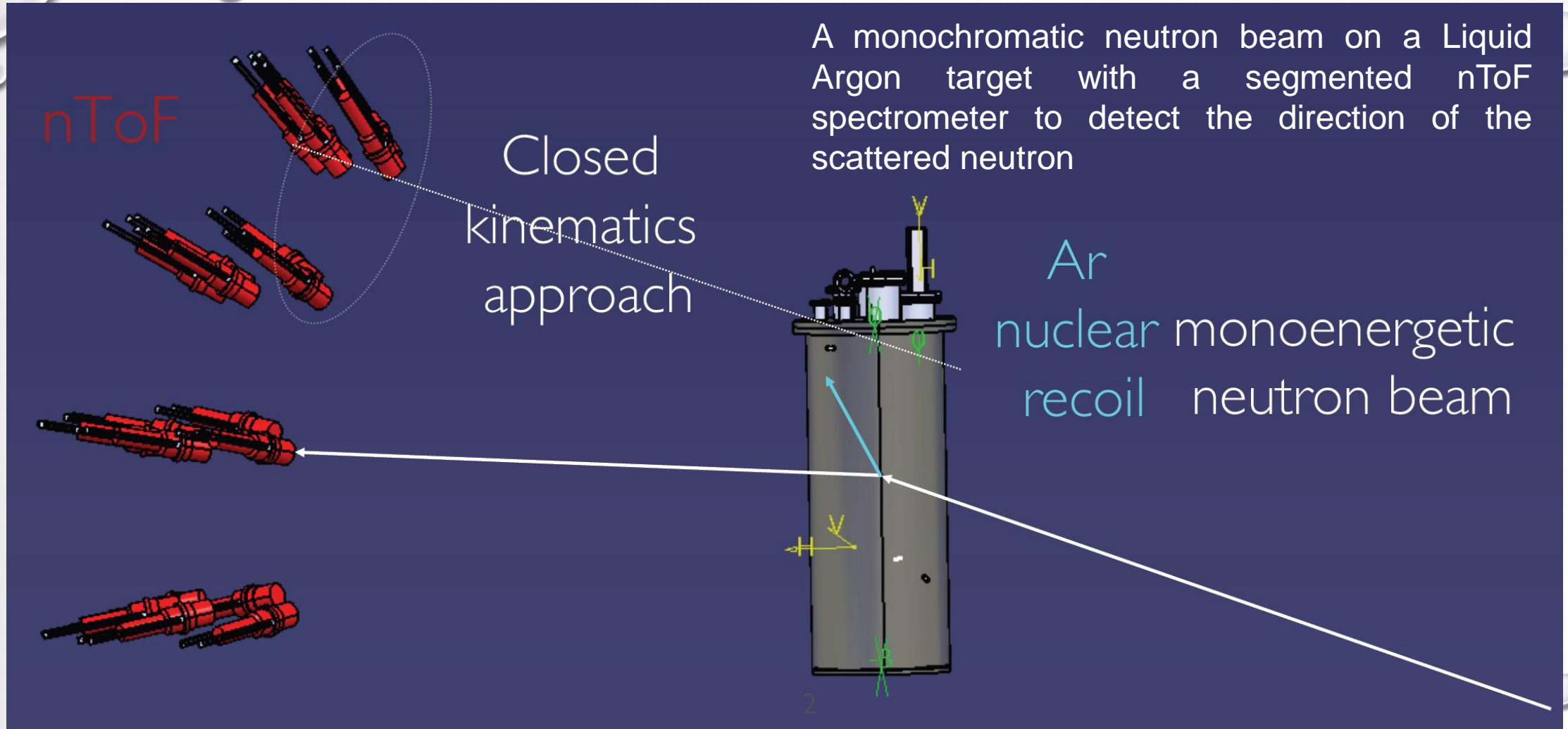
Ionization



CR small: less light (S1), more charge (S2)



Essential Setup of the ReD experiment



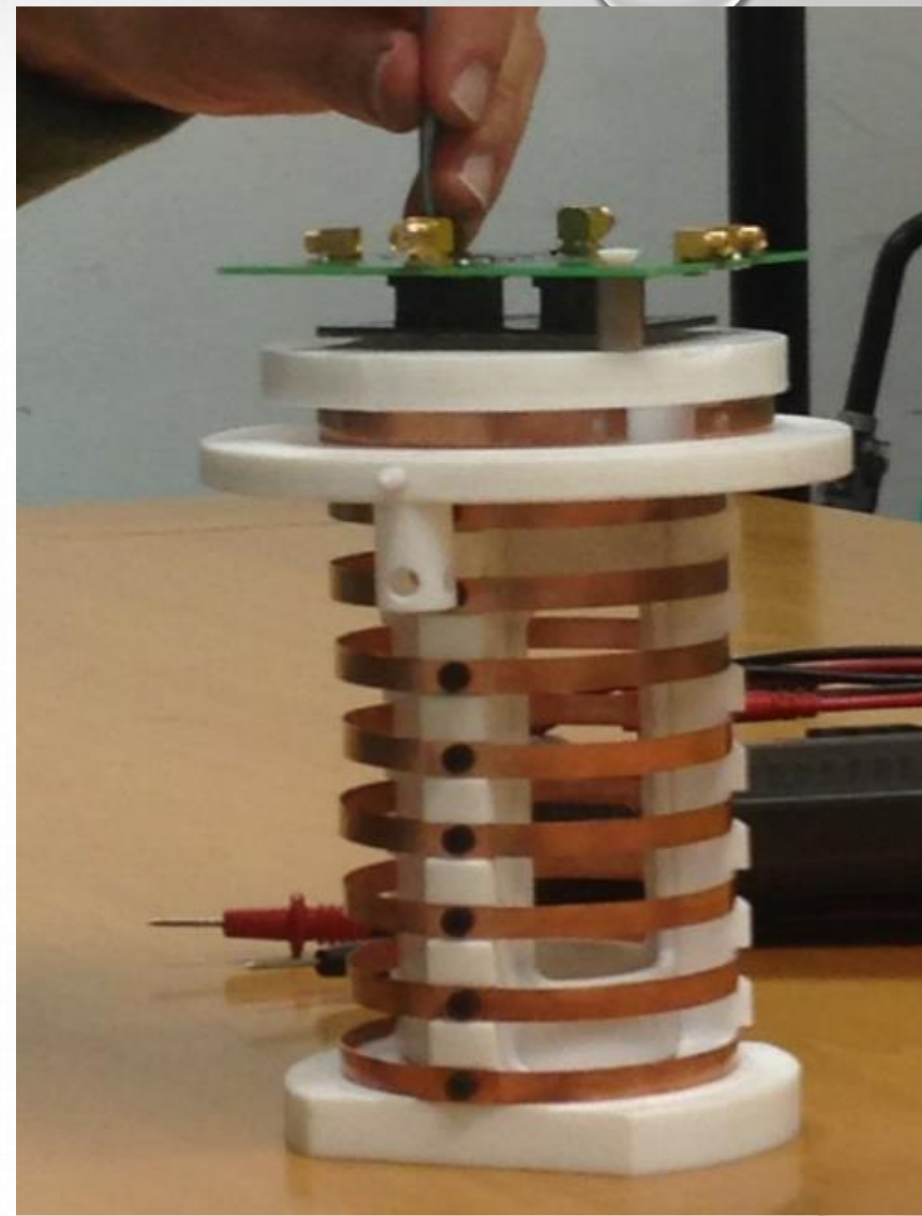
- Monochromatic proton beam on an appropriate target will produce a beam of $\sim 1\text{-}4\text{MeV}$ neutrons
- The TPC is placed at a chosen angle to intercept neutrons of the desired energy
- Recoils ($10\text{-}200\text{ keV}$) in the LAr produce S1 and S2 signals detected by SiPMs.

RED@Unina: the GAP-TPC

- GAP-TPC can have improved light yield using **Silicon Photomultipliers**
- Higher PDE compared to PMTs
- Individual readout of top SiPMs provides improved spatial resolution of the X-Y position of the S2 signal
- Low noise at cryogenic temperatures
- Low radioactivity (for DM application)



The current prototype uses two commercial SensLJ-series TSV arrays of 64 SiPMs



G. Fiorillo, B. Rossi, P. Trinchese, S. Walker

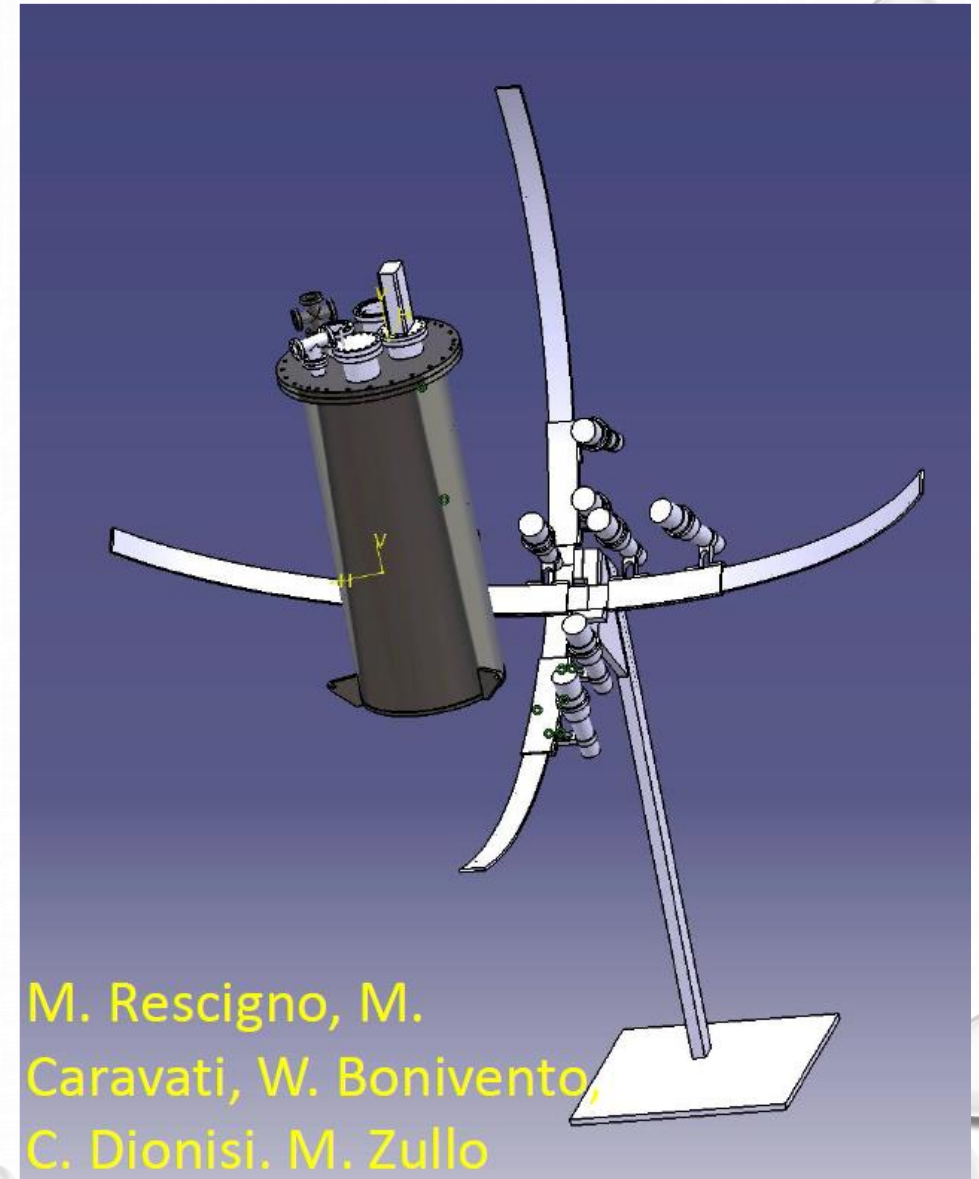
Timeline of the RED experiment

Phase 1: aiming at confirming the results obtained by the SCENE experiment

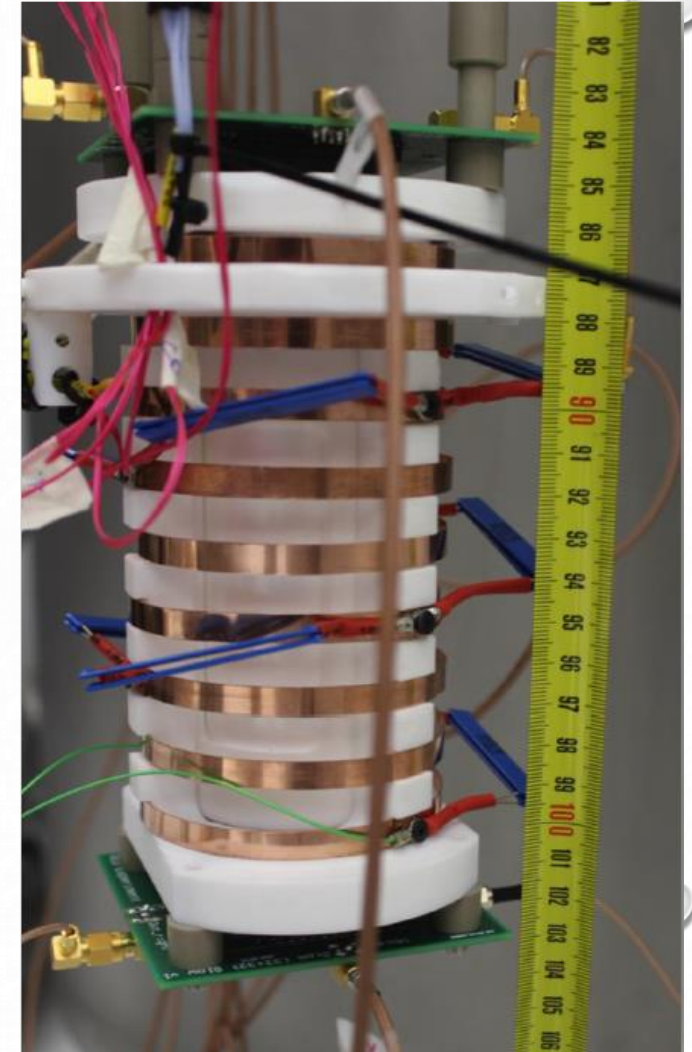
- Data taking campaign on the neutron beam line with a preliminary experimental configuration provisional neutron beam setup;
- GAP-TPC prototype installed in the final cryogenic system; preliminary nToF spectrometer (few LSci detectors).

Phase 2: directionality studies

- Detectors in final configuration and neutron/gamma data taking optimised beam target + collimator,
- final GAP-TPC with ancillary systems
- full size nToF spectrometer.



Preliminary Data Taken has already Started



Conclusions

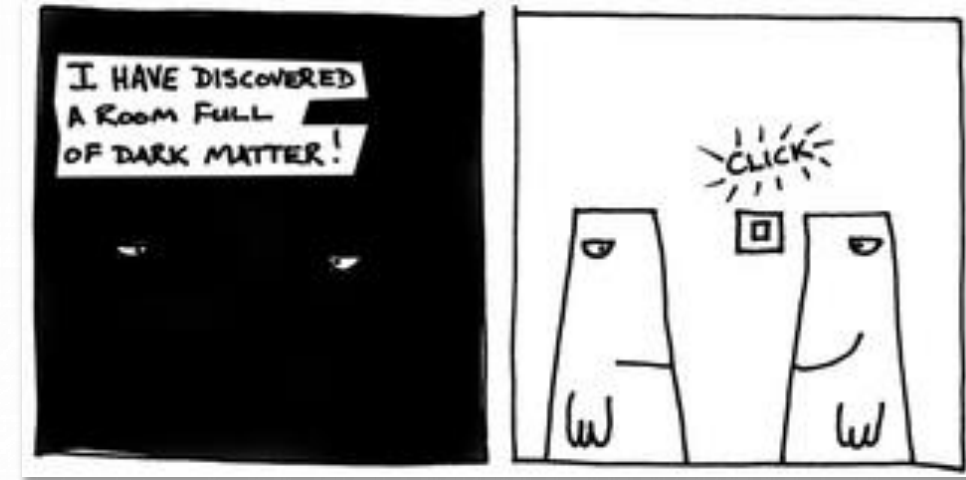
Directional detection is a very promising Dark Matter search strategy thanks to the expected strong direction dependence of the WIMP signal.

- ReD will test the feasibility of using columnar recombination to detect the direction of possible WIMP signals using ton-scale liquid Argon TPCs
- Experimental results can be used to verify and/or improve the theoretical models for columnar recombination

Bringing this new tool into the DarkSide program will make the future very exciting!

In the near future, from the phenomenological side:

- A study to explore the **impact of direction-sensitivity on the neutrino floor** in dark matter direct detection.



The results demonstrate that **directional detectors offer the most promising experimental technique for the future WIMPs discovery and Columnar recombination provides the best possibility** for combining directional sensitivity with the ton-scale size of experiment needed to this search.

Thanks for your attention



BACKUP

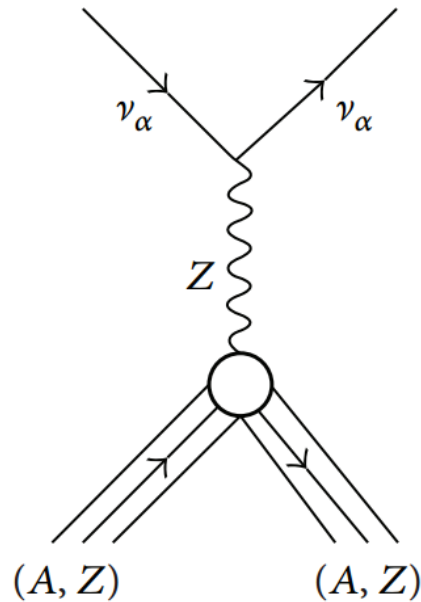


Facing the problems of past and future WIMP detection

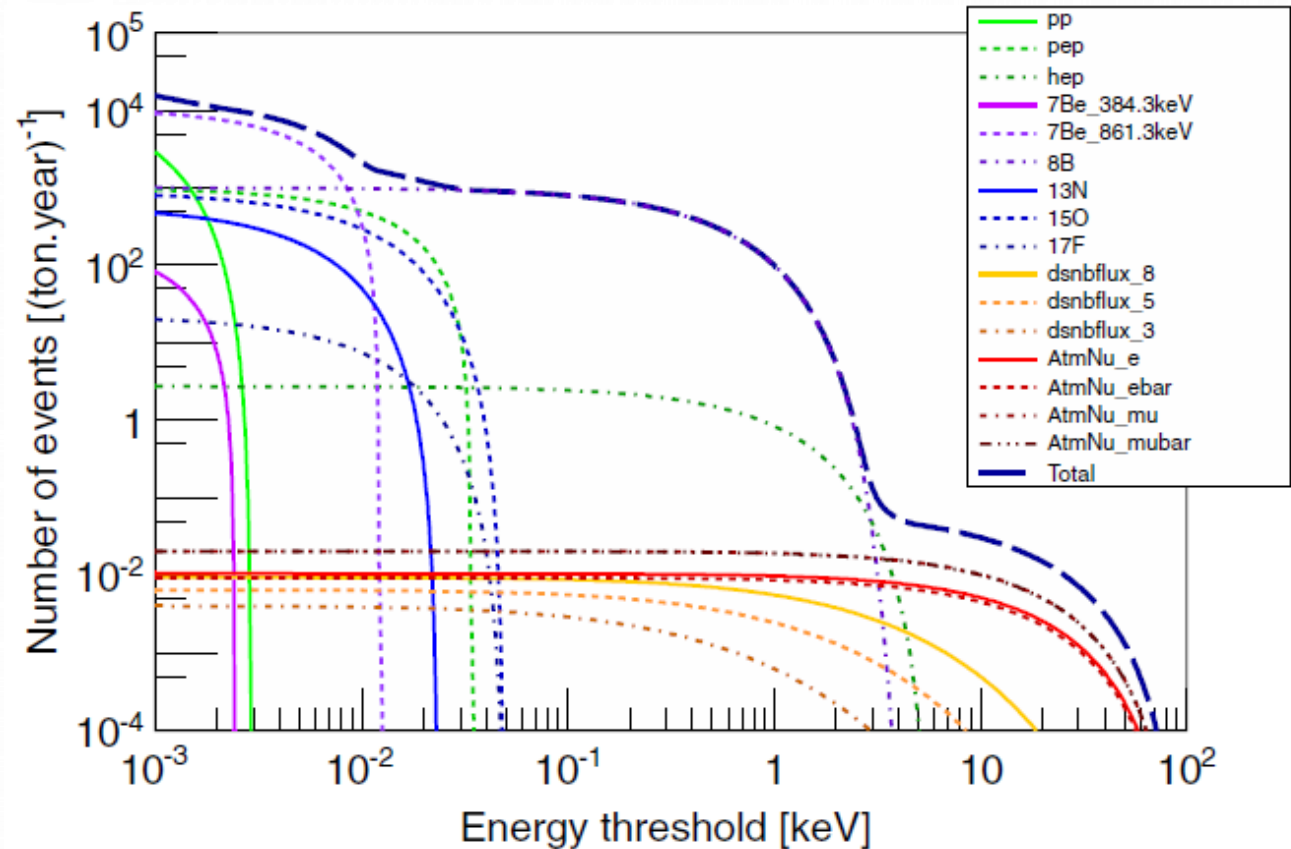
Upcoming direct dark matter detection experiments will have sensitivity to detect neutrinos from several astrophysical sources (Sun, atmosphere, and diffuse Supernovae).

Coherent neutrino scattering (CNS)

$$\nu_x + (A, Z) \rightarrow \nu_x + (A, Z)$$



$$\frac{d\sigma^{CNS}(E_\nu, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_w^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2} \right) F^2(E_r)$$



Number of neutrino-induced nuclear recoils per ton-year for Xe target as a function of the energy threshold

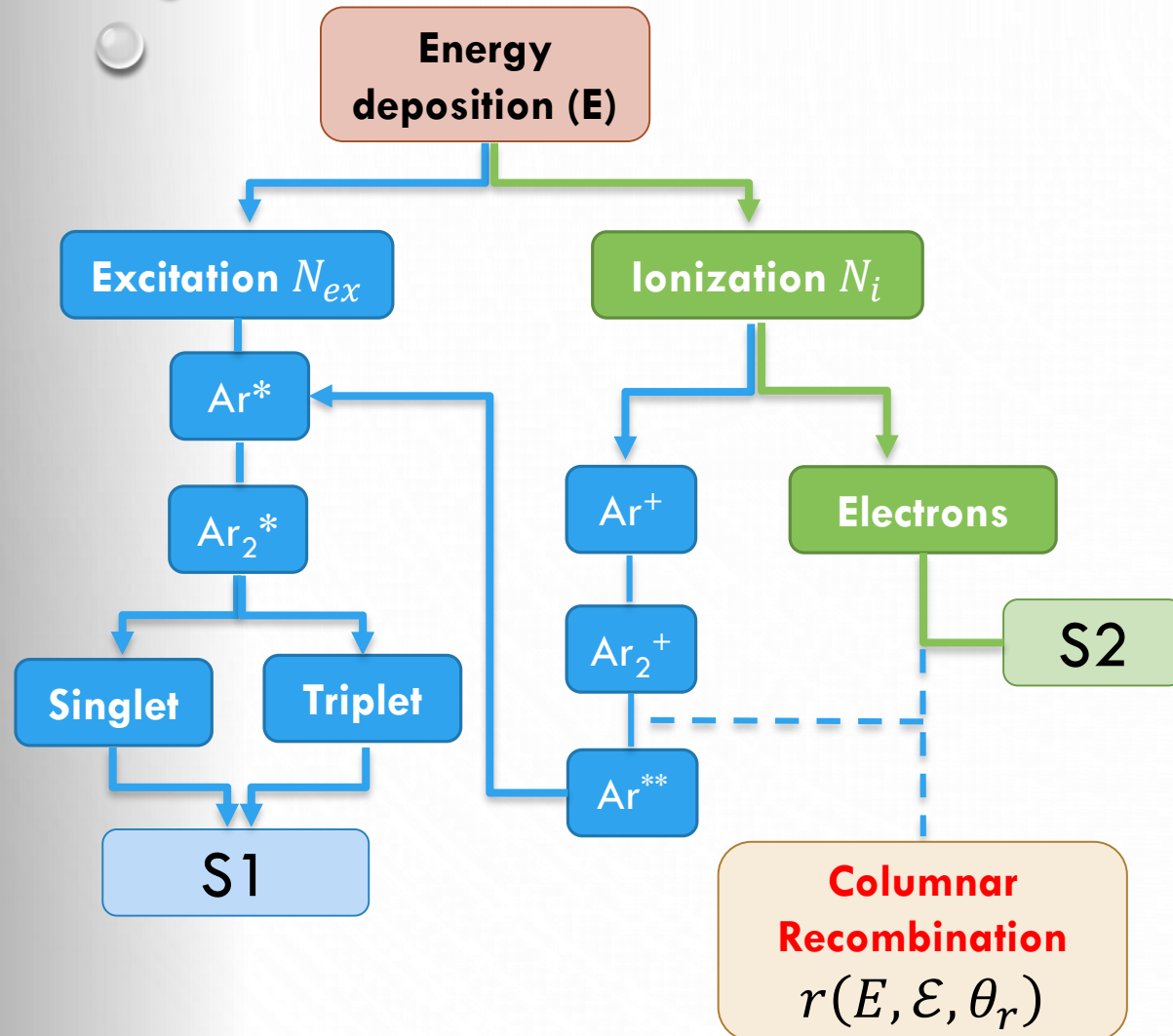
Simulating S1 and S2 signal with the Columnar Recombination

A simple first-order three-parameters approximation that maintains the main features of more detailed **Columnar Recombination theoretical models** is

$$\frac{r_0}{r(E, \mathcal{E}, \theta_r)} = 1 + \frac{\mathcal{E}}{\mathcal{E}_0} (\xi + \sin \theta_r)$$

where the intrinsic recombination probability in absence of field, r_0 , the electric field scale, \mathcal{E}_0 , and the relative strength of the isotropic recombination, ξ , depend on the energy deposit E .

This parameterization ensures that the recombination probability satisfies $0 \leq r \leq r_0 \leq 1$ and that r is linear in the component of the field orthogonal to the track, $\mathcal{E} \sin \theta_r$, to first order.



Simulating S1 and S2 signal

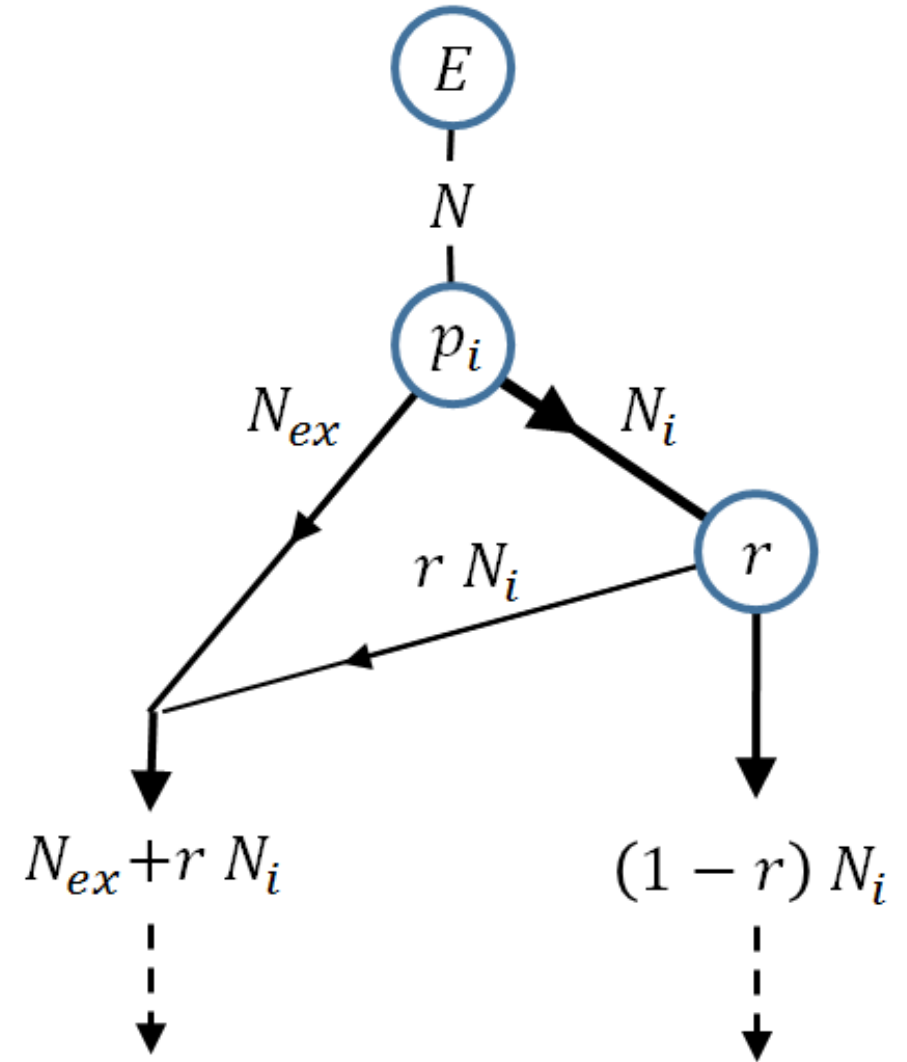
We study the possibility of discriminating events corresponding to different **recombination probability, r** , in the plane (S2, S1).

It is already very interesting to distinguish recoils that are parallel to the electric field \mathcal{E} (**vertical events**, $\sin \theta_r = 0$) from recoils that are perpendicular to \mathcal{E} (**horizontal events**, $\sin \theta_r = 1$). We consider two recombination probabilities: for **parallel**, r_{\parallel} , and **perpendicular** r_{\perp} , recoils.

$$\frac{r_0}{r(E, \mathcal{E}, \theta_r)} = 1 + \frac{\mathcal{E}}{\mathcal{E}_0} (\xi + \sin \theta_r)$$

with some typical field value $\mathcal{E} = \mathcal{E}_0$, we use

$$r_{\parallel} = \frac{r_0}{1+\xi} = 0.4 \quad \text{where } r_0 = 0.8 \text{ and } \xi = 1.$$
$$r_{\perp} = \frac{r_0}{2+\xi} \approx 0.27$$



$$S1 = g_1(N_{ex} + rN_i)$$

$$S2 = g_2(1 - r)N_i$$

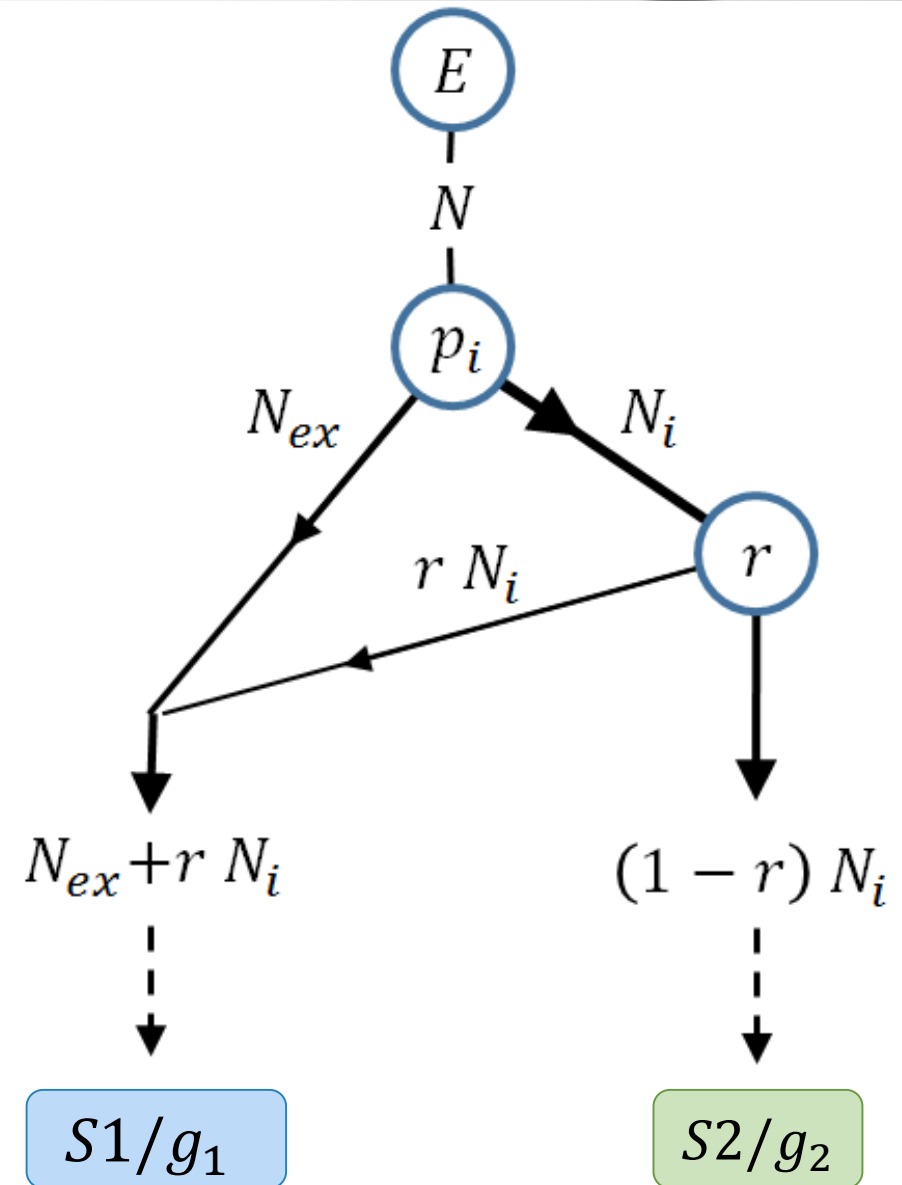
Simulating S1 and S2 signal

Steps of the simulations

1. A number N of primaries is extracted from a Poissonian distribution with mean N .
2. These primaries are split into N_{ex} primary scintillation photons and N_i electrons according to a binomial distribution with ionization probability $p_i = 0.5$.
3. The N_i electrons split on average into rN_i excitons from recombination and $N_{ie} = (1 - r) N_i$ remaining electrons according to a binomial distribution with recombination probabilities $r_{\parallel} = 0.4$ for vertical recoils and $r_{\perp} = 0.27$ for horizontal recoils. The excitons from recombination contribute to the total number of scintillation photons

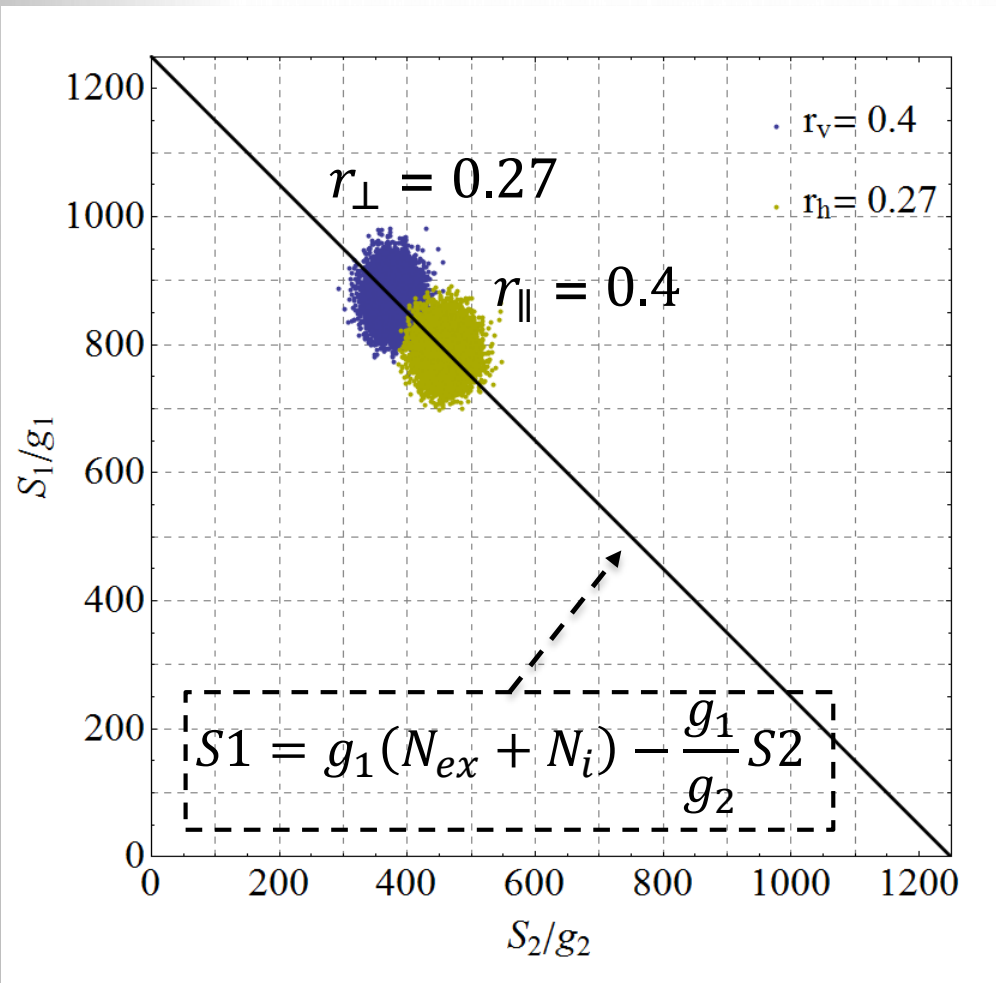
$$N_{ph} = N_{ex} + r N_i$$

The resulting signals are $S1/g_1$ and $S2/g_2$



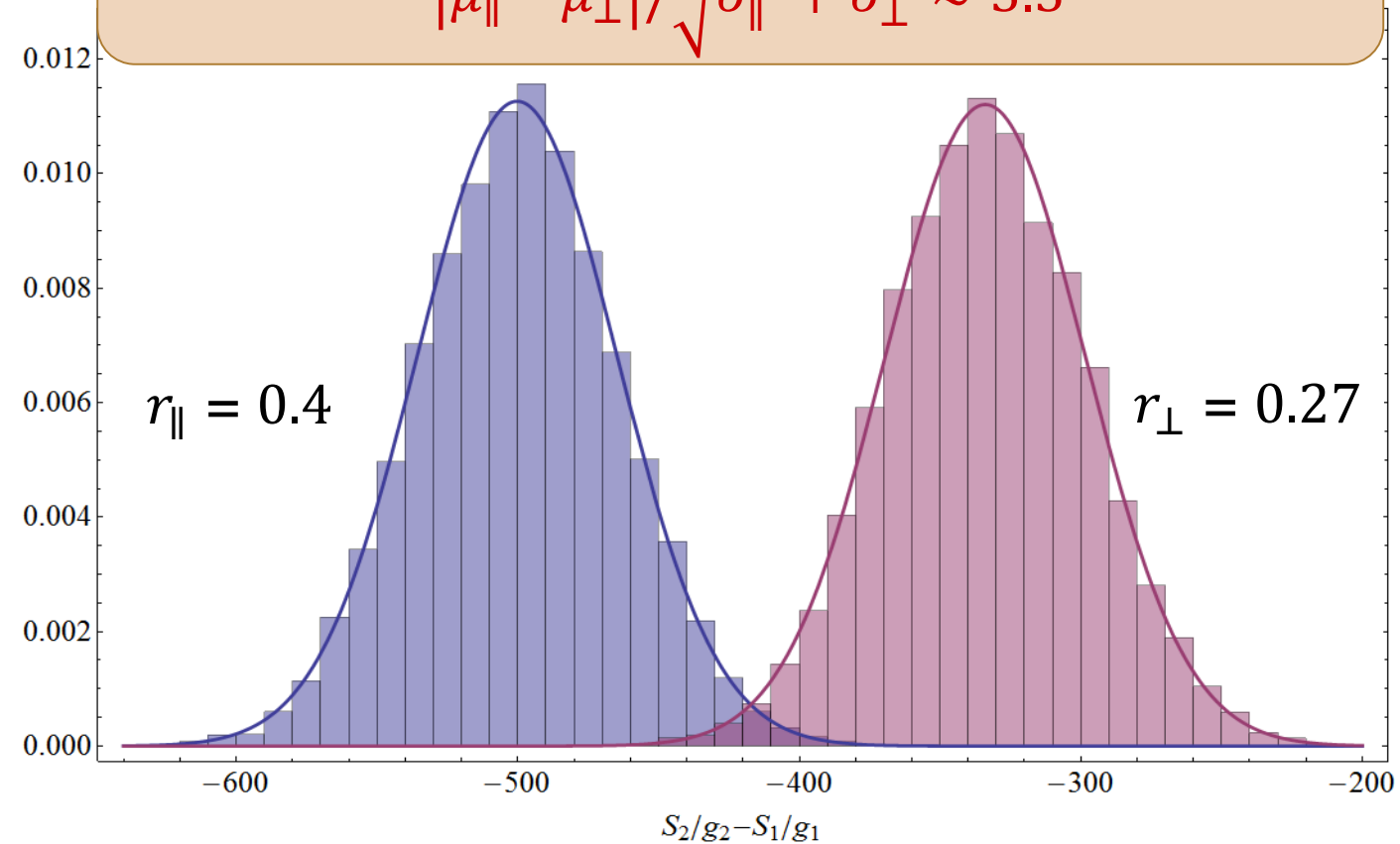
Simulating S1 and S2 signal

Vertical and horizontal events are very well discriminated. On the right figure the distributions of the same events are shown as a function of $\Delta_{2-1} = \frac{S_2}{g_2} - \frac{S_1}{g_1}$, the best variable to discriminate different values of r .



The two distributions lead to a 3σ discrimination

$$|\mu_{\parallel} - \mu_{\perp}| / \sqrt{\sigma_{\parallel}^2 + \sigma_{\perp}^2} \approx 3.3$$



Seasonal effects

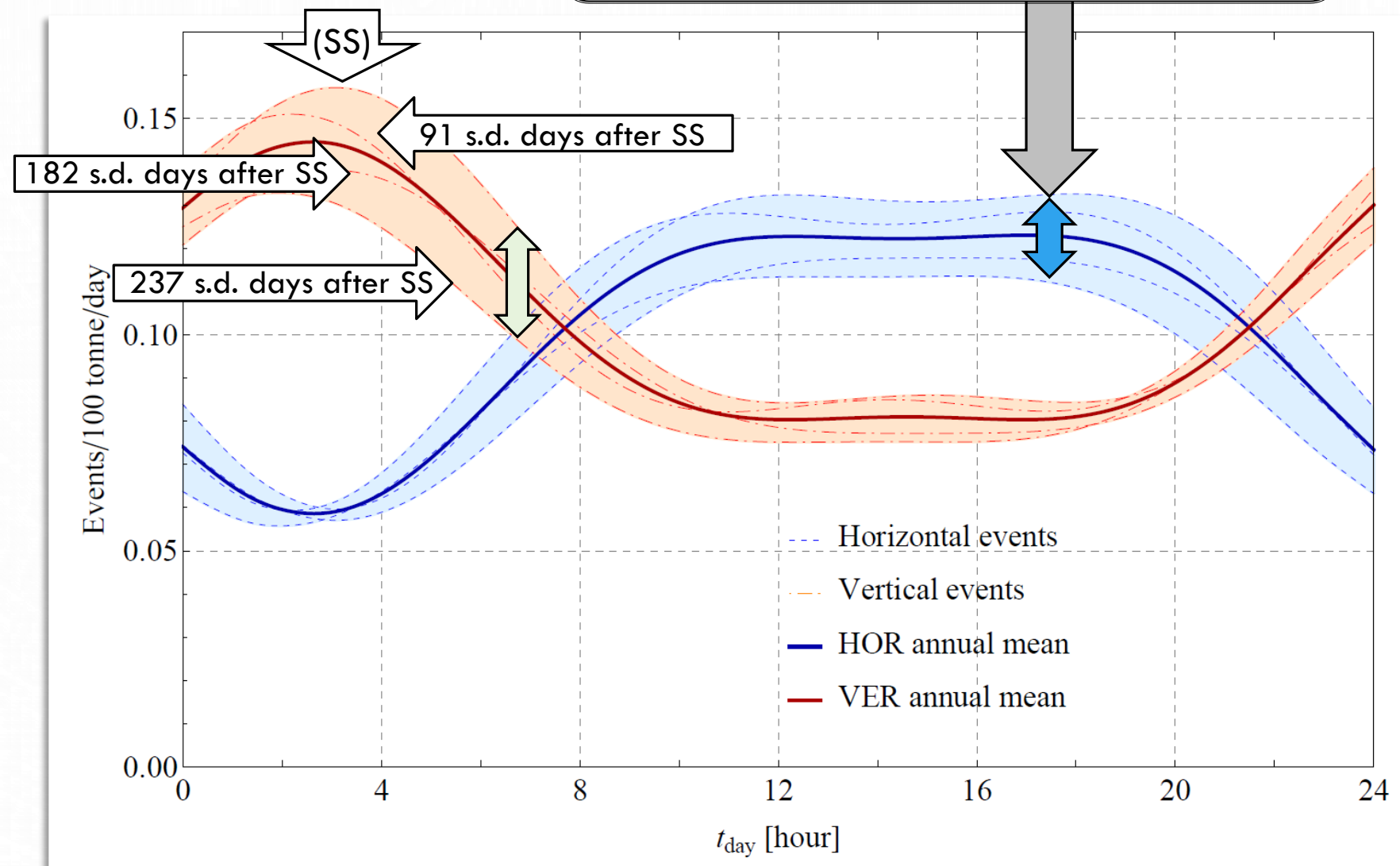
Sidereal day VS solar day

Use of the **sidereal day** (s.d.) as a unit is convenient because after a sidereal day the Cygnus constellation returns exactly in the same position in the sky

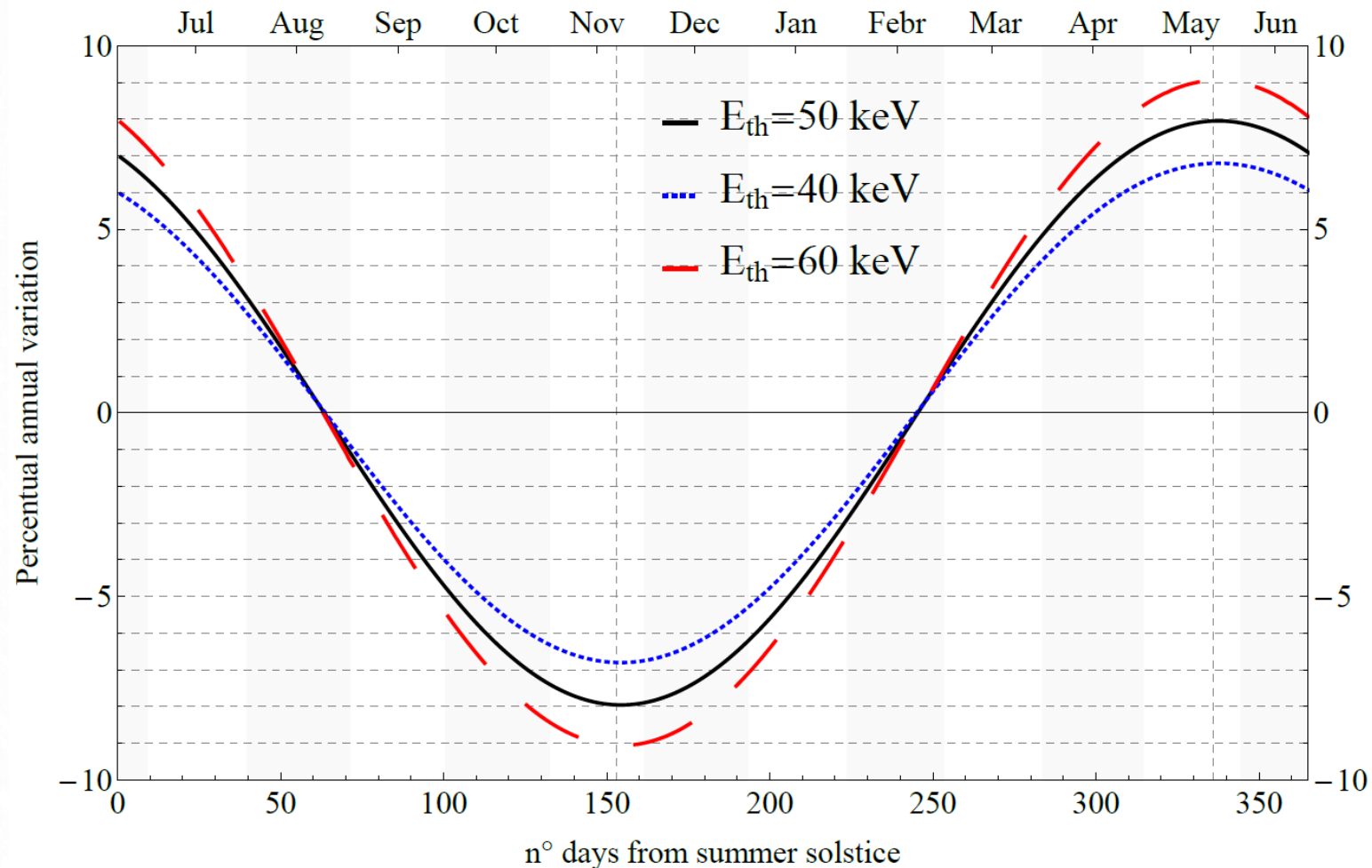
Seasonal variation

Here, the different colored dotted lines refer to the rate evaluated at summer solstice (SS) and **91**, **182** and **237** sidereal days after it, while the solid black line is the annual mean.

The overall variation registered in the HOR components among the different sidereal days of the year is shown by the blue band.

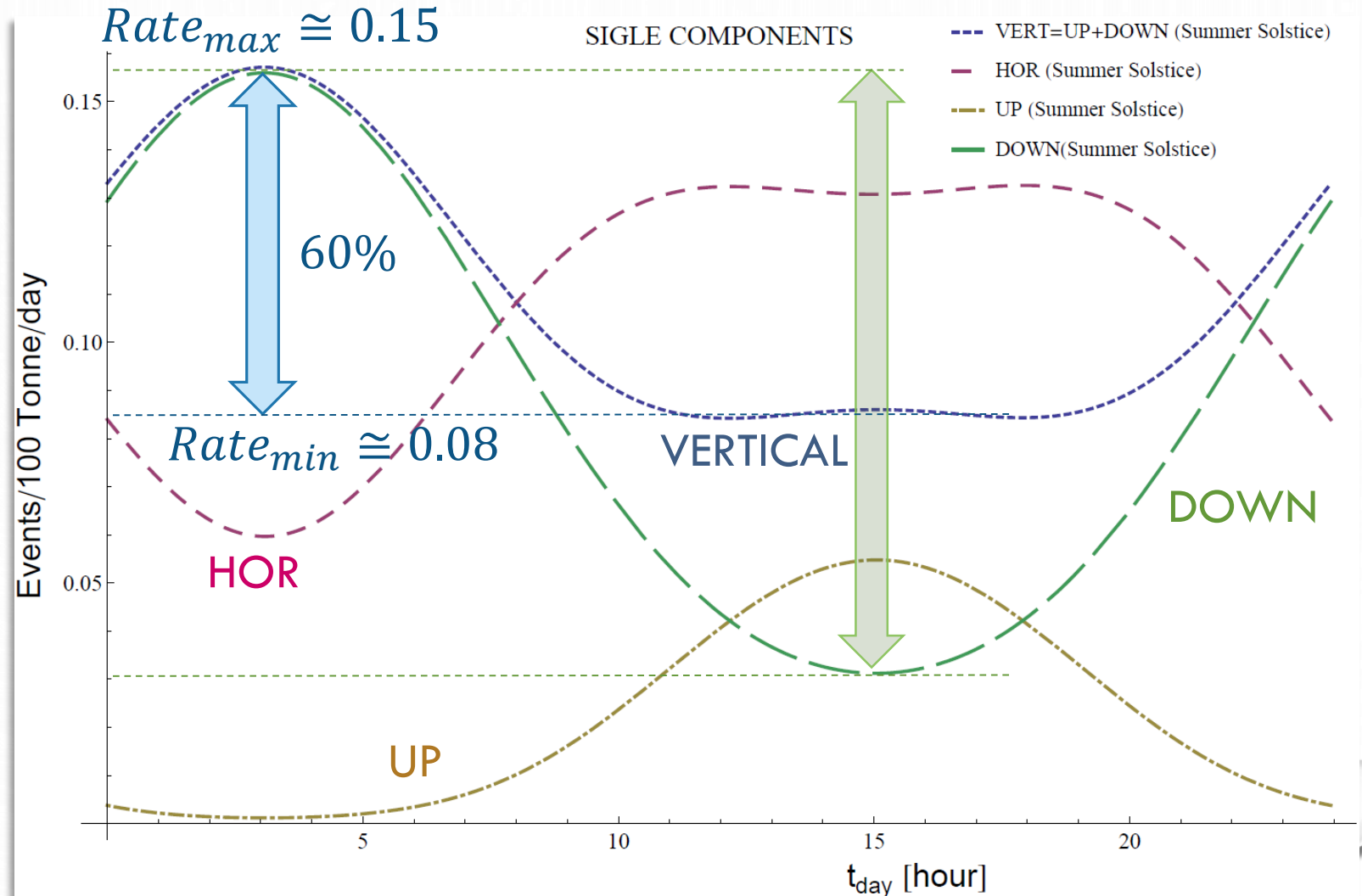
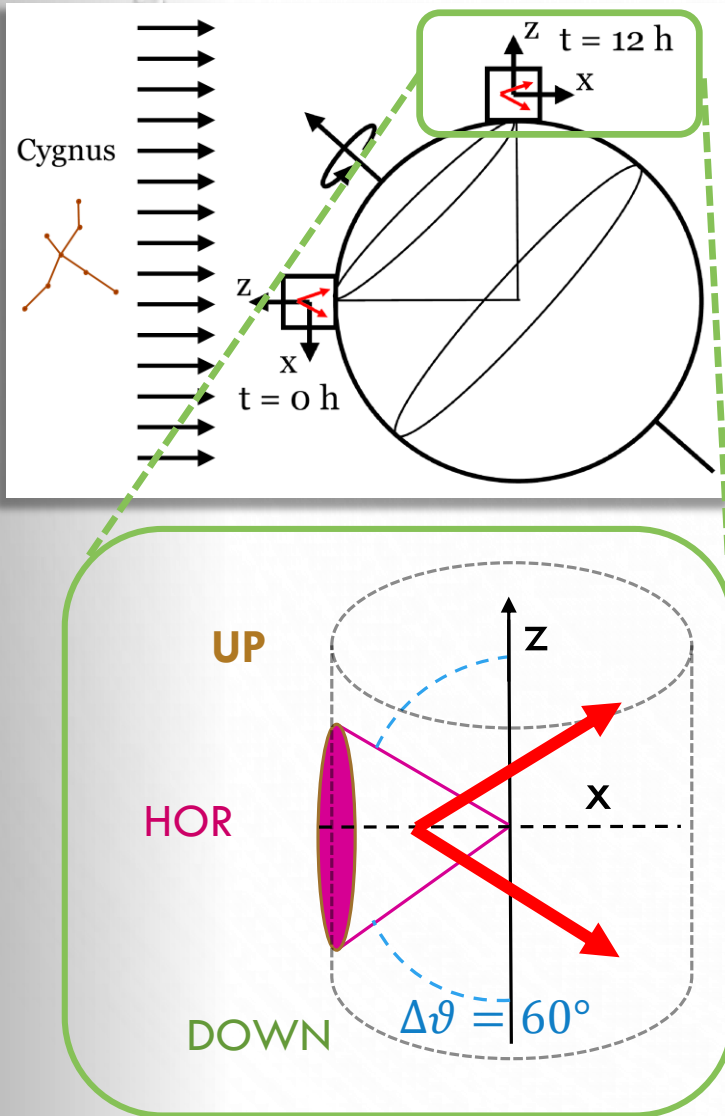


*Energy threshold effects on annual modulation

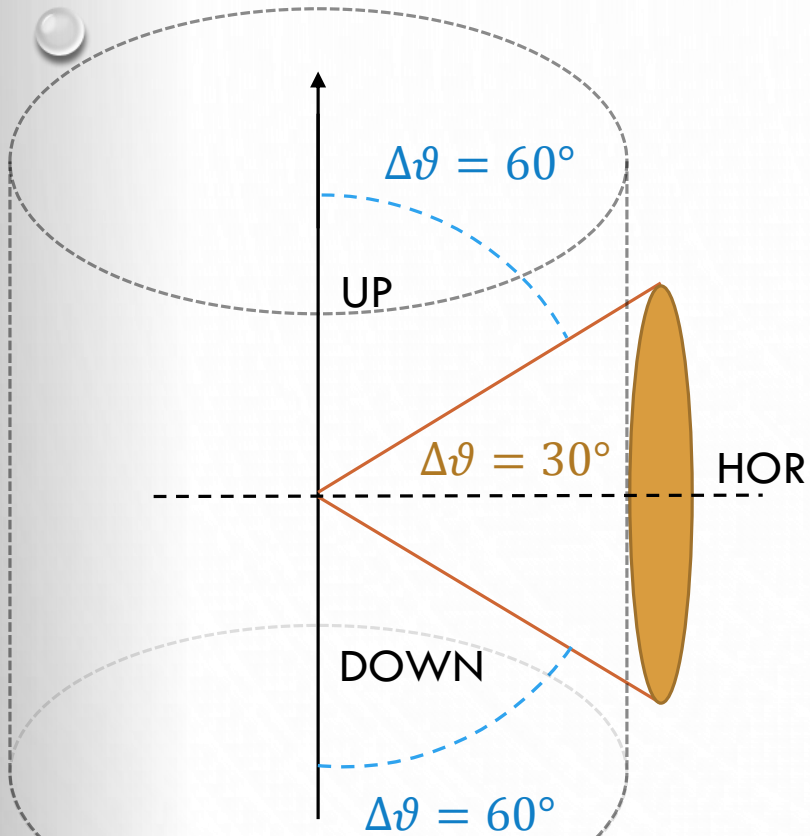


Diurnal modulation (with directionality)

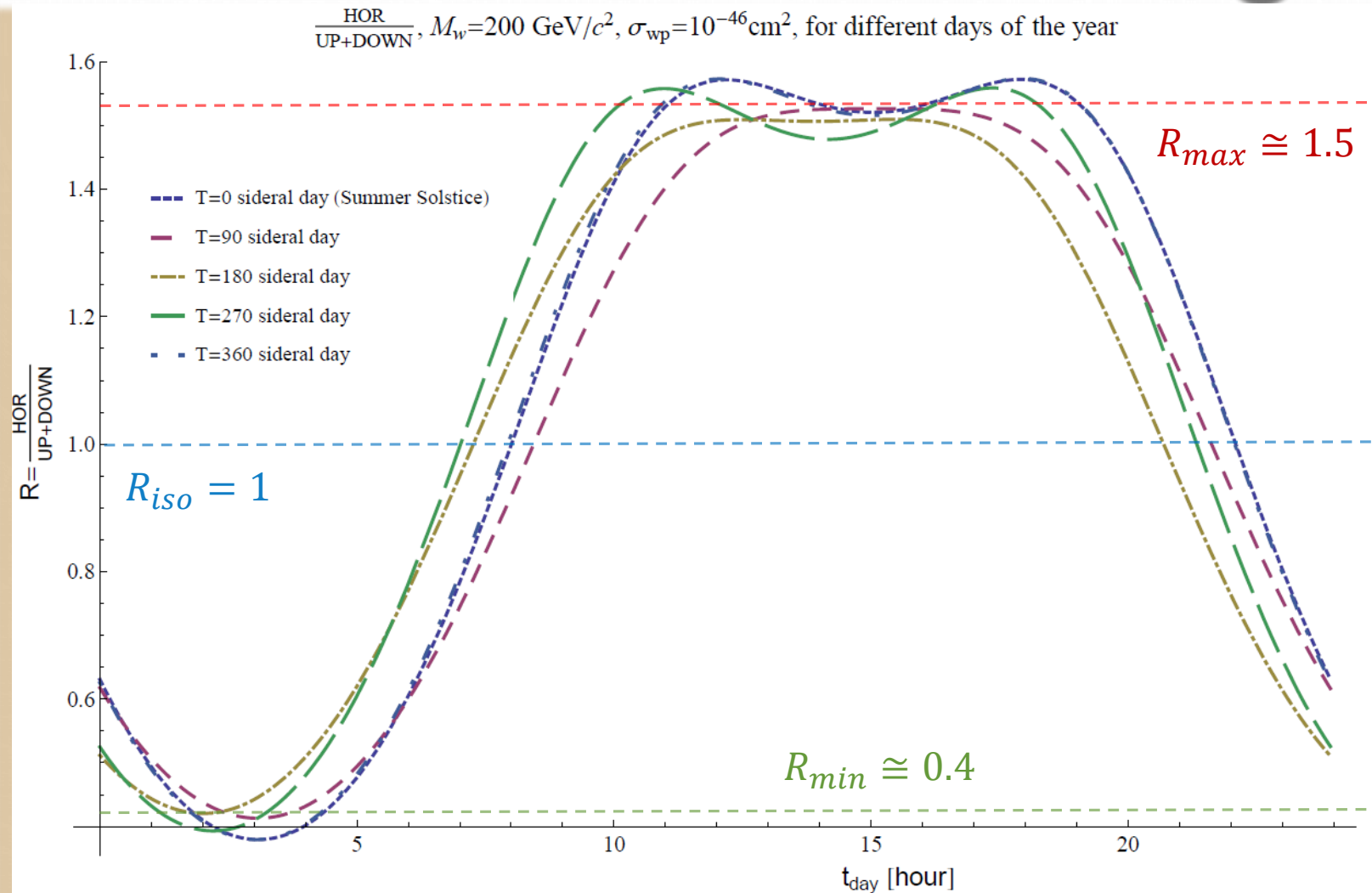
* The ϕ angle is integrate $[0, 2\pi]$



Event ratio Horizontal/Vertical (different acceptance)

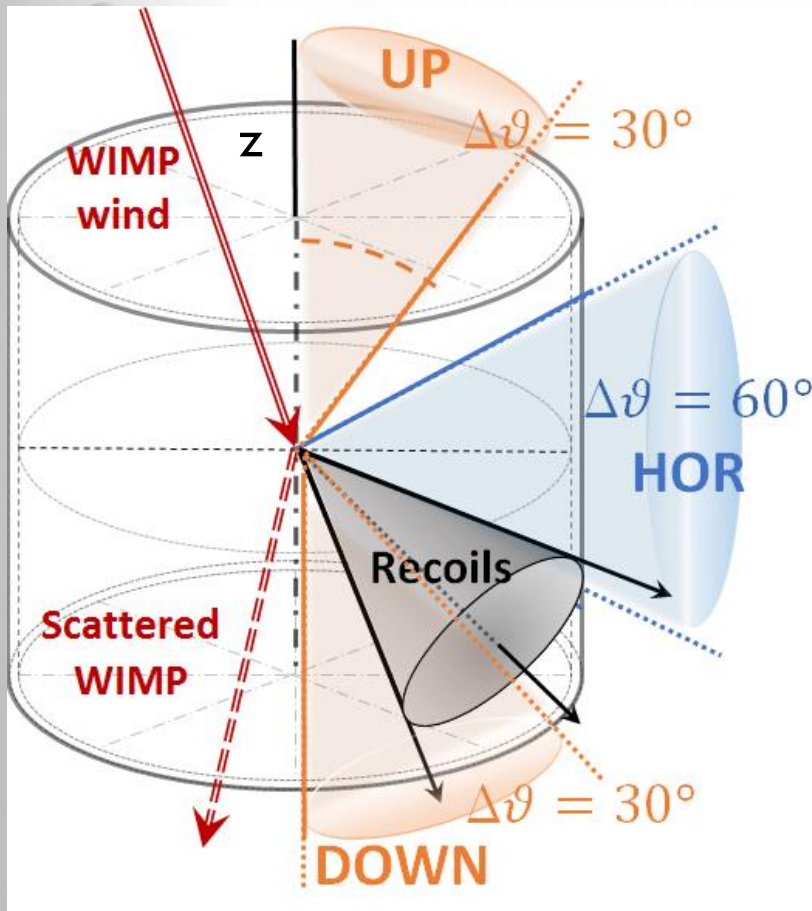


$$R = \frac{HOR}{UP + DOWN} = \frac{HOR}{VERTICAL}$$

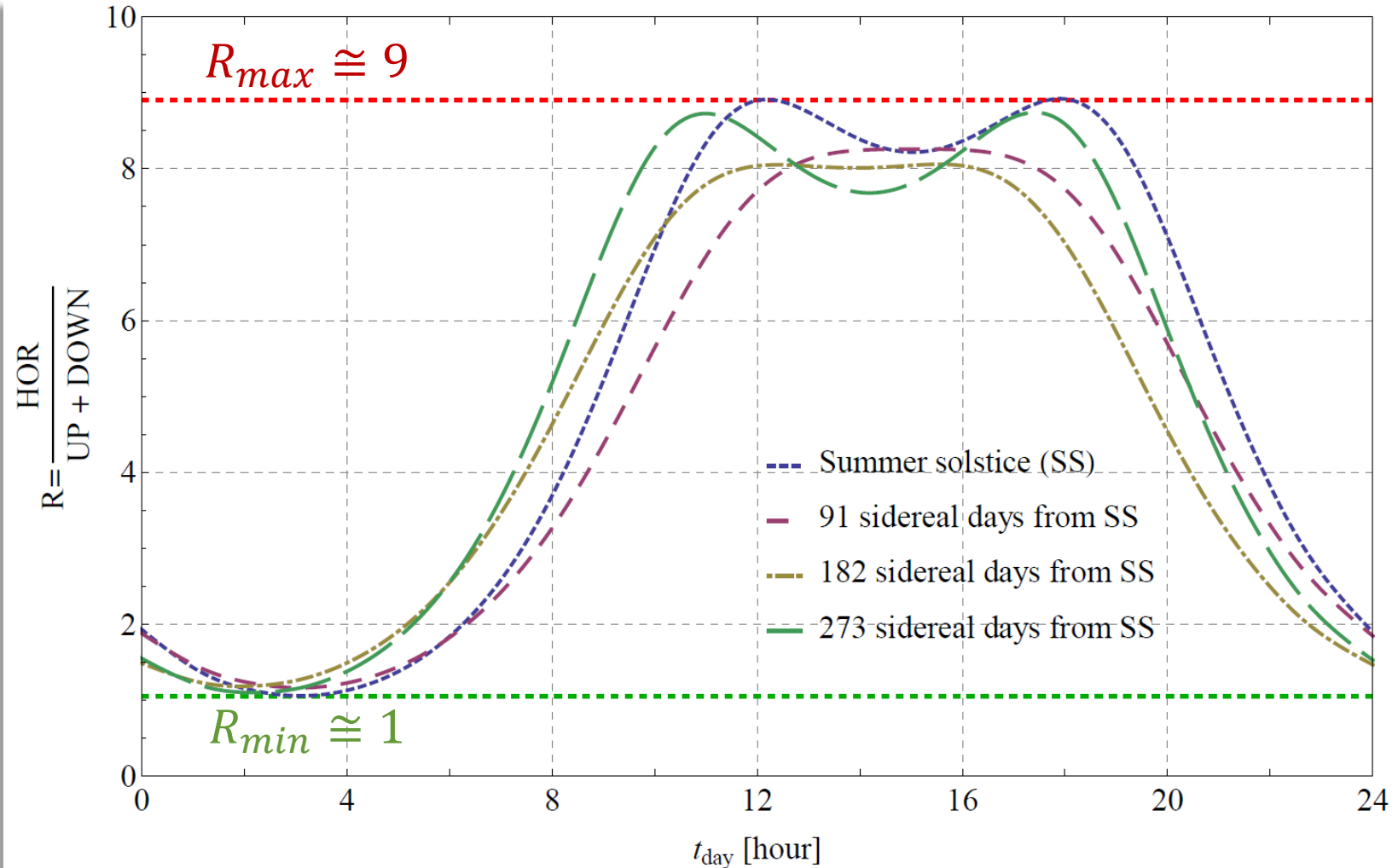


Angular resolution effect ratio HOR/VER

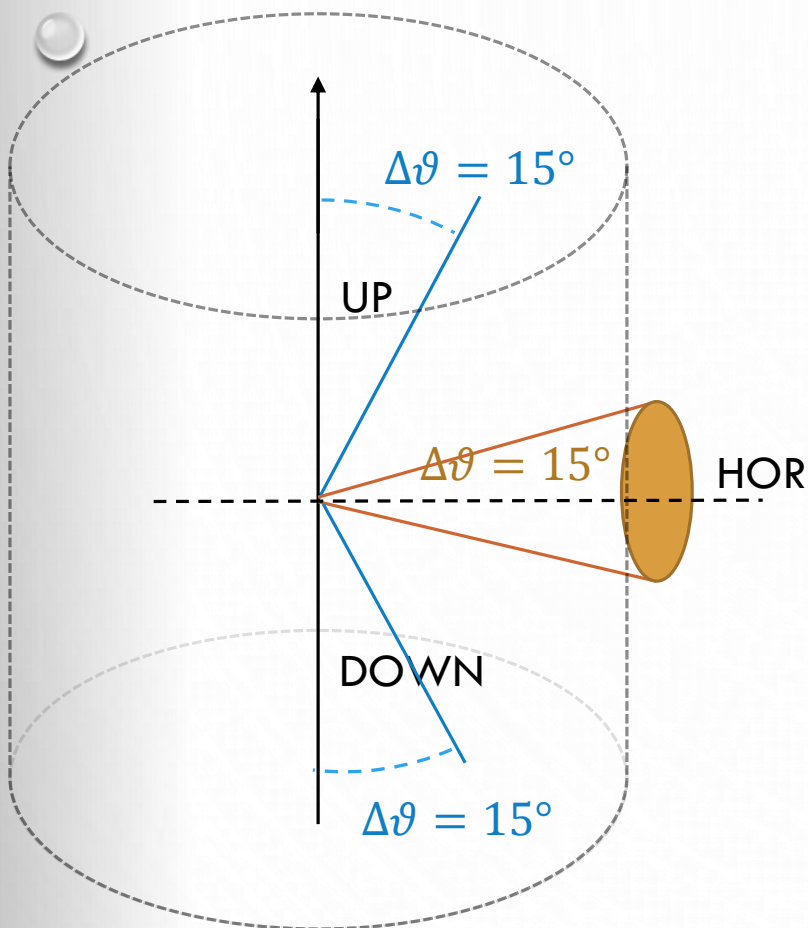
Ratio of **horizontal** WIMPs induced Ar recoils to **vertical** ones varies by a factor $f \sim 10$ over the day (acceptance $\pm 30^\circ$)



$$R = \frac{HOR}{UP + DOWN} = \frac{HOR}{VERTICAL}$$



Event ratio Horizontal/Vertical ($\pm 15^\circ$ acceptance)



$$R = \frac{HOR}{UP + DOWN} = \frac{HOR}{VERTICAL}$$

