RED

An experiment to sense recoil directionality in LAr

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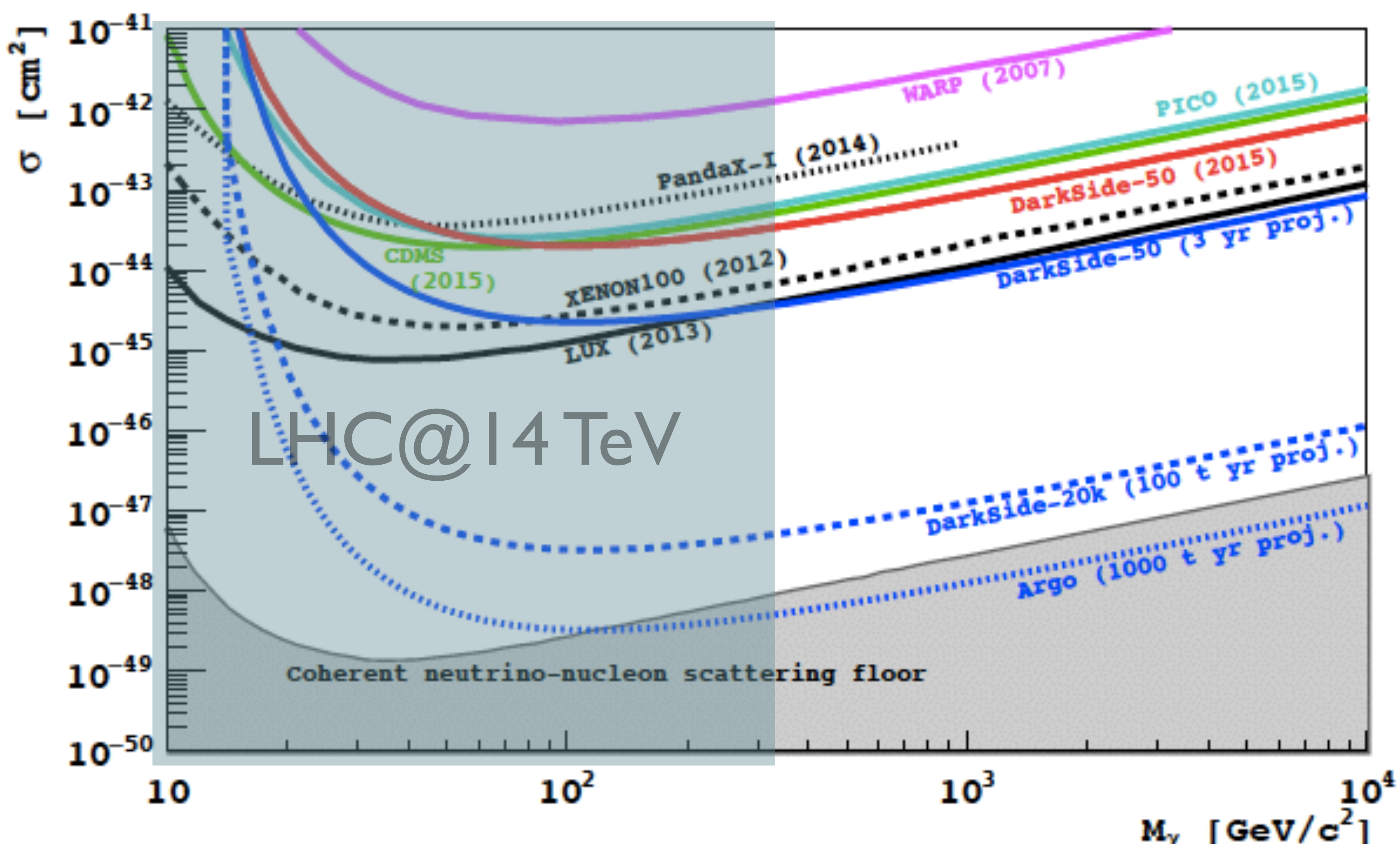
THE CASE FOR A DIRECTIONAL ARGON DETECTOR



LHC

Post Run I viable SUSY models predict high mass and low cross section WIMPs (even below the neutrino floor)

DARKSIDE

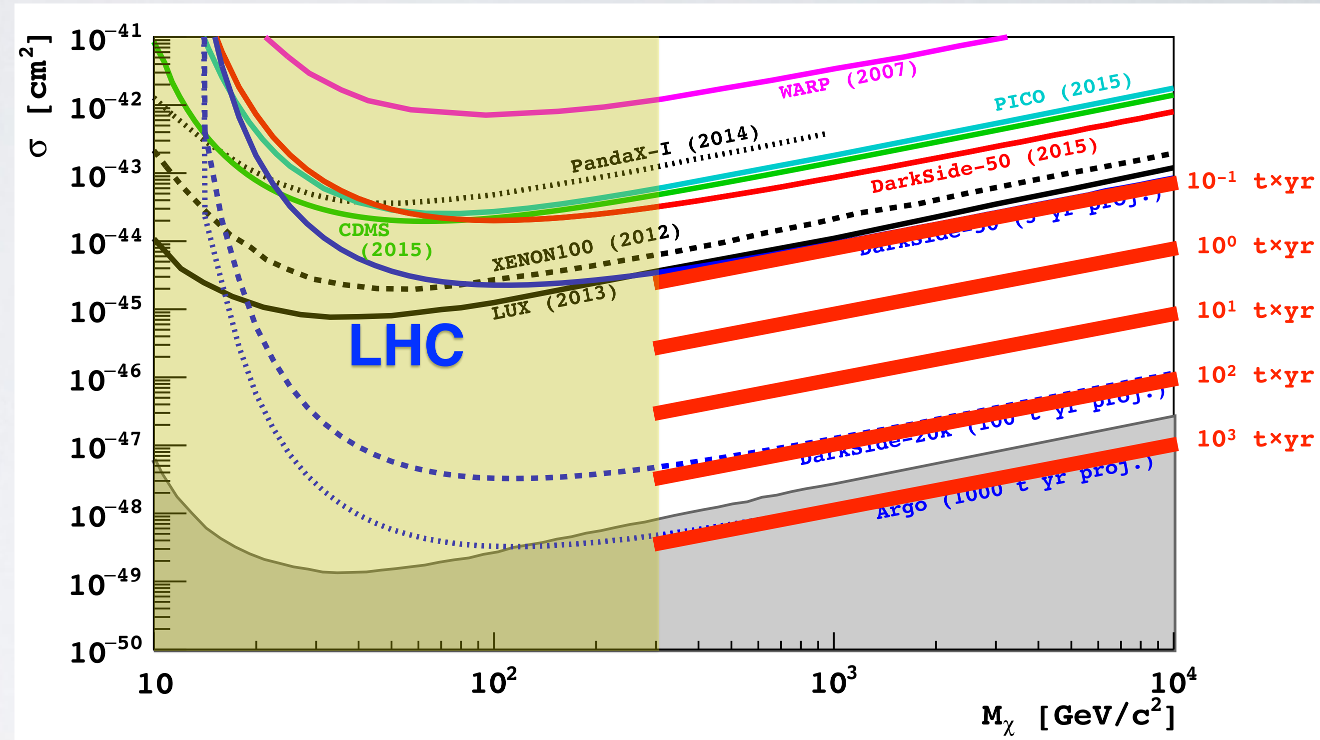
A program for the Ultimate DM Search with 39Ar-suppressed Argon TPCs

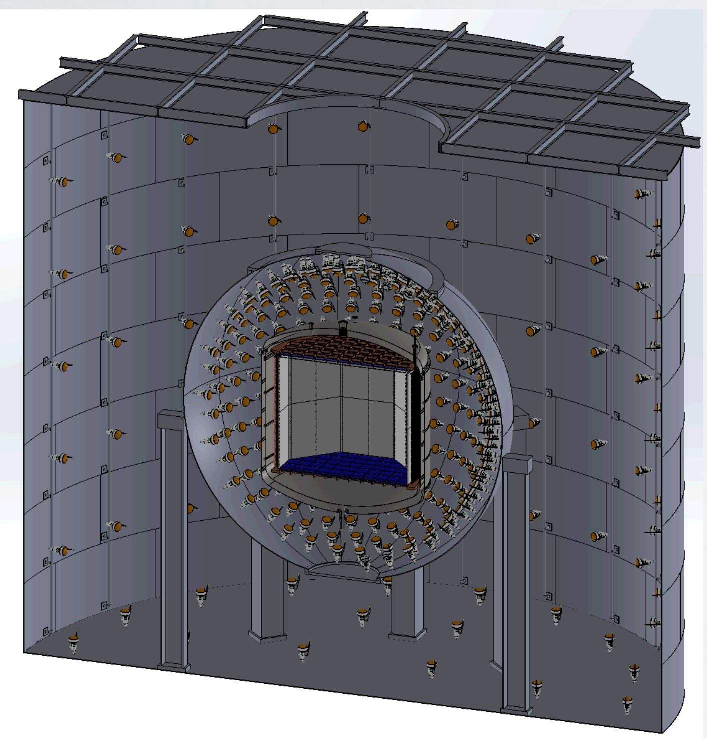
- WIMPs are still excellent candidates for particle dark matter
  - SUSY WIMPs with masses > 100 GeV and cross sections: 10^{-45} - 10^{-49} cm^2
- **Observation of a few WIMP-like events might not be enough to claim discovery**

➔ Directional detection allows for background discrimination and unambiguous discovery

AN INTEGRATED PROGRAM FOR THE ULTIMATE DM SEARCH WITH ^{39}AR-SUPPRESSED ARGON TPCS

Ultimate search requires 1,000 tonne×yr **background-free exposure**
^{39}Ar-suppressed Ar TPC can deliver thanks to unprecedented capability of suppression of β/γ background





DarkSide-50 (now)

zero background experiment in operation

ArDM-1t (now)

ton-scale TPC operations and 39Ar platform

All key enabling technologies funded and ongoing:

- Cryogenic SiPM (PDE>50%, dark rate <0.1 Hz/mm^2)
- Urania: 100 kg/d procurement of underground argon
- Aria: active isotopic separation of ^{39}Ar via cryogenic distillation

DarkSide-20k (≈2020?)

100 tonne×yr background-free search

Argo (≈2025?)

- 1,000 tonne×yr background-free search → *reach the "neutrino floor"*
- precision low-E solar neutrino measurements

DIRECTIONAL SENSITIVITY IN ARGON

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

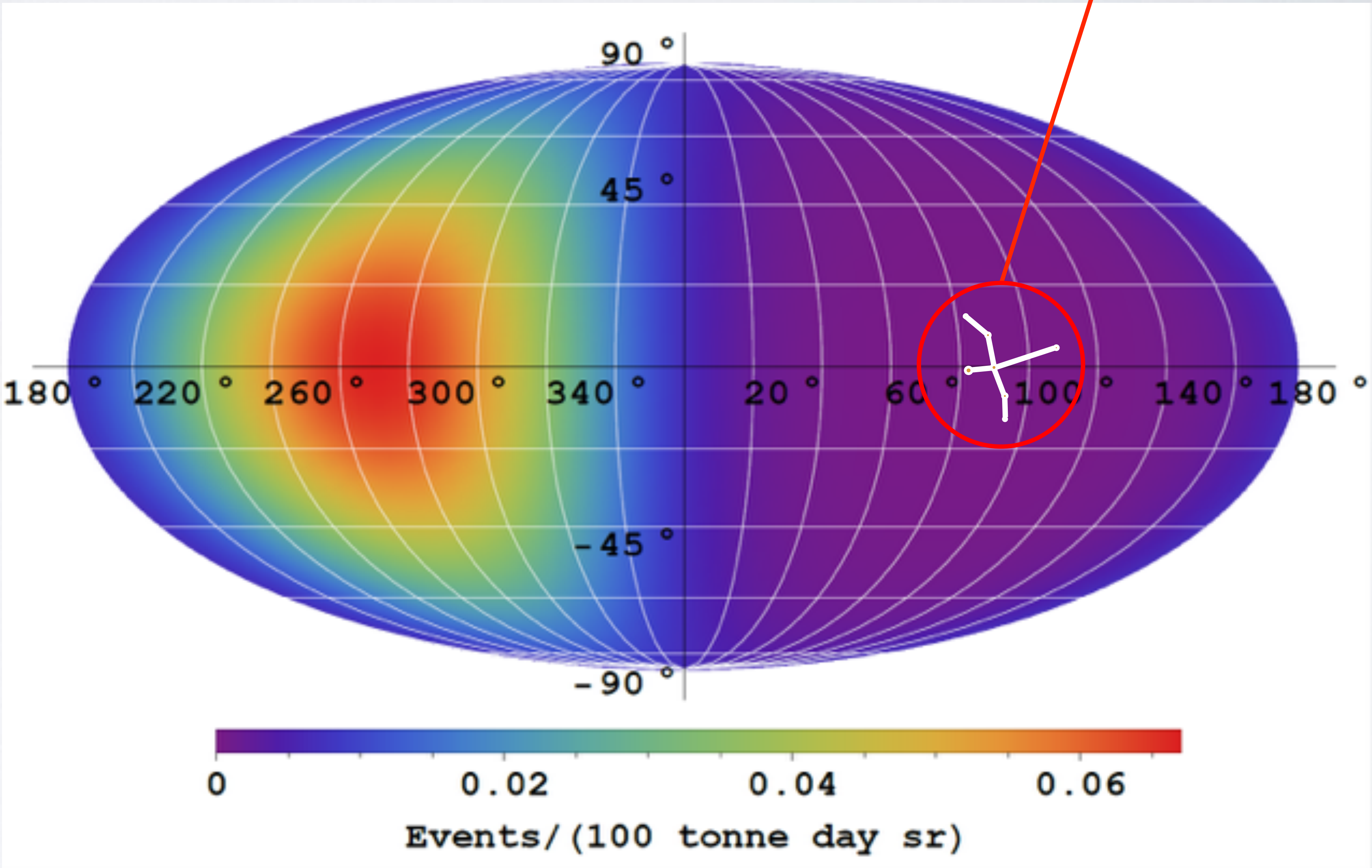
Cygnus Constellation: Galactic Coordinates (l=90°,b=0°)

Angular distribution of Argon recoils

- 50 keV $<E_R<$ 200 keV
- M_W=200 GeV
- $\sigma=10^{-46}$ cm^2

Sidereal variation of WIMP wind from Cygnus results in a substantial anisotropy in Argon recoils

➡ Hard for a background to mimic the directional signal



Mollweide equal area projection map of the celestial sphere in galactic coordinates (l, b)

M. Cadeddu

DIRECTIONAL WIMP RECOIL SPECTRUM

$$\frac{dR}{dE_r\, d\Omega(\theta,\phi)} = \frac{\sigma_{w-n}}{4\pi\, M_w\, \mu_n^2} A^2 F^2(E_r)\,\rho \underbrace{\int \delta(\boldsymbol{v}\cdot\boldsymbol{w} - v_n) f(\boldsymbol{v}) d^3\boldsymbol{v}}_{\text{Radon transform } \equiv \hat{f}(v_n,\boldsymbol{w})}$$

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.

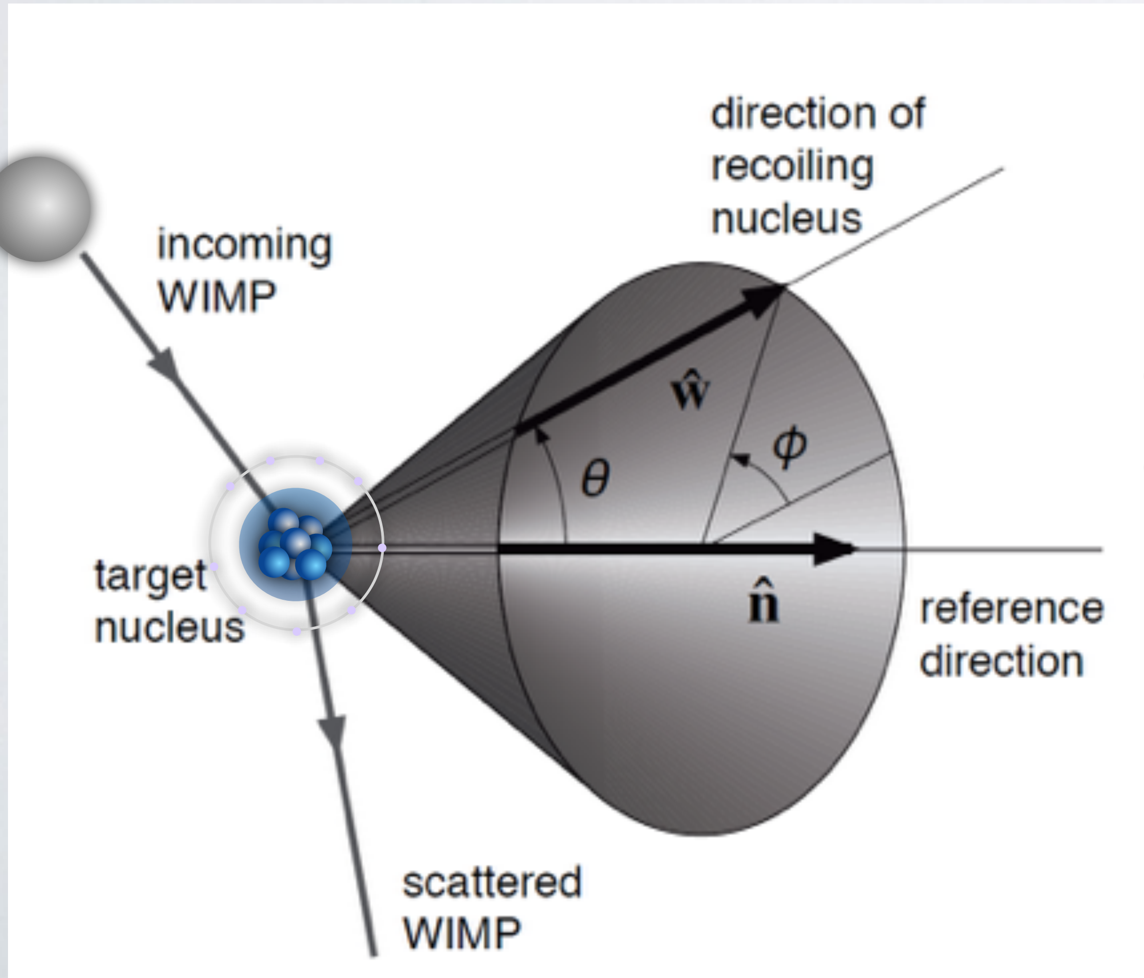
$$\Rightarrow \hat{f}(v_n,\boldsymbol{w}) = \frac{1}{\sqrt{2\pi\sigma_v^2}} \exp\left[-\frac{1}{2}\frac{(v_n - \boldsymbol{w}\cdot\boldsymbol{V})^2}{\sigma_v^2}\right]$$

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

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 I 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**.

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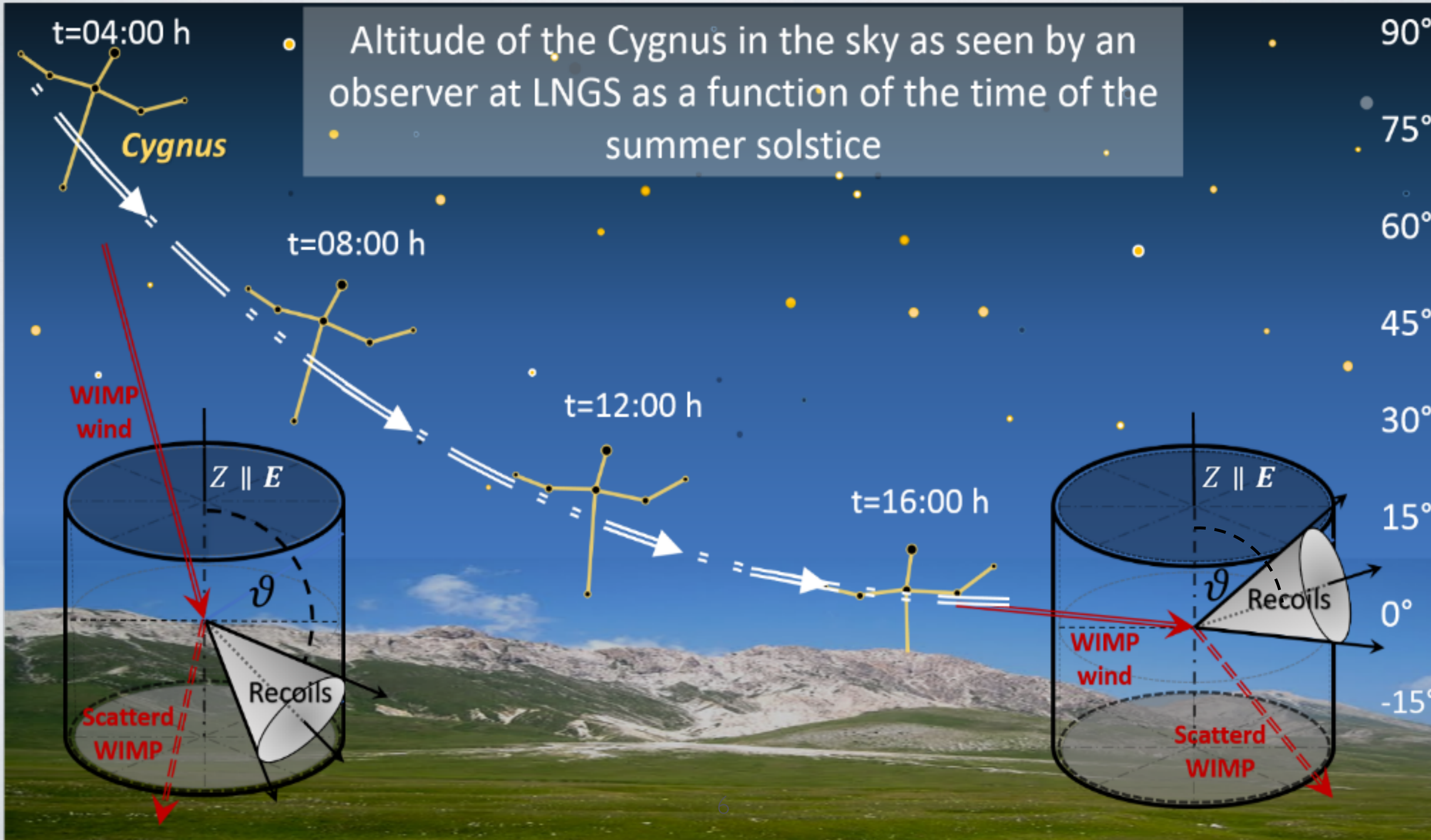
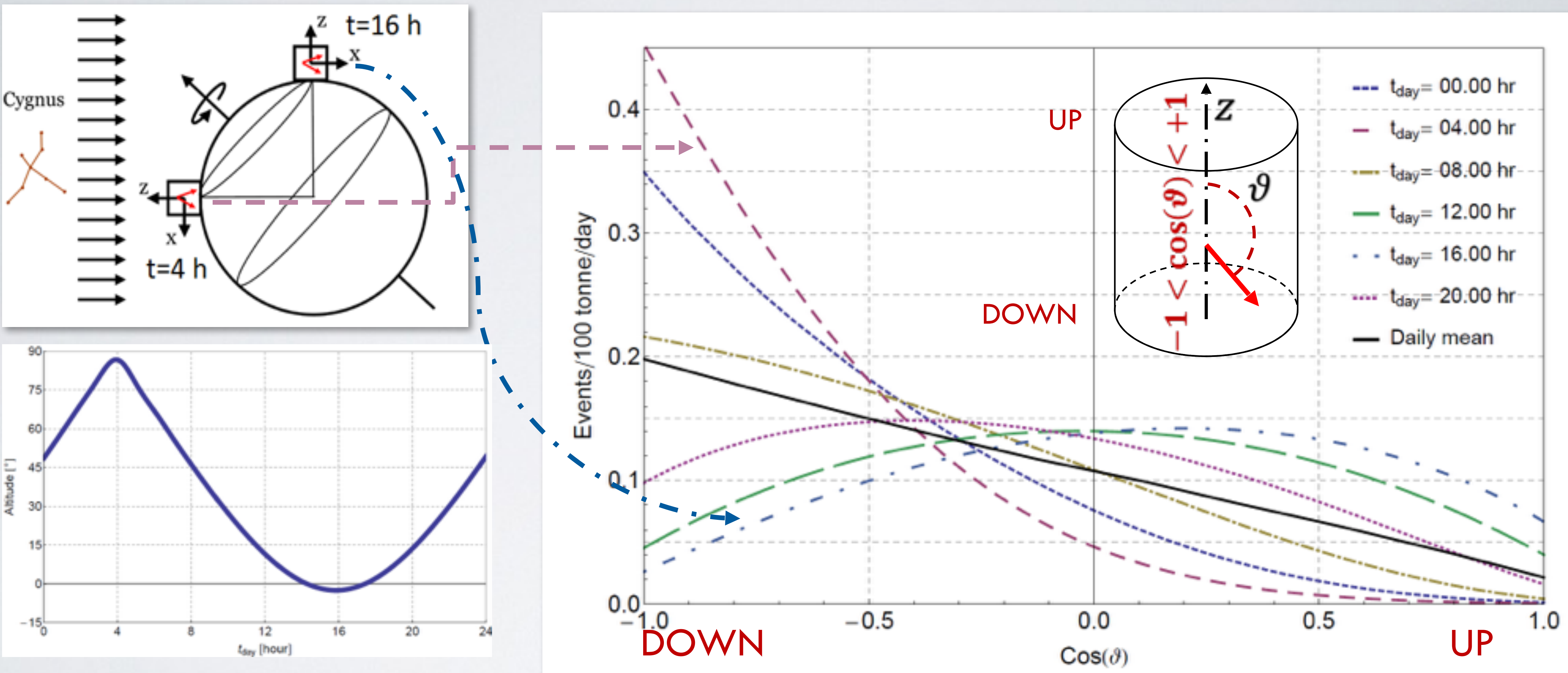
WIMP DIRECTIONALITY @ LNGS



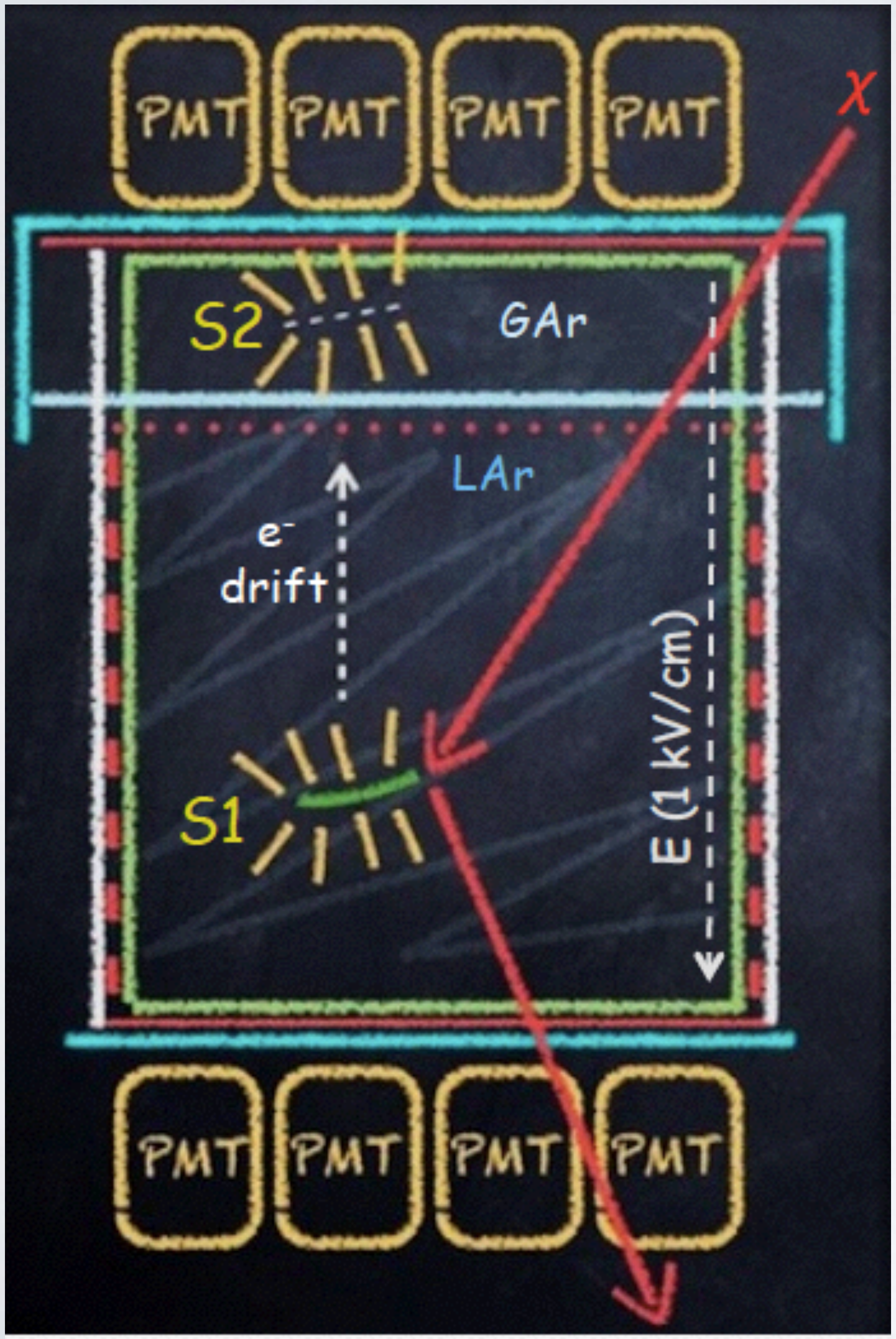
WIMP DIRECTIONALITY @ LNGS

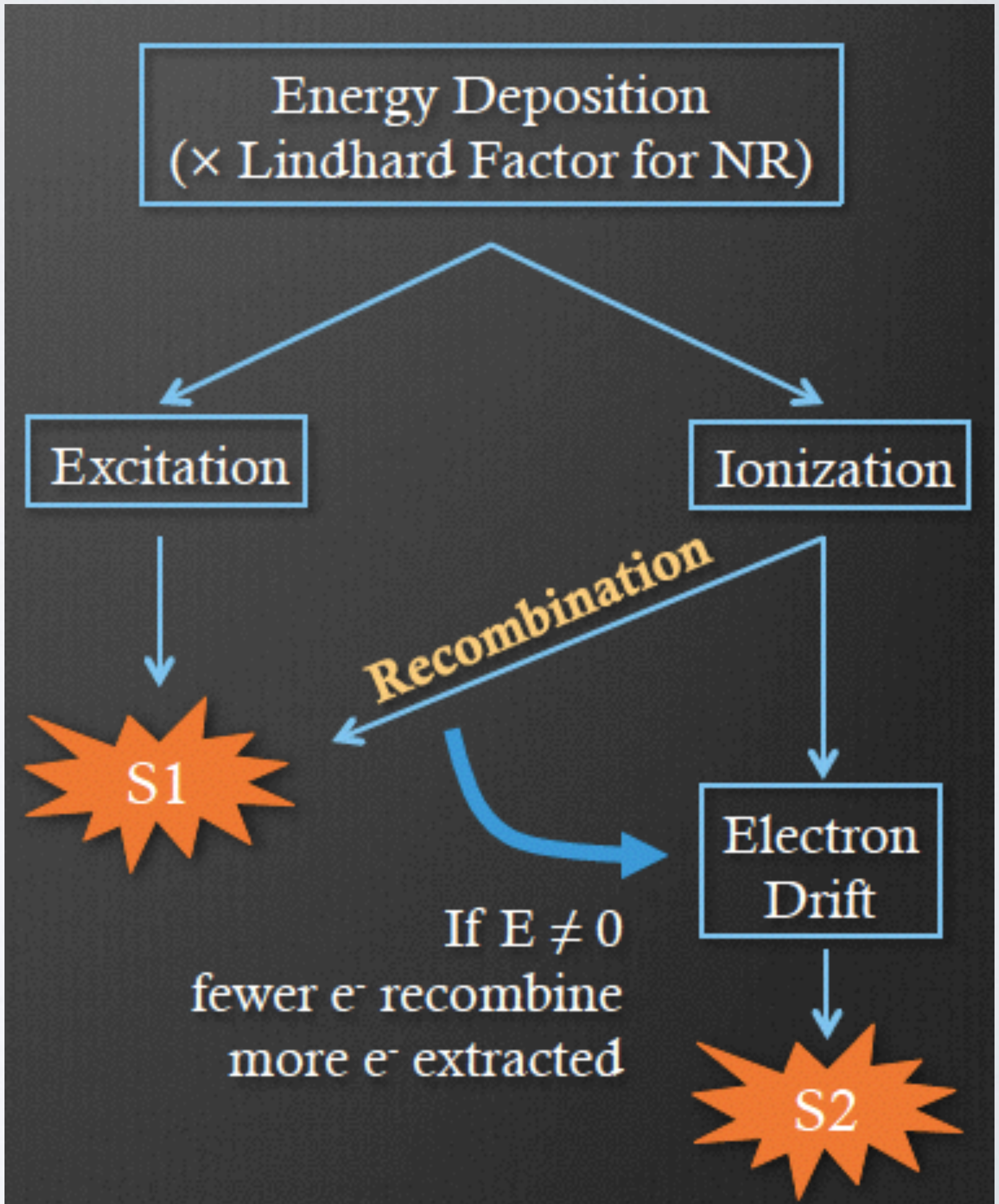


Strong angular dependence of the event rate with respect to the z-axis of the detector as a function of the time of the day.

Can we measure the direction of argon recoils in a LAr TPC?

LIQUID ARGON TPC: A PRIMER





COLUMNAR RECOMBINATION

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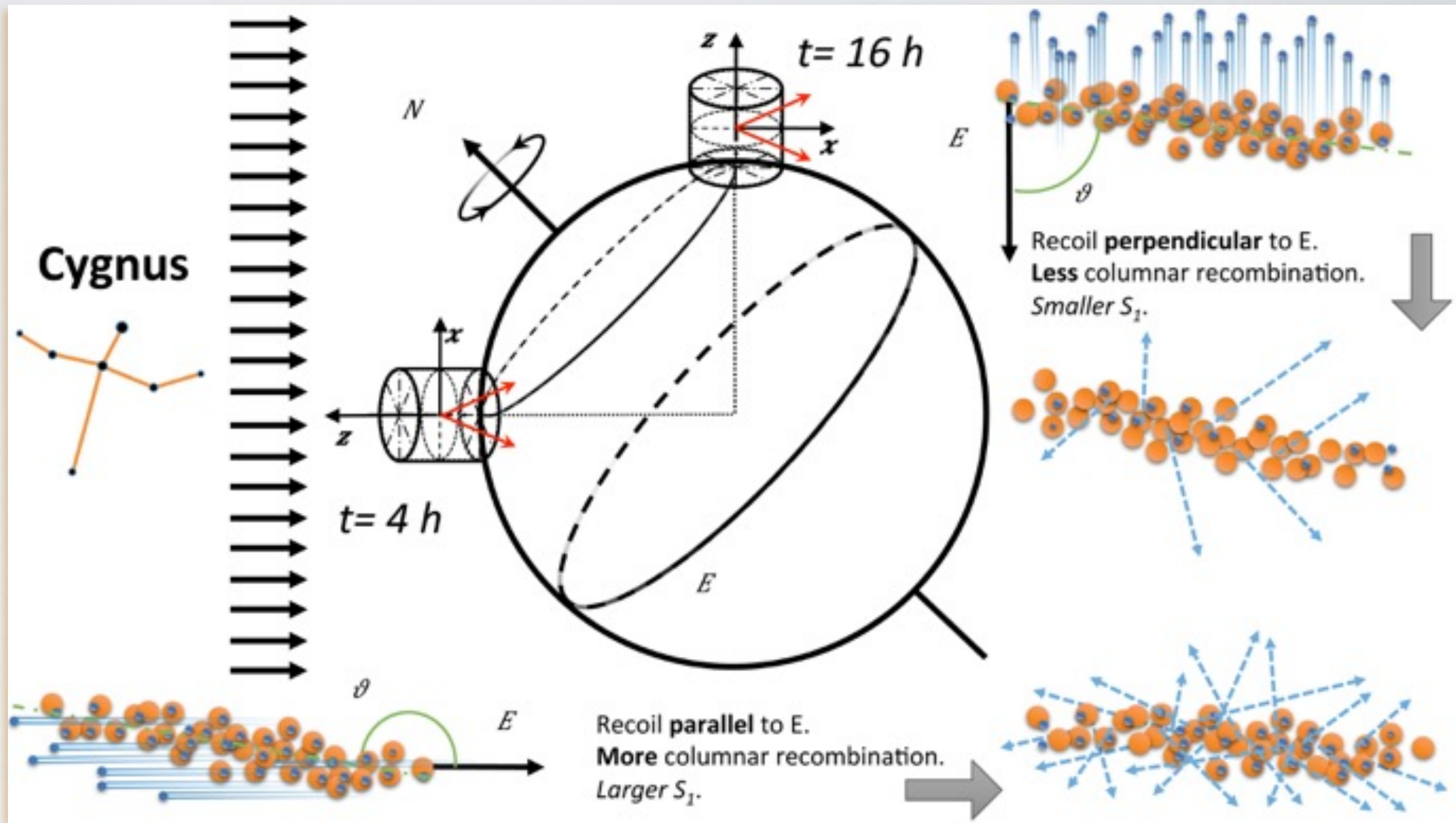
The basic idea of CR:

When a nuclear recoil is parallel to the electric field, there will be more electron-ion recombination since the electron passes more ions as it drifts through the core of the track.



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

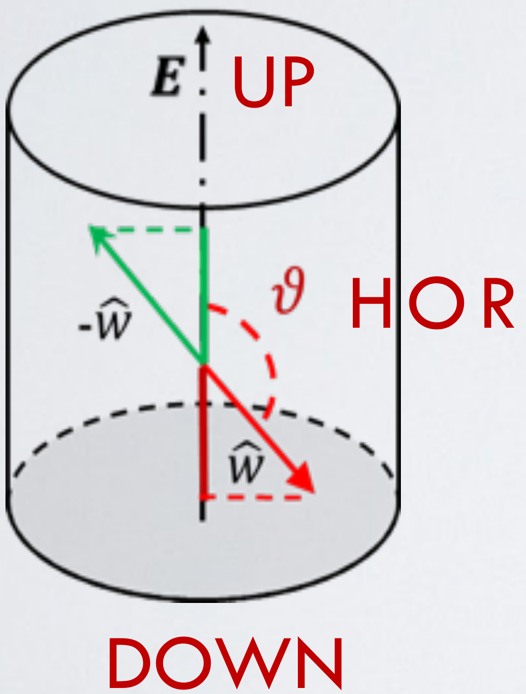
⇒ a CR detector could have 1D-directional sensitivity

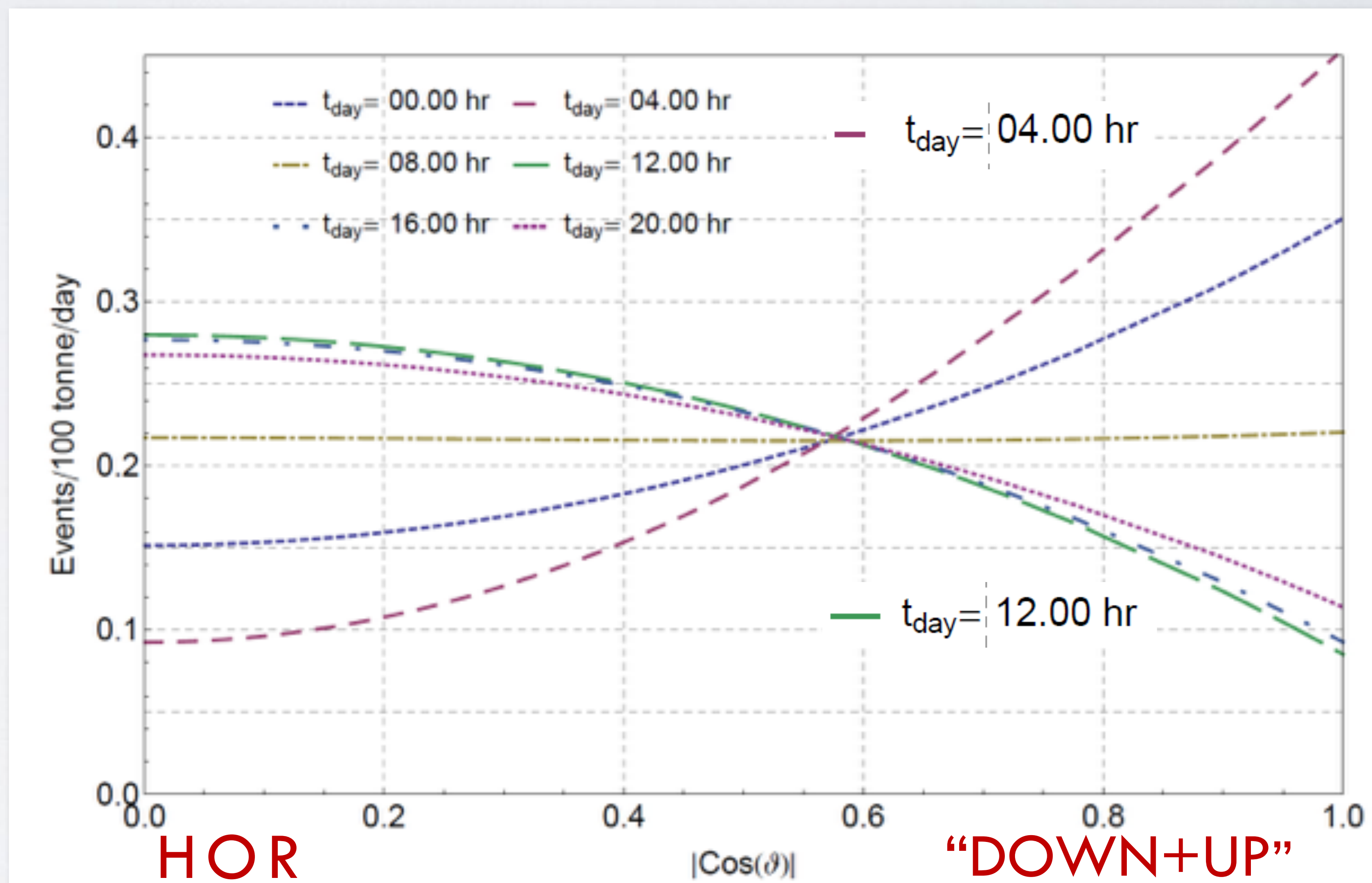
DIRECTIONALITY IN A CR DETECTOR

Recoils at 180° give the same signal
→ no head/tail discrimination

"folded" recoil rate:

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





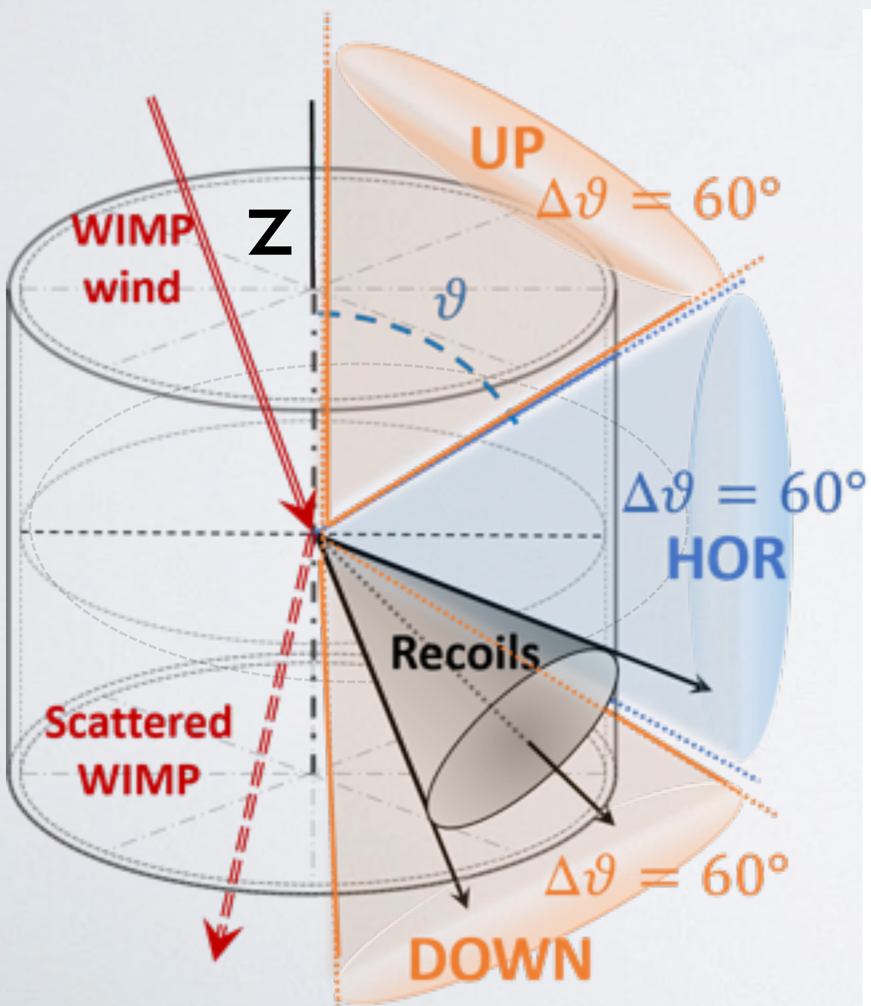
Strong angular dependence of the event rate with respect to the z-axis of the detector as a function of the time of the day

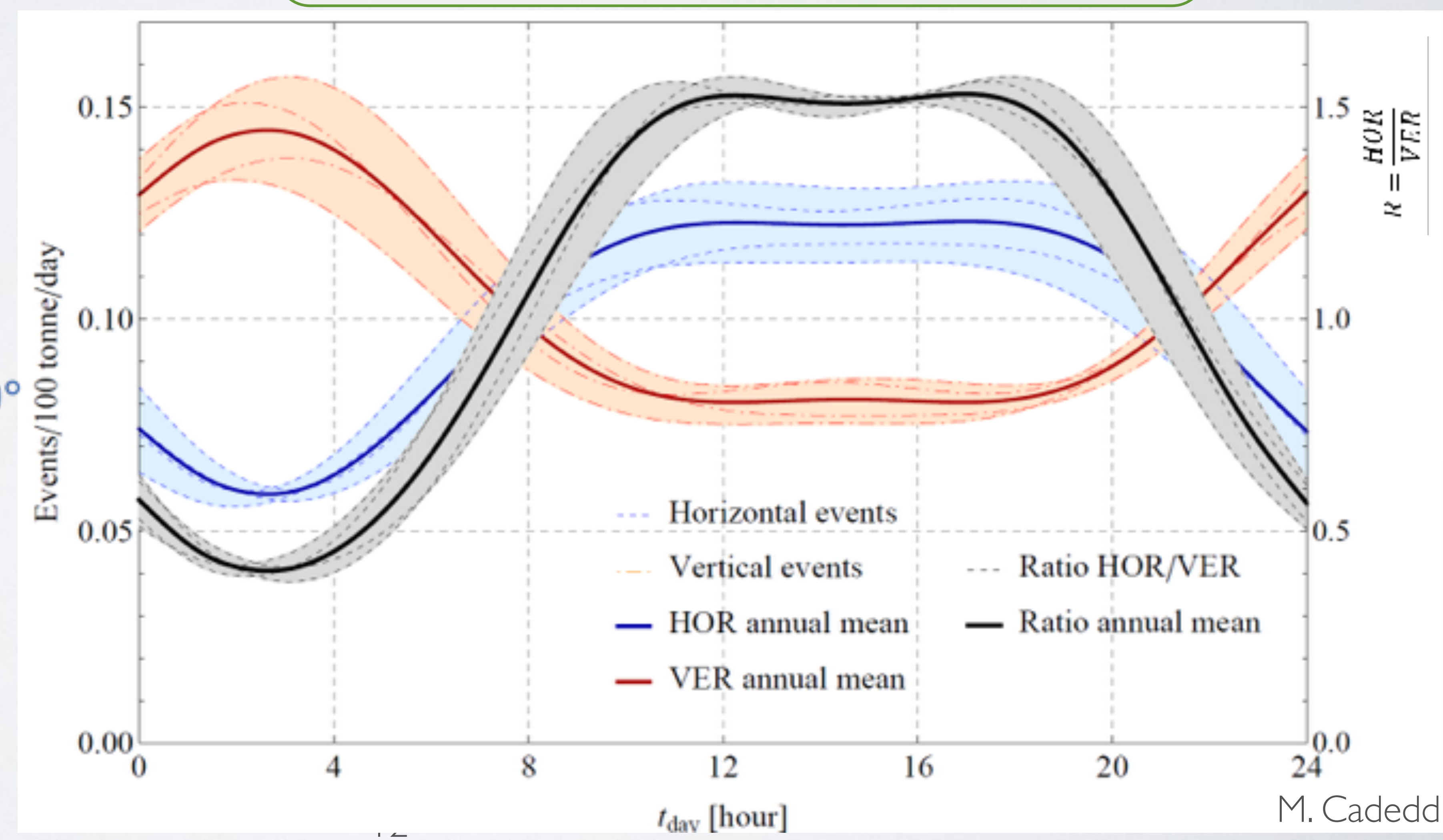
DIRECTIONALITY IN A CR DETECTOR

For a detector located at LNGS, capable of distinguishing only horizontal or vertical directions, with no head-tail discrimination:

Ratio of horizontal WIMP induced Ar recoils to vertical ones varies of a factor **4** over the day (acceptance ±30°)

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





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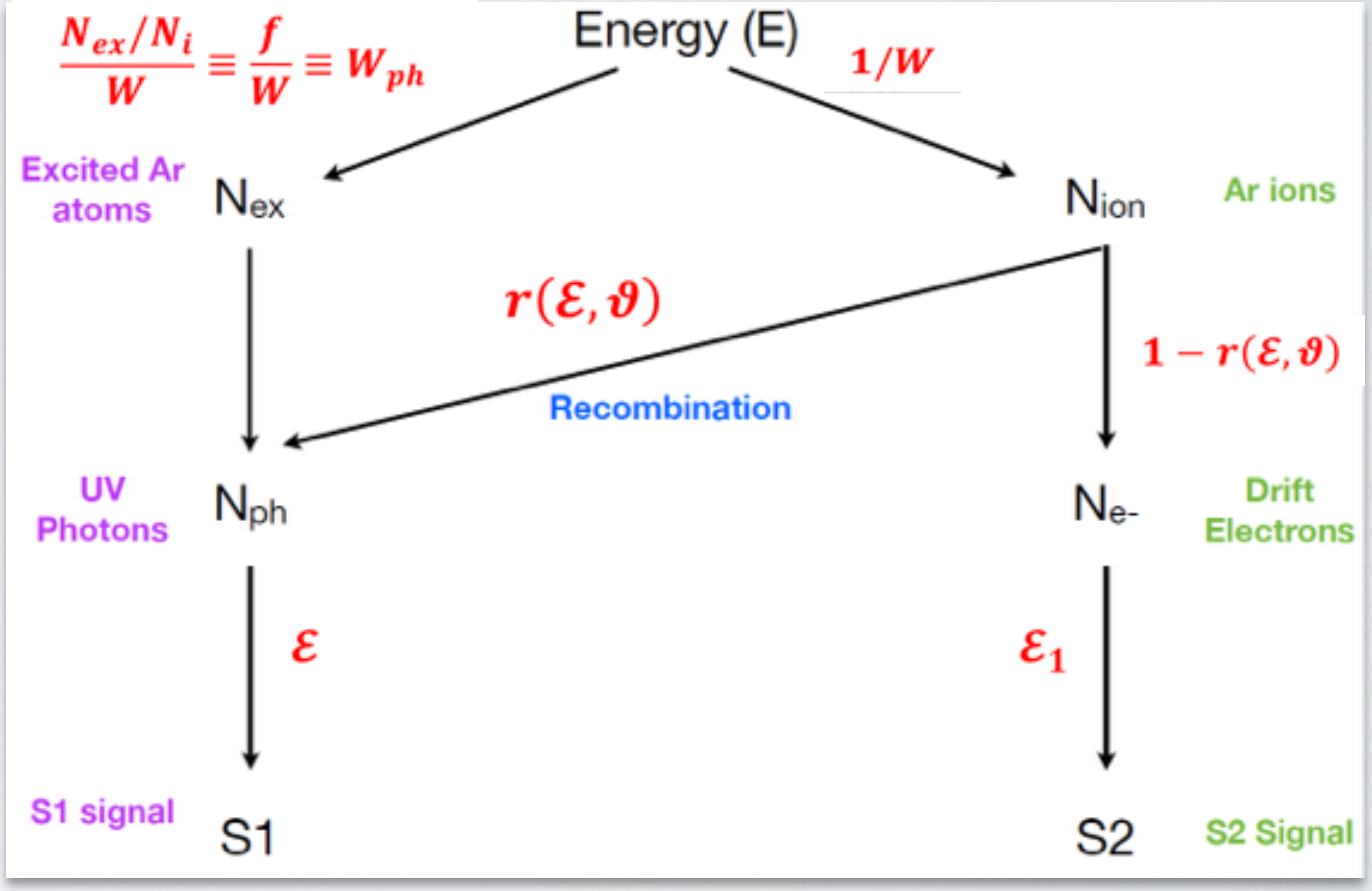
FROM THEORY TO EXPERIMENT NUCLEAR RECOILS IN LIQUID ARGON

$$S1 = g_1(N_{ex} + r\, N_i\,), \qquad S2 = g_2\,(1 - r)N_i = g_2\, R_j\, N_i$$

- Energy ≠ S1: energy deposited into 3 channels (excitation, ionisation and "heat", prominent for NR, reducing their S1 & S2)
- Excitation and recombination lead to the S1, while escaping ionization electrons lead to the S2
- Divisions at each stage are functions of particle type, electric field, and dE/dx or energy, **eventually also ϑ**



⇒ S1 and S2 expected to depend on **E** and θ_R

$$\frac{S_1}{g_1} = N_{ex} + r(\mathcal{E},\vartheta)\, N_i, \quad \frac{S_2}{g_2} = \left(1 - r(\mathcal{E},\vartheta)\right) N_i\,; \qquad \frac{S_1}{g_1} + \frac{S_2}{g_2} = N_{ex} + N_i = const$$

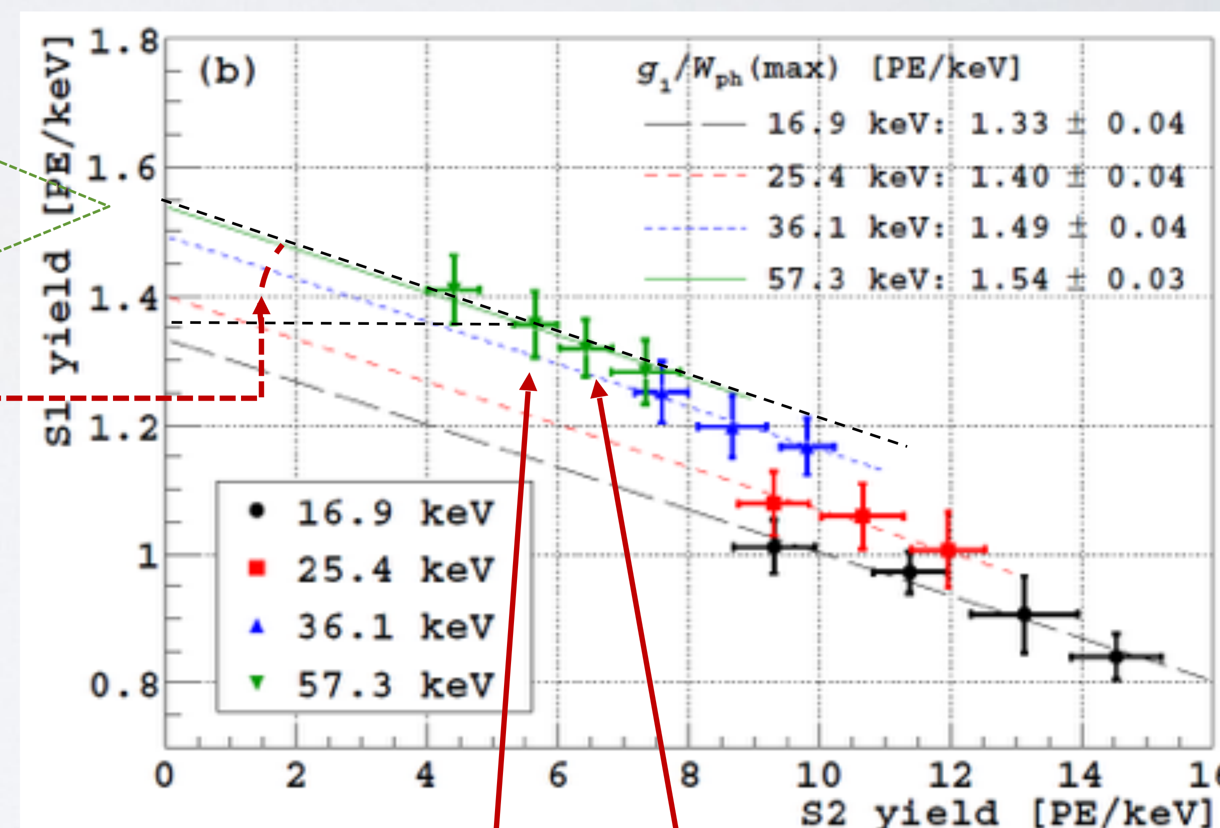
SCENE DATA: SCINTILLATION AND IONIZATION SIGNALS IN ARGON

We want to quantify the capability of a typical double-phase LAr-TPC detector to discriminate the possible effect of the columnar recombination as a function of the angle.

$$S1 = g_1(N_{ex} + r\, N_i\,), \qquad S2 = g_2\,(1 - r)N_i = g_2\, R_j\, N_i$$

The inherent S1-S2 anticorrelation in the recombination model can now be expressed as

$$\frac{S1}{E} = -\frac{g_1}{g_2}\frac{S2}{E} + \frac{g_1}{W_{ph}(max)}$$



Same ϑ, different Electric Field intensity $\mathcal{E}$

Angular dependence of R_j

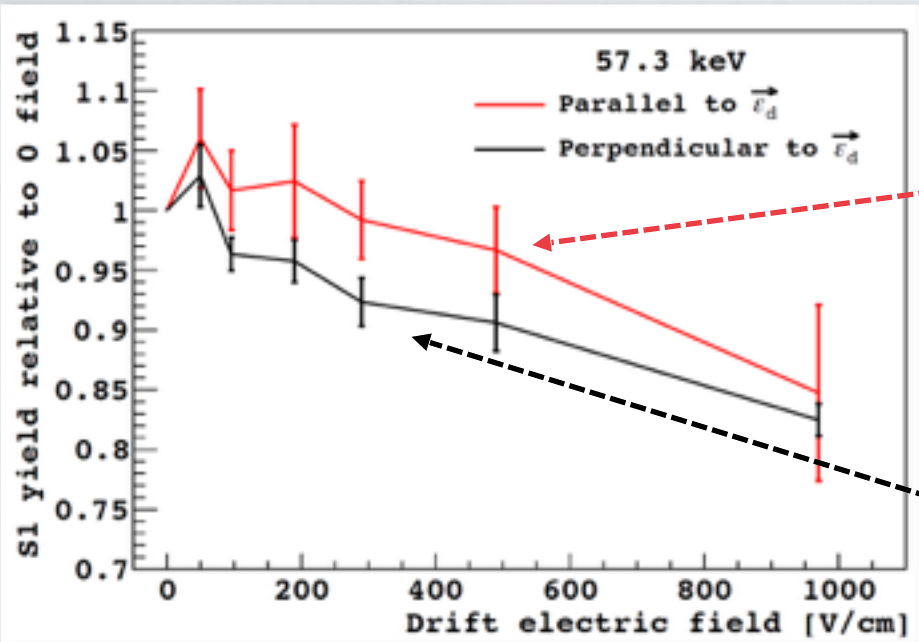
$$R_j(\mathcal{E},\vartheta) = \frac{1}{\left(1+\frac{\alpha N_0}{8\pi D}\sqrt{\frac{\pi}{z'}}\int_0^\infty \frac{e^{-s}ds}{\sqrt{s\left(1+\frac{s}{z'}\right)}}\right)} \sim R_I(\mathcal{E},\vartheta) = \frac{1}{\left(1+\frac{k_c\frac{dE}{dx}}{\mathcal{E}\sin\vartheta}\right)}$$

With $z' = \frac{1}{2}\left(\frac{b\mu\,\mathcal{E}\sin\vartheta}{D}\right)^2$

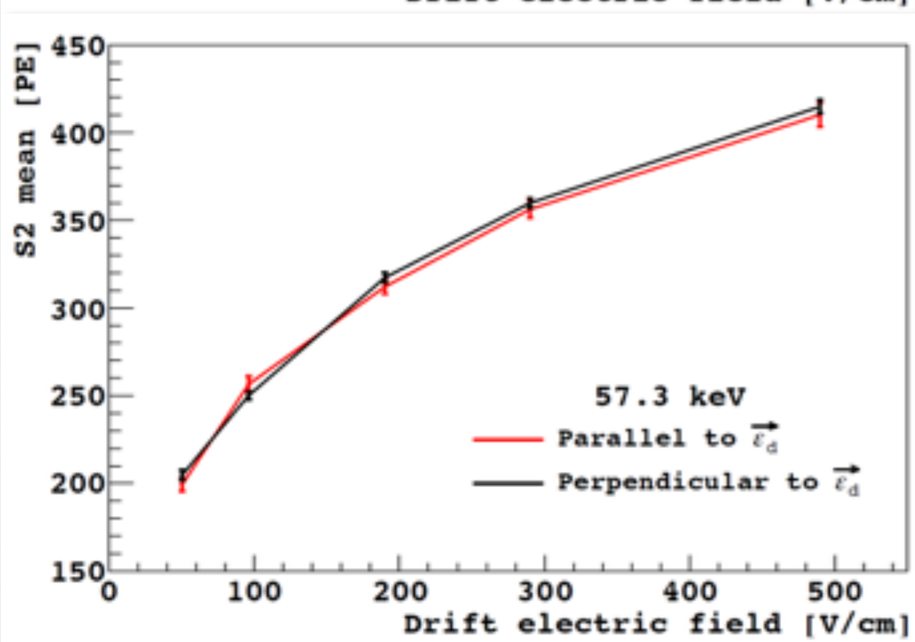
H. Cao et al. (SCENE Collaboration)
Phys. Rev. D 91, 092007

COLUMNAR RECOMBINATION AS SEEN BY SCENE

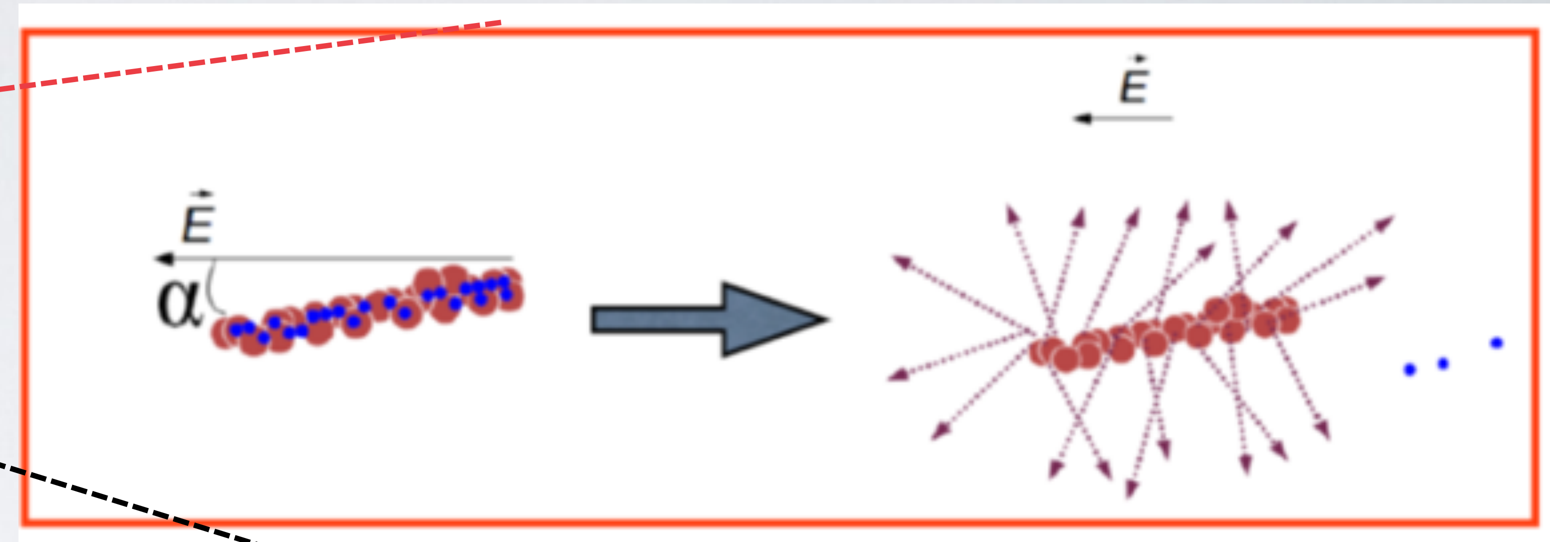
Scintillation



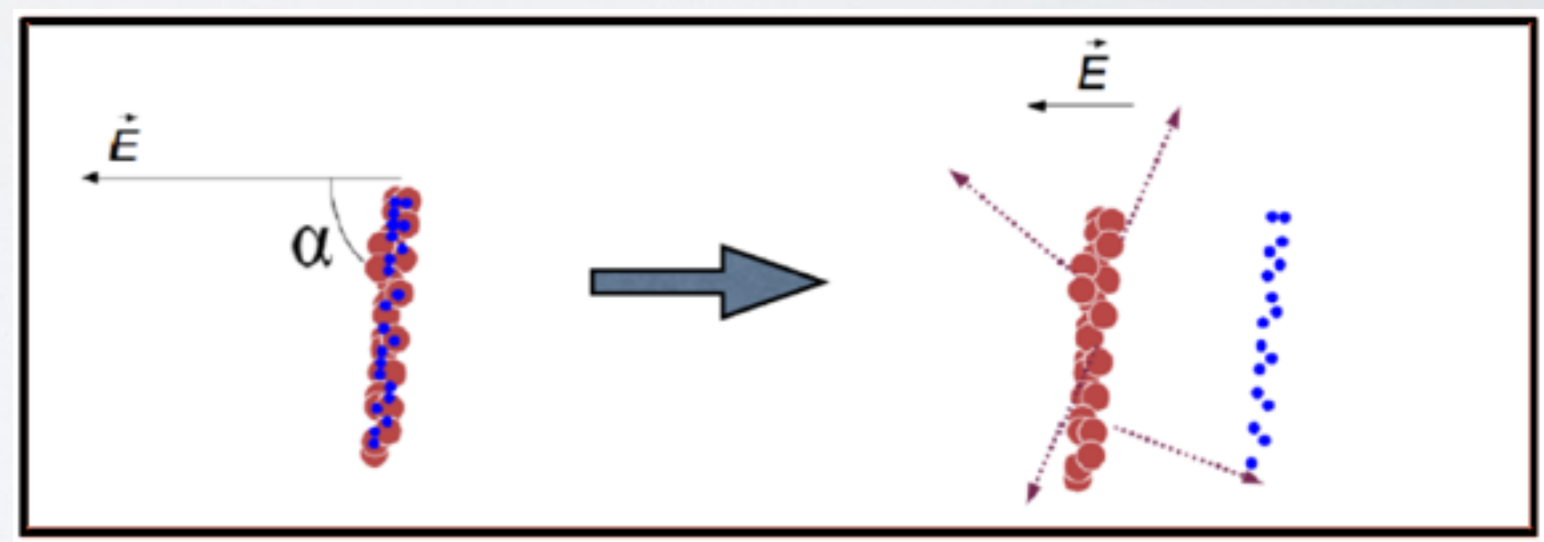
Ionization



Substantial CR: more light, less charge



CR small: less light, more charge



Hint for anisotropy of 57.2 keV nuclear recoils

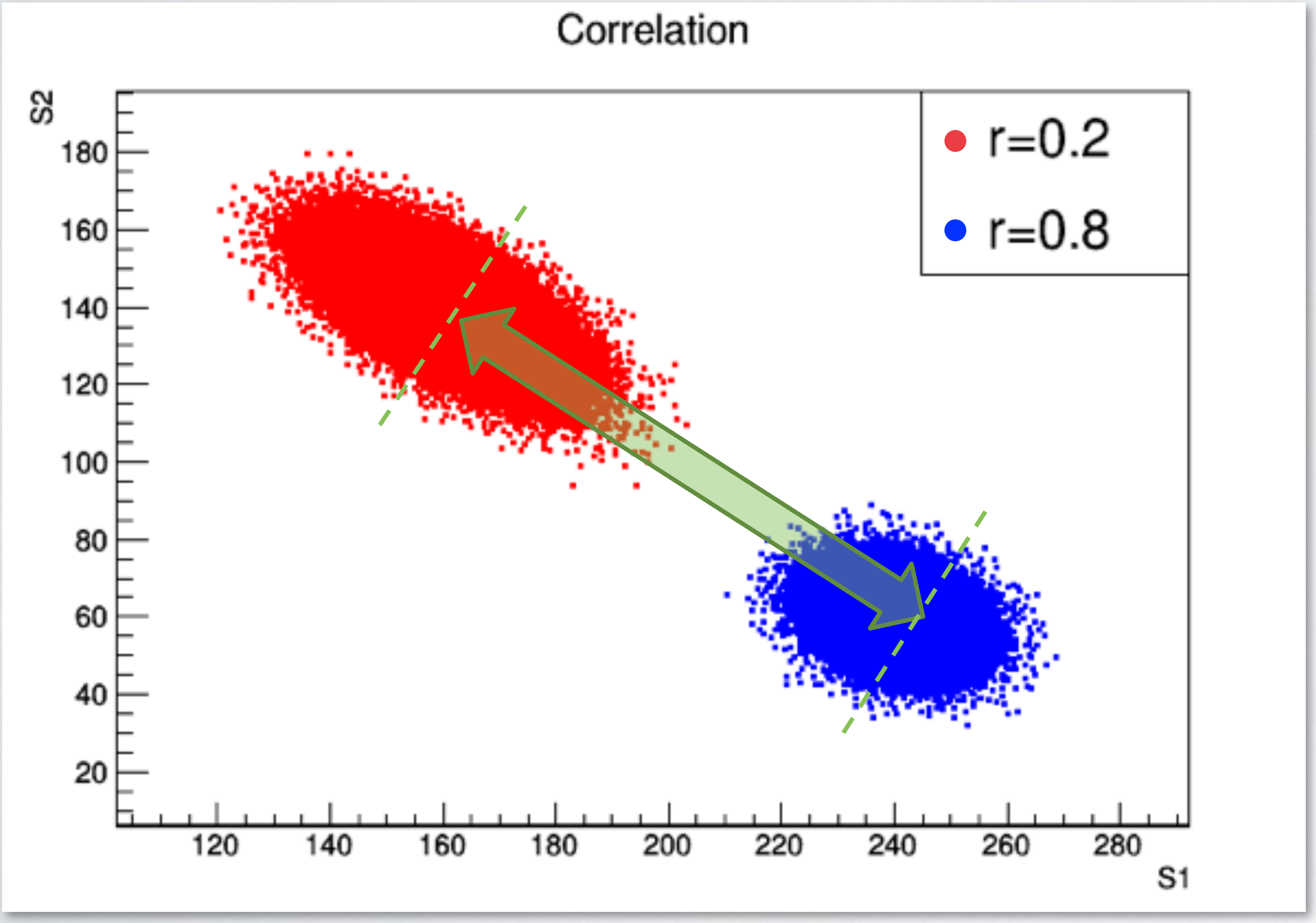
⬇⬇

RED will provide further investigation with more precise measurements, an improved detector and an optimized experimental setup

IMPROVING ON SCENE: DIRECTIONAL MEASUREMENT

$$\frac{S_1}{g_1} = N_{ex} + r(\mathcal{E},\vartheta)\, N_i, \quad \frac{S_2}{g_2} = \left(1 - r(\mathcal{E},\vartheta)\right) N_i\, ; \quad \frac{S_1}{g_1} + \frac{S_2}{g_2} = N_{ex} + N_i = const$$

$$\frac{N_{ex}}{N_i} = \mathrm{CONSTANT} = \frac{S1}{S2} \times \frac{g2}{g1} \quad \left[1 - r\left(\varepsilon, \vartheta, {}^{dE}/_{dx}\right)\right] - r\left(\varepsilon, \vartheta, {}^{dE}/_{dx}\right)$$

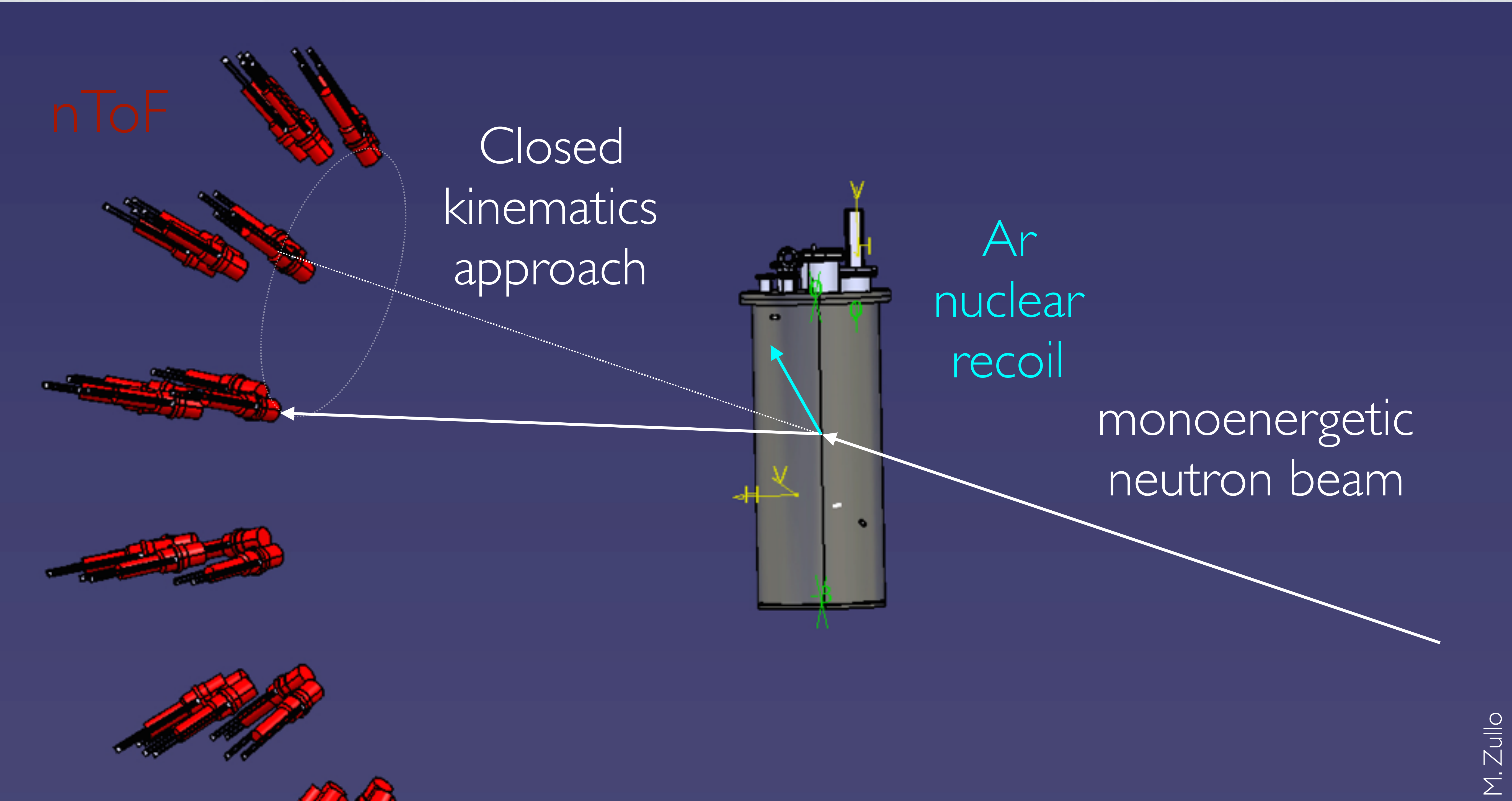


angular resolution depends on S1 and S2 resolutions

RED CONCEPTUAL DESIGN

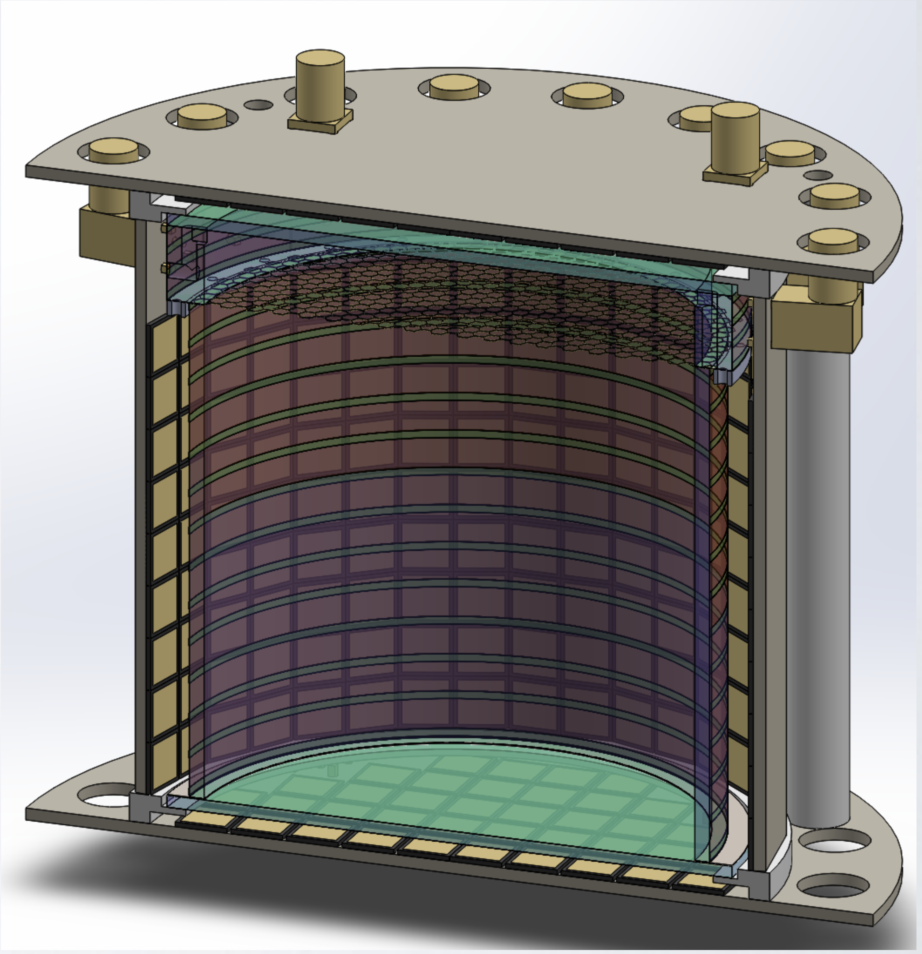
An experiment to sense recoil directionality in Liquid Argon

A monochromatic neutron beam on a Liquid Argon target with a segmented nTOF spectrometer to detect the direction of the scattered neutron



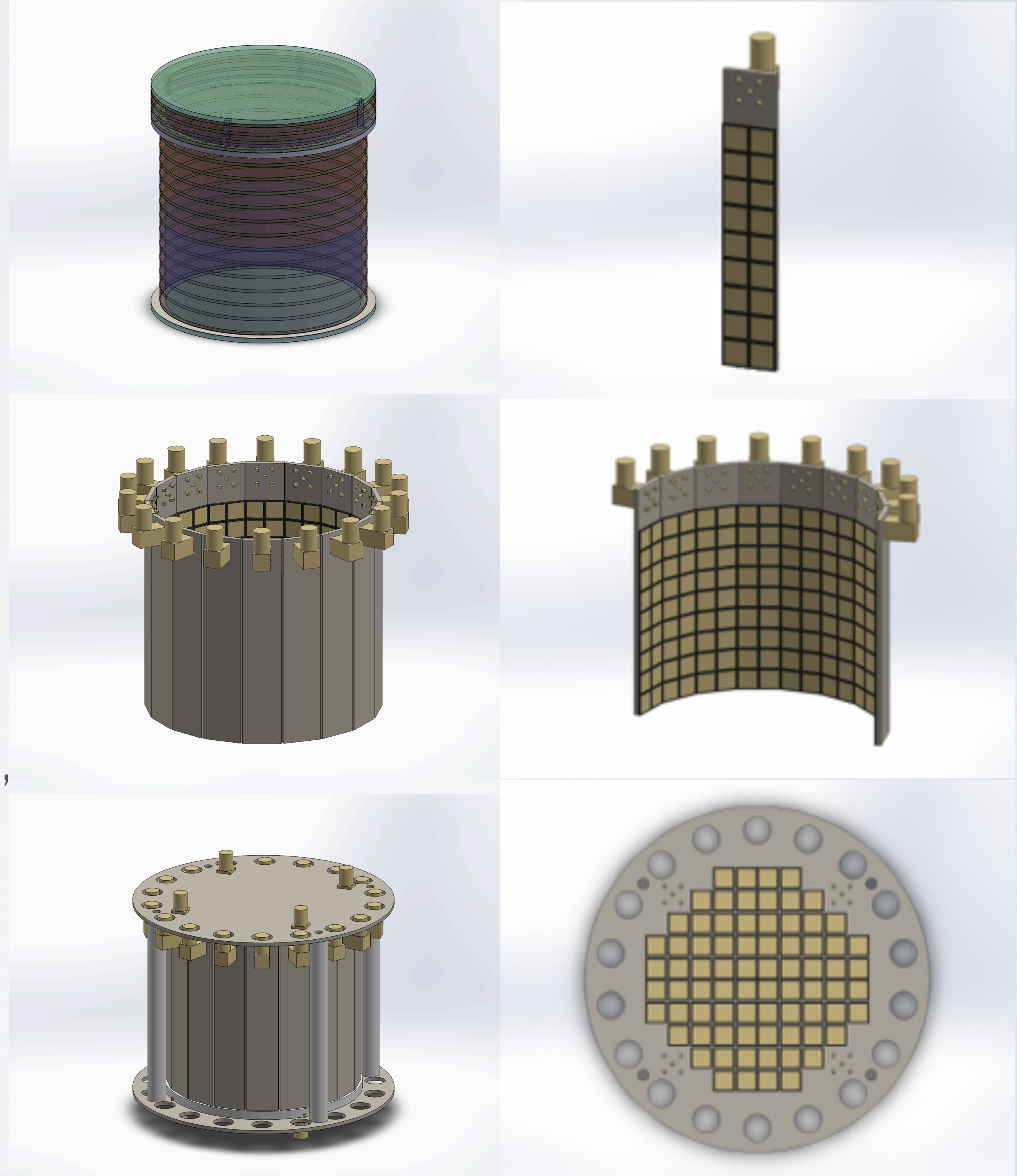
RED OVERCOMES THE WEAK POINTS OF PREVIOUS EXPERIMENTS

- GAP-TPC: an innovative SiPM-based LAr detector with unprecedented performance in terms of S1 and S2 resolution
- Cryostat optimised to minimize neutron multiple scattering
- A dedicated neutron beam line to accumulate enough statistics and permanent space allocated at UNINA Tandem laboratory
- A beam collimator to select neutron energy with high accuracy and to shield undesired gammas
- Large acceptance, modular, nToF spectrometer to minimise data taking systematics



GAP-TPC

- Compact, no dead spaces to minimise multiple scattering → fused silica vessel
- A drift distance such as to have a good separation between S1 and S2 signals
- An higher extraction field to optimise S2 measurement
- Innovative solutions for a **4π optical coverage**
- Very uniform drift field
- Very high light yield LY >12 phe/keV_{ee}
- Exceptional single photon resolution (< 5-10%),
- Stable, high efficiency, high granularity pixellated photosensors
- Sub-cm (3-5 mm) spatial resolution on the XY plane to detect multiple scatterings and surface events.



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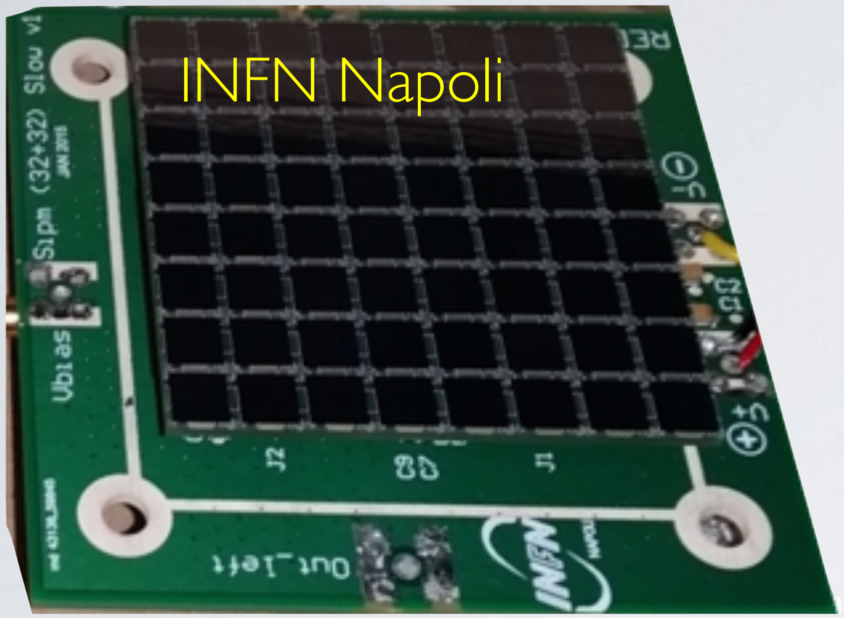
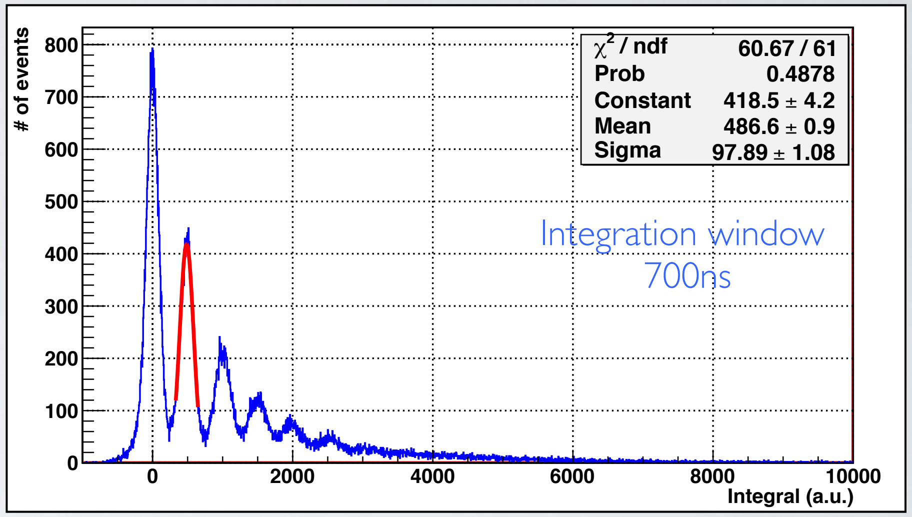
PRELIMINARY WORK: COMMERCIAL SIPM ARRAY @77K



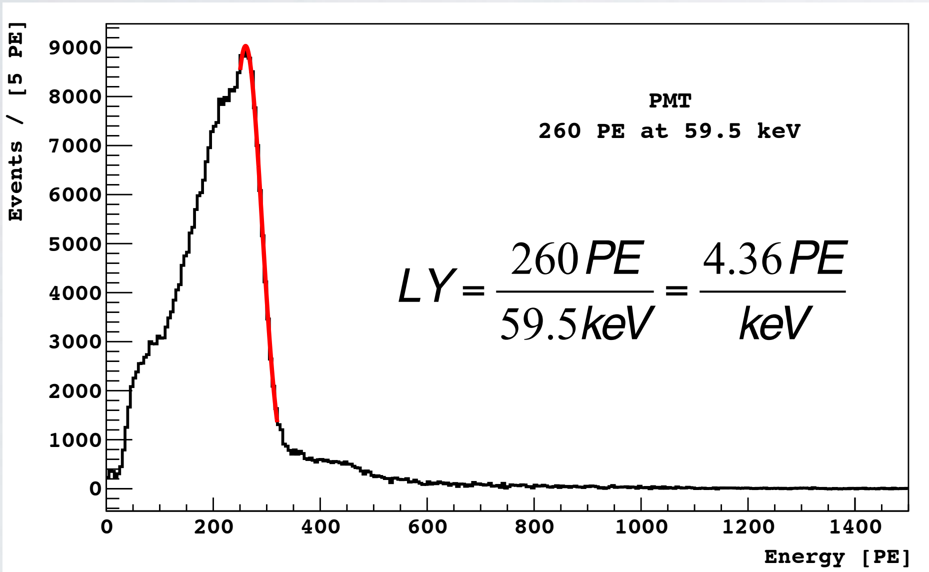
SensL-ArrayC-60035-64P

- Array size: 5x5 cm2 (active 2304 mm2)
- 64 SiPMs of 6x6 mm2
- SPAD size 35 um
- SPAD capacitance ≈150 fF (@RT)
- Nominal SiPM PDE: 41% (@5Vov)
- SiPM Capacitance 3nF/channel
- Array fill factor about 76%
- Cryogenic readout board with 2 outputs 32 channels summed each

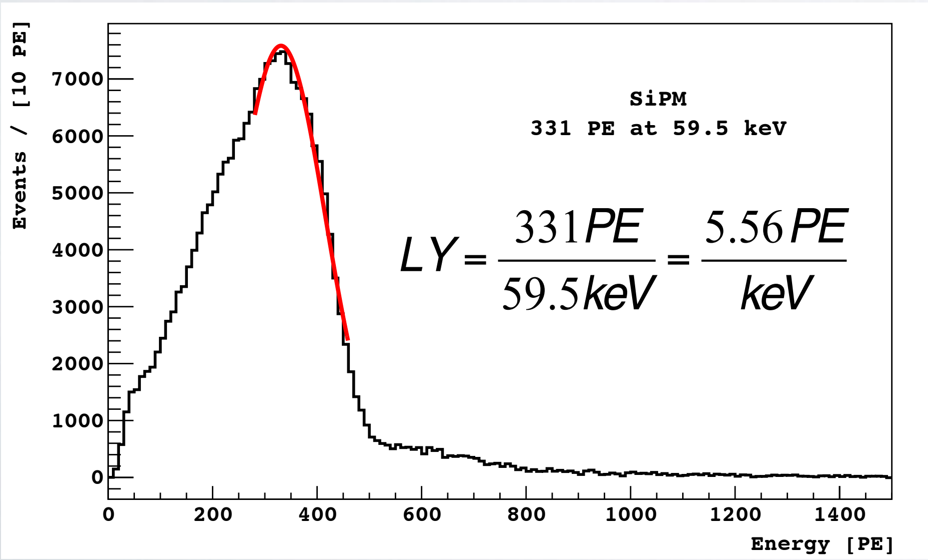
Single Photoelectron spectrum



PMT



SiPM



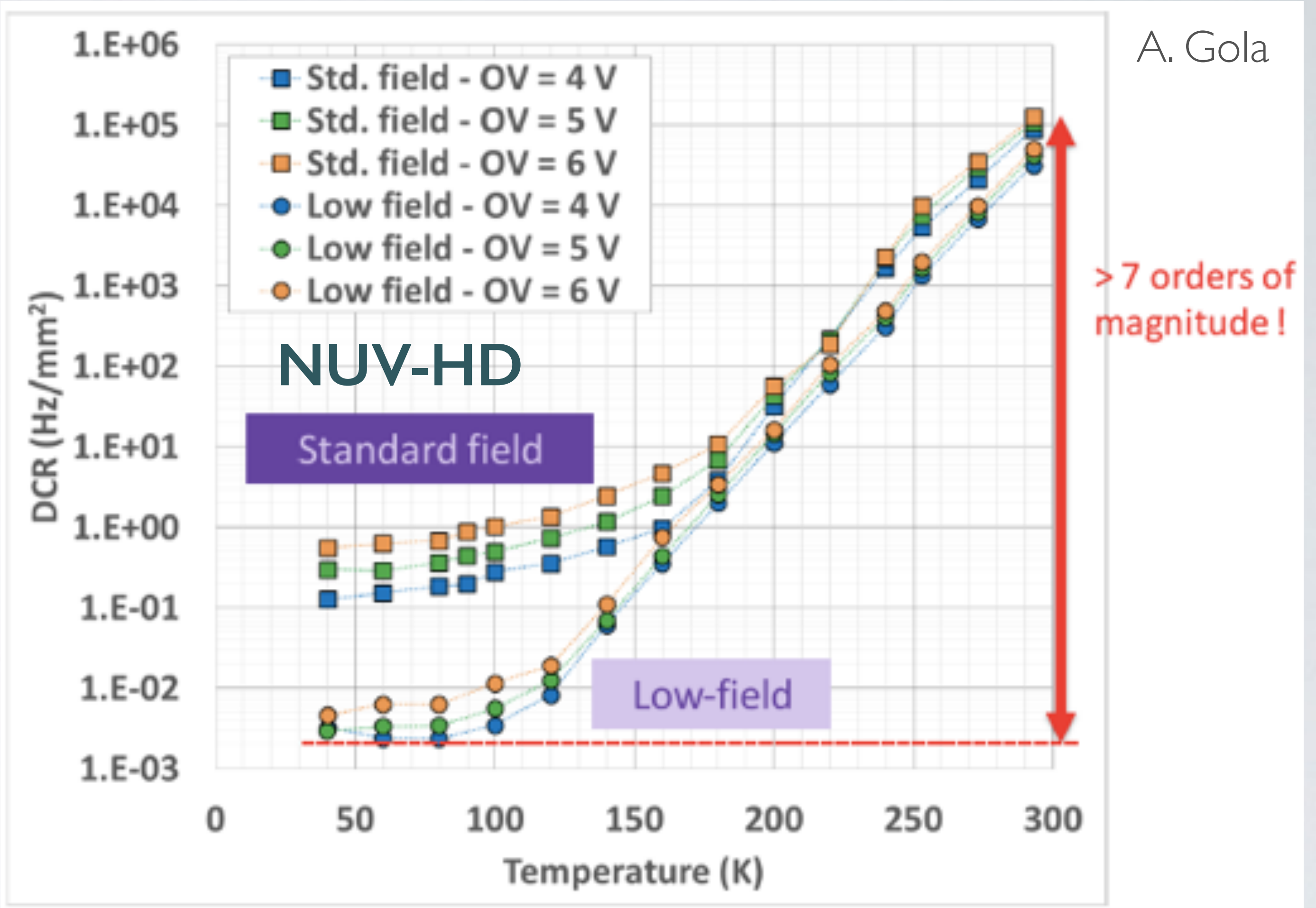
- Cryogenic readout board very robust and performing well
- Excellent photon counting capabilities (SPE resolution)
- Best Light Yield ever achieved in LAr TPC 9.9 PE/keV
- SiPM detects >25% more light than the PMT

Very promising result in view of the RED experiment

B. Rossi et al., JINST 11 (2016) 02, C02041

SIPM DEVELOPMENT AT FBK

- Custom SiPMs featuring a very sharp peak in the single cell response and a slow recharge
  - **suppressed afterpulsing**
- NUV-HD technology
  - small microcells (< 30 um)
  - high FF (up to 78%)
  - **PDE in excess of 55% at 410 nm**
  - low correlated noise
- Very efficient packaging and **very high fill factor at the tile level** (≃90%)



A 10x10 cm² SiPM array would have a total DCR < 100 Hz!

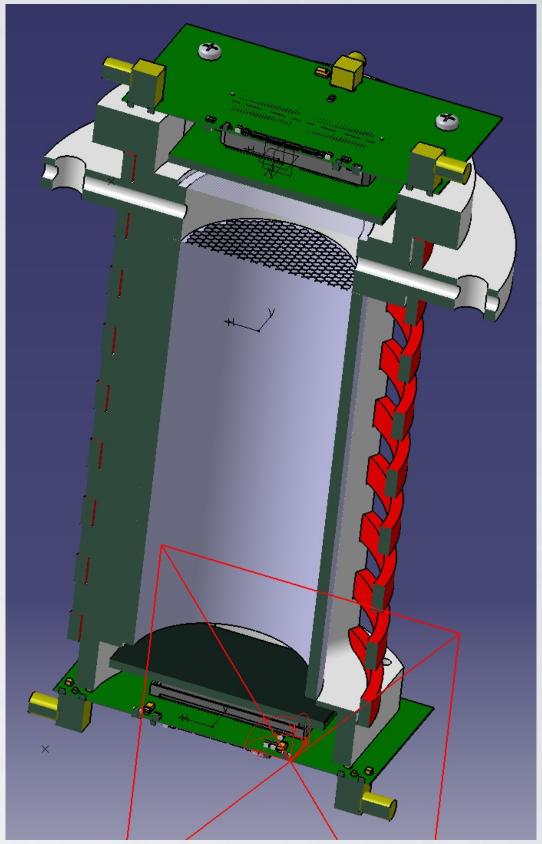
DarkSide SiPM R&D

Significant part of the preliminary work to identify the device specifications and to optimise the technology already performed

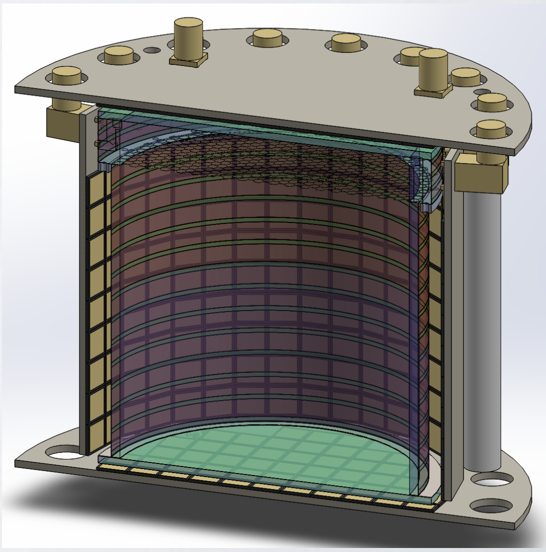
Synergy with the ongoing DarkSide R&D program. Productions are sufficient to assemble enough tiles to perform preliminary tests and equip the GAP-TPC.

TIMELINE OF THE RED EXPERIMENT

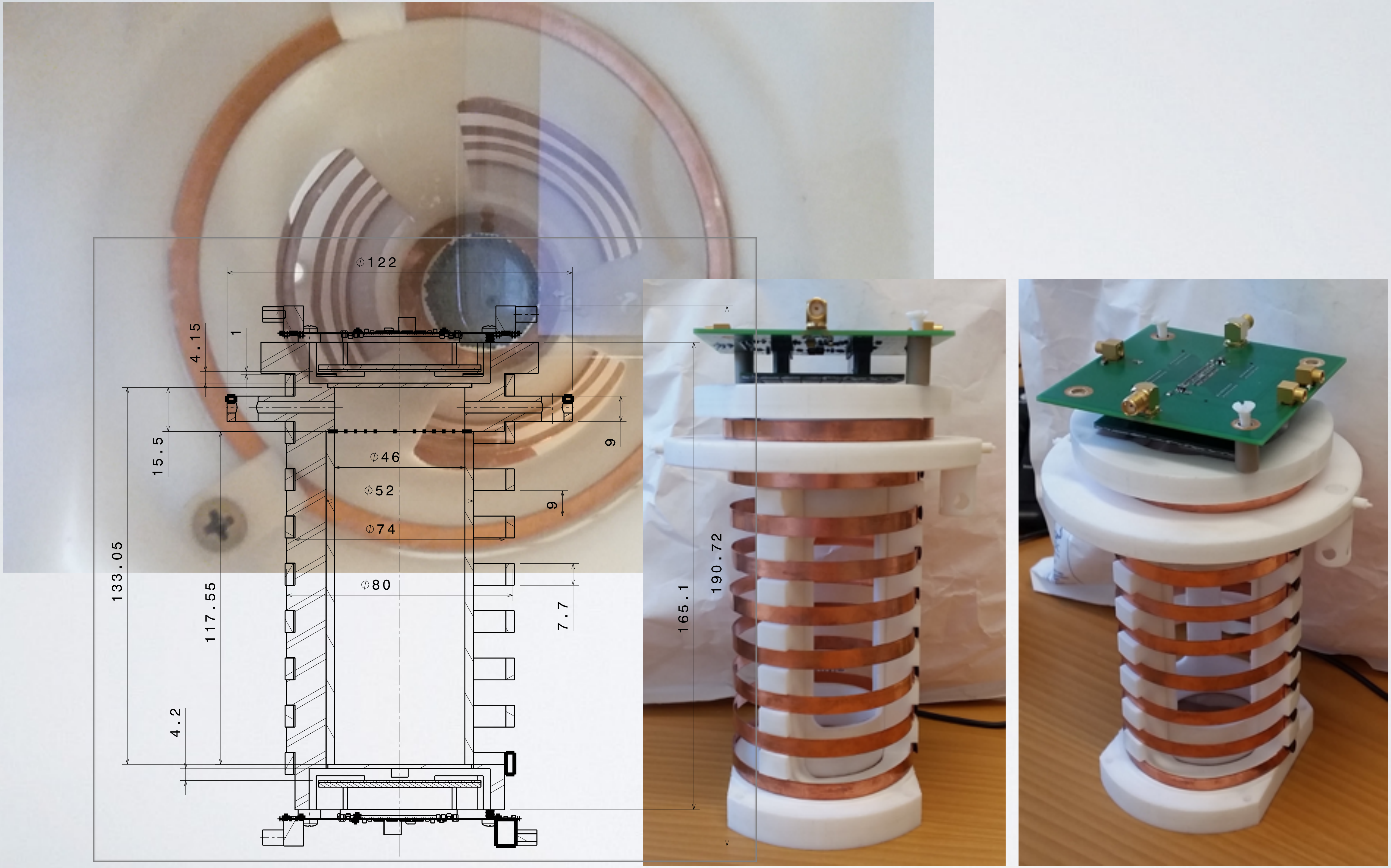
- **Phase 1: aiming at confirming the results obtained by the SCENE experiment.**
  - Data taking campaign on the neutron beam line with a preliminary experimental configuration
    - provisional neutron beam setup;
    - GAP-TPC prototype installed in the final cryogenic system;
    - preliminary nToF 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.



GAP-TPC PROTOTYPE



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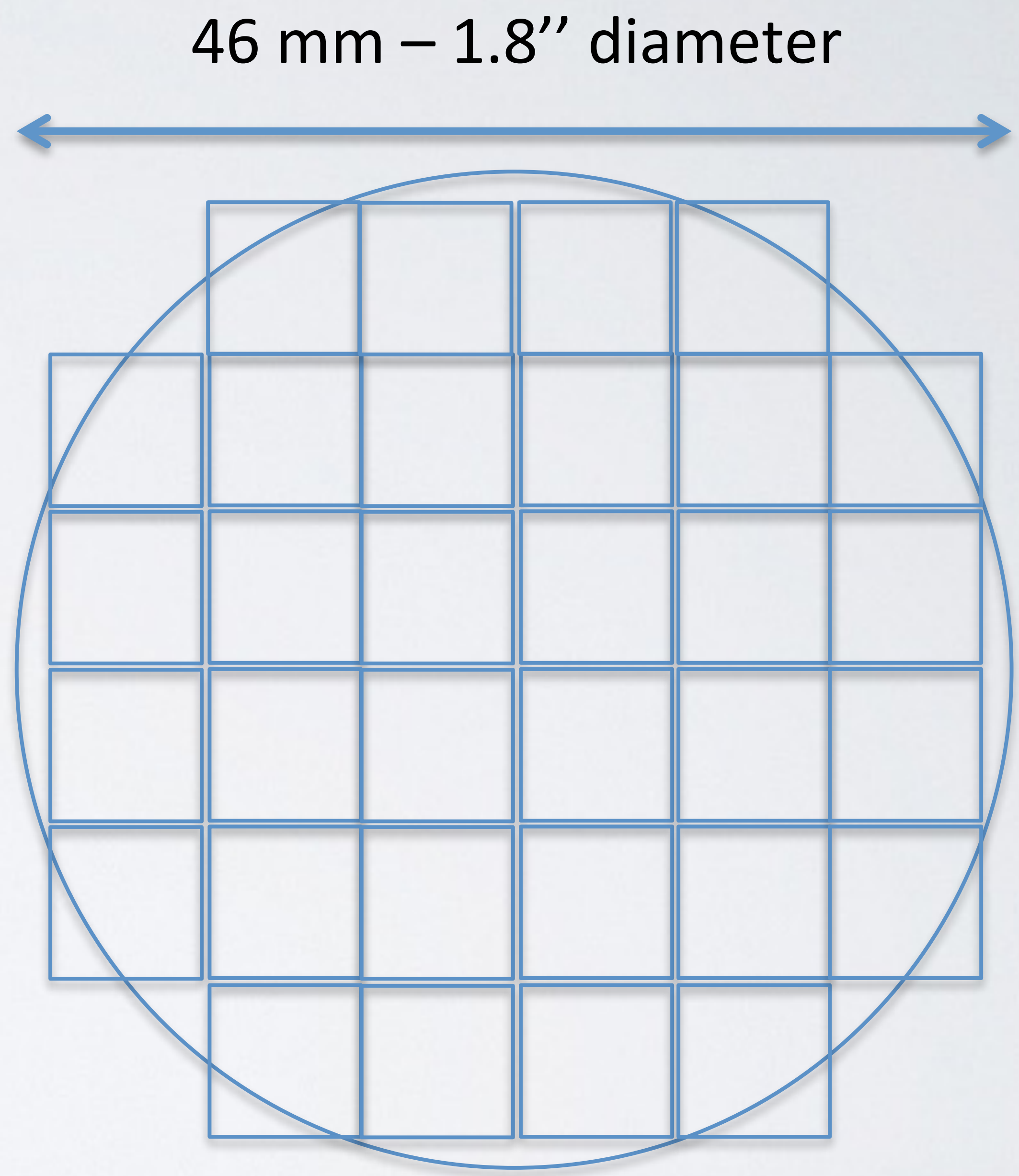
GAP-TPC PROTOTYPE: FE R/O & DAQ

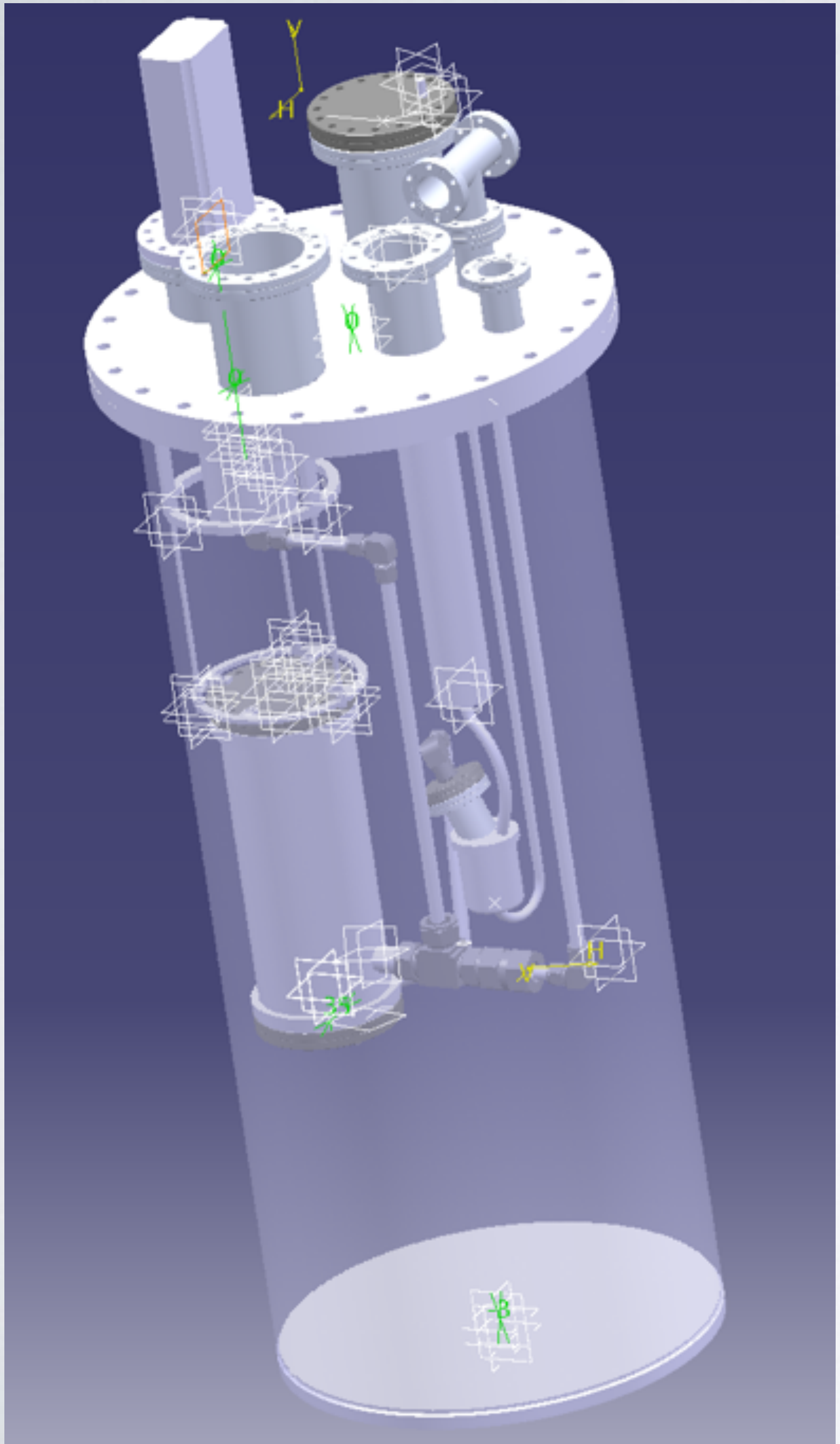
- Top:
  - Number: 32 SIPMs
  - Size: 6x6mm2 active area- 7.2x7.2mm2 size)
- Bottom:
  - 16+16 SiPM → 2 outputs
- READOUT STRATEGY
  - A. Single pixel readout (32 outputs) + 2 bottom
  - B. 1.4x0.6cm2 grouping (16 outputs) +2 bottom
  - C. 1.4x1.4cm2 grouping (8 channels) +2 bottom
- DAQ system
  - TPC:
    - 2xV1730
    - Total channels: 16+8 ch
    - Sampling: 2 ns
    - Resolution: 14 bit
  - NToF (LSci):
    - 2xV1724
    - Total channels: 8 ch
    - Sampling: 10 ns
    - Resolution: 12 bit

Actual inner size of the prototype



Readout configurations B&C already fulfilled
10ch missing for Configuration A

B. Rossi



RED CRYOGENICS

G. Fiorillo, B. Rossi, M. Rescigno, M. Zullo, T. Zullo

THE RED PROJECT

REcoil Directionality

- **Timely**
  - Adding directional sensitivity to next generation LAr multi-tonne detectors (DarkSide-20k, in run by 2020)
- **Highly innovative**
  - GAP-TPC is the first LAr detector to use SiPM readout and a 4π geometry
- **Large potential impact on direct DM searches**
  - Close the gap between detectors with the potential to reach neutrino floor and beyond and those with directional sensitivity → a difference of 3 orders of magnitude in mass

- Status:

  detector under construction, commissioning expected by the Summer

  simulation and physics studies ongoing

- Participating groups:

  INFN (Cagliari, Genova, LNGS, Napoli, Pisa, Roma1, TIFPA)

  APC-IN2P3, Princeton, Temple, UCLA

New collaborators are welcome!