

# Incorporating theoretical blazar models into neutrino stacking analyses with KM3NeT/ARCA



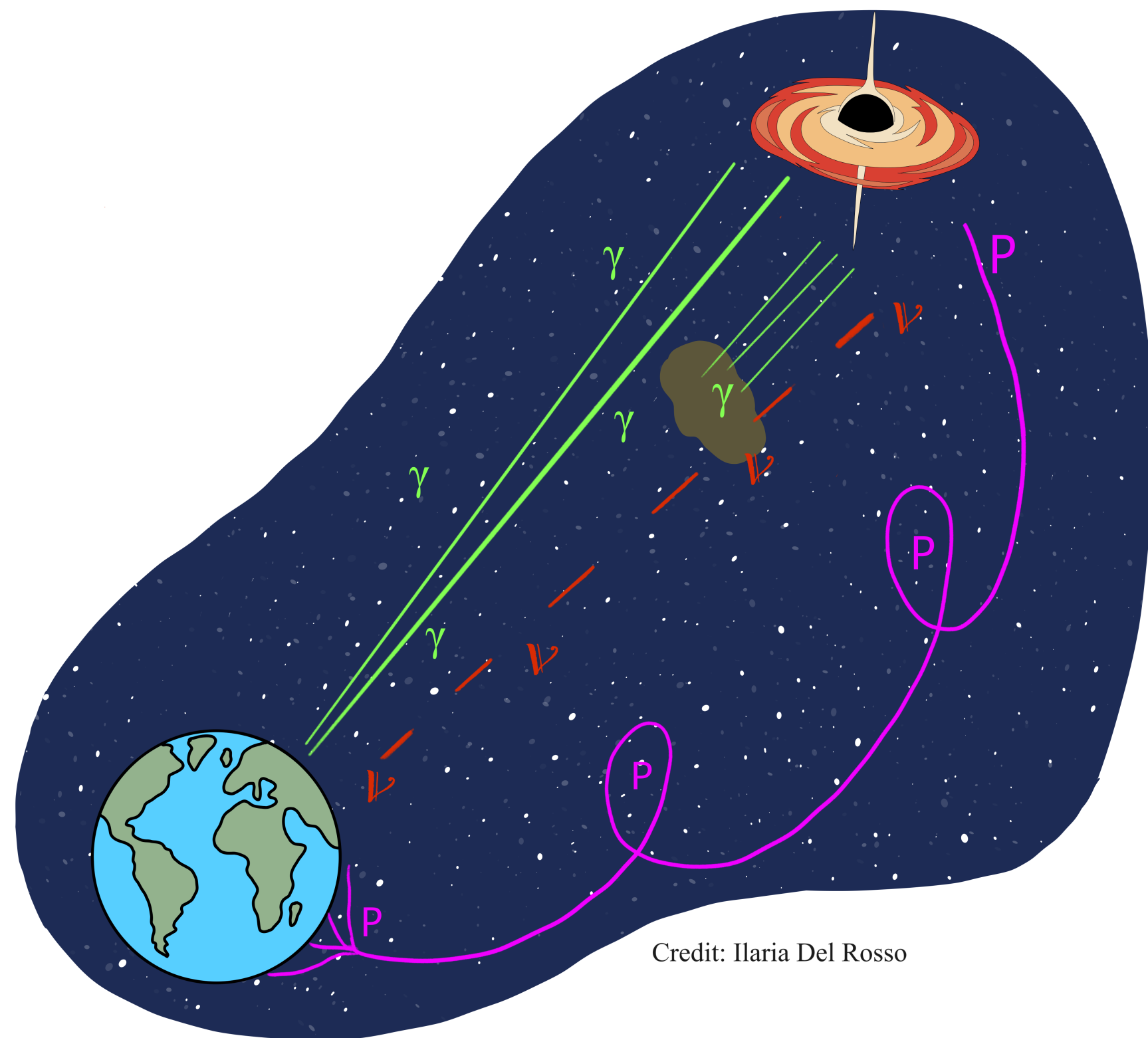
Francesco Carenini<sup>(1)</sup> on behalf of the KM3NeT Collaboration and Matteo Cerruti<sup>(2)</sup>  
Cosmic Rays and Neutrinos in the Multi-Messenger Era 2024, APC laboratory (Paris)

<sup>(1)</sup>Department of Physics and Astronomy of the University of Bologna, INFN-Bologna, International PhD College

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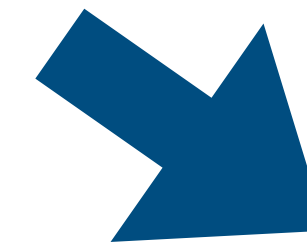
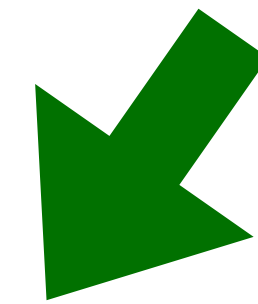


# Neutrinos in multi-messenger astronomy



## Neutrinos as ideal messengers

- **stable and electrically neutral**
- **weakly interacting particle**
- **produced only via hadronic processes**



## Advantages

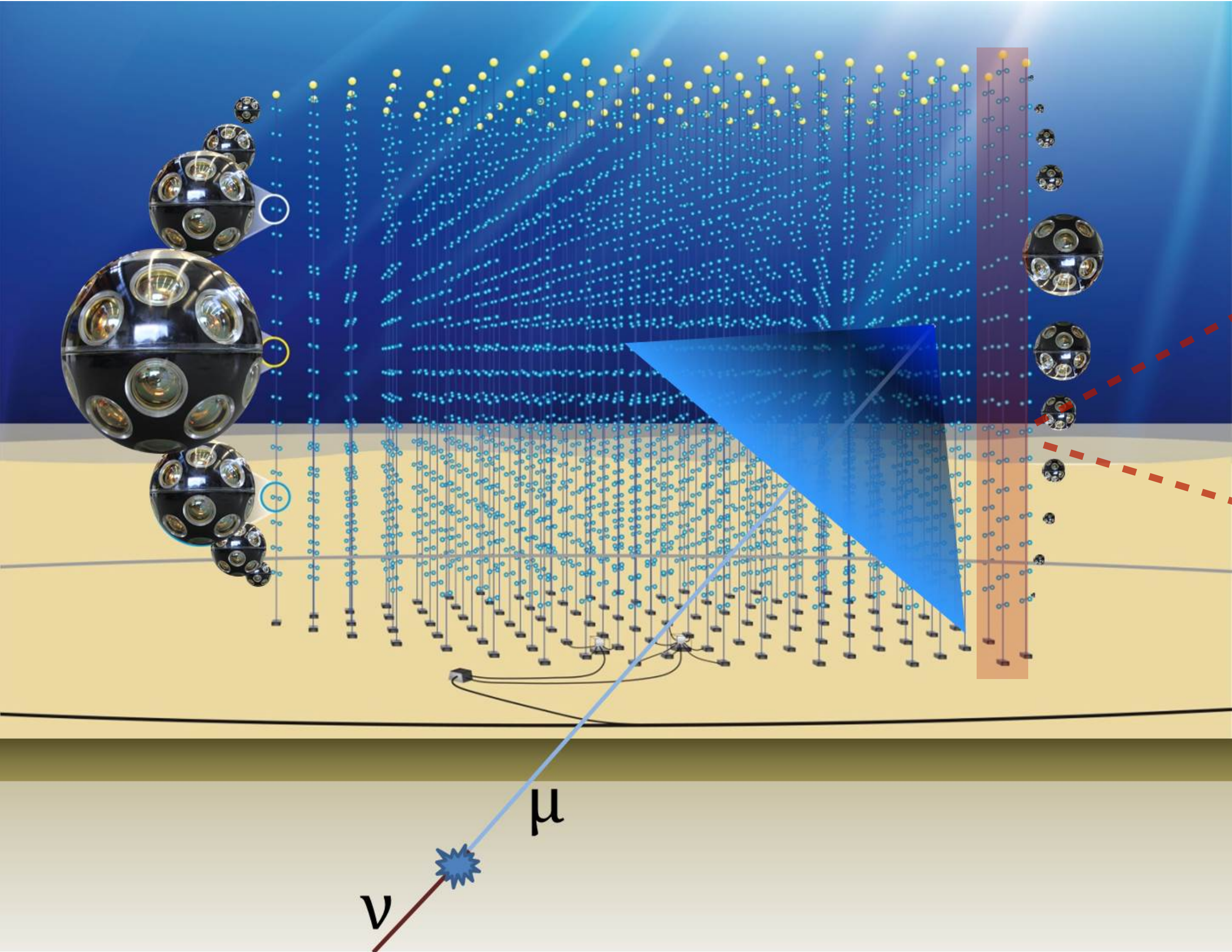
- **are undeflected and trace back their production site**
- **probes for UHECRs acceleration**

## Challenges

- **low fluxes**
- **background contamination from atmospheric muons and neutrinos**

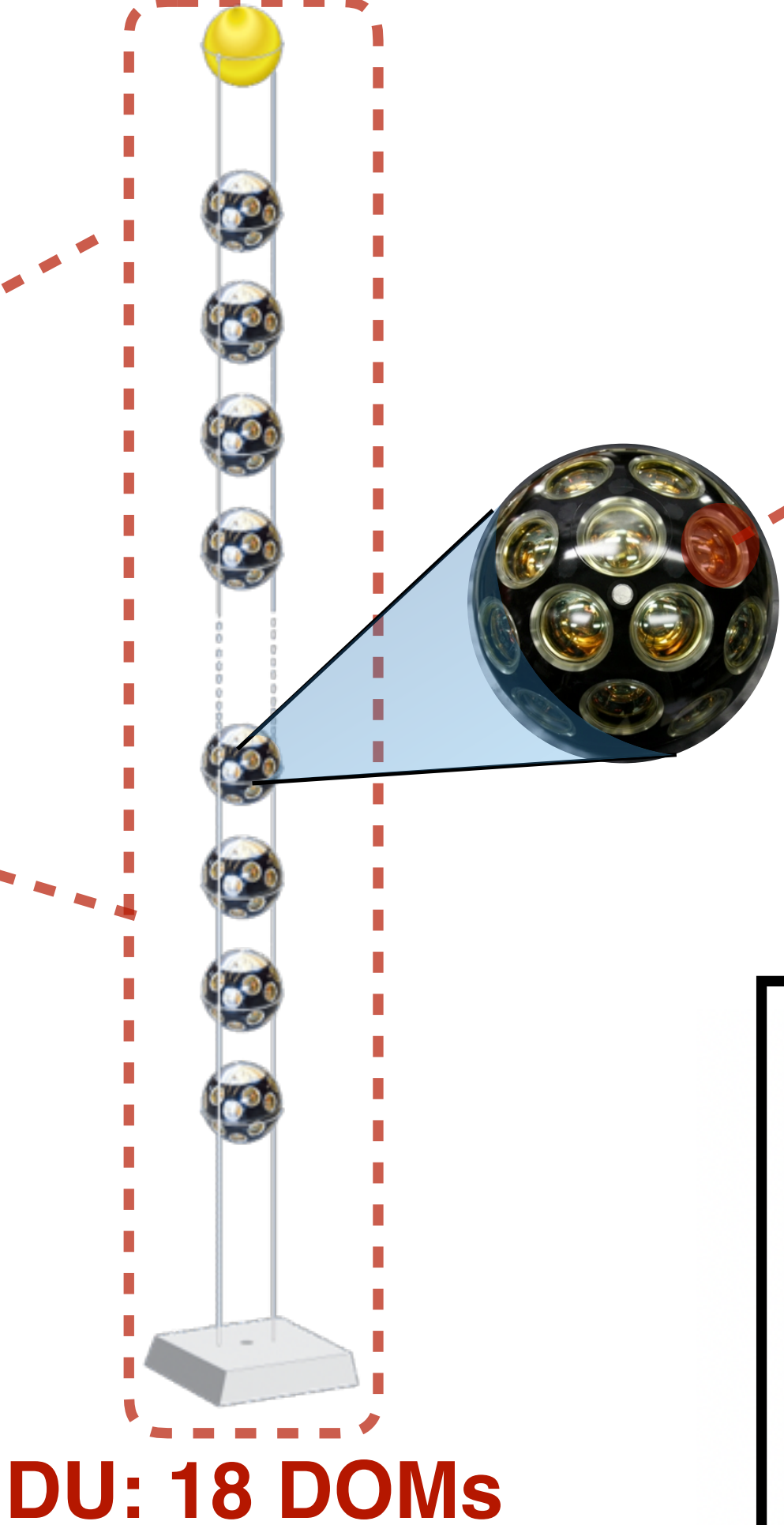


# KM3NeT



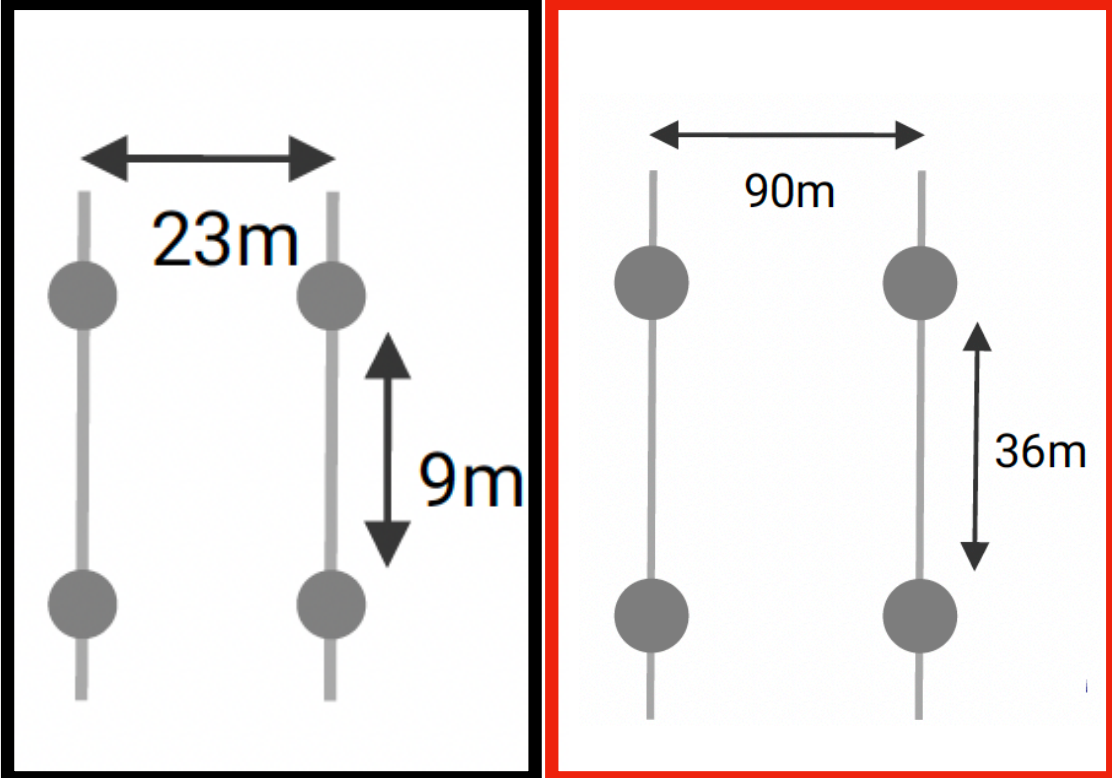
Building Block: 115 DUs

KM3NeT/ARCA final configuration: 230 DUs instrumenting about a  $\text{km}^3$  volume



DOM: 31 PMTs

17" glass sphere containing 31x3" PMTs



ORCA

ARCA

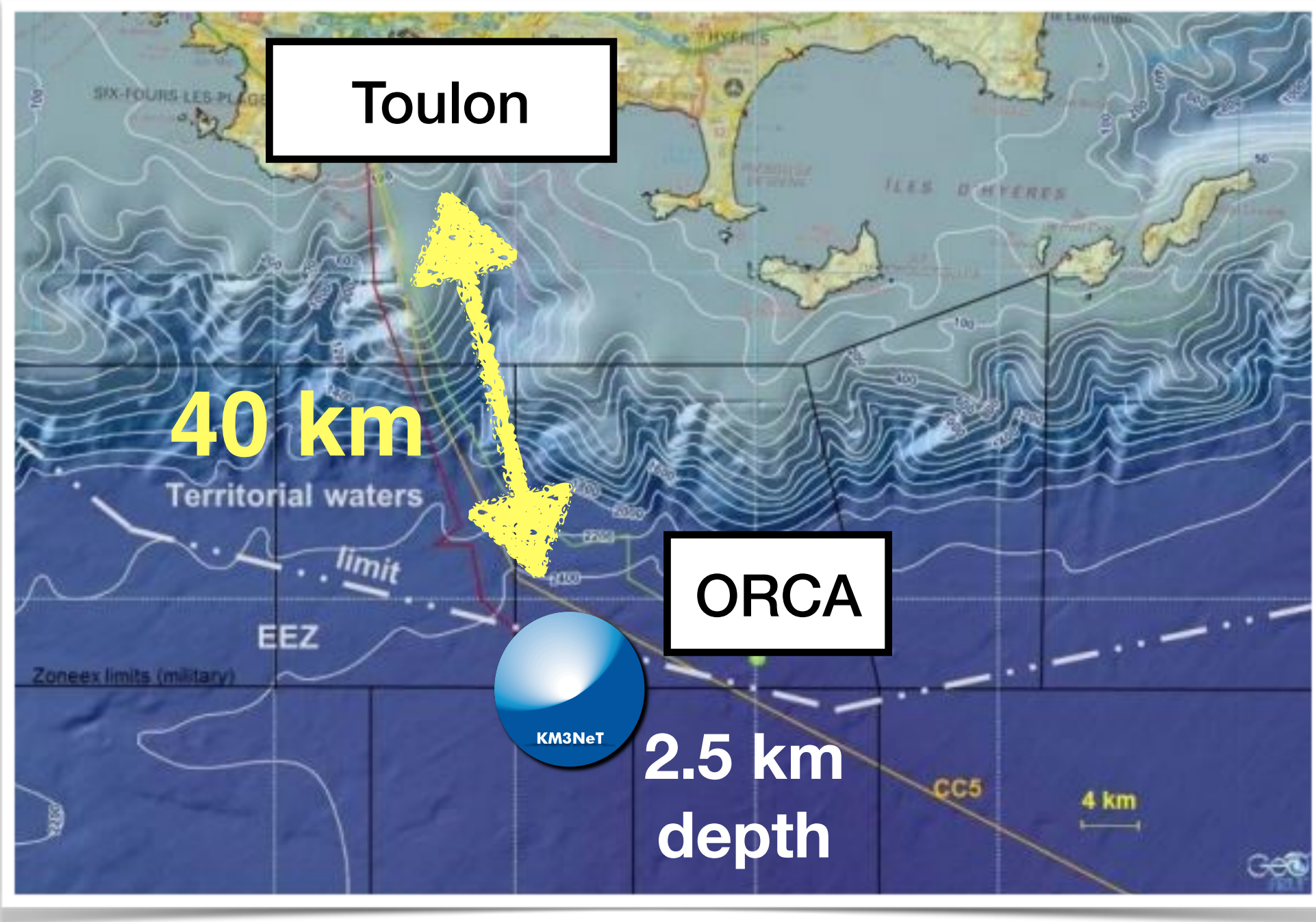


# KM3NeT: sites location

- Deep infrastructure under construction in the Mediterranean Sea
- Two instrument sites: KM3NeT/ARCA (Italy) and KM3NeT/ORCA (France)

**33 DUs**

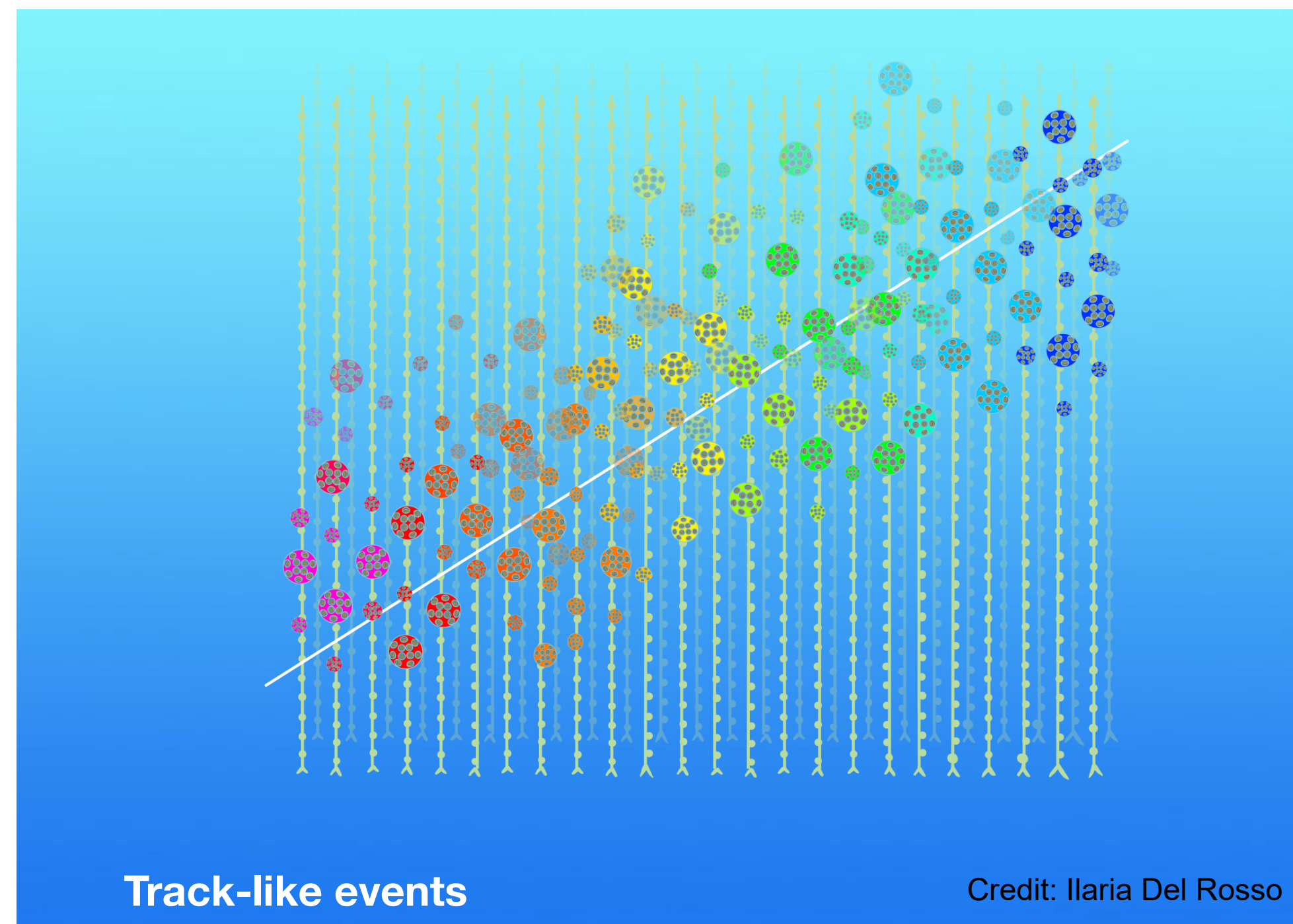
**24 DUs**





# KM3NeT: dataset

- The analysis will be applied to the data collected from the partial configurations of KM3NeT/ARCA
- Livetime: until the latest available data for a total of more than 600 days
- Track-like events are considered



## Track like events selection

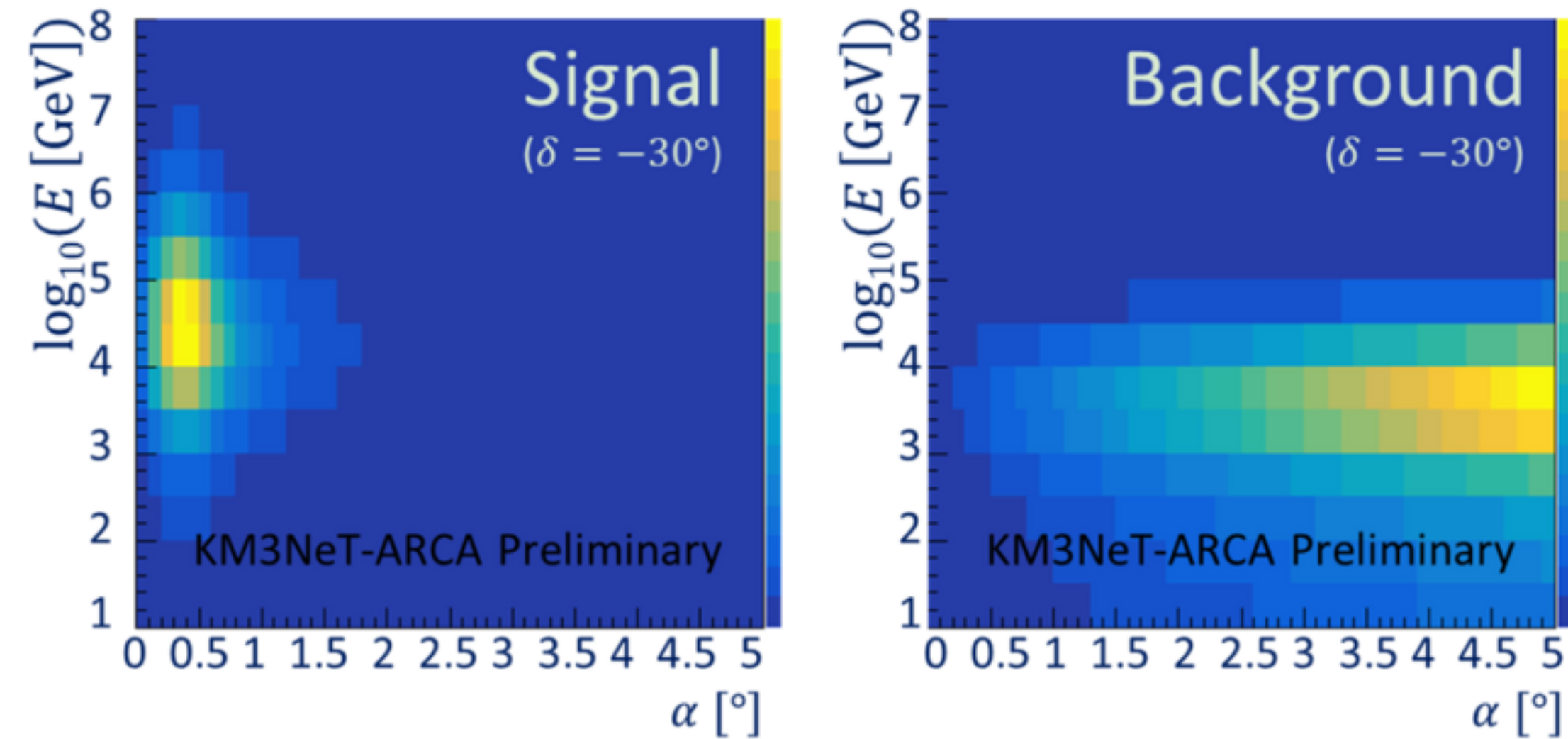
- Select horizontal and upgoing events
- Selection on the quality of reconstruction variables
- Antinoise cuts
- Selection using a BDT (boosted decision tree) optimized for good track up-going events



# Stacking analysis framework

**Goal: search for a combined emission considering an astrophysical source population**

- Binned likelihood framework:
  - 2D PDFs in  $\log(E_{rec}/GeV) \in 1 - 8$  and  $\alpha[^\circ] \in 0 - 5$
- H0 (background-only) and H1 (signal + background) models are constructed using Monte Carlo simulations for the signal and scrambled data to represent the background



PDFs for KM3NeT/ARCA in 21 strings configuration  
 Spurio, M. (2024). <https://doi.org/10.5281/zenodo.13898931>.

$$\mathcal{L}_{tot} = \sum_i^N \log(\mathcal{L}_i) \longrightarrow TS_{tot} = \log(\mathcal{L}_{tot}(\hat{\lambda}) - \mathcal{L}_{tot}(0))$$

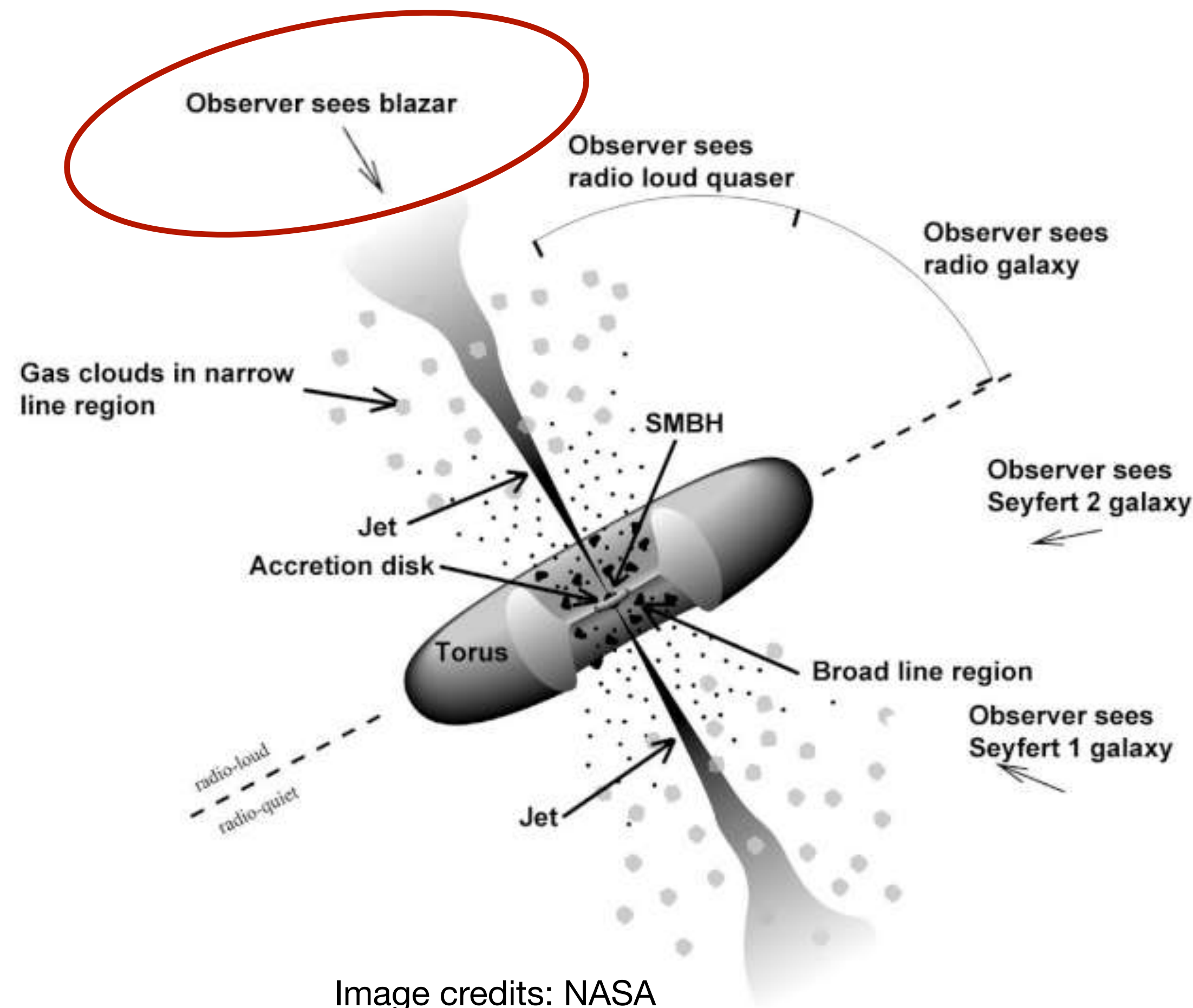
$$\mathcal{L} = \prod_{i \in \text{bins}} P(n_i, \lambda \mu_s^i + \mu_b^i)$$

$n_i$  is the observed number of events  
 $\lambda$  is the signal strength, kept as free parameter  
 $\mu_s^i$  is the expected number of signal events  
 $\mu_b^i$  is the expected number of background events

- Define a total binned log-likelihood  $\mathcal{L}_{tot}$  to evaluate the sensitivity to a  $N$ -sources catalogue
- For a given signal strength, the sum is calculated for each pseudo-experiment.
- After the global fit of  $\hat{\lambda}$ , the test-statistic  $TS_{tot}$  is calculated and 90% C.L. limits are extracted.



# The physics case: blazars



- **Blazars: radio-loud AGN**
- **Relativistic jet: directed toward the observer.**
- **Radiative emission, primarily non-thermal, dominates across the electromagnetic spectrum from radio to gamma-rays, exhibiting fast variability.**

**Flat spectrum  
radio quasar**

**BL Lacertae  
objects**

**Focus on: High-frequency peaked BL Lacs (HBLs).  
Synchrotron peak in the UV/X-ray.**

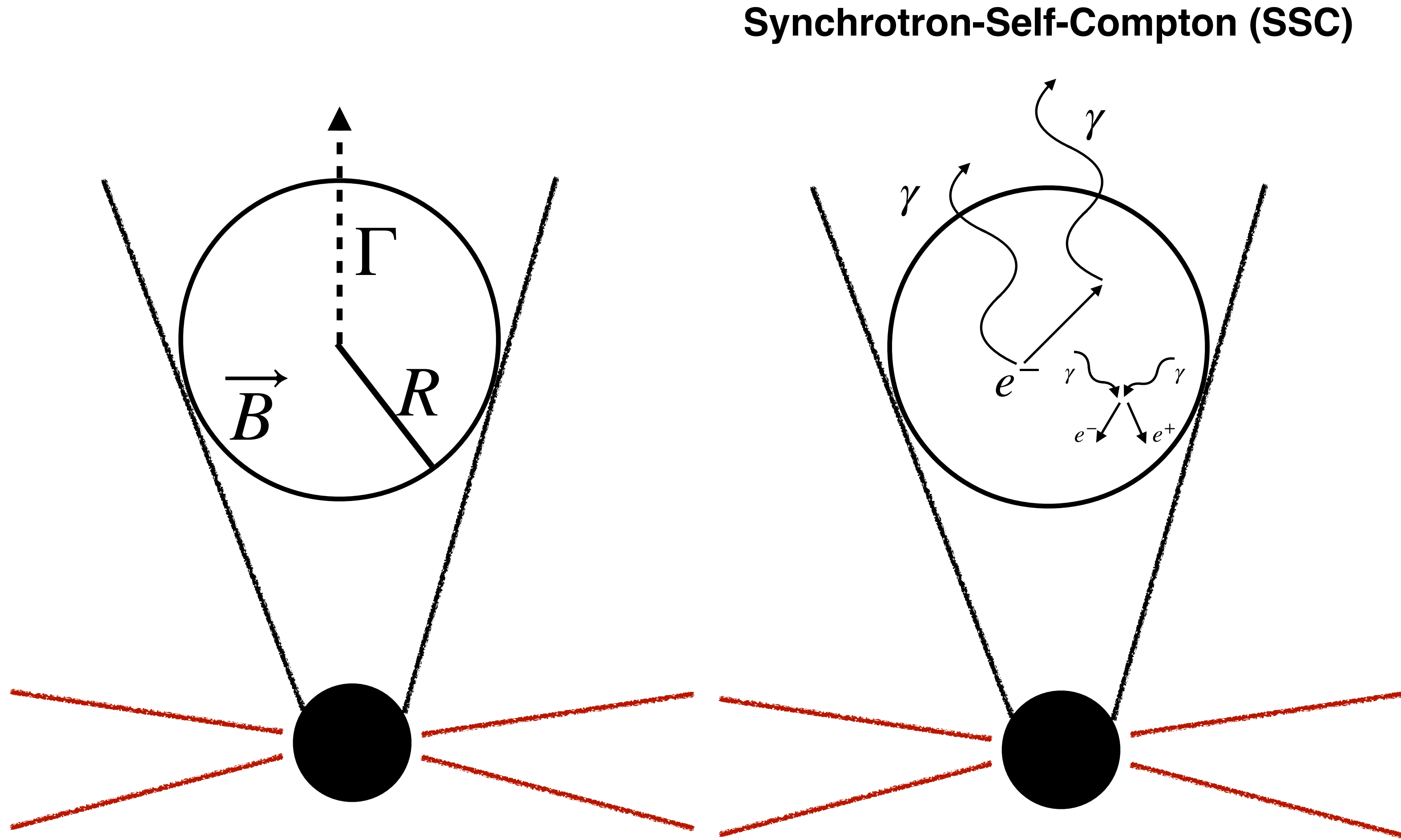


# LeHa-Paris code\*: leptonic models

- **Low-energy SED component: synchrotron emission by relativistic electrons**
- **High-energy SED component:**
  - **leptonic models suggest it arises from inverse Compton (IC) scattering, where the same leptons responsible for synchrotron emission upscatter low-energy photons**

**Synchrotron Self-Compton (SSC): leptons scatter their own synchrotron photons (HBL state-of-art model)**

**$\gamma - \gamma$  internal absorption: a secondary population of leptons coming from  $\gamma - \gamma$  pair production**

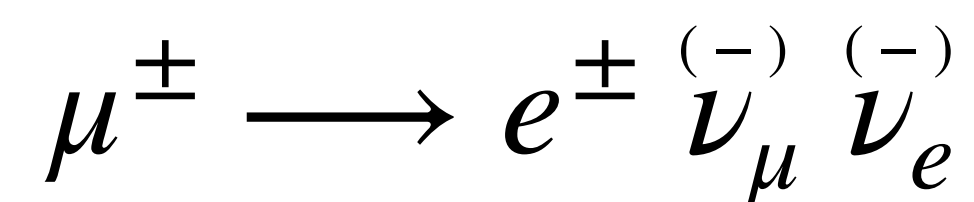
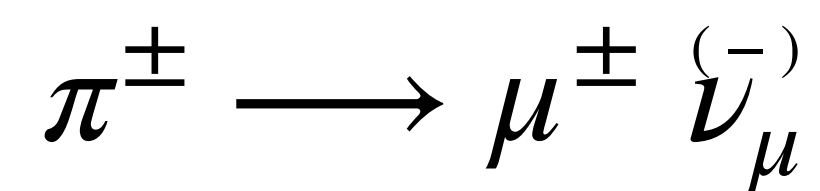
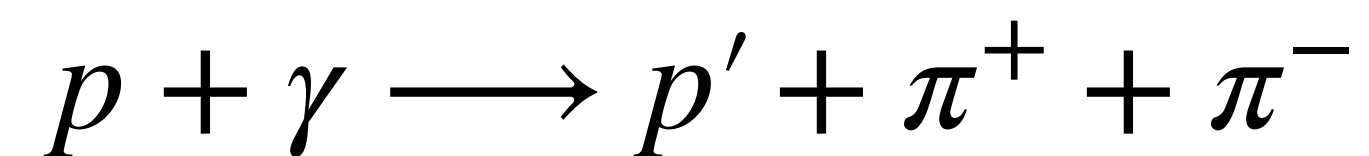
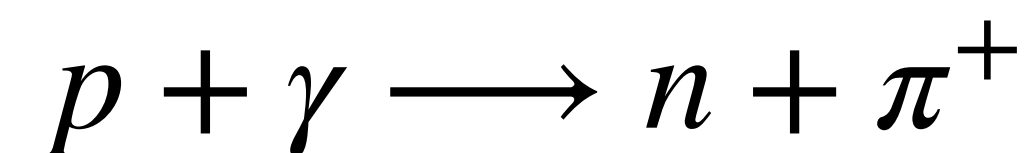
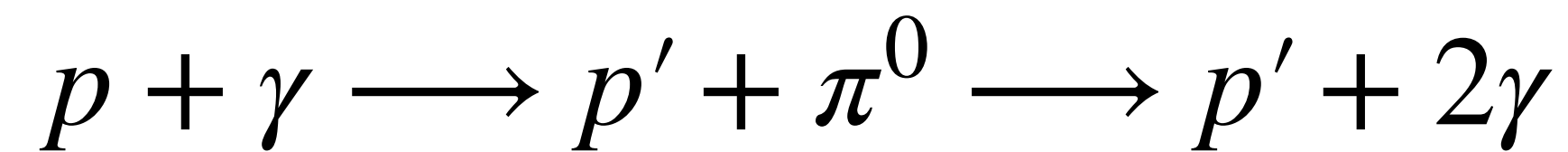


\* Cerruti, M., et al. (2015). MNRAS, 448(1), 910–927.

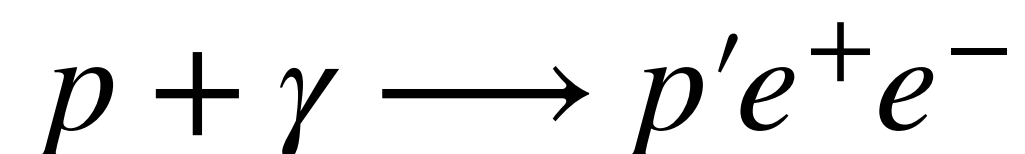


# LeHa-Paris code: hadronic models

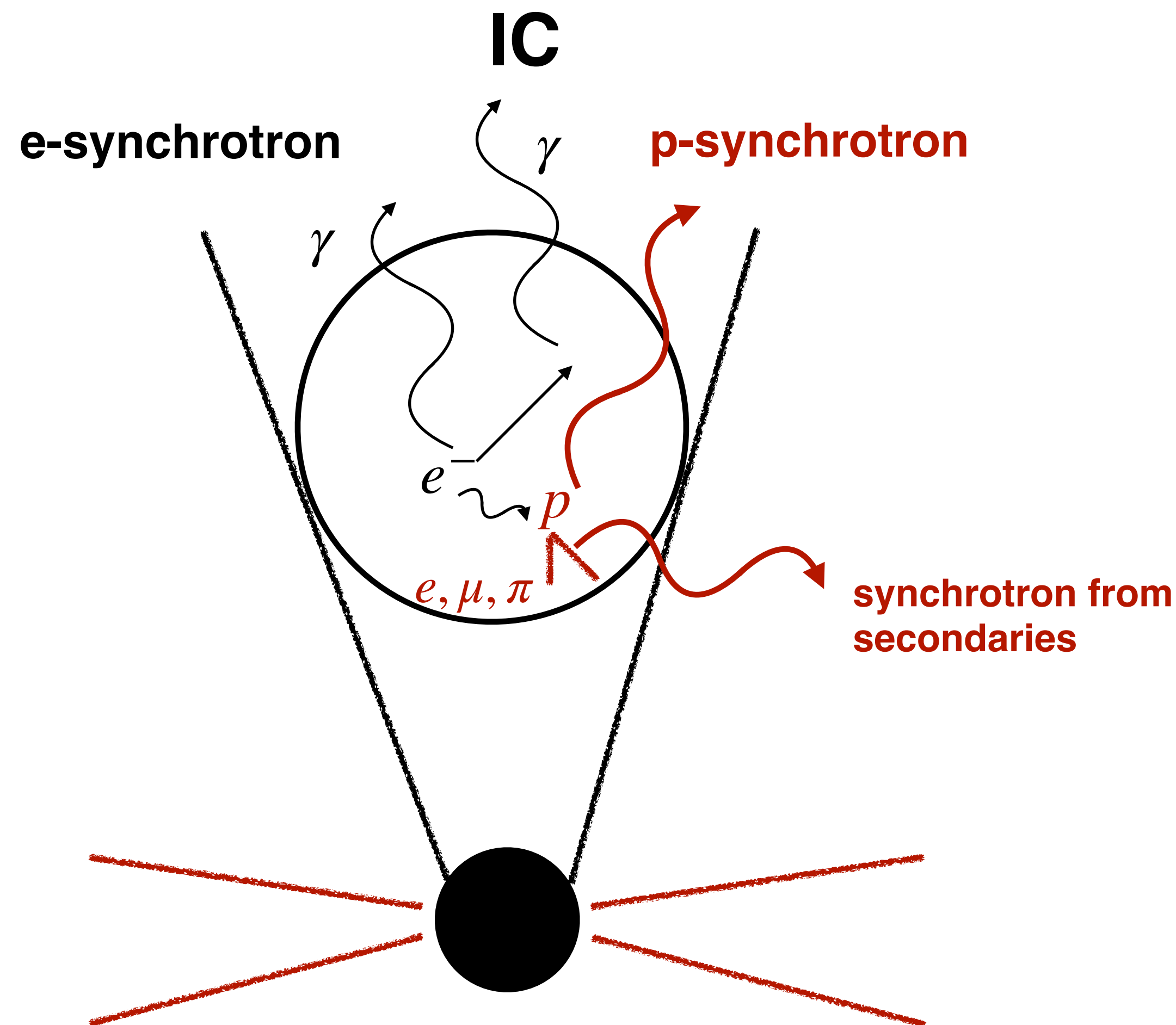
## Photo-mesons interactions



## Bethe-Heitler pair production

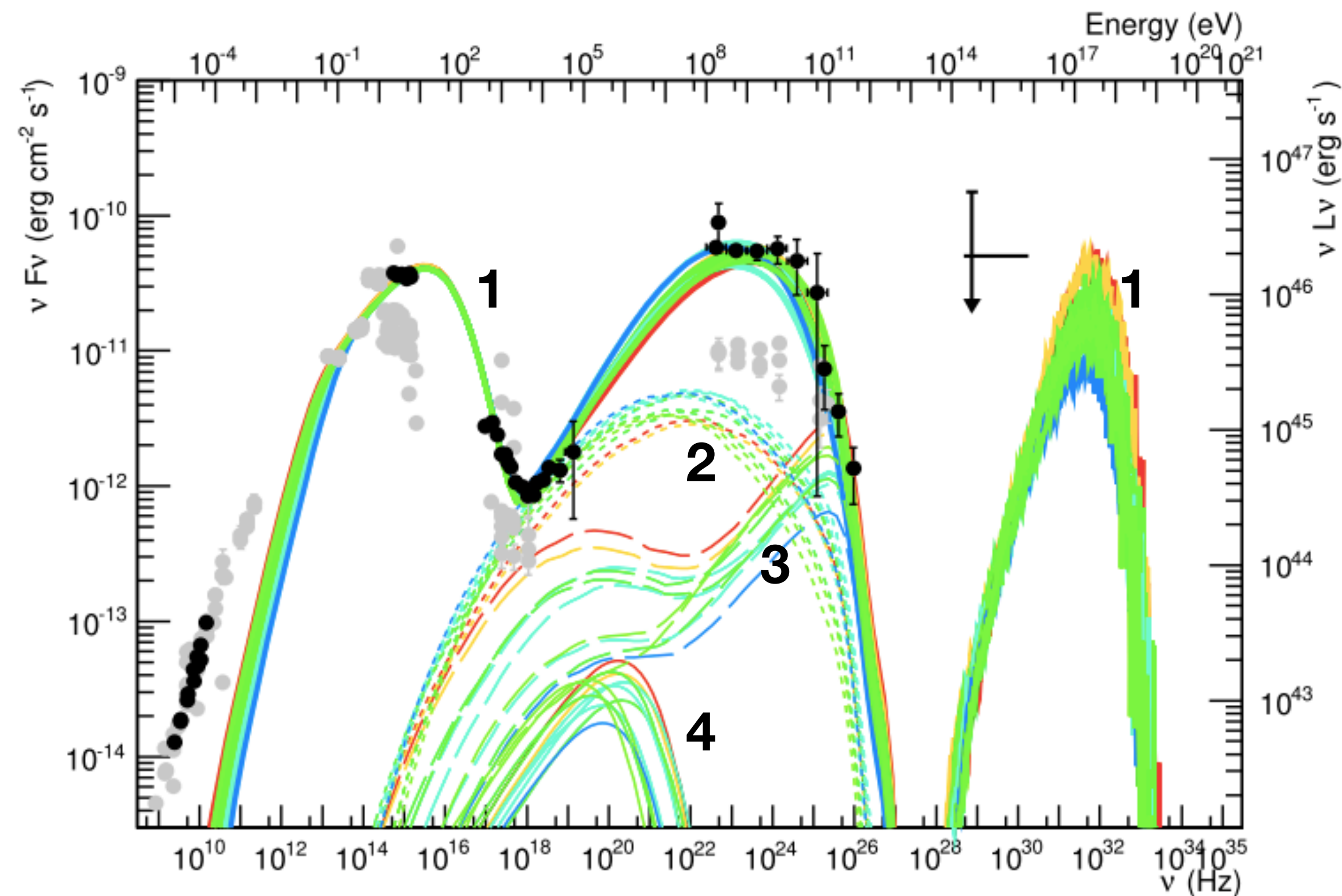


- p-p interactions are omitted in these models because of low protons densities
- muon-synchrotron and synchrotron from pairs cascades are also considered





In general it is possible to investigate purely leptonic (or purely hadronic) and lepto-hadronic solutions



1. **Bold lines: total emission in photons or single-flavor neutrinos**
2. **Dotted: synchrotron from pions cascades**
3. **Dashed: synchrotron from Bethe-Heitler cascades**
4. **Dotted-dashed: proton synchrotron**

**The favored scenario is a leptonic electromagnetic emission, with subdominant hadronic component**

Cerruti, M., et al. (2019). MNRAS Letters, 483(1), L12–L16.



**INFN** **Incorporating theoretical blazar models into neutrino stacking analyses with KM3NeT/ARCA**

Francesco Carenini<sup>1,2,3</sup> on behalf of the KM3NeT Collaboration and Matteo Cerruti<sup>4</sup>

Cosmic Rays and Neutrinos in the Multi-Messenger Era 2024

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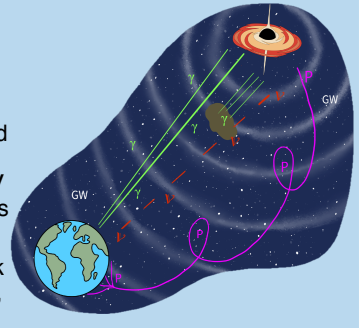
Contact: francesco.carenini@unibo.it

### 1. Motivations

The identification of blazar TXS 0506+056 [1] as a potential cosmic neutrino source has highlighted blazars as key candidates for such emissions.

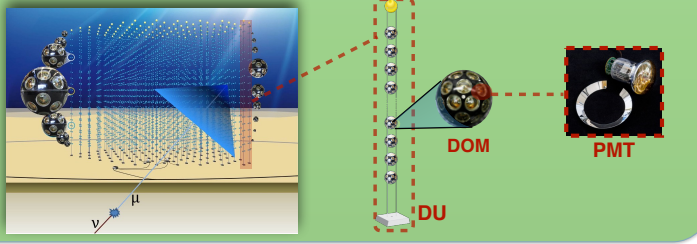
Neutrino data with large statistics and excellent angular resolution are expected thanks to the development of the next-generation neutrino telescope KM3NeT/ARCA, currently operating in a 33-strings configuration.

This study introduces a novel framework integrating theoretical blazar models, derived using the LeHa-Paris code [2], into KM3NeT/ARCA's binned likelihood stacking analyses.



### 2. KM3NeT/ARCA

- Located ~100 km offshore Portopalo di Capo Passero, in Sicily, at 3.5 km depth [3].
- Dedicated to high-energy neutrino studies (up to multi-PeV).
- Final design: 230 DUs, each carrying 18 digital optical modules, with 31 photomultiplier tubes (PMTs).



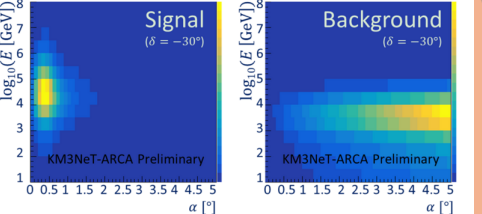
### 3. Dataset

- The analysis will be applied to the data collected from the partial configurations of KM3NeT/ARCA.
- Lifetime:** until the latest available data for a total of more than 600 days.
- Track-like events are considered.**
- Selection criteria:** cuts on the number of hits used in the reconstruction, the reconstructed direction, the fit quality, and a boosted decision tree (BDT) model.

### 4. Stacking analysis framework

- The analysis is performed with **2D Probability Density Functions (PDFs)**, considering the angular distance to the source ( $\alpha \in [0, 5^\circ]$ ) and the event energy ( $\log_{10}(E[\text{GeV}])$  from 1 to 8).
- PDFs relative to KM3NeT/ARCA in a 21 string configuration, at declination  $\delta = -30^\circ$ , are shown on the right [4].
- H0 (background-only) and H1 (signal + background)** models are built using Monte Carlo simulations for signal and scrambled data for background.
- For a  $N$ -sources catalogue, a **total binned log-likelihood** is defined:  $\mathcal{L}_{tot} = \sum \log(\mathcal{L}_i)$ . The signal strength  $\lambda$  is kept as free parameter.
- For a given signal strength, the sum is calculated for each pseudo-experiment.
- After the global fit of  $\hat{\lambda}$ , the **test-statistic  $TS_{tot}$  is calculated:**  

$$TS_{tot} = \log(\mathcal{L}_{tot}(\hat{\lambda})) - \log(\mathcal{L}_{tot}(\lambda = 0))$$
- 90% C.L. limits are then extracted.



### 5. LeHa-Paris code

**Inverse Compton**  
e-synchrotron      p-synchrotron

**LEPTONIC PROCESSES**

- Electron-synchrotron
- Synchrotron Self-Compton (SSC)
- $\gamma - \gamma$  internal absorption

**HADRONIC PROCESSES**

- Proton-synchrotron
- Photo-meson interactions on a target synchrotron field
  - $\pi^+$  and  $\pi^-$  components
  - $\pi^0$  component
- Bethe-Heitler pair production

**Low-energy SED component:** well explained by synchrotron emission by relativistic electrons and positrons.

**High-energy SED component:** favorite scenario is a leptonic electromagnetic emission by SSC, with a subdominant hadronic component, as reported e.g. by Cerruti et al. (2019) in the study of the blazar TXS 0506+056 [5].

### 6. Next steps

- Ongoing work on HBL class of blazars in order to **define a catalogue for the stacking analysis.**
- Starting point: optimal lepto-hadronic model reproducing the low-state spectral energy distribution of the blazar Mrk 501.
- Derive the corresponding neutrino fluxes** for the whole catalogue using the LeHa-Paris code.
- Insert those fluxes as **input spectrum into the stacking binned likelihood framework** of KM3NeT/ARCA.

**References**

- IceCube Collaboration. Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert. In: Science 361.6398 (July 2018), pp. 147–151.
- Cerruti, M., et al. (2019). A hadronic origin for ultra-high-frequency-peaked BL Lac objects. MNRAS, 448(1), 910–927.
- S. Adrián-Martínez et al. (KM3NeT Collaboration), 2016. Letter of Intent for KM3NeT 2.0. J. Phys. G: Nucl. Part. Phys. 43 084001.
- Spurio, M. (2024). Time-integrated search for astrophysical neutrino emission with 2 years of KM3NeT/ARCA data. Zenodo. <https://doi.org/10.5281/zenodo.13898931>
- Cerruti, M., et al. (2019). Leptohadronic single-zone models for the electromagnetic and neutrino emission of TXS 0506+056. MNRAS Letters, 483(1), L12–L16.

- By incorporating these theoretical models within the stacking data analysis of KM3NeT/ARCA, the proposed methodology aims to improve the sensitivity of neutrino searches from HBL blazar subclass

- Ongoing work on HBL class of blazars, starting from Mrk 501 low-state SED

- Next steps:
  - Define a catalogue
  - Derive neutrino fluxes with LeHa-Paris
  - Insert those neutrino fluxes into the stacking framework of KM3NeT/ARCA





*Thanks for your attention!*

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