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

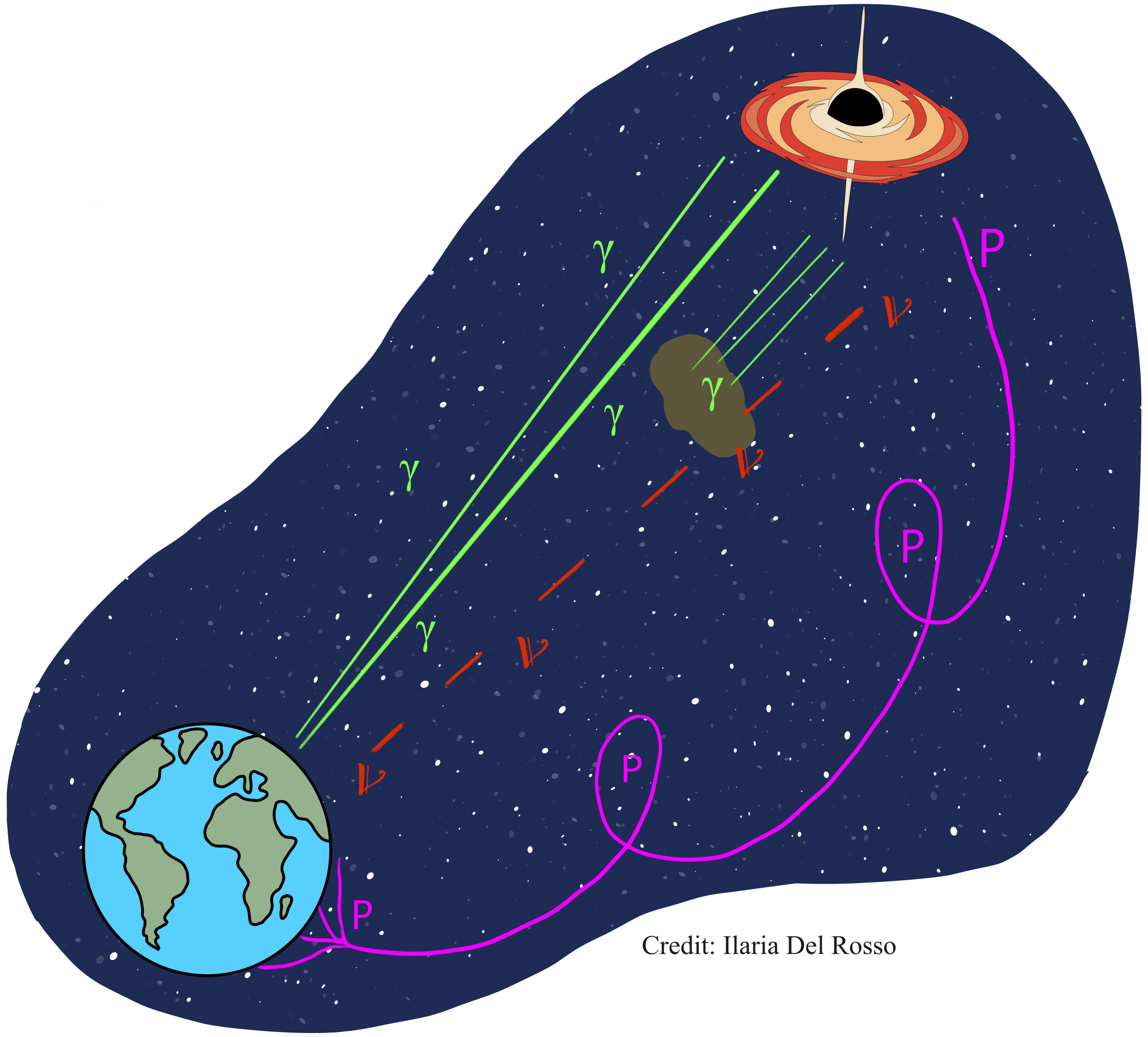
Francesco Carenini[1] on behalf of the KM3NeT Collaboration and Matteo Cerruti[2]

Cosmic Rays and Neutrinos in the Multi-Messenger Era 2024, APC laboratory (Paris)

[1]Department of Physics and Astronomy of the University of Bologna, INFN-Bologna, International PhD College

[2]Université Paris Cité, Astroparticule et Cosmologie (APC)

Neutrinos in multi-messenger astronomy



Credit: Ilaria Del Rosso

Neutrinos as ideal messengers

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

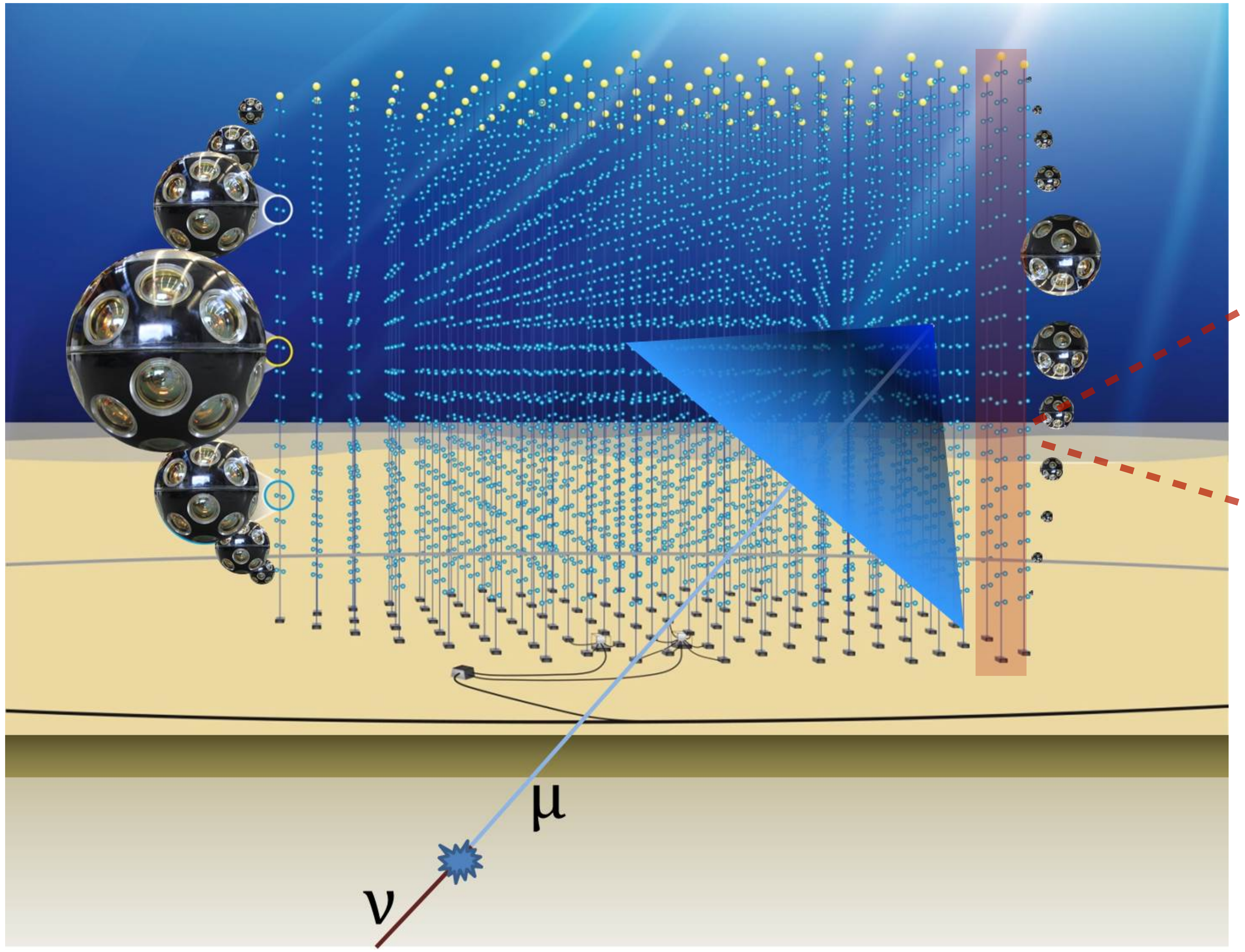
Advantages

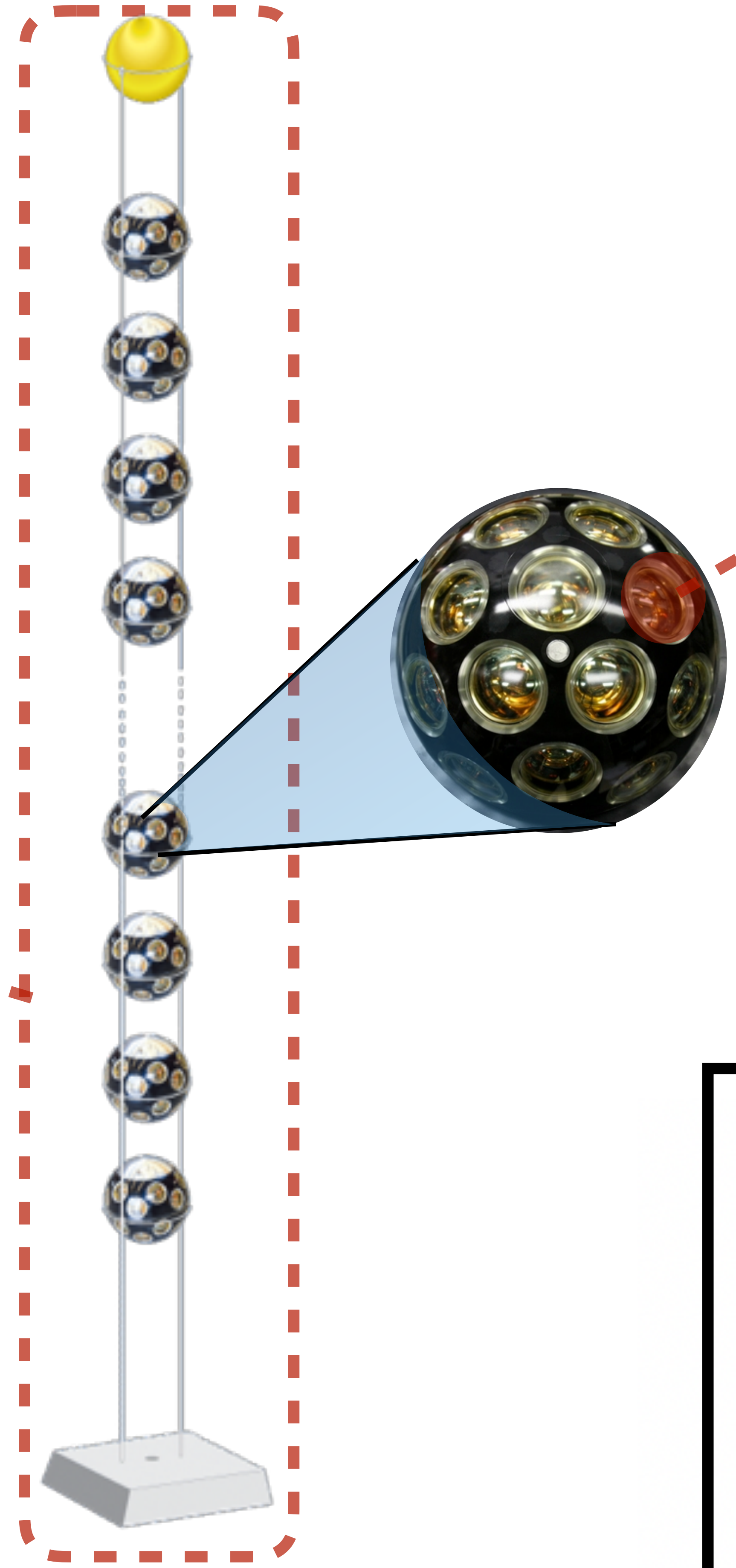
- **are undeflected and trace back their production site**
- **probes for UHECRs acceleration**

Challenges

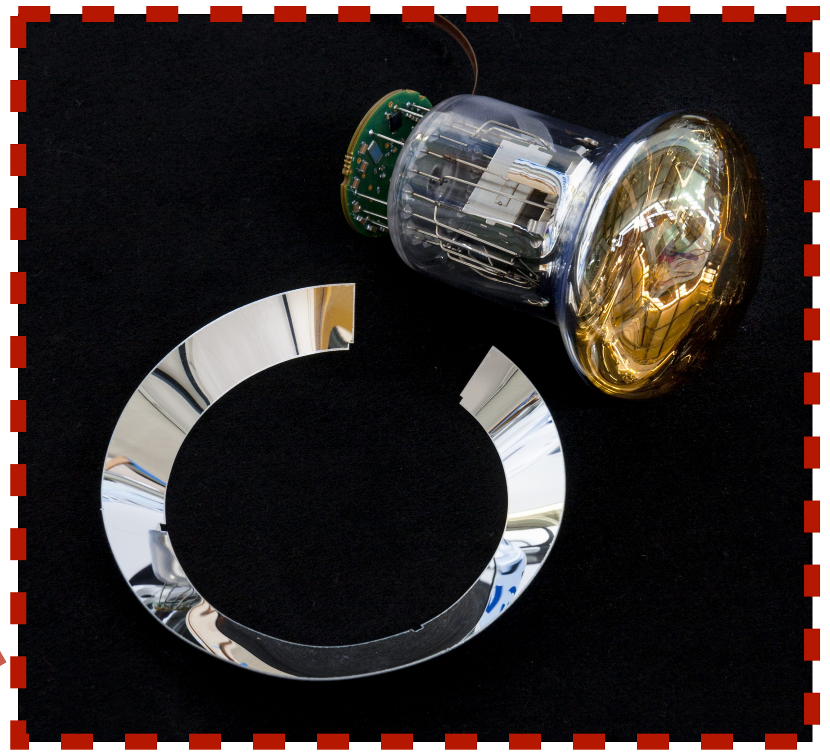
- **low fluxes**
- **background contamination from atmospheric muons and neutrinos**

KM3NeT



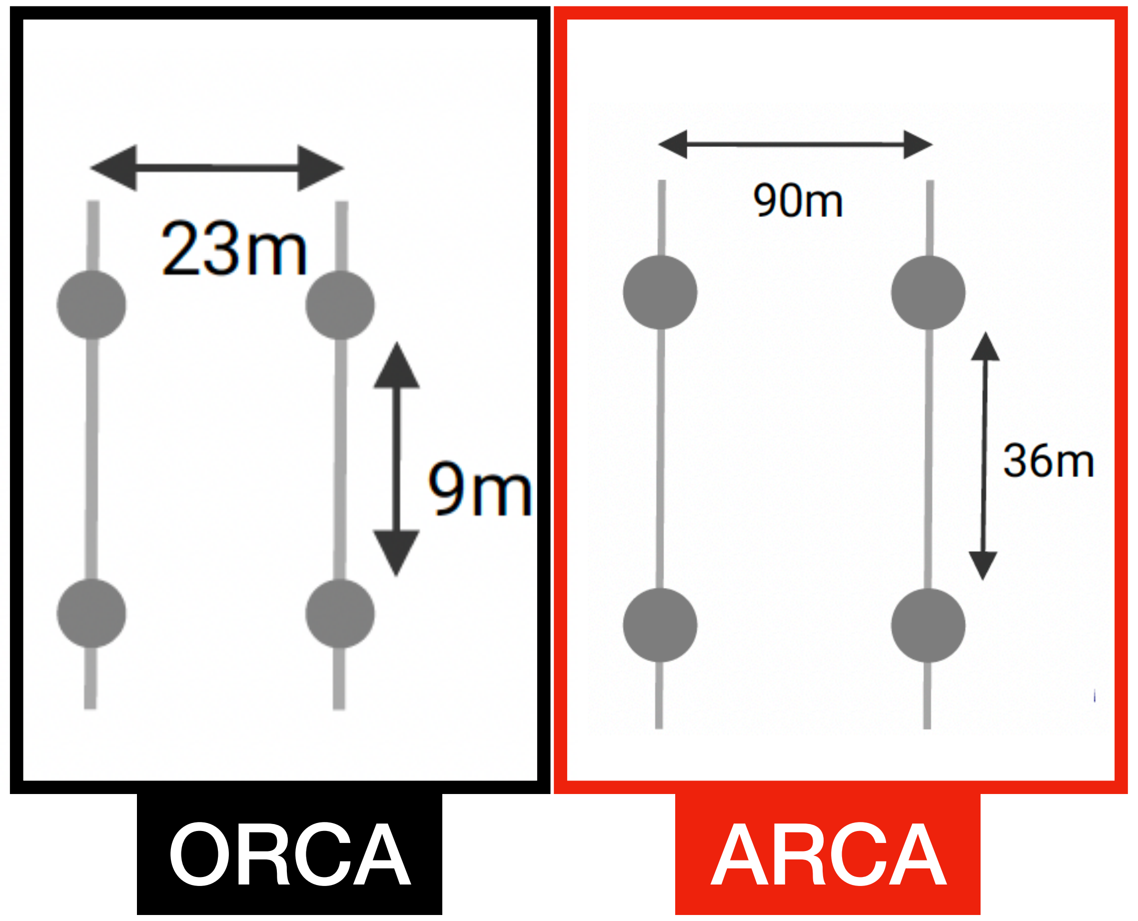


DU: 18 DOMs



DOM: 31 PMTs

17” glass sphere containing
31x3” PMTs



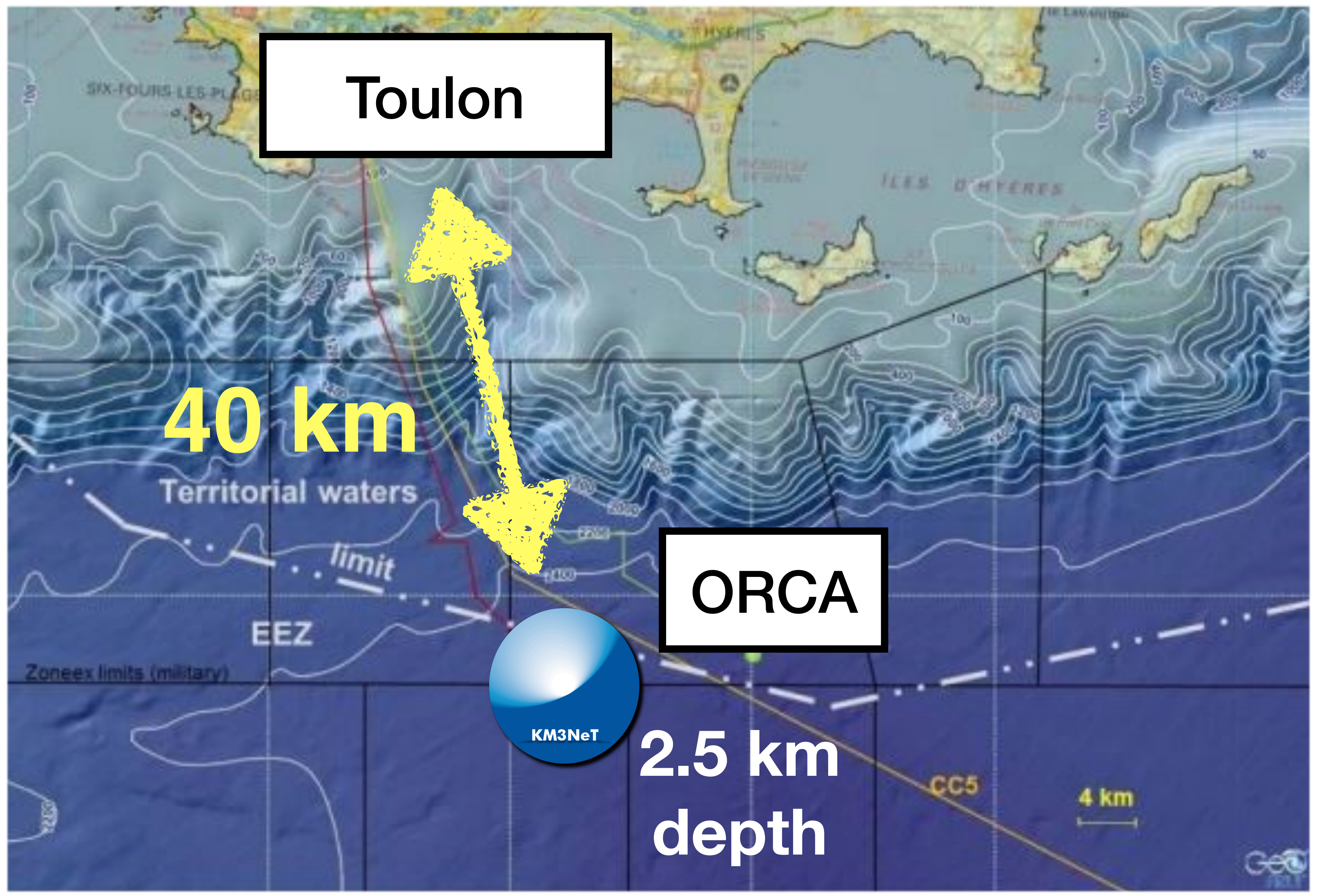
Building Block: 115 DUs

KM3NeT/ARCA final configuration: 230 DUs instrumenting about a km^3 volume

KM3NeT: sites location

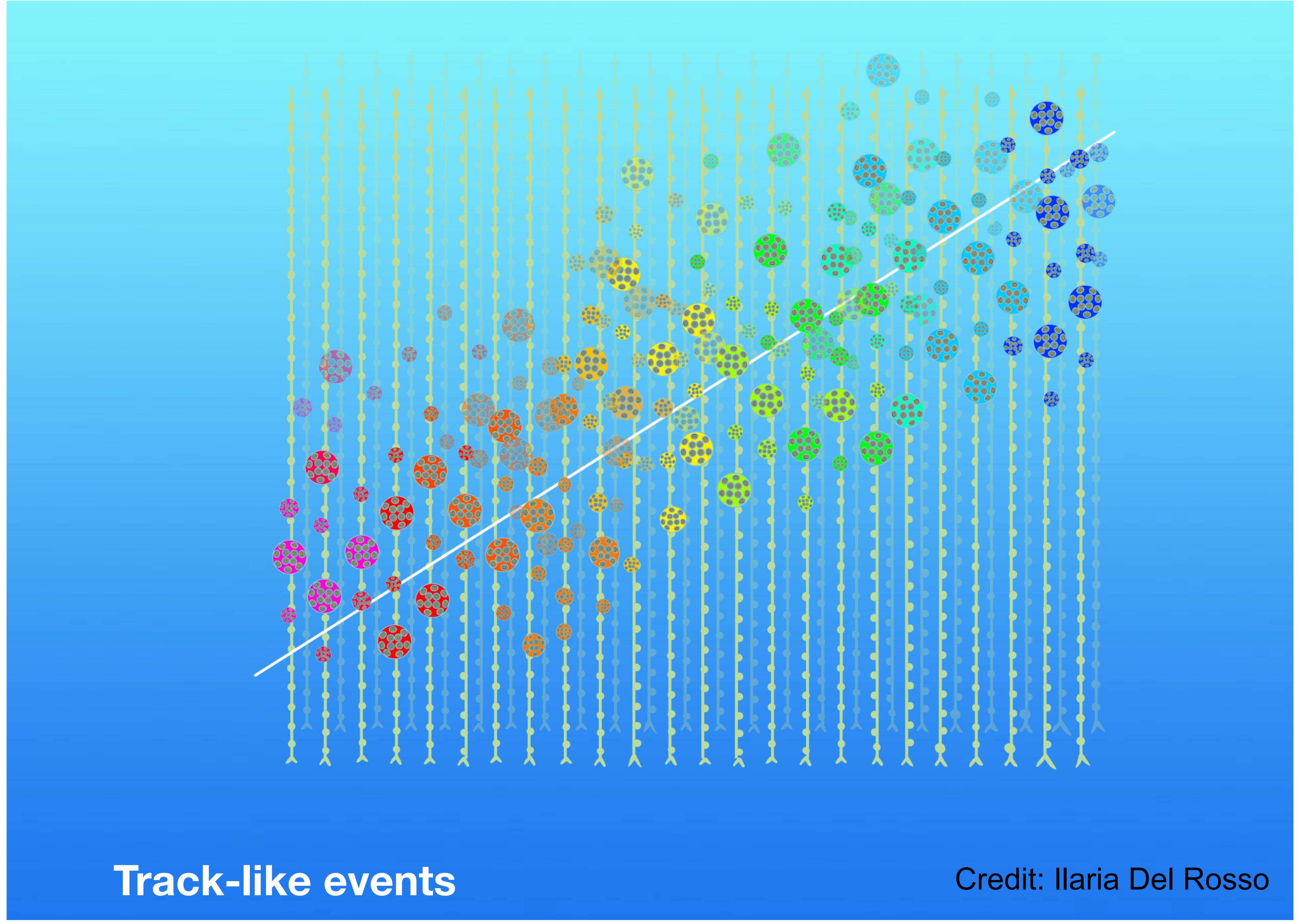
- **Deep infrastructure under construction in the Mediterranean Sea**
- **Two instrument sites: KM3NeT/ARCA (Italy) and KM3NeT/ORCA (France)**

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**

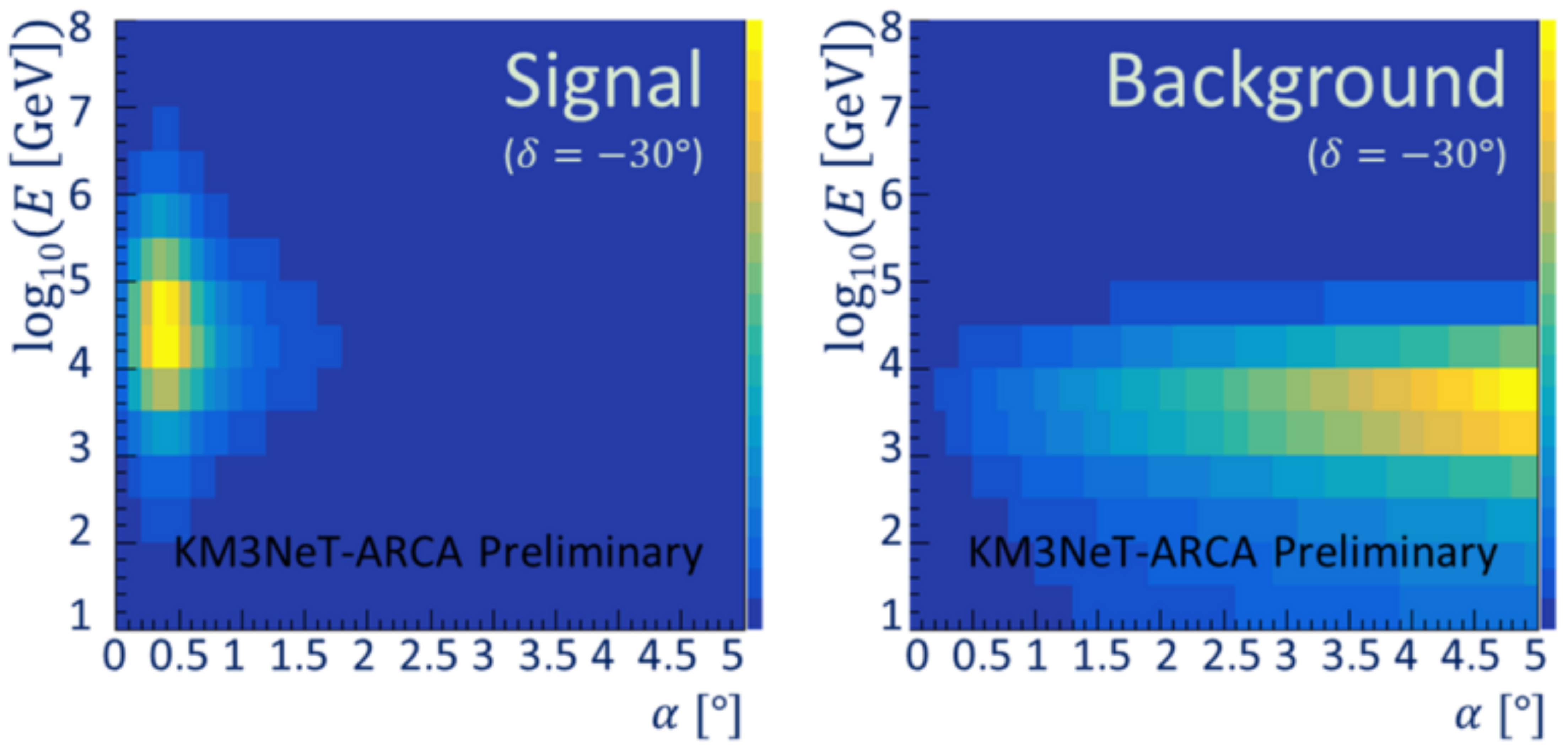


Track like events selection

- **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



PDFs for KM3NeT/ARCA in 21 strings configuration

Spurio, M. (2024). https://doi.org/10.5281/zenodo.13898931.

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

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

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

n_i is the observed number of events
λ is the signal strength, kept as free parameter
μ_s^i is the expected number of signal events
μ_b^i is the expected number of signal events

- **Define a total binned log-likelihood $\mathscr{L}_{tot}$ 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

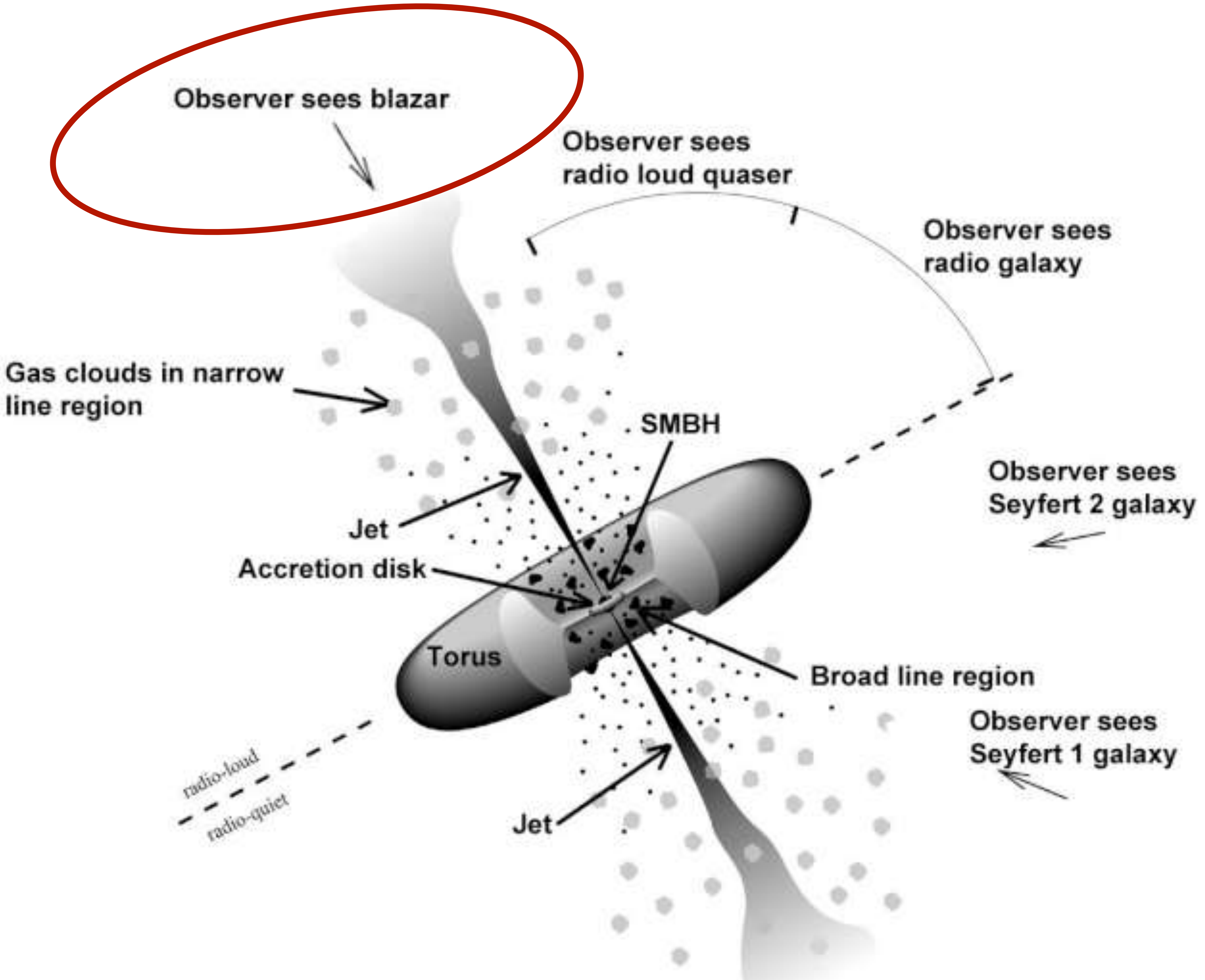


Image credits: NASA

- **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.**

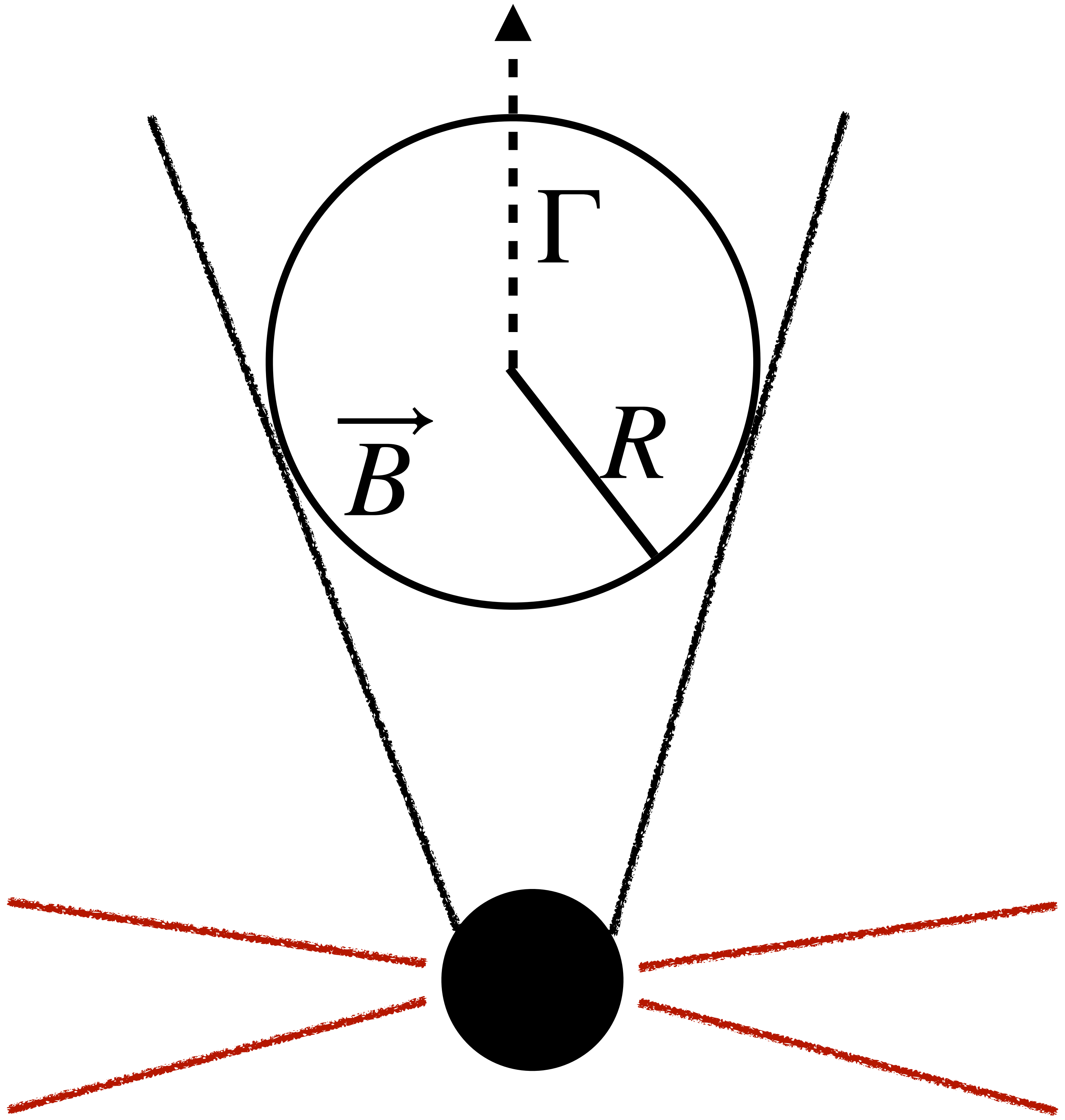
Flat spectrum radio quasar

BL Lacertae objects

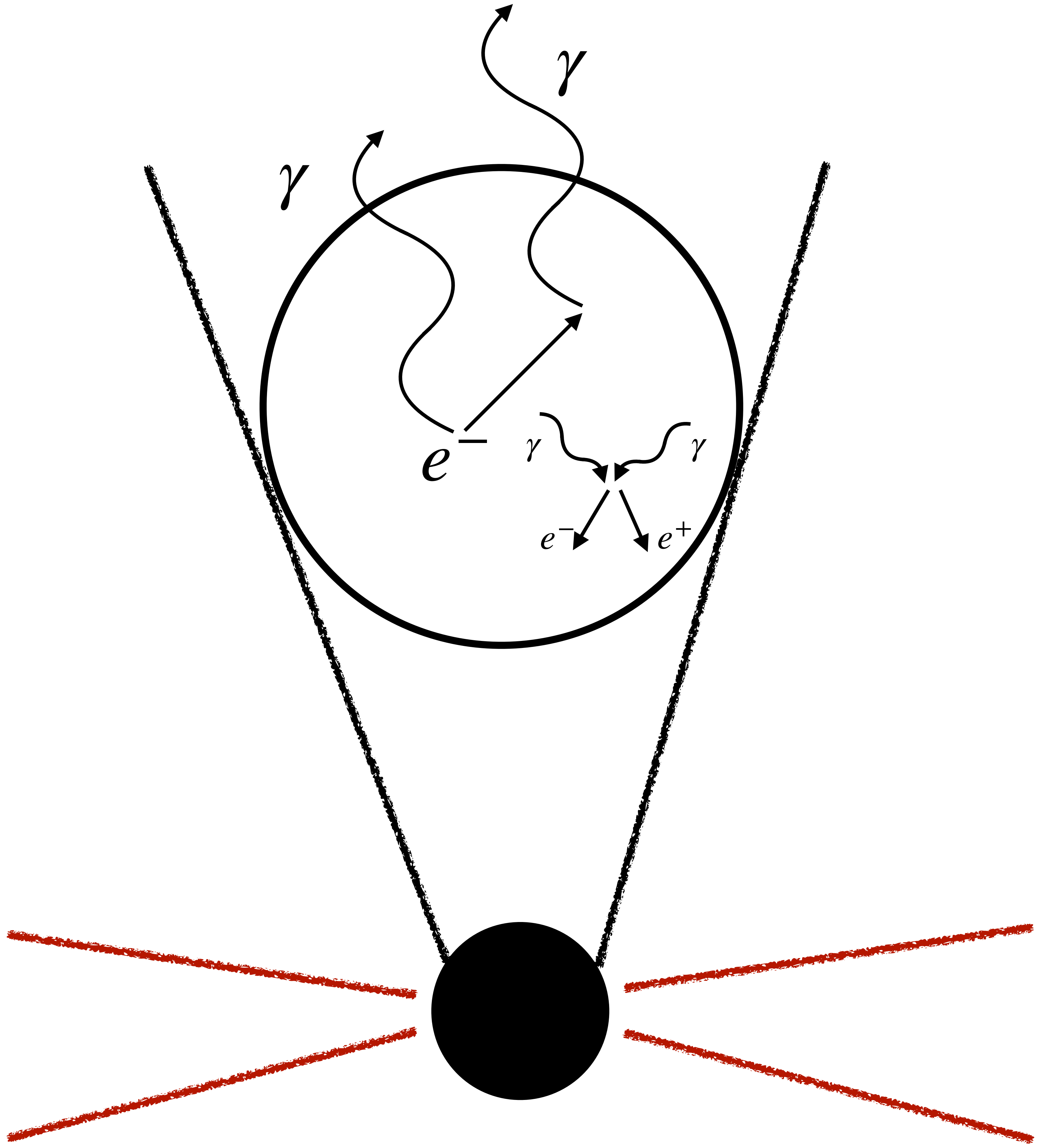
Focus on: High-frequency peaked BL Lacs (HBLs). Synchrotron peak in the UV/X-ray.

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)



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 γ –γ pair production

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

LeHa-Paris code: hadronic models

Photo-mesons interactions

$$p + \gamma \longrightarrow p' + \pi^0 \longrightarrow p' + 2\gamma$$

$$p + \gamma \longrightarrow n + \pi^+$$

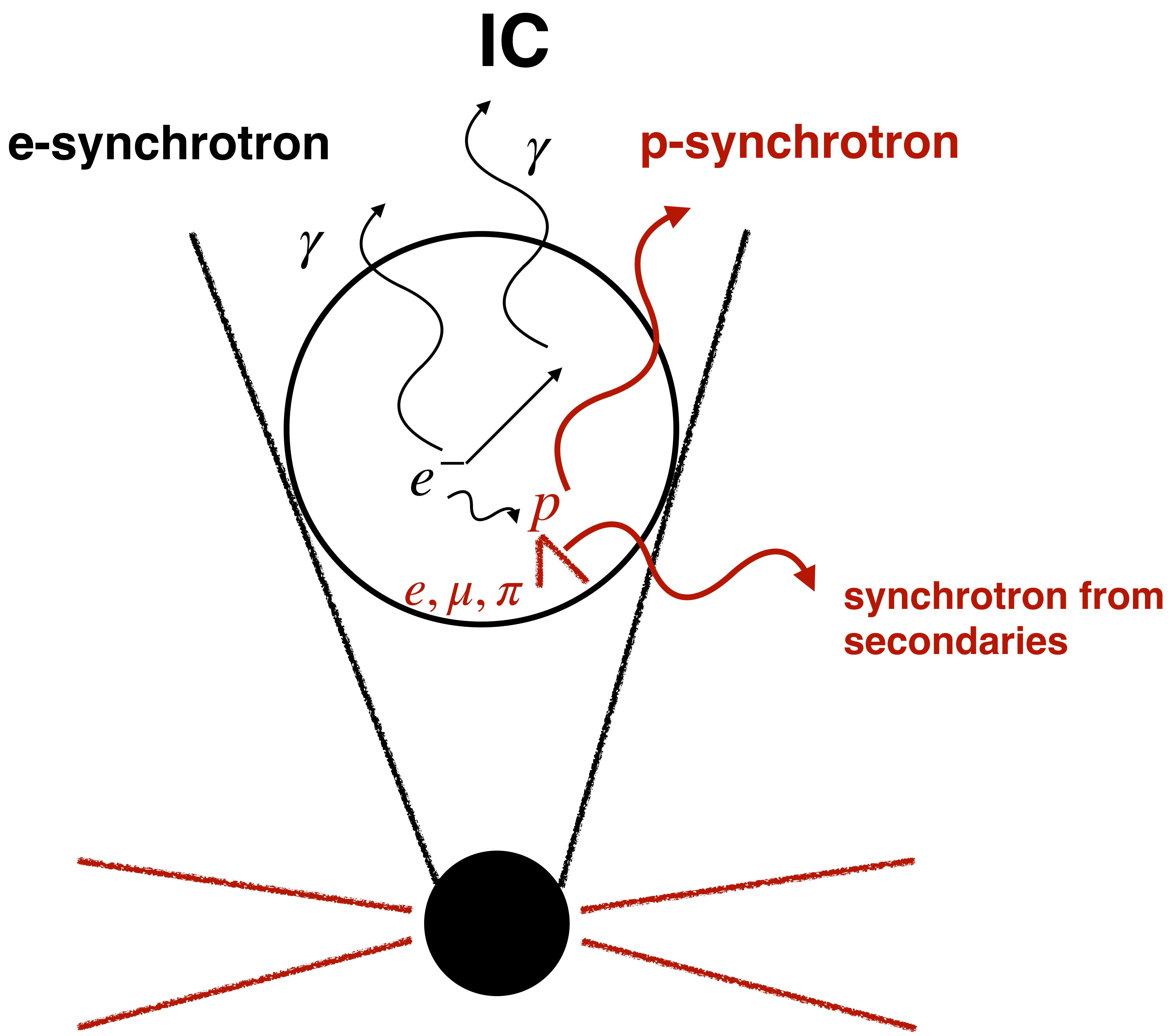
$$p + \gamma \longrightarrow p' + \pi^+ + \pi^-$$

$$\pi^\pm \longrightarrow \mu^\pm \overset{(-)}{\nu}_\mu$$

$$\mu^\pm \longrightarrow e^\pm \overset{(-)}{\nu}_\mu \overset{(-)}{\nu}_e$$

Bethe-Heitler pair production

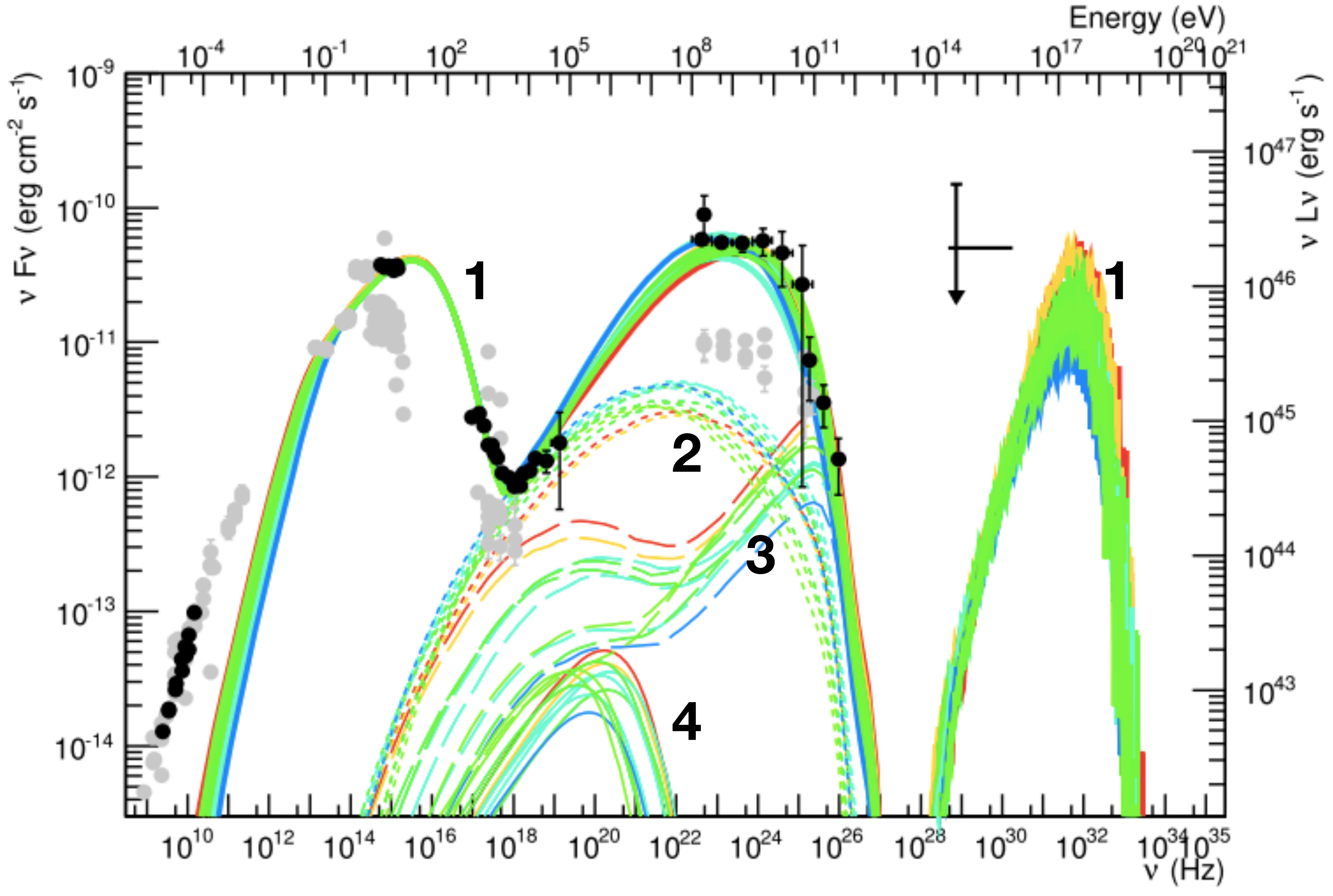
$$p + \gamma \longrightarrow p' e^+ e^-$$



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

LeHa-Paris code

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

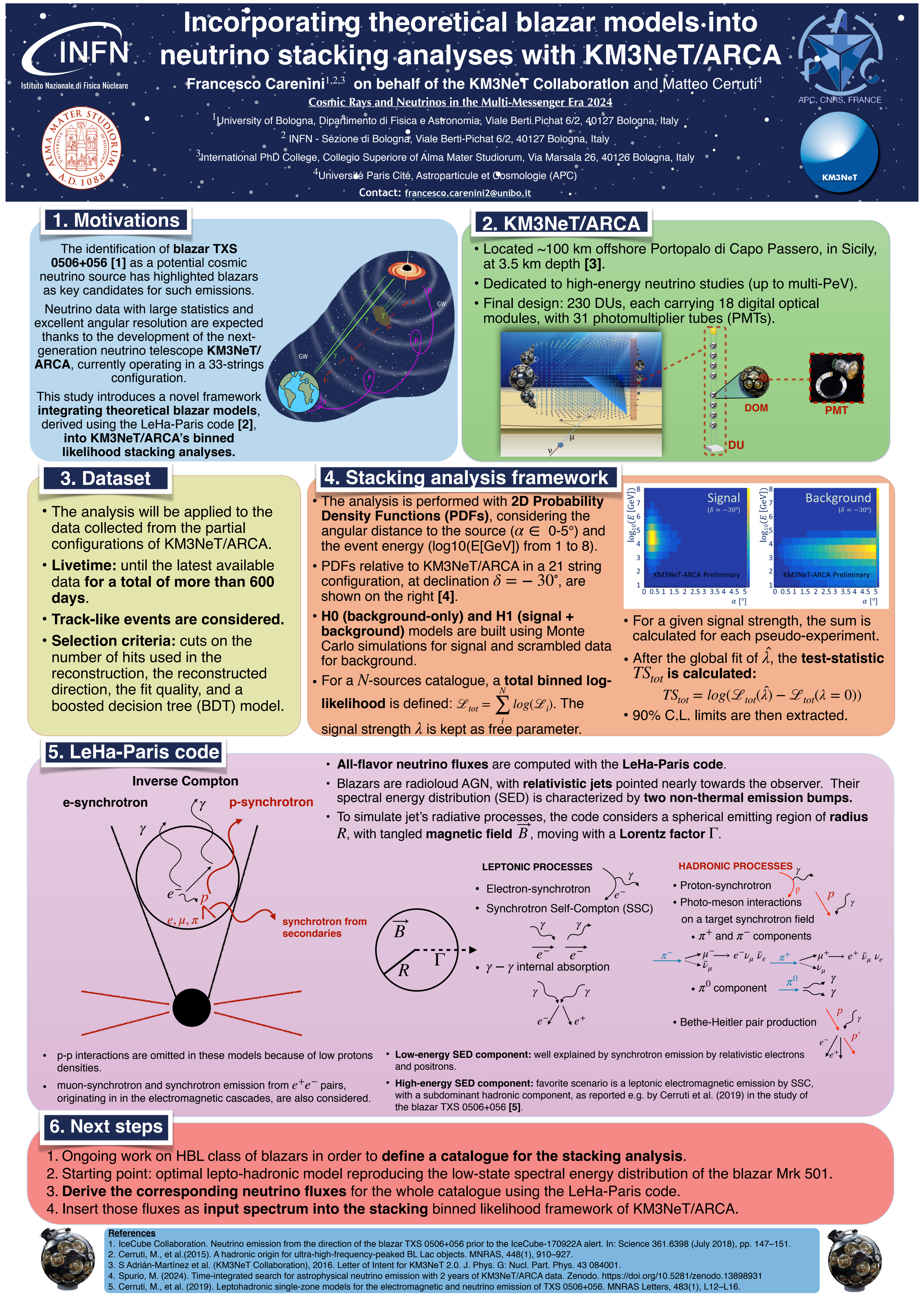


Cerruti, M., et al. (2019). MNRAS Letters, 483(1), L12–L16.

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

Outlook



- **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:**
  1. **Define a catalogue**
  2. **Derive neutrino fluxes with LeHa-Paris**
  3. **Insert those neutrino fluxes into the stacking framework of KM3NeT/ARCA**

Thanks for your attention!

Contacts: francesco.carenini2@unibo.it

https://www.unibo.it/sitoweb/francesco.carenini2/en