Methods of analysis in HE neutrino astronomy

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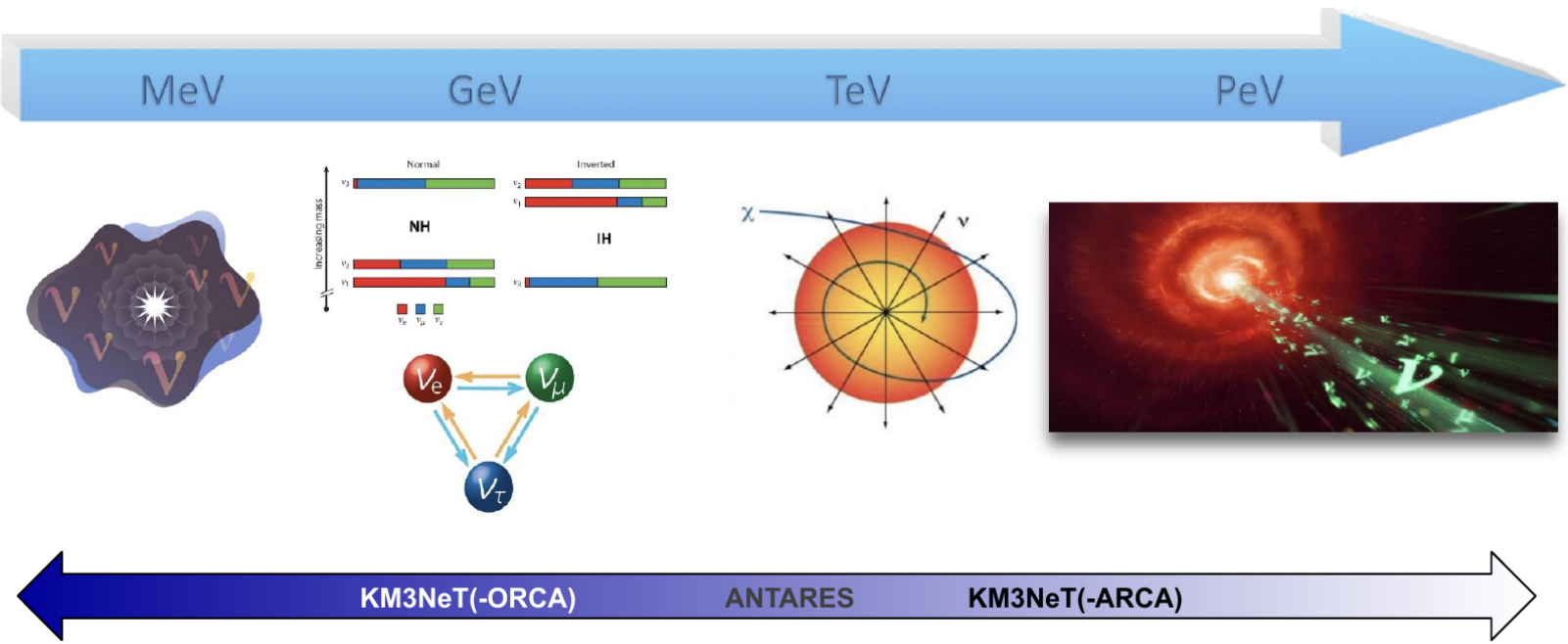
Analyses with HE neutrino telesopes

- Supernovea explosions $\sim$ MeV
- Neutrino Physics (oscillations) $\sim$ GeV
- Dark matter and exotic searches $\sim$ TeV
- Cosmic-ray-related neutrinos $\sim$ TeV-PeV



Search for astrophysical sources

Time-independent searches

- Point-like sources:
  - All-sky blind search (lots of trials)
  - Targeted search: list of sources $N \sim 100$ (reduce trial factors)
  - Population study: perform one global fit (stacking) or many individual fits and then combine
- Diffuse emission:
  - Galactic plane / Galactic ridge
  - Fermi Bubbles

Time-dependent searches

- Point-like objects with variability:
  - GRB, Micro-Quasars,$\gamma-$ray binaries, Blazars, FRB!
- Gravitationnal waves follow-up

Analyses strategy

Different types of analyses optimized for each topic

- "Simple" counting methods: cross-correlation with a catalog, counts in a RoI
- Likelihood-based methods: binned or un-binned

Different parametrization of the signal and background

- Data-driven approach: scrambling of real data
- Monte-Carlo-driven: use MC to predict signal/background distributions

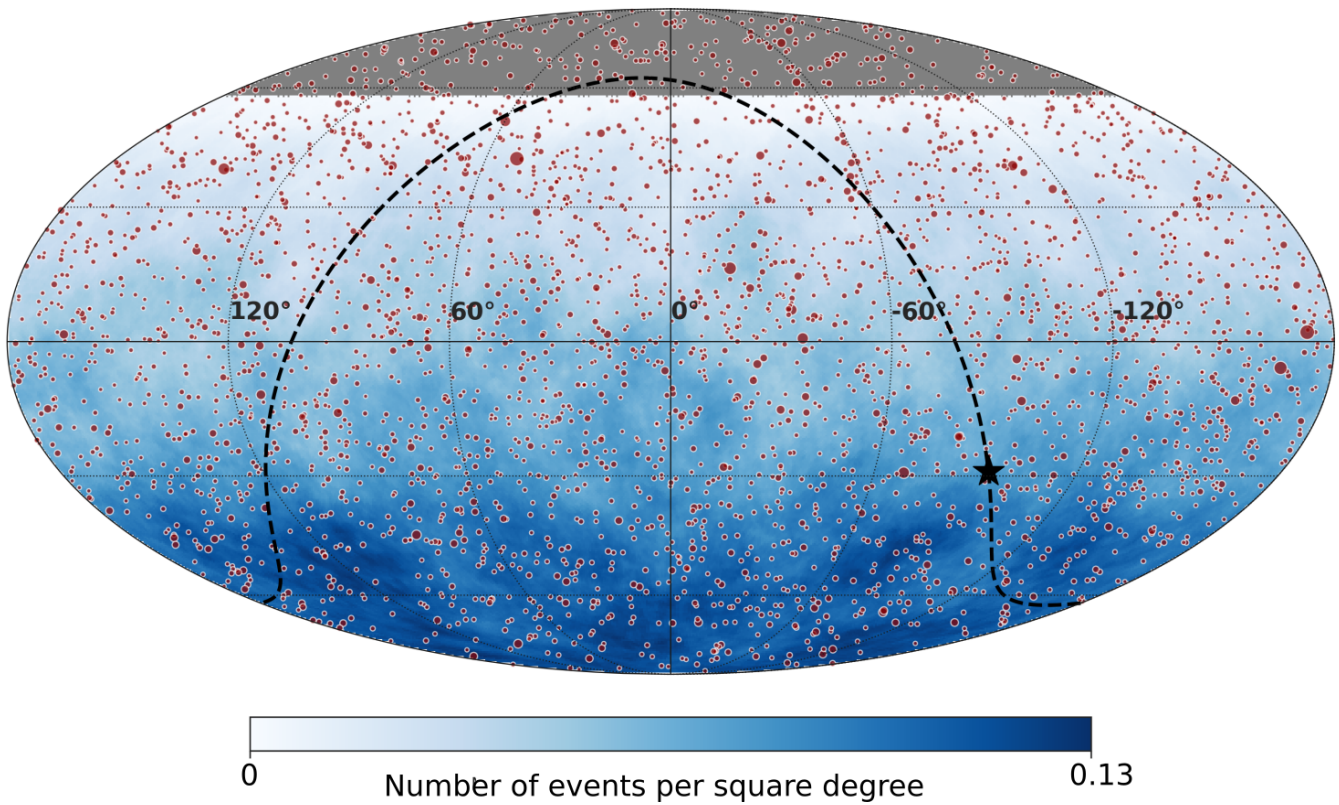
Neutrino data set:

- Online (send or answer to alerts) vs Offline reconstruction
- Selection criteria needs to be optimized
- Effective field of view will depend on background rejection

Example of Point Source analysis

Searches for neutrinos in the direction of radio-bright blazars with the ANTARES telescope (Submitted to ApJ.)

`https://doi.org/10.48550/arXiv.2309.06874`



Neutrio-blazar correlation analysis

Search for space and time correlation between ν and blazars

Neutrino Data set:

- ANTARES final data sample 2007-2022 (3845 days livetime)
- Track-like (10504) + Shower-like events (227)
- Selection cuts: up-going + $\beta < 1^\circ$ + $\Lambda > -5.2$
- Median angular resolution $\sim 0.4^\circ$ for tracks and $\sim 3^\circ$ for showers

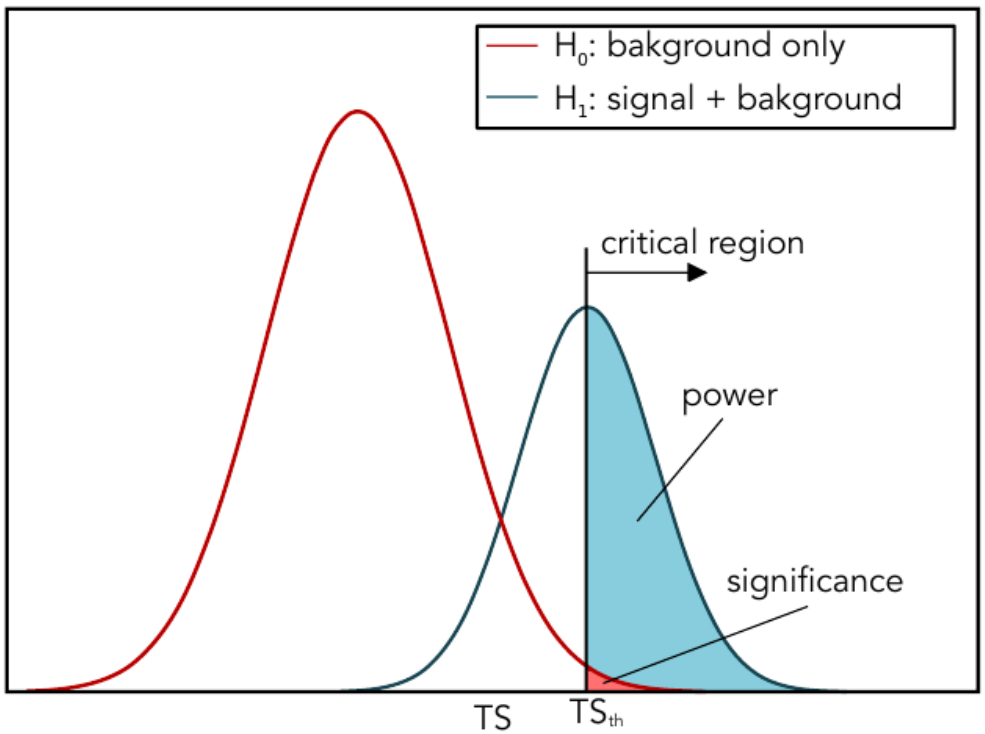
Catalog of blazars:

- Very Long Baseline Interferometry (VLBI) observations `http://astrogeo.smce.nasa.gov/sol/rfc/rfc_2021b/`
- Flux limited catalog for $S_{8\mathrm{GHz}} > 0.15$ Jy
- 3411 blazars $\sim$ uniformly on the full sky

Likelihood analysis

Hypothesis testing, build a Test Statistic (TS) to distinguish:

- Null hypothesis H_0 only background
- Alternative: H_1 background + signal



Time-integrated likelihood analysis

Extended Maximum Likelihood ratio method:

$$\log L(n_s, n_b) = \sum_i \log[n_s S_i + n_b B_i] - n_s - n_b$$

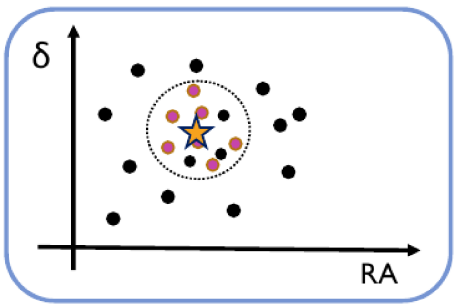
$$TS = 2 \log \left(\frac{L_{s+b}^{max}}{L_b^{max}} \right)$$

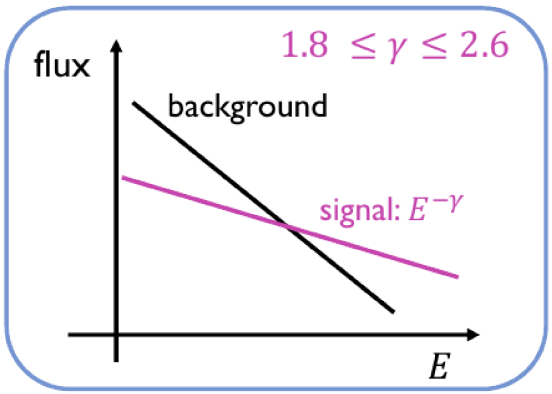
n_s, n_b: free parameters

number of detected signal n_s and background n_b events

S_i: $S = S^{space} \cdot S^{energy}$

B_i: $B = B^{space} \cdot B^{energy}$





Stacking approach:

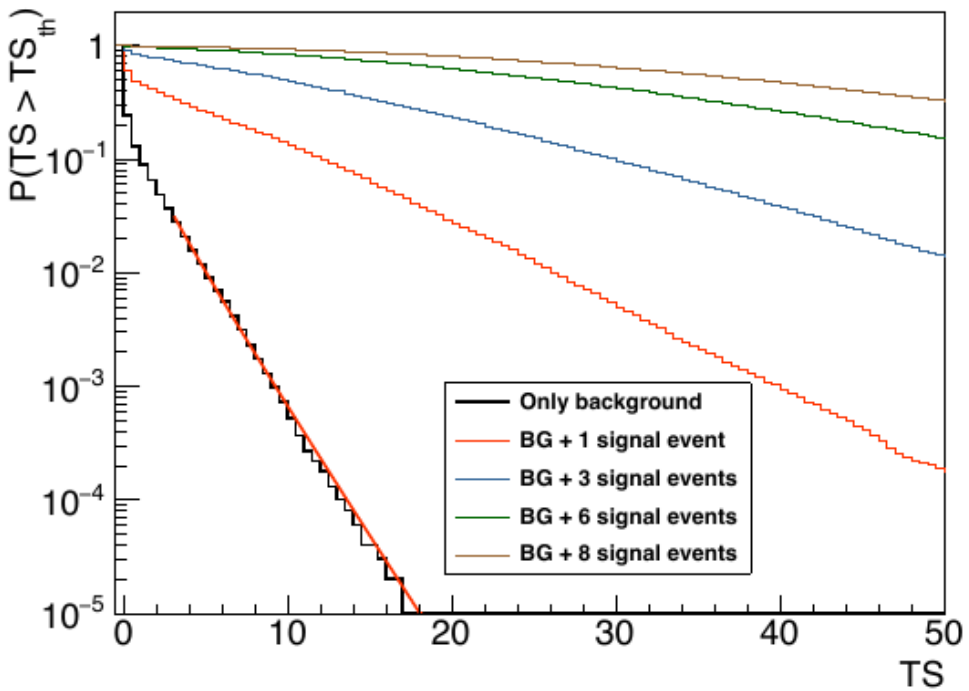
$$S_i = \frac{1}{\sum_j w_j} \sum_j^{Nsources} w_j S_{ij}$$

Two hypotheses tested:

- w_j= flux density of source j
- $w_j = 1$ for all sources

Test statistic

- TS under H_0 should asymptotically follow χ^2 with n dof with $n =$nb of free parameters in the fit
- Not always fulfilled, need MC estimation for the p-value
- Estimation of sensitivity/limits from the TS distribution



Time-dependent likelihood analysis

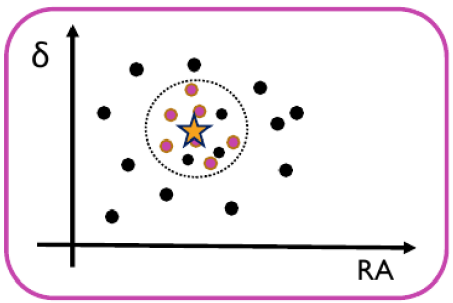
Extended Maximum Likelihood ratio method:

$$\log L(n_s, \gamma, T_0, \sigma_t) = \sum_{j \in \{tr, sh\}} \sum_{i \in j} \log\left[n_s^j S_i^j(\gamma, T_0, \sigma_t) + N^j B_i^j\right]$$

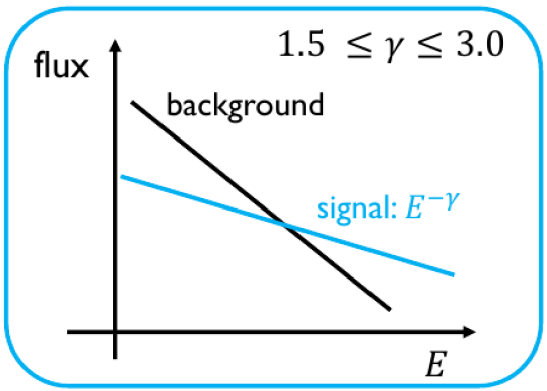
$$PDF = PDF^{space} \cdot PDF^{energy} \cdot PDF^{time}$$

Non-stacking approach: each source is analysed independently

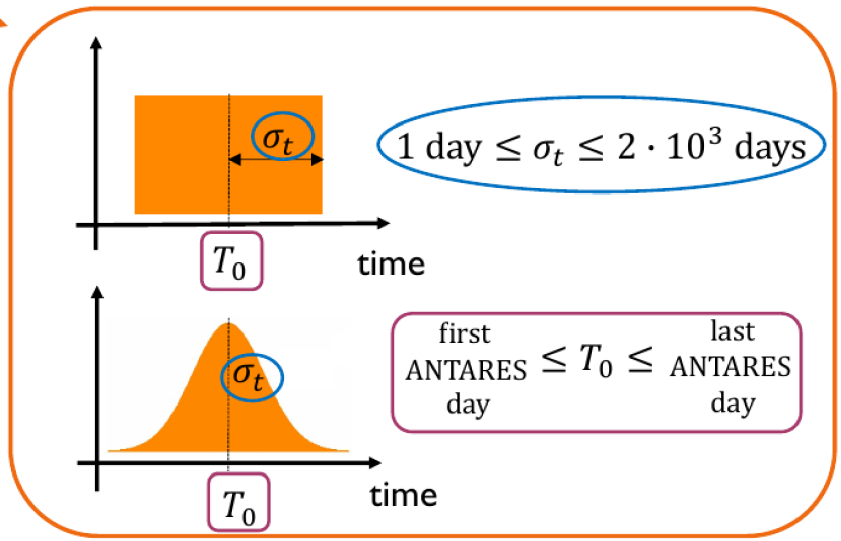
number of detected signal events



signal spectral index



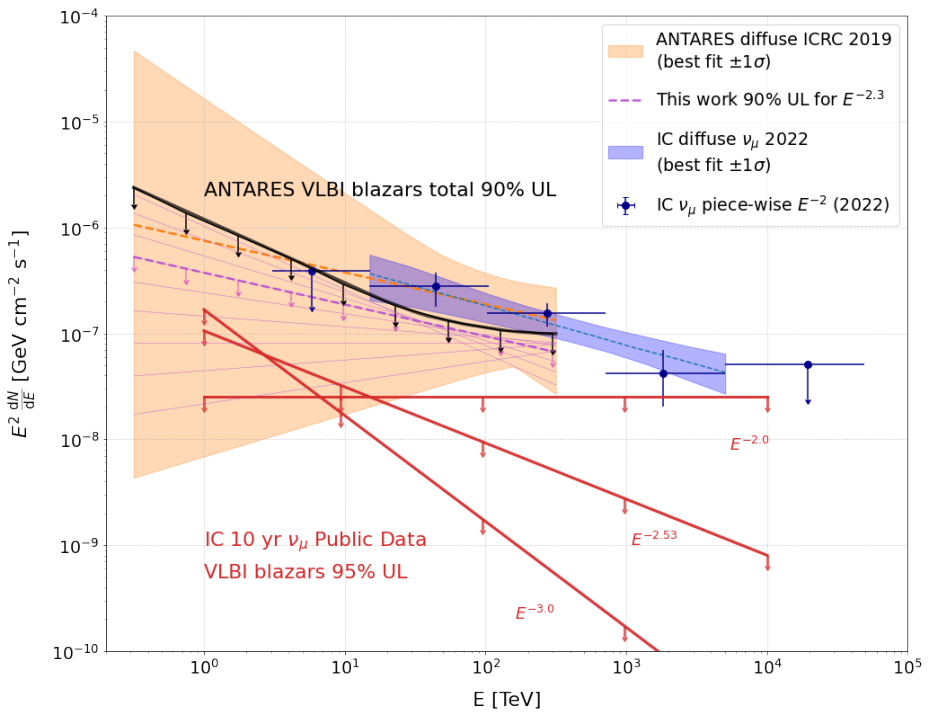
time-related parameters



Results

Time integrated:

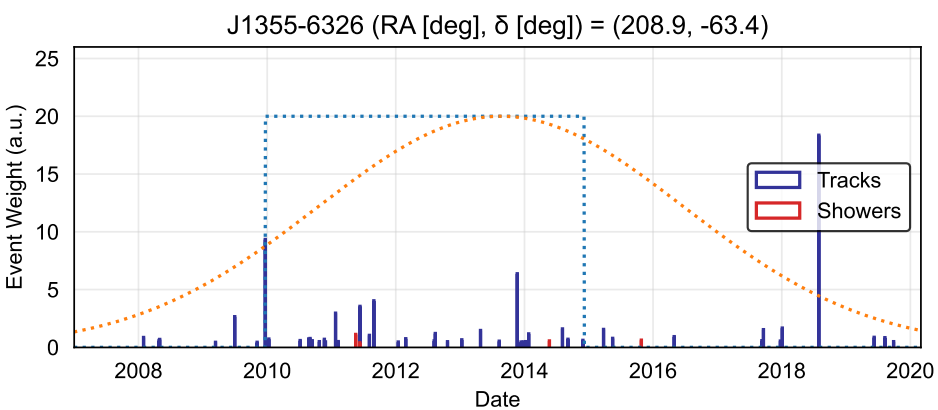
- Mild excess $p = 2.2\sigma$, upper-limits on the total flux from blazars
- Similar studies using IC 10yr ν_μ public data: $< 30\%$ of the diffuse flux

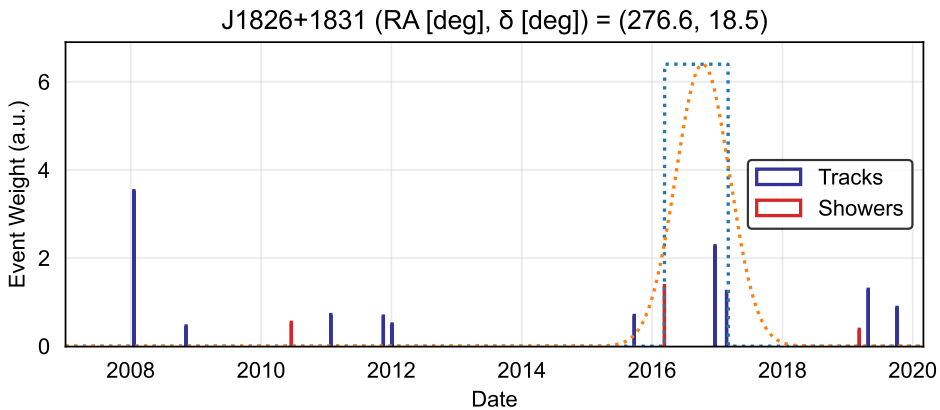


Results

Time dependent:

- 18 blazars with a pre-trial significance $> 3\sigma$
- Most significant gaussian flare for blazar J1355-6326:
  - from 3.7σ pre-trial $\rightarrow$ post-trial $P = 0.29$
- Most significant box flare for blazar J1826+1831:
  - from 3.3σ pre-trial $\rightarrow$ post-trial $P = 0.84$

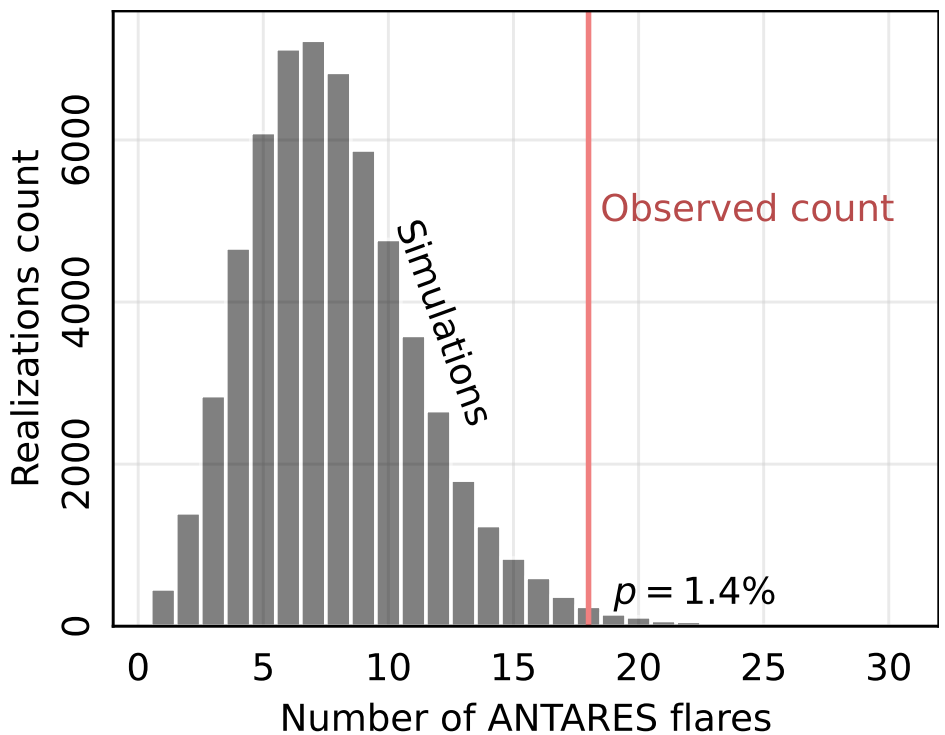




Results

Time dependent:

- 18 blazars (among 3411) with a pre-trial significance $> 3\sigma$
- Search for a cumulative excess:
  - Probability to get 18 sources or more with 3σ $p = 1.4\%(2.5\sigma)$



Stacking analyses

Different ways to perform a stacking analysis:

- Single analysis with the signal term including all sources contributions (counting or likelihood)
- Individual fits/counting and add the individual test statistics $TS = \sum_i TS_i$
- Search for cumulative excess using the p-values ($\sim$ binomial)

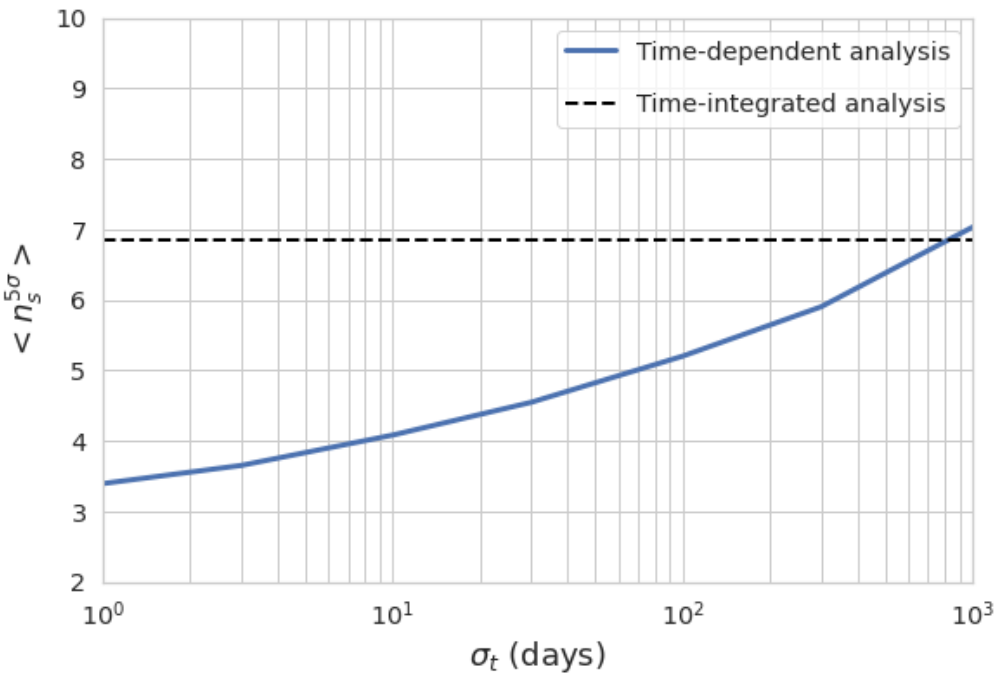
Interest of the stacking analysis:

- Individual sources are too faint to be detected
- At first order, significance $n_\sigma \sim n_s/\sqrt{n_b}$
- Stacking N identical sources would give $n_\sigma^{\mathrm{stack}} \sim \sqrt{N} \times n_\sigma$
- If only a small fraction of a population of source is ν emitter, stacking $> 10^3$ sources may be worse...

Time window

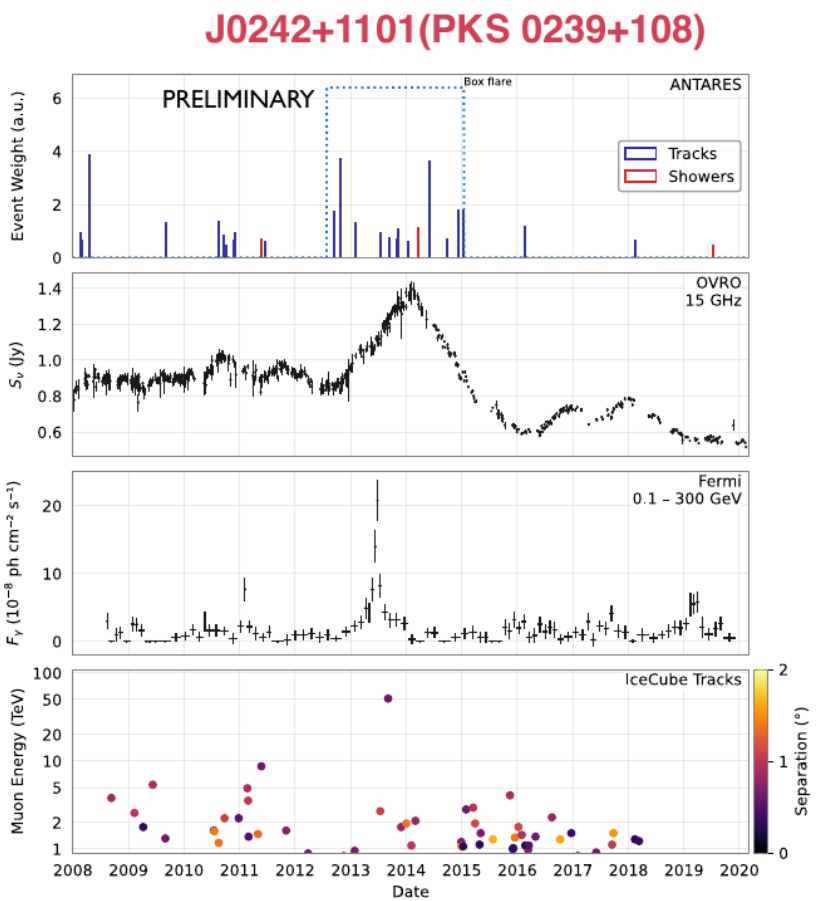
Influence of the time window

- Small time window reduces the background...
- Look for the smallest possible, but risky if we miss the signal!
- Inputs from the theory to optimized discovery potential
- Perform a safer study with more conservative time windows



Multi-messenger analysis

Search for counterparts (among the 18 blazars with $s > 3\sigma$):



ANTARES best-fit flare

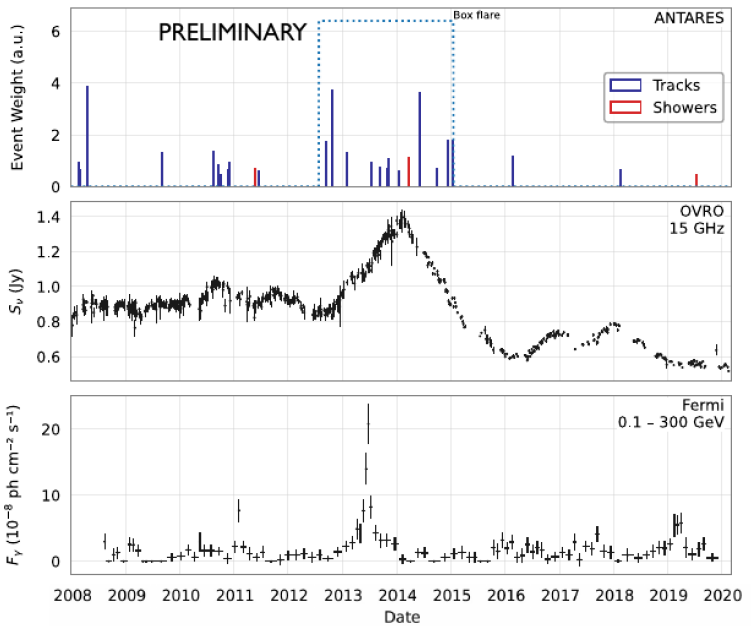
OVRO radio light-curve

Adaptive binned gamma-ray light-curve obtained from Fermi-LAT data

IceCube 10-years point-source sample
-Tracks within 90% angular error from source
- angular error < 10deg^2

Multi-messenger analysis

J0242+1101(PKS 0239+108)



How likely is it that such a multi-messenger (ν+radio+γ) correlation arises by chance?

- Run flare analysis on **scrambled data**
- Verify how many times these **conditions** are **fulfilled**:
  - the **global maximum** of the **radio/gamma** light-curve **falls** within the ANTARES flare duration $\hat{T}_0 \pm \hat{\sigma}_t$
  - ratio between maximum and median flux is
    - above **1.6** for **radio**
    - above **3.5** for **gamma**

    as seen in J0242+1101

Result

0.5% (2.9σ) chance probability of ν+radio+γ correlation

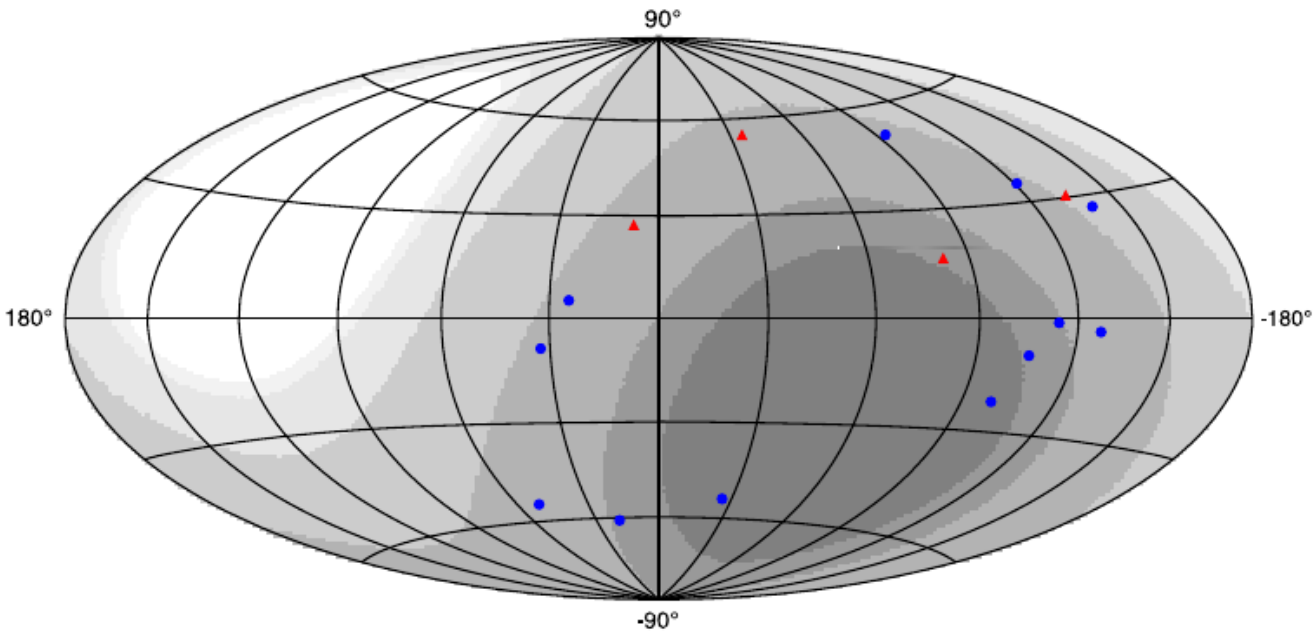
Total of 335 blazars with light-curves available both in radio (OVRO) and gamma (Fermi-LAT)

ANTARES FRB analysis

The search for high-energy neutrinos coincident with fast radio bursts with the ANTARES neutrino telescope

MNRAS 482, 184–193 (2019)

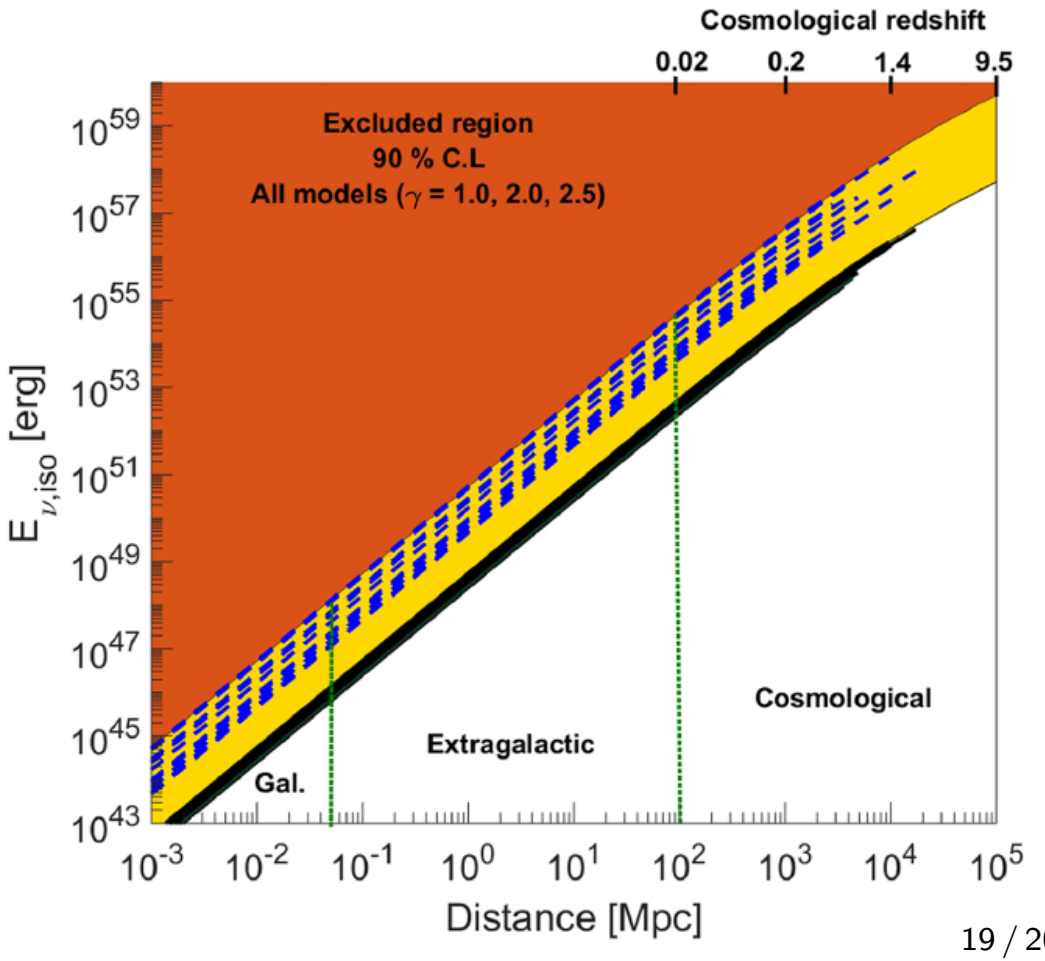
- Time period 2013-2017: 16 FRB detected (Parkes+UTMOST+ASKAP)
- Only 12 in the ANTARES FoV (up-going) + good conditions



ANTARES FRB analysis

Method:

- Counting up-going events within 2° search cone
- Time window around FRB $T_0 \pm 6$h
- Selection cuts such that 1 detected event $\longrightarrow 3\sigma$
- No signal: UL on the ν fluence for different pure power-law indexes



Search for FRB with neutrinos

For a more recent example of analysis with KM3NeT
$\longrightarrow$ see Felix's talk !