Unveil Neutrino Multimessenger Astronomy with Super-Kamiokande

First general meeting of the Fellini programme

Mathieu Lamoureux
mathieu.lamoureux@pd.infn.it

INFN Sezione di Padova

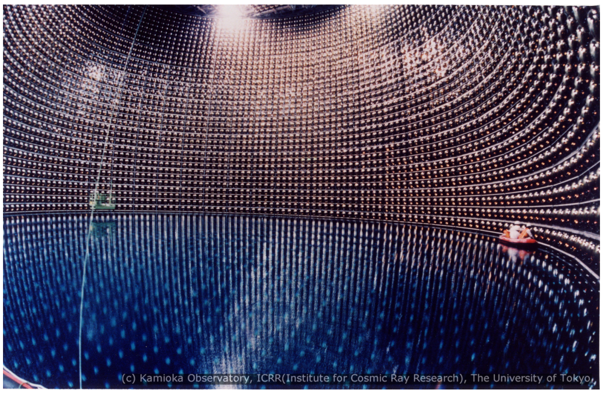
February 24, 2020

This work was financially supported by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 754496 - FELLINI

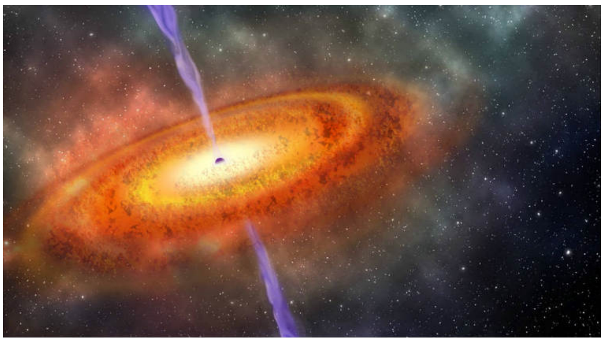
Overview

- **Title of project:** Unveil Neutrino Multimessenger Astronomy with Super-Kamiokande [UNMASK]
- **Main topics:** experimental neutrino physics and astrophysics, follow-up of external triggers, supernovae and study for future detectors
- **Institute:** INFN Padova
- **Contract period:** March 2019 - March 2022

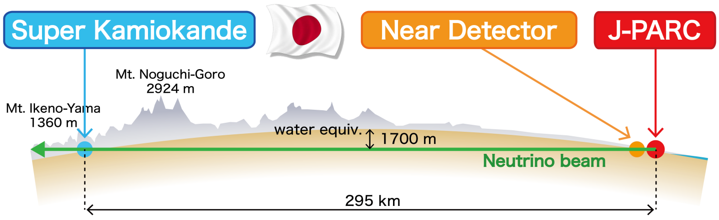
Super-Kamiokande



Neutrino astronomy



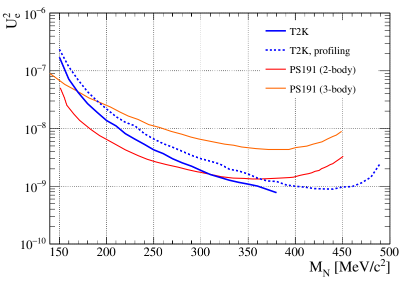
PhD thesis in 2015-2018 in CEA Paris-Saclay (France) on neutrino physics and the T2K experiment **Supervisor:** Marco Zito

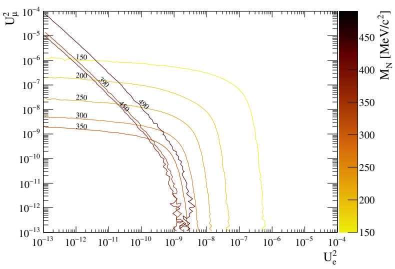


Neutrino oscillation experiment in Japan

Main topic: search for hypothetical heavy neutrinos with T2K

- Would explain Baryon Asymmetry in the Universe (Baryogenesis via Leptogenesis)
- Produced alongside standard neutrinos in T2K beam
- Detected through their decay in the near detector





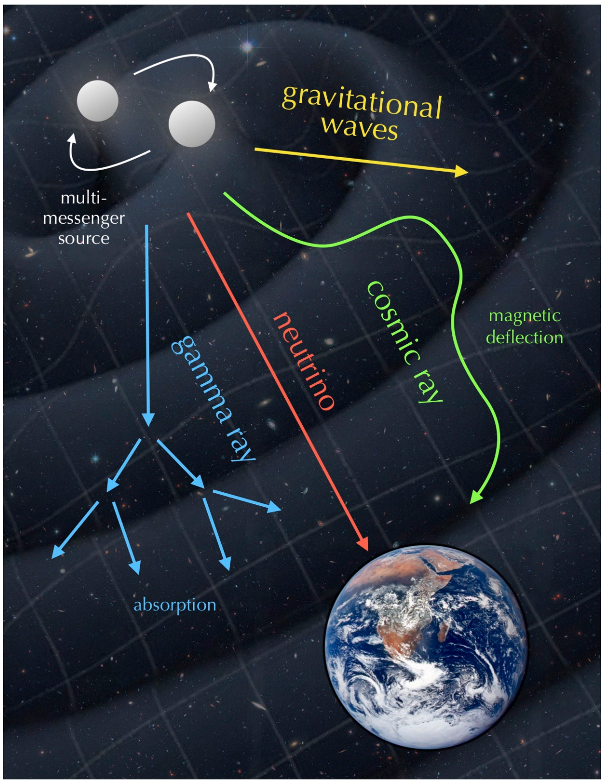
No discovery so far

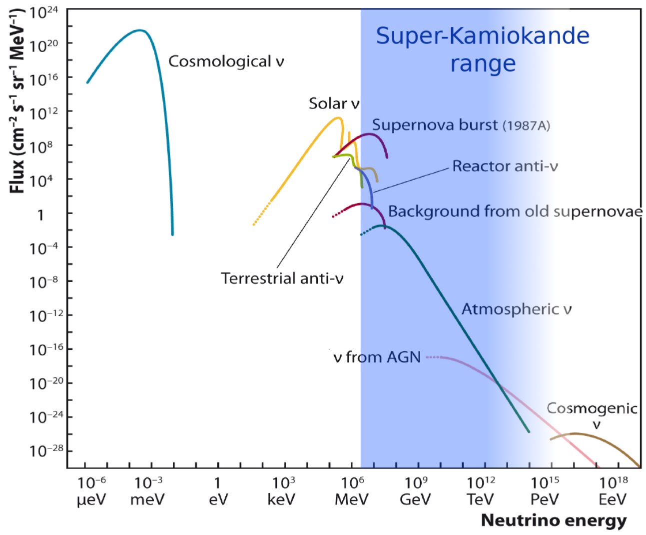
Results published in PRD in September 2019

Fellini project

Why neutrino astronomy?

Understanding of the mechanisms behind astrophysical sources

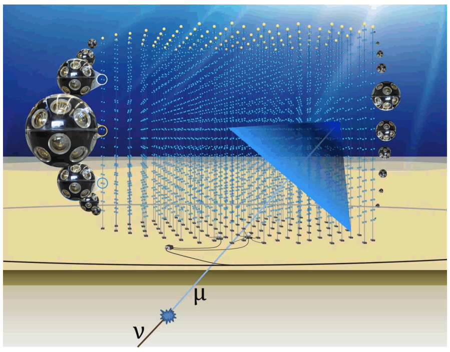
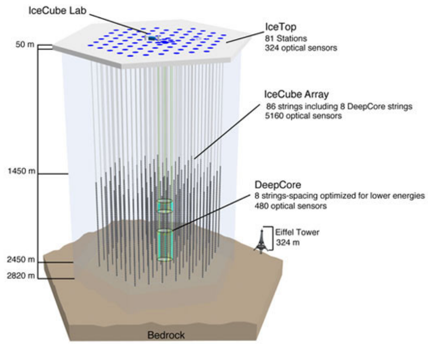
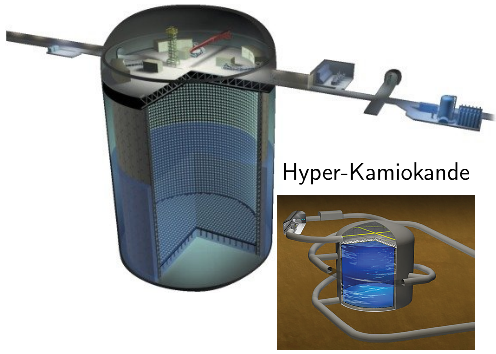




- ✔ Neutrinos propagate in straight line from the source and almost unabsorbed
- ✖ But they are difficult to detect (small cross sections) $\rightarrow$ **need huge detectors**

Neutrino telescopes

Main technology is water Cherenkov detectors (neutrinos detected with Cherenkov light emitted by charged particles from neutrino interaction)

In the sea	**In ice**	**In a tank**
		

Running

ANTARES (35 Mton)	IceCube (1 Gton)	Super-Kamiokande (50 kton)

Future

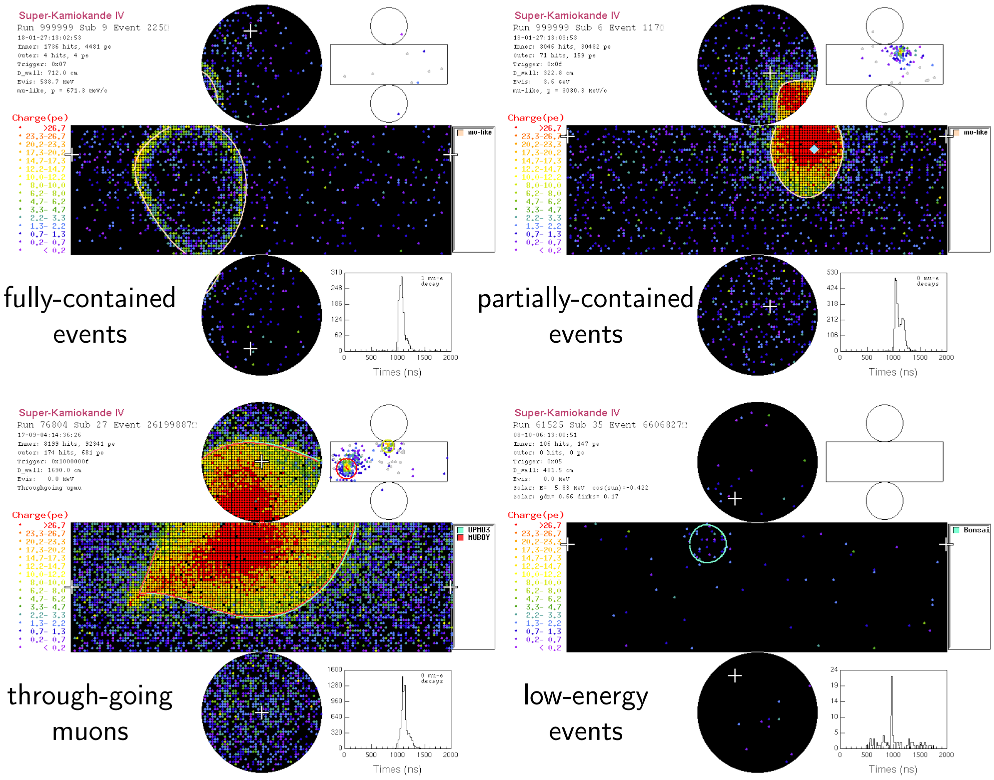
KM3NeT (1 Gton)	IceCube-Gen2 (10 Gton)	Hyper-Kamiokande (258 kton)

Energy sensitivity

$E \gtrsim 0.1 - 1$ TeV	$E \gtrsim 1$ TeV	$E \gtrsim 4.5$ MeV

Neutrinos at Super-Kamiokande

Cherenkov light detected with the $\sim$ 13000 PMTs of the detector.
High-energy samples are dominated by **atmospheric neutrinos**.

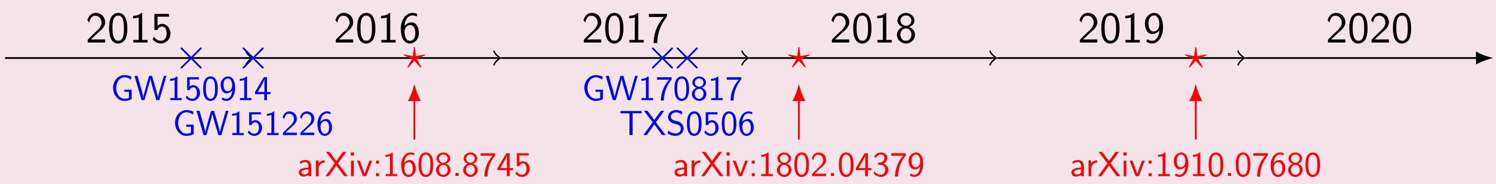


Proper Cherenkov rings:
- $0.1 < E < 100$ GeV
- good energy reconstruction
- good particle ID

(**LEFT**) Upgoing muons:
- $E >$ few GeV
- $\sim 100\%$ efficiency
- no energy reconstruction

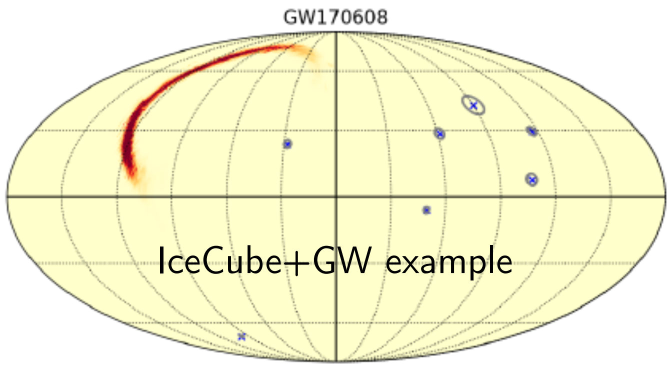
(**RIGHT**) Low-Energy events:
- $E > 4.5$ MeV
- solar/supernova neutrinos

The Super-Kamiokande collaboration has done several follow-ups of astrophysical events detected by other experiments, looking for events in time and/or spatial coincidence, in the 4 samples.



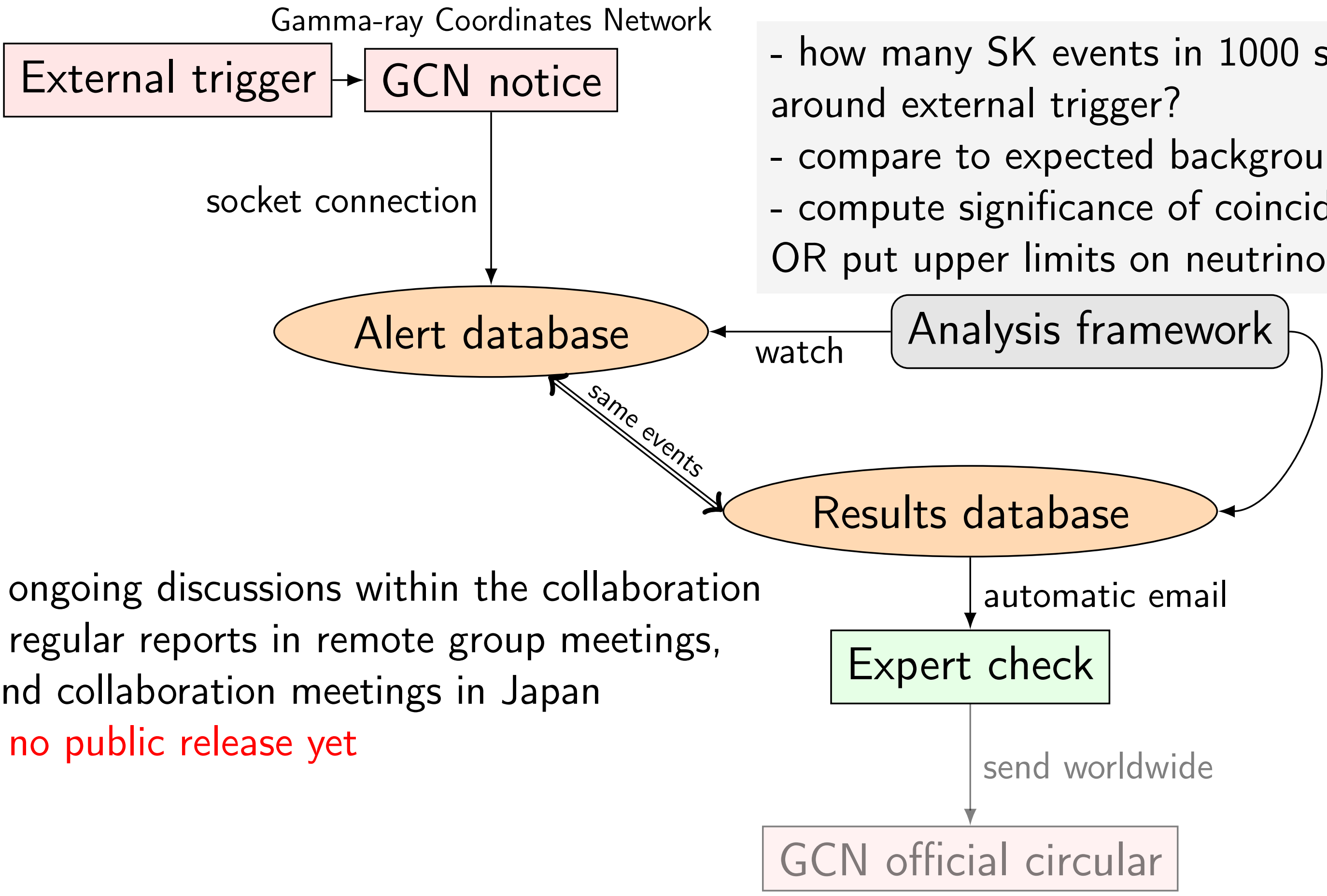
Need faster and more automatic analysis as the number of interesting astrophysical events to follow up is getting higher and higher.

Example of GW+ν analysis



- LIGO/Virgo alerts are public since 04.2019
- Binary mergers are astrophysical objects for which both GW and ν are expected
- ✖ Detected GW are not well localized in sky
- ✔ Neutrinos have a better pointing capability
- Increase the chance of observing EM counterparts (pointing telescopes)

Framework for realtime follow-up

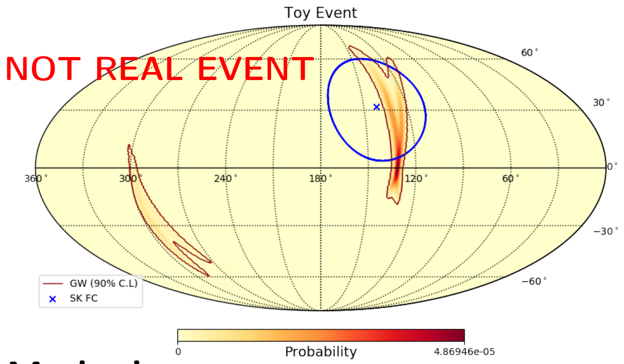


- how many SK events in 1000 sec around external trigger?
- compare to expected background
- compute significance of coincidence OR put upper limits on neutrino flux

- ongoing discussions within the collaboration
- regular reports in remote group meetings, and collaboration meetings in Japan
- no public release yet

Statistical analysis

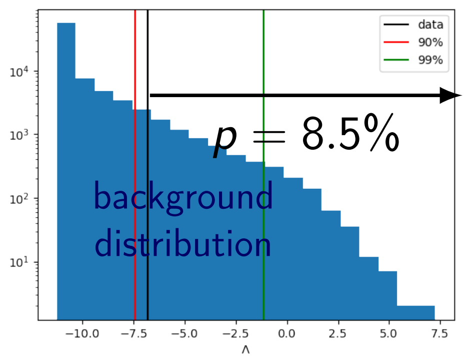
If there is a neutrino event in time coincidence with the GW trigger, how likely is it to be from the same astrophysical source?



Goal: compute significance/p-value from spatial correlations of GW+ν
$\Rightarrow$ *What is the probability that this observation comes from random background?*

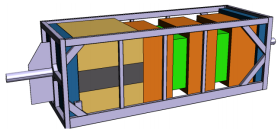
Method:

- define a test statistics TS with detector resolution, atmospheric ν distribution...
- compute TS distribution for pure background
- compare TS of real data to this background distribution, $p = \int_{TS_{\mathbf{data}}}^{\infty} P_{\text{bkg}}(TS)dTS$

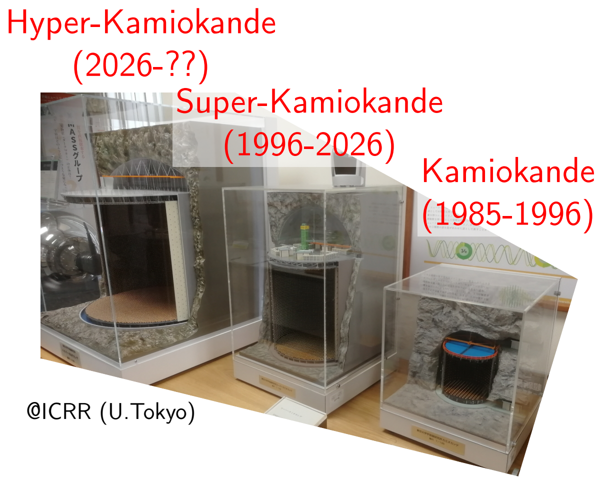


Different TS formulae under investigation: log-likelihood ratio (arXiv:1908.07706), combined χ^2 (arXiv:0801.1604), Bayesian (arXiv:1810.11467)...

- Extend current SK framework for follow-up of public **IceCube** (TeV-scale neutrinos) and **GRB** alerts
- Supervision of a *Master project* on new selection of **supernovae neutrinos**, in the context of SNEWS2.0
- Simulation/reconstruction and prototype tests for the **upgrade of the T2K Near Detector ND280**



- Hyper-Kamiokande (HK) detector is the next generation water tank with enlarged volume (50 $\rightarrow$ 260 kton)
    - **HK detector sensitivity** (assuming SK-like reconstruction)
    - study of a potential novel energy reconstruction, taking benefit of better granularity of the detector



Various points

Diffusion, training and other activities

Collaboration-wide

- Regular video meetings within SK astro and atmospheric groups
- Super-Kamiokande / T2K / Hyper-Kamiokande collaboration meetings
- Detector shifts for Super-Kamiokande and T2K

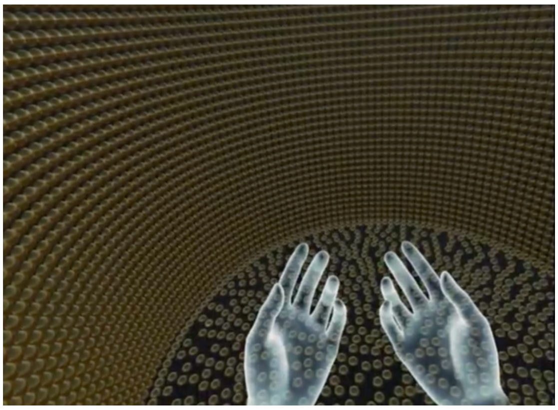
Workshops and conferences

- Participation to workshops for training purposes on topic related to astrophysics (NuTel in 03.2019, KM3NeT Town Hall in 12.2019).
- Presentation of collaboration or analysis results to conferences on neutrino physics and astrophysics (TAUP in 09.2019, NEUTRINO in 06.2020 ?, another conference in 2021 ?).

Outreach activities

For the next European Researchers' Night in Padova:

- Exhibition of Super-Kamiokande photomultiplicators (20cm⌀available in LNL, possibility to get a 50cm⌀to be investigated).
- Possibility to have a VR show using a software already designed in the collaboration.
- Construction of a small model of Super-Kamiokande with LEDs representing the photo-detectors, allowing showing some real events.



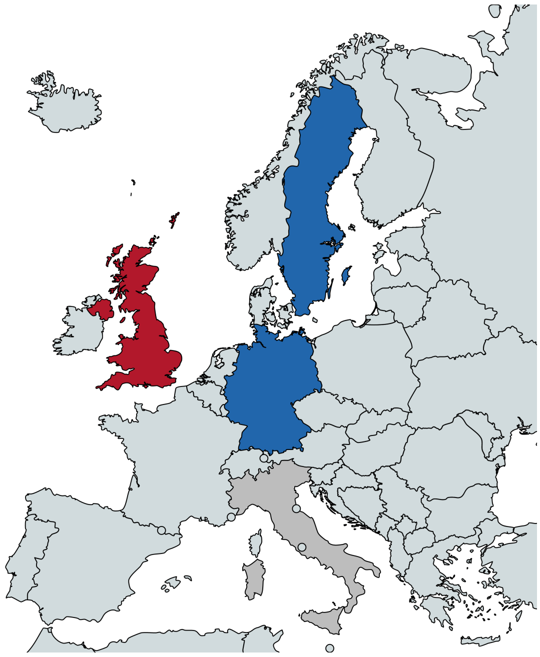
VR show used for event at the Royal Society (London)

Interactive model (in London too)

Leads for the secondment

Different possibilities related to the Fellini project:

- Joint analysis SK-IceCube in search for neutrino sources:
  - Possibilities in Germany (e.g. DESY Zeuthen)
  - Possibility in Stockholm/Uppsala Universities
- Focus on Hyper-Kamiokande analysis
  - In discussion with researchers from Queen Mary (London)



Choice is not done yet as it strongly depends on:

- the evolution of the current project in the next month (officialisation of SK analysis, studies with HK...)
- the administrative conditions for the secondment

Summary

- Multimessenger neutrino astronomy with Super-Kamiokande
- Current work on realtime follow-up of Gravitational Wave events
- *Main study so far:* full implementation of framework + computation of statistical significance of GW+nu event
- *Other studies:*
    - use the same framework for GRB/IceCube events
    - supernovae neutrinos with Super-Kamiokande
    - simulation/reconstruction efforts for ND280 Upgrade
    - extension of current work to Hyper-Kamiokande (sensitivity)
- *Outreach:* European Researchers' Night with exhibition/VR/model
- *Secondment:* leads for extension of analysis to Hyper-Kamiokande or work on IceCube-SK combined analysis

Backups

More on the statistical analysis: method (I)

1. For each point of the sky, using real data and GW skymap, compute[1]

$$\mathcal{L}(n_S, \vec{x_s}) = \frac{e^{-(n_S+n_B)}(n_S+n_B)^N}{(N)!} \prod_{i=1}^{N} \frac{n_S \mathcal{S}_i + n_B \mathcal{B}_i}{n_S + n_B}$$

$$\Lambda(\vec{x_s}) = 2 \ln \left[\frac{\mathcal{L}(n_S = \widehat{n_S}, \vec{x_s})}{\mathcal{L}(n_S = 0, \vec{x_s})} \right] + 2 \ln \left[w_L(\vec{x_s}) \right]$$

   with w_L = GW probability and $\widehat{n_S}$ is the value maximising $\mathcal{L}(n_S, \vec{x_s})$.
2. The final Test Statistic is $\Lambda_{\mathrm{max}} = \mathrm{max}_{\mathrm{sky}} \left[\Lambda(\vec{x_s}) \right]$
3. Repeat steps 1 and 2 with many background toy experiments to get the background distribution $P_{\mathrm{bkg}}(\Lambda_{\mathrm{max}})$.
4. Compute p-value $= \int_{\Lambda_{\mathrm{max}}^{\mathrm{data}}}^{\infty} P_{\mathrm{bkg}}(\Lambda_{\mathrm{max}})\, d\Lambda_{\mathrm{max}}$.

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[1] Hussain, R. et al. A Search for IceCube Neutrinos from the First 33 Detected Gravitational Wave Events. arXiv:1908.07706

- Define likelihood[2]

$$\mathcal{L}(\vec{x_S}) = \frac{S_{GW}(\vec{x_s})\prod_j S_\nu^j(\vec{x_s})}{B_{GW}(\vec{x_s})\prod_j B_\nu^j(\vec{x_s})} \text{ and } \mathcal{L} = \int \mathcal{L}(\vec{x_s})d\vec{x_s}$$

- Compute $\mathcal{L}_{\text{data}}$, $P_{\text{bkg}}(\mathcal{L})$ and $p_{\text{sky}} = \int_{\mathcal{L}_{\text{data}}}^{\infty} P_{\text{bkg}}(\mathcal{L})\, d\mathcal{L}$
- Compute $\begin{cases} p_{GW} = 1 - \mathrm{Poisson}(0, T \cdot \text{FAR}) \\ p_\nu^{(j)} = \int_{E_\nu}^{\infty} P_{\text{bkg}}(E'_\nu)\, dE'_\nu \\ p_{\text{cluster}} = 1 - \sum_{i=0}^{N-2} \mathrm{Poisson}(i, \sum n_B^k) \end{cases}$
- Compute $\chi^2_{\text{data}} = -2\ln\left[p_{\text{sky}} \times p_{GW} \times \prod_j p_\nu^{(j)} \times p_{\text{cluster}}\right]$
- Repeat the procedure for background toys to get $P_{\text{bkg}}(\chi^2)$.
- Compute p-value $= \int_{\chi^2_{\text{data}}}^{\infty} P_{\text{bkg}}(\chi^2)\, d\chi^2$.

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[2] Baret, B., et al. Multimessenger Science Reach and Analysis Method for Common Sources of Gravitational Waves and High-energy Neutrinos. PhysRevD.85.103004

Other studies

Same framework can be used for other follow-ups with wide range of physics:

- Ultra-high energy neutrino alerts from IceCube (public)
- Gamma-Ray Burst alerts from Fermi/Swift

Project: adapt current implementation

Super-Kamiokande is very sensitive to supernovae neutrinos [$E \sim \mathcal{O}(10)$ MeV] (arXiv:1601.04778). Alerts are propagated through SNEWS.

Project: work with a Master student on a new selection (sensitive to farther events)

SNEWS

SuperNova Early Warning System

The T2K near-detector ND280 (main component of T2K with Super-Kamiokande) upgrade is currently under development.

Work: participate in simulation/reconstruction efforts as well as prototype tests at CERN/DESY.