Current results from LEAK

IRN Neutrino meeting June 29-30 2022

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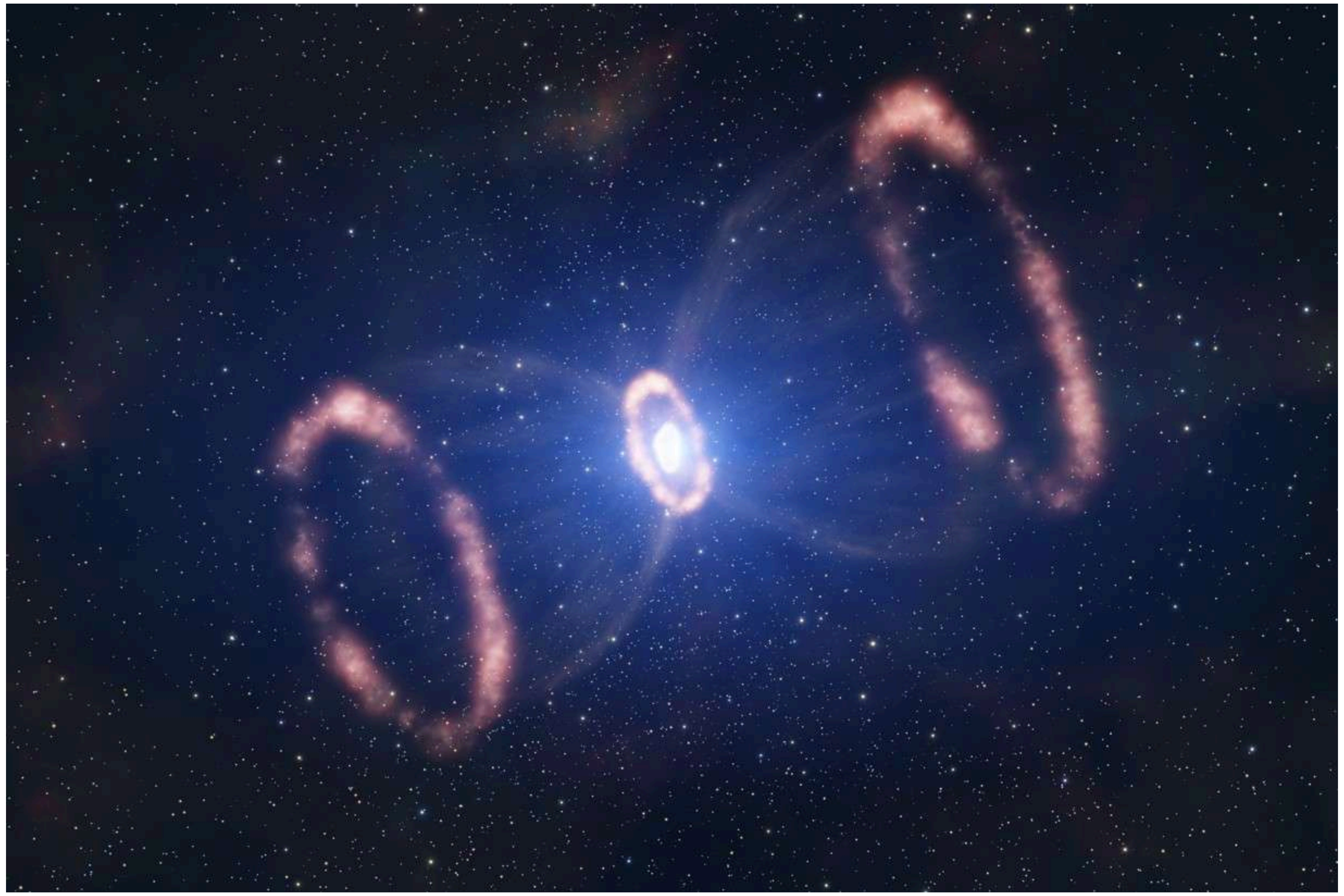
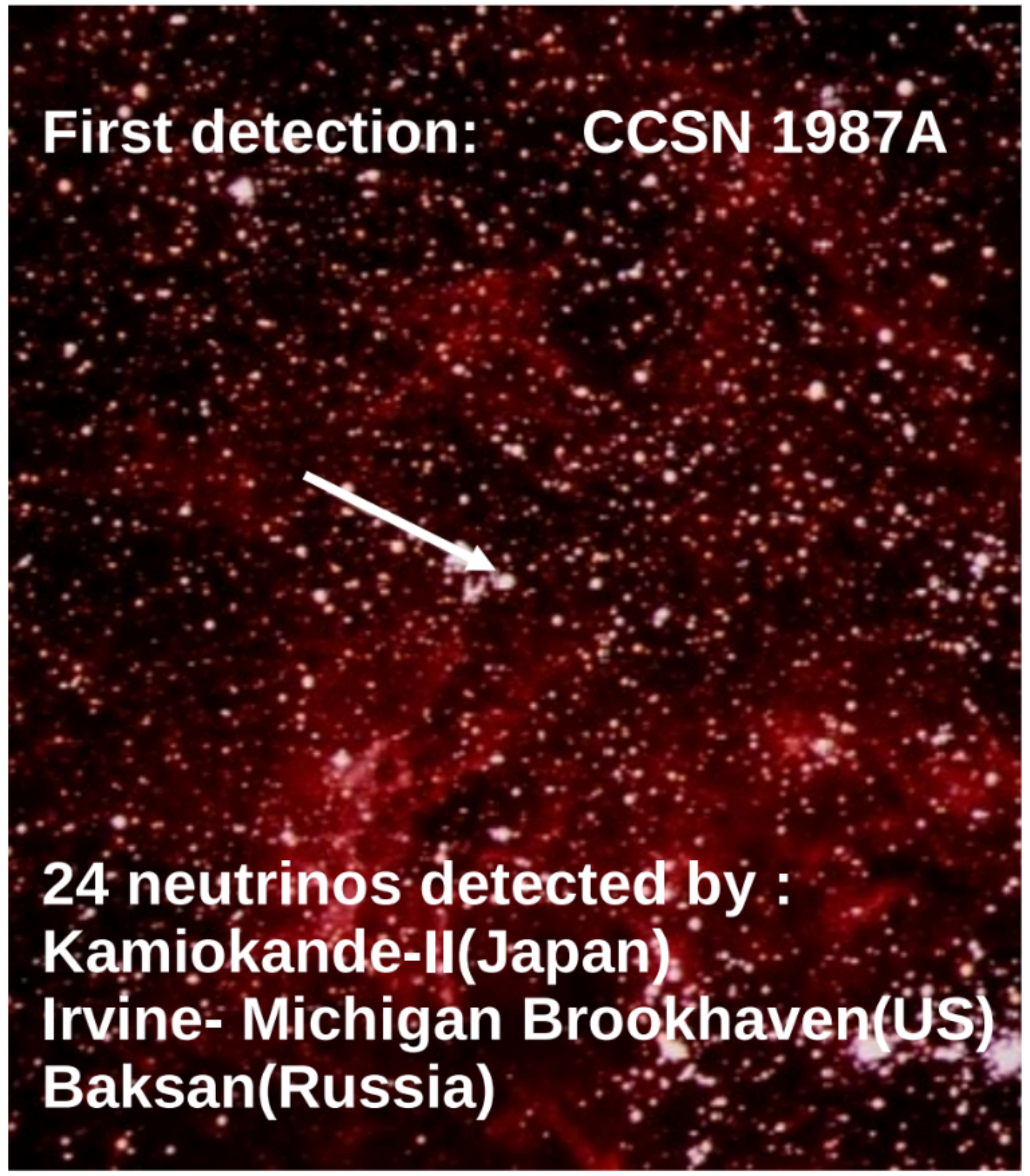
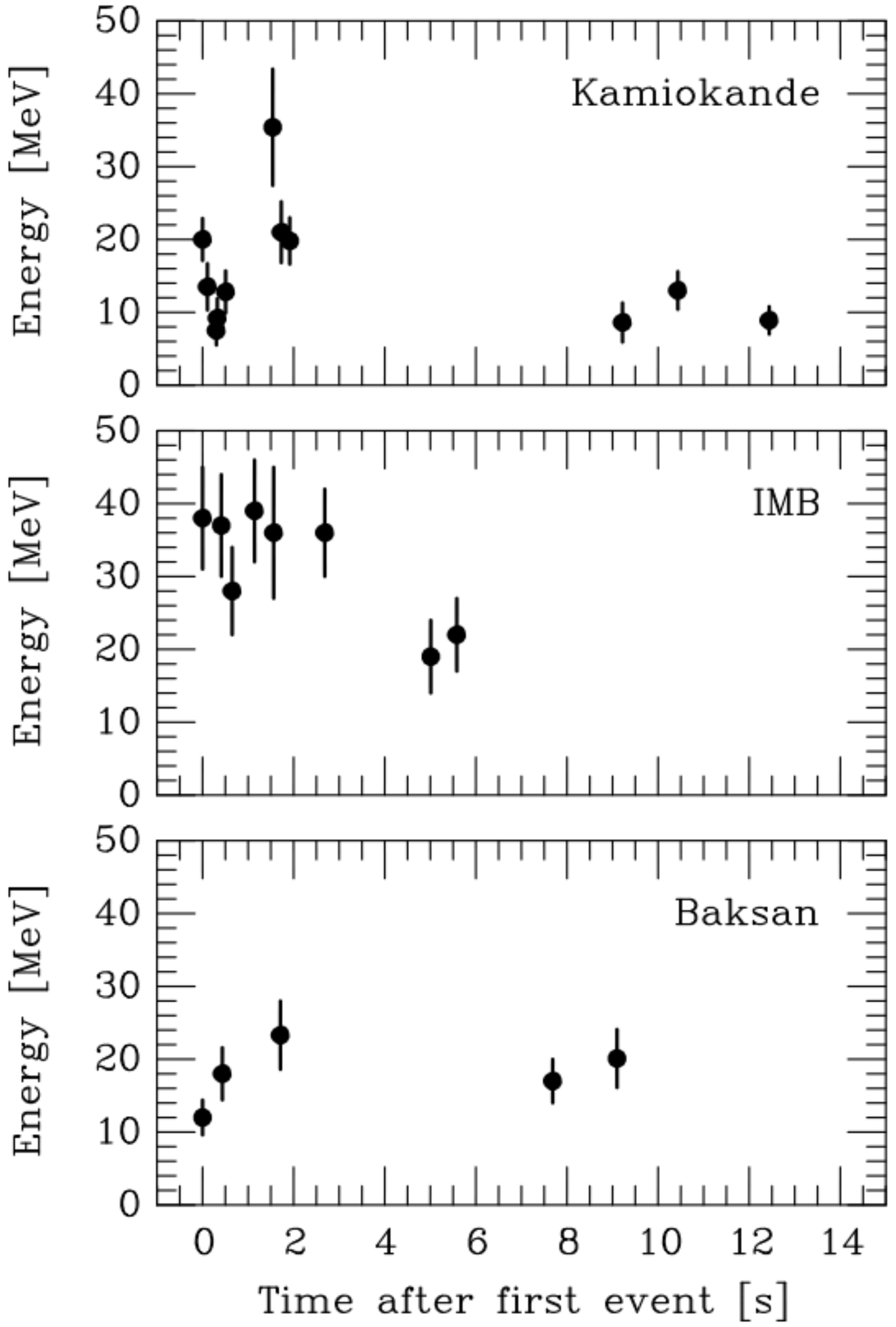
Introduction

The beginning of multi-messenger astronomy

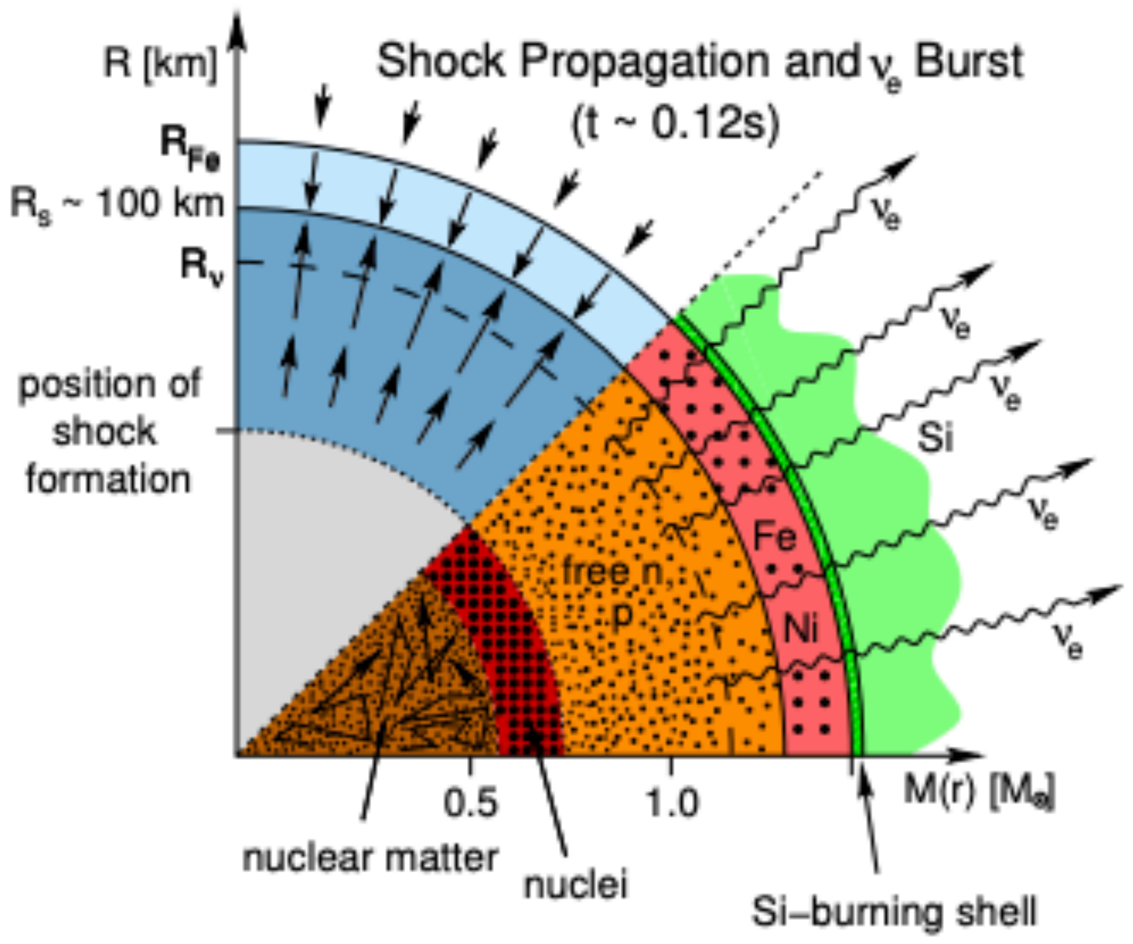


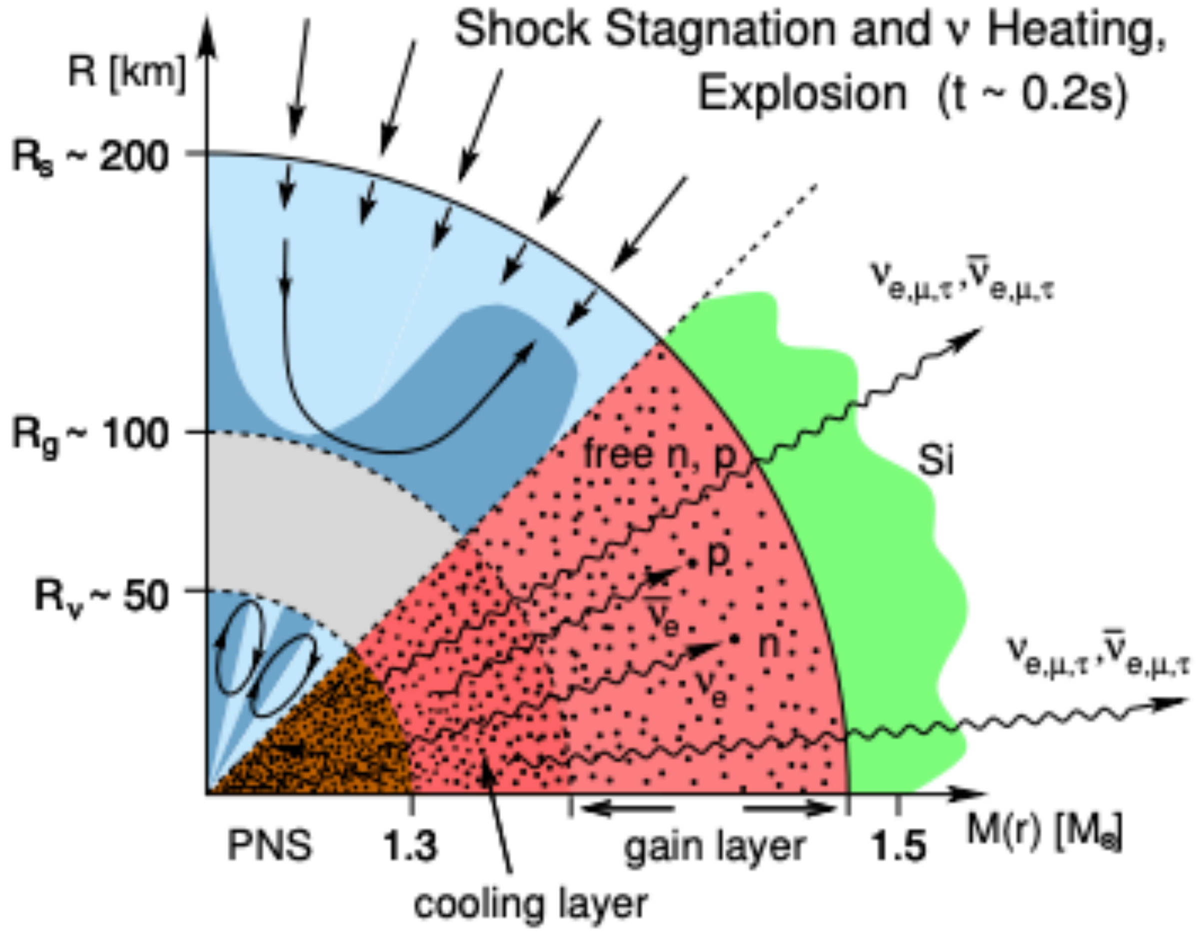


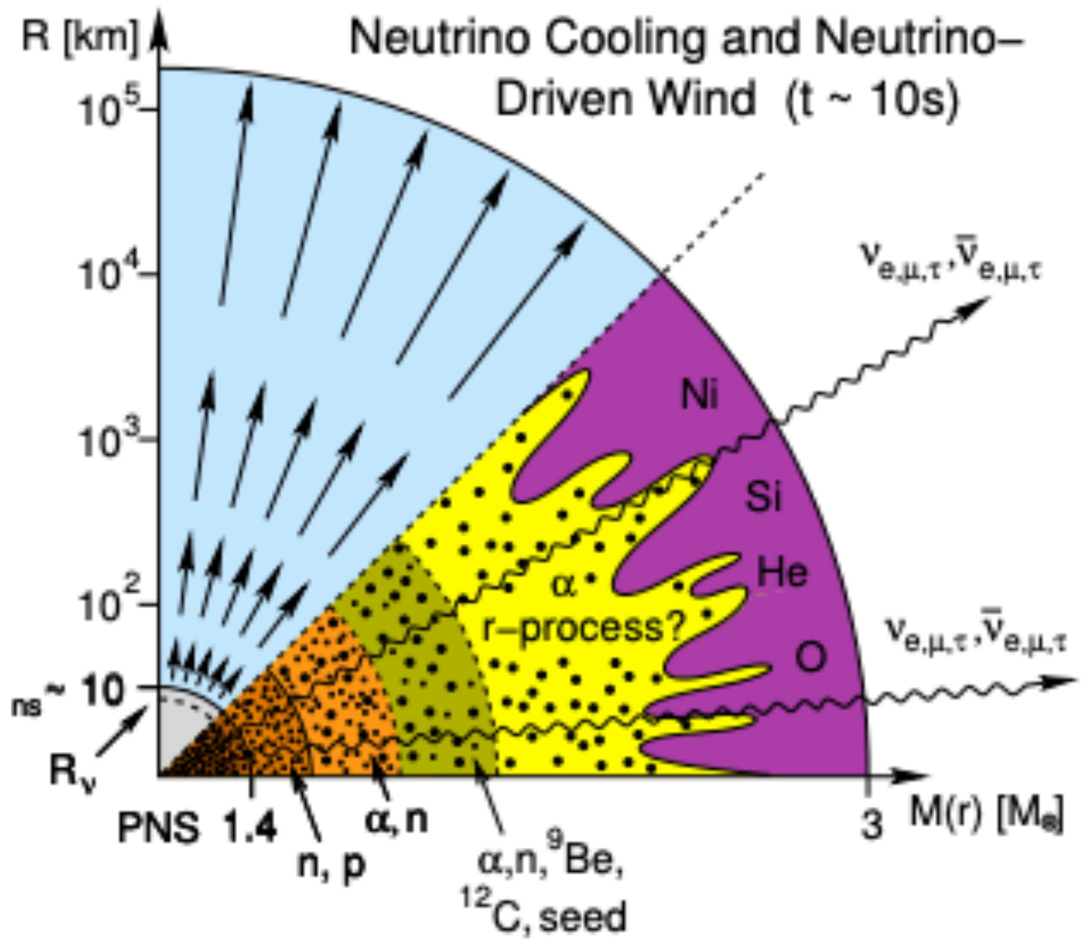


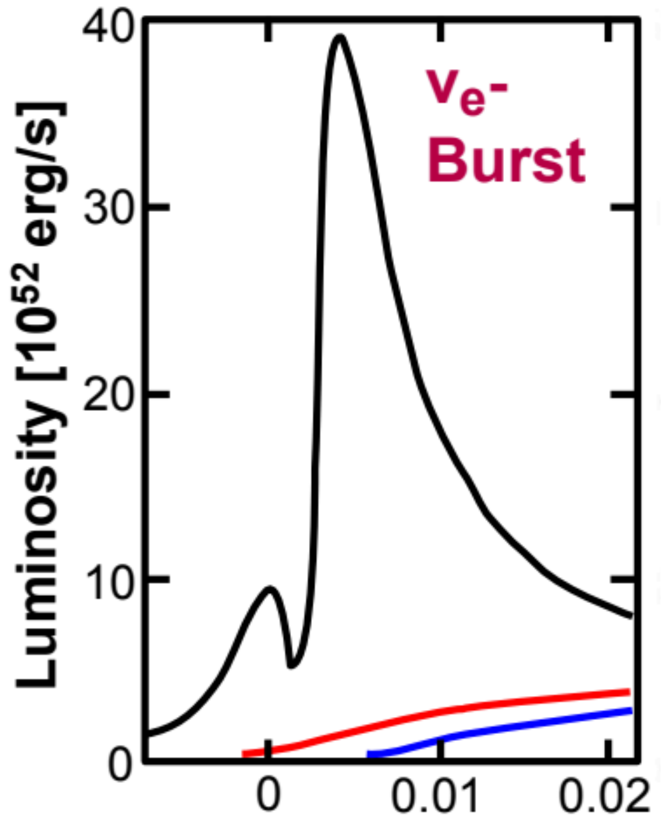
~99% of the gravitational binding energy released in the form of neutrinos with energies of a few tens of MeV over a timescale of a few seconds

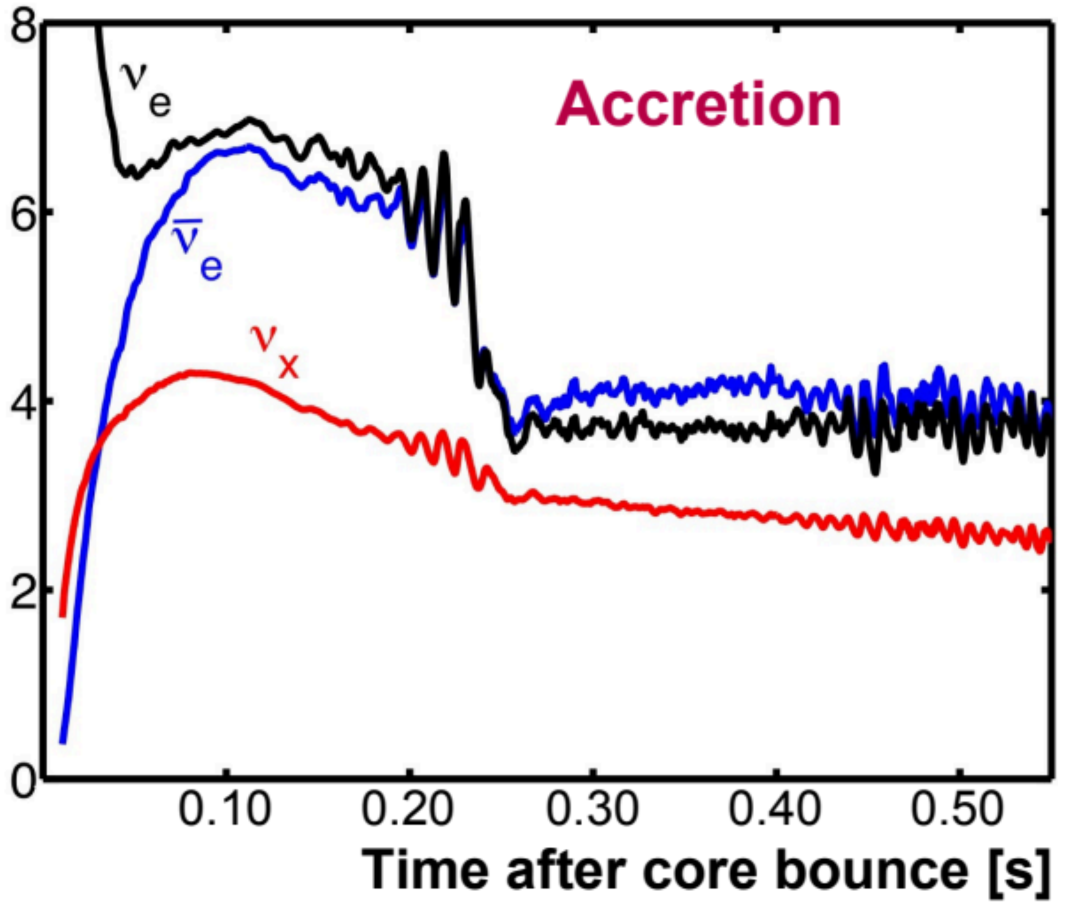
Supernova explosion phases and neutrino emission

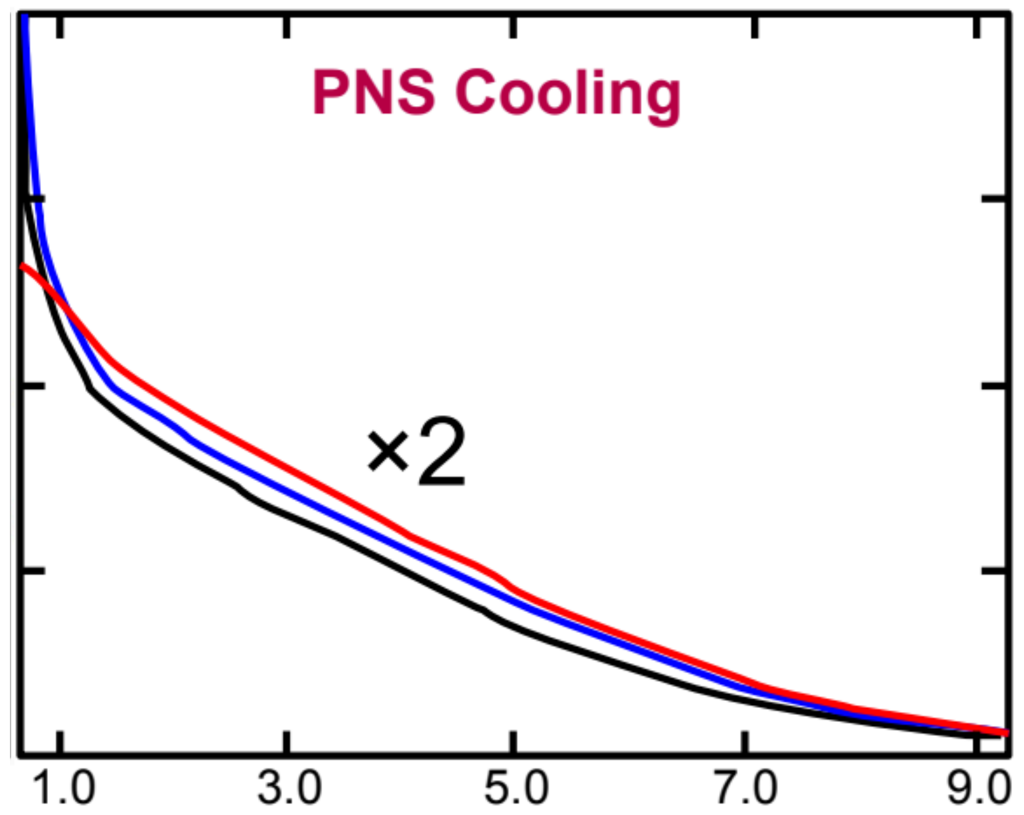












- Iron photodissociation
- Electron capture
- Electron neutrino take few ms to escape

- nu and anti nu of all flavors are thermally produced

- Few differences between fluxes and spectra
- The luminosity decreases exponentially with a decay time scale of seconds

Janka H.-T., in: Handbook of Supernovae (2016); arXiv:1702.08713

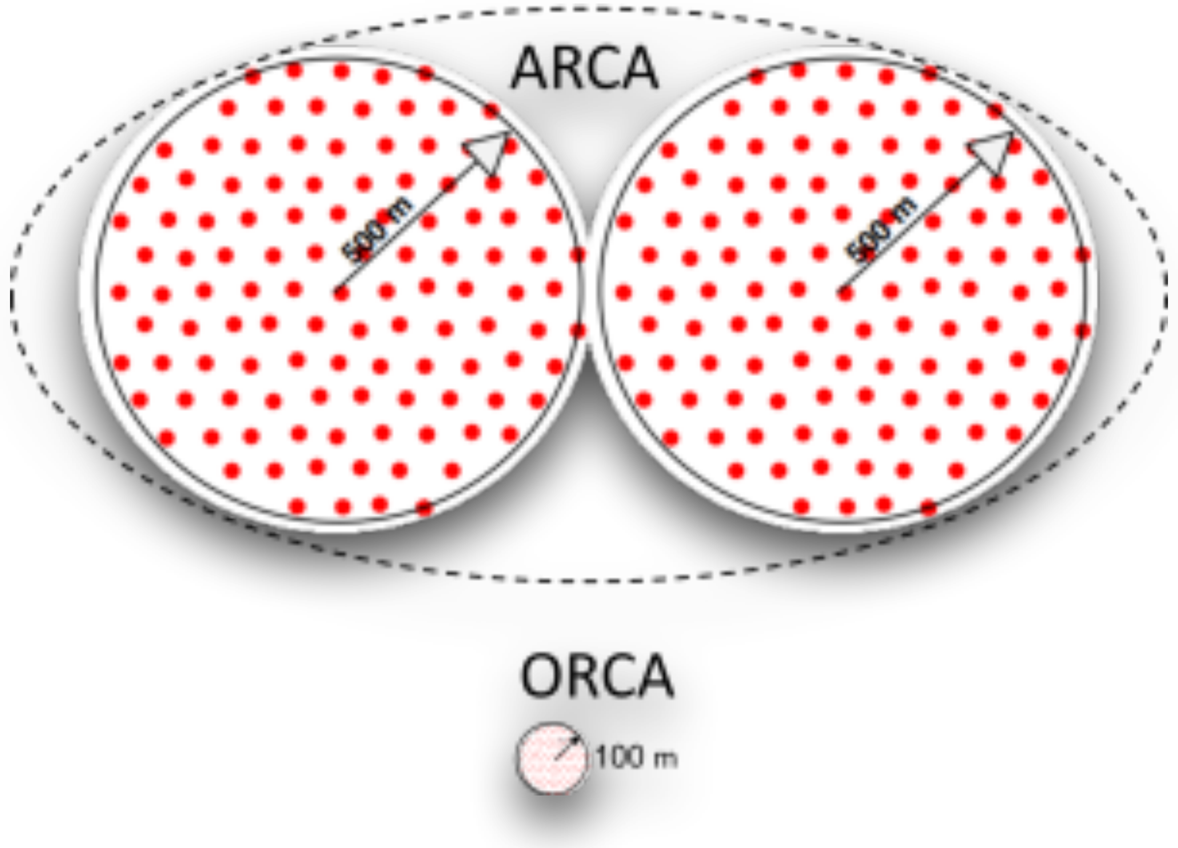
KM3NeT *Cubic Kilometre Neutrino Telescope*

KM3NeT Collaboration: 2 sites

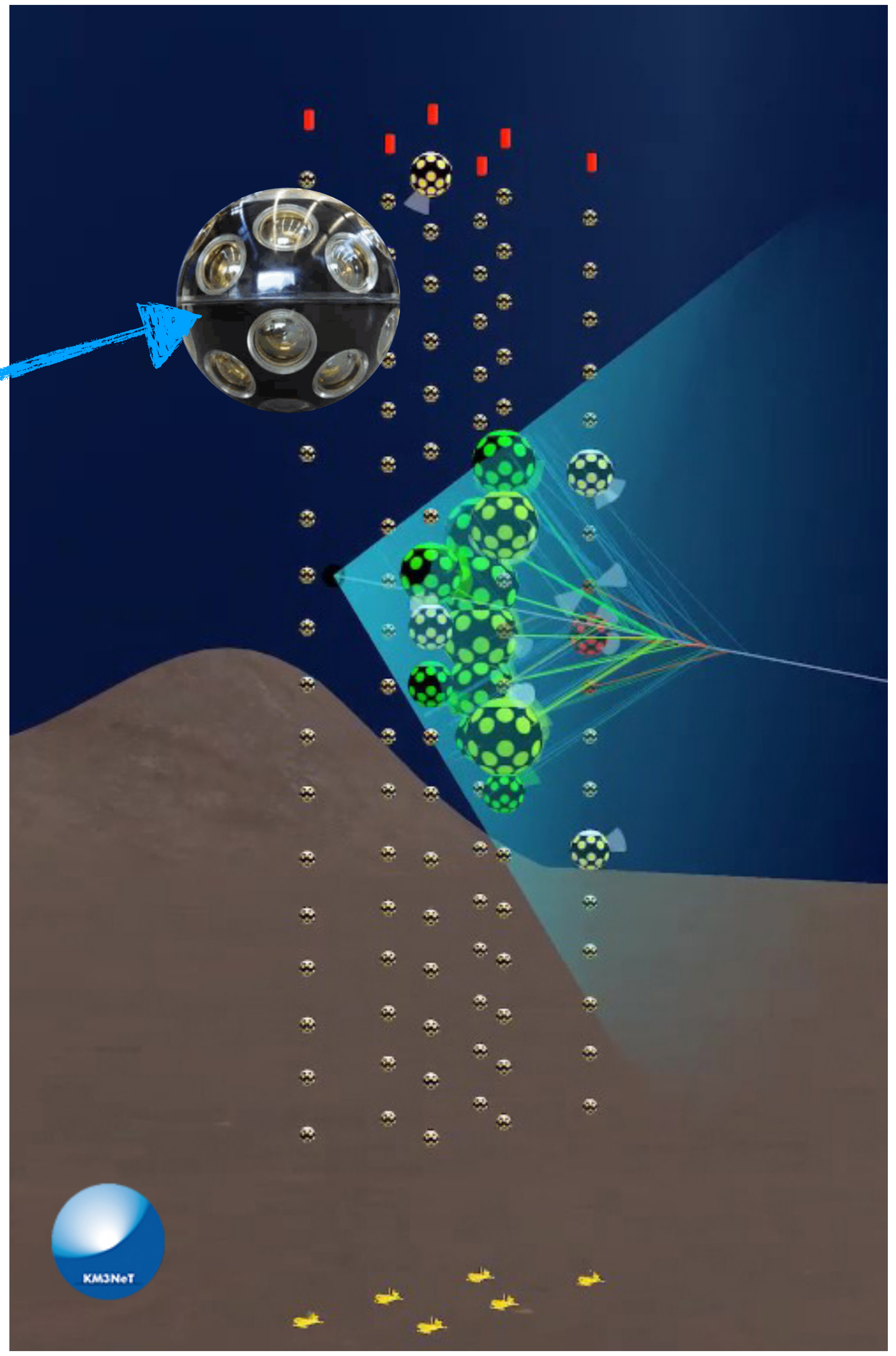
Cherenkov detectors under construction in the Mediterranean sea

ORCA:(in France)
115 strings
18 Digital Optical Modules / string with 9 m spacing
Depth of about 2500 m
1-100 GeV energy range
Main goal: Neutrino oscillations

ARCA:(in Italy)
230 strings (115 for each blocks)
18 Digital Optical Modules per string with 36 m spacing
Depth of about 3500 m
TeV-PeV energy range
Main goal: High energy astrophysics

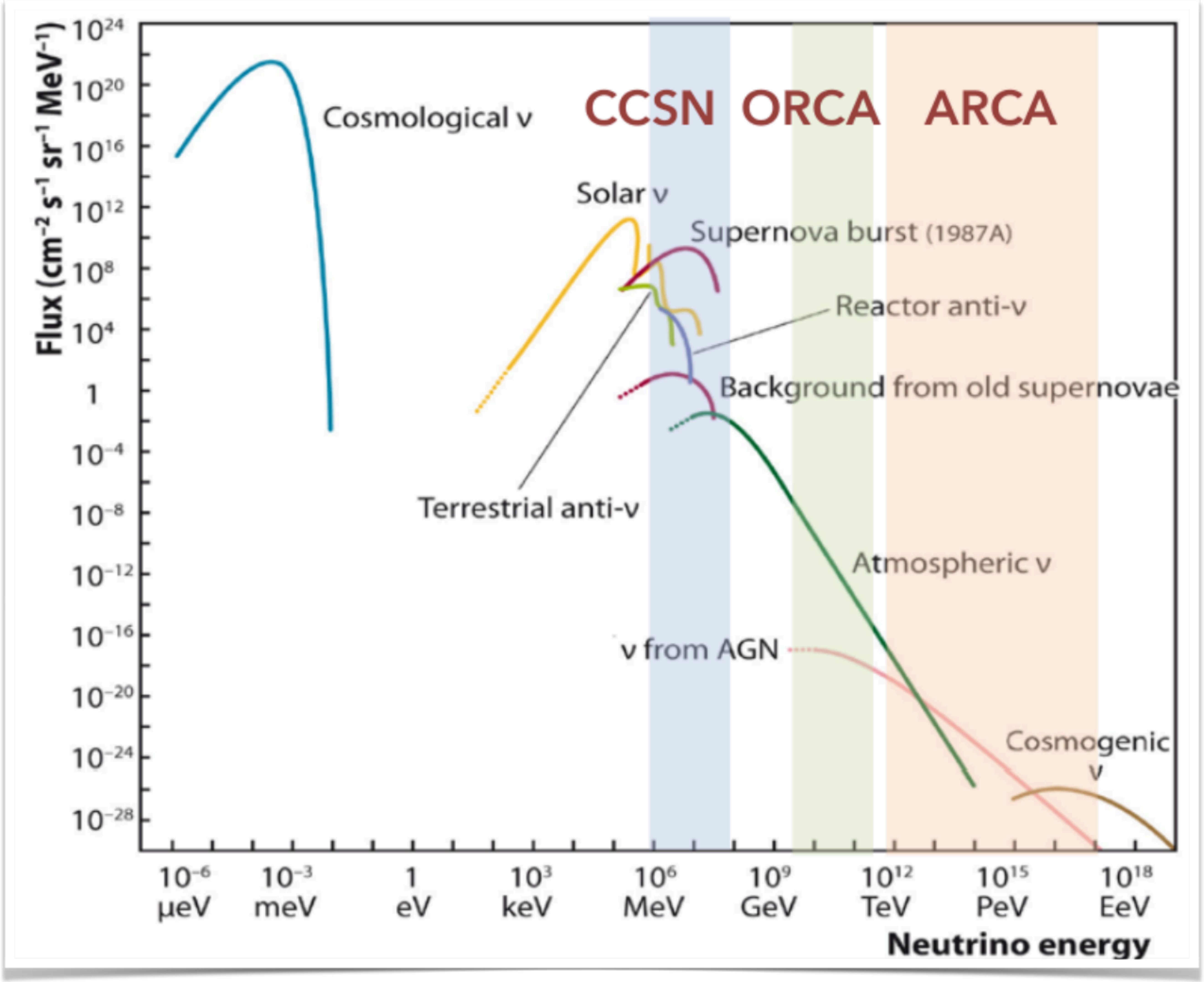


31 PMTs/DOM
PMT: photomultiplier
DOM: Digital Optical Module



The **detection is** based on the measurement of cherenkov light emitted by the product particles

Core collapse Supernovae neutrino detection



CCSN: Core collapse supernova

KM3NeT detectors are optimized for the detection of atmospheric neutrinos in the **GeV** range (KM3NeT-ORCA) and cosmic neutrinos in the **TeV-PeV** domain (KM3NeT-ARCA).

Environnemental noise in KM3NeT (MeV scale):

- 40K decay in sea water
- Bioluminescence
- Atmospheric muons

Core collapse supernovae neutrino energy range:

1-100 MeV

KM3NeT is not optimized to detect MeV neutrinos from CCSN

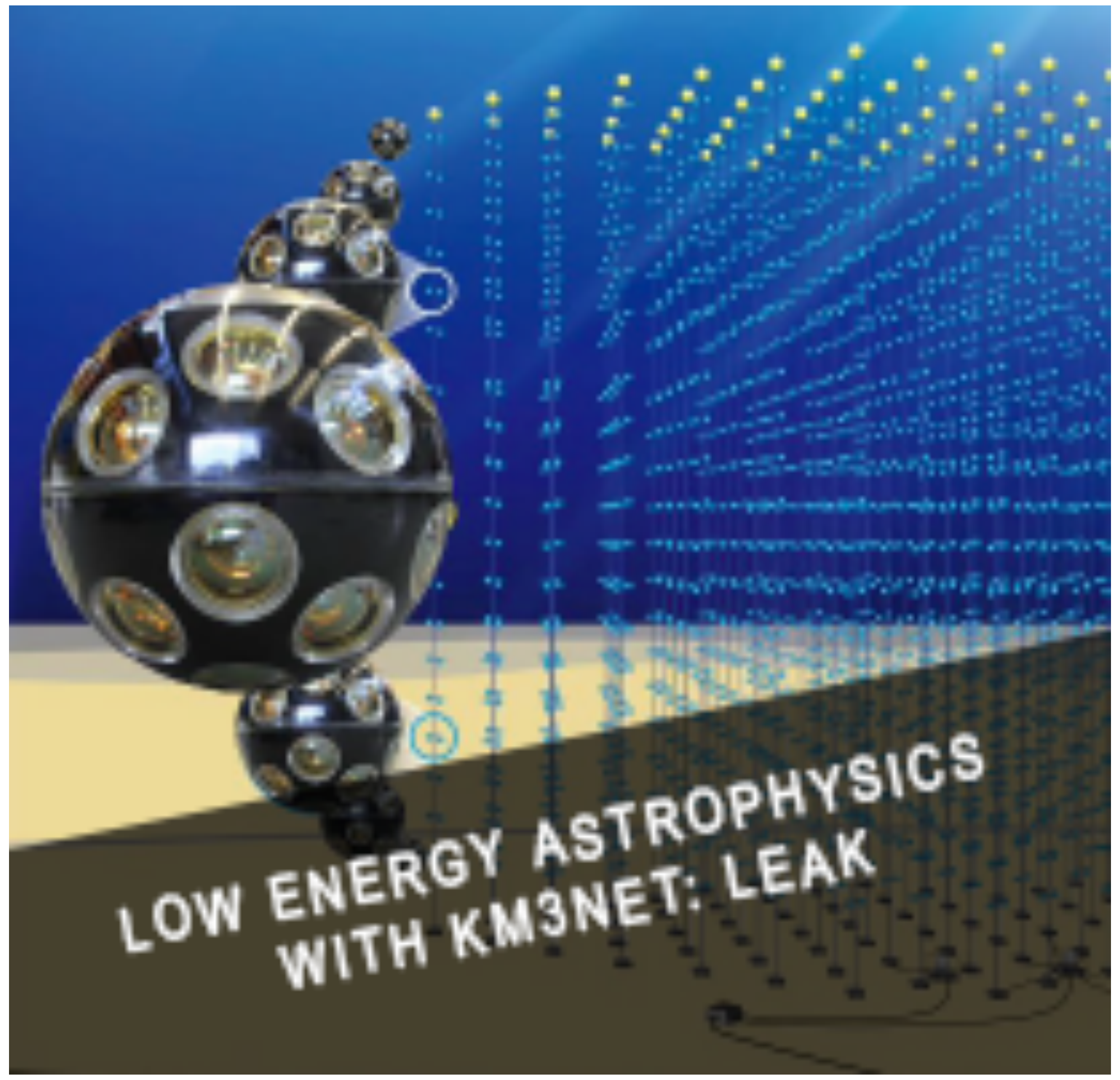
Main interactions in water Cherenkov detectors at low energy:

IBD interaction $\bar{\nu}_e + p \rightarrow e^+ + n$

The Exploratory project: **Low Energy Astrophysics with KM3NeT** (LEAK)

Low Energy Astrophysics with KM3NeT (LEAK)

Experts in core collapse supernova physics and members of the KM3NeT collaboration study the capability of the KM3NeT neutrino telescopes (optimized for GeV-PeV neutrinos) to detect MeV neutrino signal from the next close-by core collapse supernova.



Methods:

- Exploit the multi-PMT technology of optical modules
- Catalogue of neutrino spectra from **in-house supernova simulations**
- **Combine neutrino spectra** expected at KM3NeT, DUNE, DarkSide-20k

Current status

- **KM3NeT analysis:** identify neutrinos using dimensionality reduction on single-DOM observables
  Presented by G. de Wasseige at VIVNT 2021

- **Experimental synergies between KM3NeT, DUNE and DarkSide detectors:**
  - Study the neutrino mass ordering and the progenitor mass for a supernova around the galactic center
  - Exploring the Impact of magnetic field on CCSN neutrino observation
  Presented by M. Bendahman at ICRC 2021 and Neutrino 2022

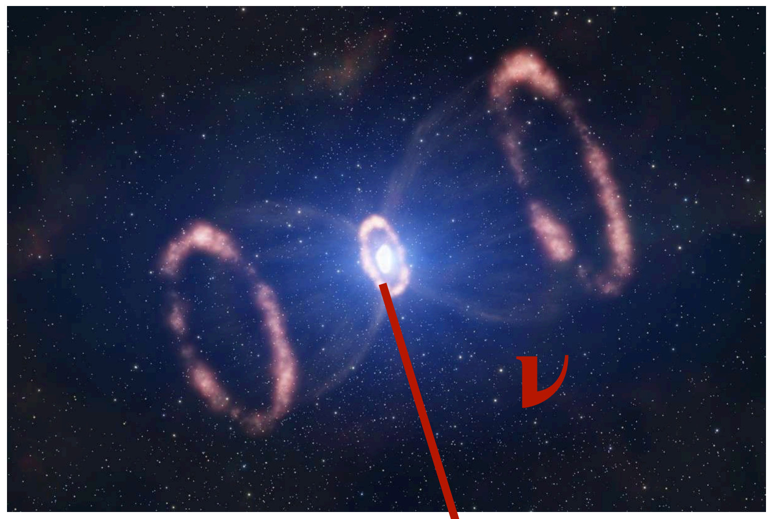
Current results of LEAK

- Identify low-energy neutrinos in KM3NeT using single-DOM observables
- Multi-detector analysis : Neutrino mass ordering and progenitor mass
- Exploring the Impact of magnetic field on CCSN neutrino observation

CCSN neutrino detection with KM3NeT

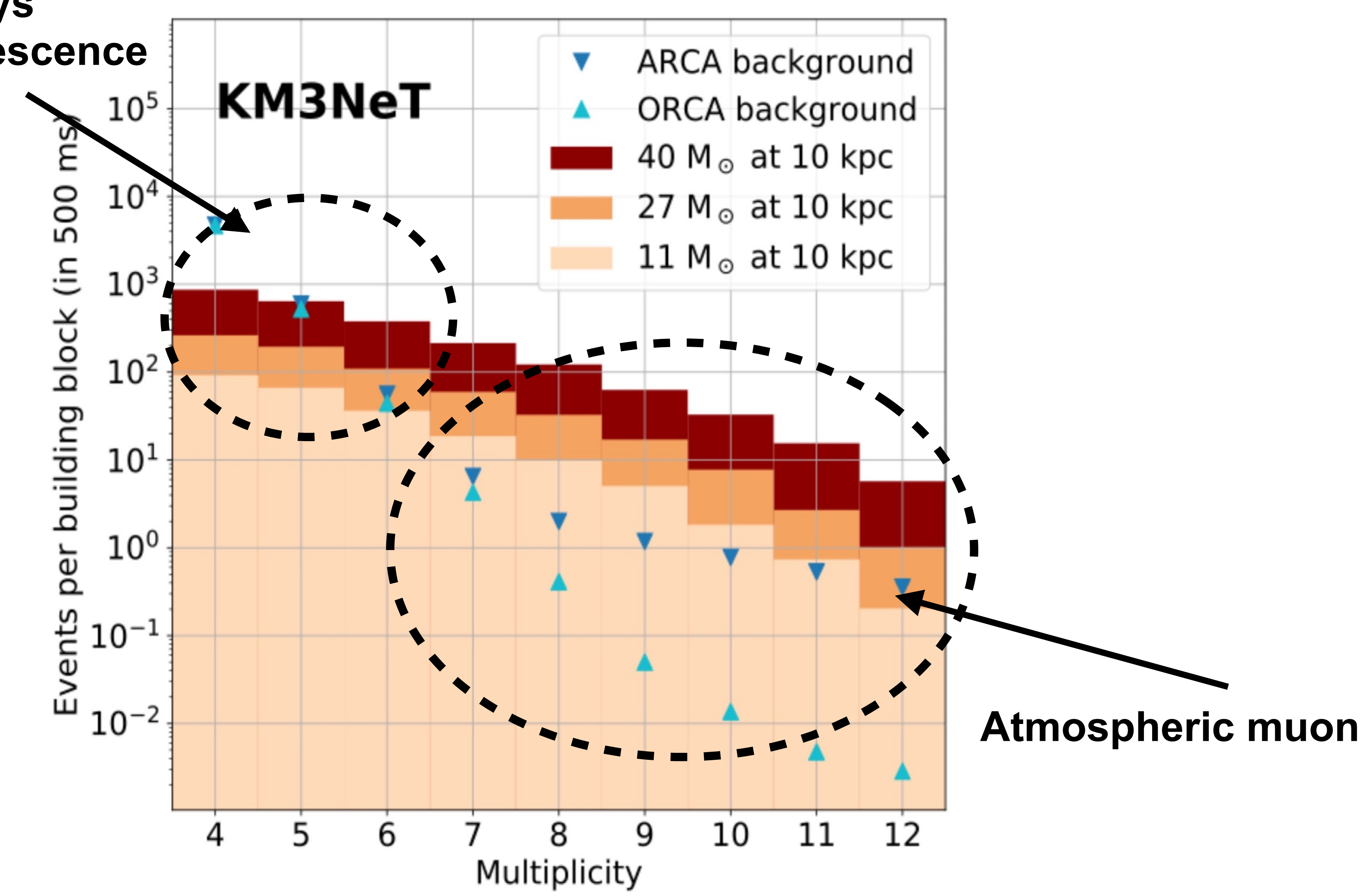
CCSN neutrino detection at MeV range with KM3NeT

- Low energy neutrinos and high background due environnemental noise
- The MeV neutrino signals from the supernovae can be identified by the multi-PMT technology of optical modules



The **MeV** neutrino signals from the Supernovae can be identified by the **multi-PMT technology** of optical modules

Combining: background + filtering and simulated signal events

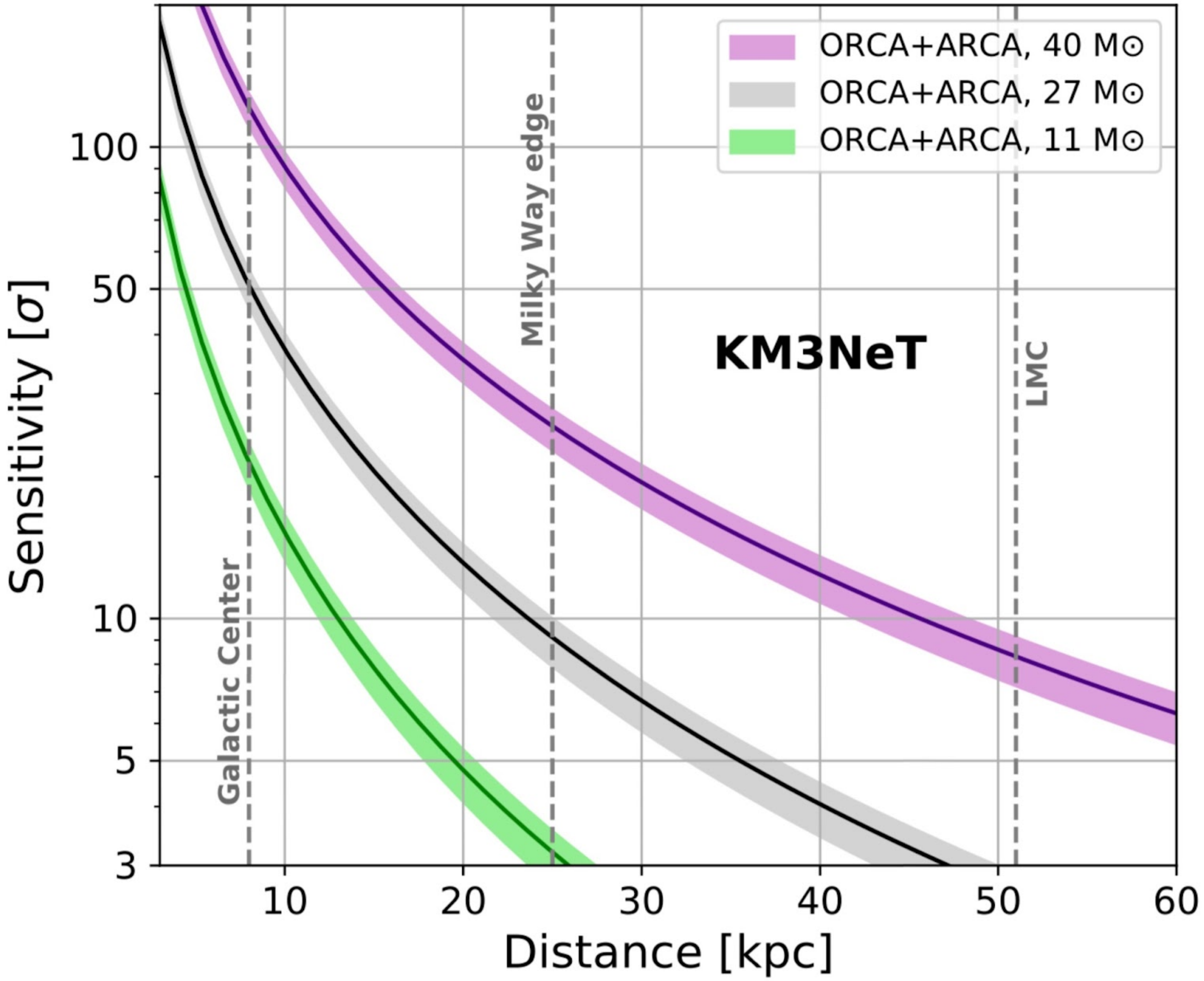


https://arxiv.org/pdf/2102.05977.pdf

Multiplicity: The number of coincidence in a Digital optical module in 10 ns

Results: KM3NeT detection sensitivity

- ORCA + ARCA combined sensitivity of 5 σ at 25 kpc for a 27 M⊙ progenitor.
- ORCA sensitivity above 5 σ at the Galactic Center for a 11 M⊙ progenitor.



https://arxiv.org/pdf/2102.05977.pdf

Identify neutrinos using dimensionality reduction on single-DOM observables

Motivation

- Preliminary investigations to determine whether KM3NeT could gain sensitivity in the 100 MeV to GeV energy range

Description of the adopted approach

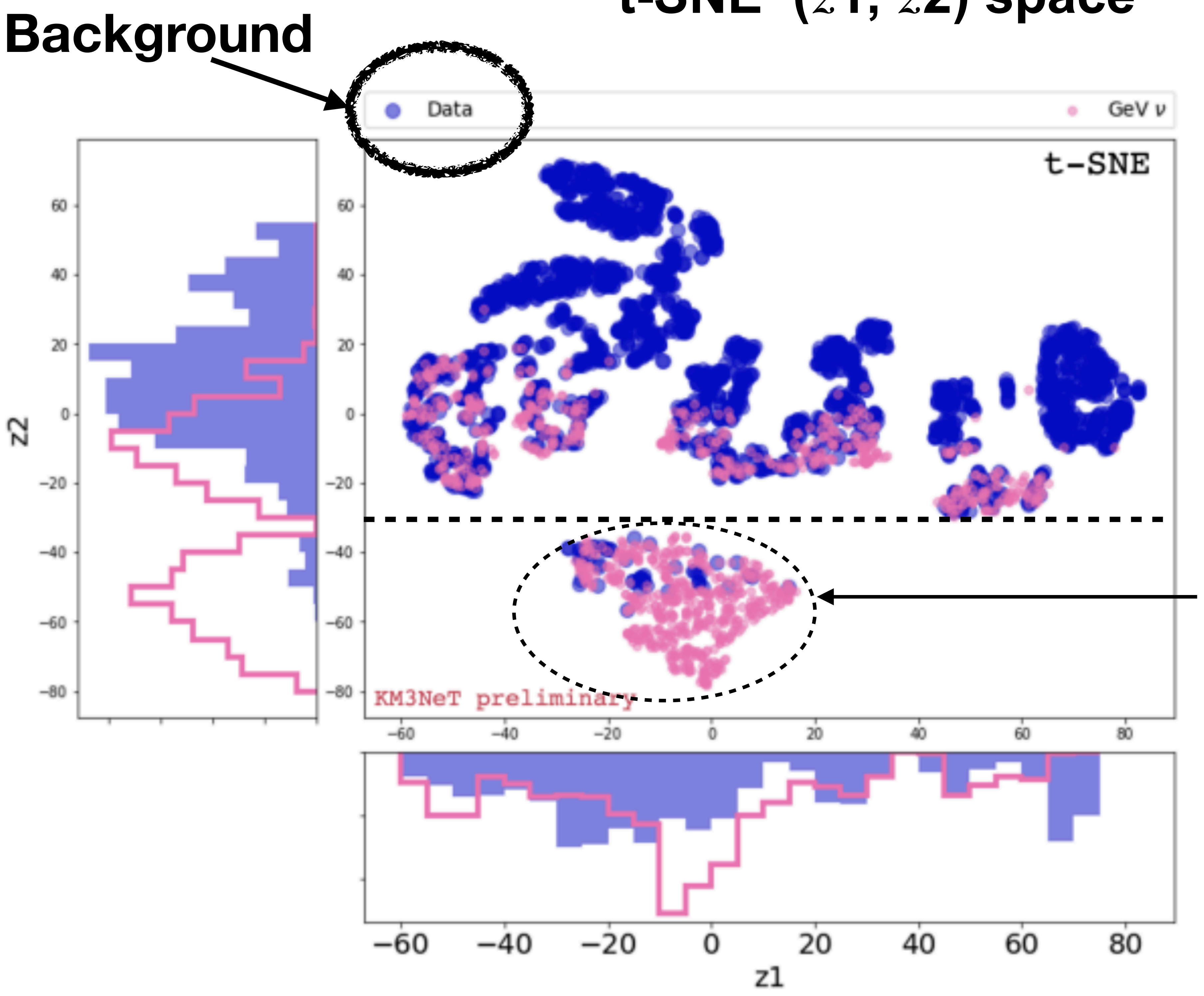
- Focus on the signature recorded on single DOMs
- Apply similar event selection criteria to ORCA and ARCA
- Build new variables based on the low-level observables
- Dimensionality reduction techniques

Number of hits recorded on the DOM

Mean position of the hits recorded on the DOM in the 10 ns

Time between consecutive hits

Distribution of data (blue) and sub-GeV neutrino (pink) events , t-SNE (z1, z2) space



50% of the GeV neutrino interactions and only 2% of the minimum data.

G. de Wasseige, VIVNT 2021, https://arxiv.org/pdf/2108.07062.pdf

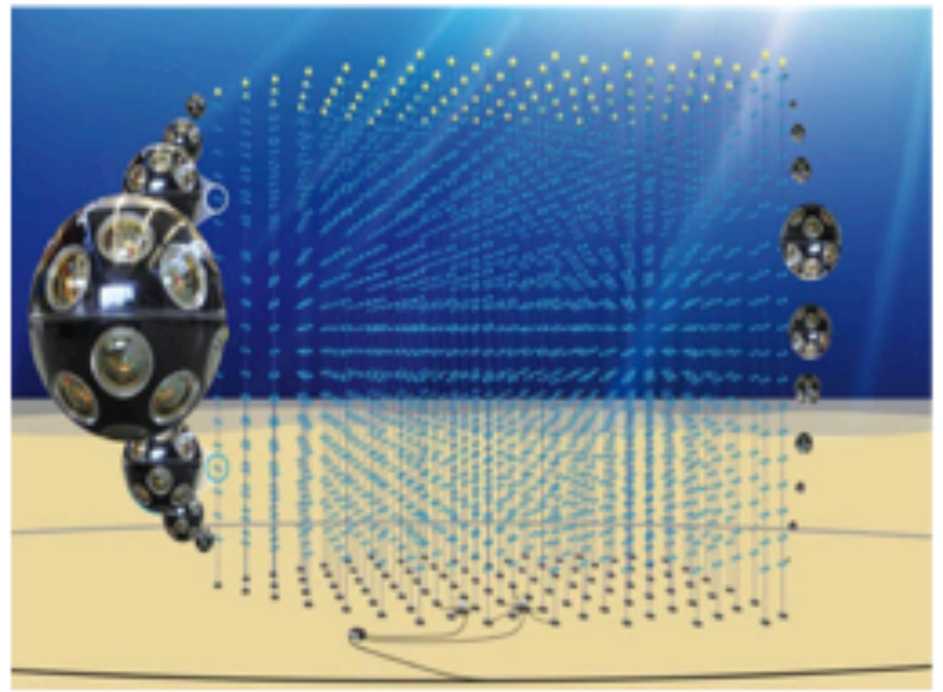
Islands are observed in the data distribution where a fraction of the GeV neutrinos is isolated from the data

Applicable to MeV supernova signal-> Applying other machine learning techniques

Multi-detector approach for enhancing the scientific output

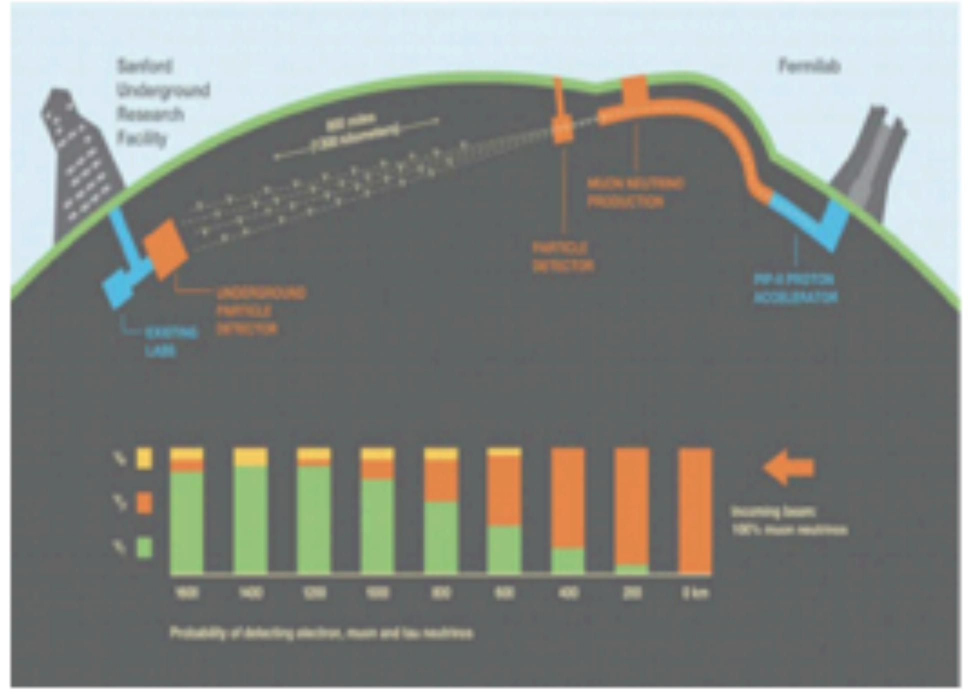
Goal: Set constraints on the models and discriminate between different supernova models

KM3NeT



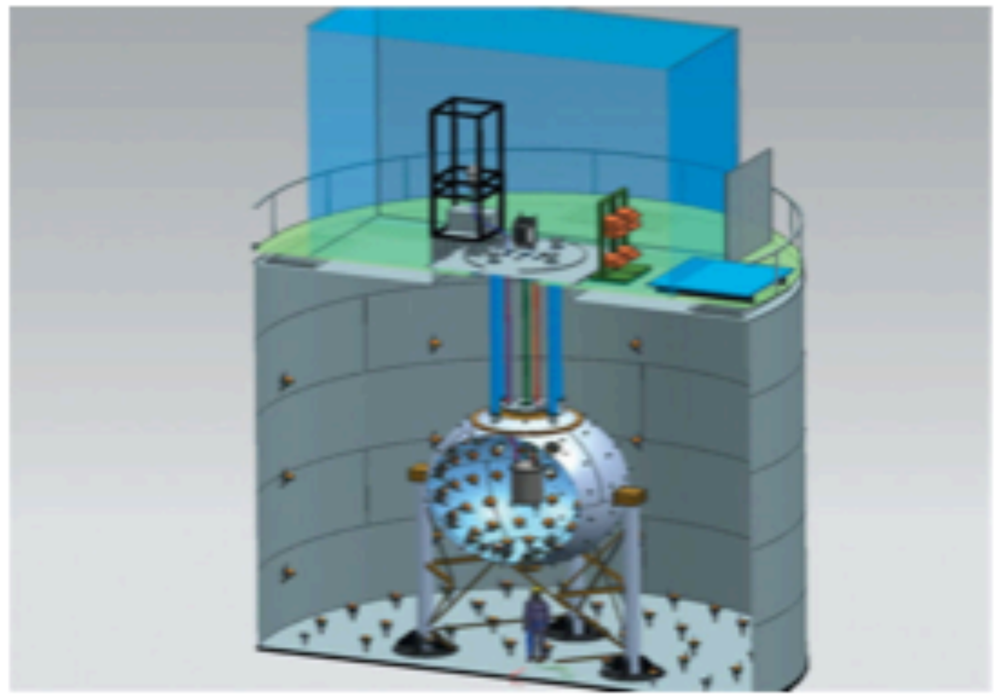
Water Cherenkov detector
Sensitive to anti nue
Effective mass = 100 kt

DUNE



Argon detector
Sensitive to nue
Effective mass = 40 kt

DarkSide



Dark matter (argon) detector
Sensitive to all nu flavors
Effective mass = 0.02 kt

Determine the neutrino mass ordering and estimate the mass of the progenitor

- Ordering dependence study for 11 Msun and 27 Msun
- Mass dependence study for normal and inverted ordering

Multi-detector approach for enhancing the scientific output

1. Estimation of the CCSN neutrino event rate in the detector as the product of the differential neutrino flux, the cross section, the detextion efficiency and the detector volume.

2. Light curve comparison using ratios and asymmetries between the number of neutrinos predicted in KM3NeT, DUNE and DarkSide.

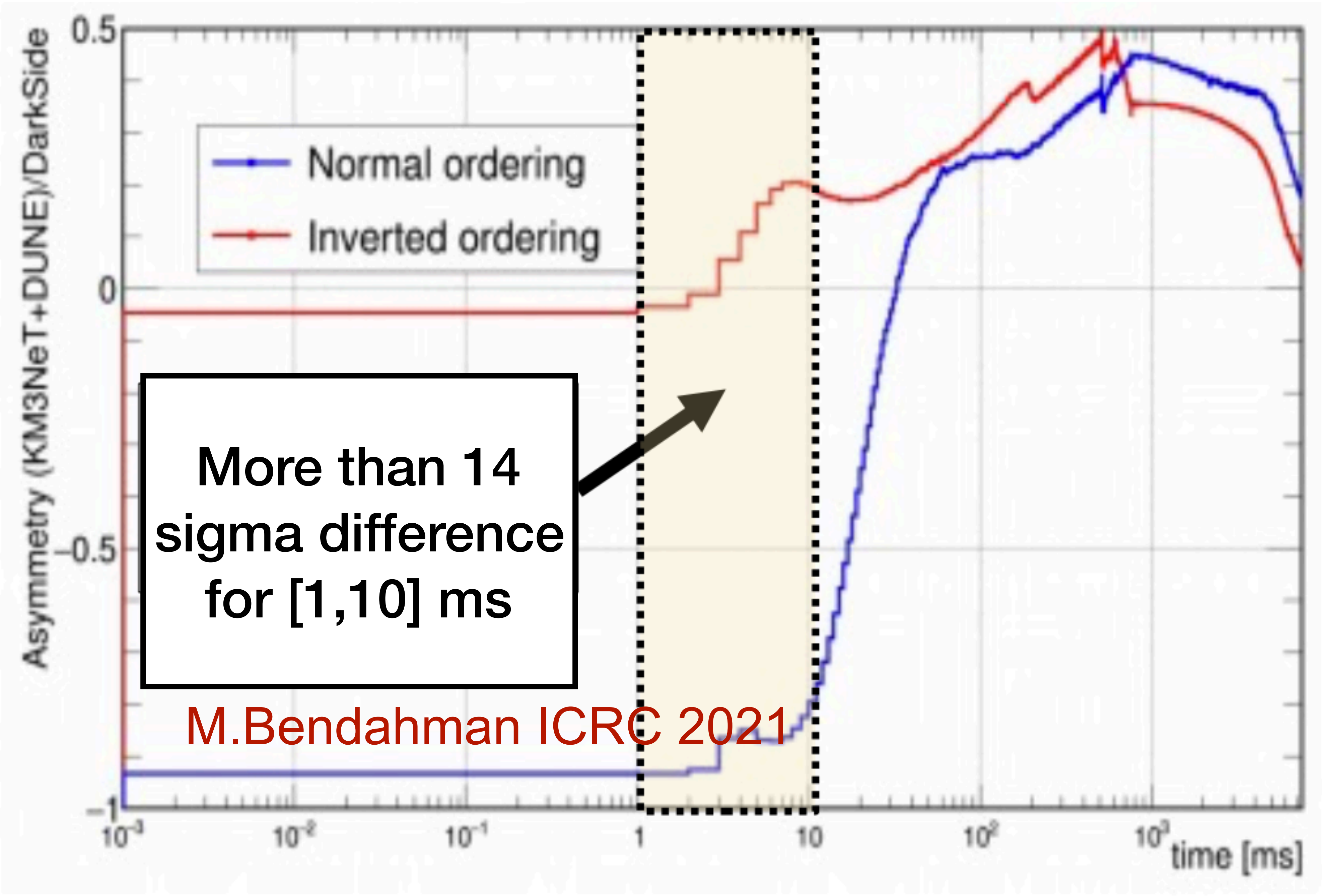
- $\mathbf{Ratio = NdetA/NdetB}$
- $\mathbf{Asymmetry = (NdetB - NdetA)/(NdetB + NdetA)}$

3. Statistical methods for model discrimination by computing the optimal time windows in milliseconds to estimate the significance of the difference between the testing hypotheses:

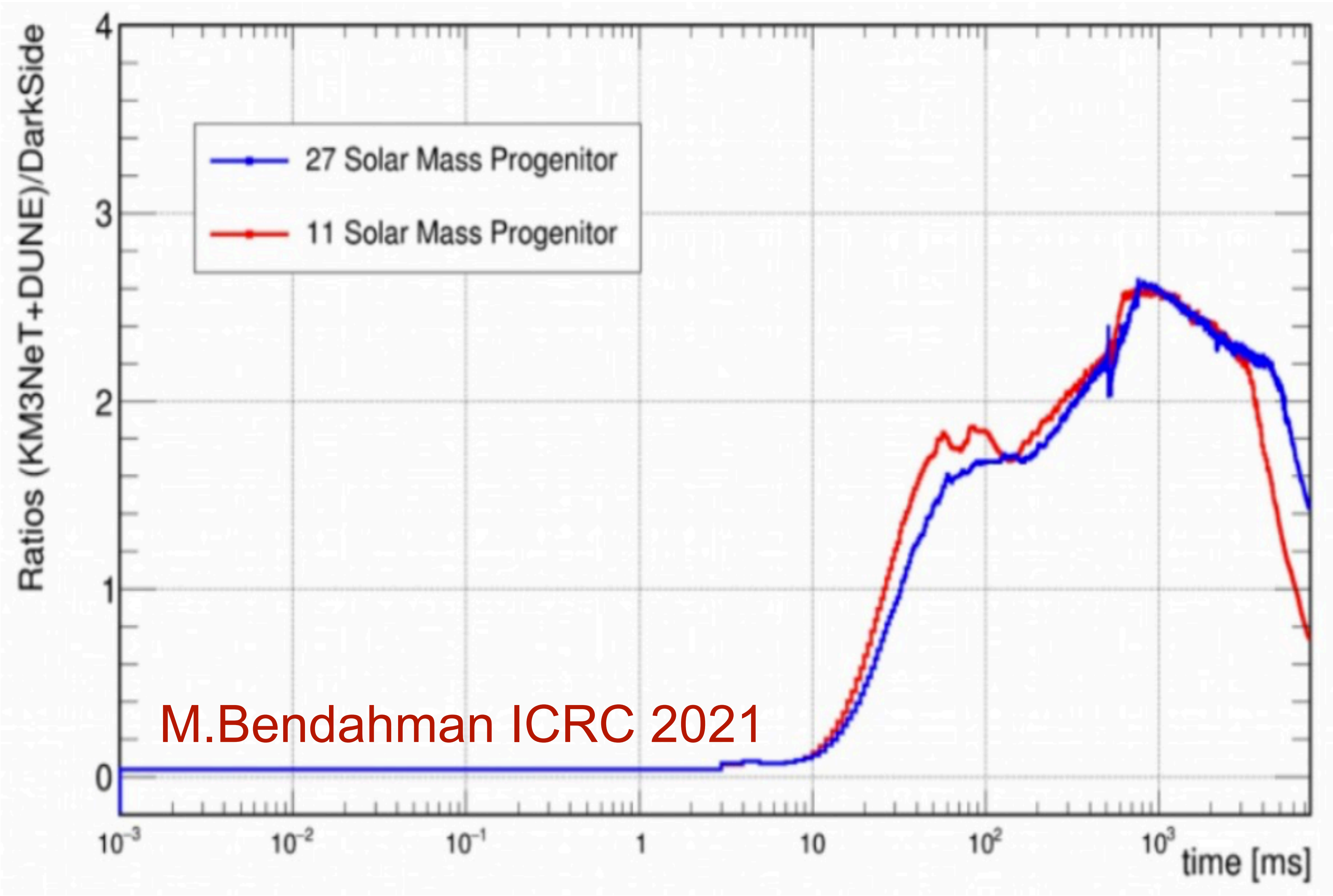
- Loop over time throughout the duration of the light curves.
- Calculate the difference between two hypotheses.
- Select the time window giving the highest difference between two hypotheses.

Multi-detector approach for enhancing the scientific output

Neutrino mass ordering



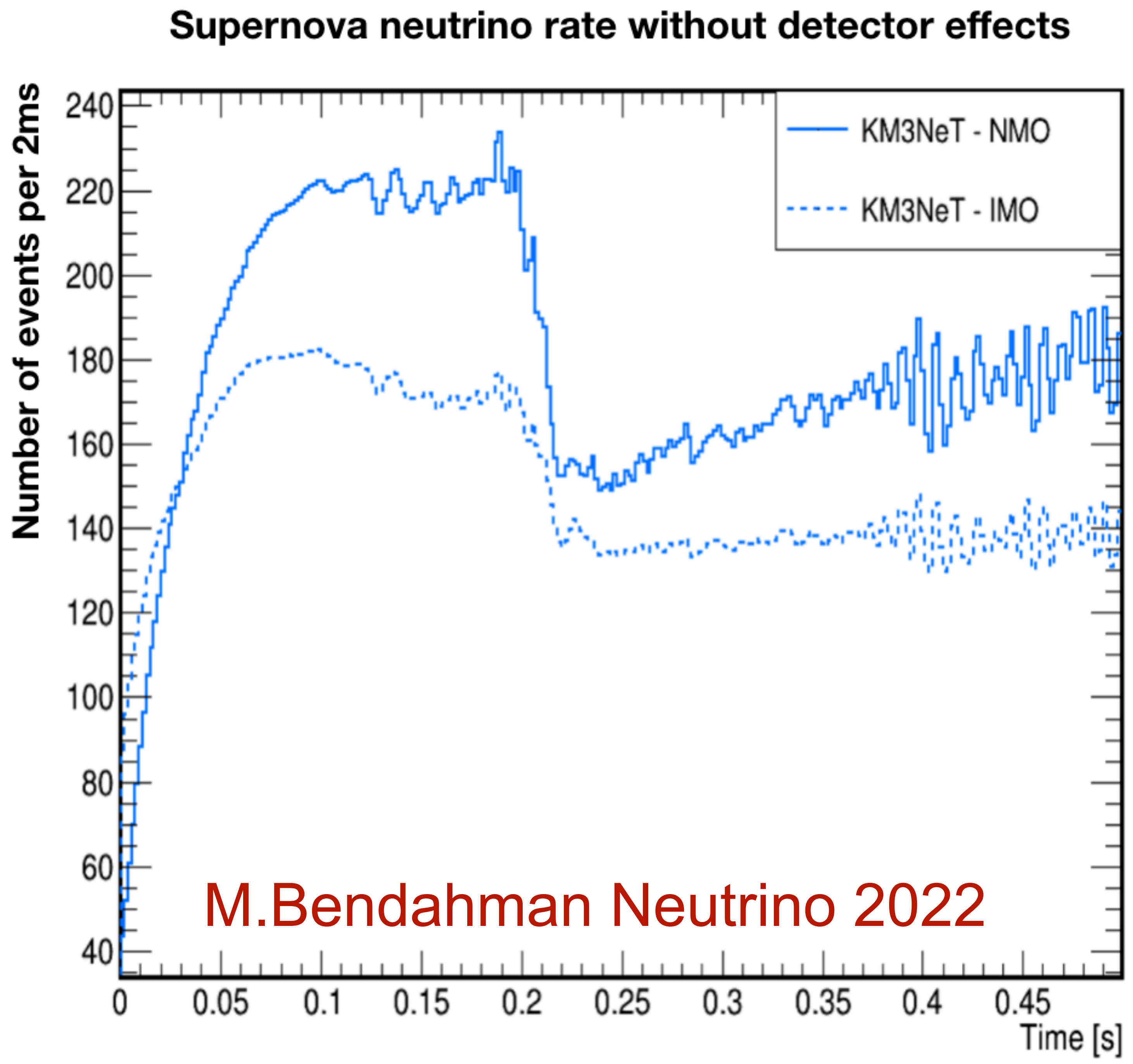
Progenitor mass



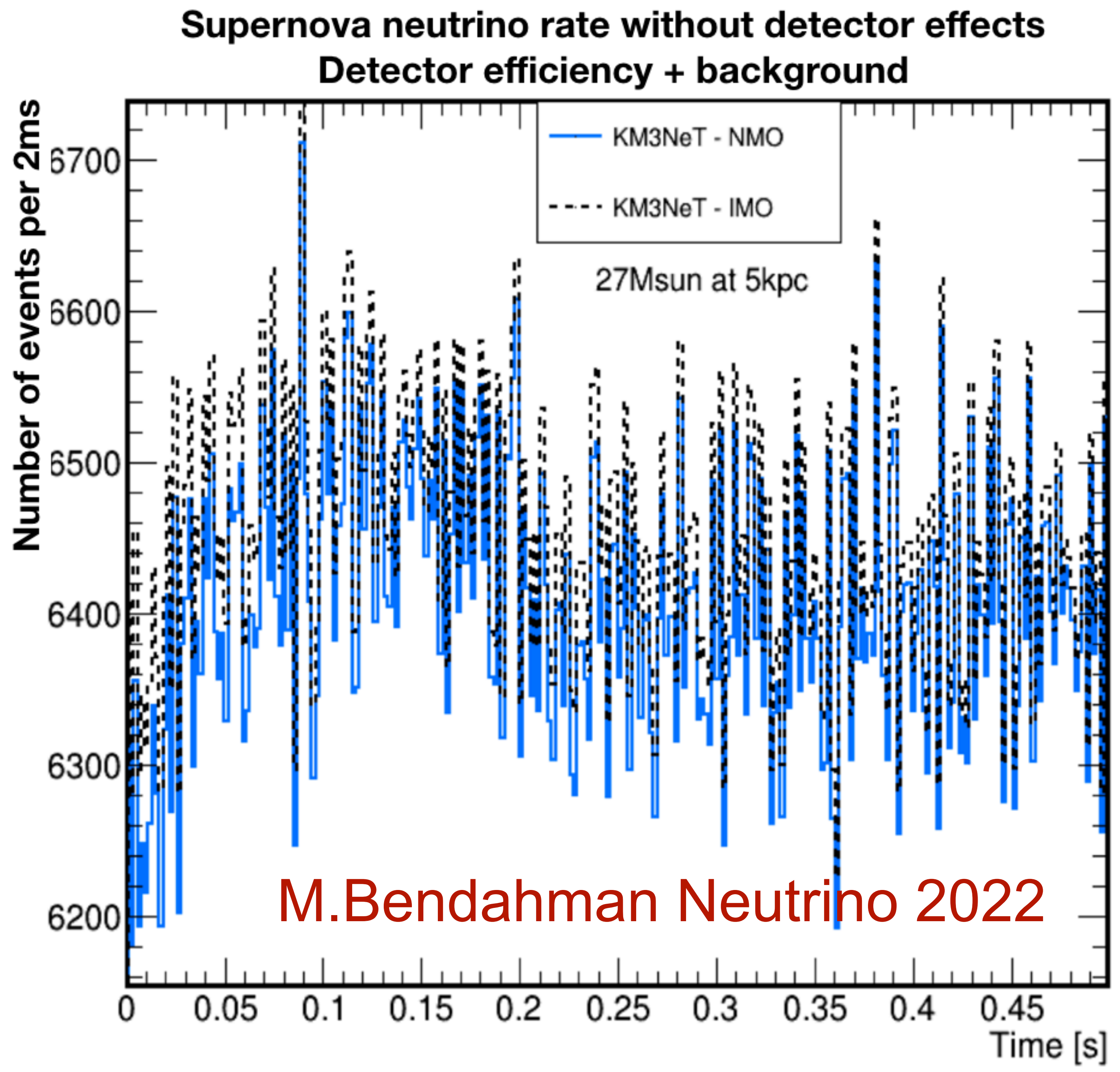
- **Significant difference between neutrino rates for normal and inverted mass orderings at 10kpc**
- **Discrimination at 1.5 sigma for progenitor mass study at 10kpc**

Adding detector effects and background

- Light curve production using SNEWPY https://github.com/SNEWS2/snewpy
- Tambora Model
- 27 solar mass progenitor at 5kpc from the source
- 2 building blocks of KM3NeT are considered in this study.



Light curves + Poissonian background + Detector effects



- **To obtain and analyze realistic light curves, the detector effects computed for multiplicity >=2 are added to the plot in the left, the poissonian background with a mean = 570 kHz is also added.**
- **A statistical approach based on the computation of the mean difference between 2 neutrino rates in a given time window will be applied.**

Possibility to determine the neutrino mass ordering for galactic CCSNe

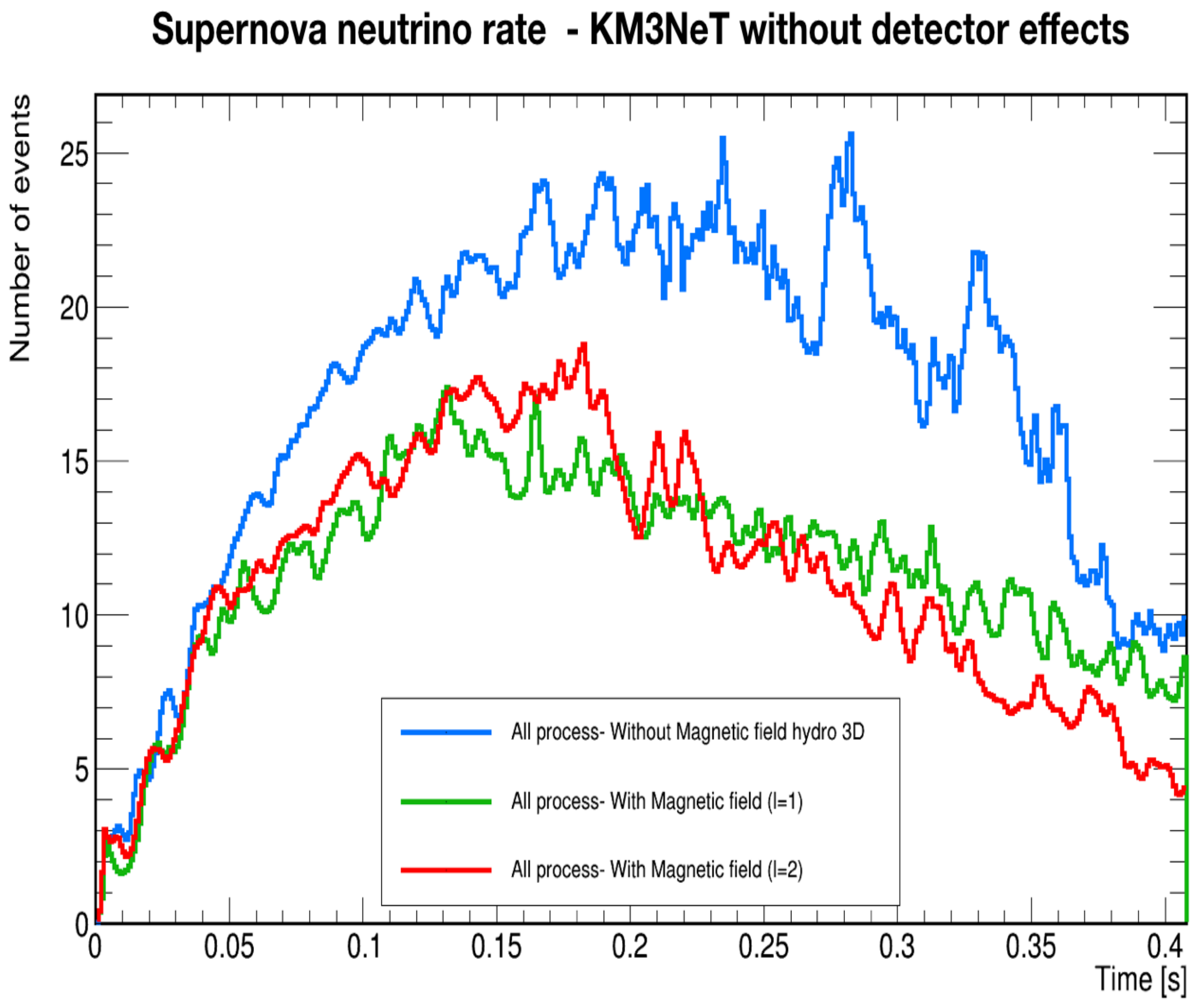
Exploring the Impact of Magnetic field on Core Collapse Supernova Neutrino Light Curves Detection

Motivation: Study the effect of the magnetic field on the neutrino light curves.

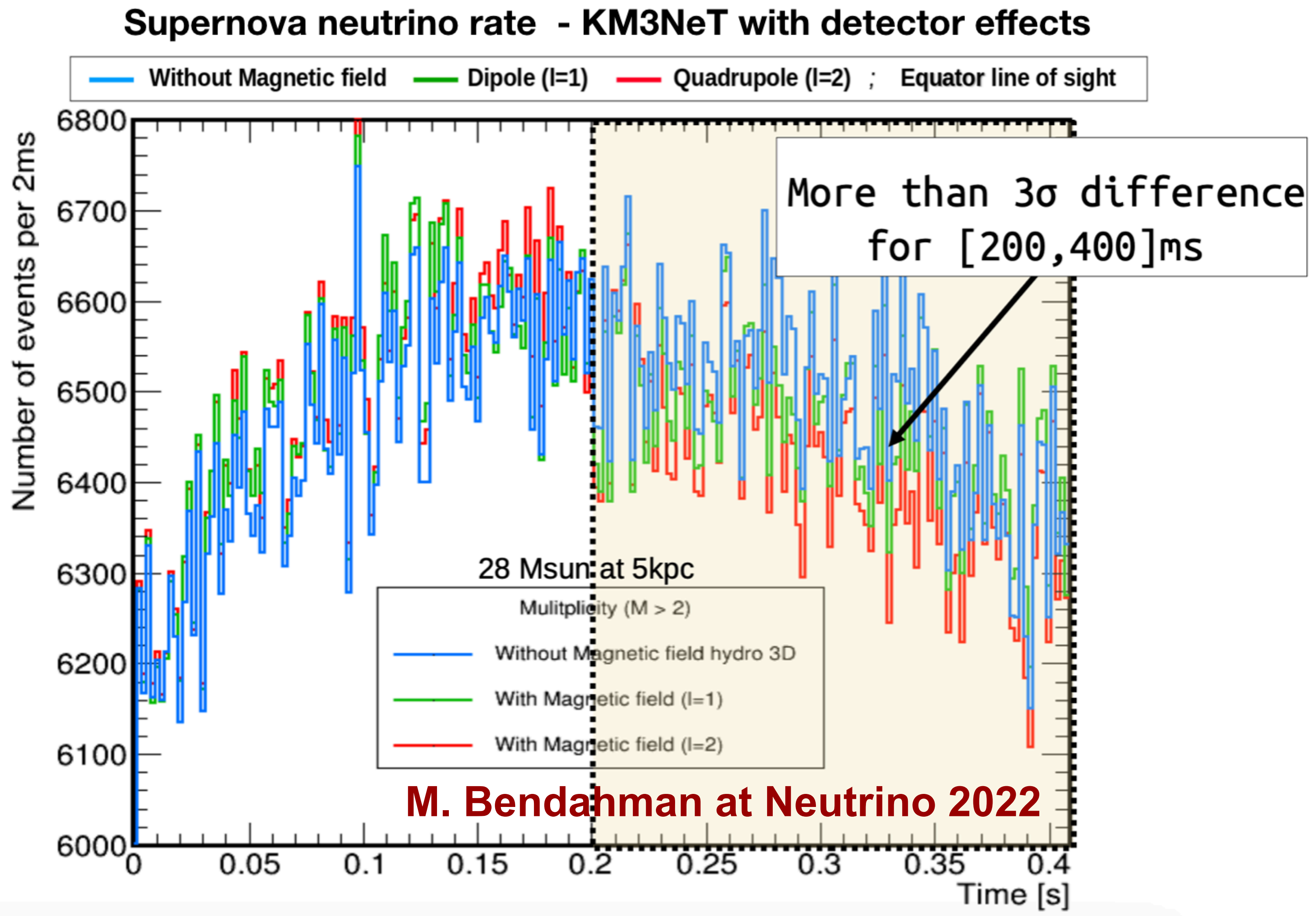
Compare between core-collapse supernova neutrino light curves considering different magnetic field topologies

Benchmark models for magnetic field impact study

- The core collapse supernova simulations start superimposing on the **hydrodynamic models (hydro 3D) by M.Bugli Matteo (AIM)** a magnetic field of **B0=10^12 G** considering dipole and quadrupole topologies (l=1 and l=2).
- Three neutrino species are considered: ve, anti ve , vx and anti ve were vx includes muonic and tauic flavors.
- All quantities are measured at 500 km from the center of the star for **a progenitor of 28.1 solar mass** with a core radius of r0 = 10^8 cm.
- The equator line of sight is considered.
- Light curve production at 5kpc from the source using SNEWPY https://github.com/SNEWS2/snewpy
- 2 building blocks of KM3NeT are considered in this study.



Light curves + Poissonian background + Detector effects



- A decrease in neutrino rate is observed in the presence of magnetic field at the equator line of sight as predicted.

- The detector effects computed for multiplicity >=2 are added to the plot in the left, the poissonian background with a mean = 570 kHz is also added.
- More than 3σ difference is observed for the time window [200,400] ms.
- A statistical approach based on the computation of the mean difference between 2 neutrino rates in a given time window will be applied.

Impact of strong magnetic fields on neutrino rates visible at KM3NeT for CCSNe up to the galactic center

Conclusion

- Significant differences are estimated for mass ordering study at 10 kpc
- Discrimination at 1.5 sigma for progenitor mass study at 10 kpc
- From a galactic supernova, we can determine mass ordering
- The impact of magnetic field on the neutrino light curves is observed to be significant

Ongoing work:

- Study of hydrodynamic instabilities inside the supernova carried out at AIM
- Study of the impact of noise and detector acceptances on the results
- New KM3NeT analysis for low energies with the new single DOM observables