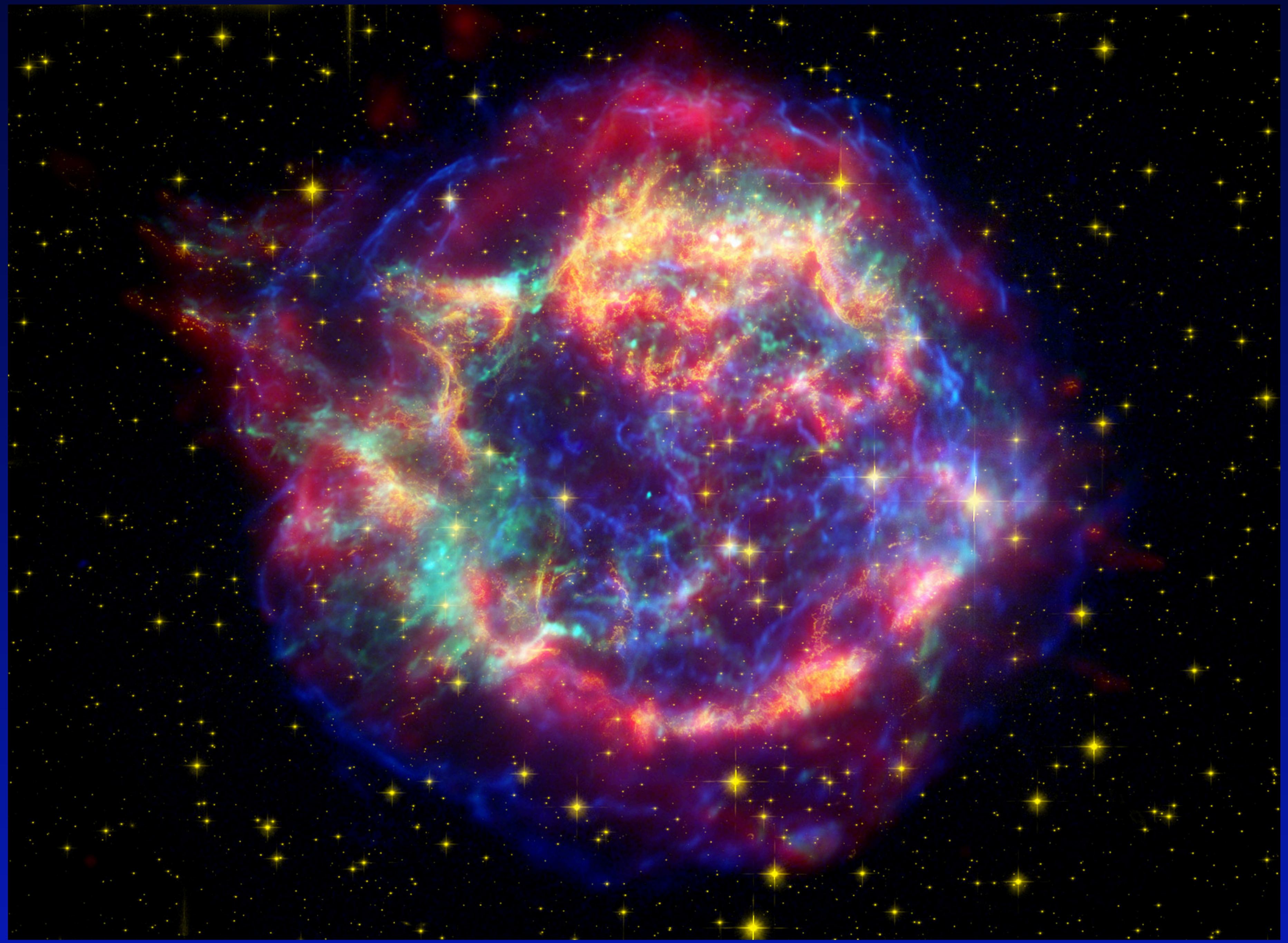
RICAP-22 Roma International Conference on AstroParticle Physics

Neutrinos from core-collapse supernovae at KM3NeT



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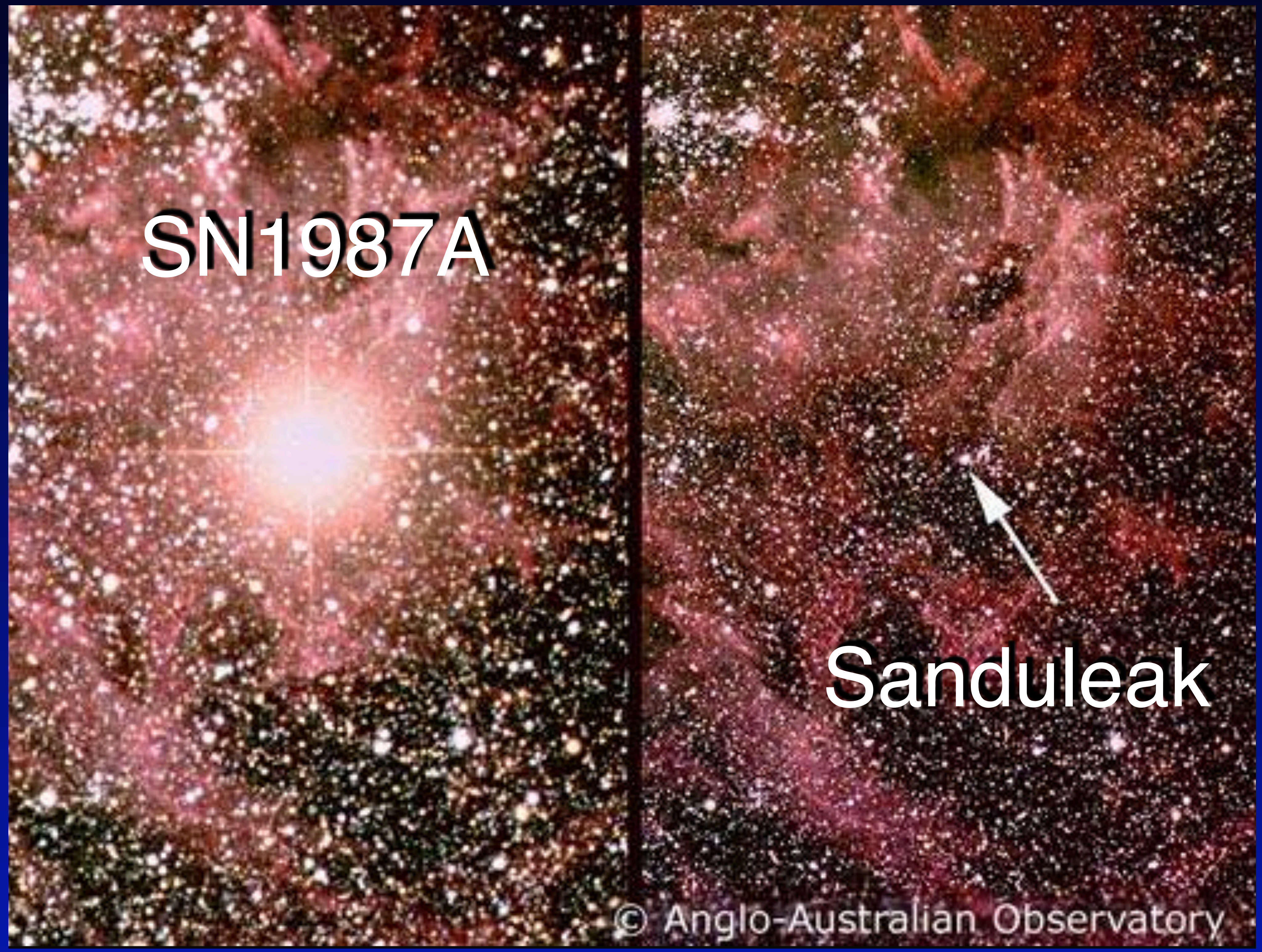
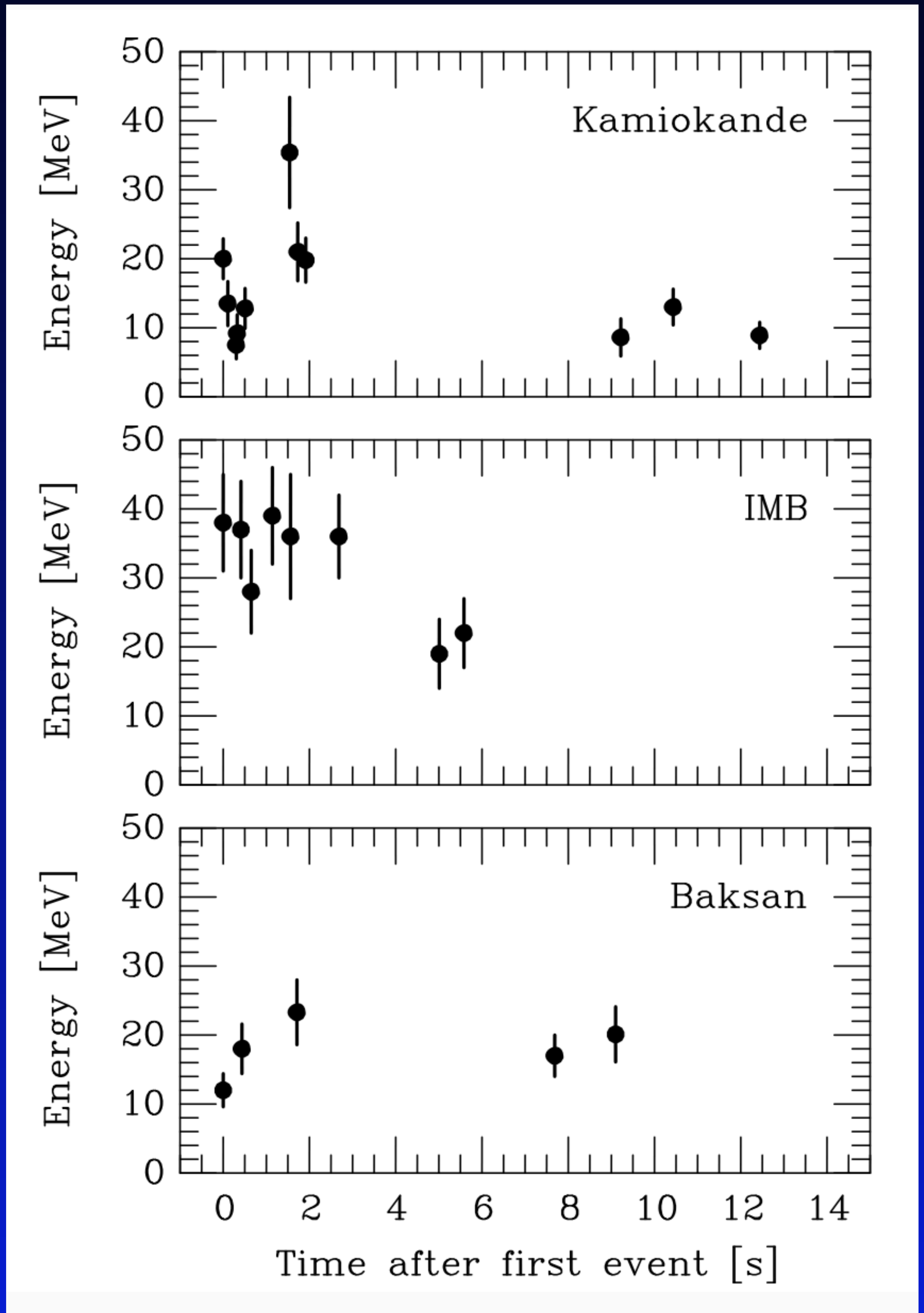
Introduction: Supernova 1987A (SN1987A)



Detection of 24 neutrino events

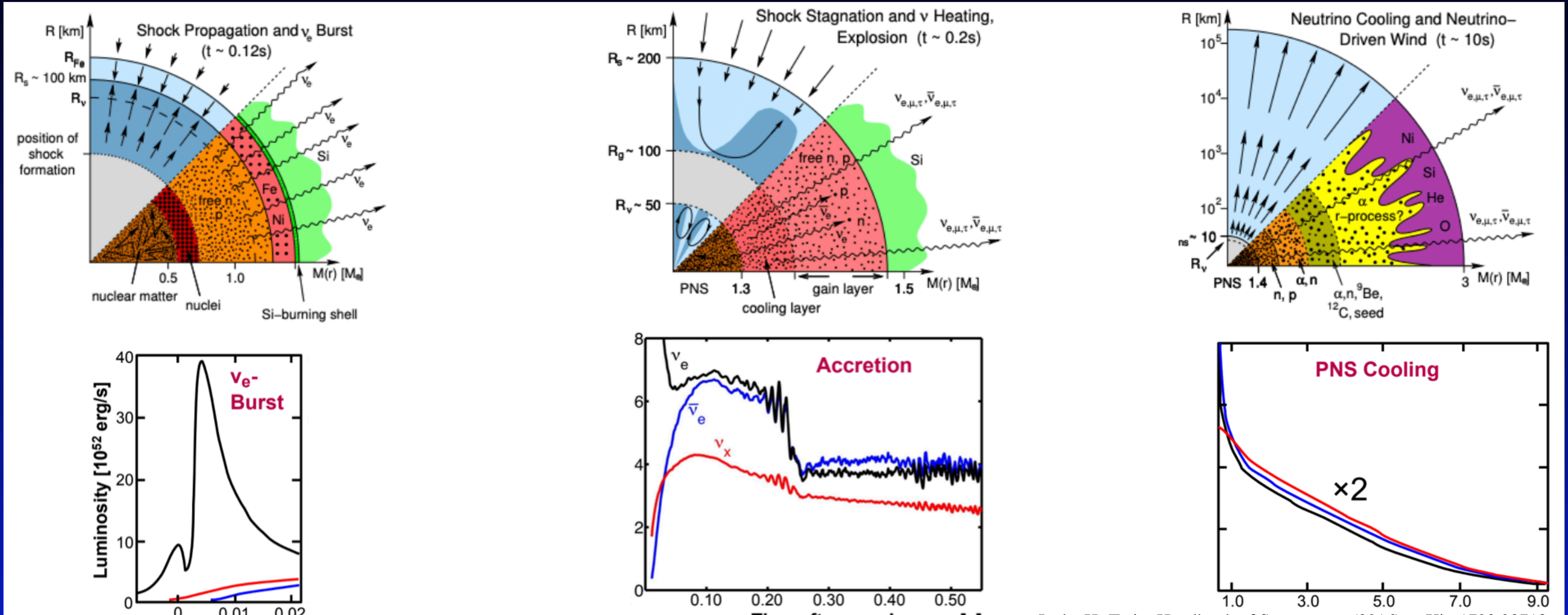


Janka H.-T., in: Handbook of Supernovae (2016); arXiv:1702.08713

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

$$E_\mathrm{b} \sim E_\mathrm{g} \approx \frac{3}{5}\frac{GM_\mathrm{ns}^2}{R_\mathrm{ns}} \approx 3.6\times10^{53}\left(\frac{M_\mathrm{ns}}{1.5\,M_\odot}\right)^2\left(\frac{R_\mathrm{ns}}{10\,\mathrm{km}}\right)^{-1}\ \mathrm{erg}$$

Introduction: Neutrino emission from Supernovae



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

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

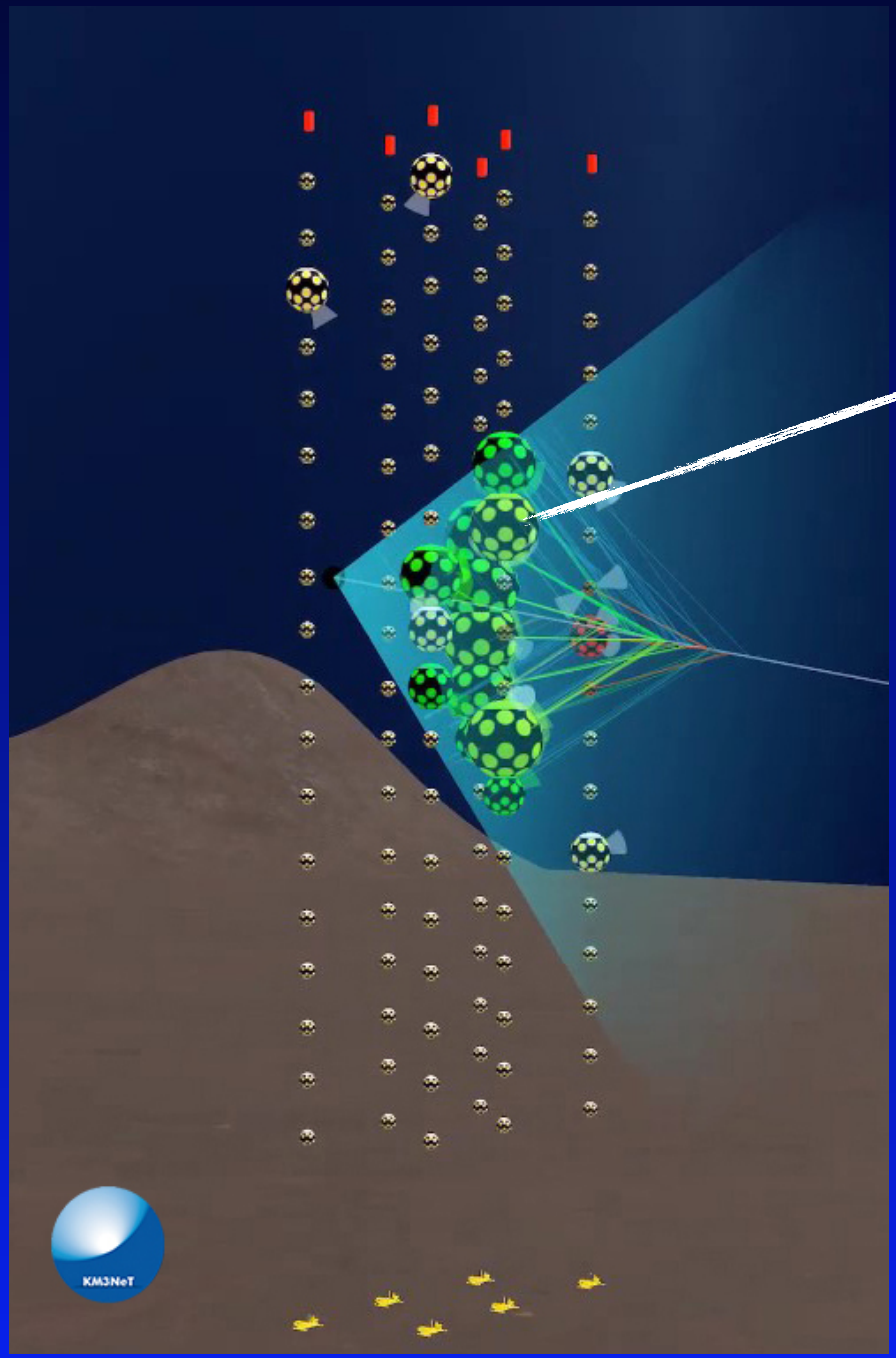
- ν and $\bar{\nu}$ are thermally produced

- Few differences between flavors
- The luminosity decreases exponentially with a decay time scale of seconds

- **KM3NeT: *Cubic Kilometre Neutrino Telescope***
- **Core collapse Supernovae neutrino detection with KM3NeT**
- **Supernova characterization**
- **Multi-messenger analysis**

KM3NeT: *Cubic Kilometre Neutrino Telescope*

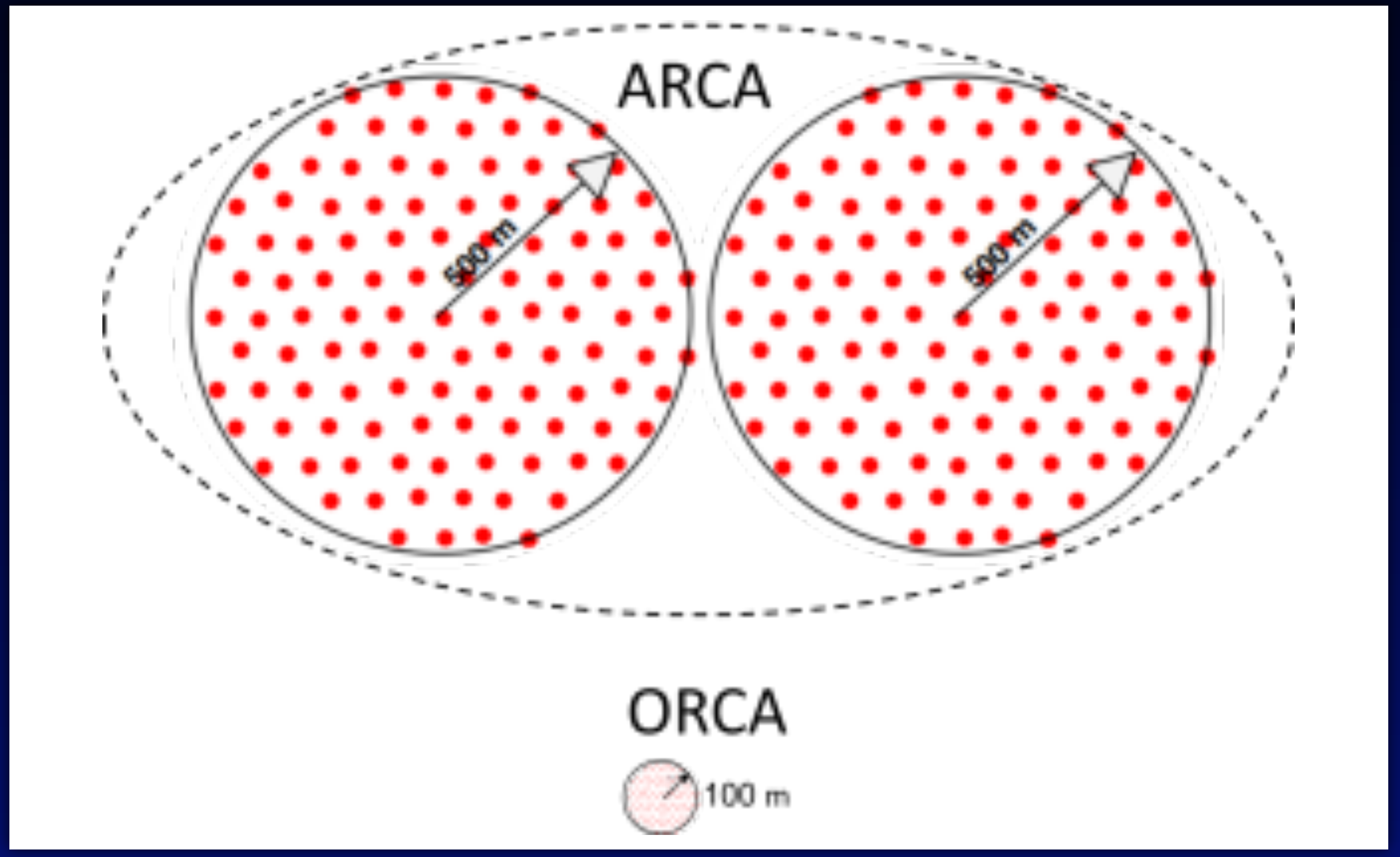
Cherenkov detectors under construction and taking data in the Mediterranean sea



31 PMTs/DOM

DOM: Digital Optical Module
PMTs: Photomultipliers

Cherenkov radiation :
The outgoing charged particle induces the production of Cherenkov light that can be detected by the PMTs.



ORCA: (in France)
115 strings
18 DOMs/ 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 block)
18 DOMs per string with 36 m spacing
Depth of about 3500 m
TeV-PeV energy range
Main goal: High energy astrophysics

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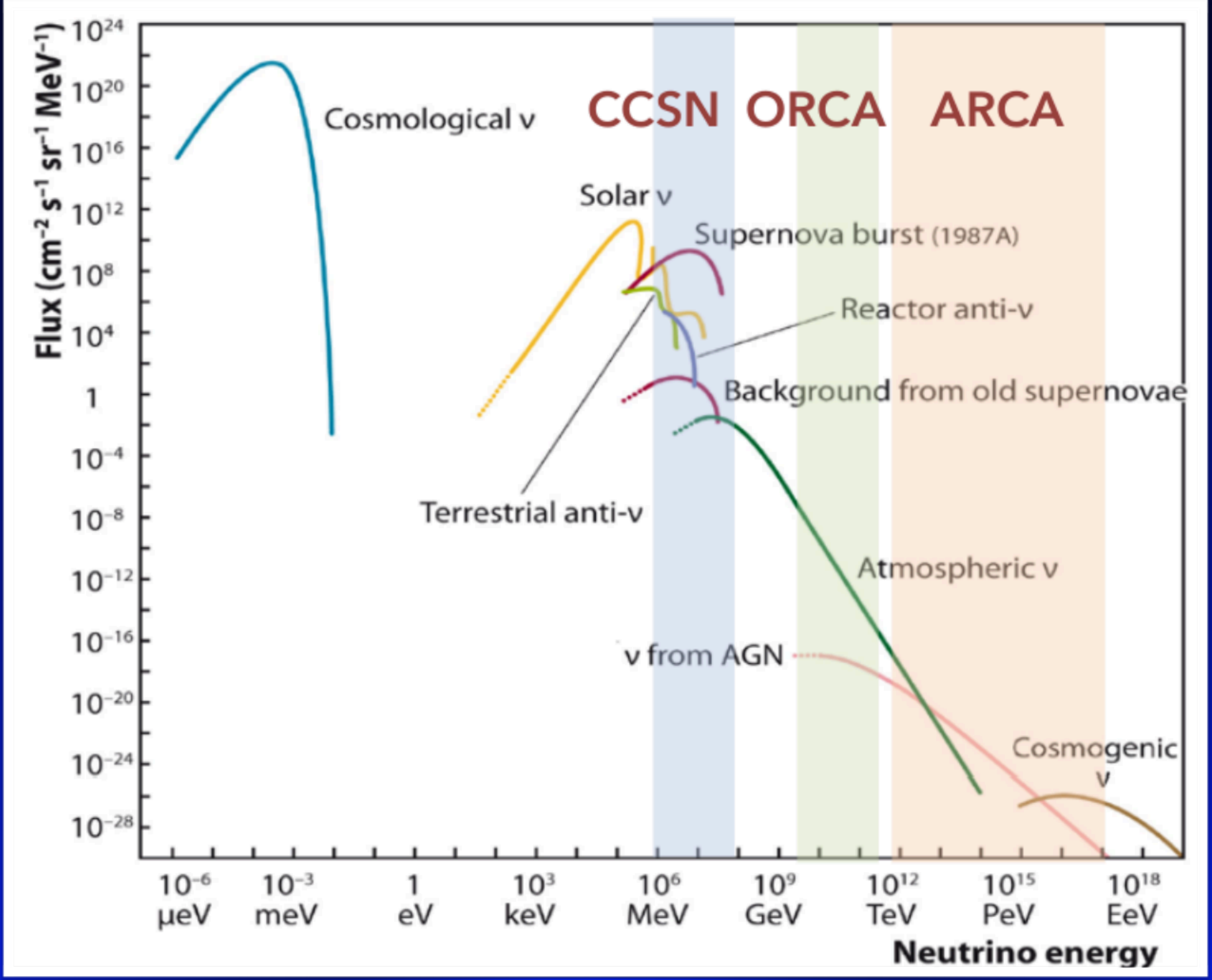
Core collapse Supernovae neutrino detection



- **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).**

- **Core collapse supernovae neutrino energy range: 1-100 MeV**

- **Main interactions in water Cherenkov detectors at low energy:**

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

Optical background in KM3NeT

K40 decays (radioactive isotopes present in sea water):
β-decays into a relativistic electron inducing Cherenkov emission.

Bioluminescence:
source coming from light emission by biological organisms in sea water.

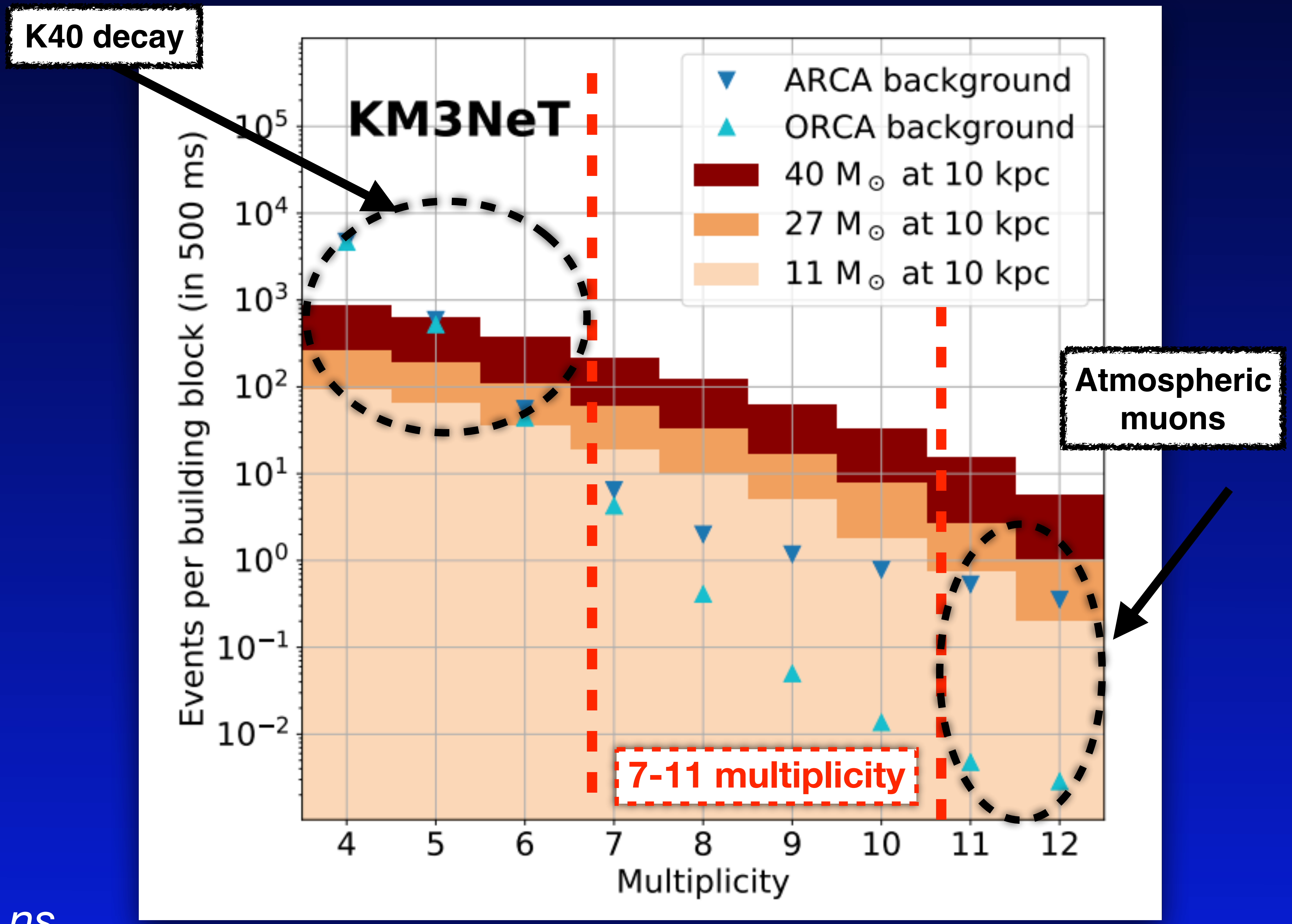
Atmospheric muons
the interaction of cosmic rays in the atmosphere generates muons producing Cherenkov radiation in seawater.

CCSN neutrino detection with KM3NeT

Combining: background + filtering and simulated signal events

Triggering on individual events is not possible.

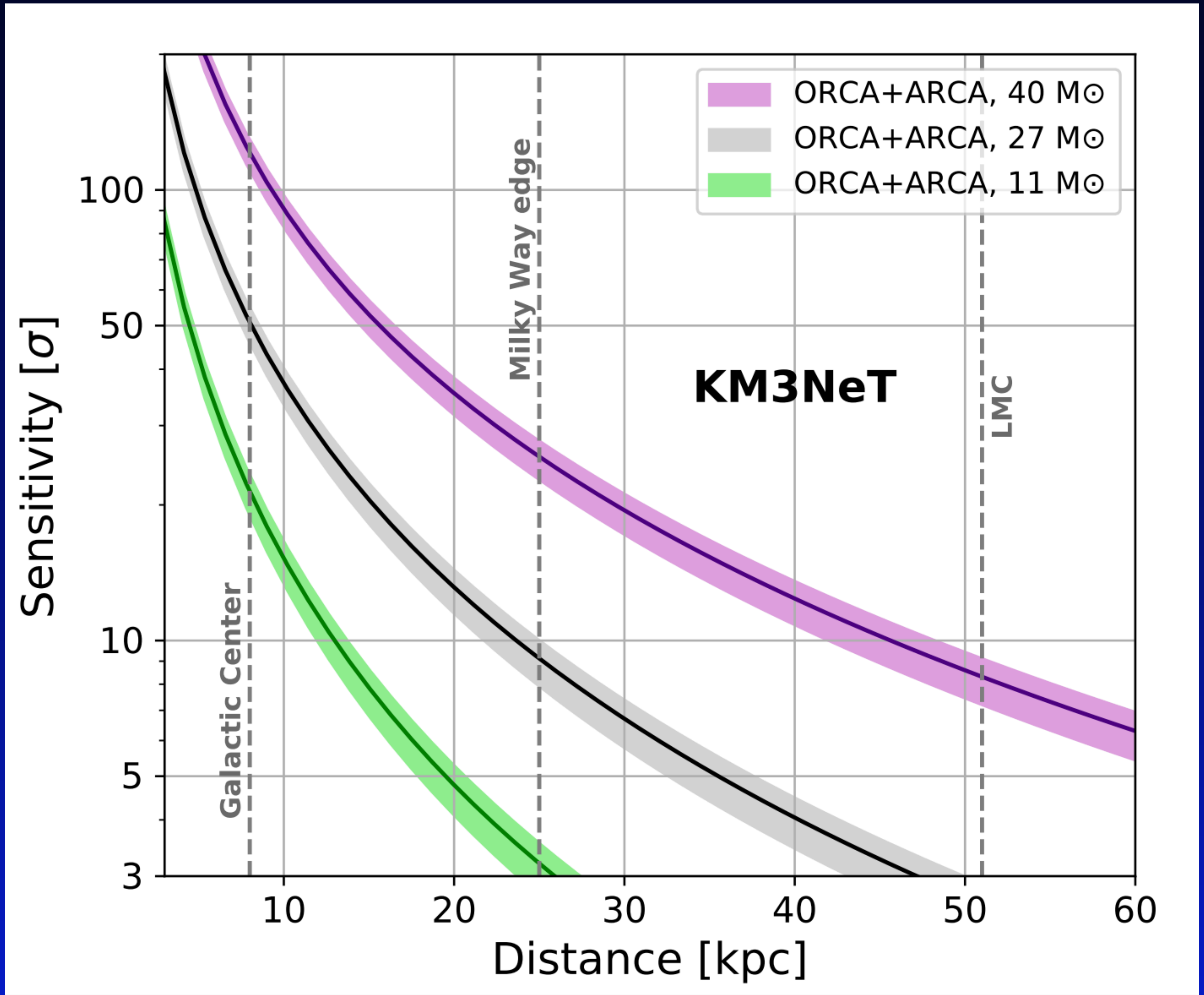
For background reduction : Selection of events producing nanosecond-scale time coincidences between the PMTs → multiplicity selection.



Multiplicity: number of PMTs in a DOM receiving a photon within 10 ns

https://arxiv.org/abs/2102.05977

KM3NeT sensitivity to CCSN neutrinos



- **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/abs/2102.05977

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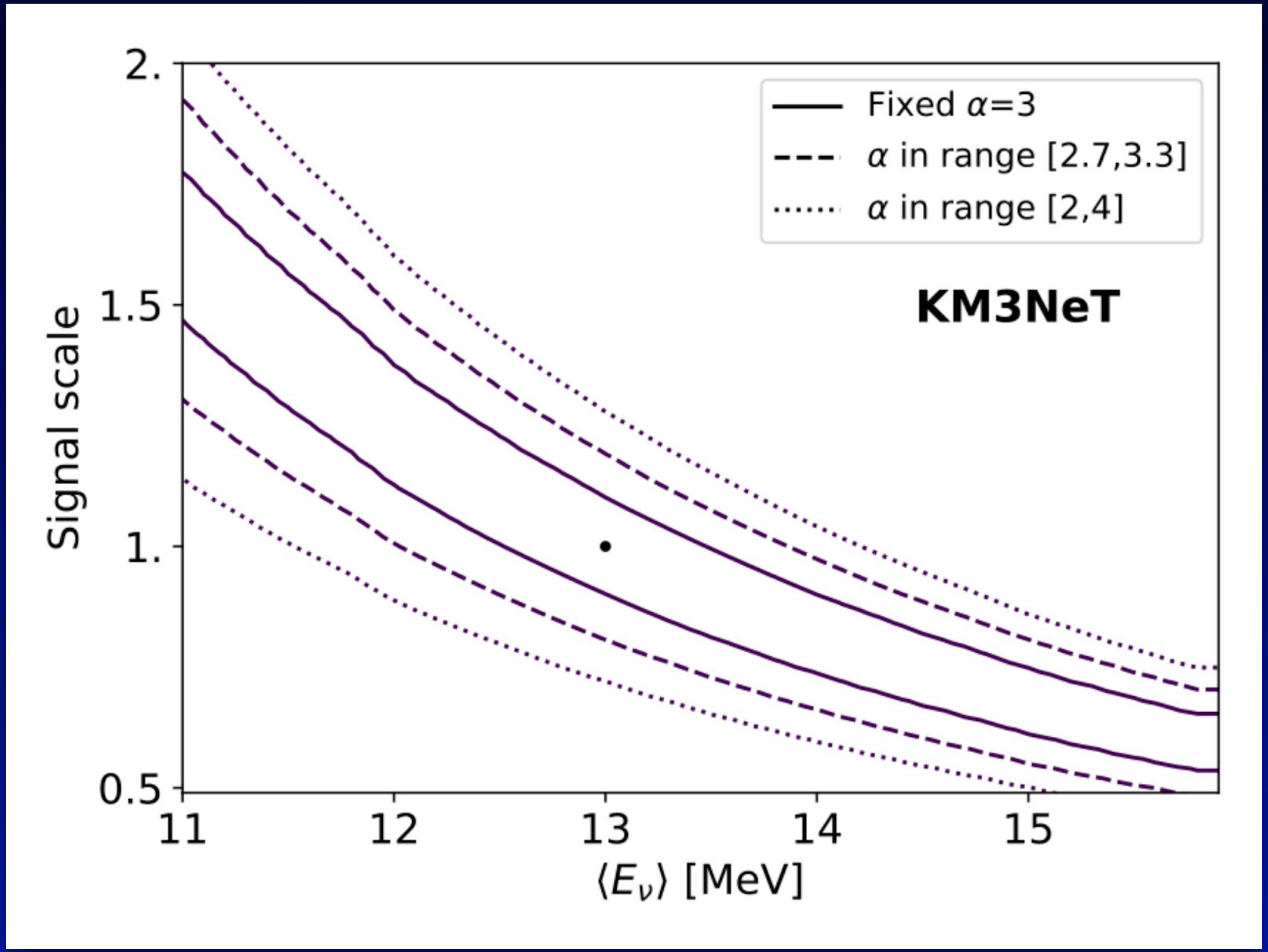
Estimation of the neutrino spectrum parameters

Parameters of interest:
- mean neutrino energy
- spectral index

$$f(E, \langle E \rangle, \alpha) = \frac{E^{\alpha}}{\Gamma(1+\alpha)} \left(\frac{1+\alpha}{\langle E \rangle} \right)^{1+\alpha} e^{\frac{-E(1+\alpha)}{\langle E \rangle}}$$

⇨ **Chi-square method**

Contours at 90% confidence level in the signal scale and neutrino energy parameter space



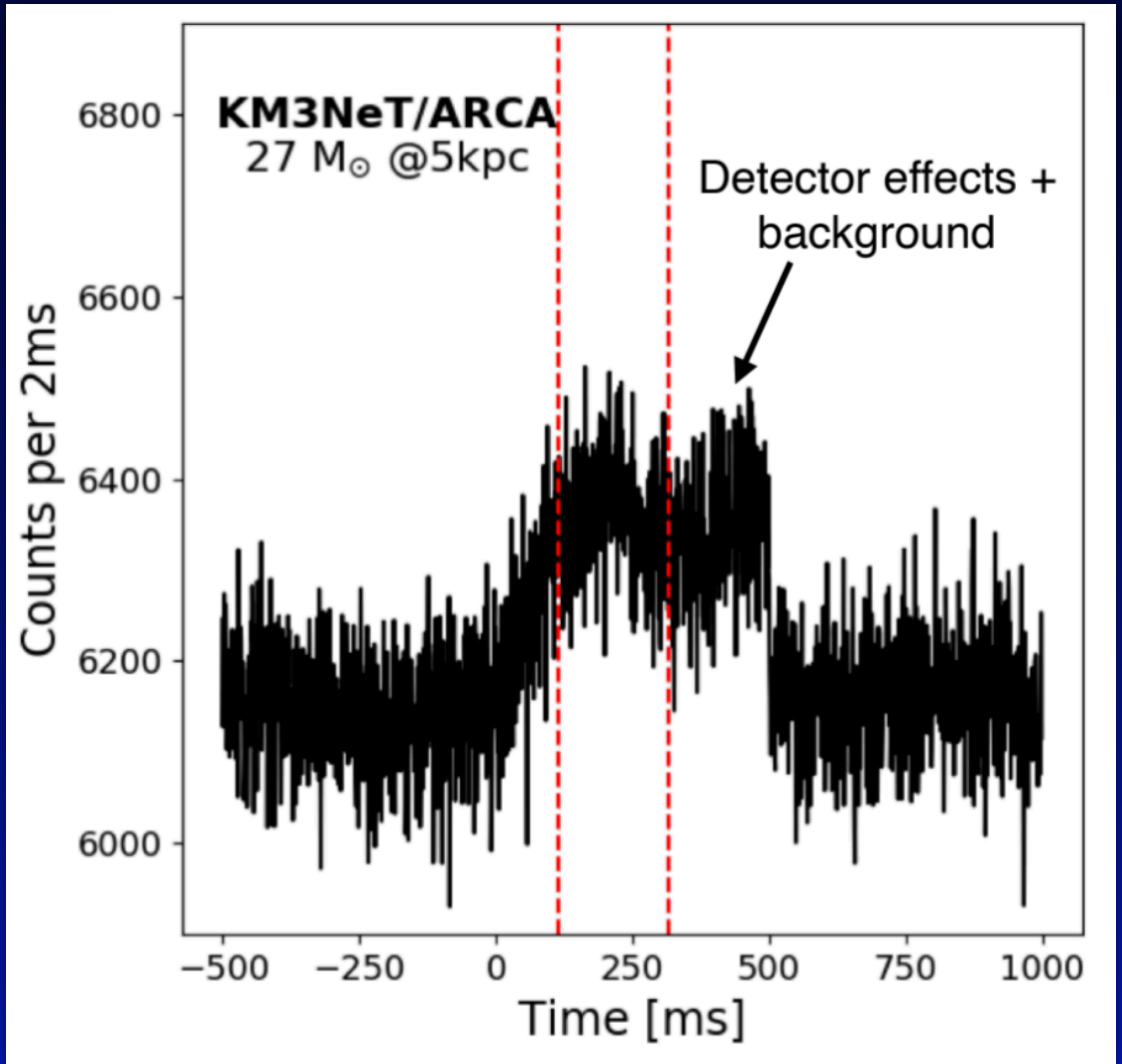
Results for the mean neutrino energy:

- ± 0.5 MeV (4%) if spectral index and signal scale are known
- below ± 1.5 MeV if they are known within a 10% variation

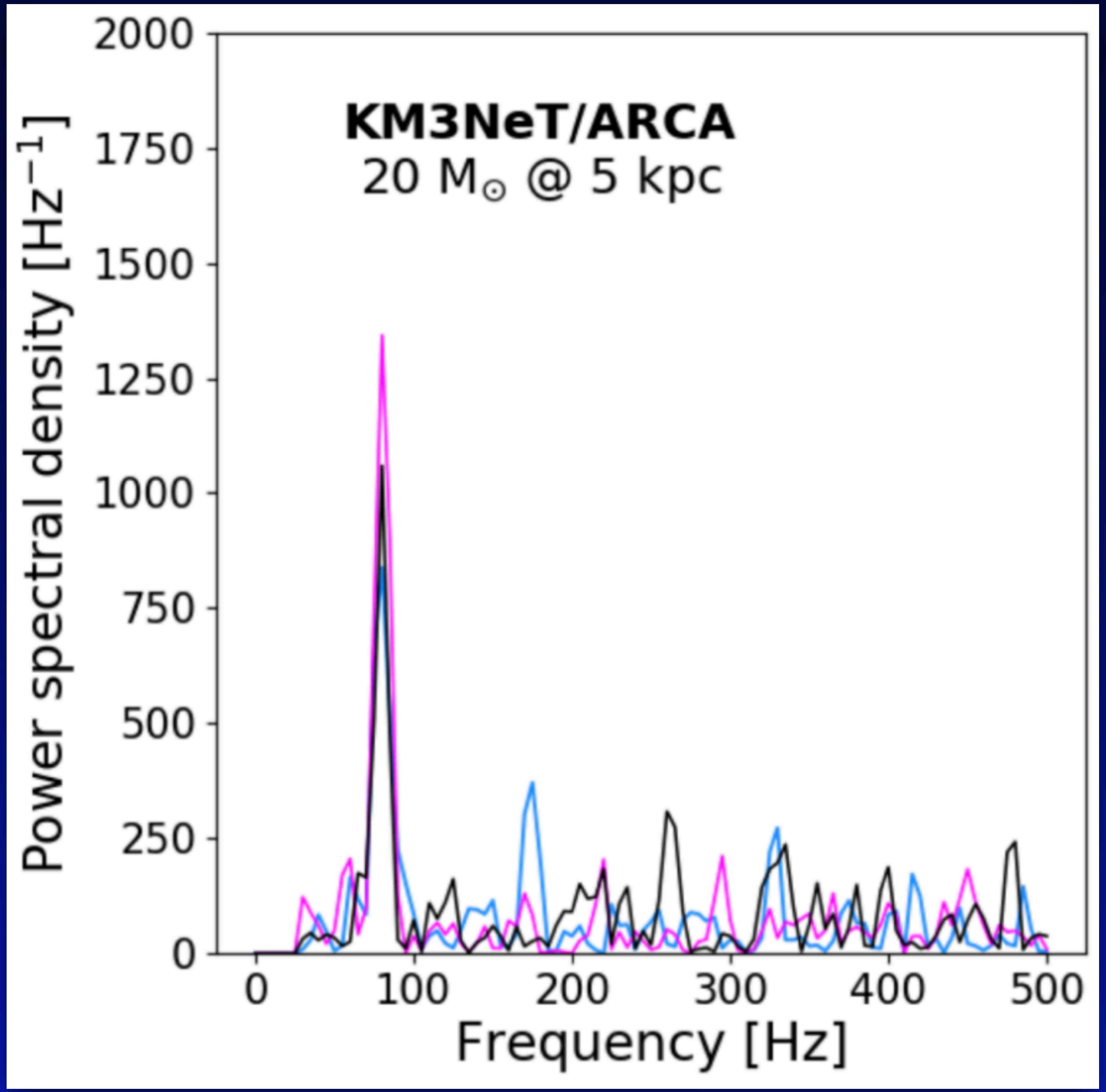
https://arxiv.org/abs/2102.05977

Detection of the Standing accretion shock instability (SASI)

Prediction of fast and asymmetric hydrodynamic motions in the core during the accretion phase
From 2D and 3D simulations of CCSNe



Spectral analysis :
Fourrier Transform



3σ sensitivity to the SASI signature is reached for Galactic progenitors at distances between 3 kpc (27M⊙) and 5 kpc (20 M⊙)

https://arxiv.org/abs/2102.05977

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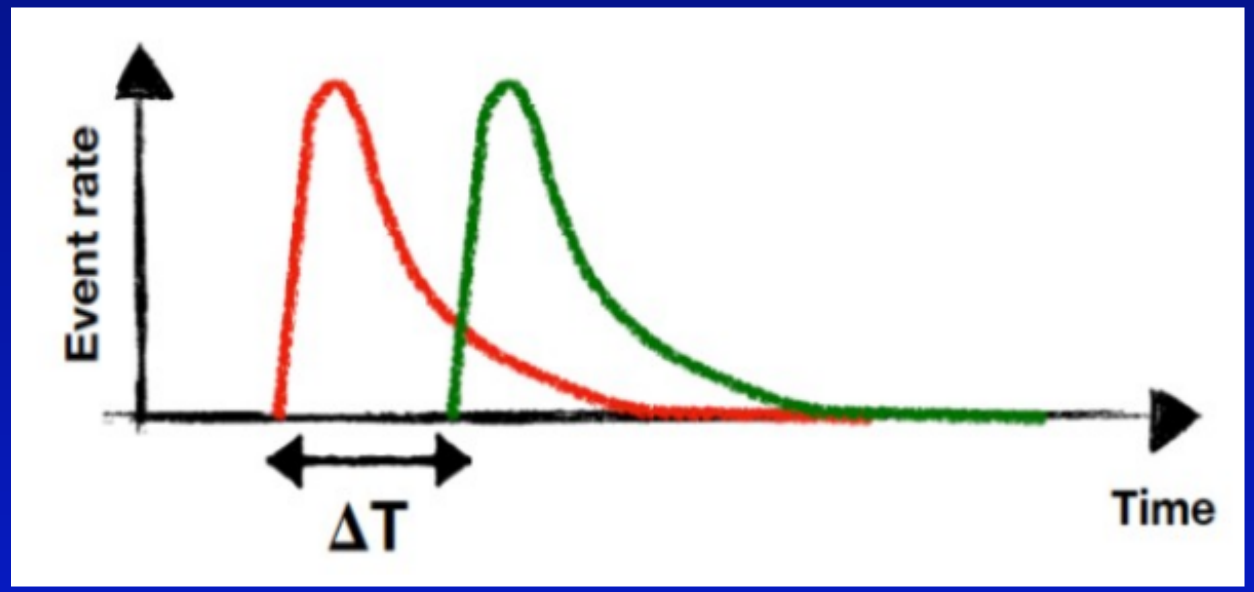
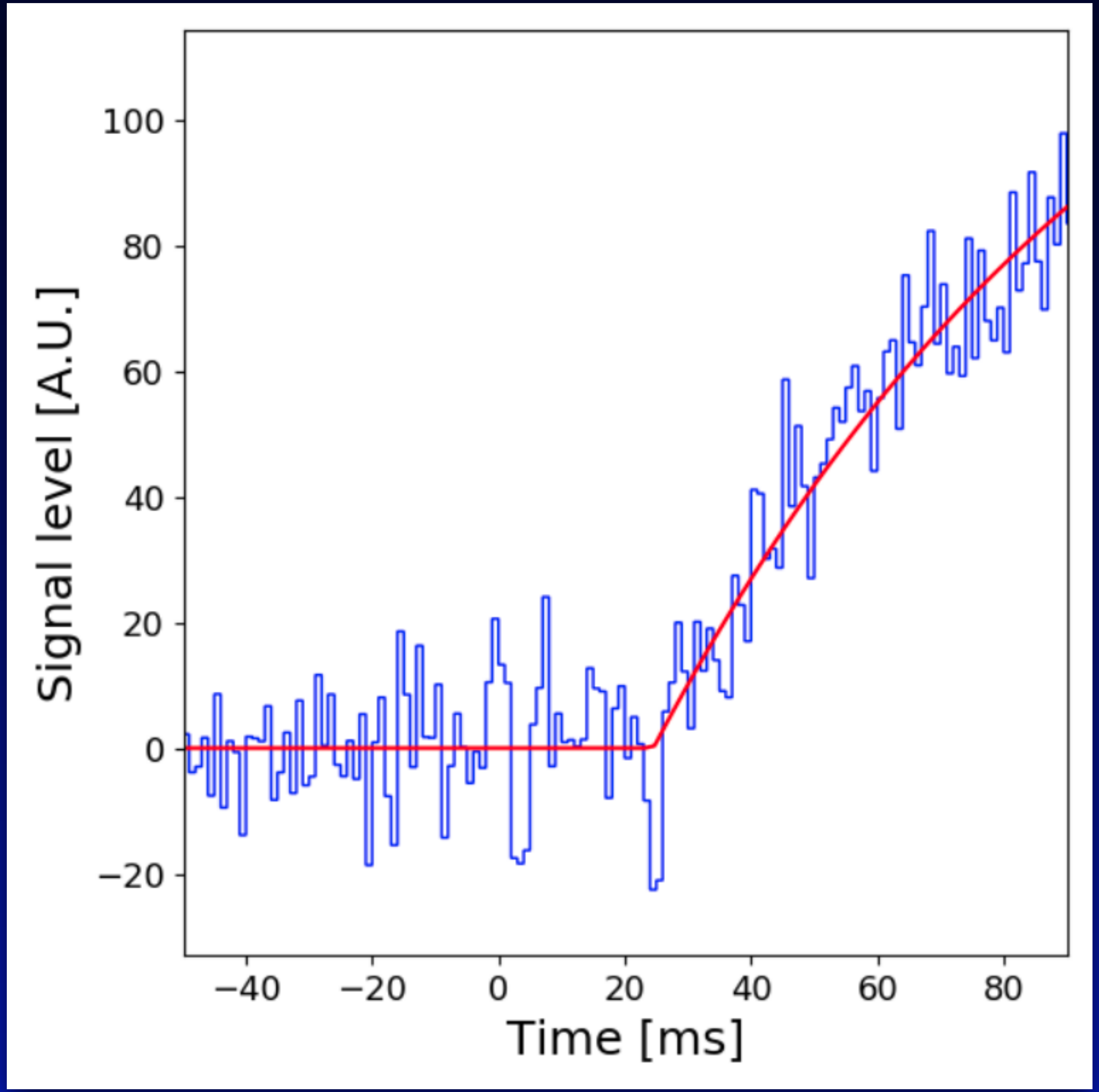
Arrival time of the CCSN neutrino signal

- **Goals**:
- **Localise the source by triangulation.**
- **Reduce the search time window for a gravitational wave.**

- **Method**:
- **- Subtracting the background**
- **- Applying a moving-average filter with a 23 ms time window.**
- **- The function is fitted to the detected neutrino light-curve using a Chi-scare minimisation algorithm.**



Time profile of the signal in ARCA (two building blocks) using all coincidences for a 20M progenitor at 5 kpc



The arrival time can be estimated with an uncertainty of 3 ms for a supernova at 5 kpc

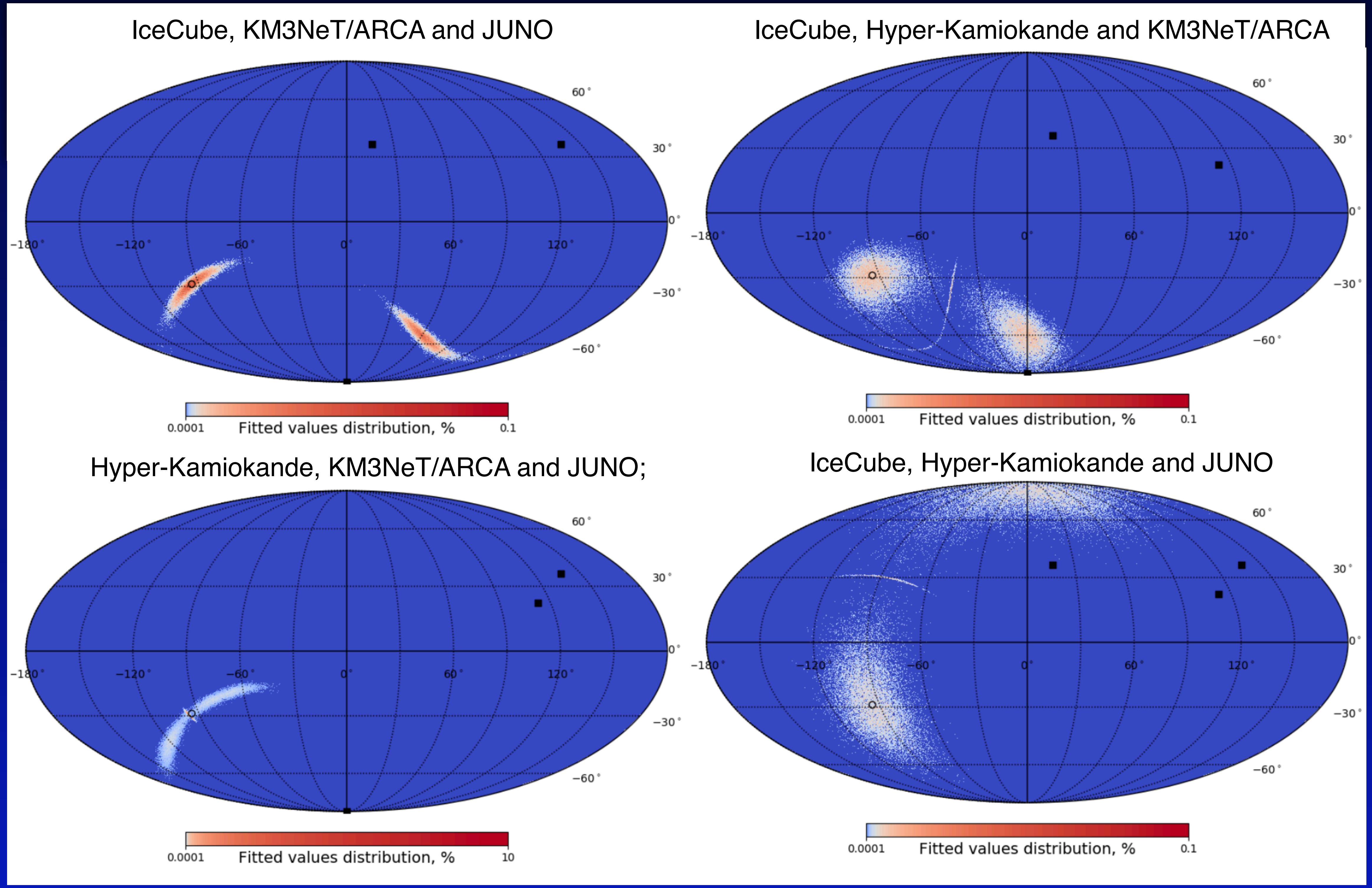
https://arxiv.org/abs/2102.05977

Multi-detector approach for CCSN triangulation

Goal: Estimate the time delay between the light curves recorded by IceCube , KM3NeT and Super-kamiokande detectors during a CCSN to estimate its position in the sky.

	IceCube	ORCA	ARCA	Super-Kamiokande	Hyper-Kamiokande	JUNO
M_{eff} [kton]	3500	90	180	22.5	560	22.5
R_{bg} [Hz]	$\sim$3e6	$\sim$1e6	$\sim$2e6	0	0	0

Confidence areas obtained by the core collapse supernova triangulation method



Fitted position distributions in equatorial coordinates for a CCSN at the Galactic Centre (black dot) computed using triangulation between different detector combinations

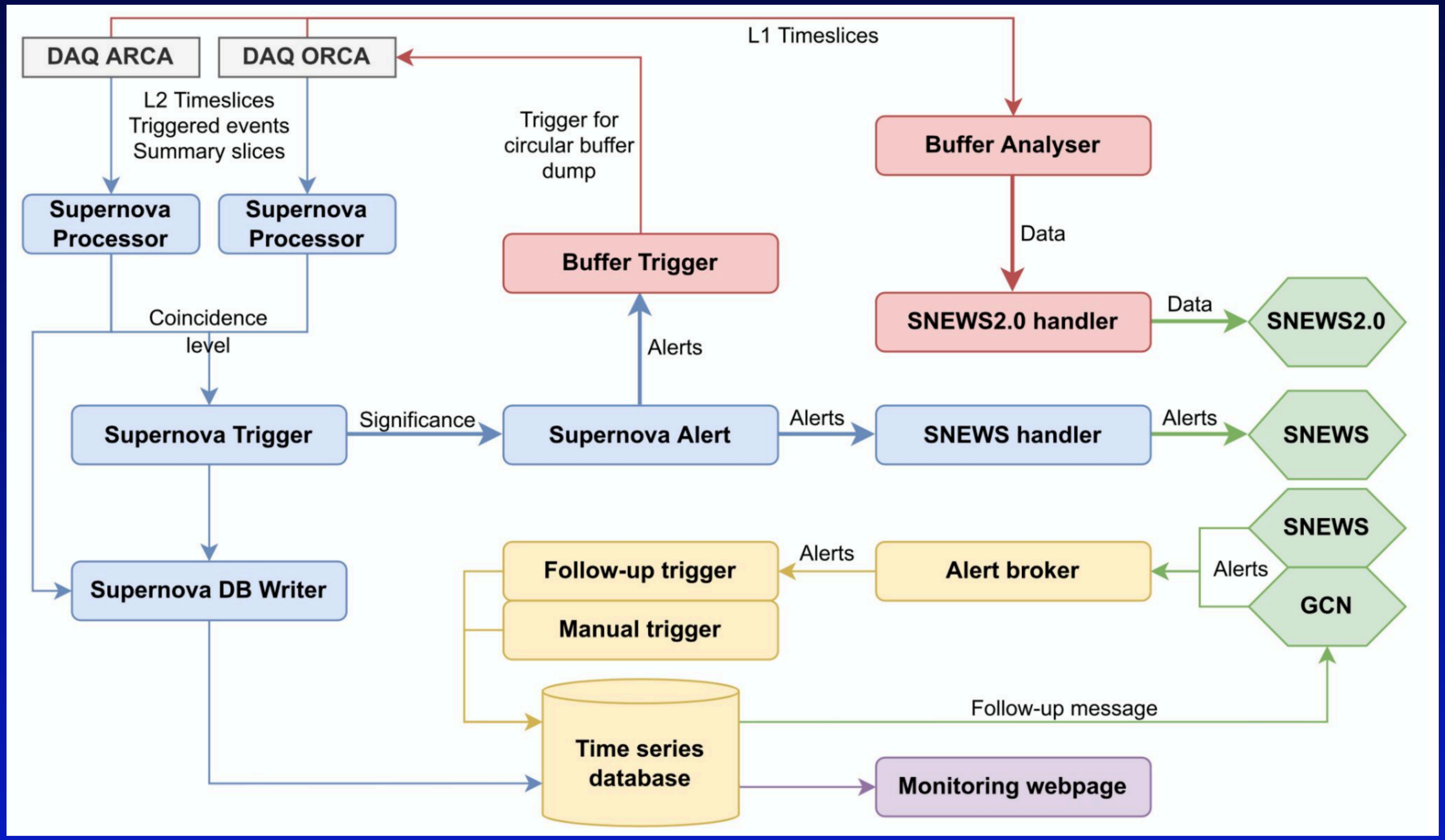
The 90% confidence area is 140±20 deg^2 when combining Hyper-Kamiokande, IceCube, JUNO and KM3NeT/ARCA detectors.

https://arxiv.org/pdf/2003.04864.pdf

Real-time Multi-Messenger Analysis Framework

- **<u>Goal</u>: CCSN monitoring because CCSN neutrinos are observed hours before the photons and thus can act as an early warning.**
- **Pipeline: the MeV CCSN monitoring pipeline monitors the coincidences of PMT hits inside each DOM (multiplicity)**
- **This pipeline is operational and sending alerts with false alarm rate less than 1/week to SNEWS.**
- **The alert generation latency is less than 20 s .**

Monitoring the neutrino sky for the next Galactic CCSN with KM3NeT
(Neutrino 2022, Godefroy Vannoye)



https://arxiv.org/pdf/2107.13908.pdf

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- Conclusion

Conclusion

- KM3NeT is sensitive to supernovae thanks to the complex structure of its DOMs.
- Combining ARCA and ORCA sensitivities, KM3NeT will be able to detect the next Galactic explosion with a 5 σ discovery potential.
- The arrival time of the CCSN neutrino signal can be estimated with an uncertainty of 3 ms for a supernova at 5 kpc.
- The 90% confidence area is 140±20 deg^2 when combining Hyper-Kamiokande, IceCube, JUNO and KM3NeT/ARCA detectors.
- This pipeline is operational and sending alerts with false alarm rate less than 1/week to SNEWS.