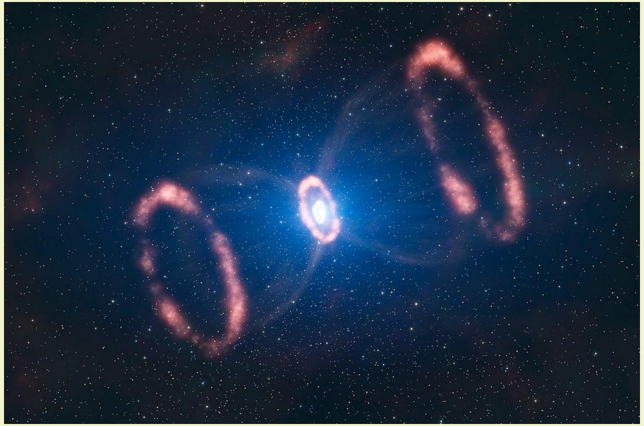
Detection of the next “nearby” core-collapse supernova through neutrinos at KM3NeT



Isabel Goos, EPAP seminar, 6/6/2025

KM3NeT | Labex UnivEarthS | Université Paris Cité | APC

Introduction: Core-collapse Supernovae (CCSNe)

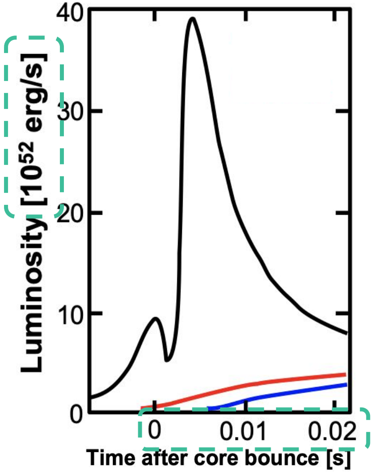
What are CCSNe?

- explosions of giant stars (>8 solar masses) at the end of their thermonuclear evolution
- give birth to neutron stars or black holes

Some open questions:

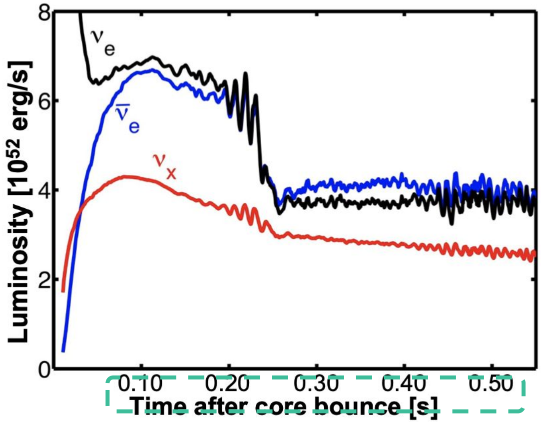
- Supernova physics: explosion mechanism - conditions that need to be met, phenomena that favour the explosion
- Particle physics: neutrino behaviour in dense environments, when propagating to Earth

Introduction: CCSNe in terms of neutrinos



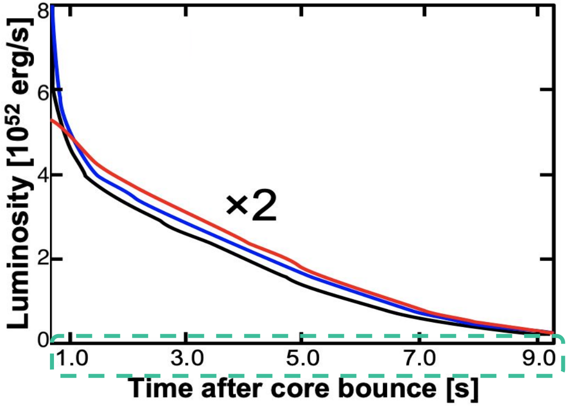
υ_e-burst

sudden transition of the shock from opaque to transparent for neutrinos created via electron capture



Accretion phase

energy loss through υ_e-burst
⇒ stagnation of the shock
⇒ revival through neutrino heating in the hot accretion mantle
⇒ explosion



Cooling phase

neutrino-driven wind - potential site for formation of trans-iron elements

arXiv:1702.08713

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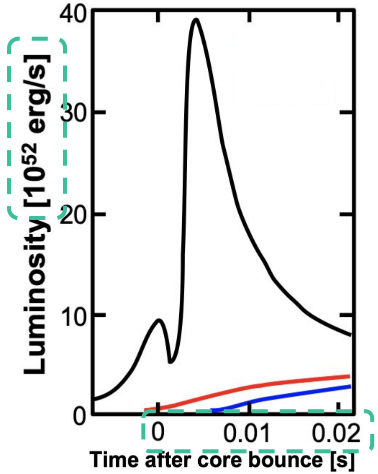

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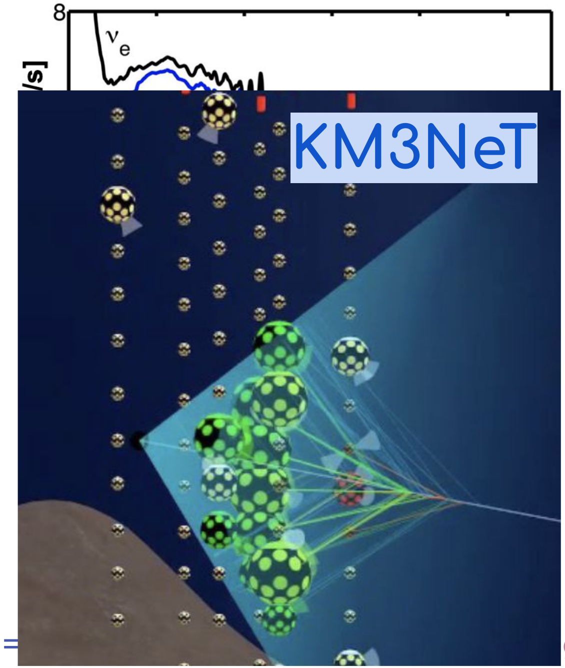

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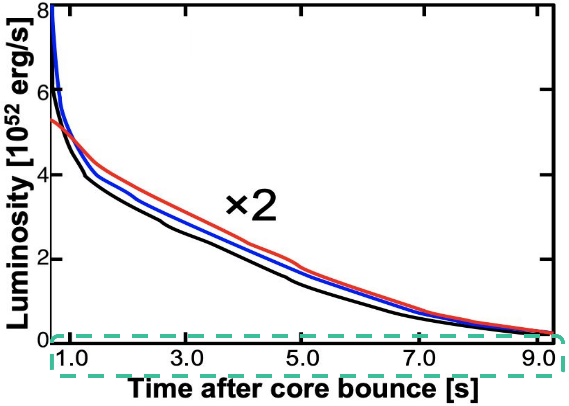
in the hot accretion mantle
⇒ explosion



Cooling phase

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Introduction: how probable is a CCSNe?

On the rate of core collapse supernovae in the milky way

Karolina Rozwadowska[a,b], Francesco Vissani[*,a,b], Enrico Cappellaro[c]

[a] *INFN, Laboratori Nazionali del Gran Sasso, Assergi (AQ), Italy*
[b] *Gran Sasso Science Institute, L'Aquila, Italy*
[c] *INAF, Osservatorio Astronomico di Padova, Padova, Italy*

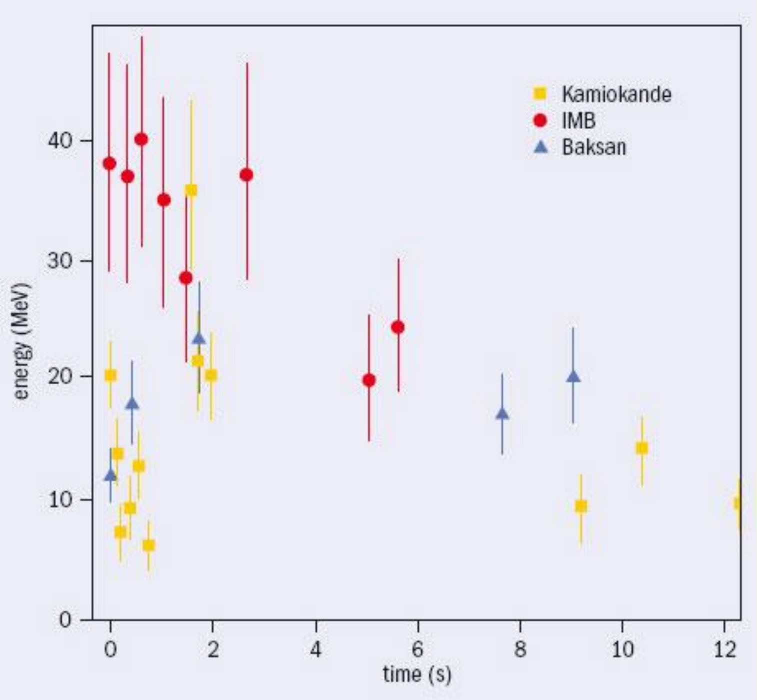
Check for updates

A B S T R A C T

Several large neutrino telescopes, operating at various sites around the world, have as their main objective the first detection of neutrinos emitted by a gravitational collapse in the Milky Way. The success of these observation programs depends on the rate of supernova core collapse in the Milky Way, R. In this work, standard statistical techniques are used to combine several independent results. Their consistency is discussed and the most critical input data are identified. The inference on R is further tested and refined by including direct information on the occurrence rate of gravitational collapse events in the Milky Way and in the Local Group, obtained from neutrino telescopes and electromagnetic surveys. A conservative treatment of the errors yields a combined rate $R = 1.63 \pm 0.46\ (100\ \mathrm{yr})^{-1}$; the corresponding time between core collapse supernova events turns out to be $T = 61^{+24}_{-14}$ yr. The importance to update the analysis of the stellar birthrate method is emphasized.

Introduction: SN1987A

Large Magellanic Cloud → ~50 kpc, ~18 solar masses

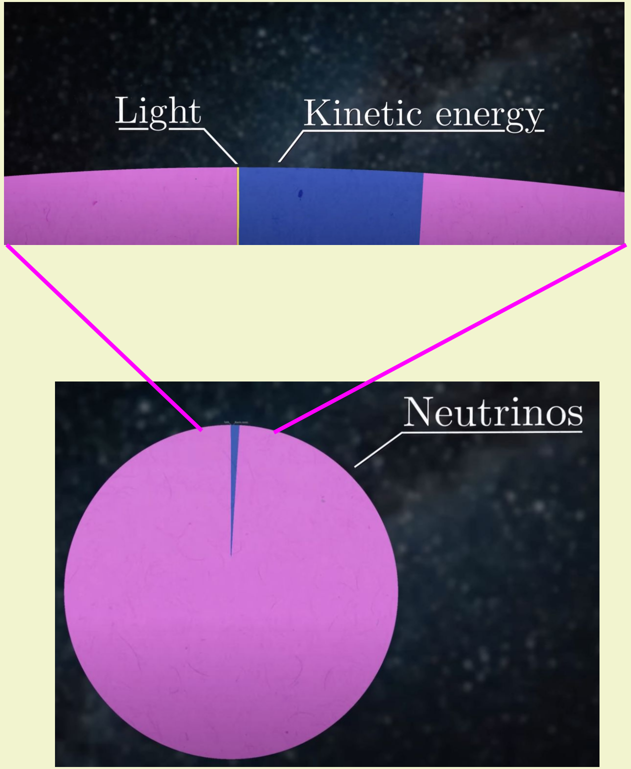


Nakahata M 2007 CERN Courier 2007

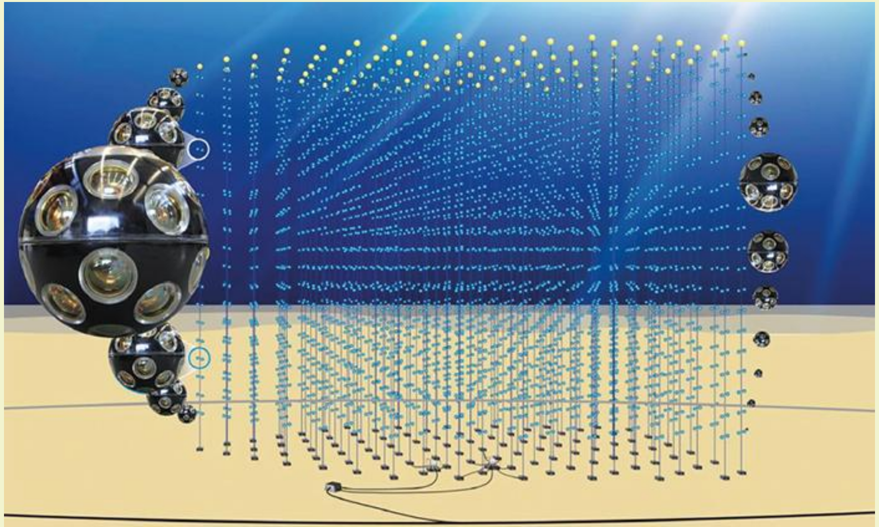
- Released energy ~3×10^{53} ergs
  ⇒ agrees well with expectations, assuming the scenario where a compact object is formed while gravitational binding energy is released
  ⇒ fundamental mechanism of a supernova is understood
- Observed number of events was to low to reveal details of the explosion

Introduction: neutrinos from a CCSN

Crab Nebula



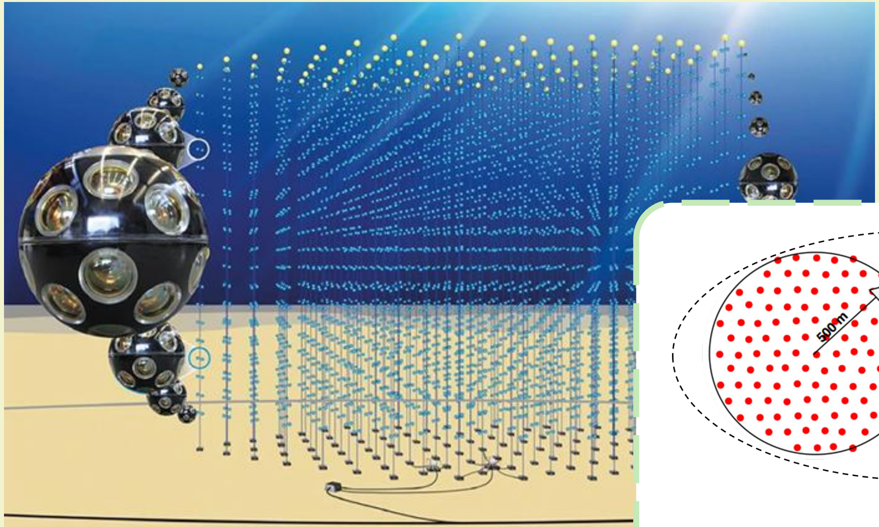
KM3NeT - the next generation ν telescopes

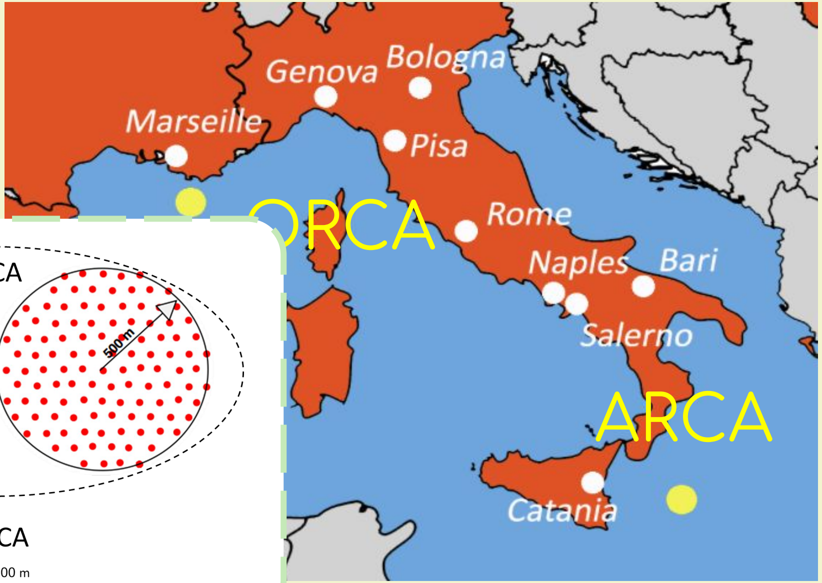


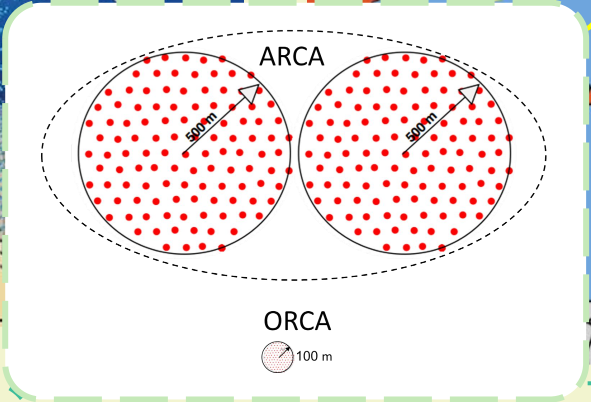
- ORCA: 1 building block, covers ~0.007 km^3 of water
- ARCA: 2 building blocks, covers ~1 km^3 of water

1 building block
→ 115 detection units (DUs)
→ each has 18 digital optical modules (DOMs)
→ each has 31 photomultiplier tubes (PMTs)

KM3NeT - the next generation υ telescopes







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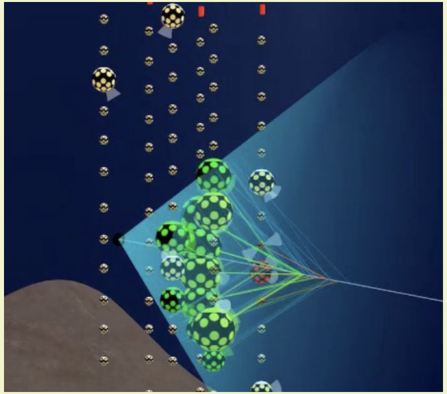

Detection mechanism

Measurement of the Cherenkov light emitted by the charged product particles that result from a neutrino interaction near the detector

ARCA

Astrophysical neutrino sources with cosmic neutrinos in the TeV-PeV energy range

ORCA

Neutrino mass ordering and oscillations with atmospheric neutrinos in the 1-100 GeV energy range

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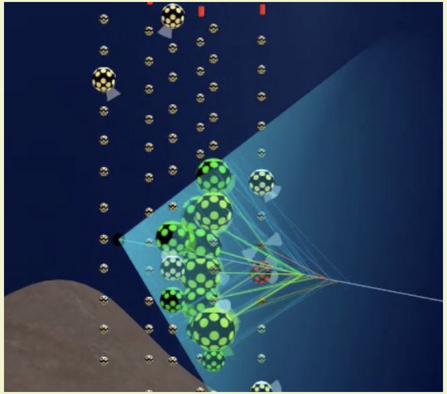

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CCSN Neutrinos:

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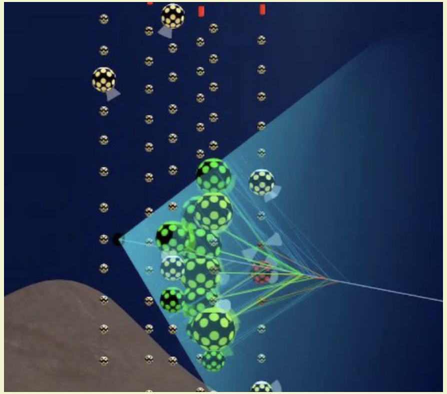

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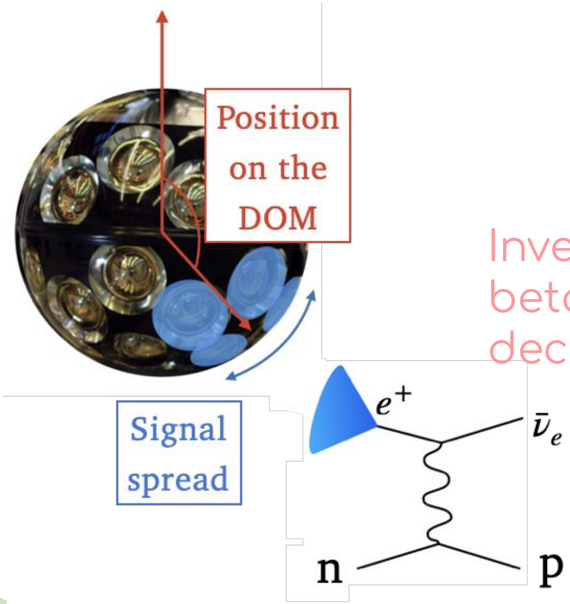

Inverse beta decay

ARCA
Astrophysical neutrino sources with cosmic neutrinos in the TeV-PeV energy range

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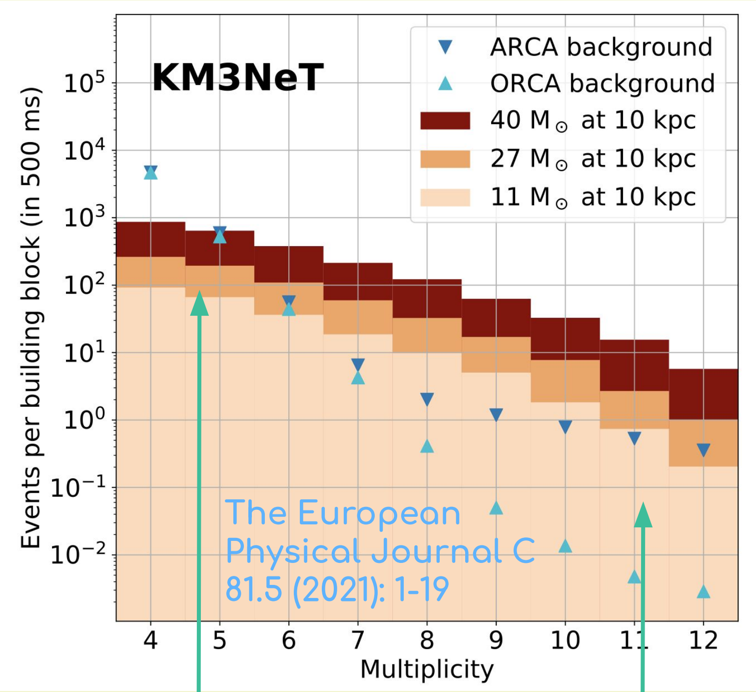
CCSN Neutrinos:
➡ 10-20 MeV energy range

Detection of CCSN neutrinos

Multiplicity = number of PMTs hit in a coincidence (10 ns)

Detection mechanism
↪single-DOM signal

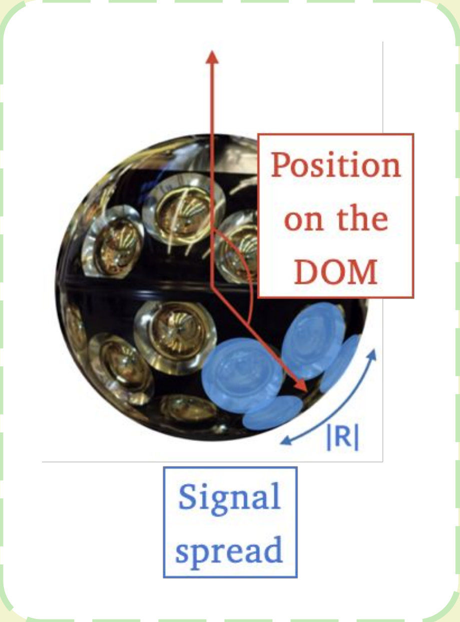
- through observation of coincidences in excess over the background taking into account all the DOMs in the detector
- the multiplicity distribution of these coincidences can be exploited to discriminate the origin of the signal on a statistical basis



Dominated by radioactive decays (K40)

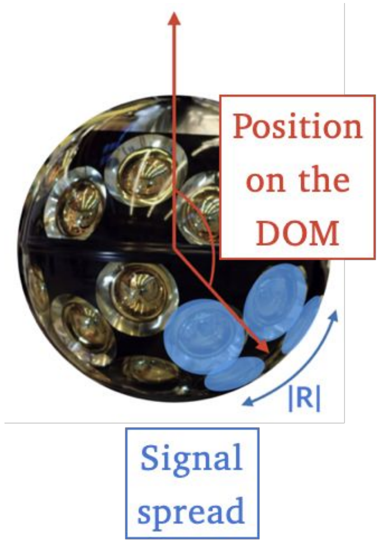
Dominated by atmospheric muons

New single-DOM observables



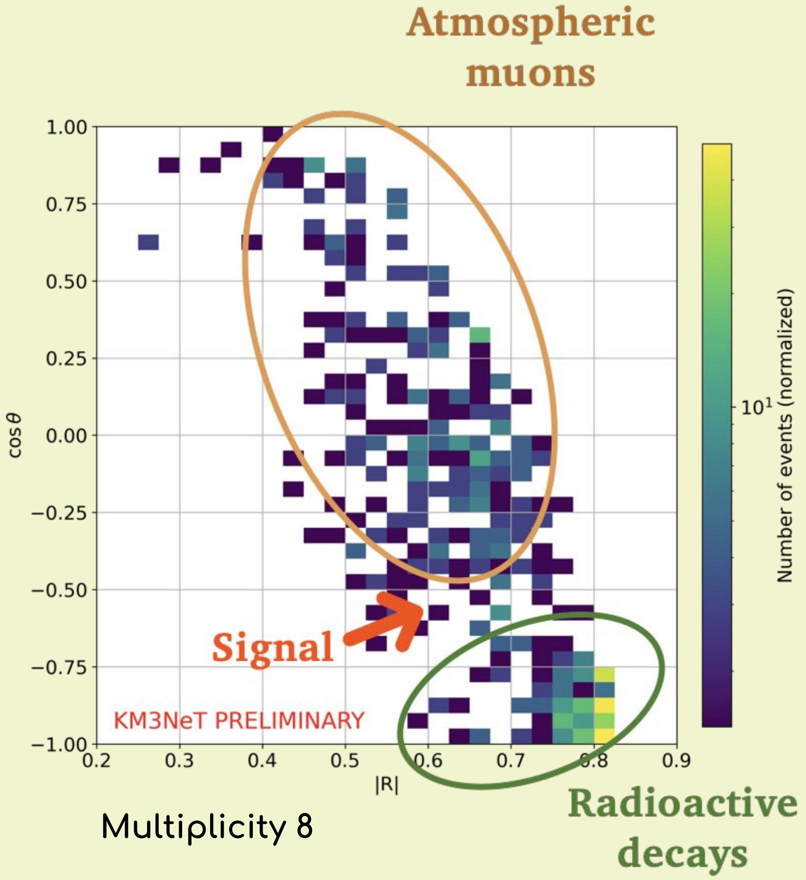
And many more..

New single-DOM observables



And many more..

Why these observables help reduce background even more



Multiplicity 8

How to make use of the new observables

Boosted decision trees (BDTs)

- Reduce the set of new observables to those with the strongest impact (highest feature importance)
- Define a final new "summarized" observable that measures signal-likeness

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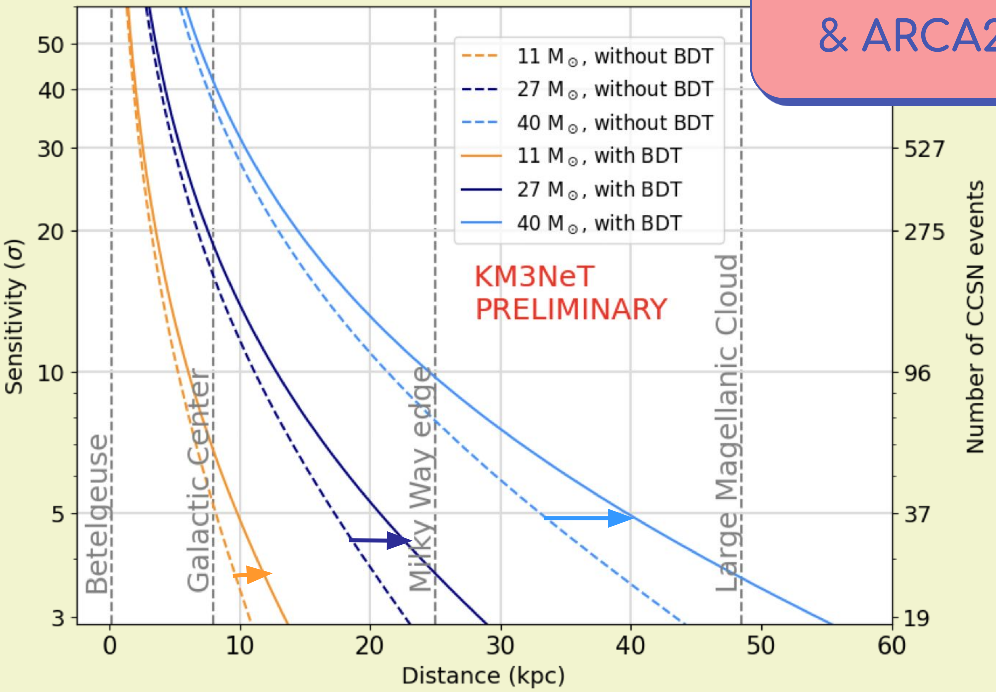
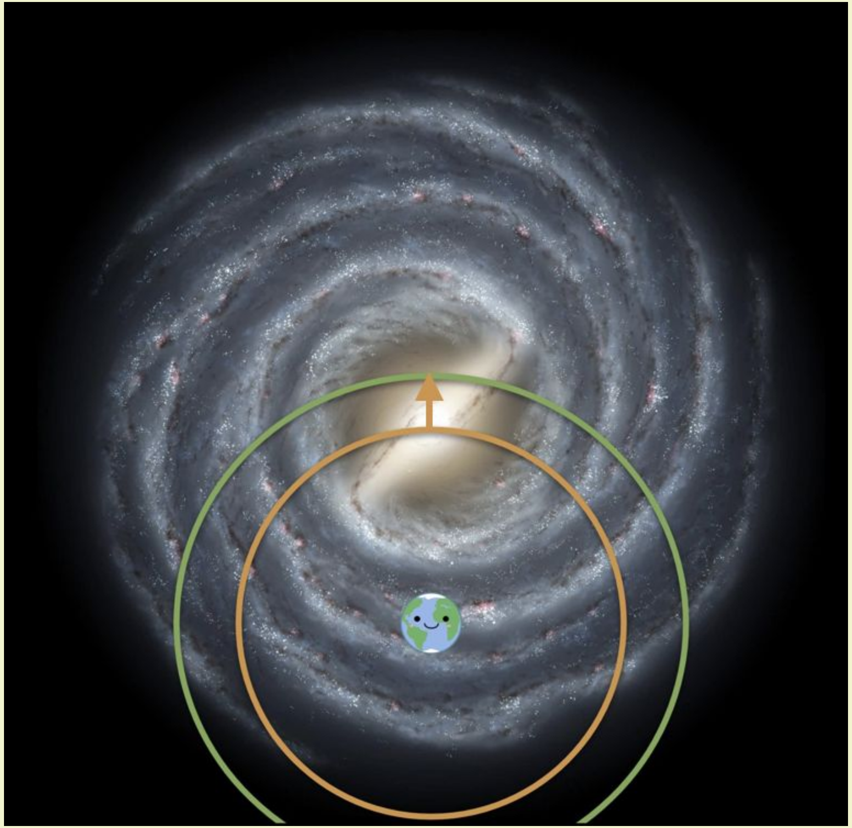
ORCA24 & ARCA29



How to make use of the new observables



Today's detector configuration:

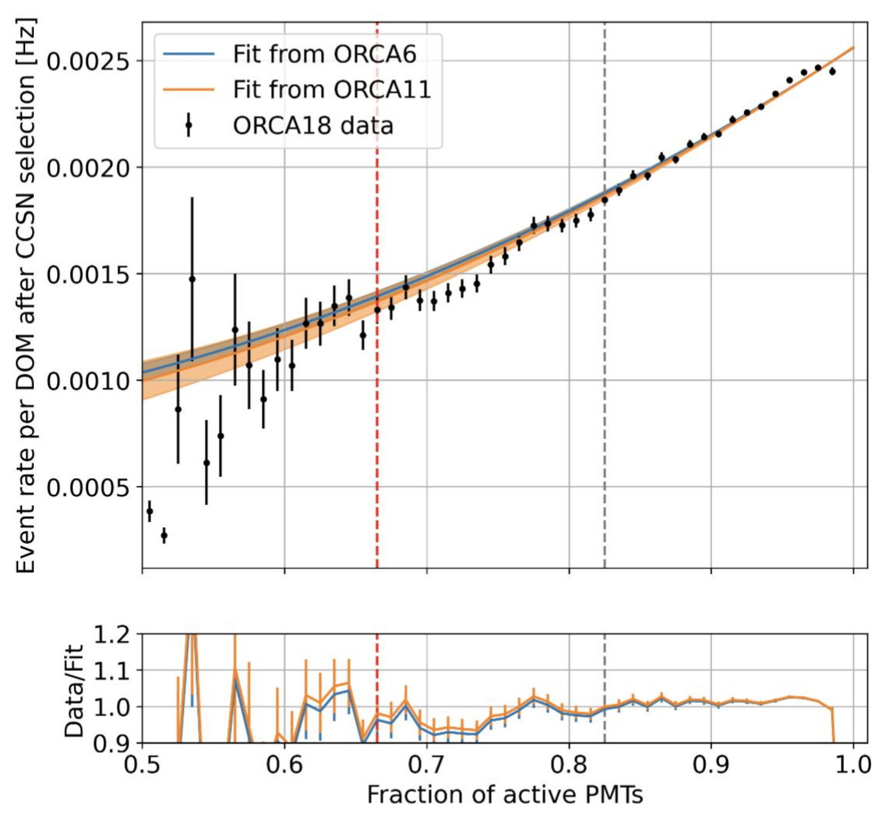
- ARCA: 33 DUs
- ORCA: 24 DUs

➡ We can now probe 43% more potential supernovae

Implementation in KM3NeT's online analysis

Varying expected background

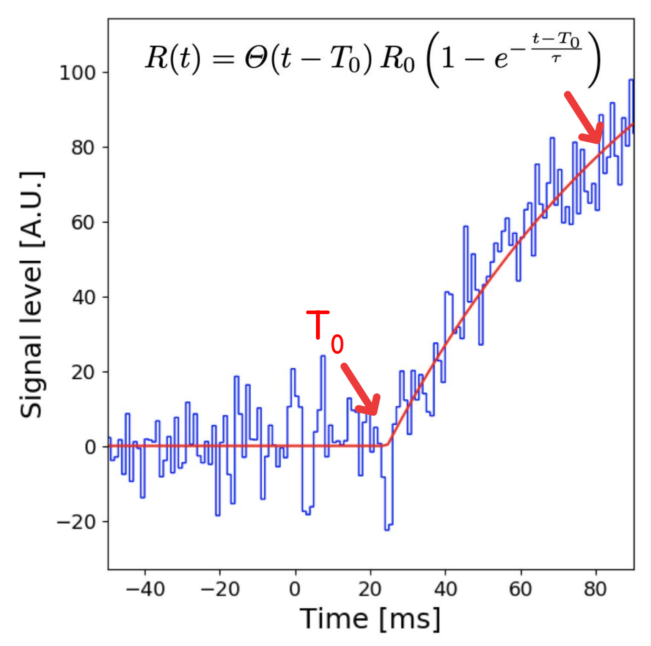
- Changing efficiency of KM3NeTs' PMTs
- Bioluminescence ⇒ varying number of active PMTs at a given moment



We use a previous detector configuration with enough statistics and rescale the rate to the new detector size

Implementation in KM3NeT's online analysis

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



- neutrinos can act as an early warning for optical follow-ups
- arrival times at different detectors ⇒ localisation of the source by triangulation
- the relative start time of the electron antineutrino signal with respect to the electron neutrino burst is tied to flavour conversion processes in the dense environment of the star, which in turn depend on the neutrino mass ordering
↳ arXiv:2204.13135

Challenge for CCSN alert systems

Disentangling, within minutes:

- CCSN localization - angular position and distance
- CCSN properties - neutron star equation of state, progenitor mass, radius
- Neutrino properties - mass ordering, interaction nature

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↳ this work: JCAP 2024, 02, 008

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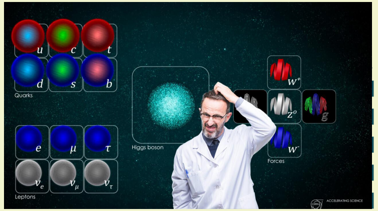
Case study: neutrino two-body decay:

$$\nu_{h,L} \rightarrow \nu_{\ell,L/R} + \phi$$



- Normalized supernova distance $\bar{r} = d/r_0$ where r_0 is the characteristic decay length for 10 MeV neutrinos
- Branching ratio of decays to active (vs sterile) neutrinos ζ

Standard model:

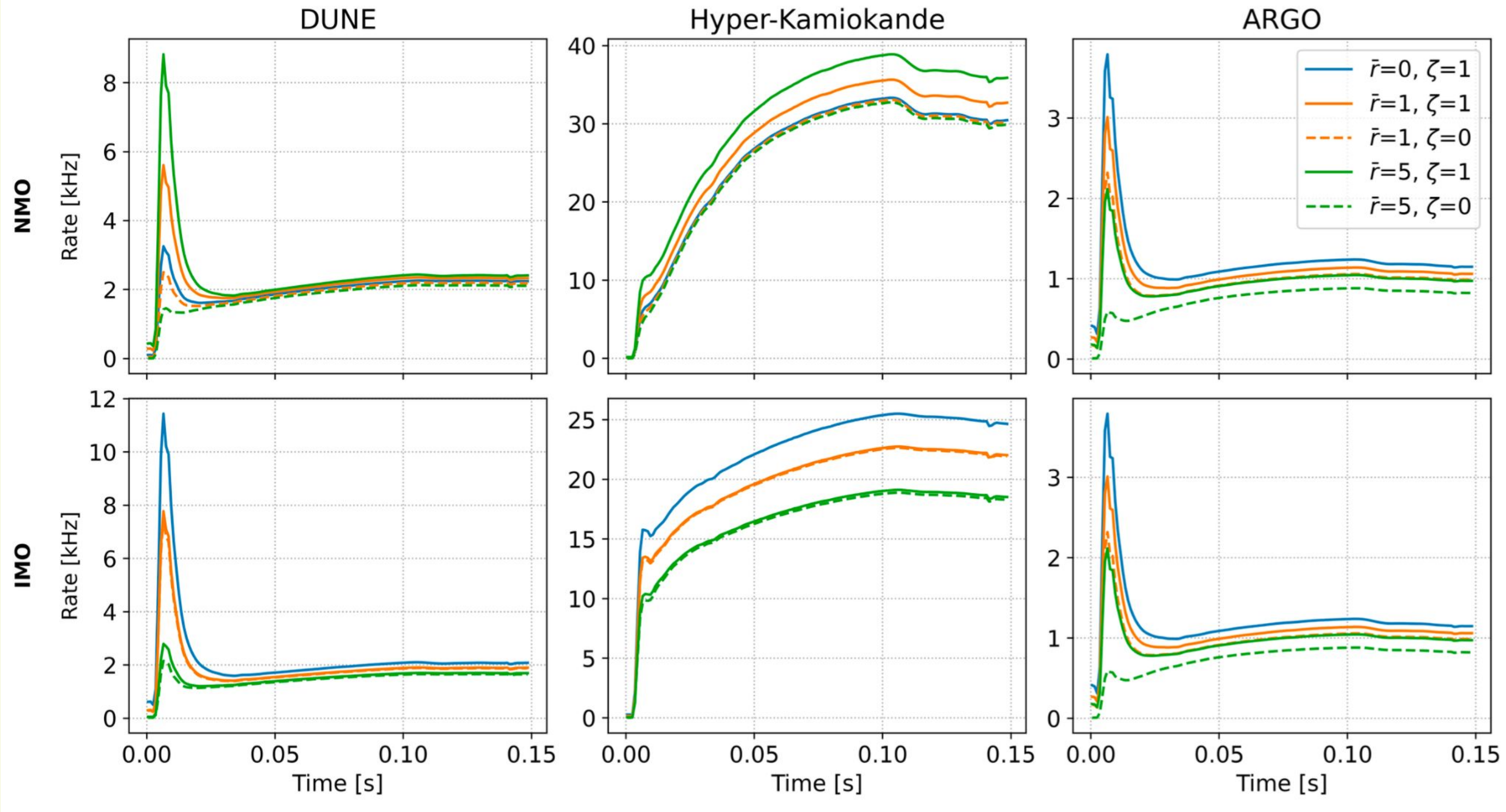
- $\bar{r} = 0$
- $\zeta = 1$

Solution: use flavor complementary detectors

<table>
<tr><th></th><th>Experiment</th><th>Detected ν flavour/type</th><th>Total mass (kT)</th><th>Efficiency at 0 MeV (%)</th><th>Background rate (Hz)</th></tr>
<tr><td rowspan="3">WC</td><td>Hyper-Kamiokande (HK)</td><td rowspan="3">anti - ν_e</td><td>260</td><td>100</td><td>0</td></tr>
<tr><td>IceCube</td><td>10^6</td><td>4.8</td><td>1.5×10^6</td></tr>
<tr><td>KM3NeT</td><td>2.1×10^5</td><td>0.07</td><td>4.5×10^6</td></tr>
<tr><td></td><td>DUNE</td><td>ν_e</td><td>40</td><td>100</td><td>0</td></tr>
<tr><td rowspan="2">CEνNS</td><td>DarkSide-20k</td><td rowspan="2">all</td><td>0.05</td><td>95</td><td>0</td></tr>
<tr><td>ARGO</td><td>0.35</td><td>95</td><td>0</td></tr>
</table>

WC: large-scale Water Cherenkov detector
CEνNS: large-scale detector sensitive to Coherent Elastic Neutrino-Nucleus scattering

How to use flavor complementary detectors



- 11 solar mass
- 10 kpc

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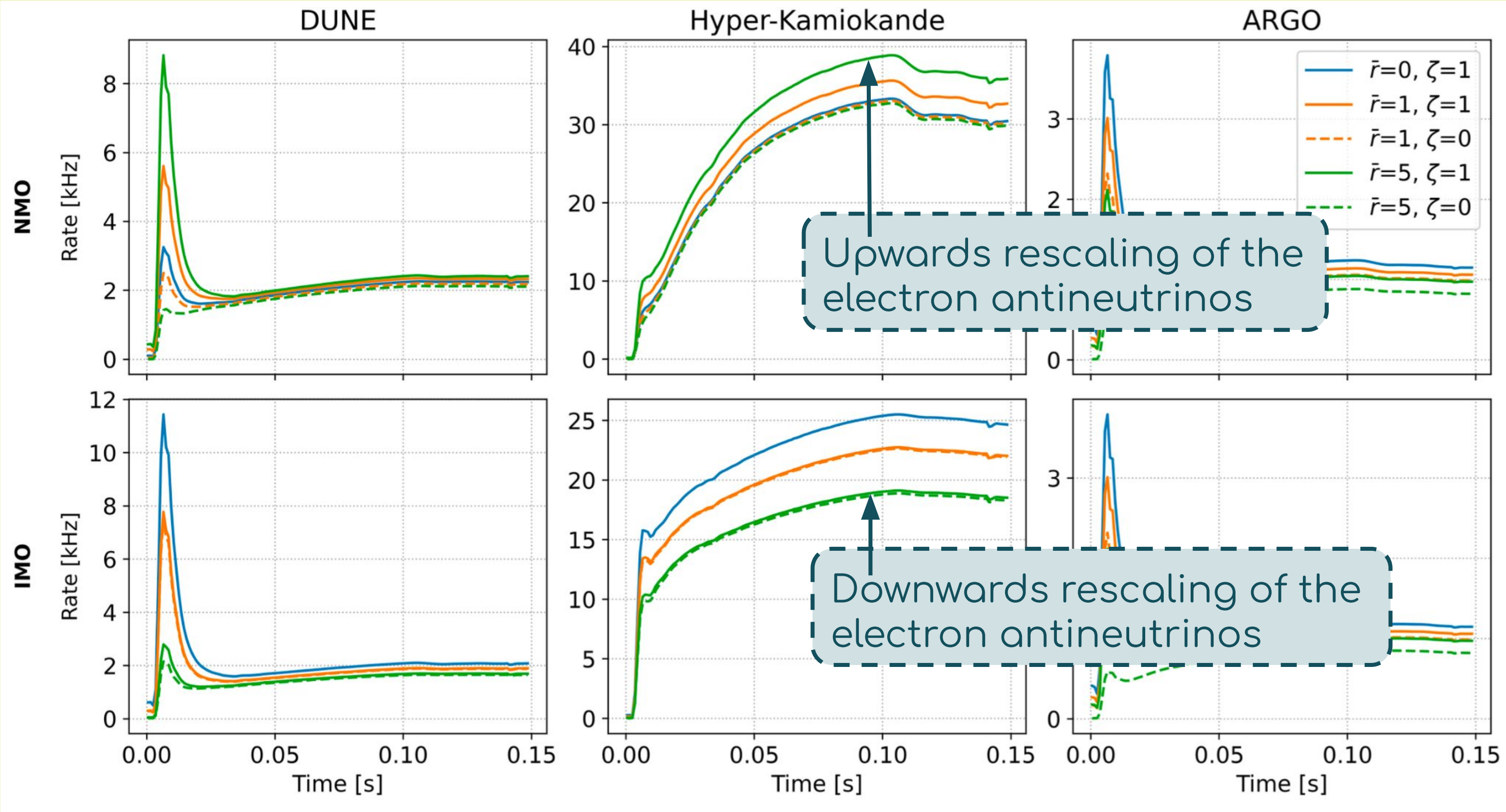


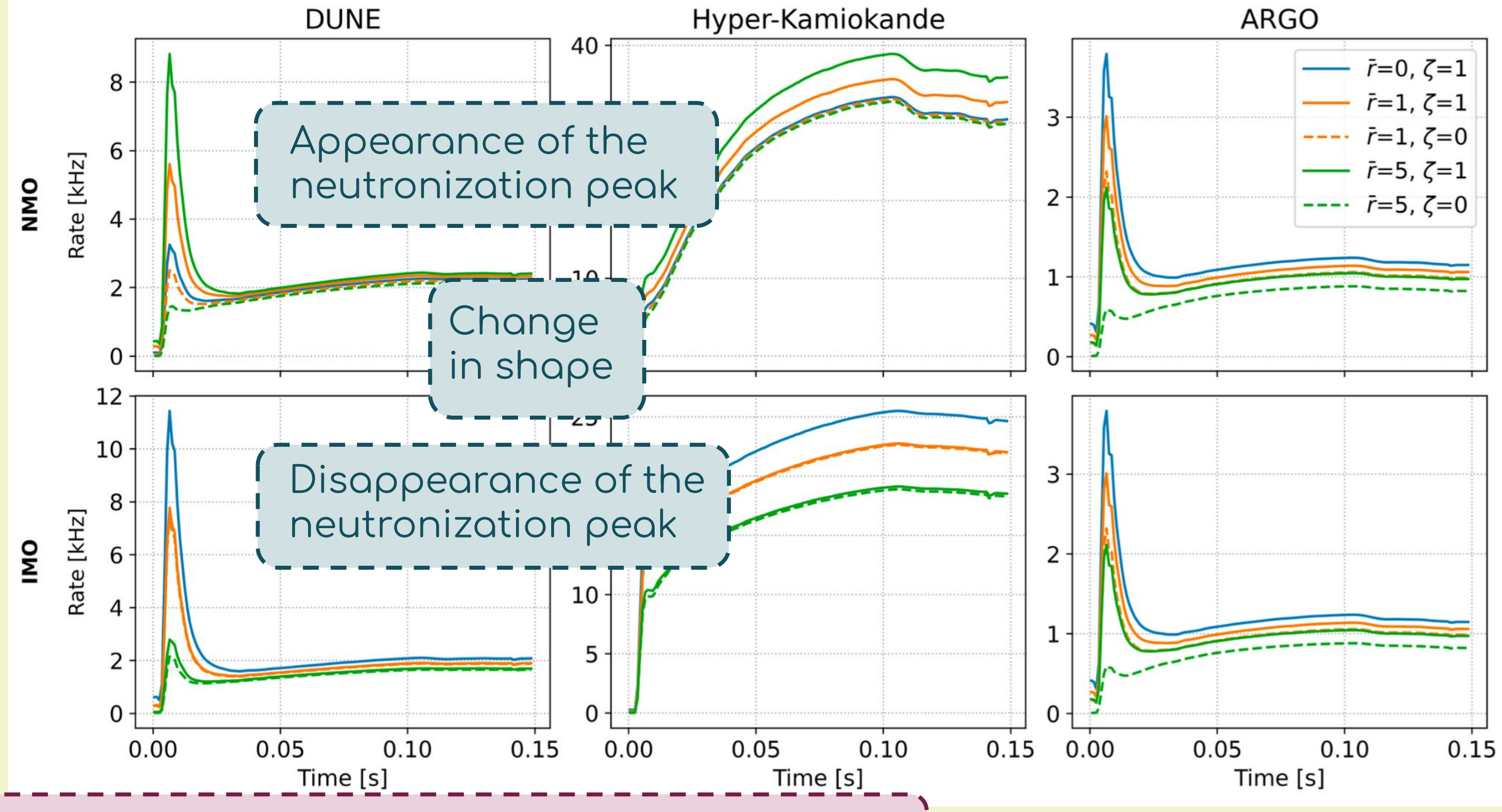
Upwards rescaling of the electron antineutrinos

Downwards rescaling of the electron antineutrinos

- 11 solar mass
- 10 kpc

Neutrino decays indistinguishable from change in distance.

How to use flavor complementary detectors



- 11 solar mass
- 10 kpc

One mass ordering mimics the other one.

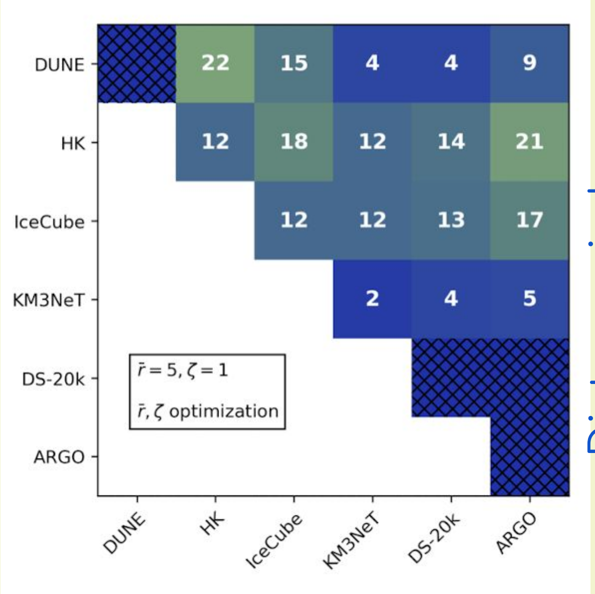
Step by step likelihood approach

Step1: determination of the mass ordering

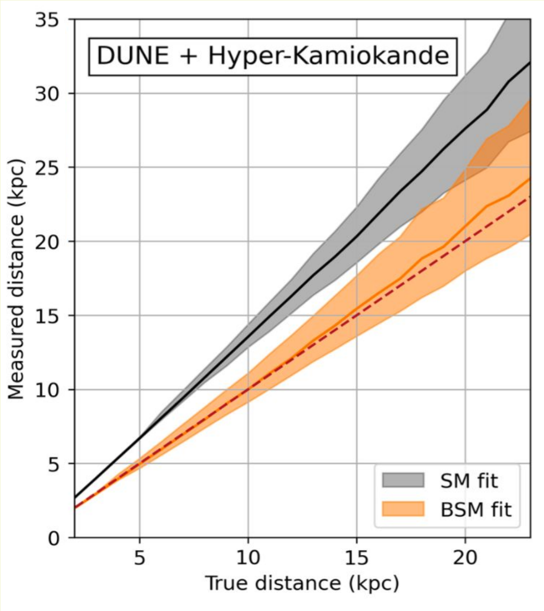
Step2: estimation of CCSN distance

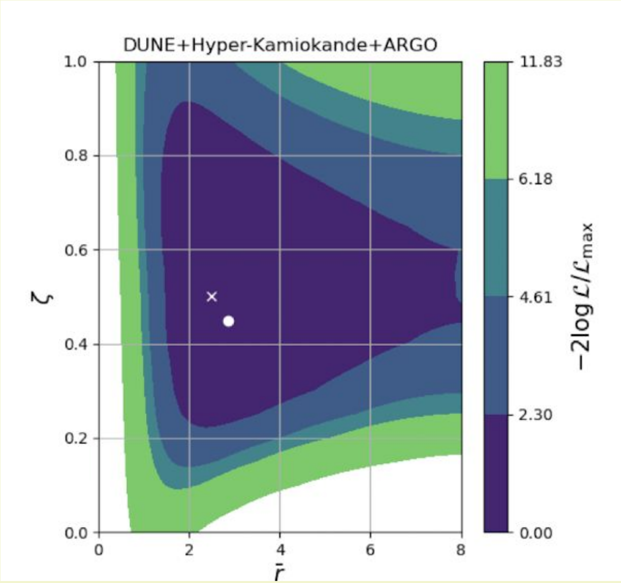
Step3: constraining the decay parameters

Maximal distance reach for 3σ IMO rejection:



Distance in kpc





Conclusions