Neutrinos from Core-Collapse Supernovae at KM3NeT

Unlocking the MeV range

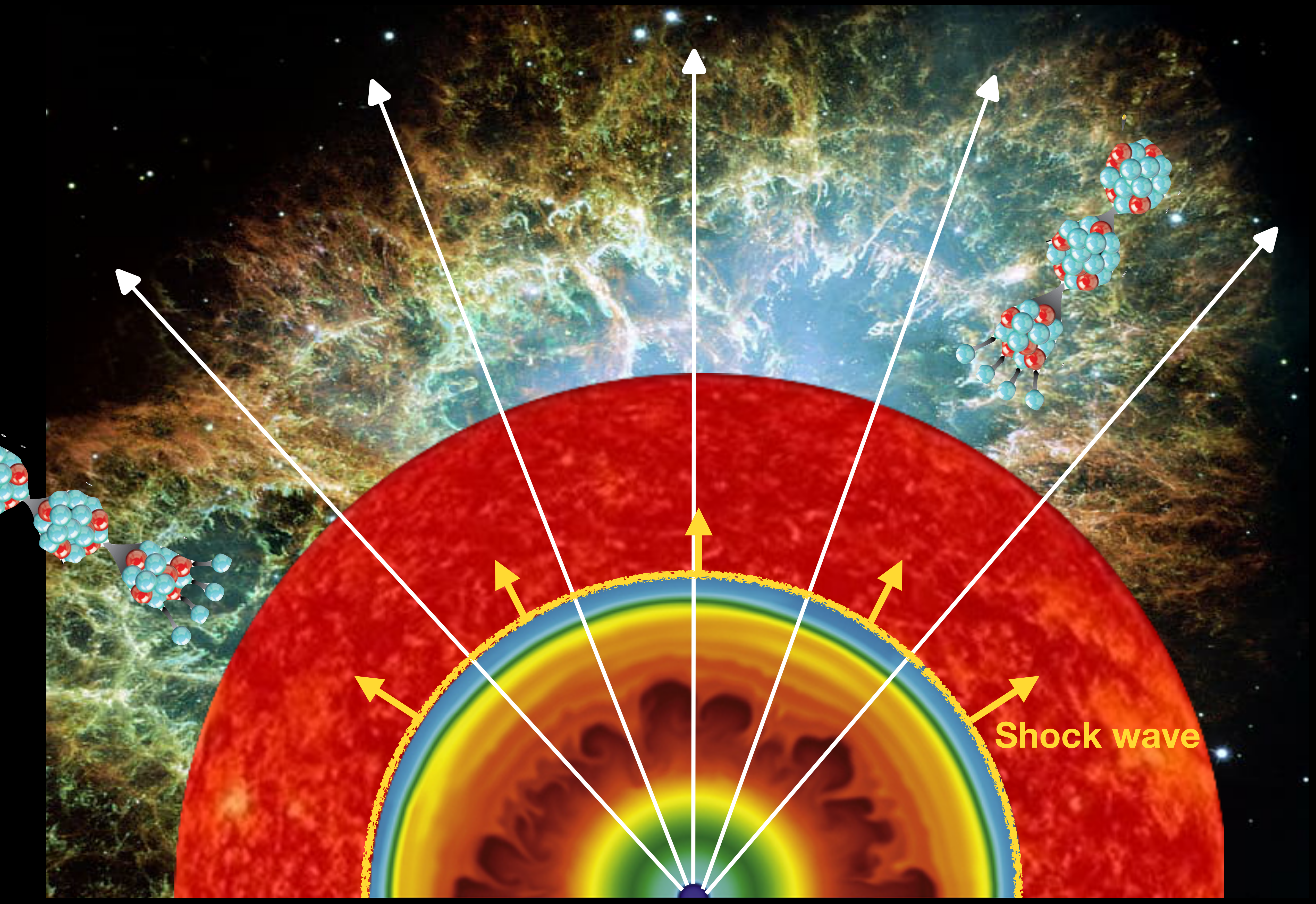
Sonia El Hedri, for the KM3NeT collaboration — 29/03/2023

KM3NeT

Labex UnivEarthS Université Paris Cité

Core-collapse supernovae

Extreme, complex, and not-fully-understood phenomena



Proto-neutron star

- End of life of a heavy star ($> 8\ M_\odot$)
- Collapse of the core of the star: explosion or black hole formation
- Nucleosynthesis of heavy elements key role in star formation
- Explosion conditions not fully understood
  $\Rightarrow$ Need to observe the core of the star

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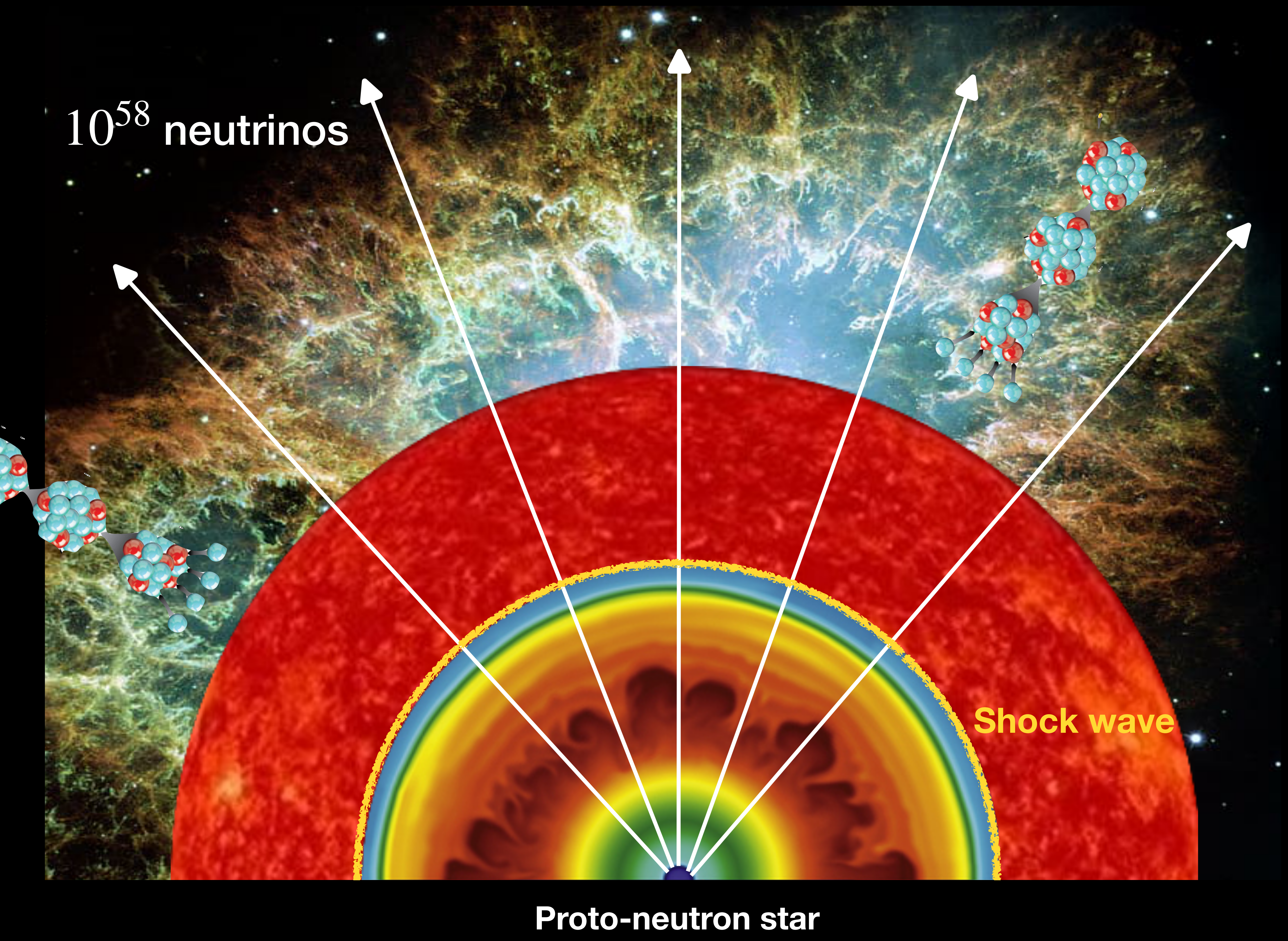

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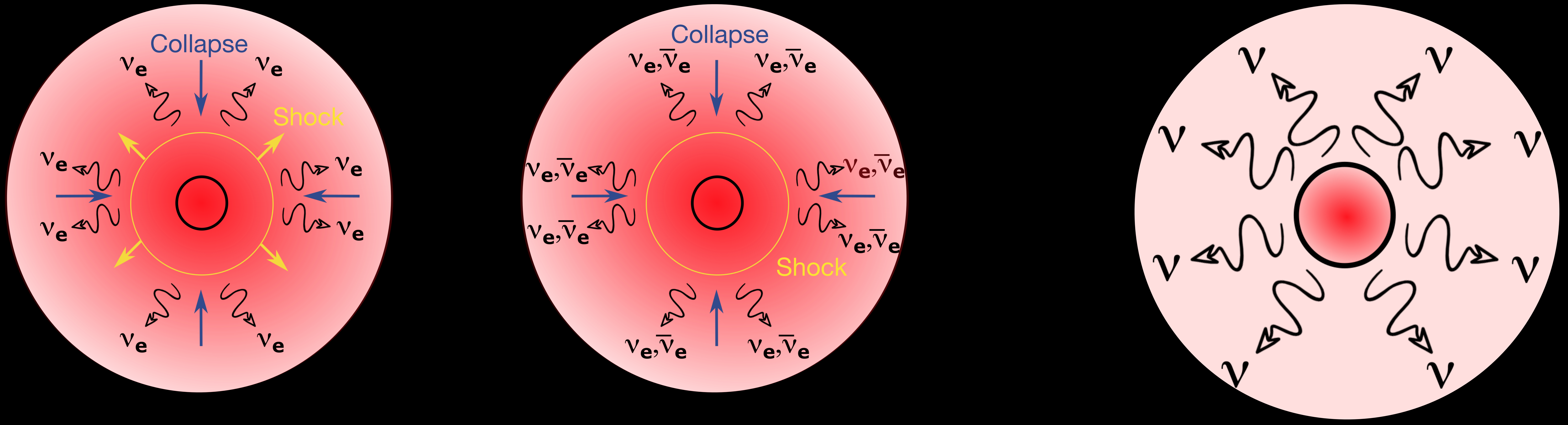
Counting supernova neutrinos

A first-hand account of the core-collapse process



H. T. Janka [arXiv:1702.08713]

- Intense burst of **thermal $\mathcal{O}$(10 MeV) neutrinos**
- **Advance warning** for telescopes + **analysis window** for gravitational wave detectors

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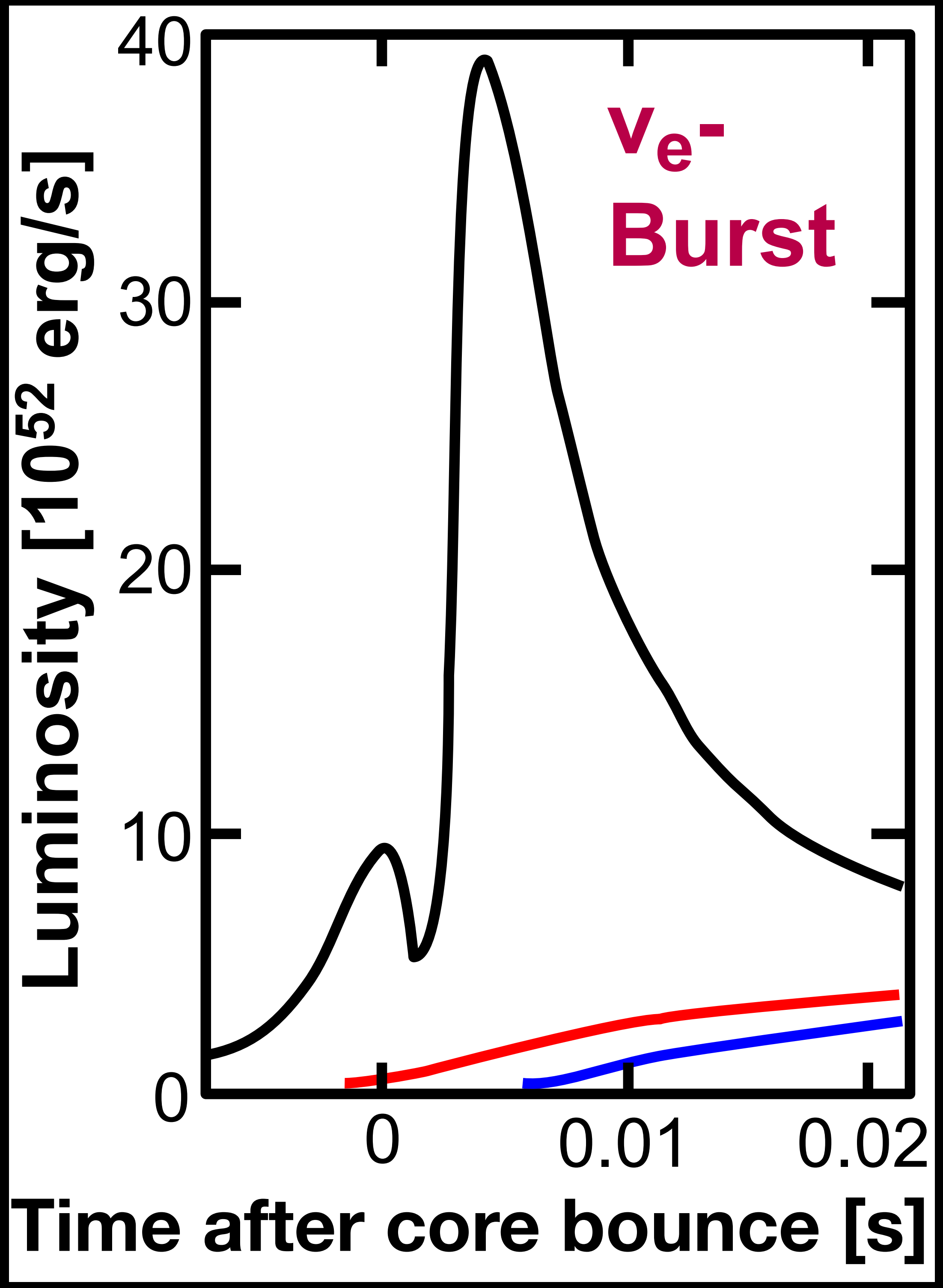

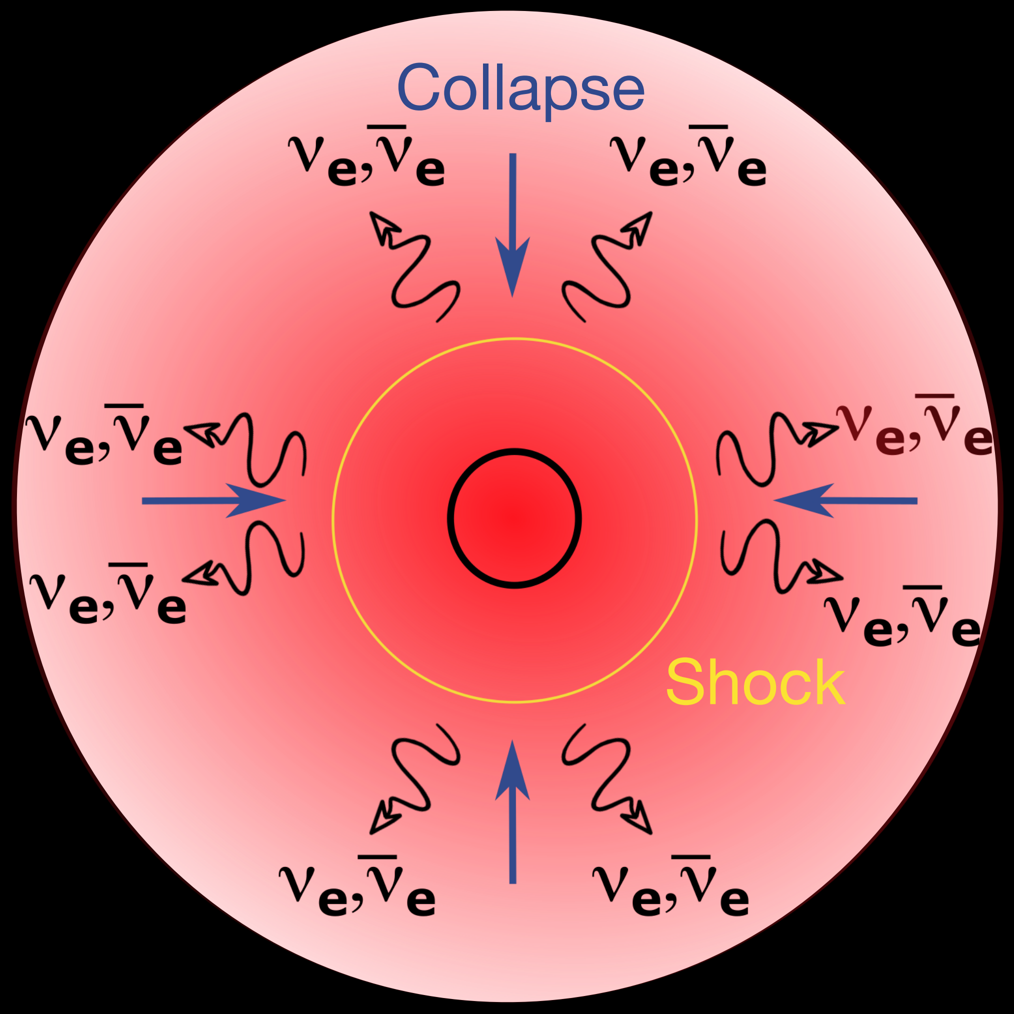

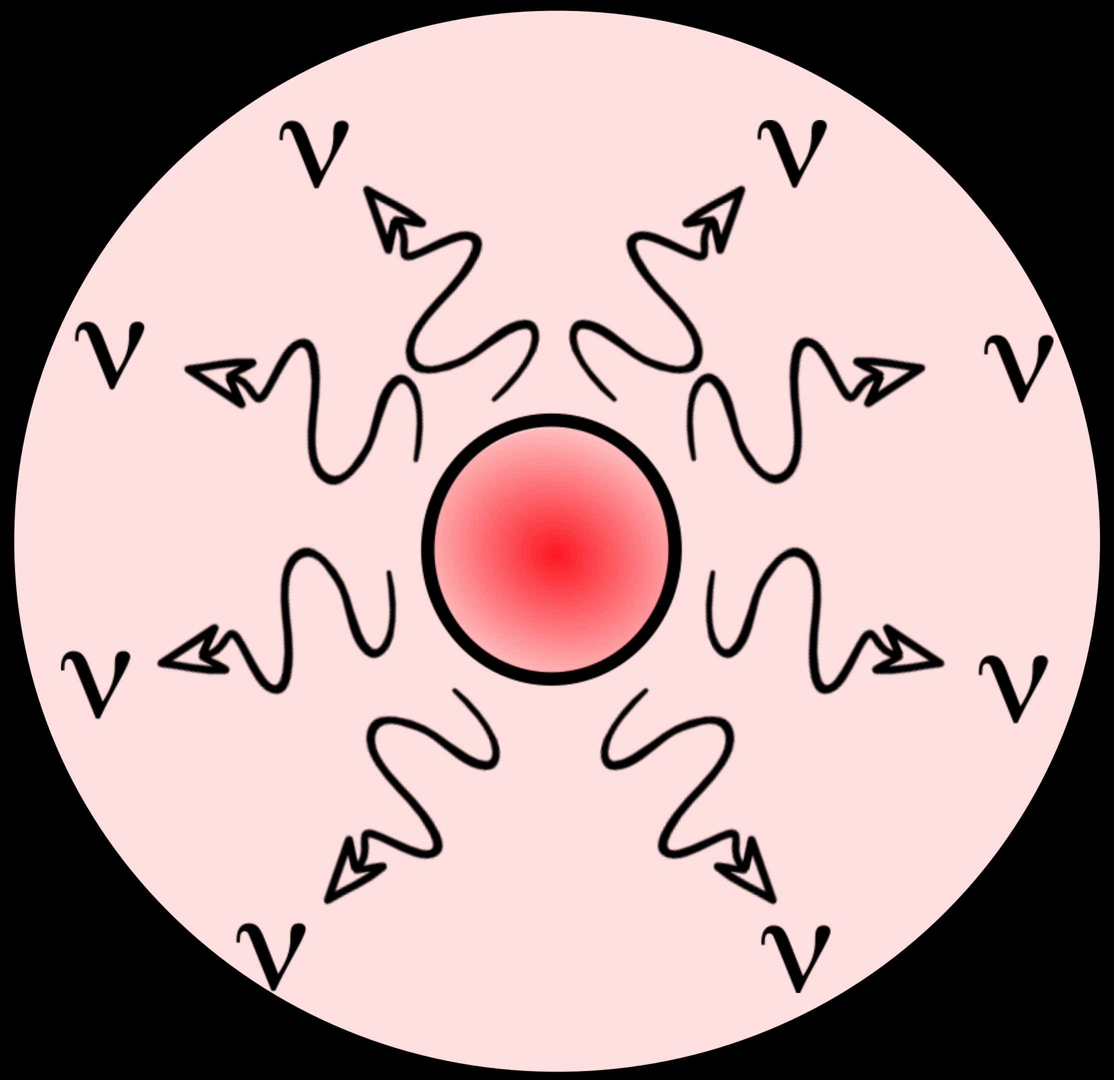

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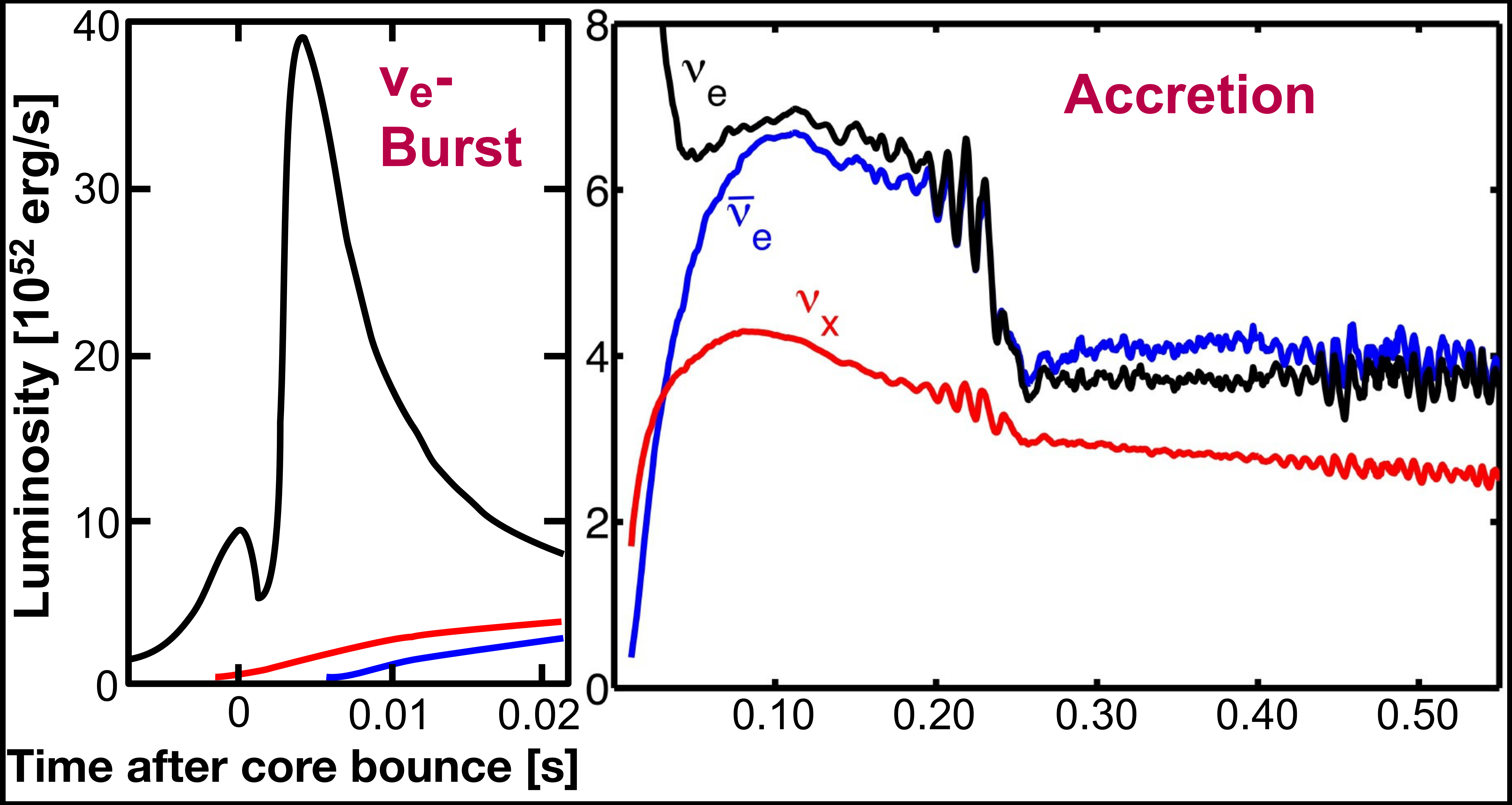

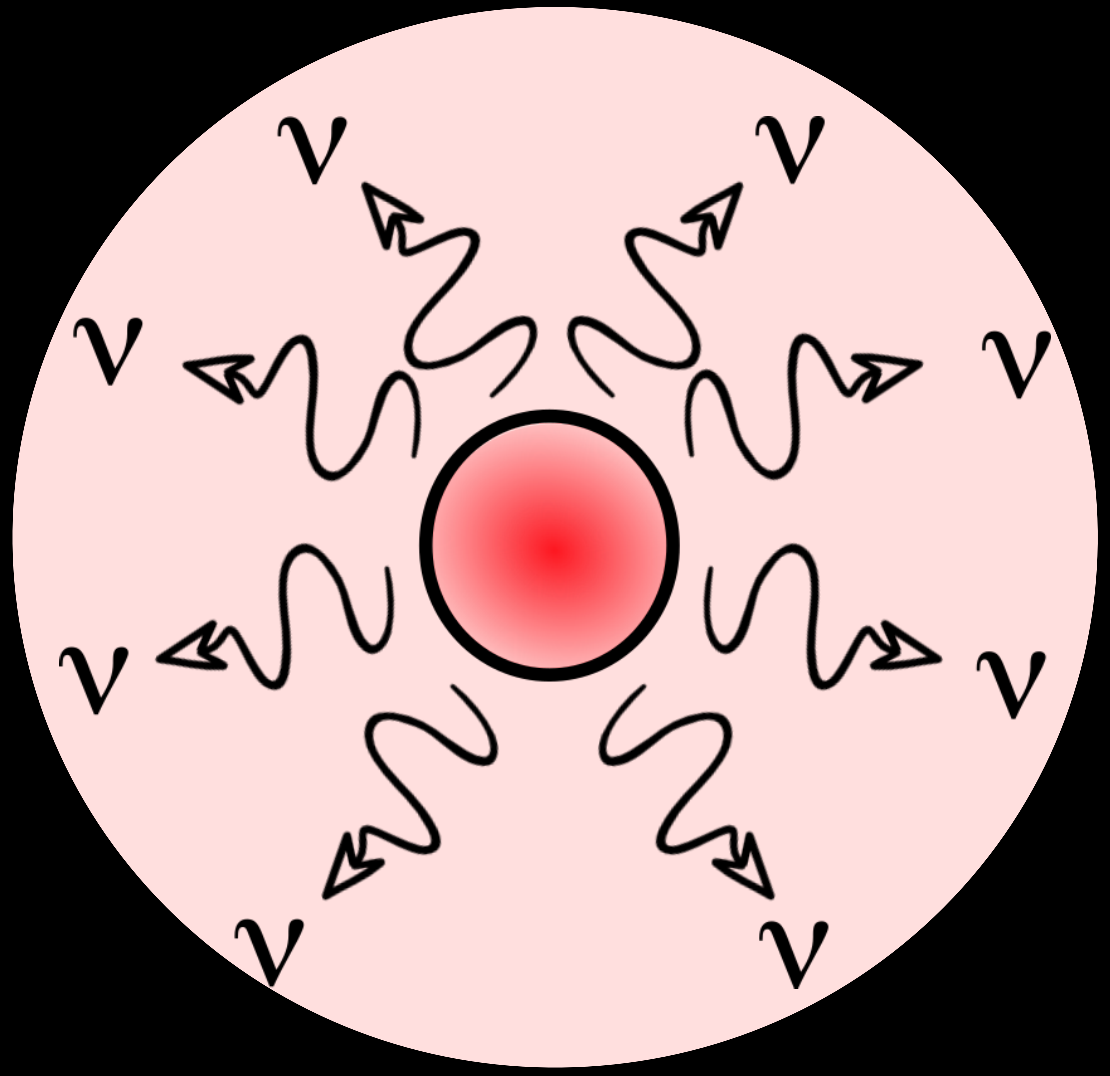

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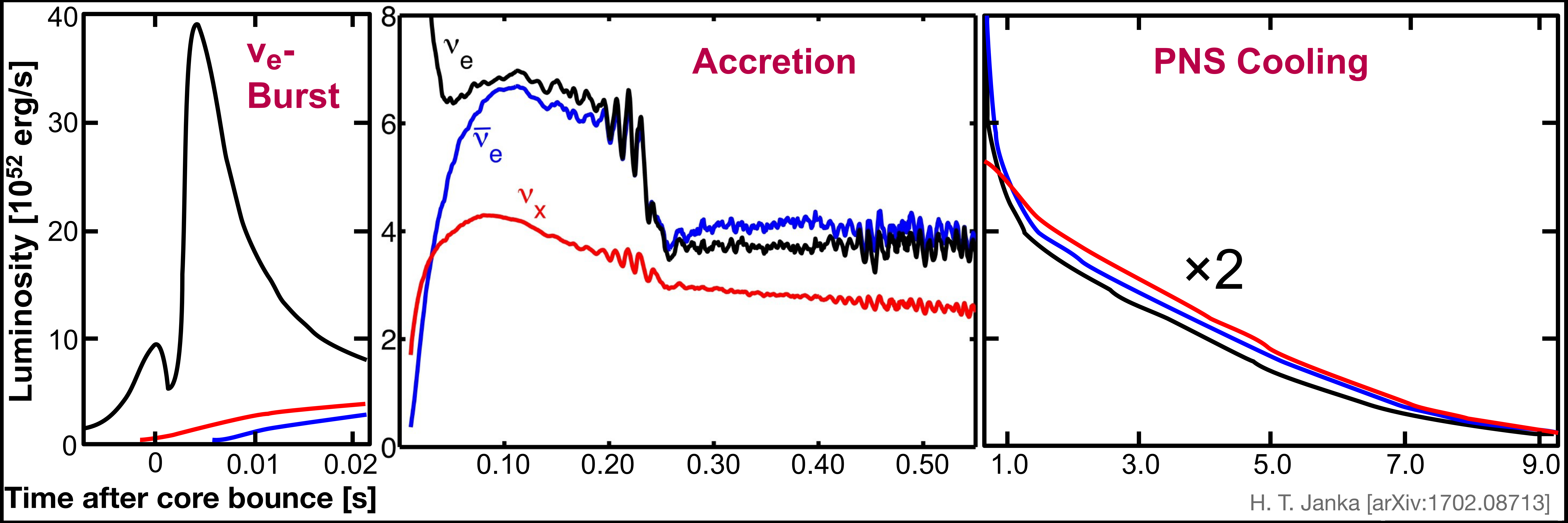

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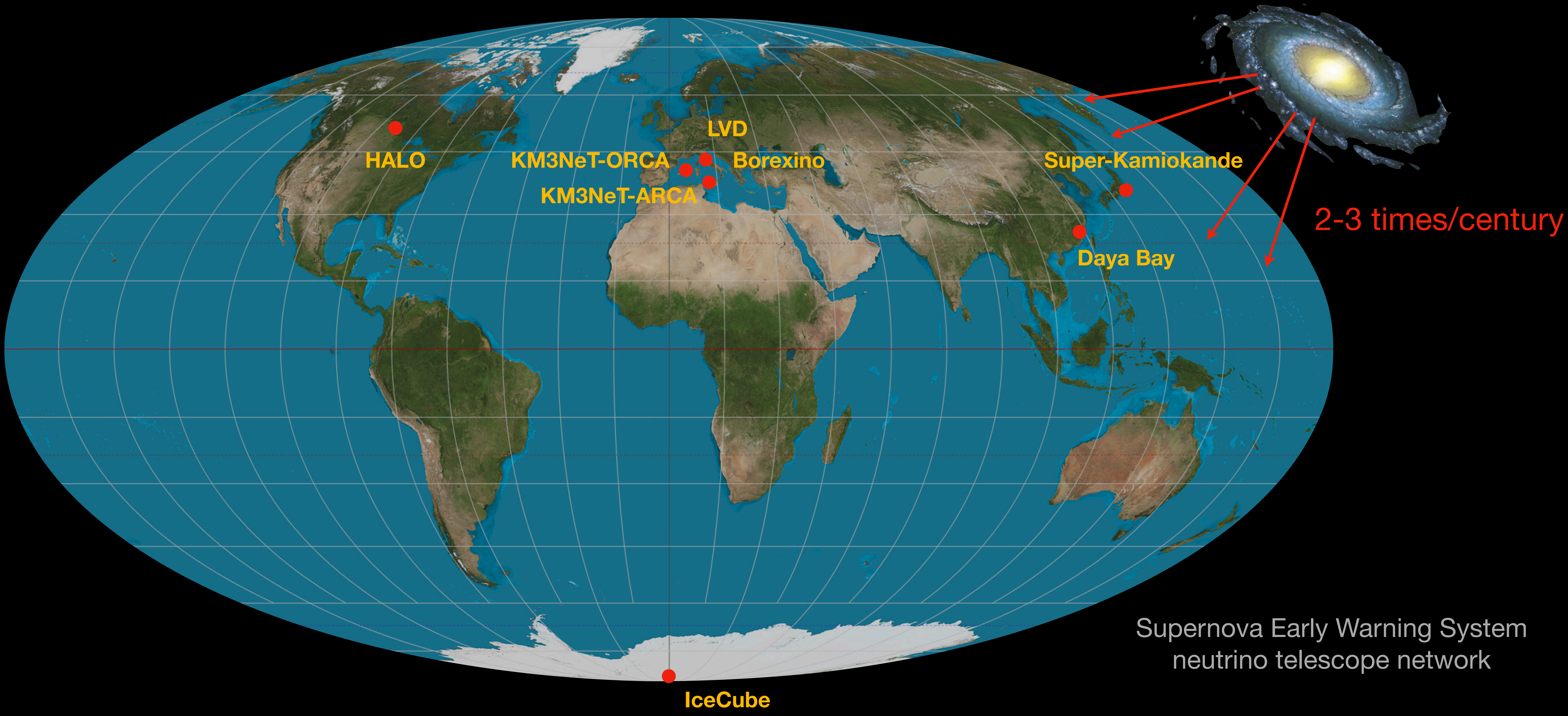
Neutrino telescope networks

Capturing an extremely rare and short event



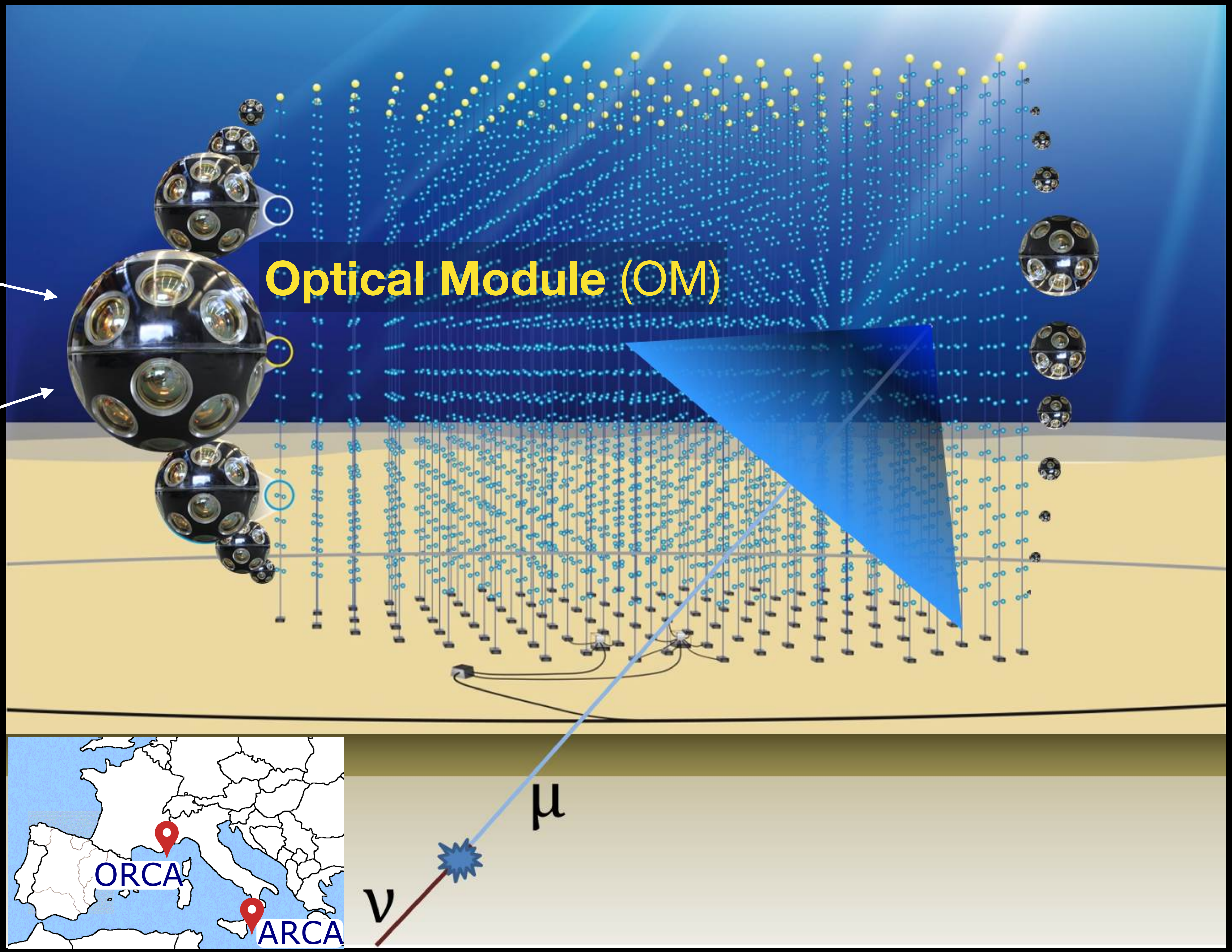
Supernova Early Warning System
neutrino telescope network

The KM3NeT experiment

Water Cherenkov detector in the Mediterranean Sea

- **ORCA**: 2500 m depth — 8 Mton
  115 lines — 2070 OMs
  1 GeV — 100 GeV neutrinos

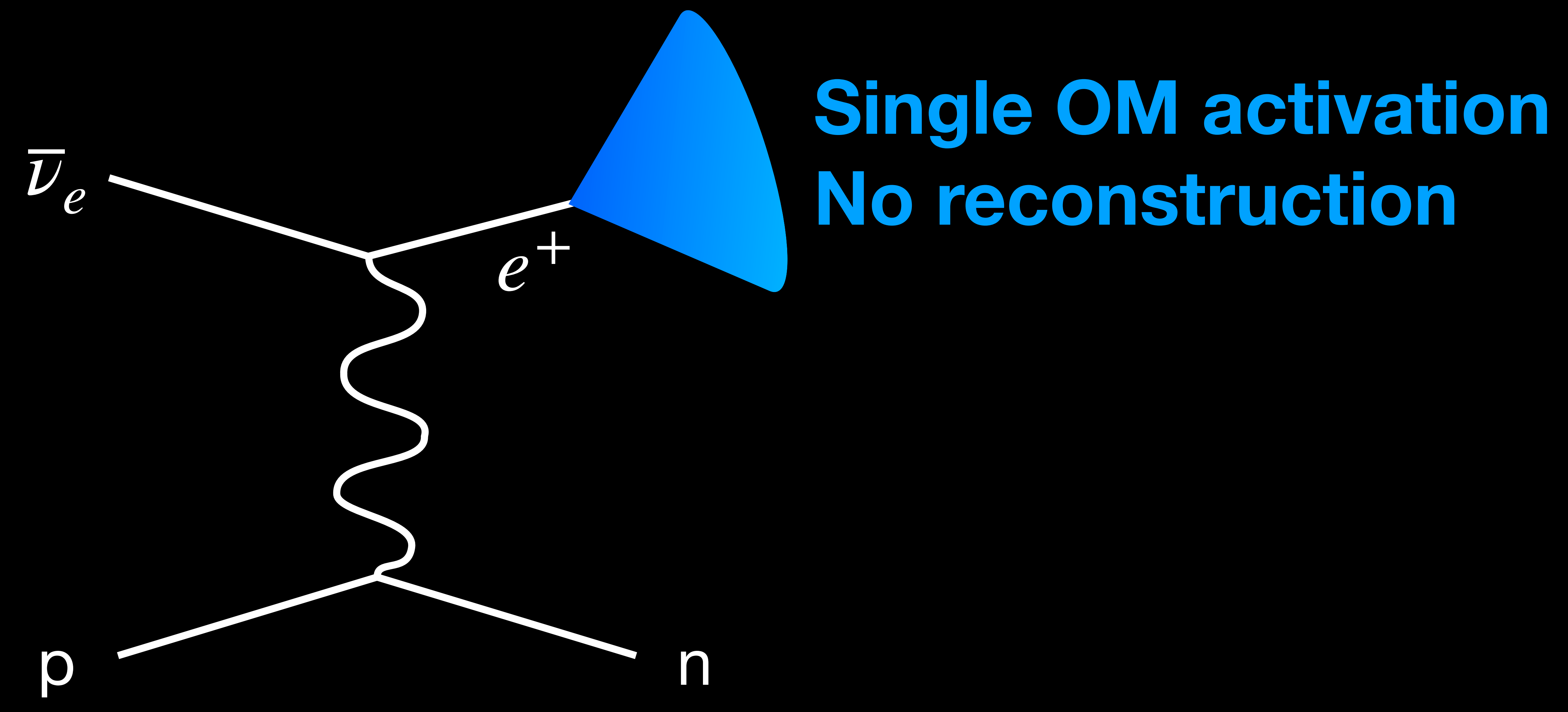
- **ARCA**: 3500 m depth — 1 km^3
  2 x 115 lines — 2 x 2070 OMs
  100 GeV — 100 PeV neutrinos



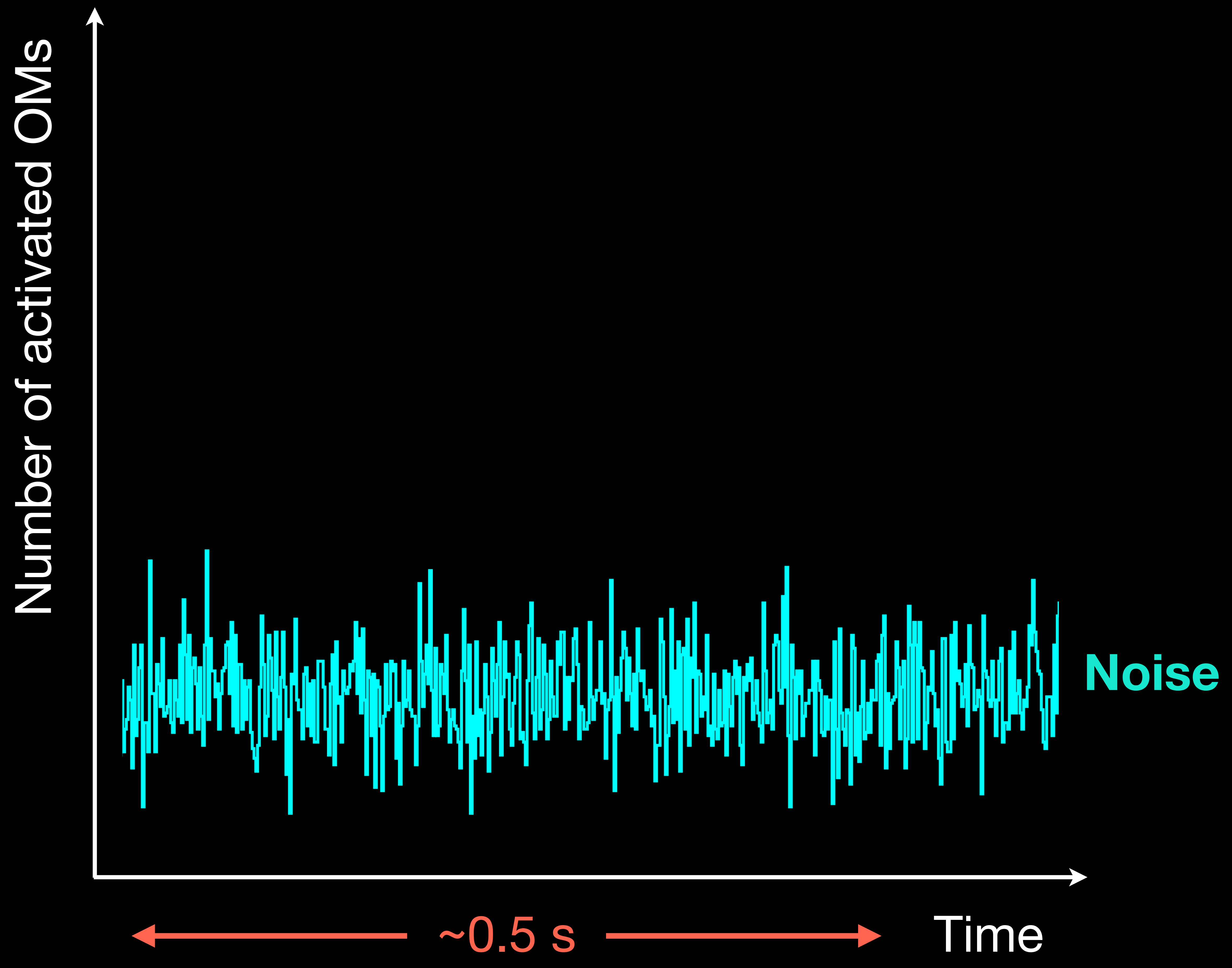
⇒ Taking data right now!
ORCA: 15 lines — ARCA: 21 lines

Counting supernova neutrinos

Monitoring supernovae without event reconstruction



Inverse Beta Decay
$\mathcal{O}$(10 MeV) electron antineutrinos



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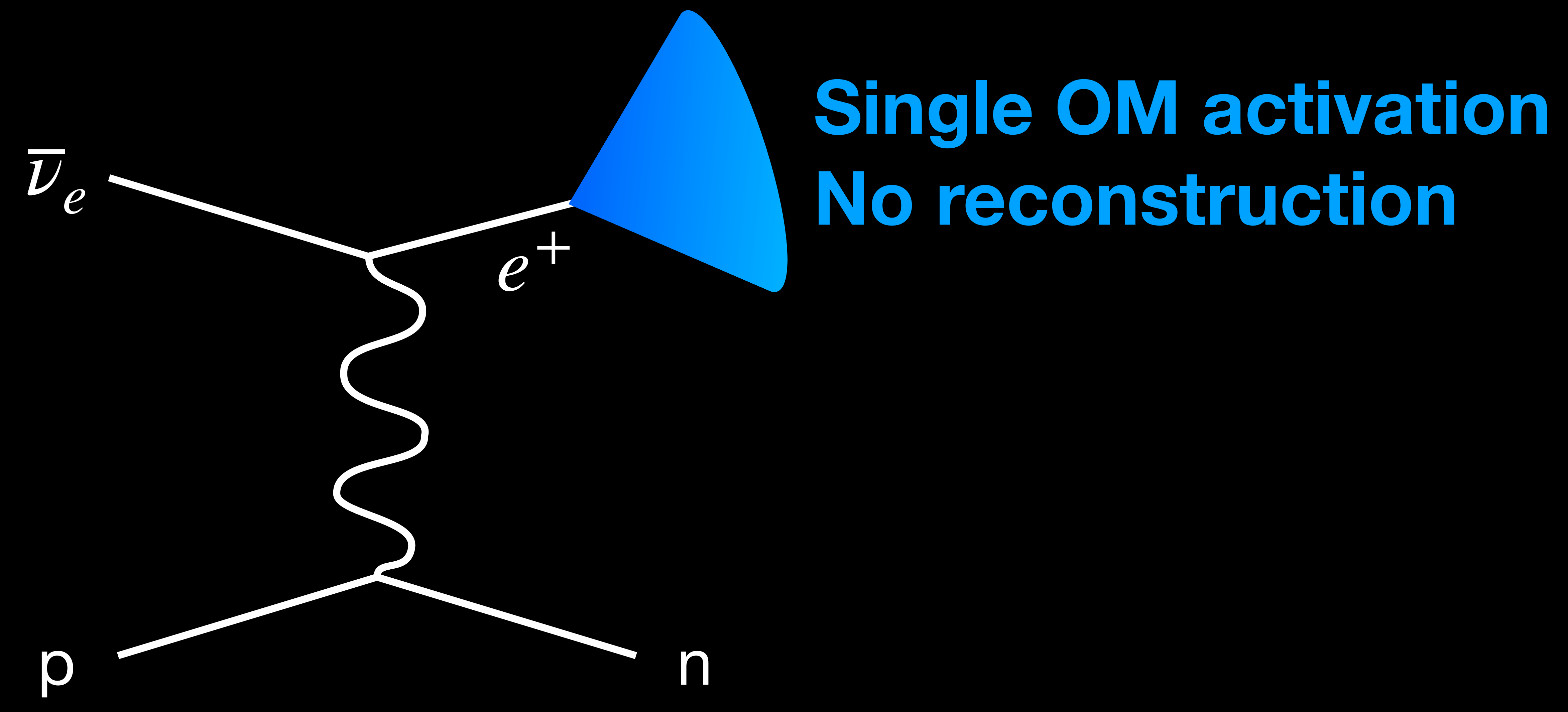

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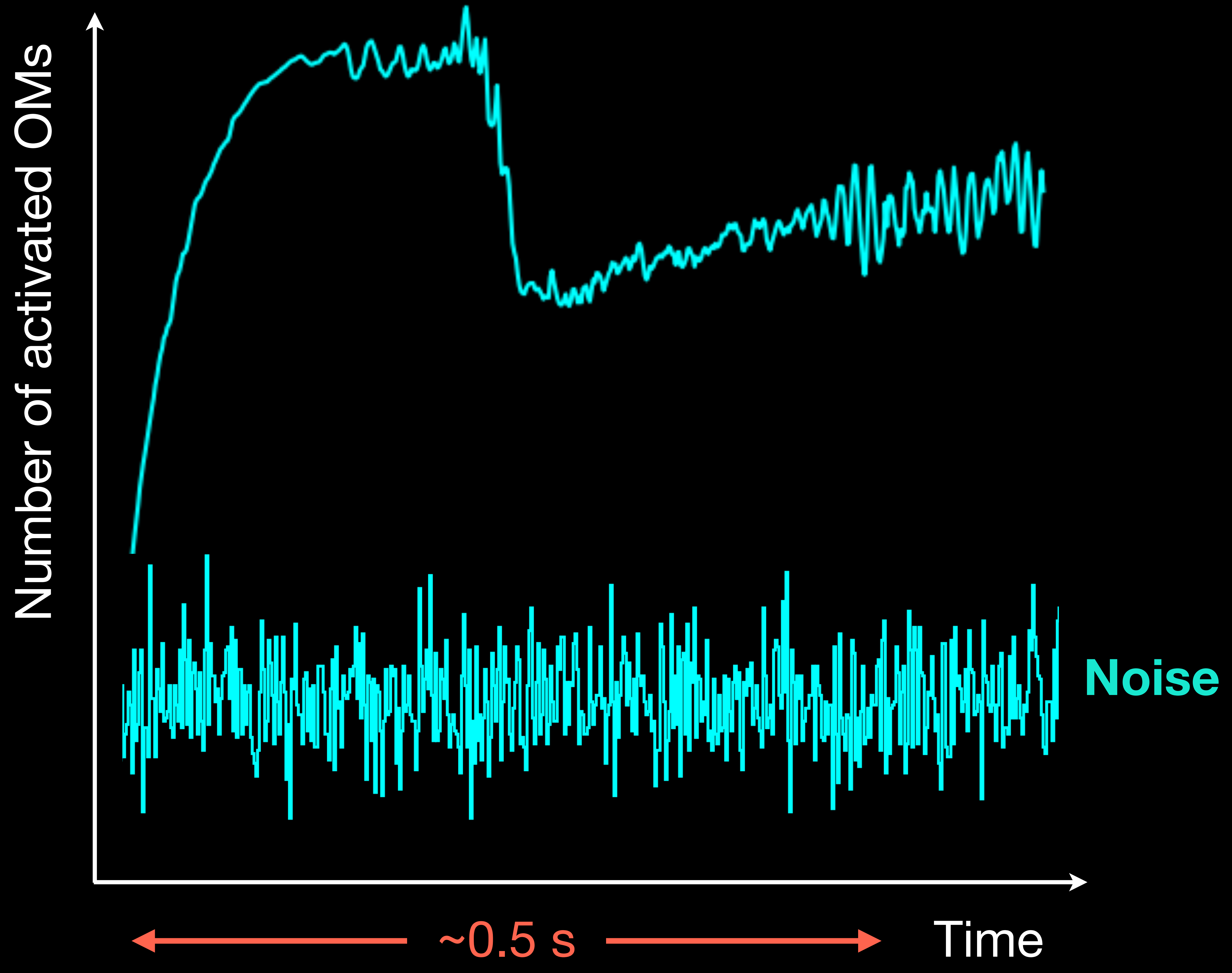

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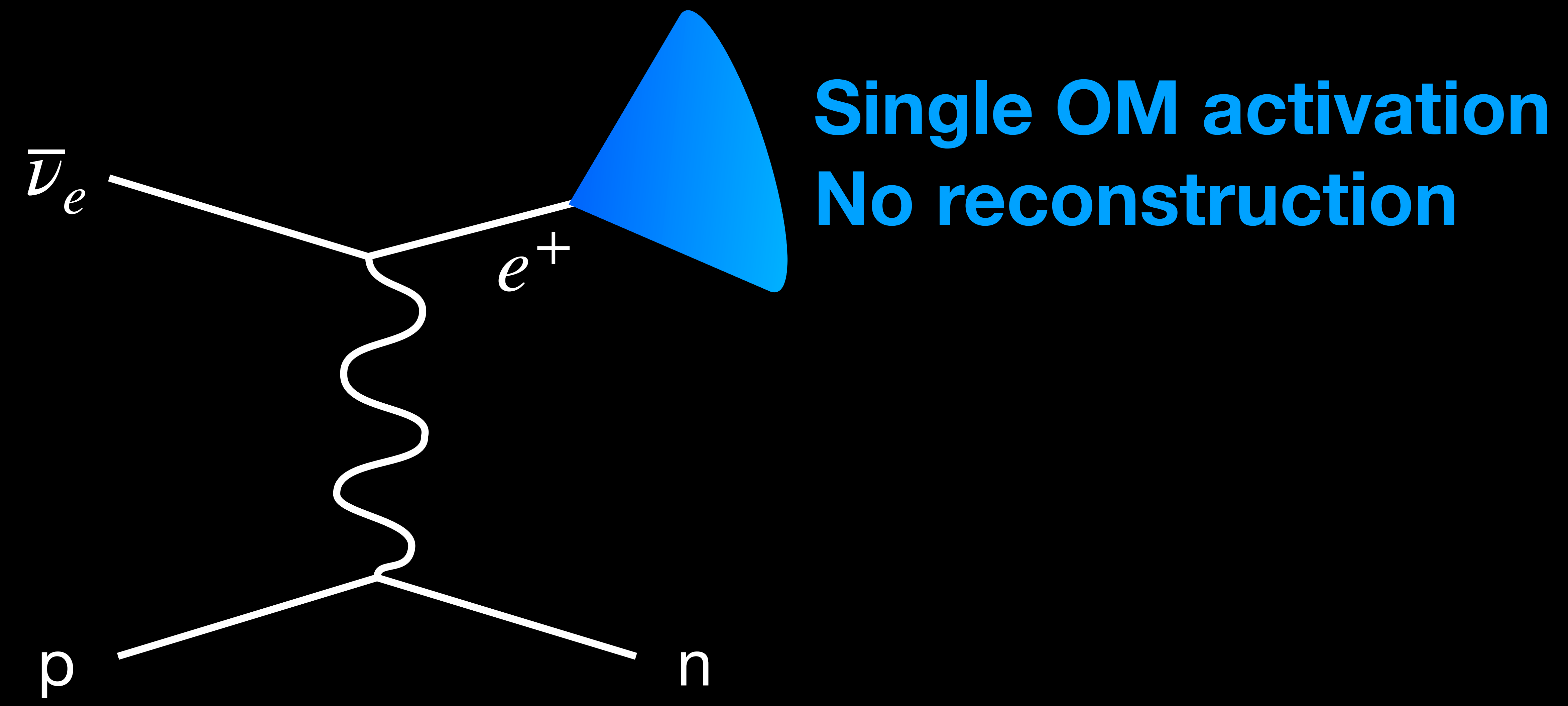

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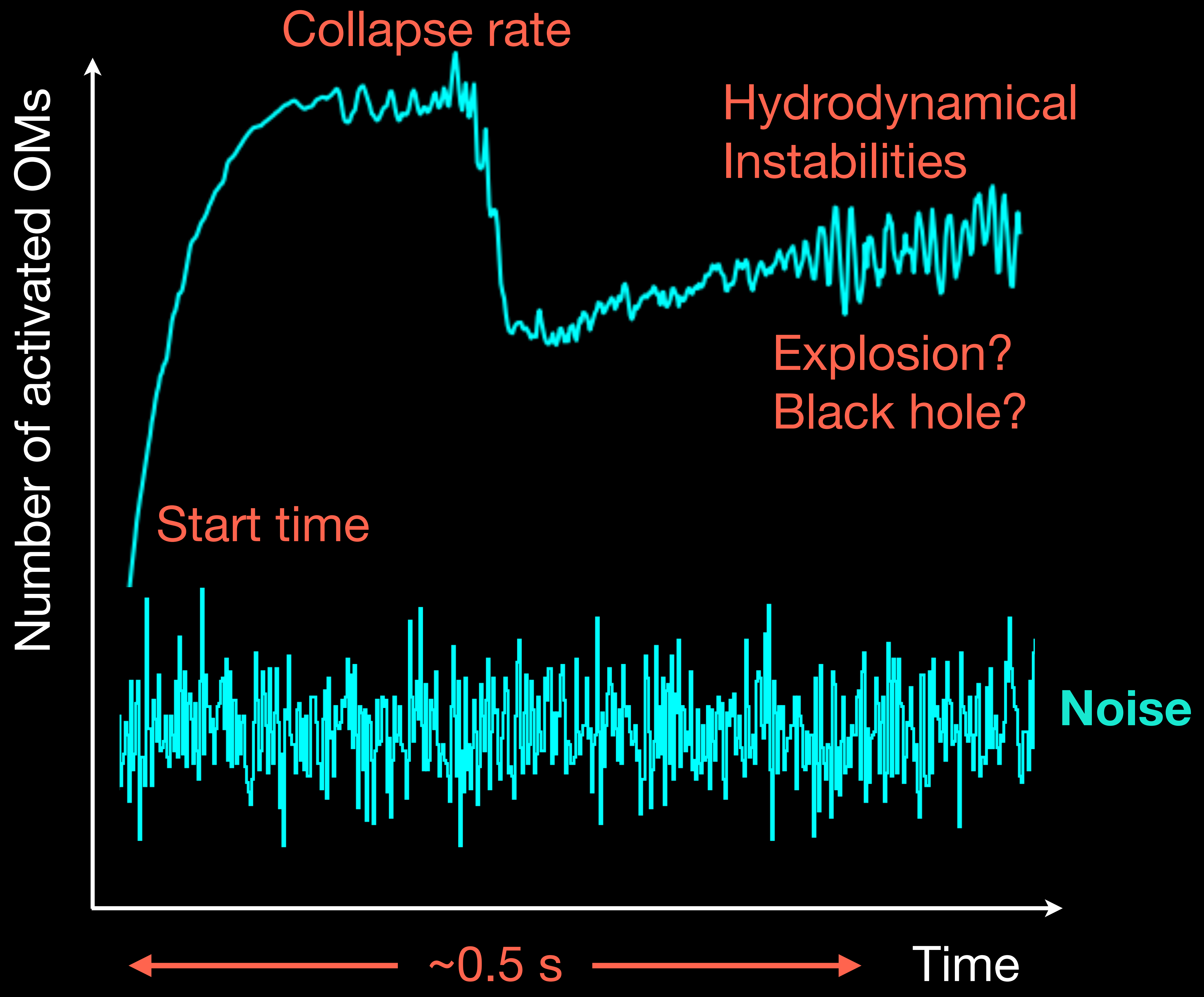


Interlude — Physics with ChatGPT

EL

Is the Mediterranean sea an ideal location to search for supernova neutrinos?

Interlude — Physics with ChatGPT

EL Is the Mediterranean sea an ideal location to search for supernova neutrinos?

Proximity to Sources: The Mediterranean Sea is located near several regions of the sky that are expected to contain many supernova explosions, such as the Milky Way and other nearby galaxies. This proximity makes it easier to detect supernova neutrinos from these sources.

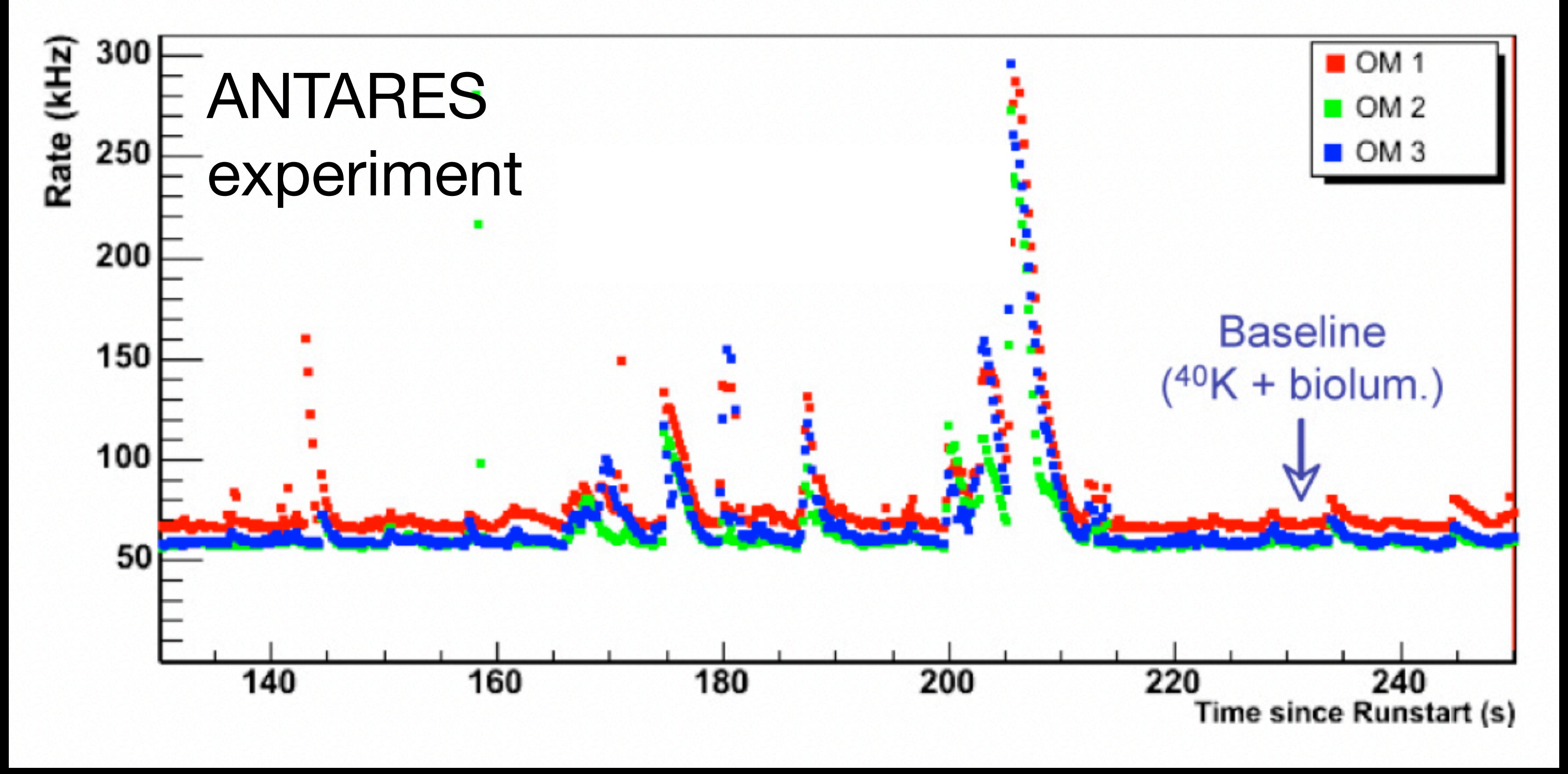
While the Mediterranean Sea is a large body of water, it does not have the infrastructure or the specialized detectors that are needed to detect supernova neutrinos. Additionally, the sea is not located underground, which would limit its ability to detect these weakly interacting particles.

Fishing low-energy neutrinos

Back to science…

- Radioactivity: ^{40}K in seawater
  + Uranium, Thorium in water & glass
  $\Rightarrow$ 100 kHz per OM

- Bioluminescence: living organisms
  seasonal variations + short bursts
  Unstable background, $\mathcal{O}$(100 kHz)/OM



KM3NeT Technical Design Report

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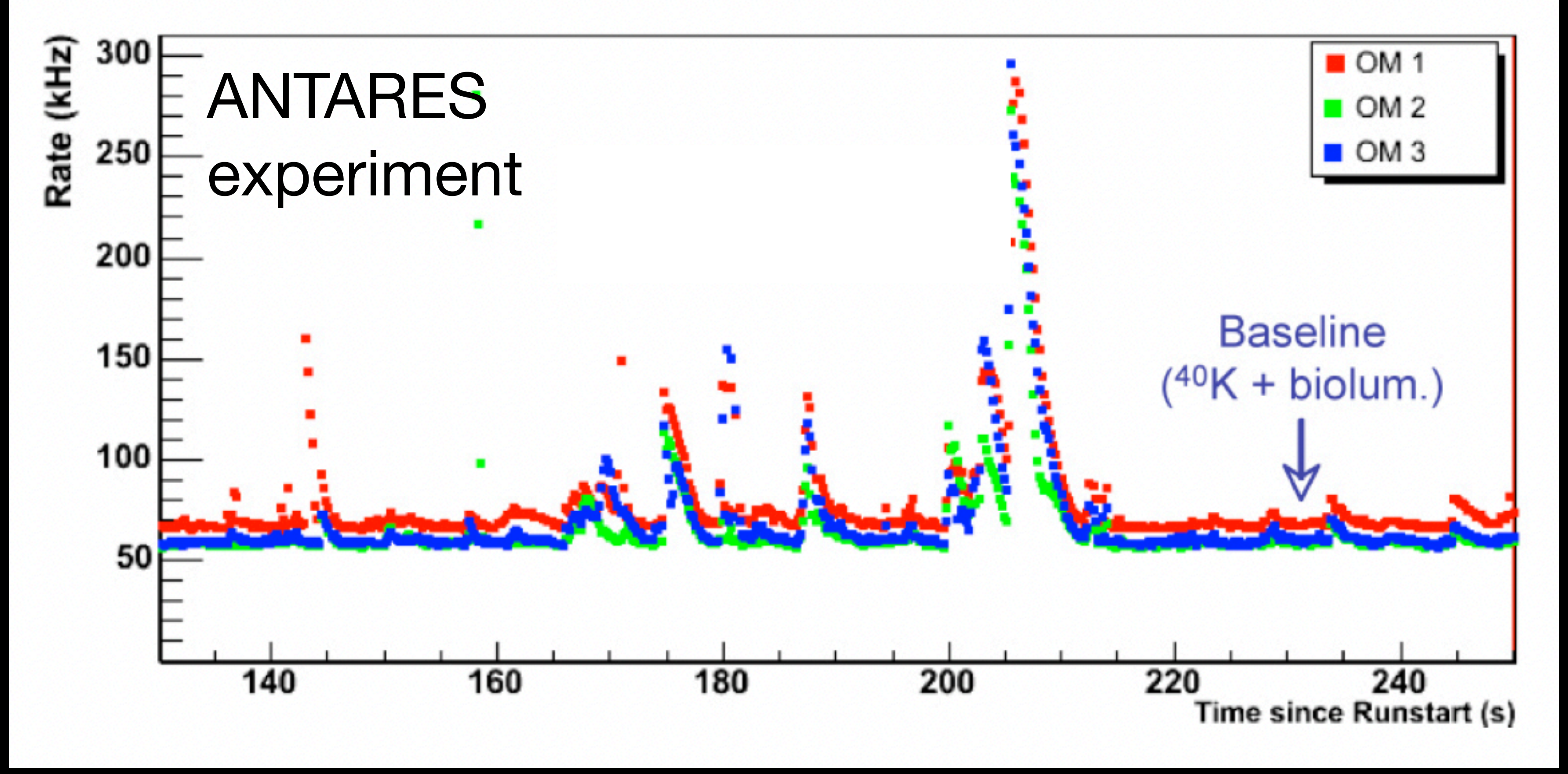
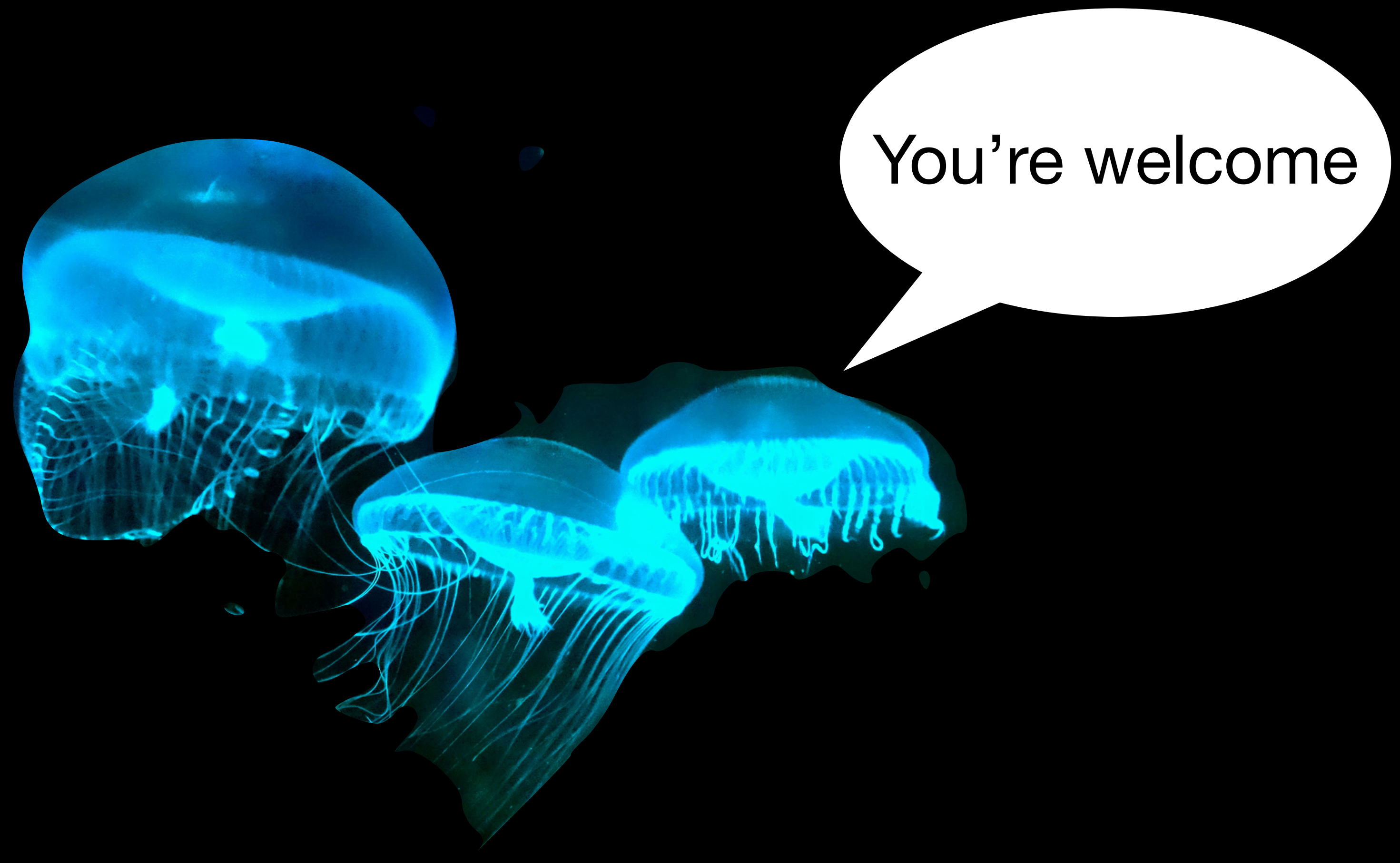


KM3NeT Technical Design Report

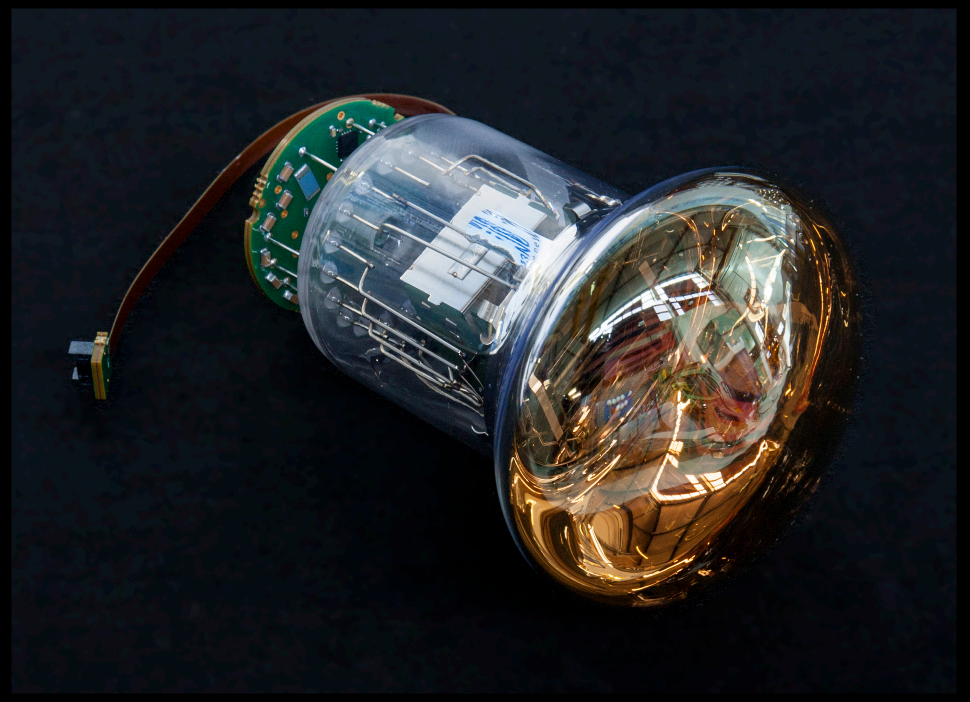
600 million background events in ORCA+ARCA in 0.5s



A game-saver: multi-PMT optical modules

A 31-pixel camera for low-energy events

44 cm

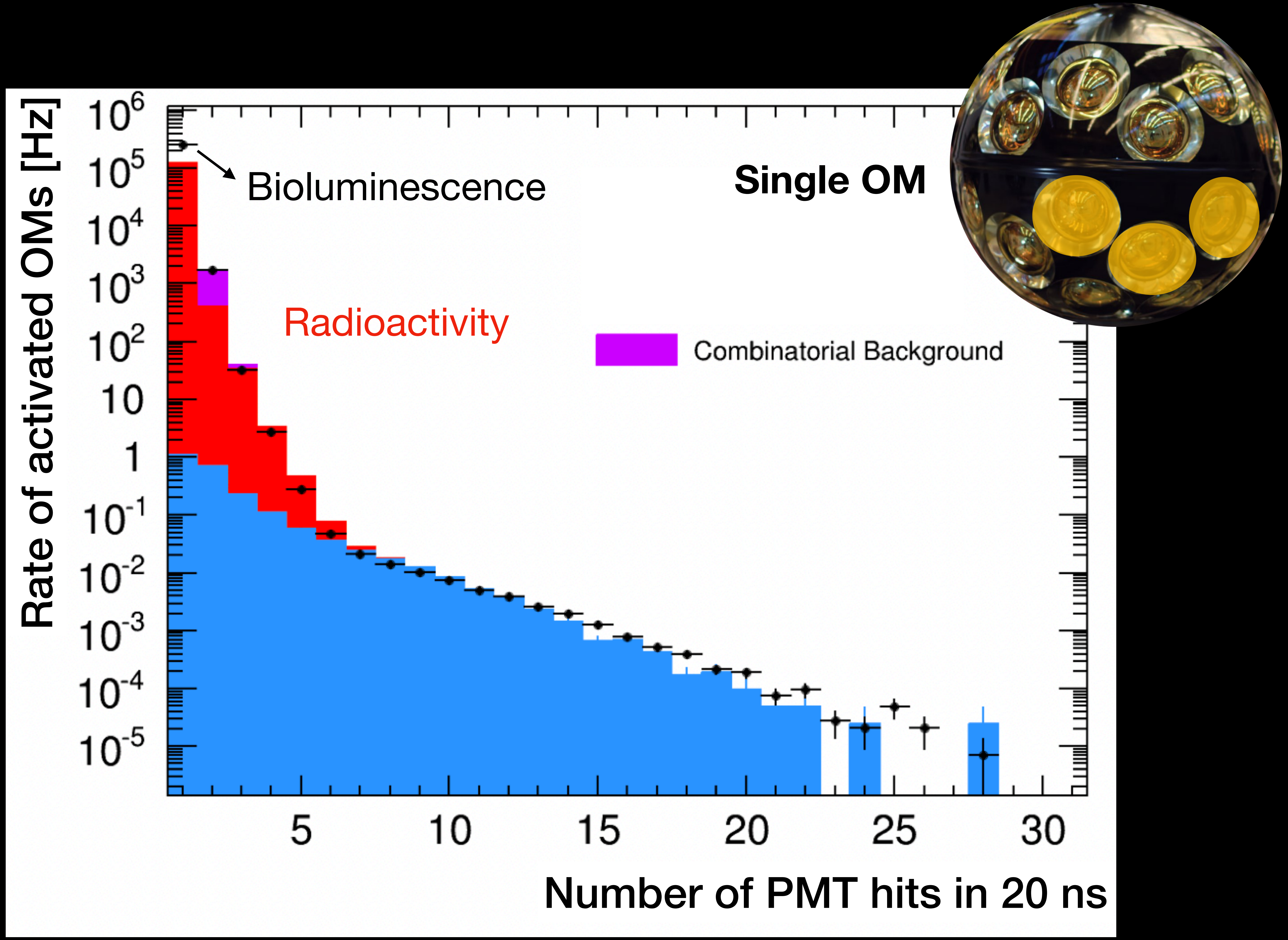


31 3-inch photomultipliers (**PMT**s)

Cherenkov light
MeV-scale particles

Counting photomultiplier hits

KM3NeT's dominant background depends on hit multiplicity



Number of activated PMTs in a 20 ns window

KM3NeT collaboration, *Eur. Phys. J. C* 74 (2014)

Counting photomultiplier hits

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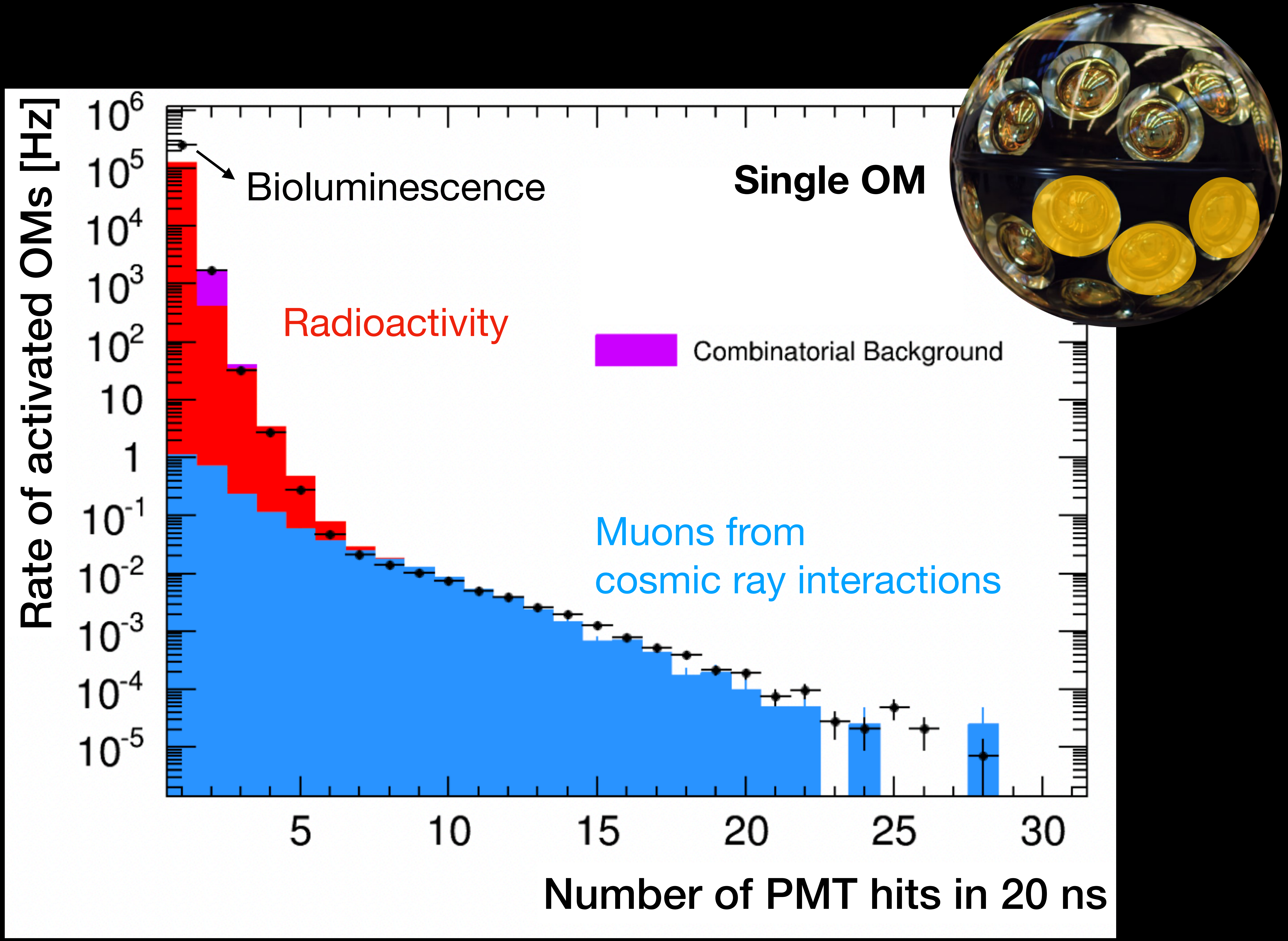

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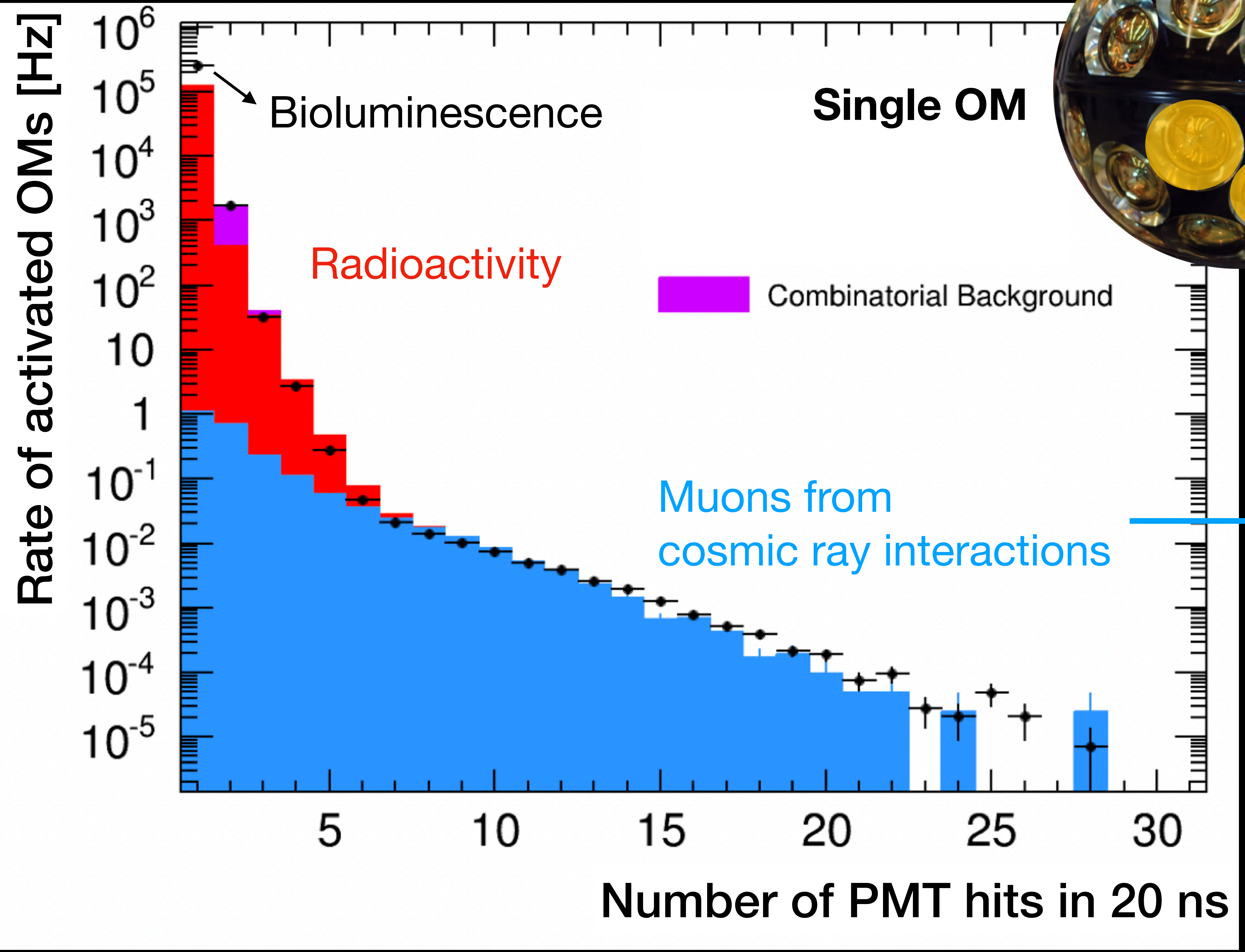

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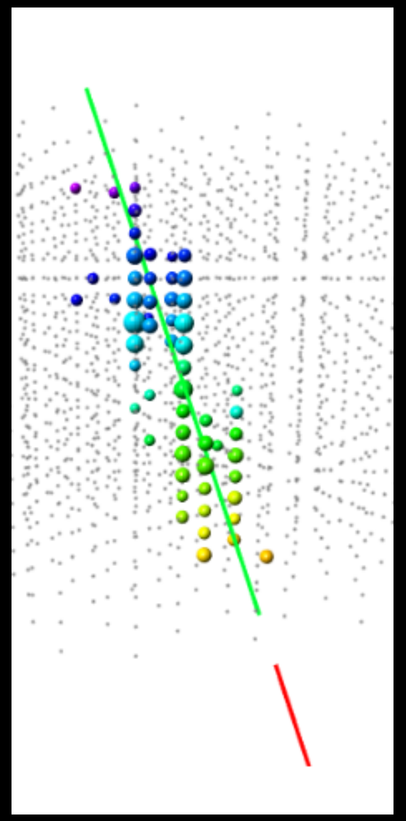


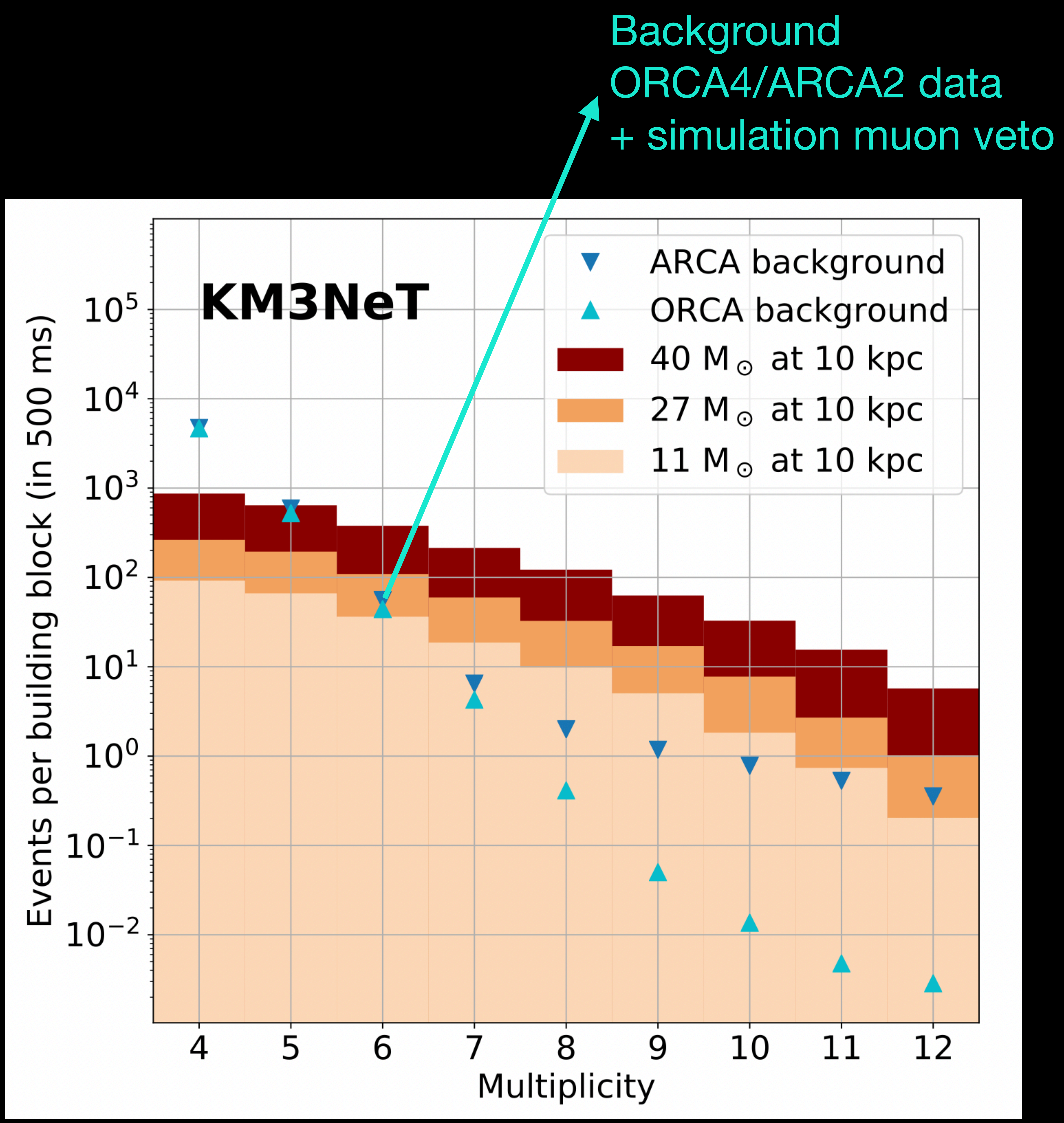
Triggered high-energy event

>90% of ORCA muons
~70% of ARCA muons

KM3NeT collaboration, *Eur. Phys. J. C* 74 (2014)

Triggering for supernovae

- **Multiplicity**: number of hits in a 10 ns window for each optical module
- **Muon veto**: remove OMs associated with KM3NeT triggers
- Cuts: maximize detection horizon, 115 lines
  data-driven background model, signal simulation
- Final selection: 7-11 hits in single OM
  6-10 hits for the current detector



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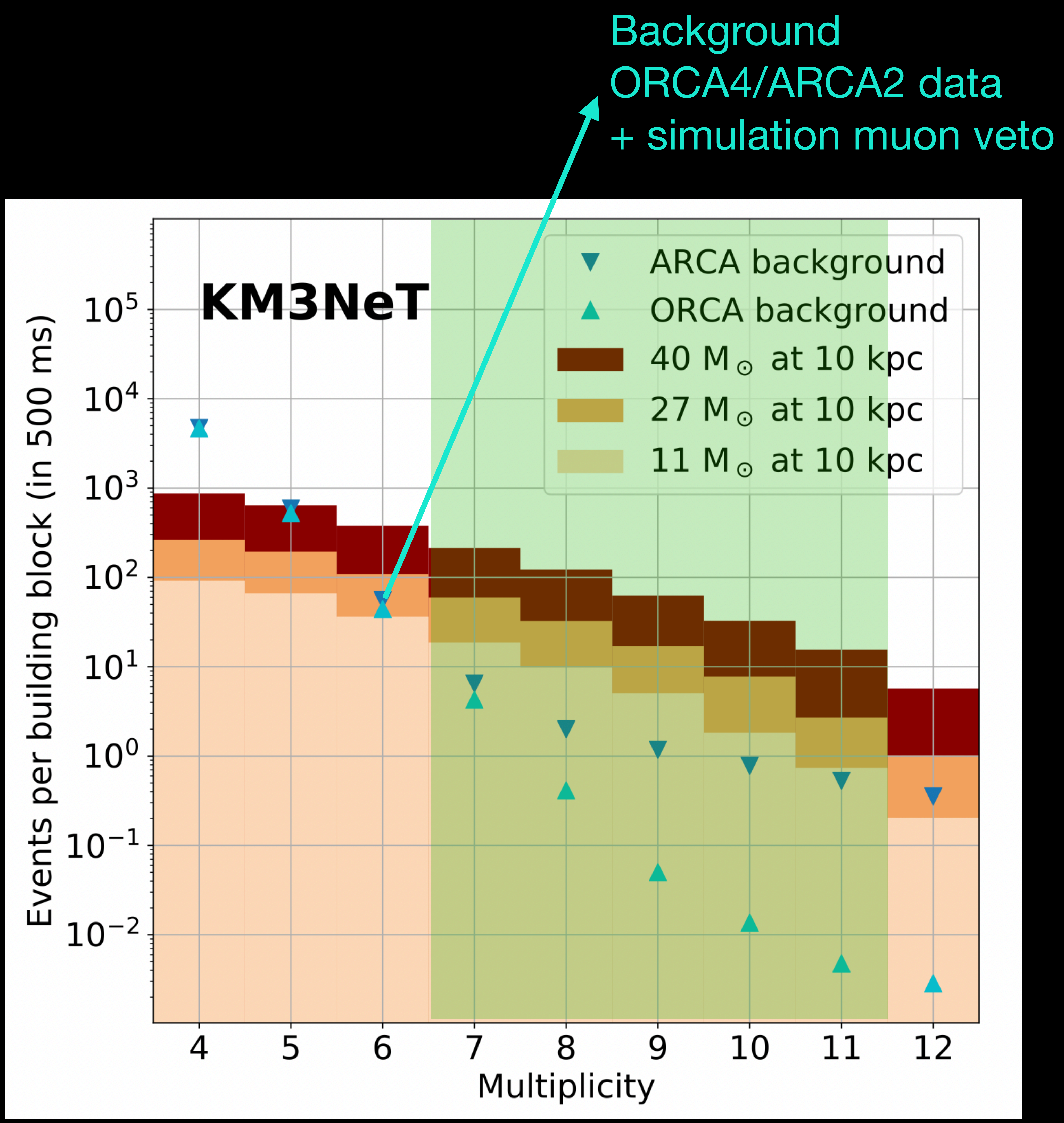
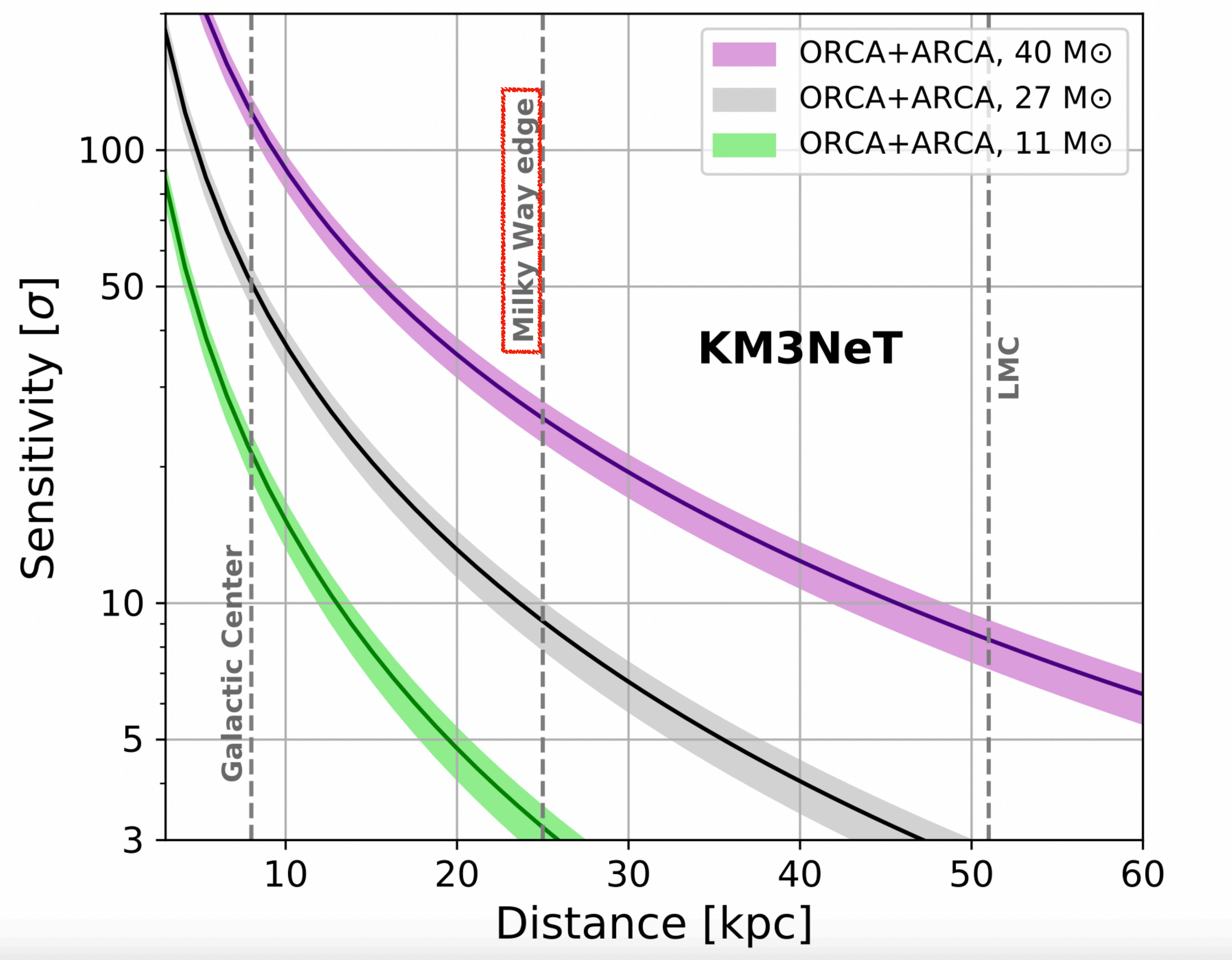


KM3NeT collaboration, *Eur. Phys. J. C* 81 (2021)

Supernova burst sensitivity

5σ sensitivity to 96% of galactic supernovae

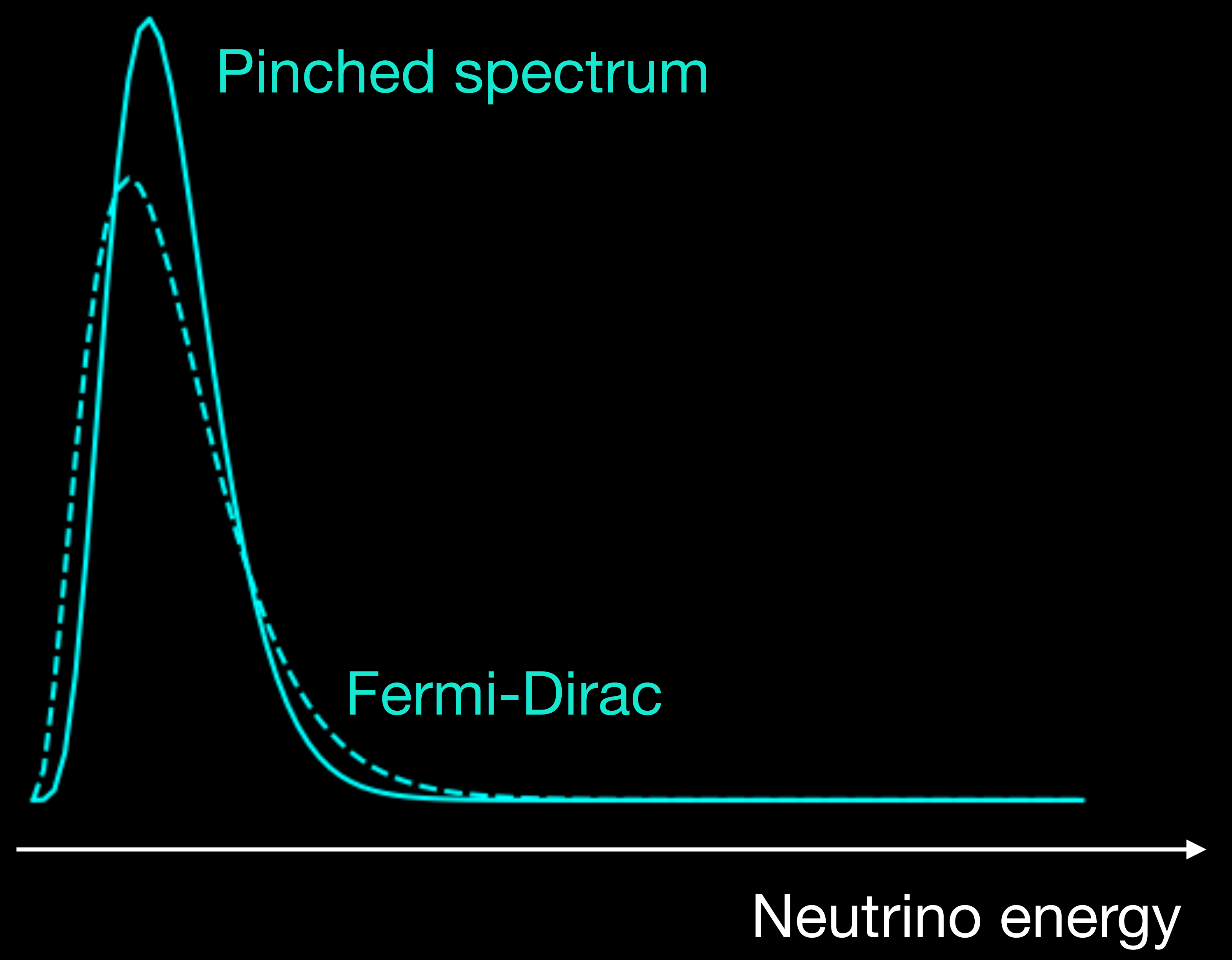


KM3NeT collaboration, *Eur. Phys. J. C* 81 (2021)

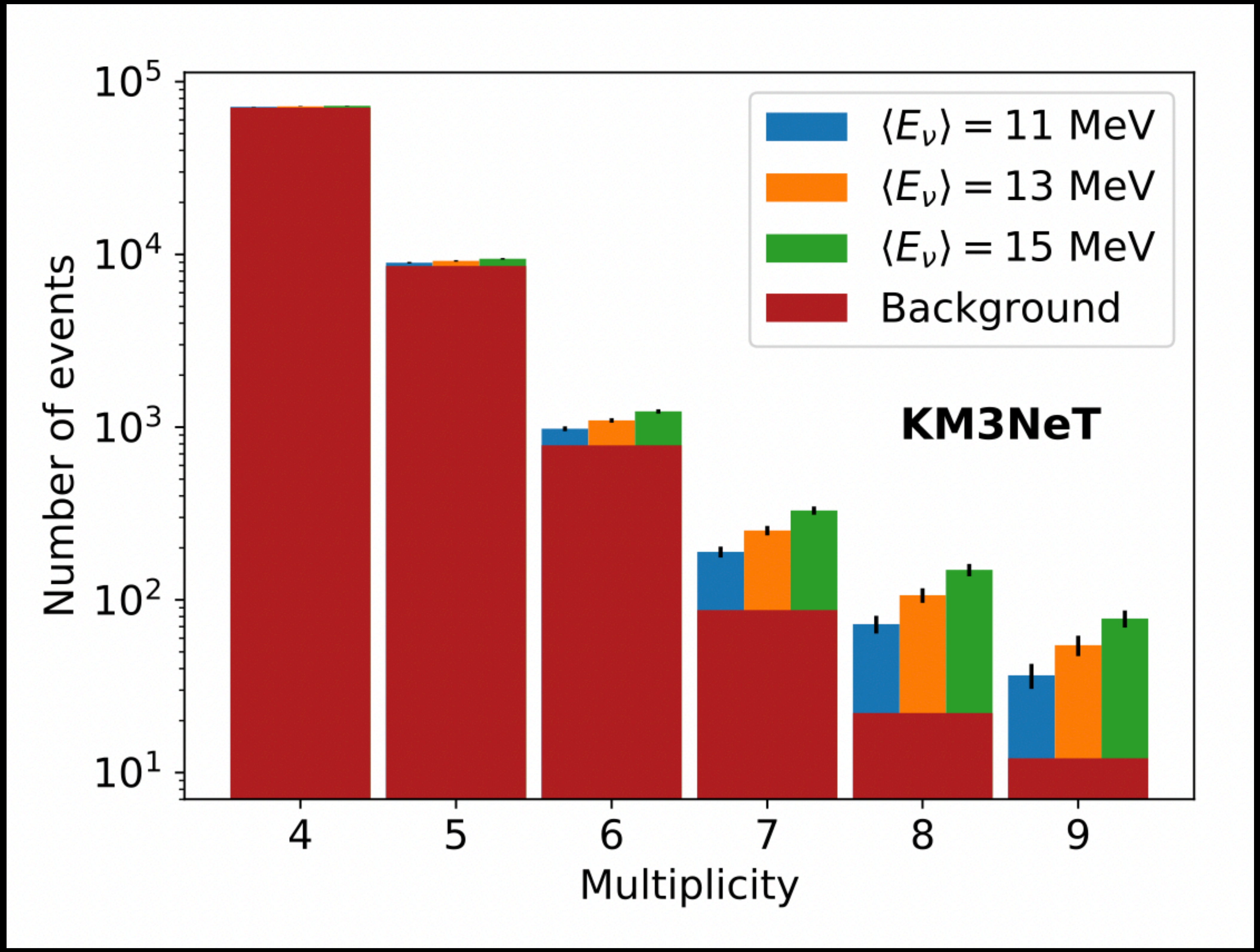
Corr. authors: M. Colomer-Molla (APC), M. Lincetto (CPPM)

Reconstructing neutrino spectra

PMT multiplicity increases with neutrino energy



$$\mathcal{S}(E_\nu) = \mathcal{N} \times \left(\frac{E_\nu}{\langle E \rangle}\right)^\alpha e^{-(1+\alpha)E_\nu/\langle E \rangle}$$



KM3NeT collaboration, *Eur. Phys. J. C* 81 (2021)

Neutrino energy spectrum

From multiplicities to pinched Fermi-Dirac parameters

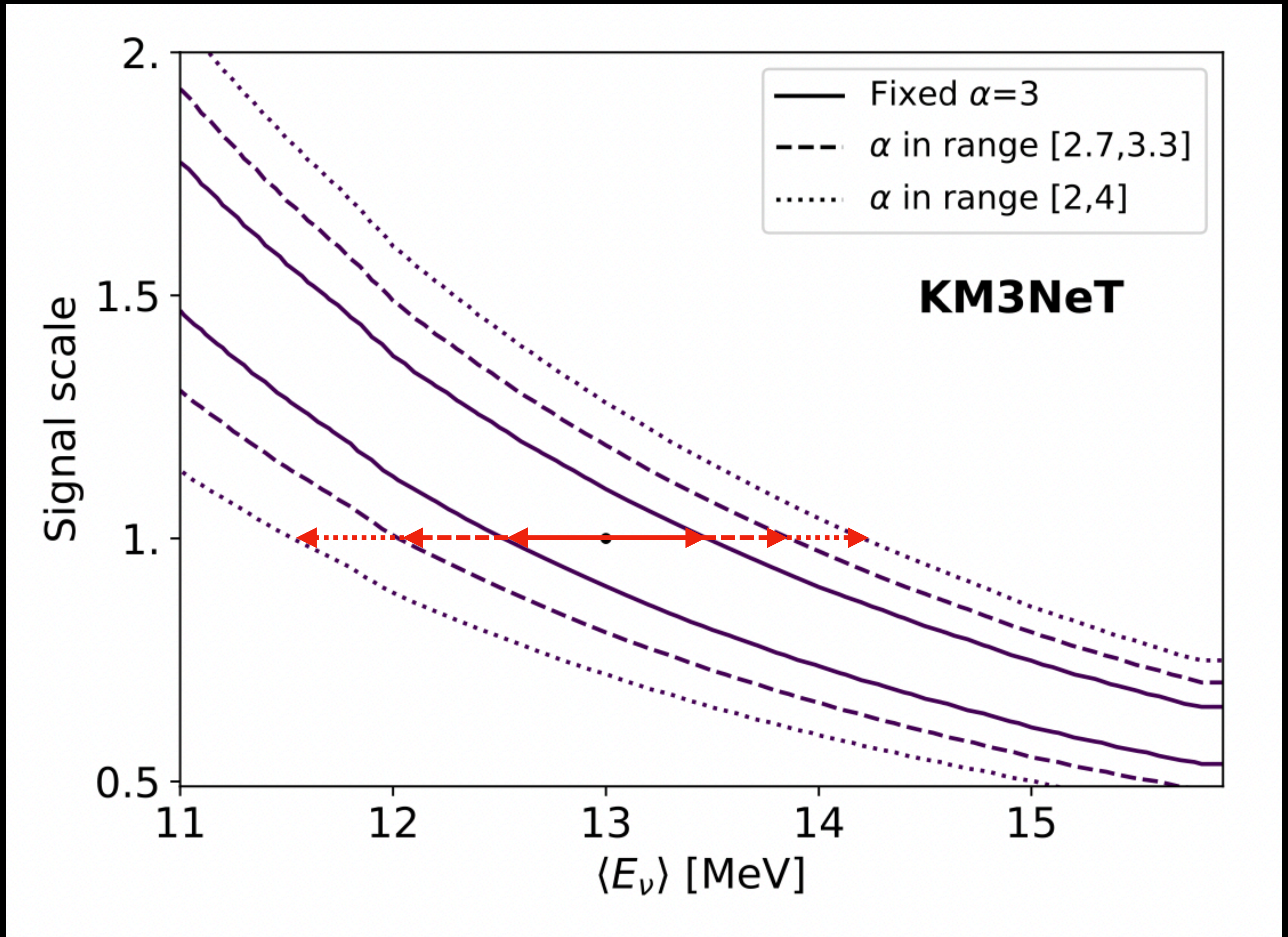
$$\mathcal{S}(E_\nu) = \mathcal{N} \times \left(\frac{E_\nu}{\langle E \rangle}\right)^{\alpha} e^{-(1+\alpha)E_\nu/\langle E \rangle}$$

< 1MeV precision on $\langle E \rangle$ if α known

~2 MeV for $\alpha \in [2.7,3.3]$

~3 MeV for $\alpha \in [2,4]$

χ^2 fit of signal + background



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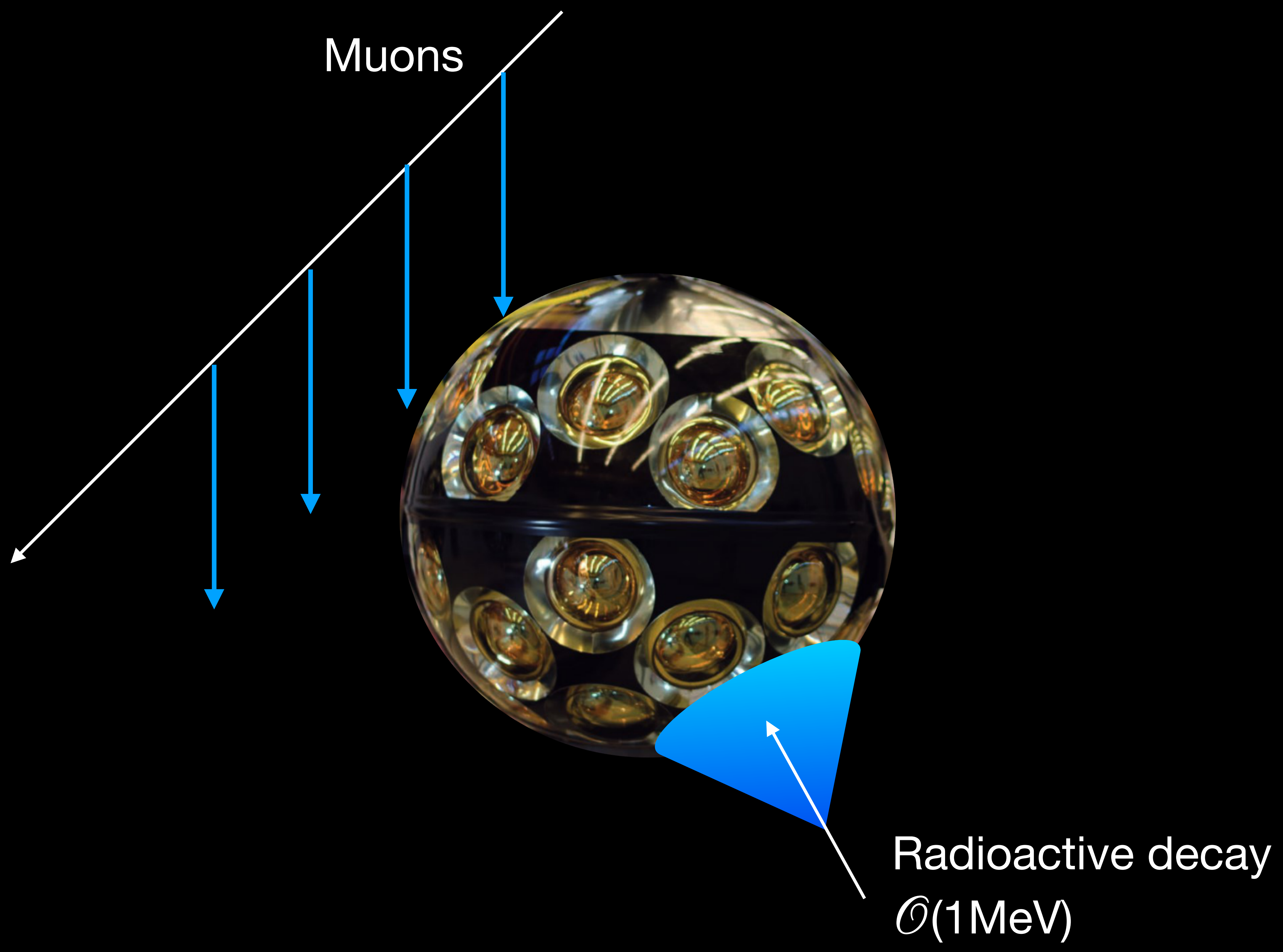
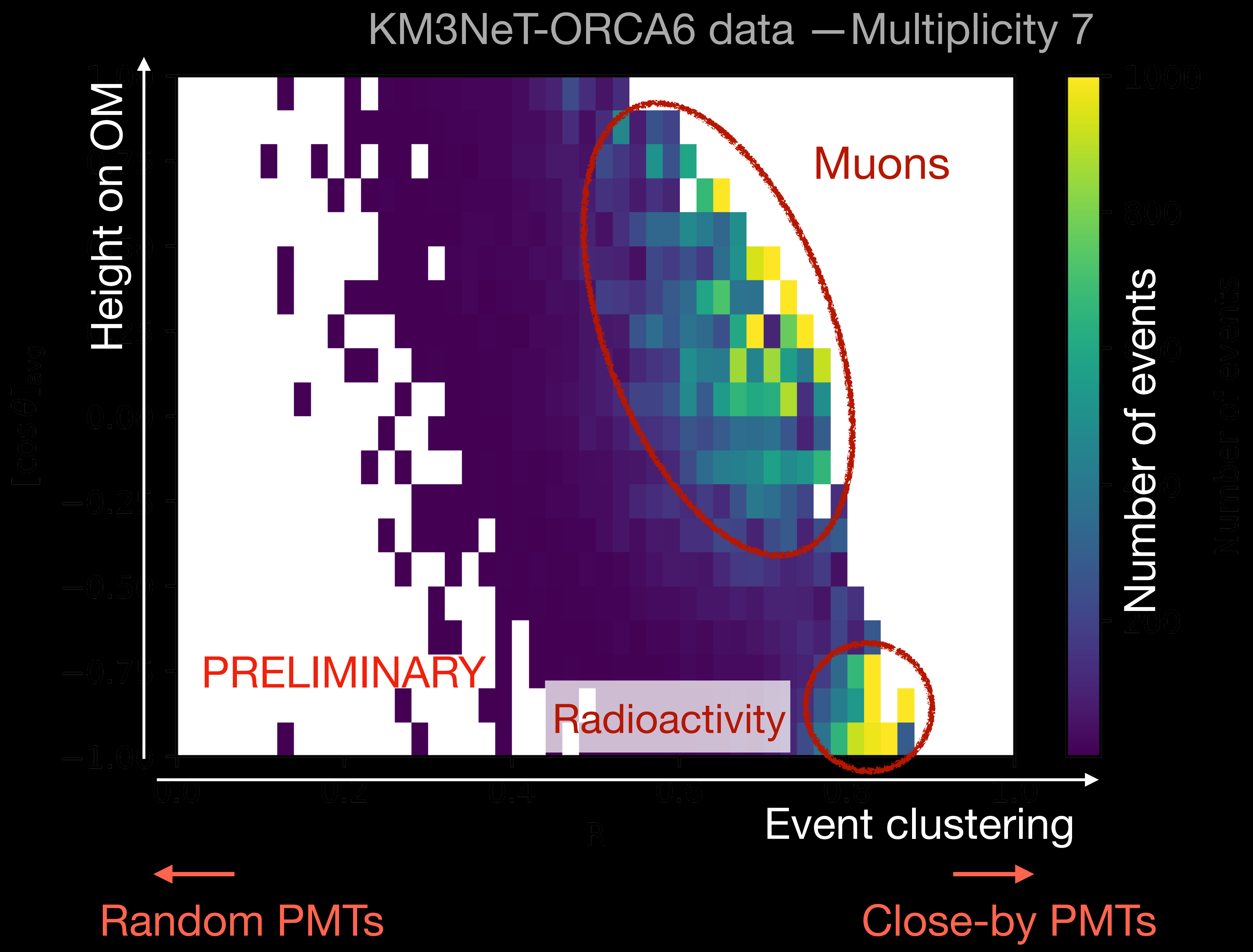
Perspectives — A 31-pixel image

Work in progress…





Talk submitted at ICRC 2023 — Isabel Goos (APC)

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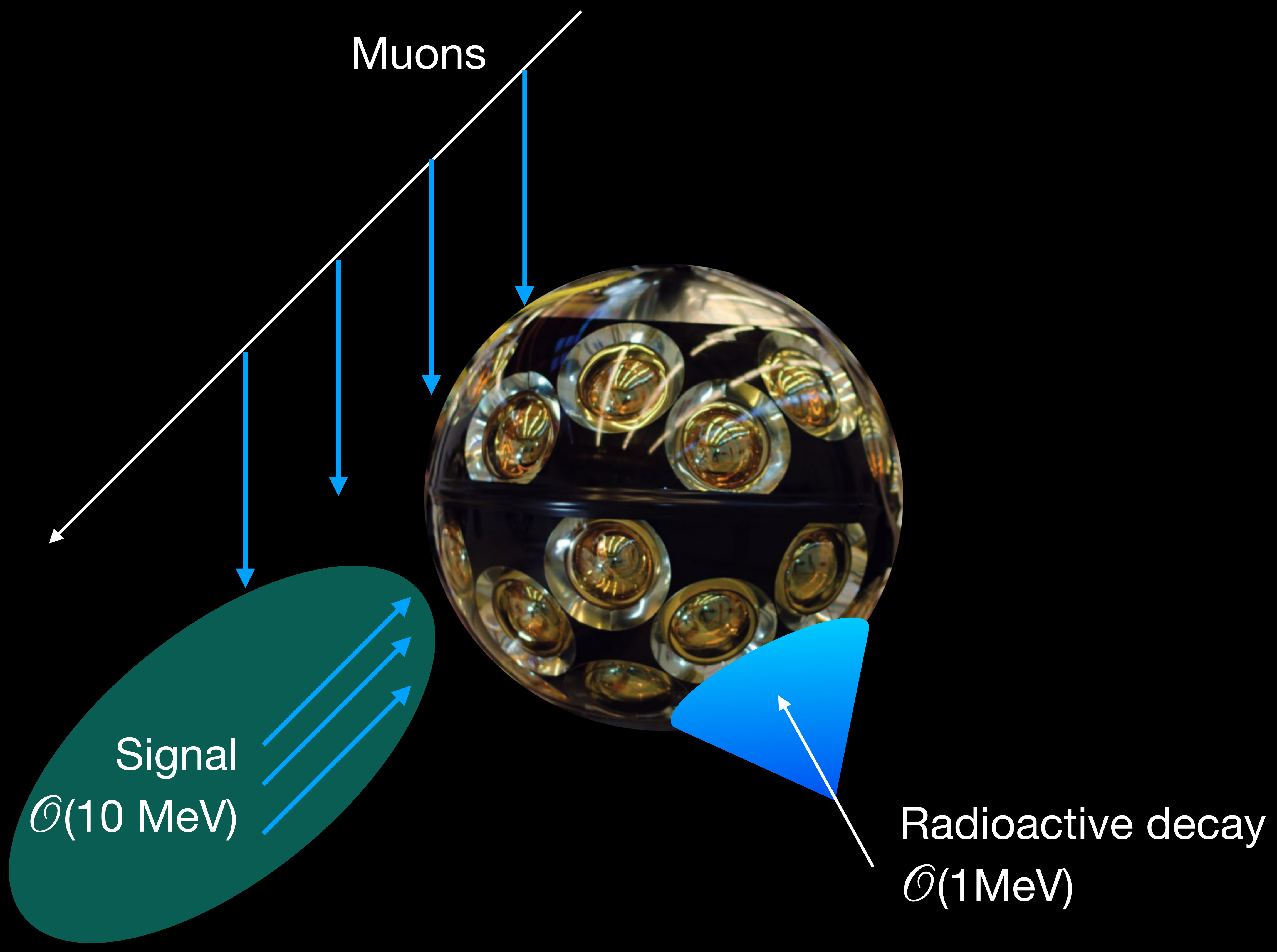

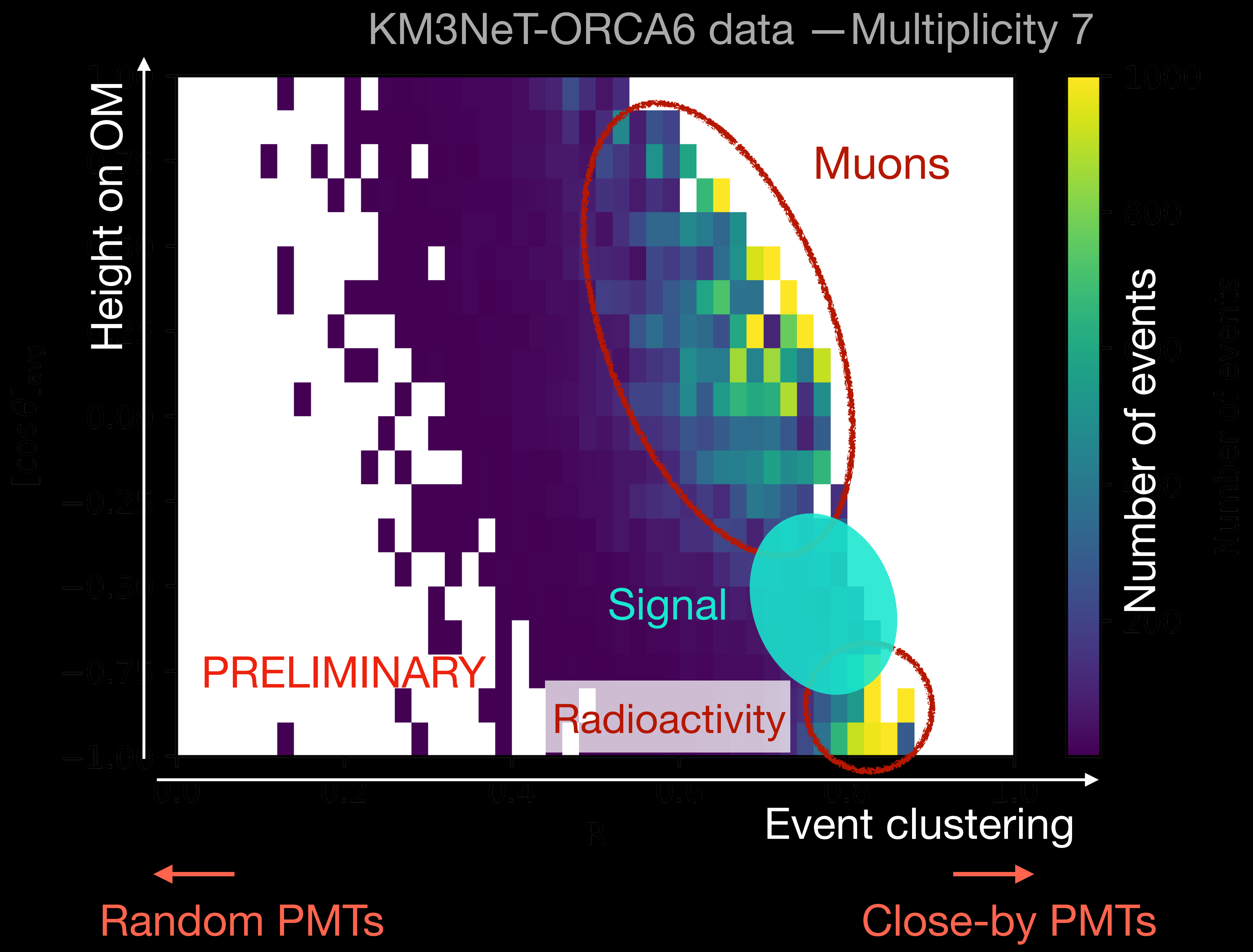

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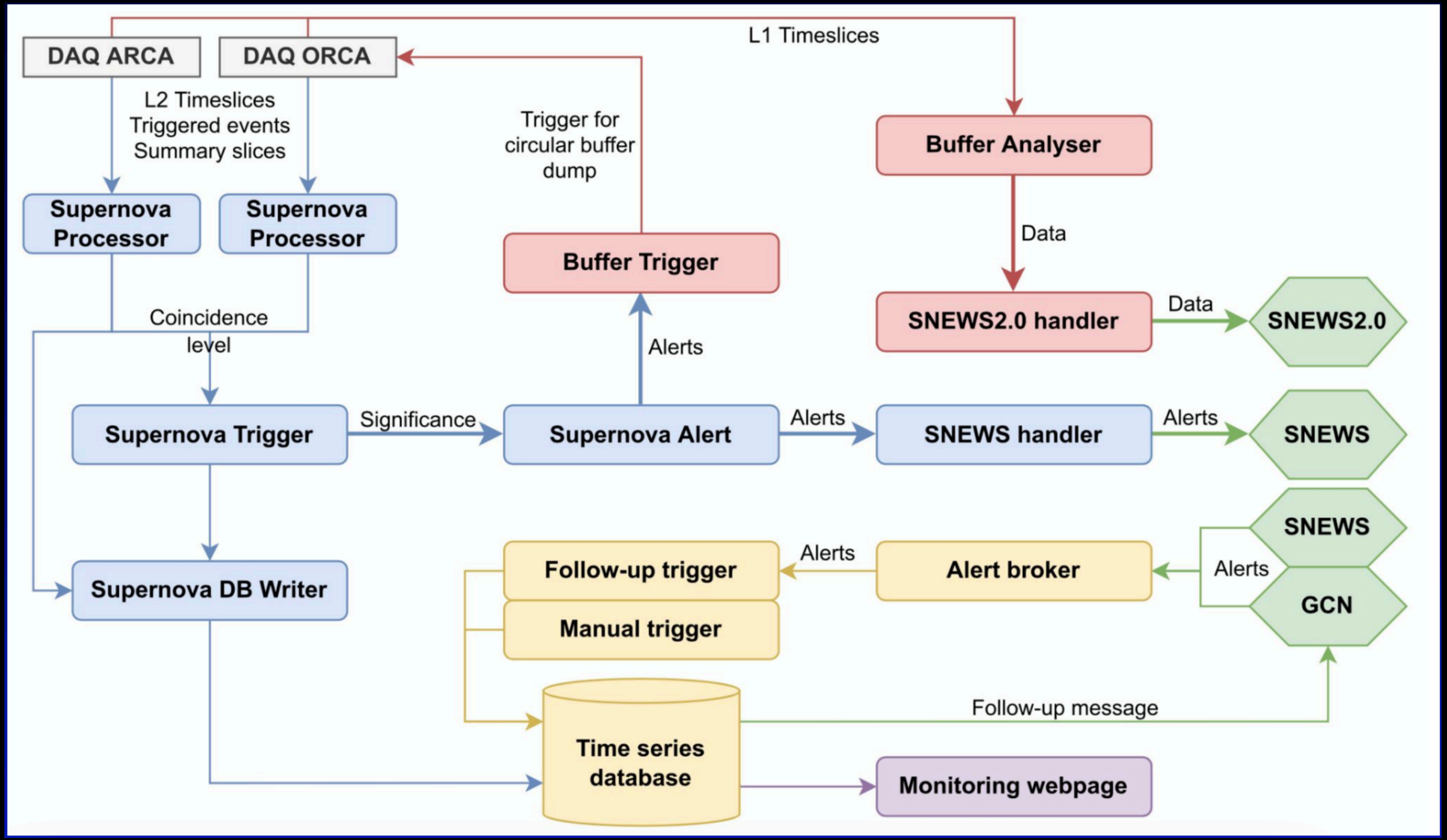
Supernova alerts

The multi-messenger connexion

KM3NeT's alert system — 20 s latency time



Supernova Early Warning System

See also: KM3NeT collaboration, *Eur. Phys. J. C* 82 (2022)

Corr. authors: G. Vannoye (CPPM), M. Lincetto (CPPM)

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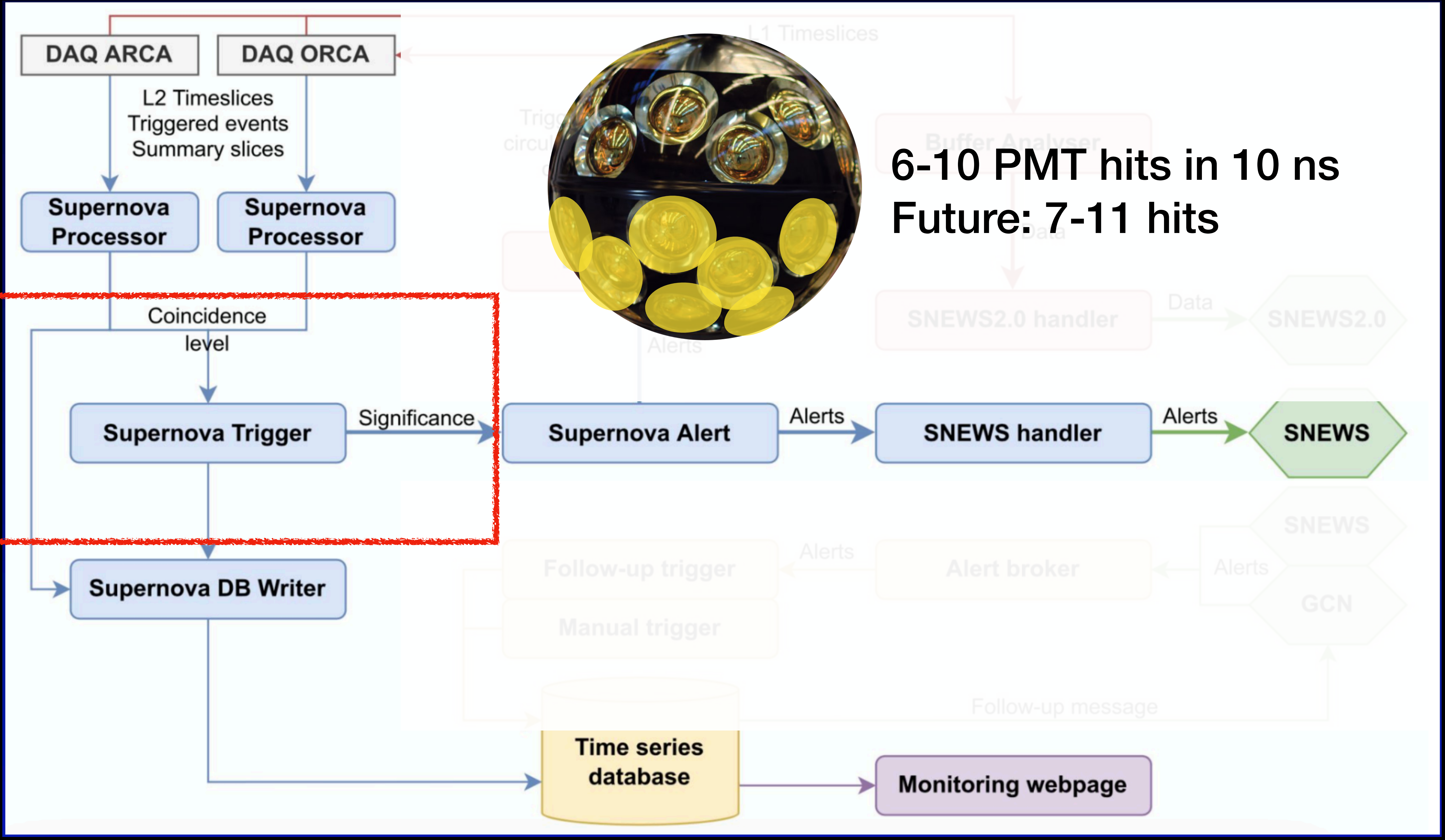
Trigger threshold

Adapt to background level
1 fake event/week



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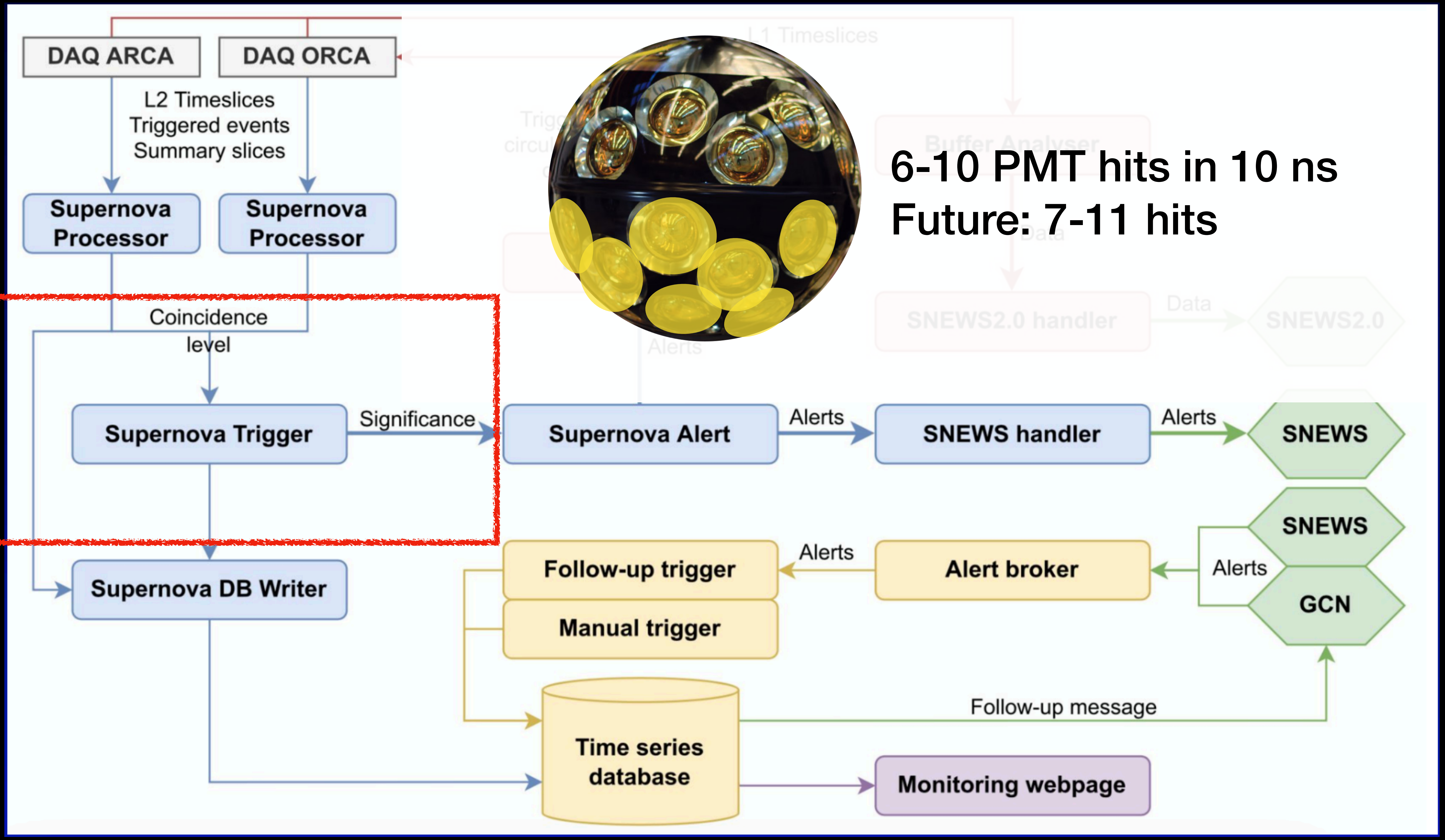

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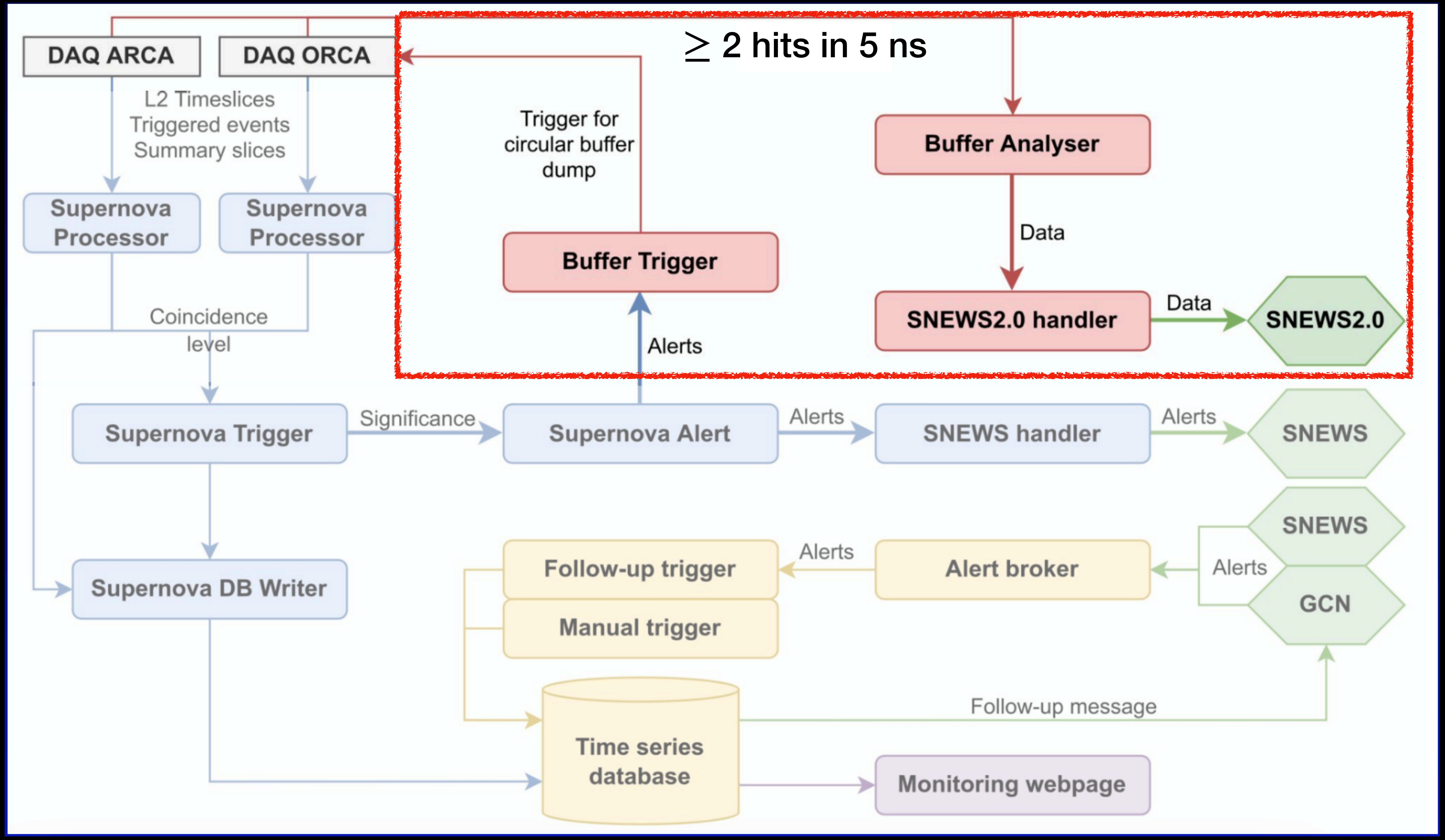
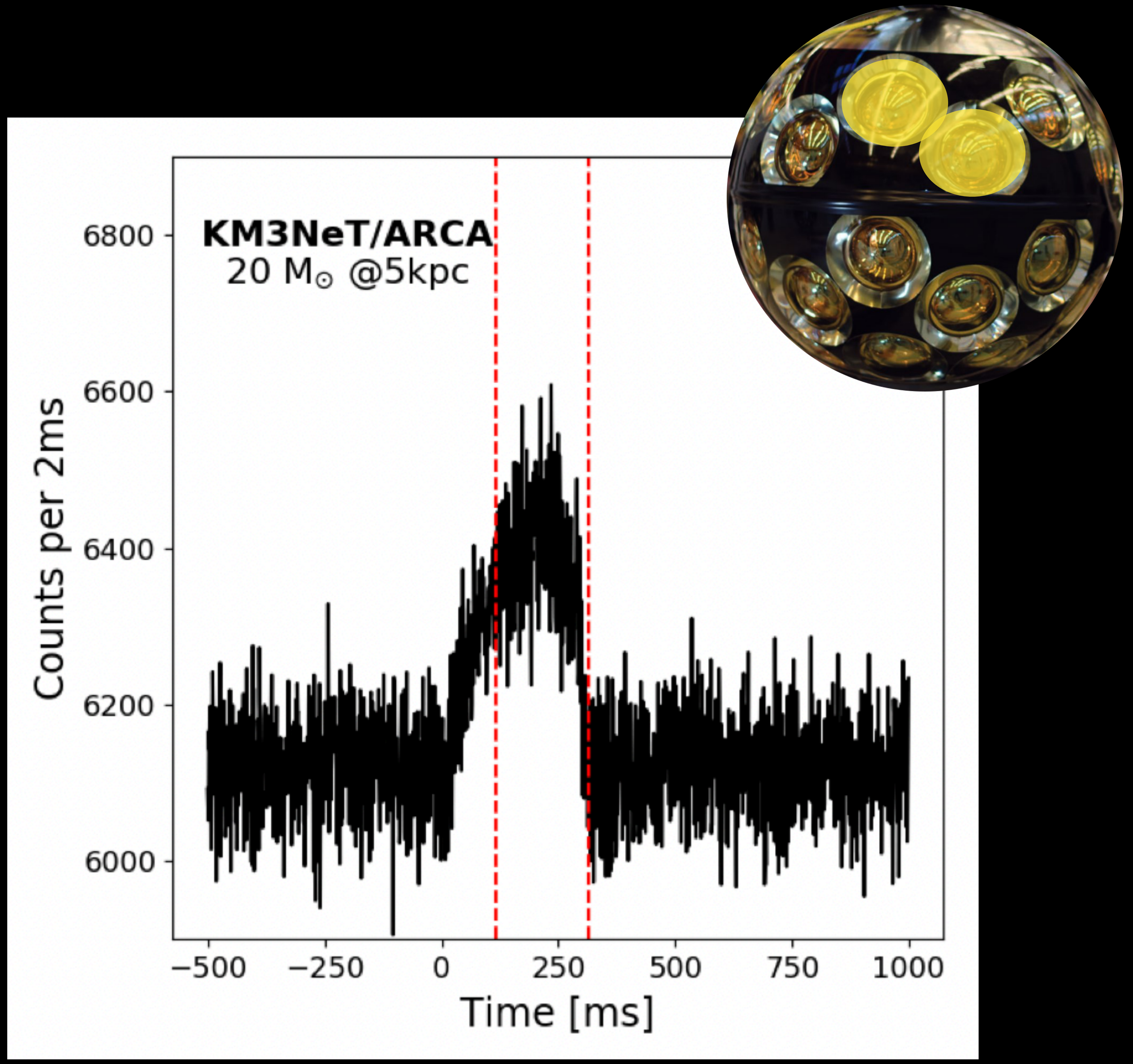
Studying supernova rates

Buffer 10 min of data — Time evolution of supernova signal

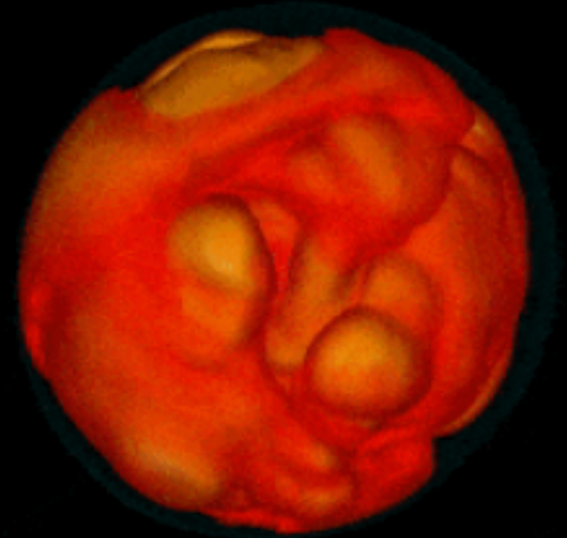


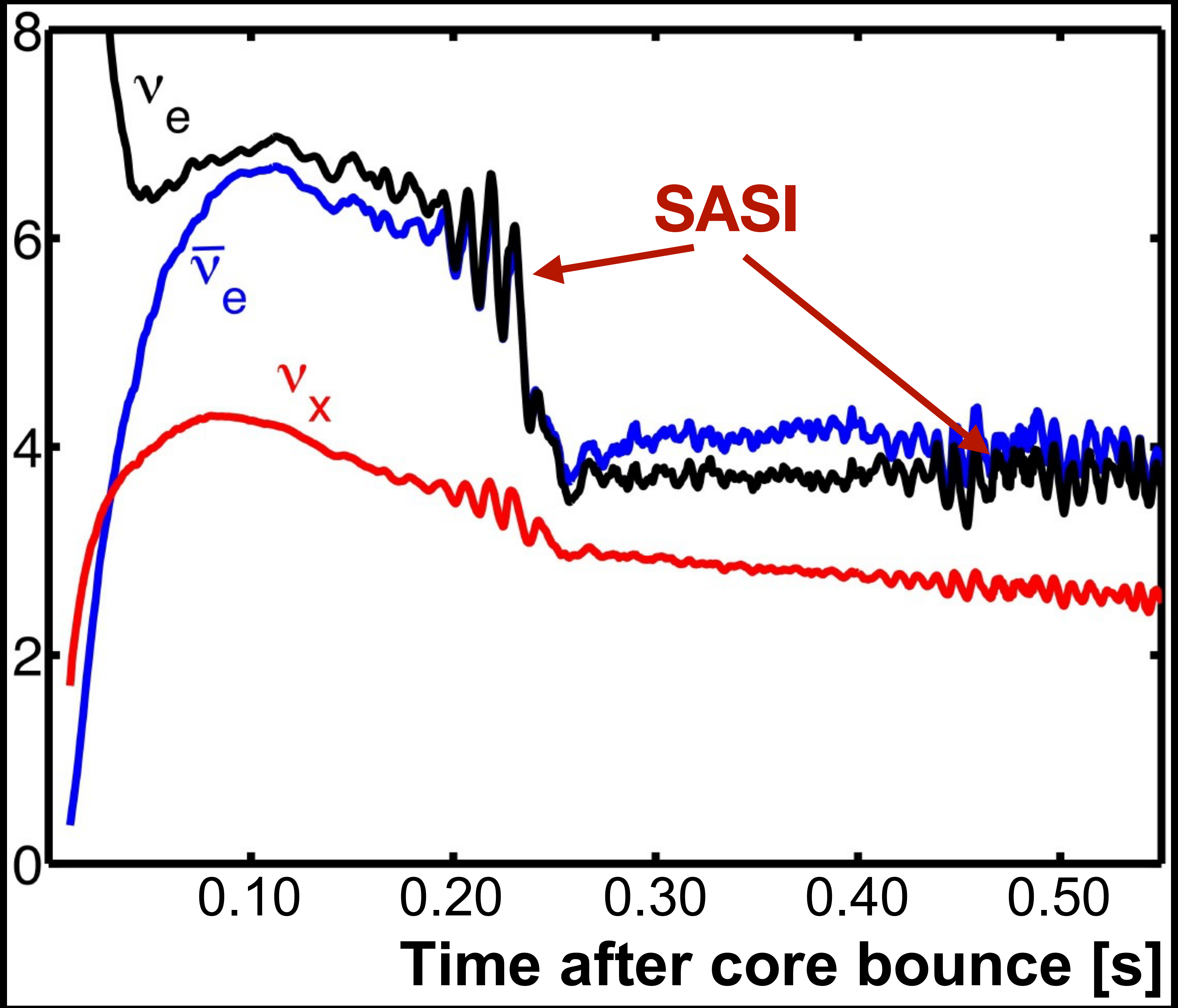


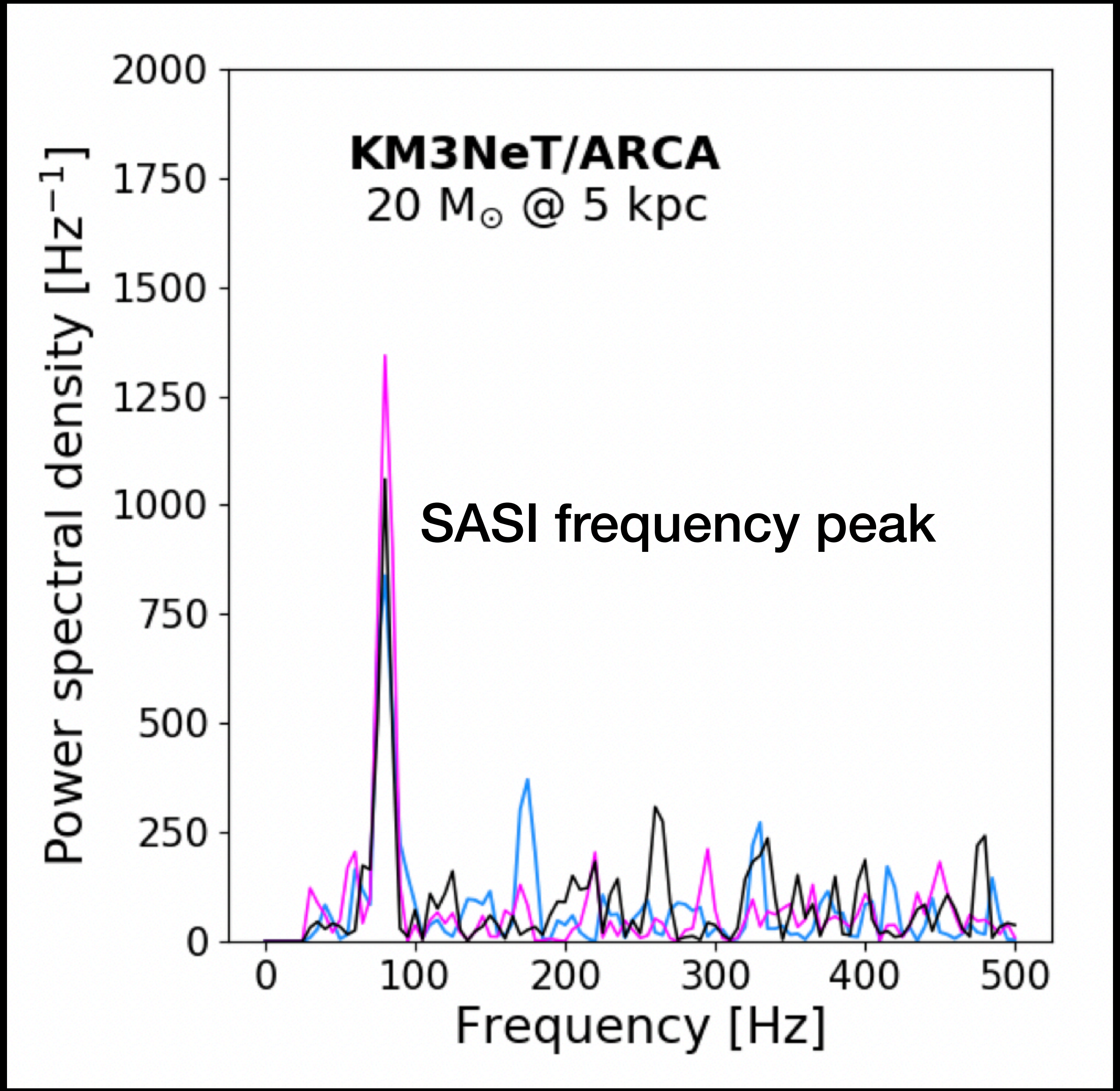
KM3NeT collaboration, *Eur. Phys. J. C* 81 (2021)

Finding hydrodynamical instabilities

Standing Accretion Shock instability — 3σ up to 5kpc







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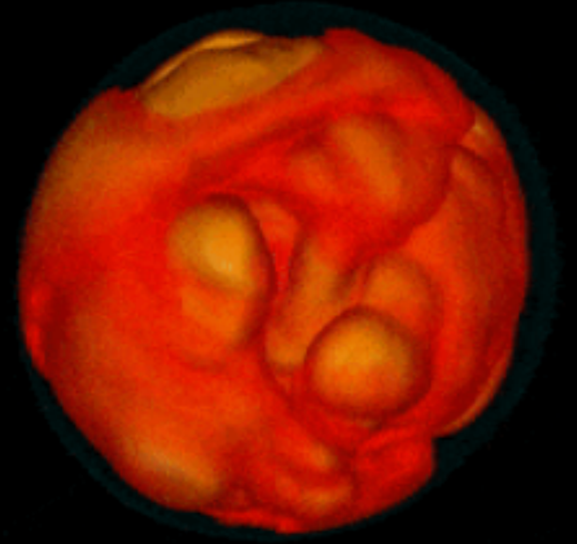
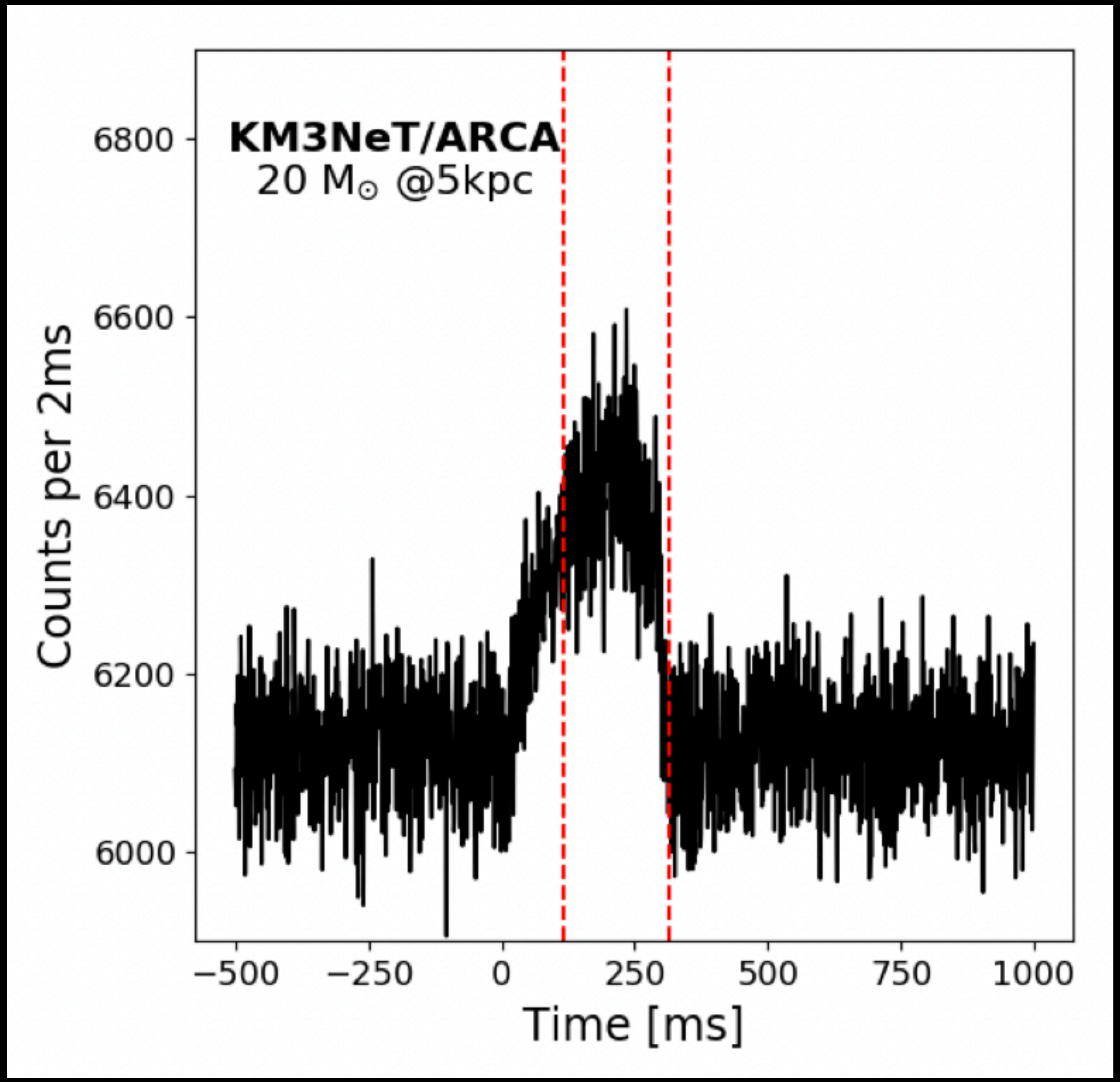
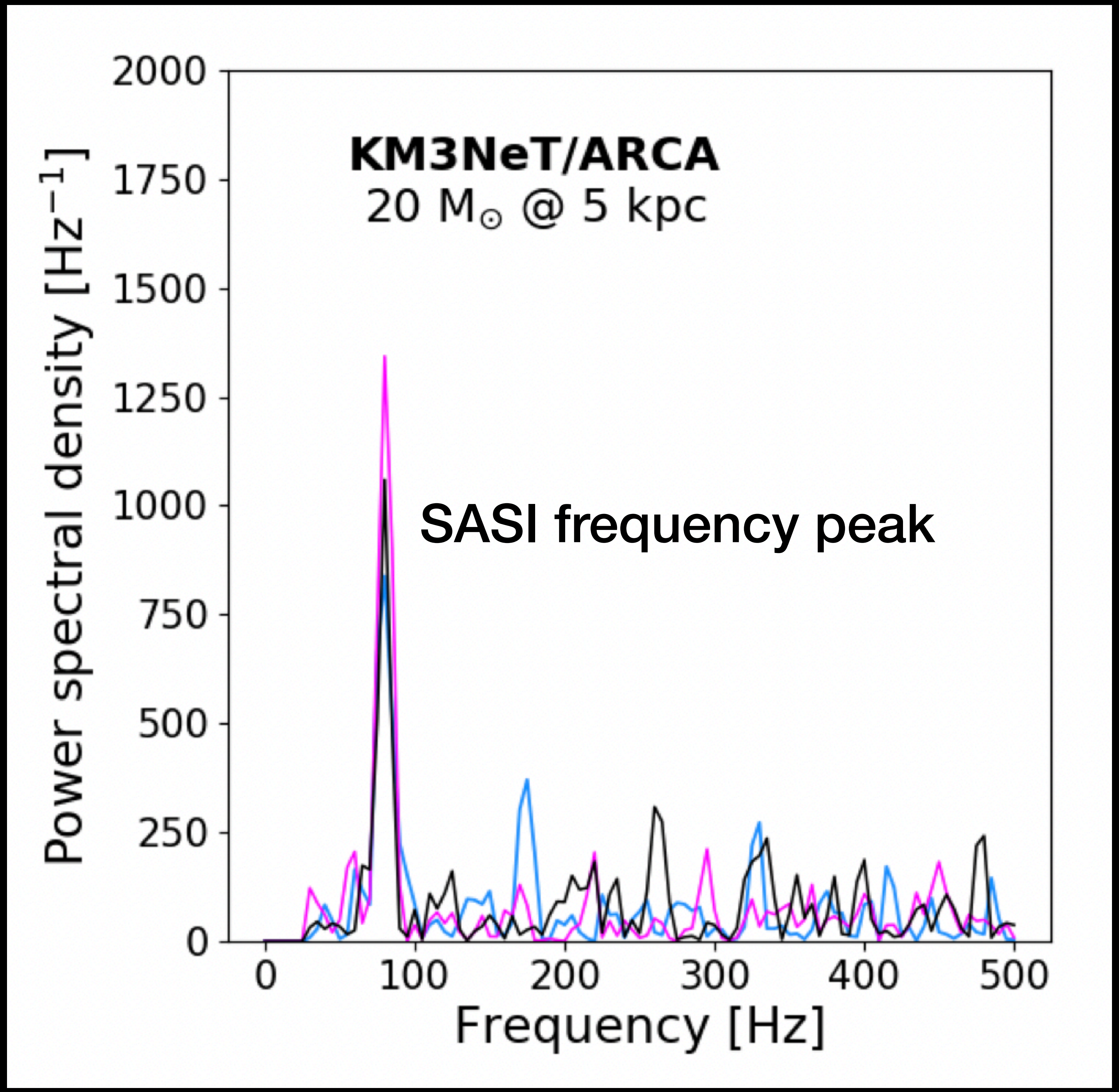




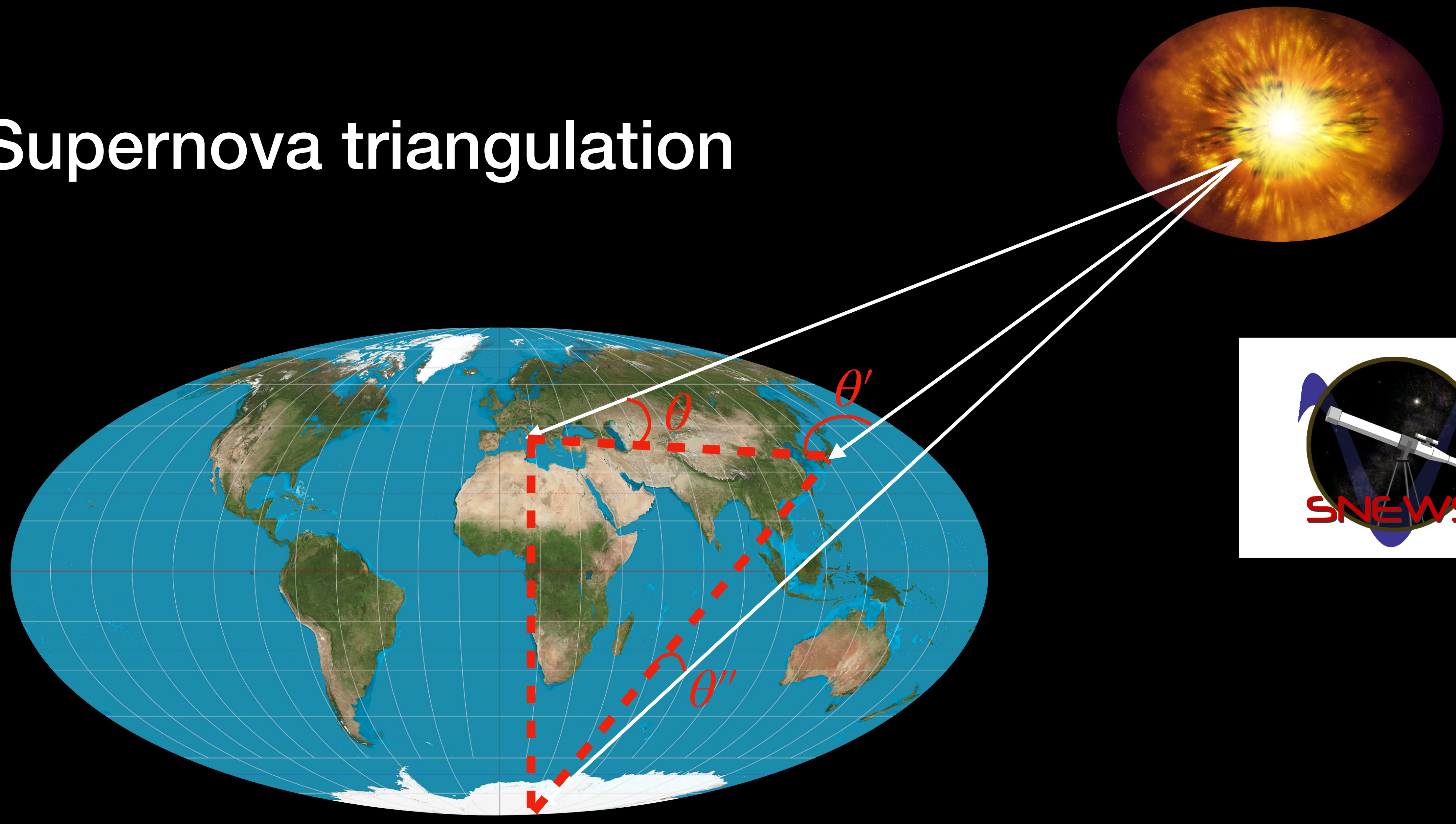


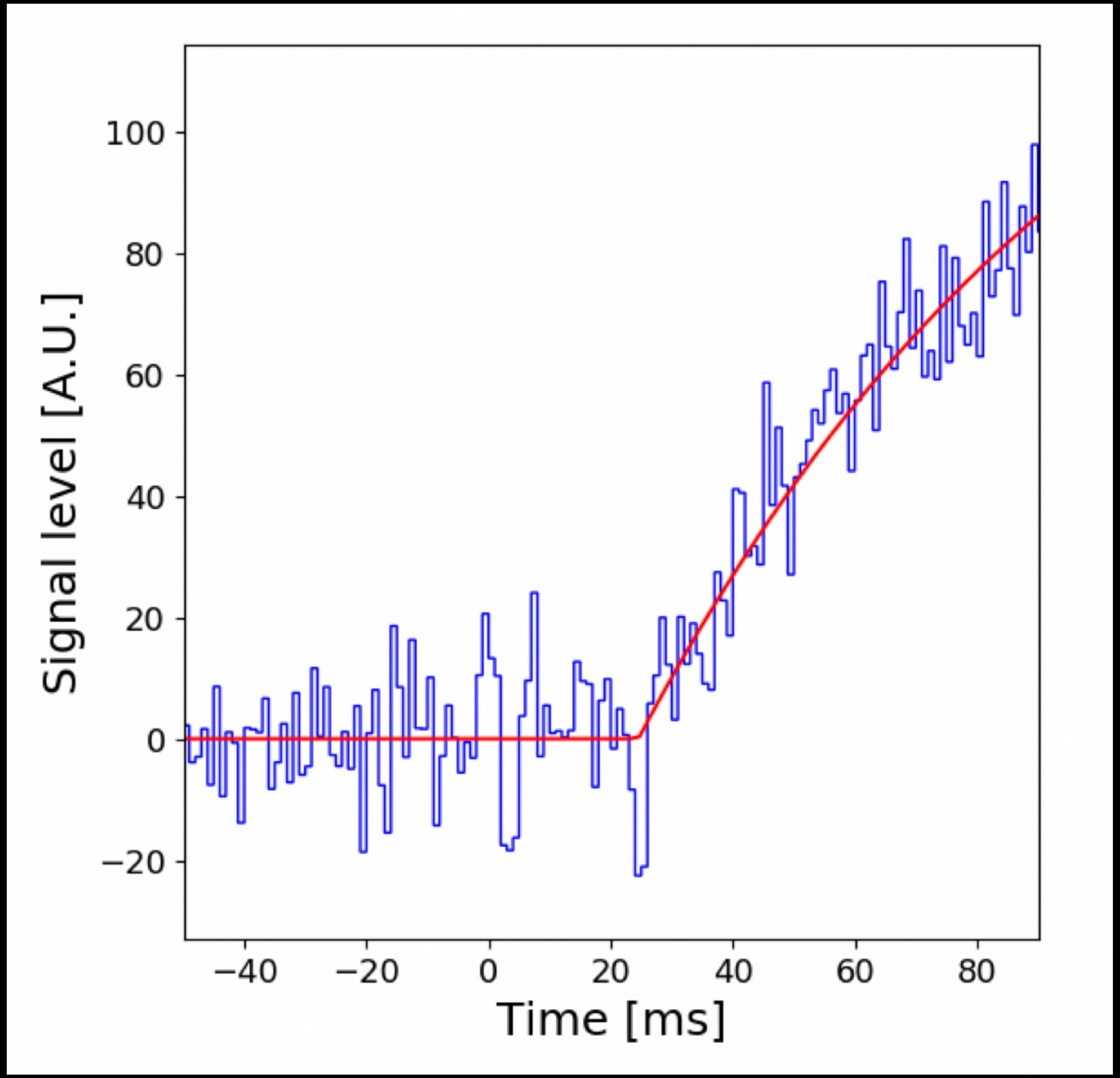
KM3NeT collaboration, *Eur. Phys. J. C* 81 (2021)

Supernova detection time: localization

- Fit the initial rate rise by an exponential
- Full ARCA: 8ms uncertainty at 8 kpc

Supernova triangulation

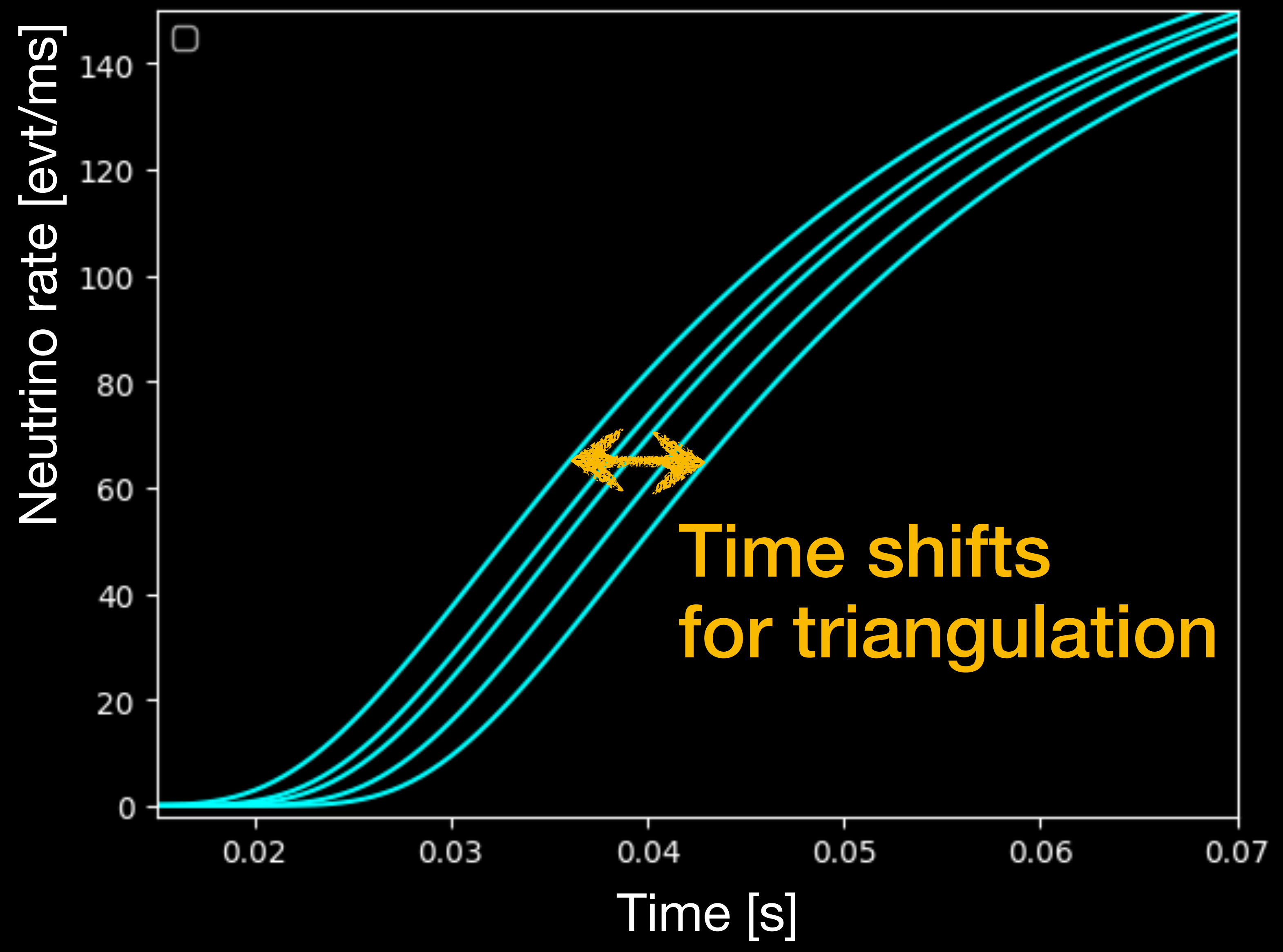


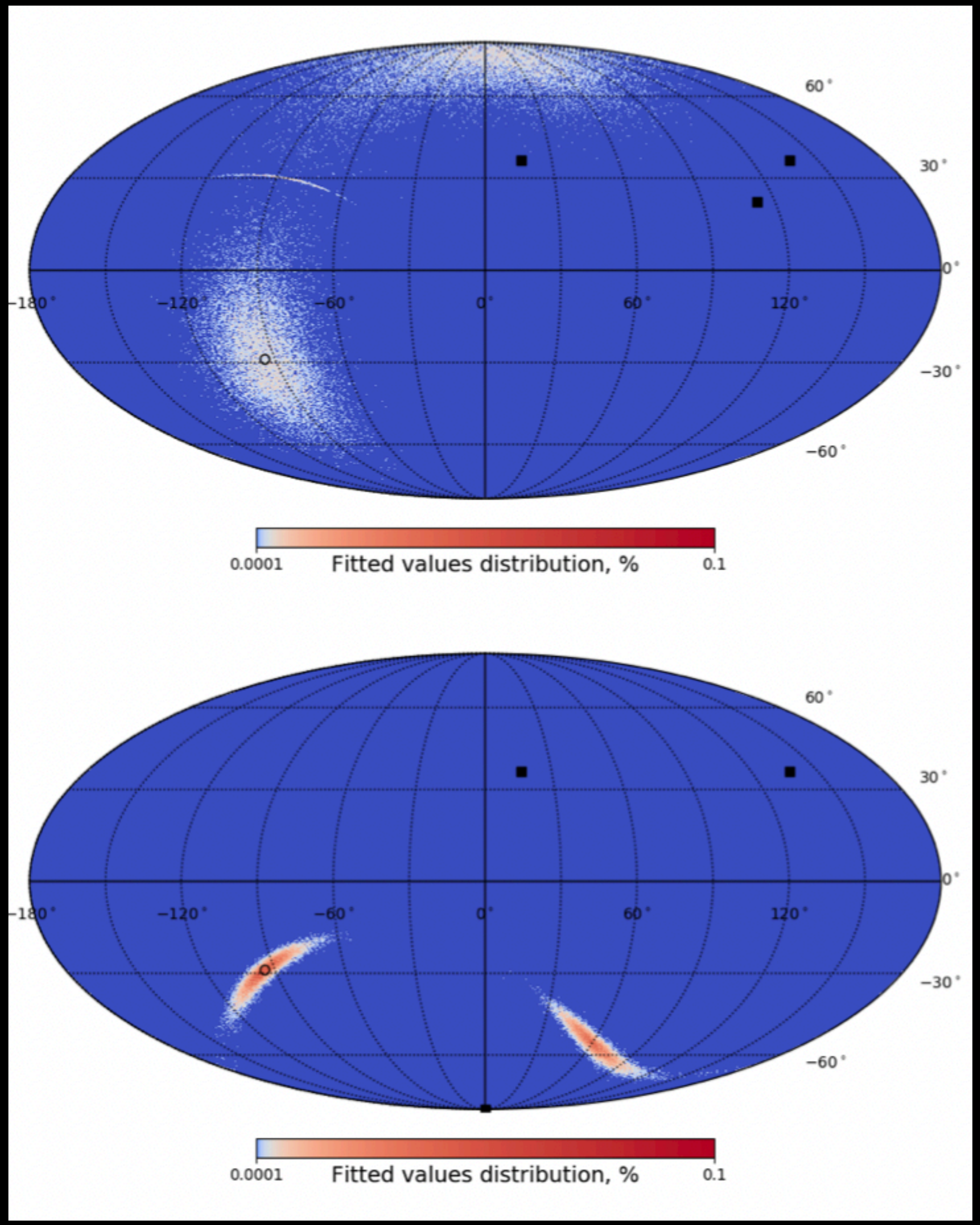


KM3NeT collaboration, *Eur. Phys. J. C* 81 (2021)

More on supernova localization

Match supernova rate increases for multiple detectors





IceCube
KM3NeT-ARCA
JUNO

Hyper-Kamiokande
KM3NeT-ARCA
JUNO

A. Coleiro *et al,* Eur. Phys. J. C 80 (2020)

Down to a 140 squared degree 90% CL region within minutes after detection

Wolf-Rayet stars: light can arrive 40 seconds after the neutrinos

Conclusion

- KM3NeT is sensitive to most galactic core-collapse supernovae
- Realtime analysis system coming (veeery) soon, communication with the Supernova Early Warning system
- Sensitivity to hydrodynamical instabilities (SASI) for close-by supernovae
- Timing information, contributing to supernova localization effort

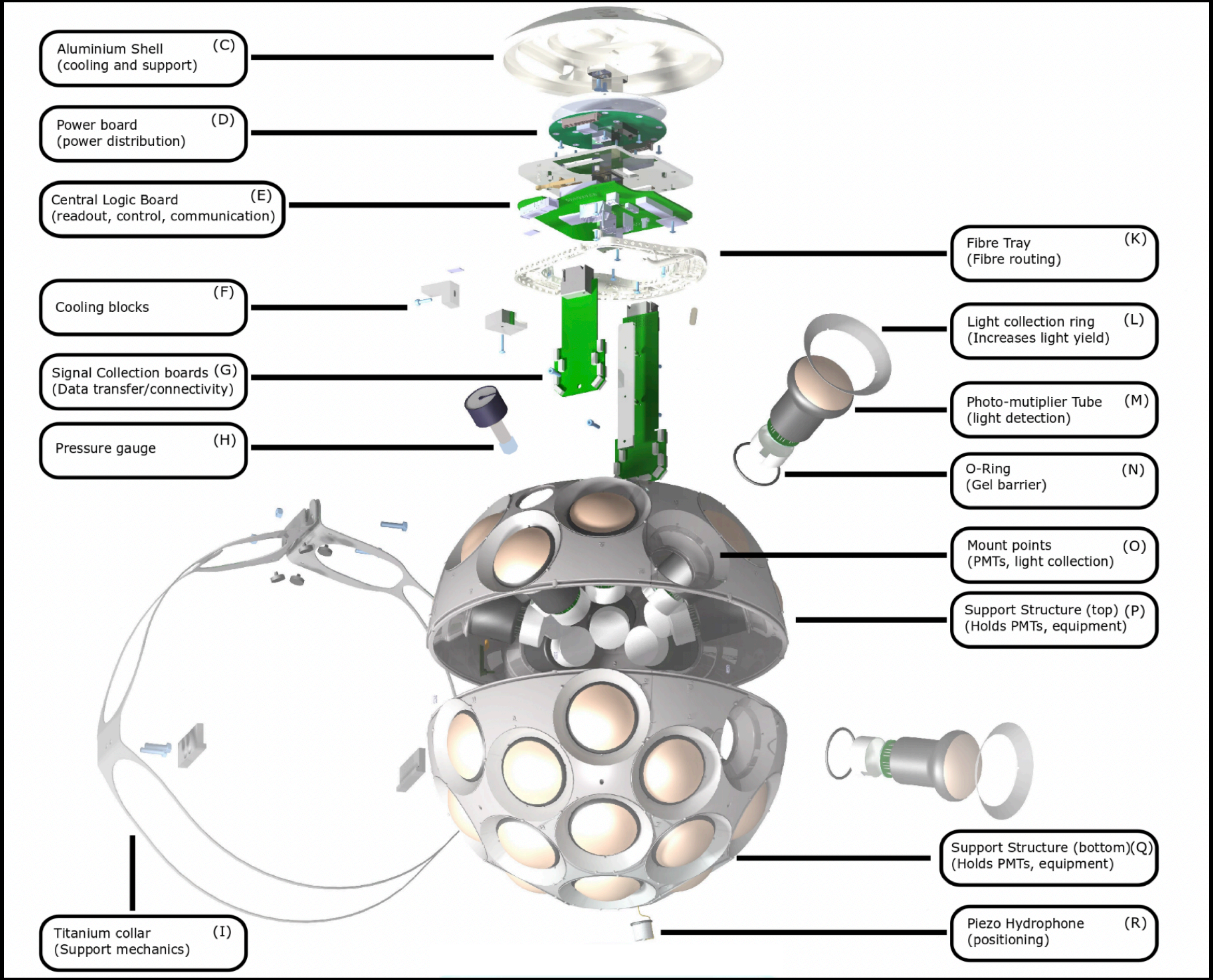
- Multi-PMT optical modules can be used for other MeV-GeV analyses (e.g. solar flares)
  Submitted ICRC talk, J. Mauro (UC Louvain)
- Testing ground for future detectors

KM3NeT

Hyper-Kamiokande

IceCube-Gen2


Thank you for your attention



S. Aiello *et al* 2022 JINST 17 P07038