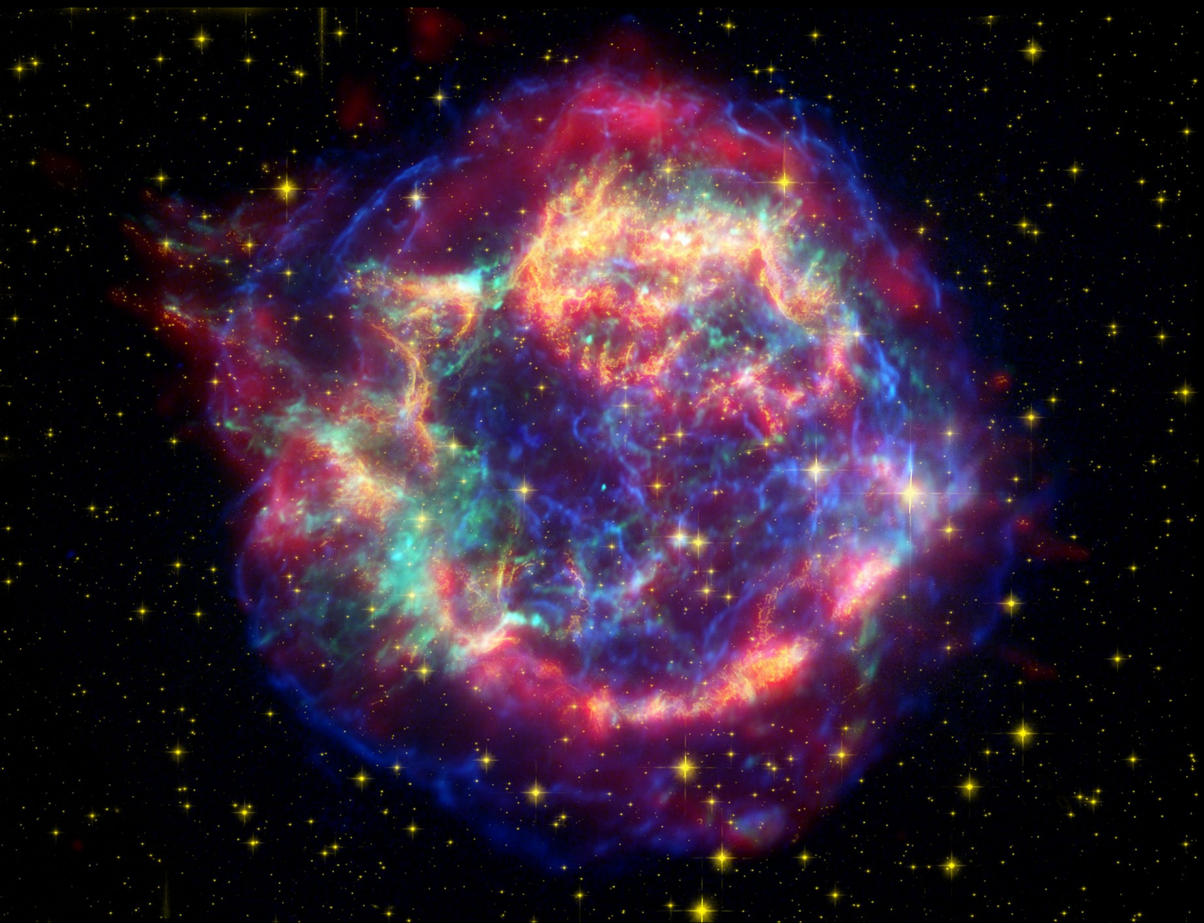
Core Collapse Supernova neutrino detection with KM3NeT

Marta Colomer Molla

GDR Neutrino
LPNHE, Paris
25-26 June 2019

Core-Collapse Supernova neutrinos:



Motivation:

- Only observation: SN1987A
→ 25 neutrinos detected
- Prove the explosion mechanism: neutrinos play a major role
- Prompt 1-100 MeV neutrino emission reviving the shock
- Constrain the theoretical models
- Neutrino properties measurements
- Extreme environment:
  → New physics

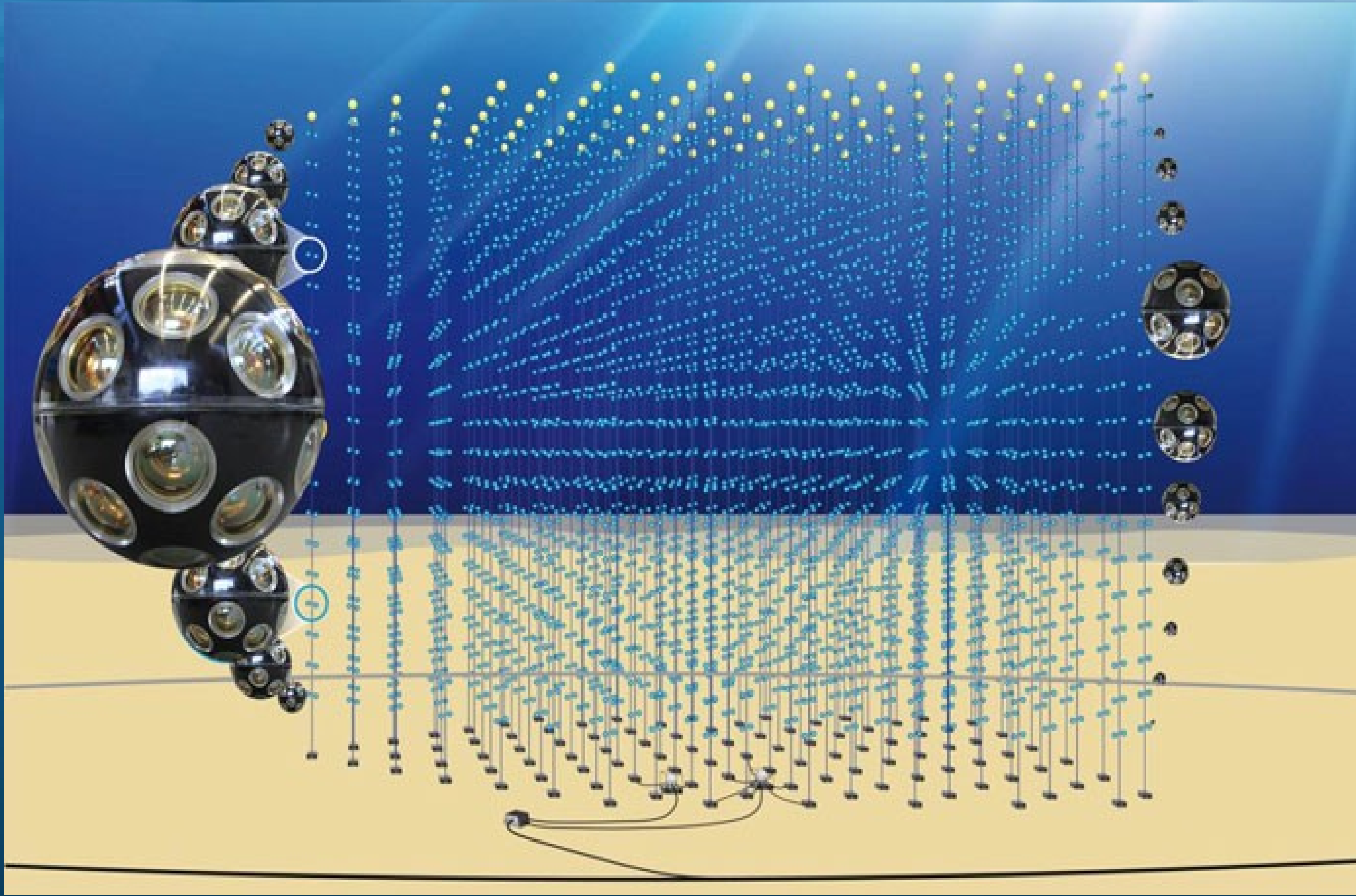
KM3NeT

Under construction
New technology

-115 instrumented lines per block
-18 Digital Optical Module (DOM) per line
-More than 2000 DOMs per block

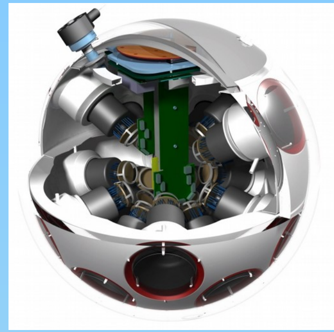
2 blocks in Italy:
ARCA (larger, 1km3)
- HE astrophysics
→ 1 line taking data!

1 block in France:
ORCA (more dense)
-Neutrino oscillations
→ 2lines taking data!



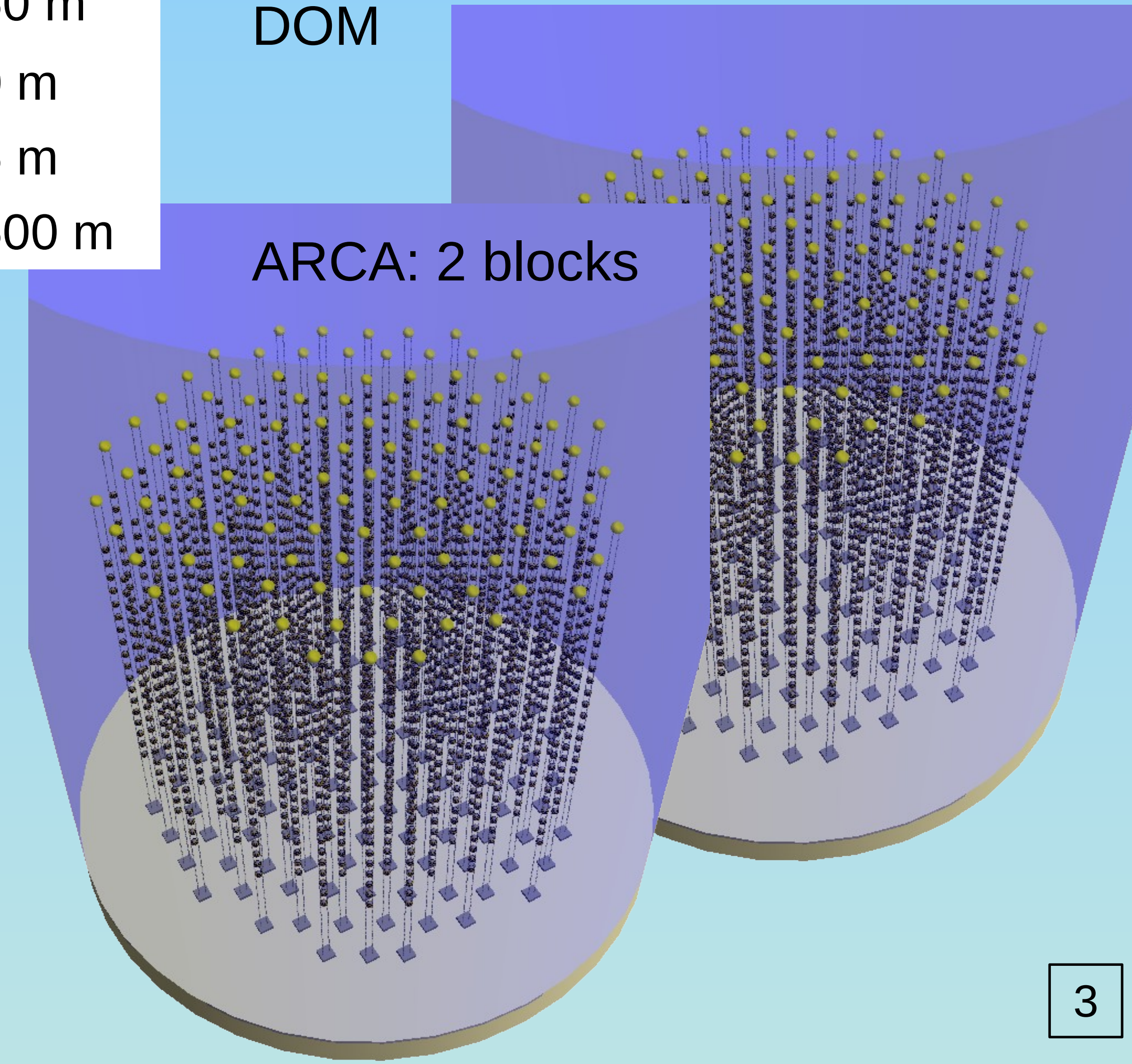
KM3NeT detectors:

	ANTARES	ORCA	ARCA
Eff. Mass	10 Mt	5.7 Mt	1 Gt
Line length	350 m	200 m	650 m
Inter-line dist	70 m	20 m	90 m
Inter-OM dist	14.5	9 m	36 m
Depth	2450 m	2450 m	3500 m

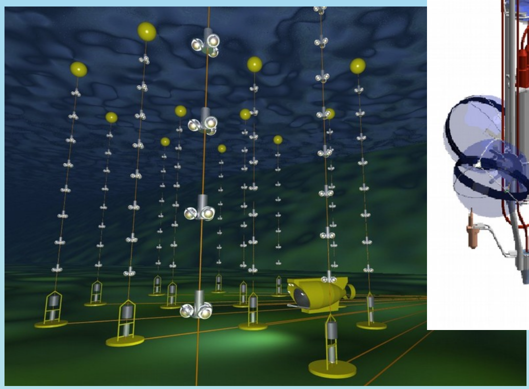


DOM

3*10” PMTs -> 31*3” PMTs
same sensitive area
+compactness
+wider angle of view
+directional information
+digital photon counting



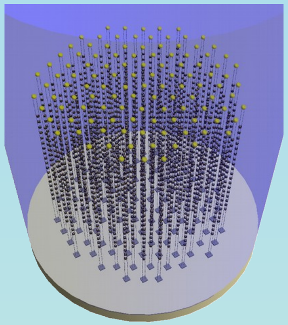
ANTARES



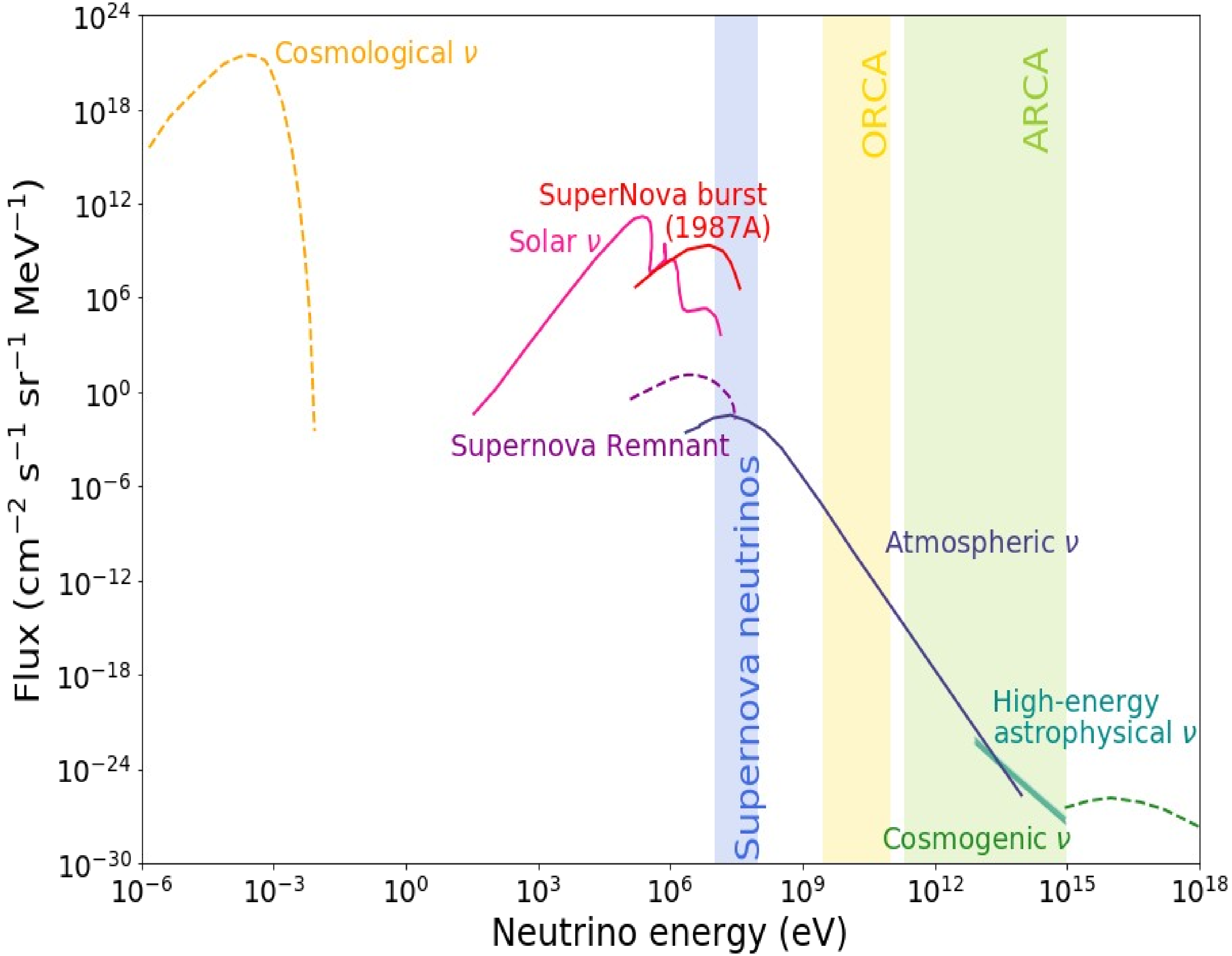
ANTARES storey

-12 lines
-25 storeys per line
-3 PMTs per storey

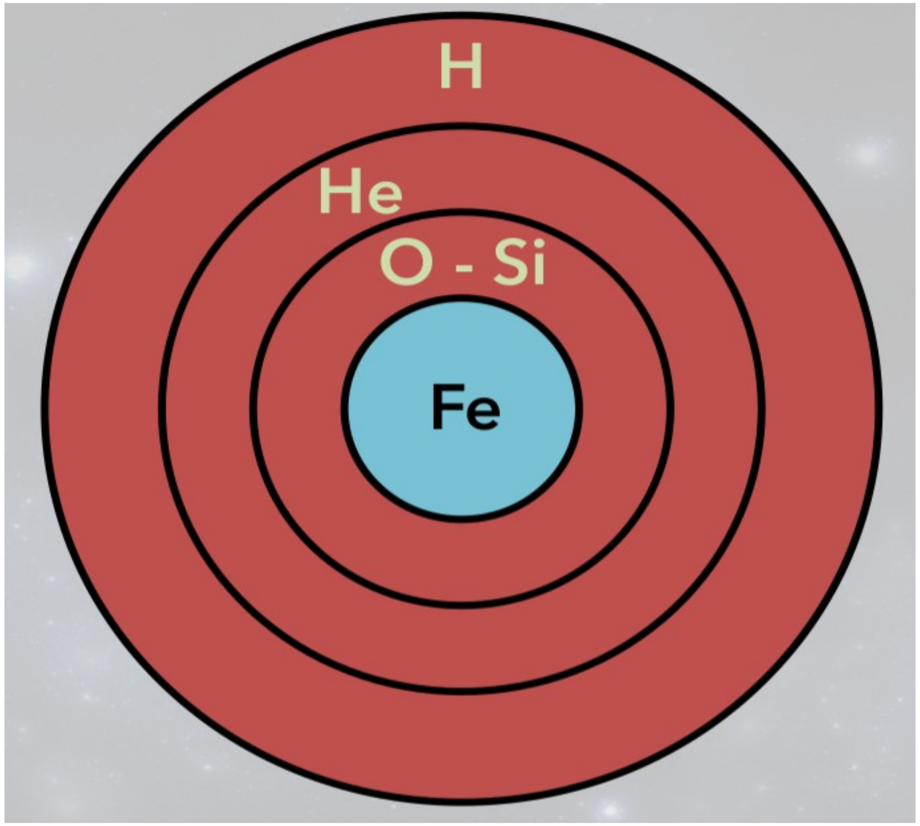
ORCA:
1 block



Multi-energy neutrino spectrum:

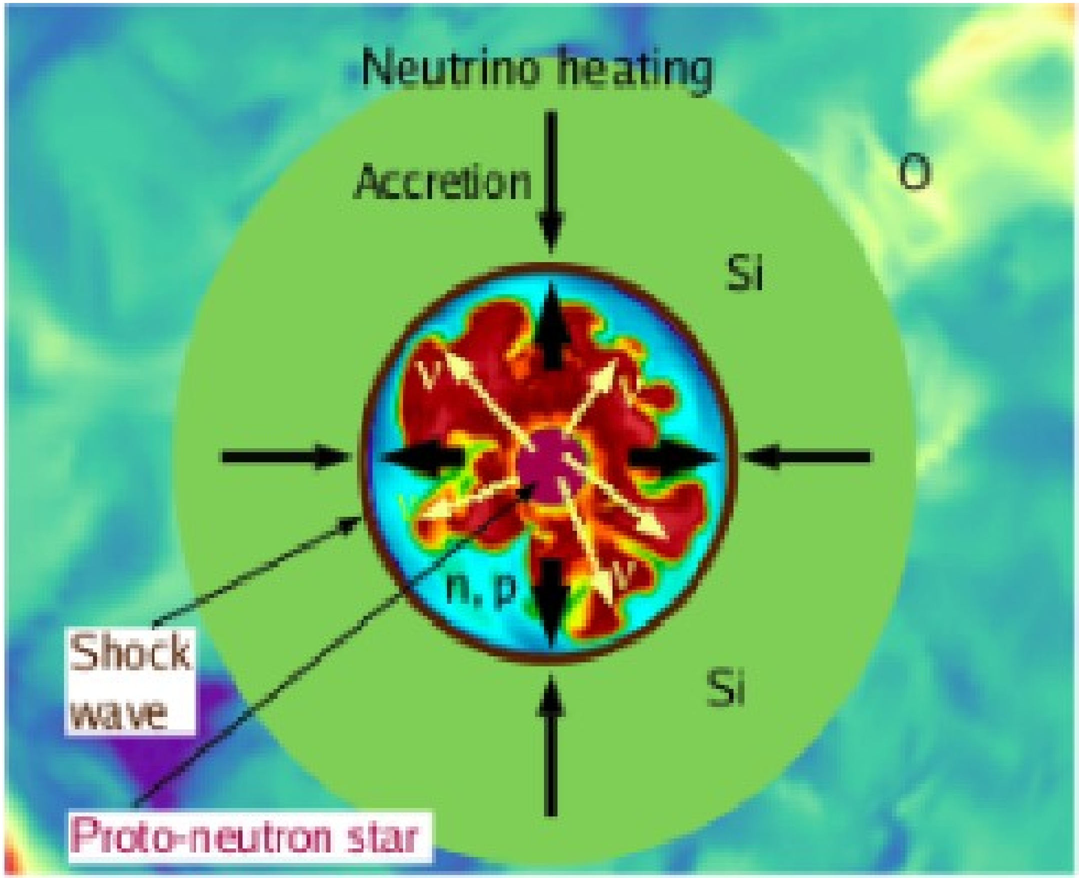


Core Collapse Supernova:
The explosion mechanism



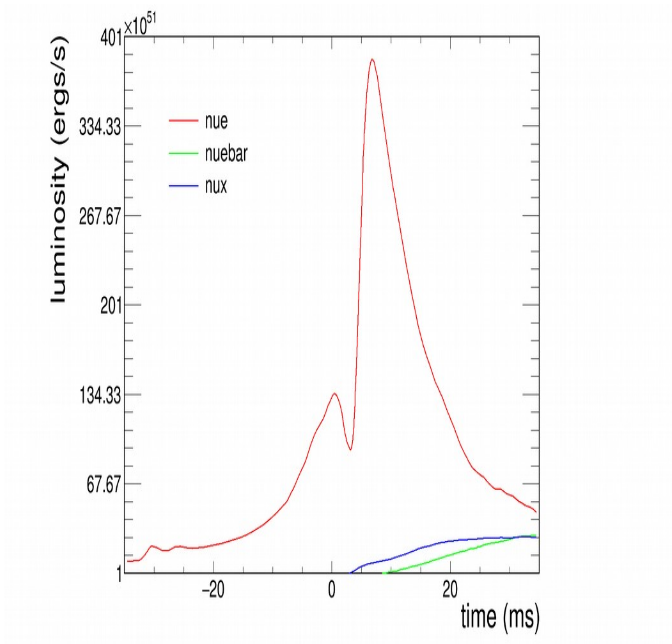
- Massif stars (>10Msun)
- Onion structure
- Gravity: Compress matter
- Temperature y pression increase
- Nuclear force: Burns H y He
- Competition between gravity and nuclear force.
- In the end, it runs out of fuel (H y He) and gravity wins.
- Gravitational collapse of the star.

Core Collapse Supernova: The explosion mechanism



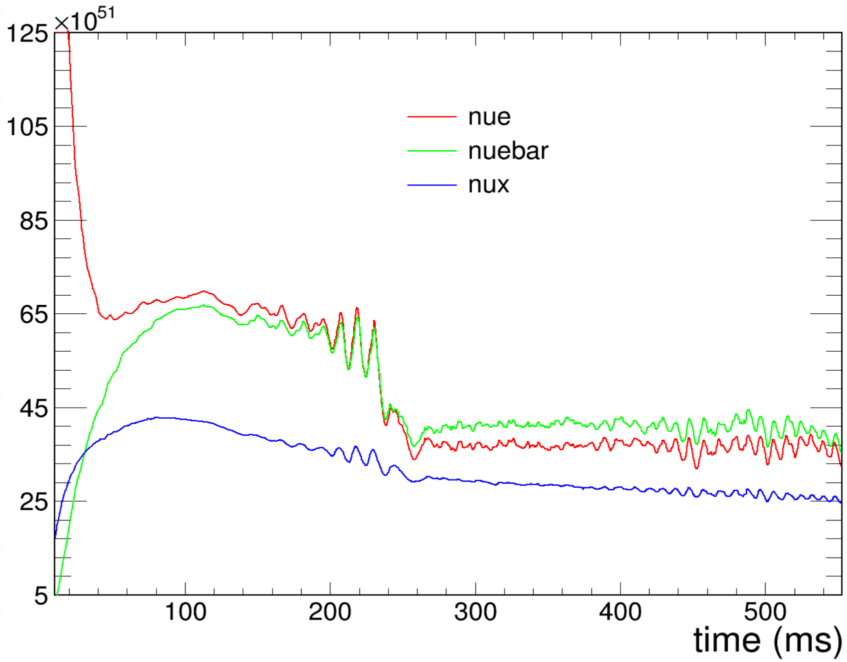
- Huge amount of neutrinos produced via nuclear reactions.
- Shock wave formation, that propagates until it stalls.
- Neutrinos revive the shock (neutrino heating) by energy deposition and allow for:
  - The final explosion
  - Stellar nucleosynthesis of heavy nuclei
- 99% of the gravitational binding energy emitted through neutrinos

Core Collapse Supernova: The explosion mechanism



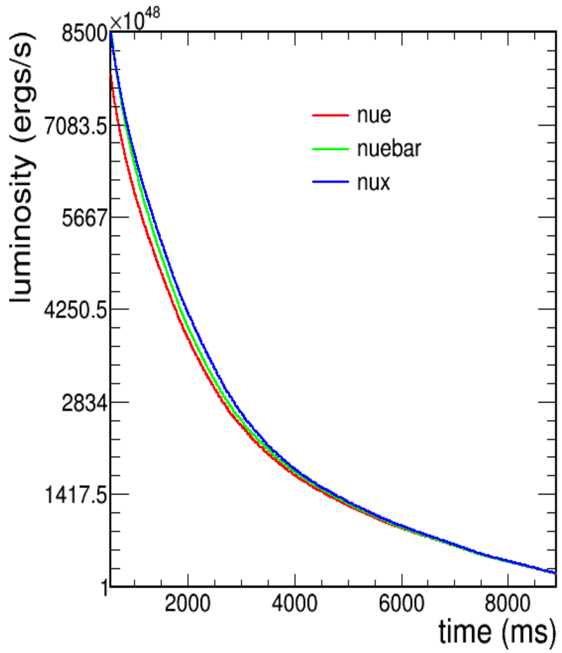
BURST

- Shock bounce and stagnation
- Electron capture
- Born of remaining compact object



ACCRETION

- Hydrodynamical instabilities/convection
- Neutrino heating
- Shock revival

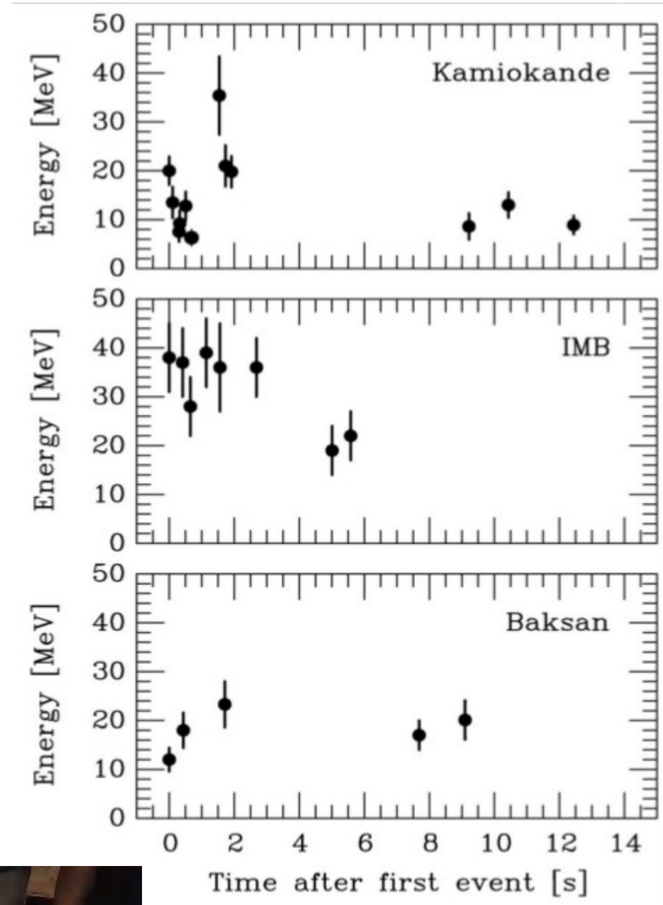


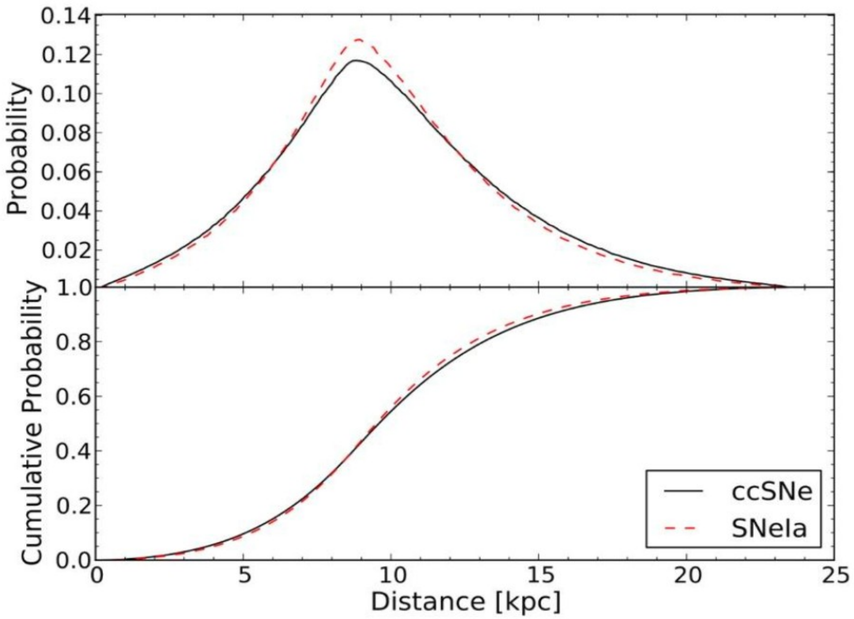
COOLING

- Neutrino pair production
- Nucleosythesis
- Explosion

What is really happening?

- Sophisticated simulations don't allow to reproduce the explosion… not for the amount of energies observed
- Only one detection (1987) of 25 neutrinos:
  we need more statistics to constrain the mechanism
- Only 1-3 Galactic CCSN per century…





CCSN neutrino detection in water:

- Large amount of 1-100 MeV promp neutrino emission:

  anti-nue dominate during accretion phase (~500ms)
- Main interaction: anti-nue with protons (IBD), also ES (~3%)
- We expect ~1000-8000 events:

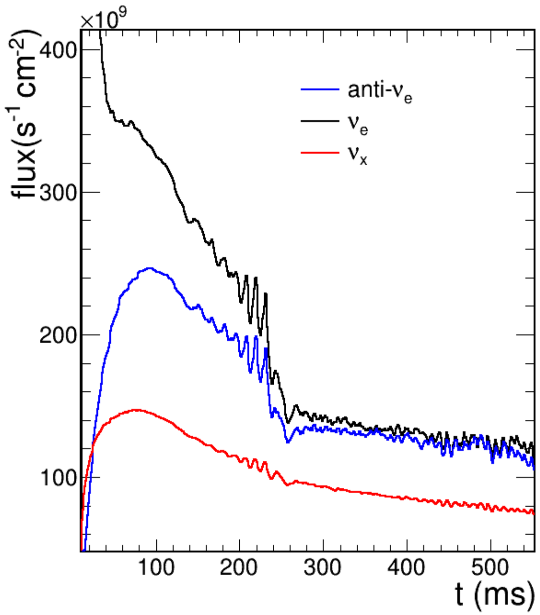
  storage of all data needed (at ms precision)

What we do:

- Detection performance + real-time alerts
- Time resolution: light-curve physical features + pointing
- Energy resolution: neutrino spectrum

Monte-Carlo simulation in KM3NeT

- Development of a low energy MC neutrino generator for KM3NeT.
- Flux from 3D CCSN simulations by Garching Group: 3 energy and time dependent parameters in the model: $L(E_\nu,t)$, $\alpha(E_\nu,t)$ and $<E_\nu>(E_\nu,t)$
- Main interaction channel → Inverse Beta Decay (IBD): $\overline{\nu}_e + p \rightarrow e^+ + n$



CCSN neutrino fluxes → Interaction rates ← Cross sections

Interaction rates

(Interactions around a DOM)

↓

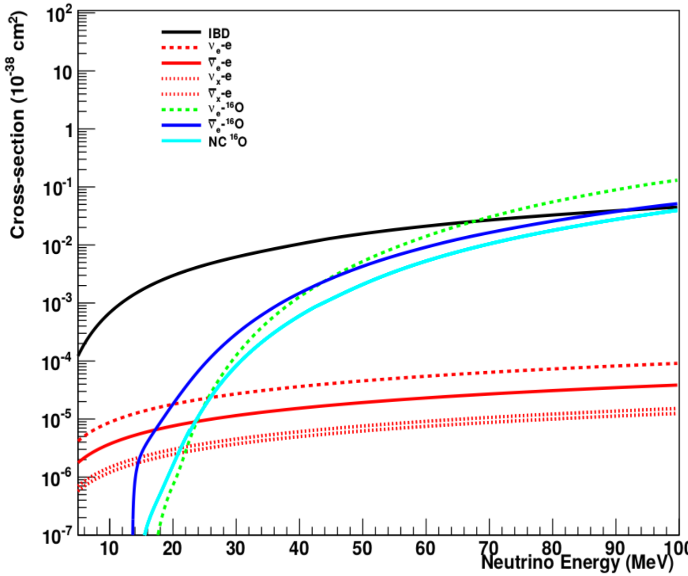
Outgoing leptons

↓

Cherenkov light ← GEANT4

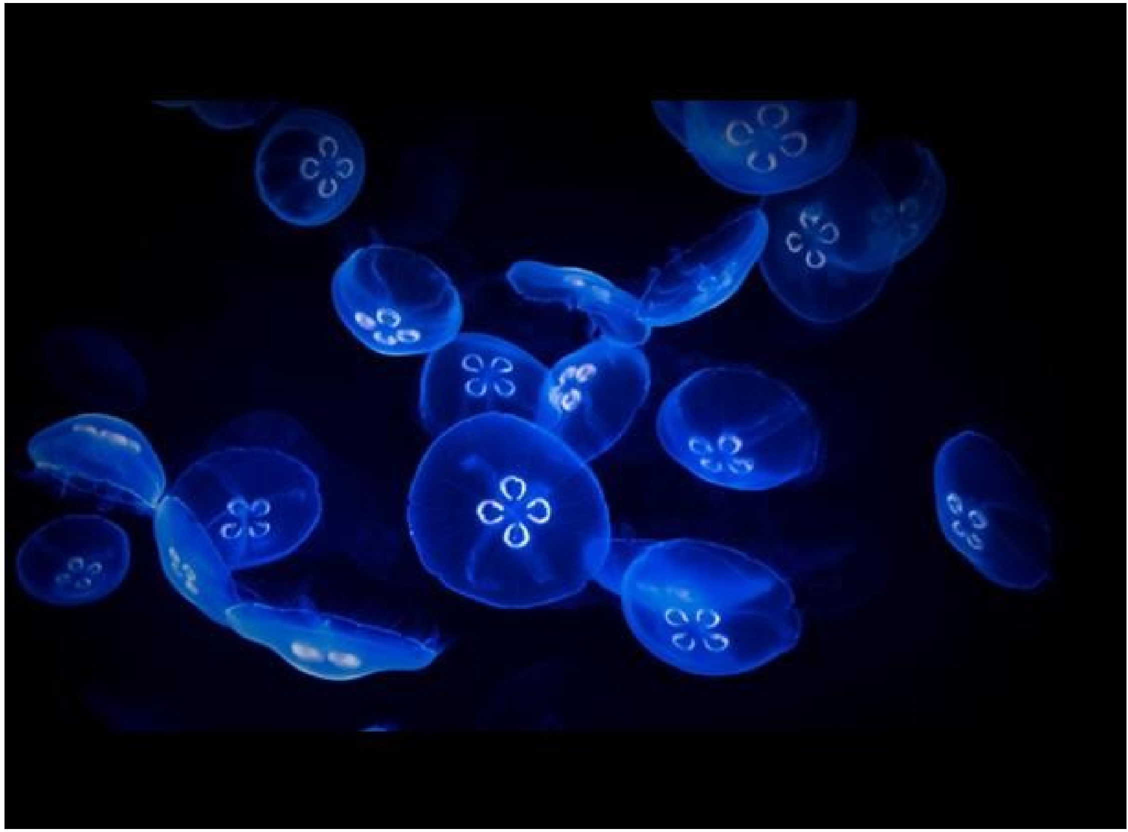
↓

PMT (detector) response

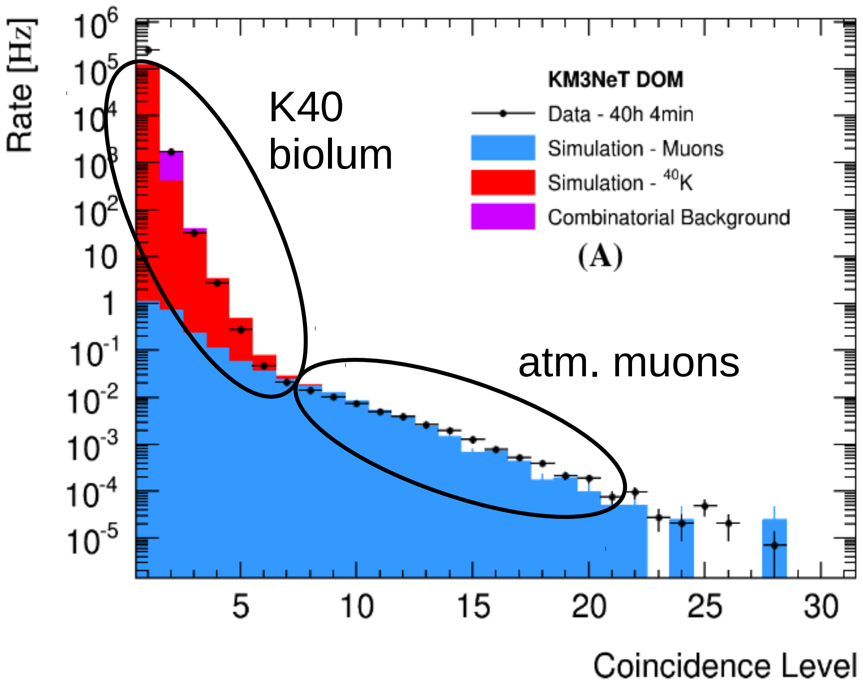


What other things produce light in sea water? (Background)

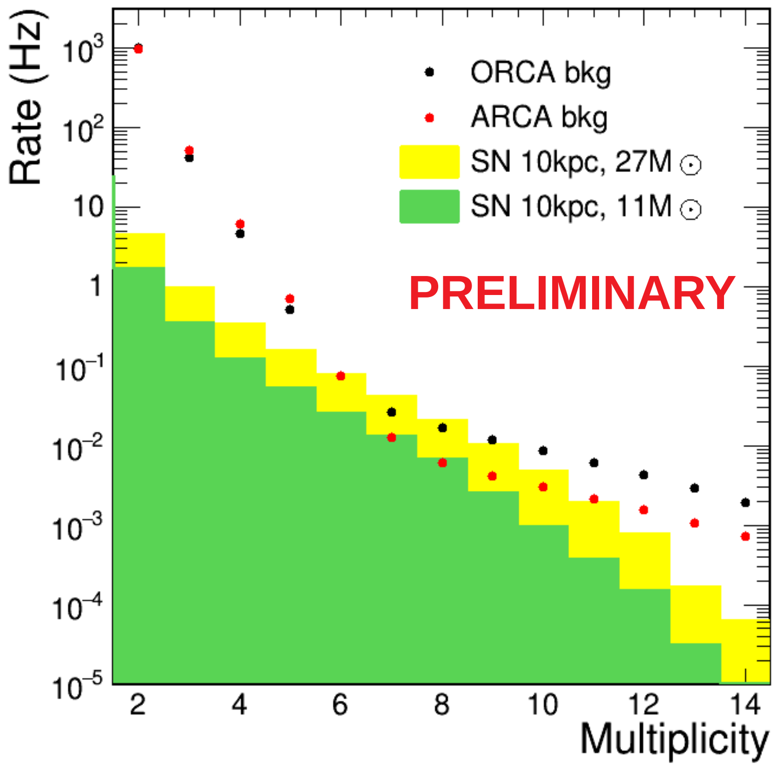
- Atmospheric muons and atmospheric neutrinos
- K40 decays (radioactive isotopes present in sea water)
- Bioluminescence:
  Plants and animals



Detection method:



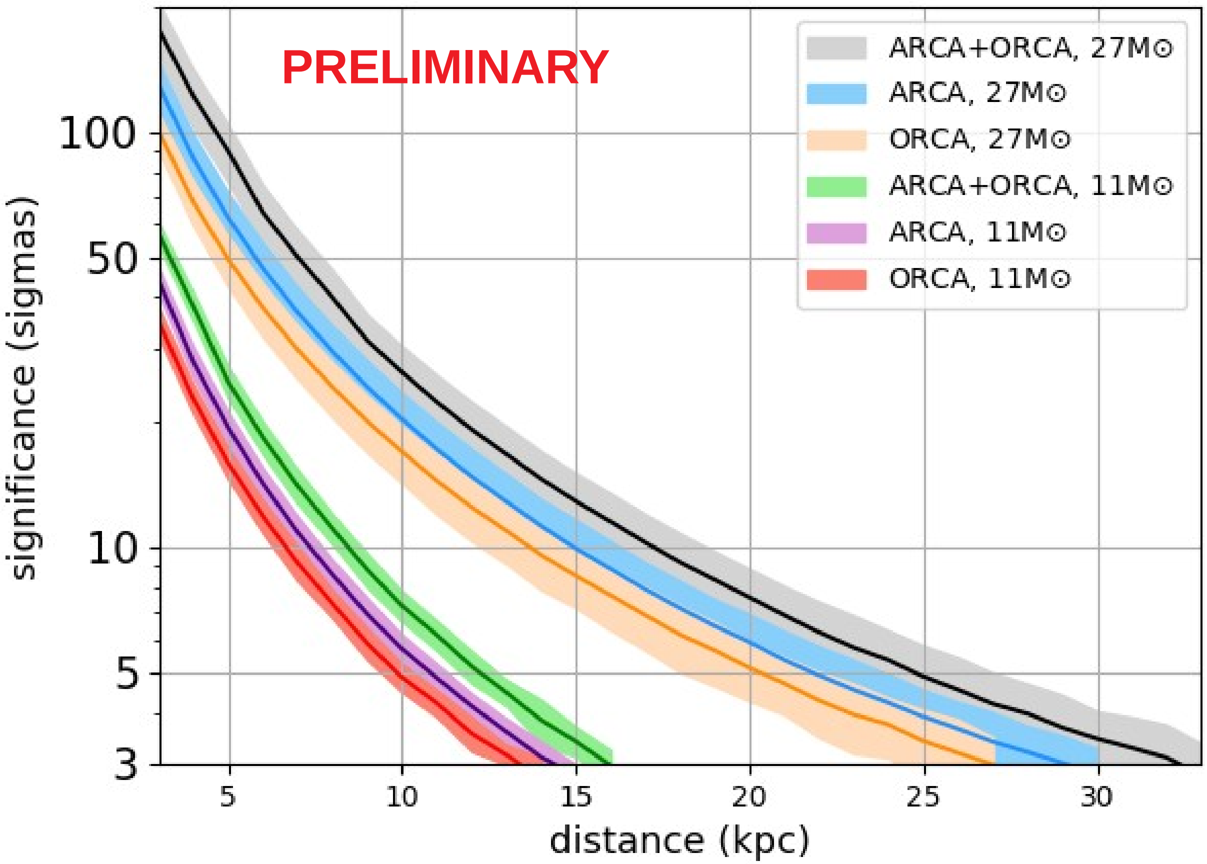
Exploit multi-PMT technology to achieve better performance!



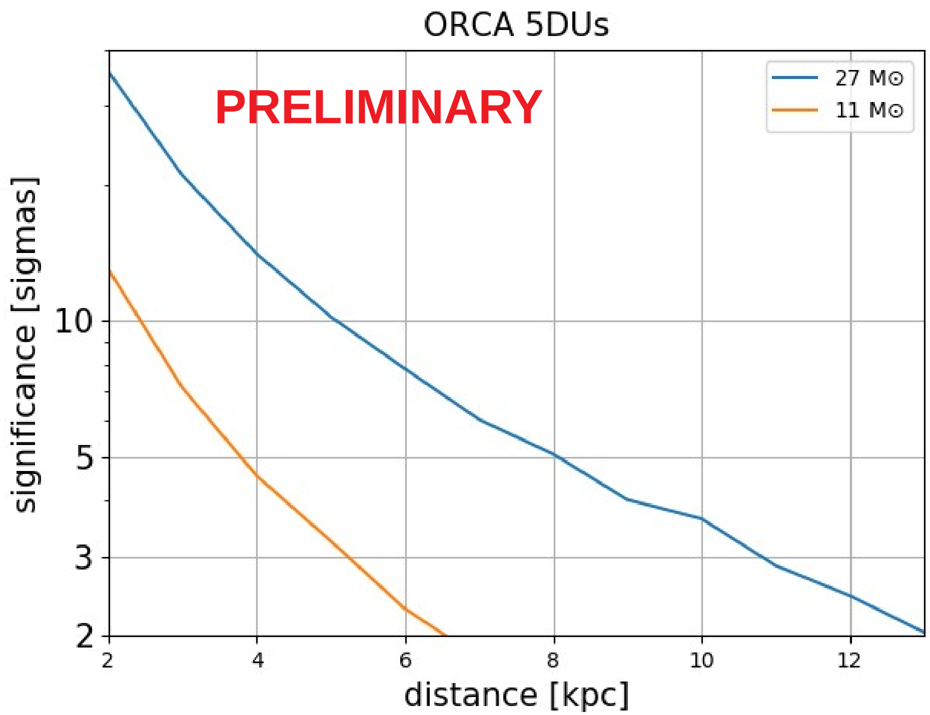
- Event reconstruction is <u>not possible</u>
- <u>Signal</u> = Overall increase of detected PMT rates over bkg expectation
- Selection of events producing few ns time <u>coincidences</u> between the PMTs to reduce bkg→ <u>multiplicity selection</u>
- Multiplicity: number of PMTs in a DOM receving a photon within 10 ns

Significance of the detection

→ Coverage of the full Galaxy combining ORCA and ARCA (27M⊙)
→ Beyond the Galactic Center with full ORCA (11M⊙)



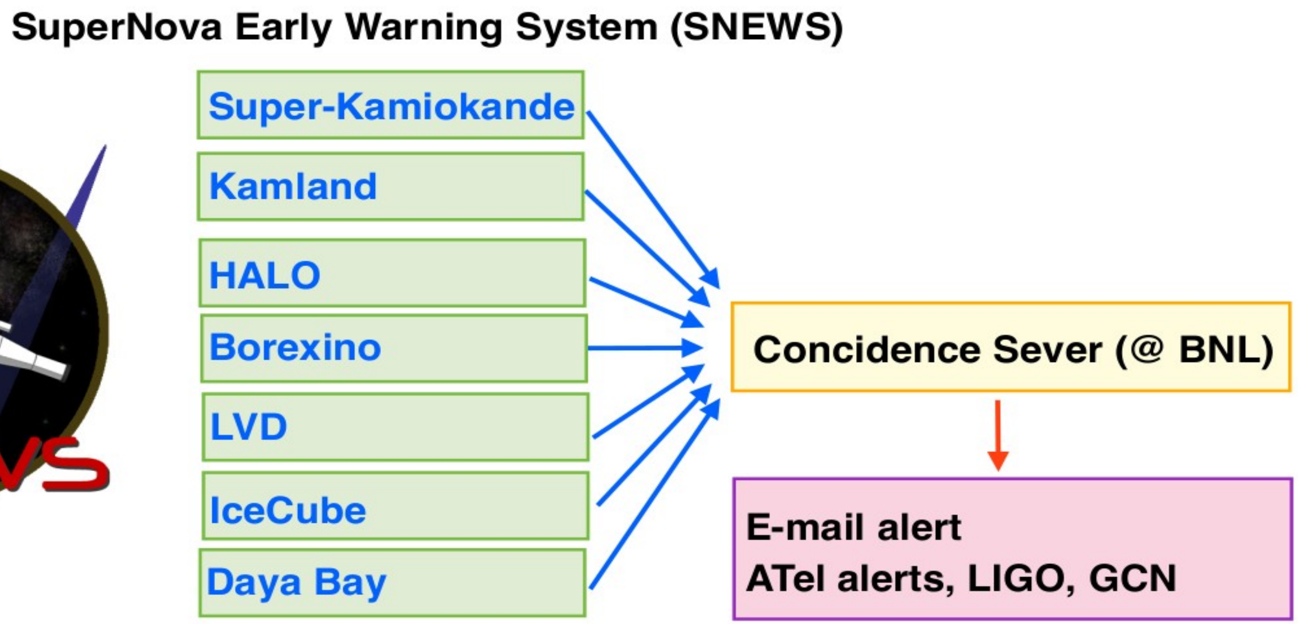
With 5DU ORCA, 5σ disc. up to: 8kpc (3.5kpc) for 27M⊙ (11M⊙)



(Time window search used in the analysis: duration of the simulation)

Real-time alerts: SNEWS

- Global network for neutrino detectors sending SN alerts
- Requirement: less than 1 fake trigger in 10 days
- Alert sent if at least 2 detectors trigger an event in coincidence (~min)
- KM3NeT is joining the network with SNEWS2.0!



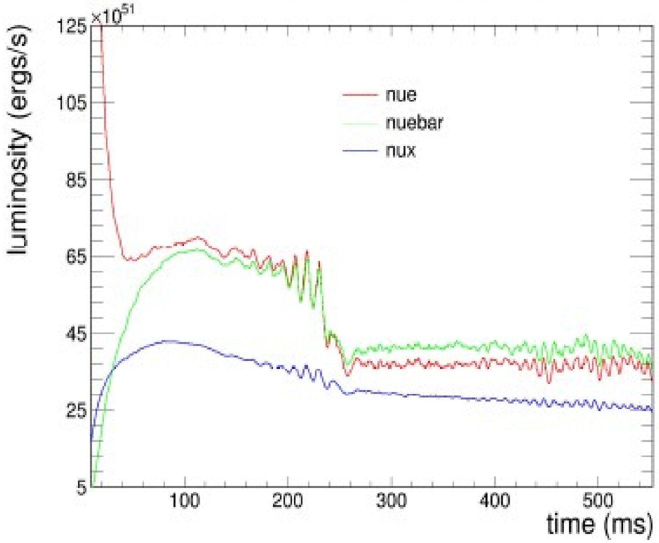
- ORCA can trigger beyond the Galactic Center!
- Online SN monitoring working stable for months now!
- Low latency: fast response, alert sent in ~20s
- Combined real-time trigger ORCA+ARCA

What to learn on CCSN neutrinos?

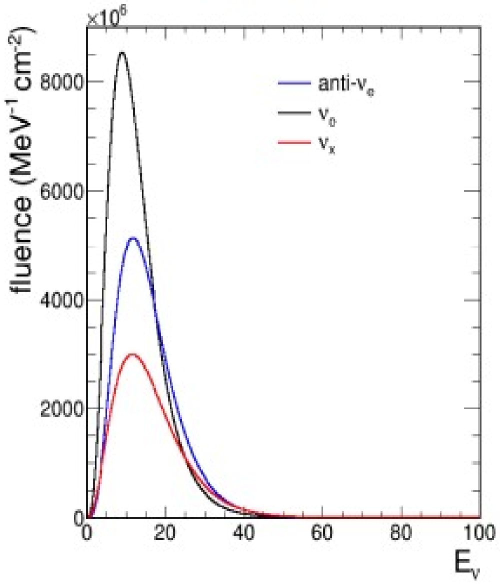
- Multi-PMTs (multiplicity) for optimal sensitivity and energy estimation
- Double coincidences for time information: high statistics (large detector)

Constrain the models!

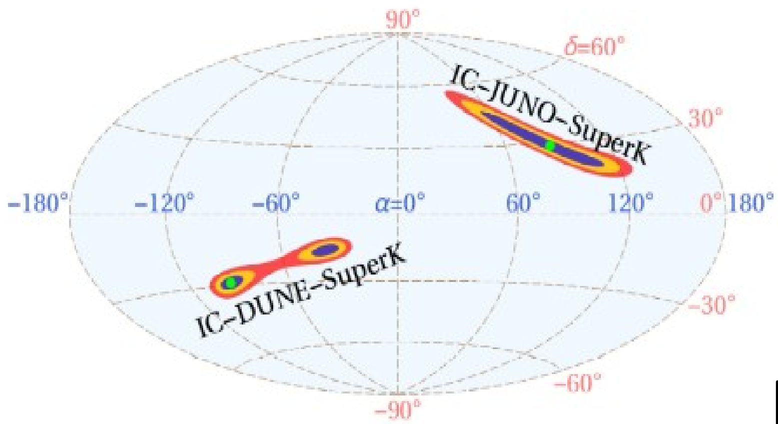
Light-curve
(time profile)



Energy spectrum



Source direction



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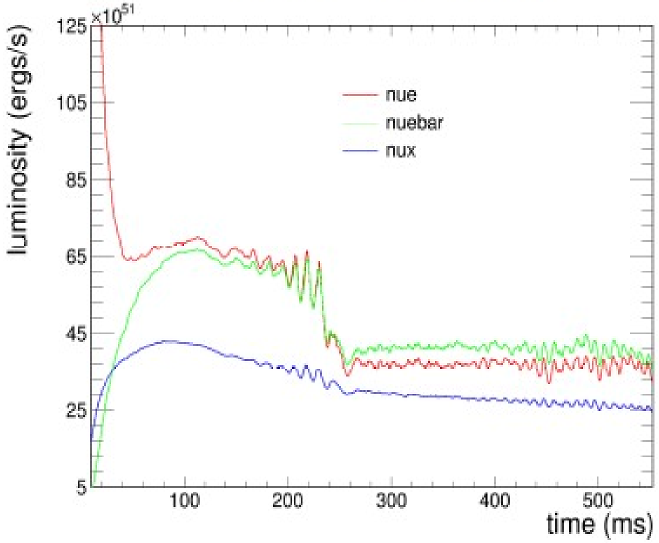

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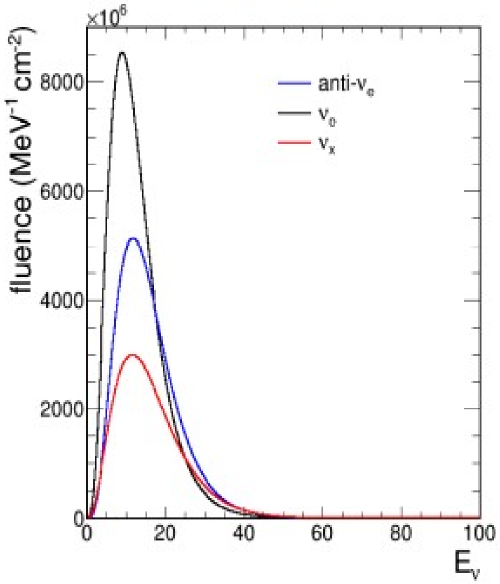

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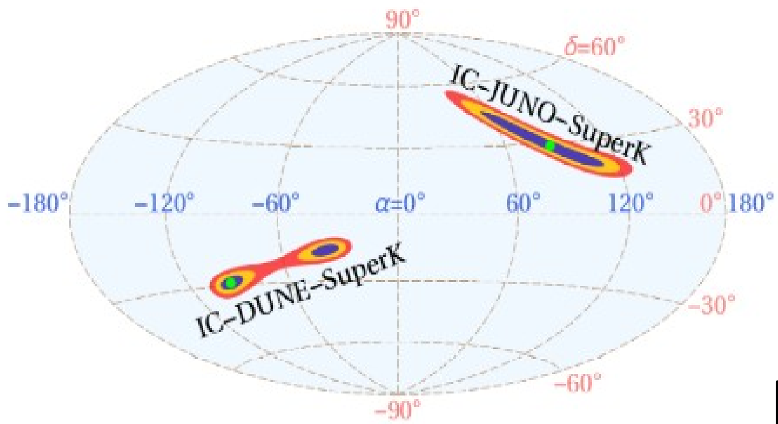
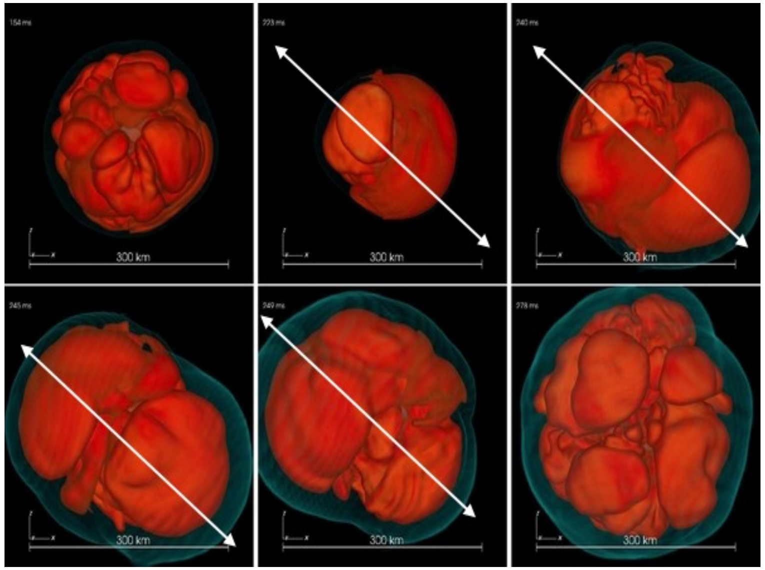
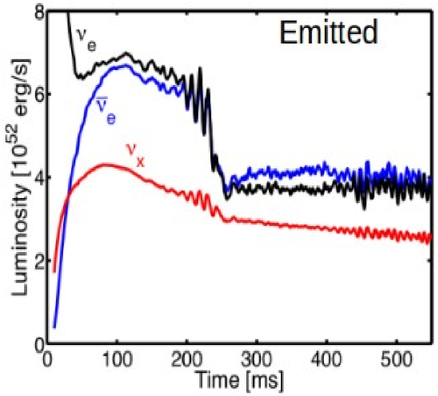
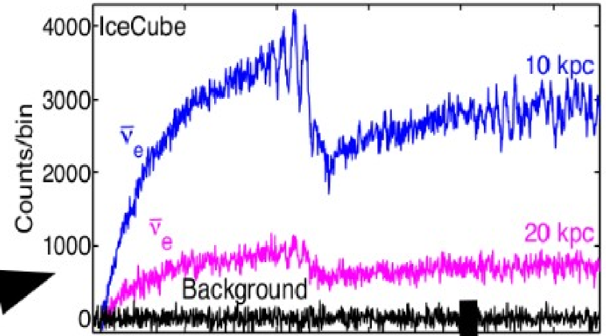


Fast time variations on the neutrino light-curve: SASI

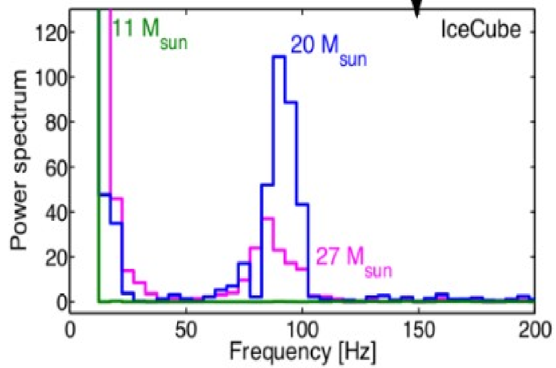
- Standing Accretion Shock Instability (SASI): hydrodynamical instabilities during CCSN predicted by recent 3D simulations → Directional effect
- Footprint: Time variations in the neutrino light-curve around 200ms
- Feature: Characteristic oscillation frequency (80Hz) seen trough Fourier analysis
- Enhances the neutrino heating favoring the explosion:
  → can help understanding the mechanism!
- Potentially correlated with GW emission!







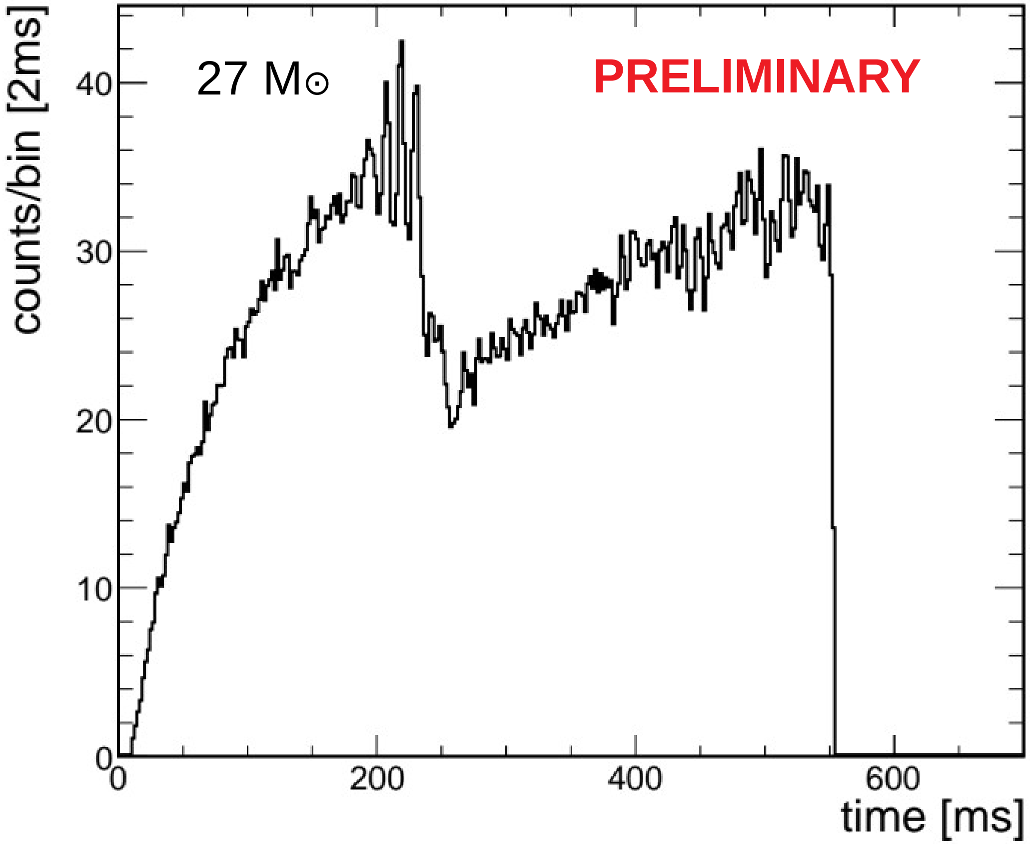
Detected IC signal and bckg

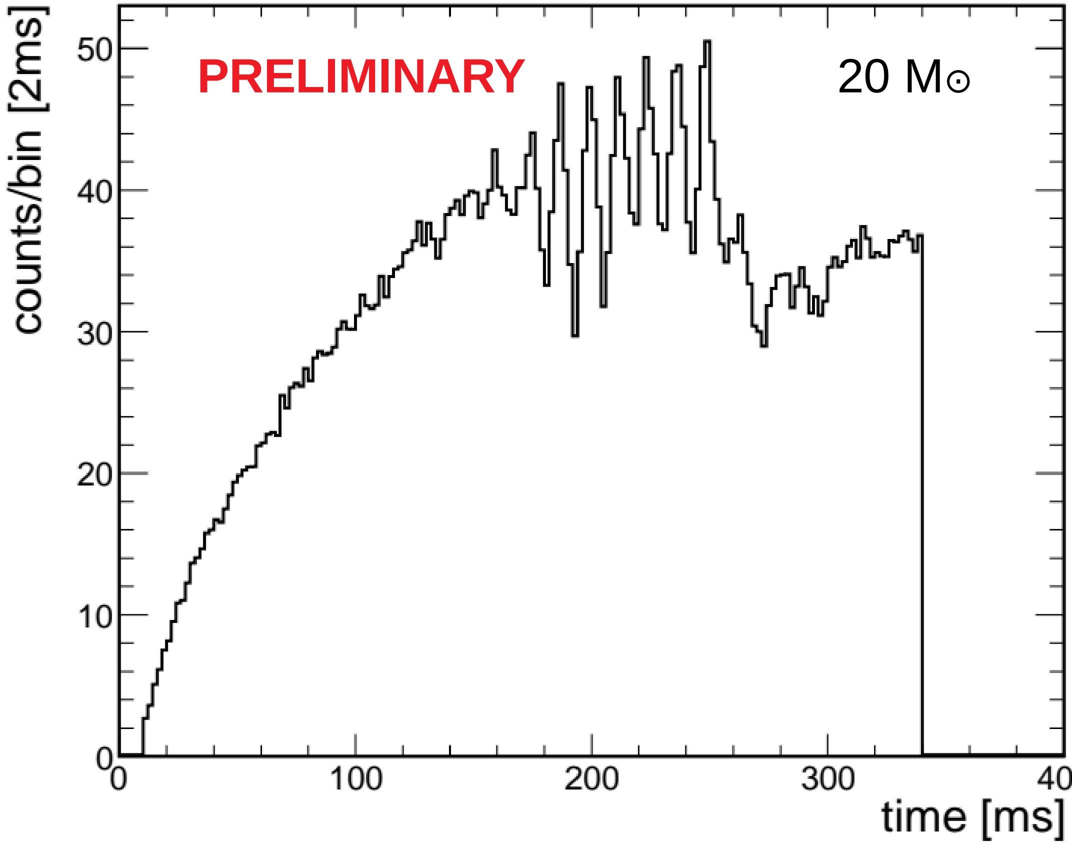


Power spectrum IC

Progenitor models and detector response to CCSN signal time profile

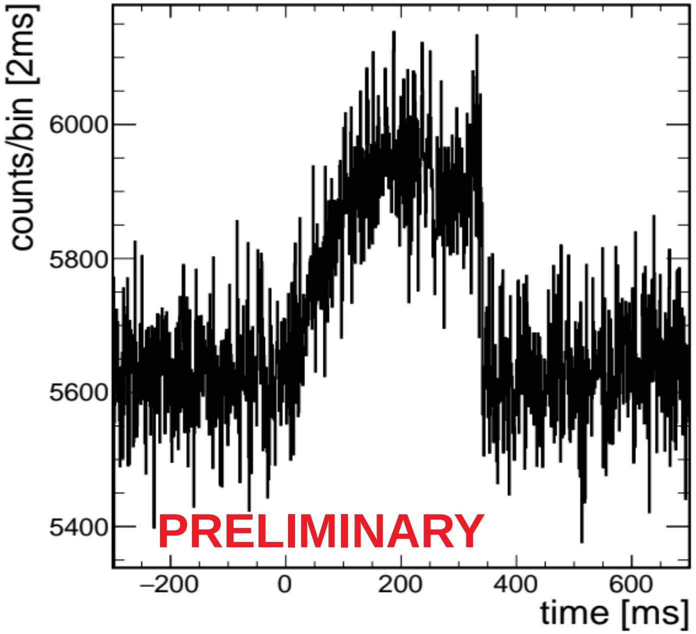
→ We use double (5ns) coincidences (high stats, reduce biolum)
→ Expected signal in 115 detection lines (1 block) @ 10 kpc



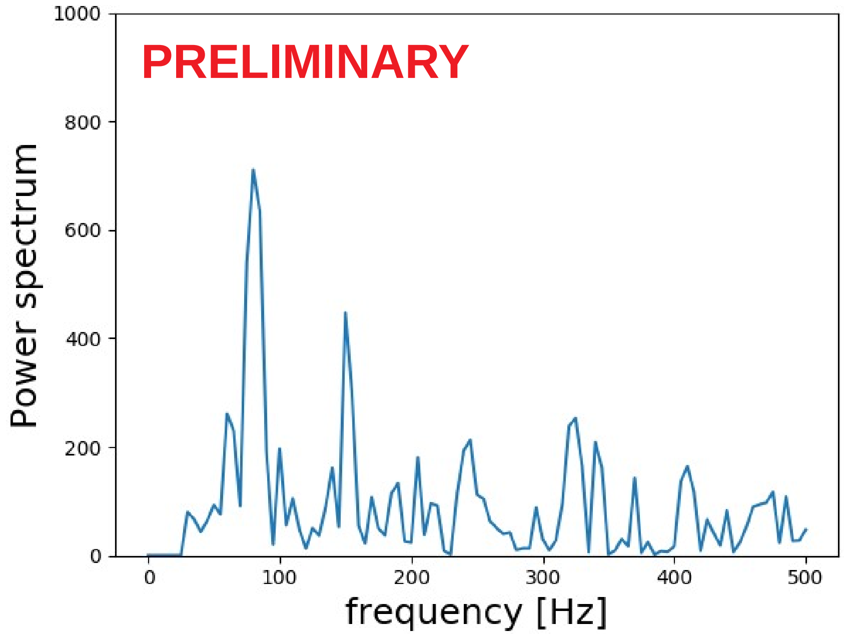


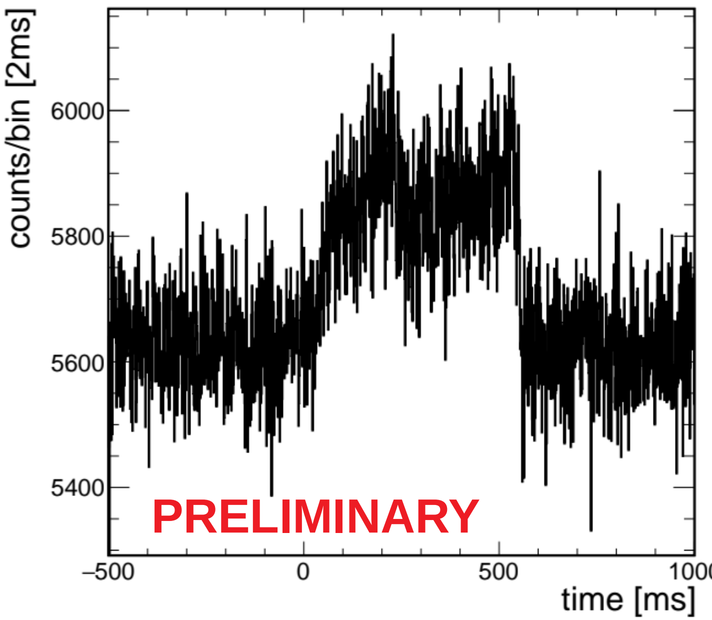
Now, add background and see...

Light-curves and Power Spectrum:

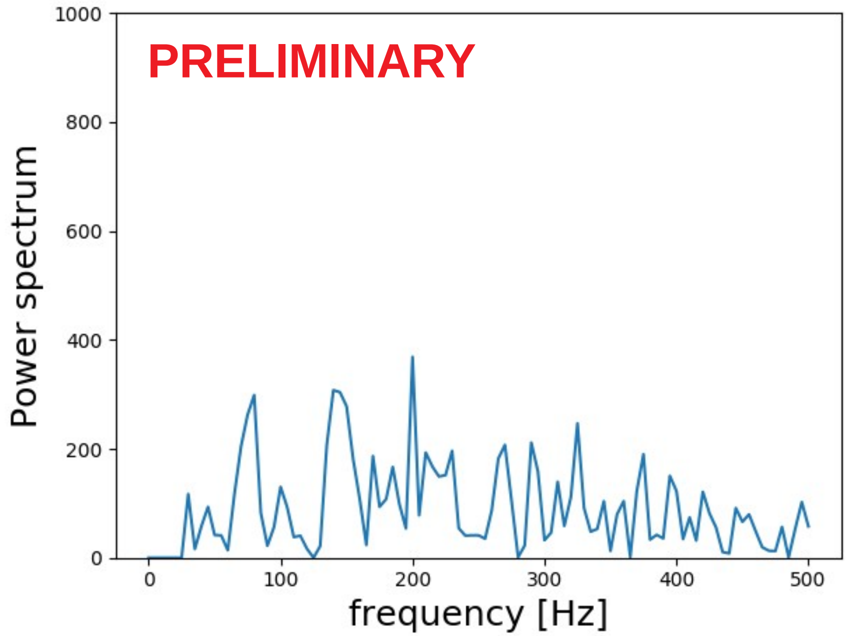


ARCA 20M⊙
@5kpc (with bkg)



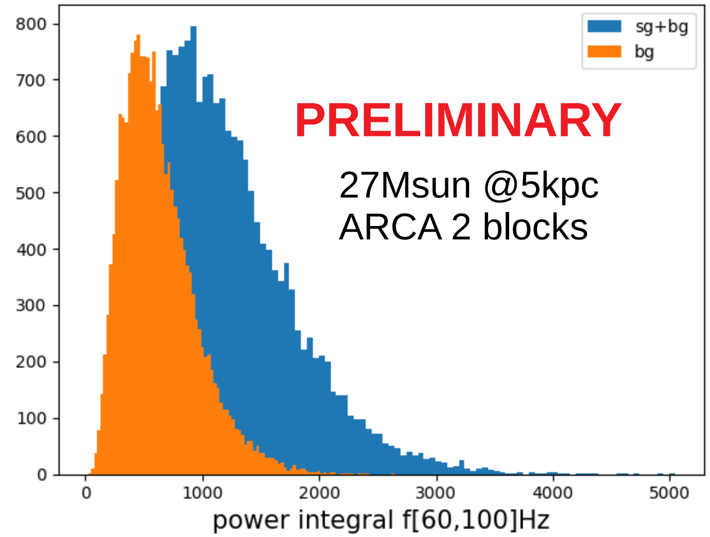


ARCA 27M⊙
@5kpc (with bkg)

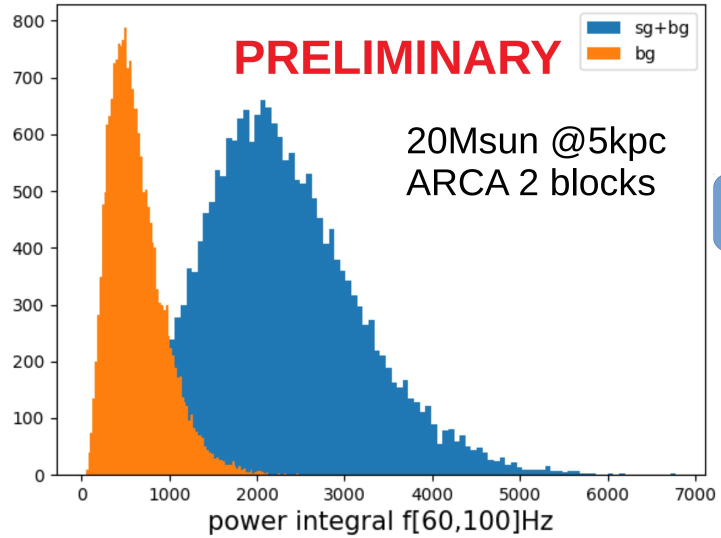


Analysis method & preliminary results:

Model dependent approach:
Look for a significant power excess around the expected SASI frequency

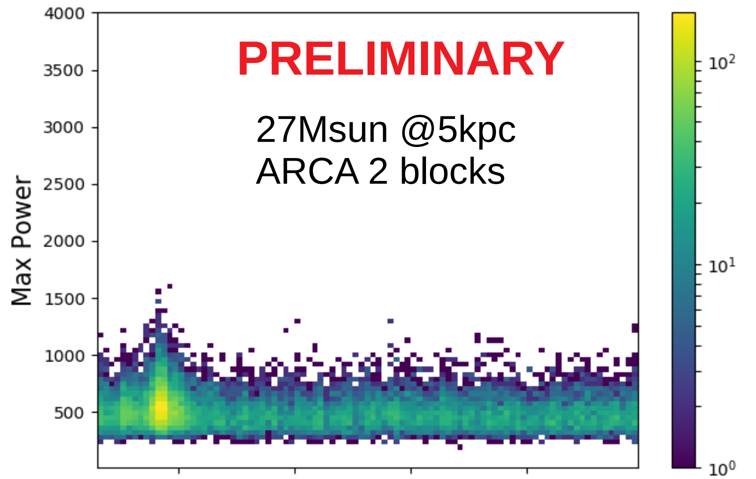


2σ

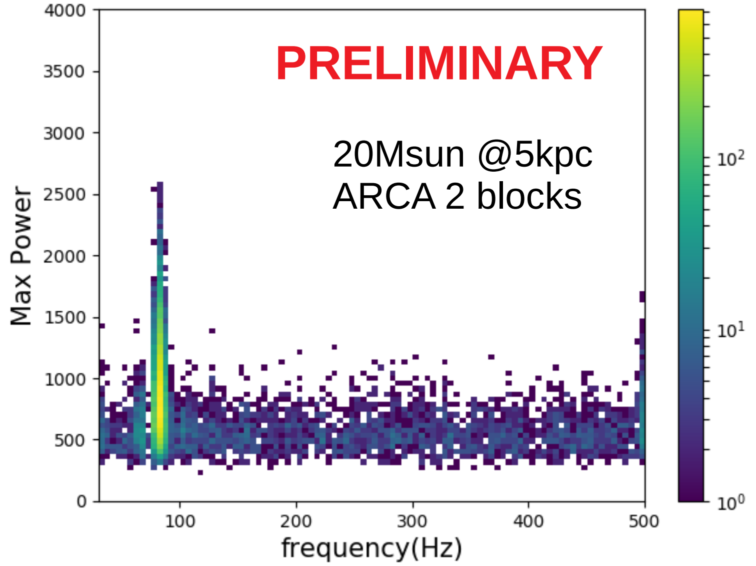


3.5σ

Model independent approach:
Look for a significant peak on the Power Spectrum at any frequency



1σ

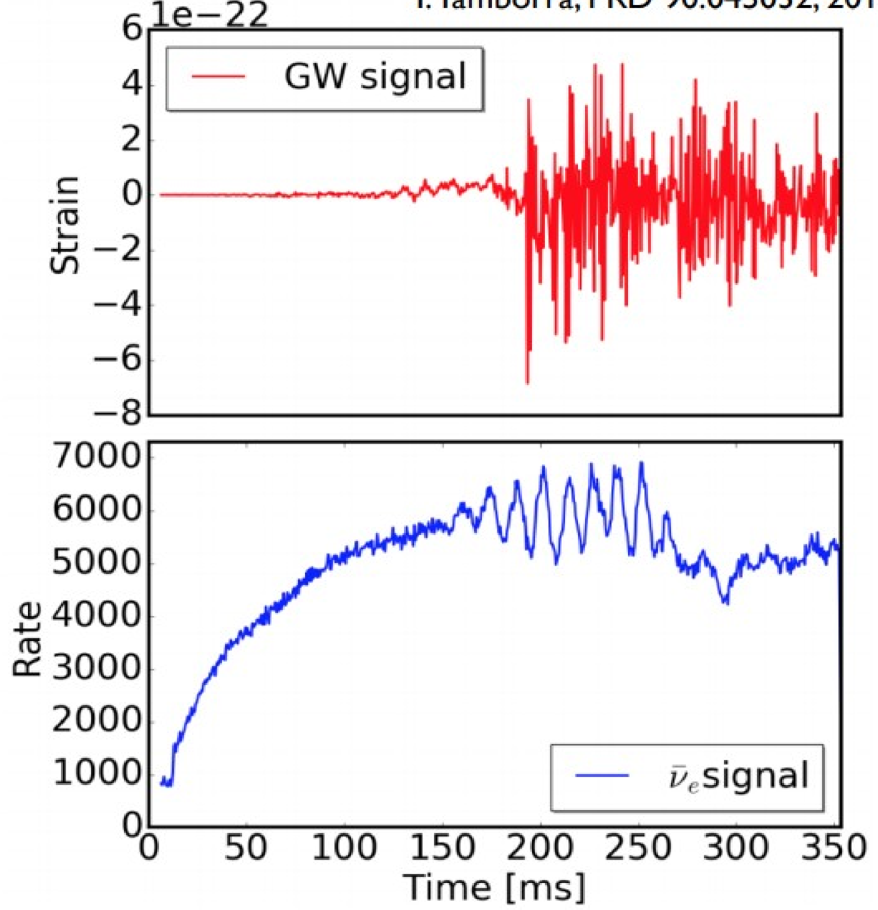


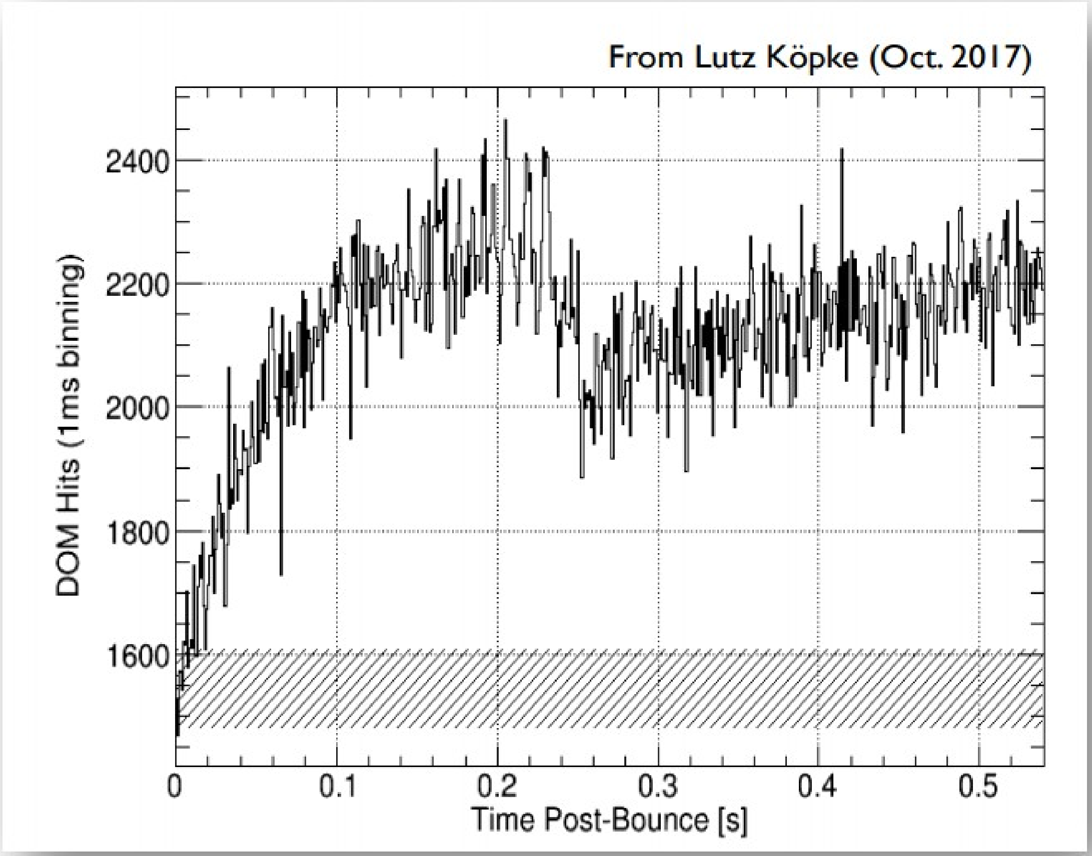
2.5σ

SASI and GW emission:

- With precise measurements of lightcurve, potential sensitivity to imprint of short time-scale phenomena.

I. Tamborra, PRD 90:045032, 2016



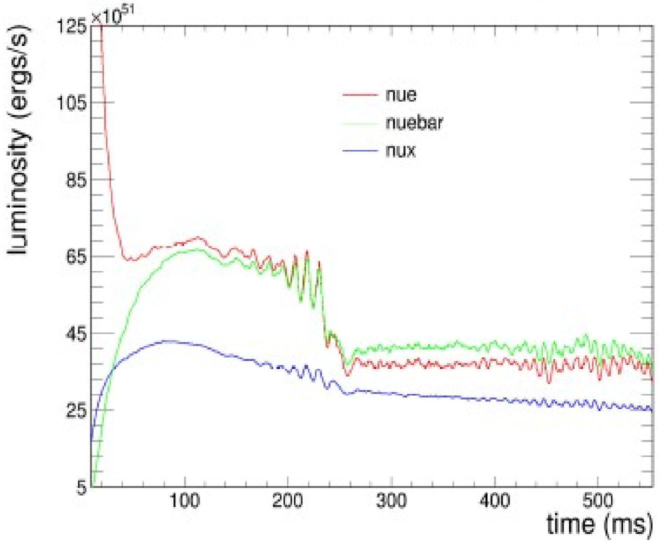


What to learn on CCSN neutrinos?

- Multi-PMTs (multiplicity) for optimal sensitivity and energy estimation
- Double coincidences for time information: high statistics (large detector)

Constrain the models!

Light-curve (time profile)



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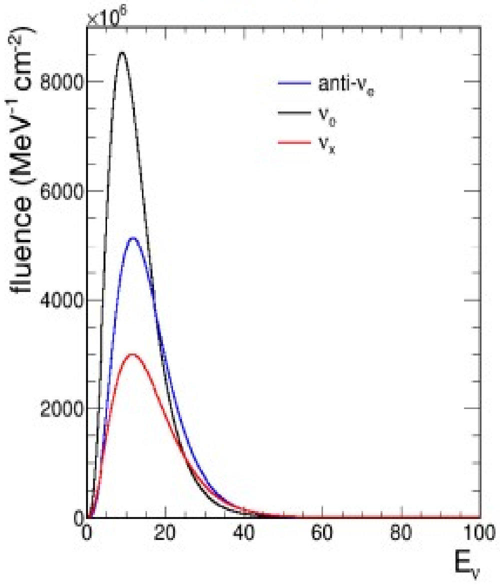
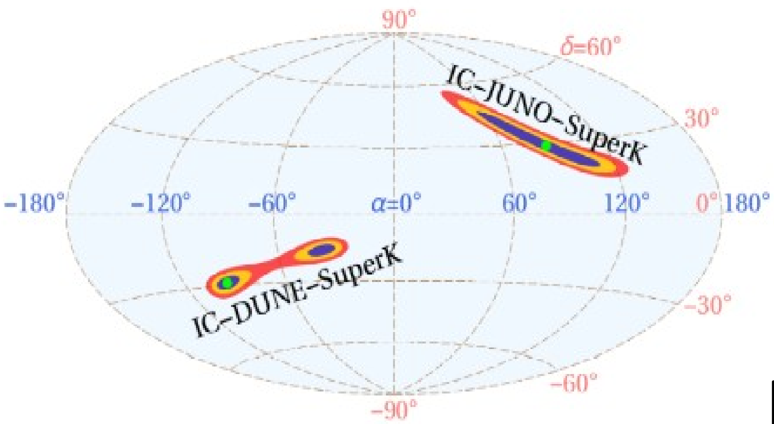


Source direction



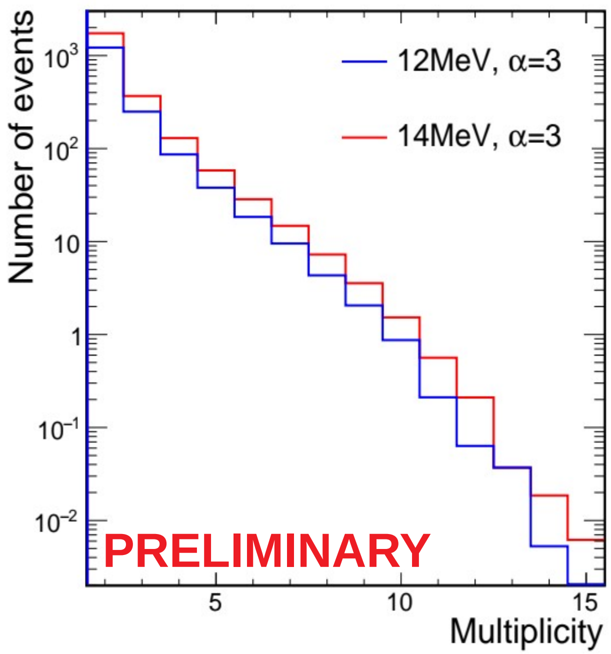
Determining the mean energy of CCSN neutrinos

- Simplified flux model used here to investigate 2D parameter space: Mean neutrino energy and pinching shape parameter (α)

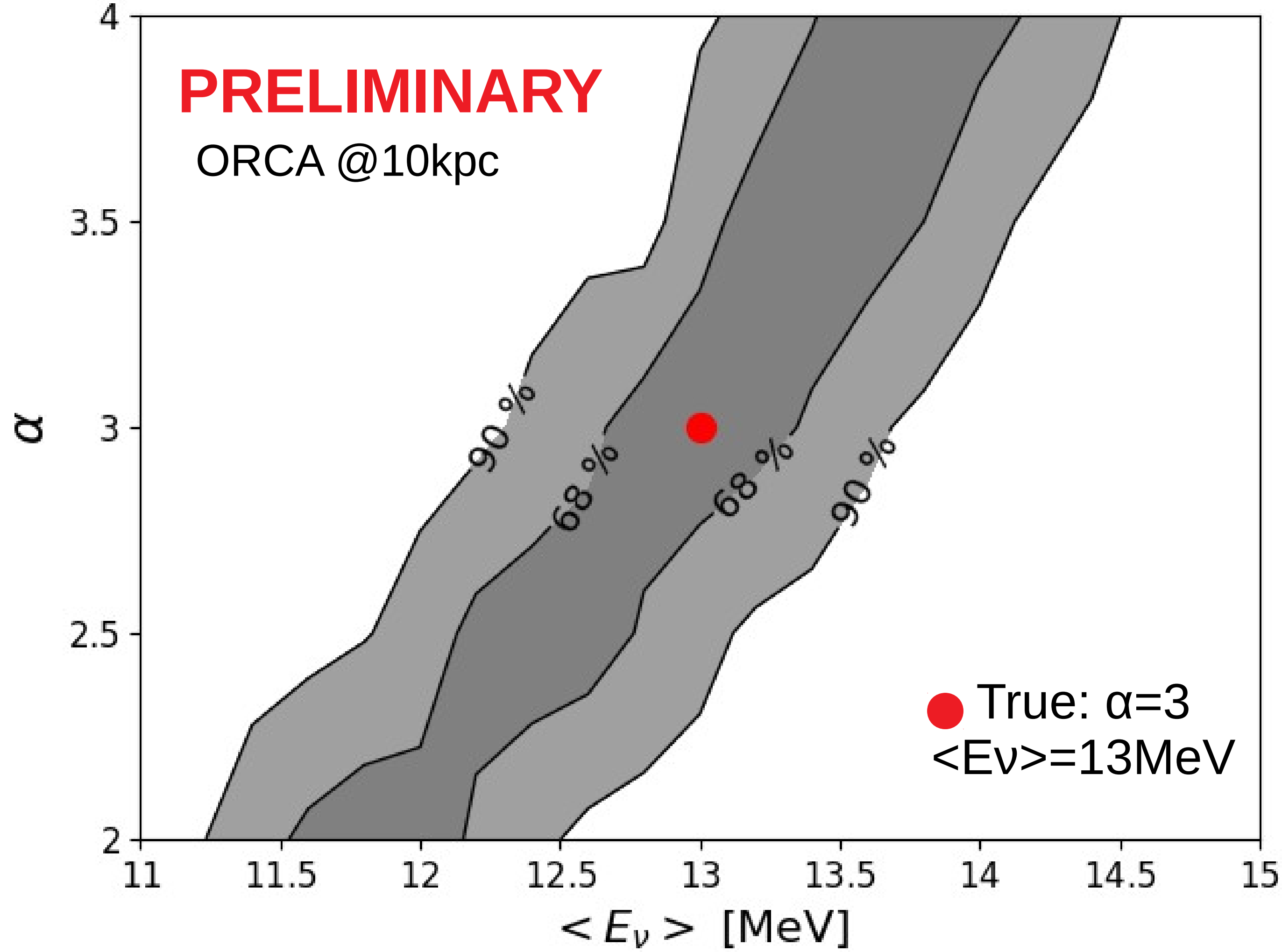
$$f_\nu^{SN} = \frac{1}{4\pi(10\ \mathrm{kpc})^2}\left\{\left[\frac{3\times10^{53}\ \mathrm{erg}}{6\ \tilde{E}_\nu}\right]\times\frac{0.25}{100\ \mathrm{ms}}\right\}\frac{E_\nu^{\alpha}\exp(-(\alpha+1)E_\nu/\tilde{E}_\nu)}{\mathrm{Normalization}}$$

- More energetic events: More high multiplicity (M) & less low M events
- Use low to high level coincidences ratio: multiplicities from 3 to 10
- 2D X^2 method to constrain $<E_\nu>$and α:

$$\chi^2(<E_\nu>,\alpha) = 2\sum_{M=3}^{M=10}\left(\mu_M - n_M + n_M \times ln\left(\frac{n_M}{\mu_M}\right)\right)$$



Constraining the mean energy of CCSN neutrinos:



Degeneracy between α and <Eν> in the 2D parameter space

Scan over <Eν> and fixed α plane yields: σ(Eν)/<Eν> ~ 2-3%

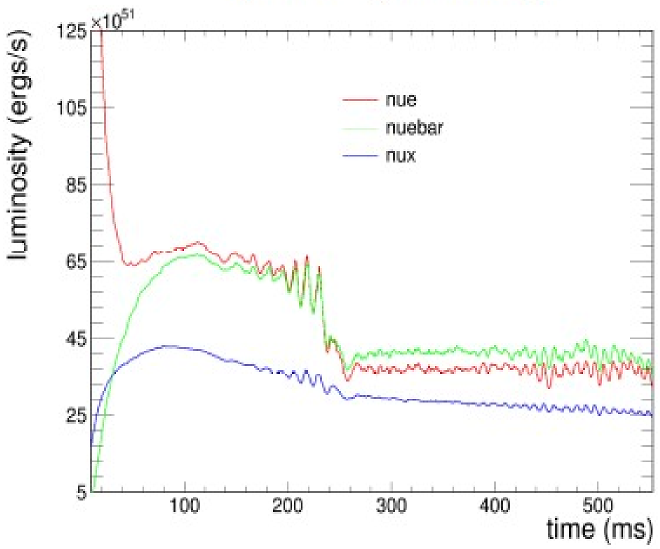
(Conservative ν flux, close to 11Msun values)

What to learn on CCSN neutrinos?

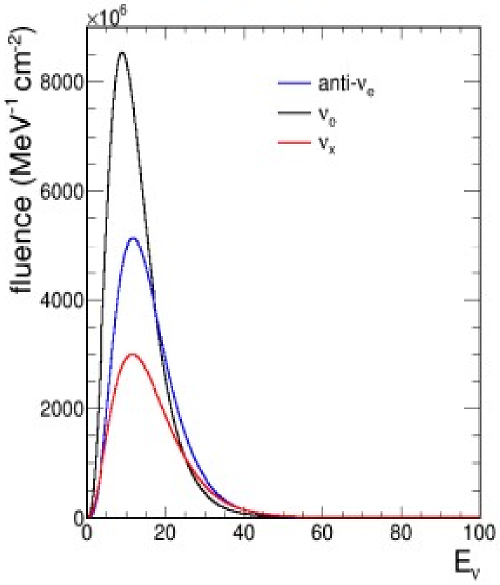
- Multi-PMTs (multiplicity) for optimal sensitivity and energy estimation
- Double coincidences for time information: high statistics (large detector)

Constrain the models!

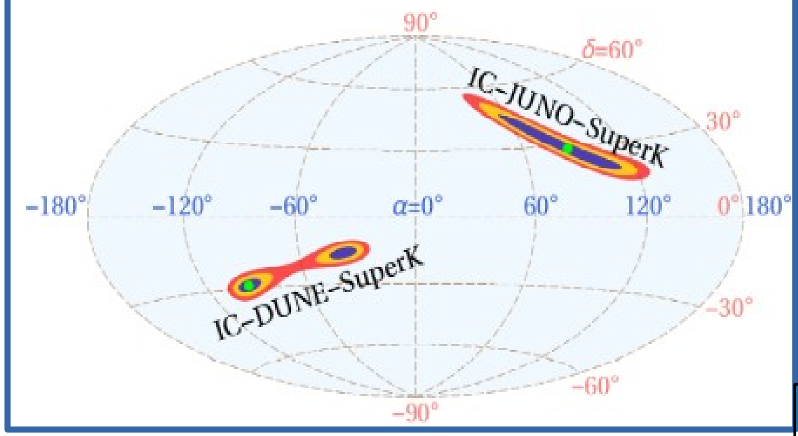
Light-curve
(time profile)



Energy spectrum



Source direction

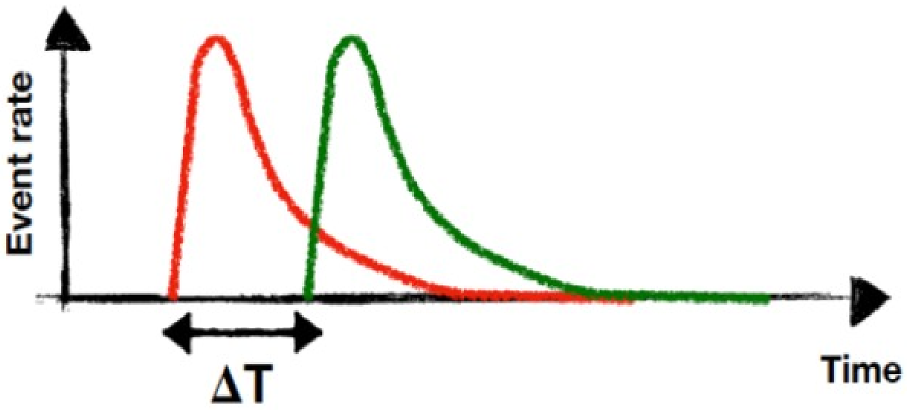


Determination of the neutrino arrival at the different detectors

Why?

- Needed for pointing to the source by triangulation
- Needed to search for an EM and/or GW counterpart

- IDEA: Extract the time delay between SN neutrinos at different detectors from experimental light-curves: Model independent
- GOAL: Include this into SNEWS system for fast localization

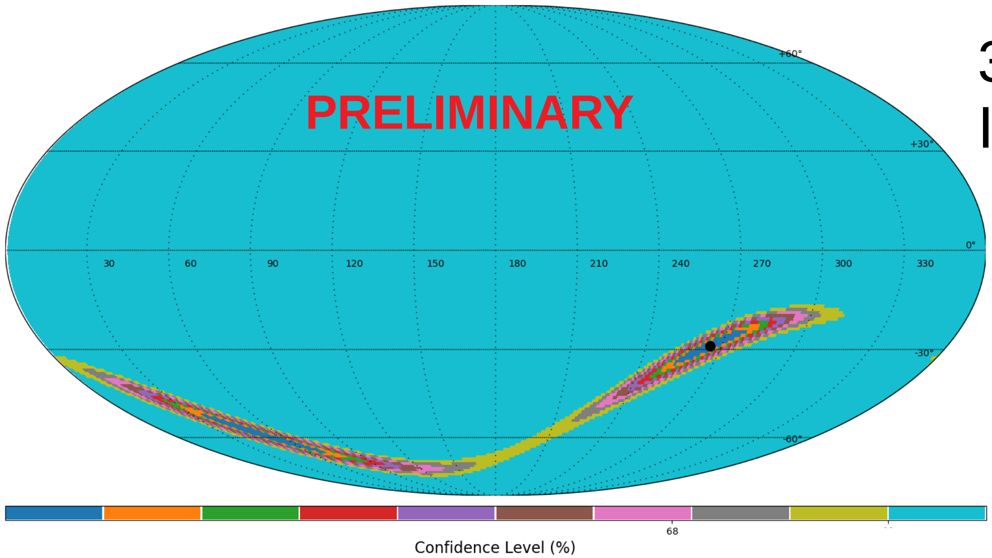


How?

- Chi2: fit time delay between signal in two light-curves
- Normalized cross-correlation
- Only (<)1sec of data needed

Pointing to CCSN with neutrinos:

→ Good time resolution needed for good localization performance!

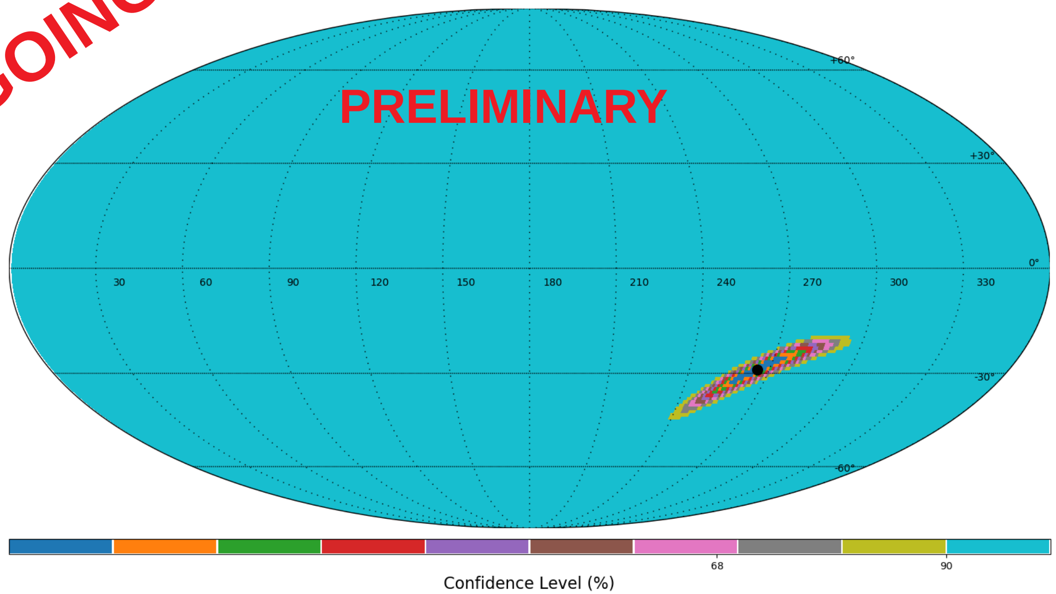


3 detectors:
IC-SK-KM3NeT

(and several detectors taking data!)

ONGOING WORK...

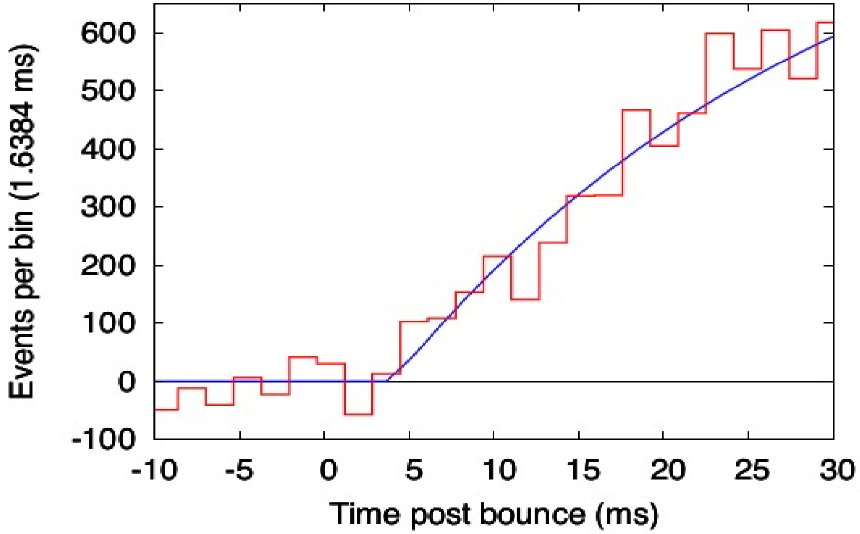
4 detectors:
IC-SK-KM3NeT-JUNO



Assumptions:

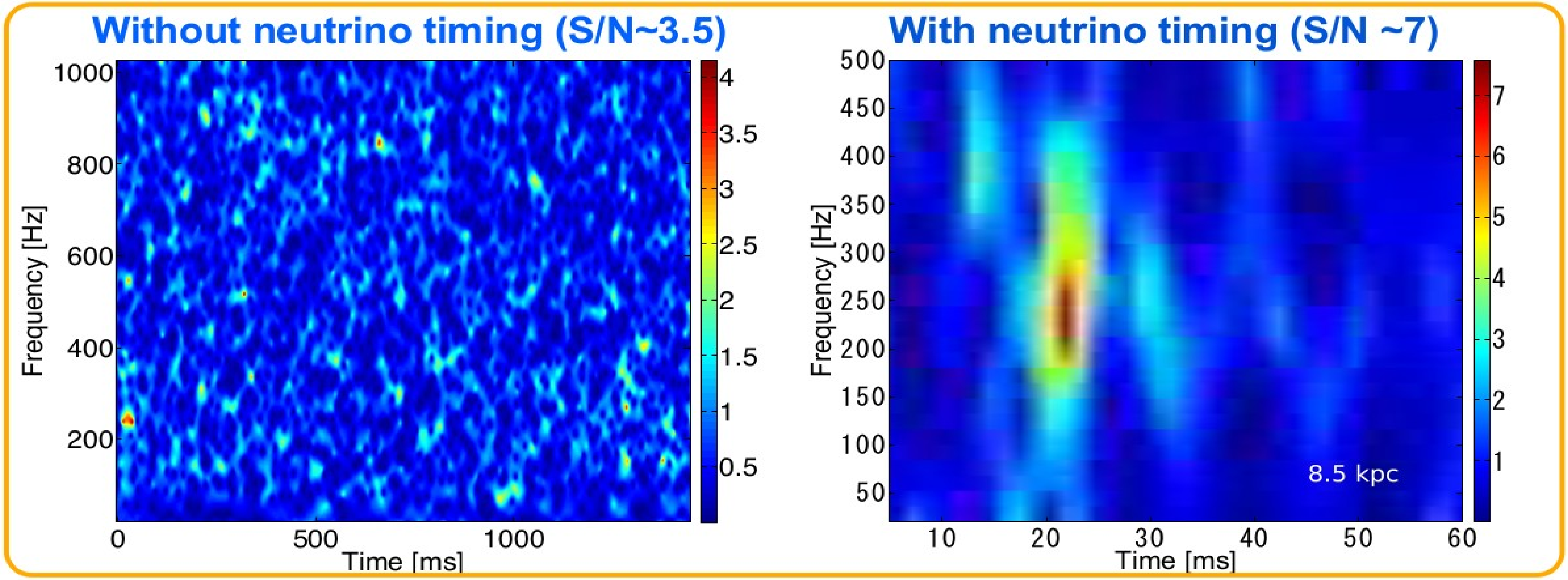
- Source at Galactic Center
- δt = 10ms if combined with KM3NeT
- δt = 1ms for other combinations
- Distance: 10 kpc

SN neutrino timing and GW identification



Probe core bounce time with neutrinos.

Timing for gravitational wave detection.



Conclusions and Outlooks:

- KM3NeT will contribute to the neutrino detector network observing the next Galactic CCSN explosion
- Potential to resolve the SN neutrino energy spectrum and light-curve → constrain the models
- Global detector network needed for triangulation and high event statistics (+ complementary channels and information) → crucial for MM observation and understanding the mechanism
- Expected improvements with multi-lines data → additional background rejection strategies possible
- More lines taking data coming this summer!
- Looking forward for the results with ORCA6+ARCA2 this year!