Offline performance studies of Core Collapse Supernova neutrino detection with KM3NeT

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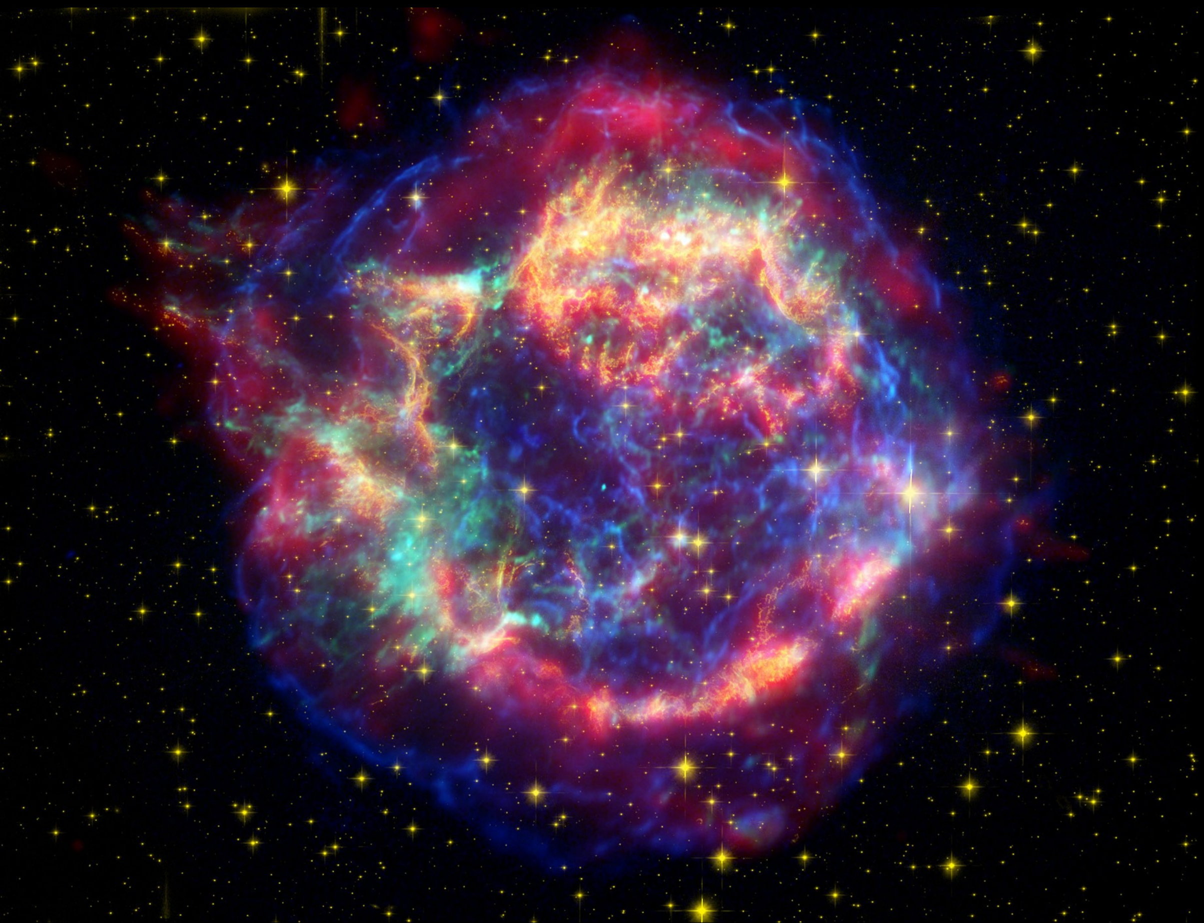
SNEWS2.0 Workshop
14-16 June 2019

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

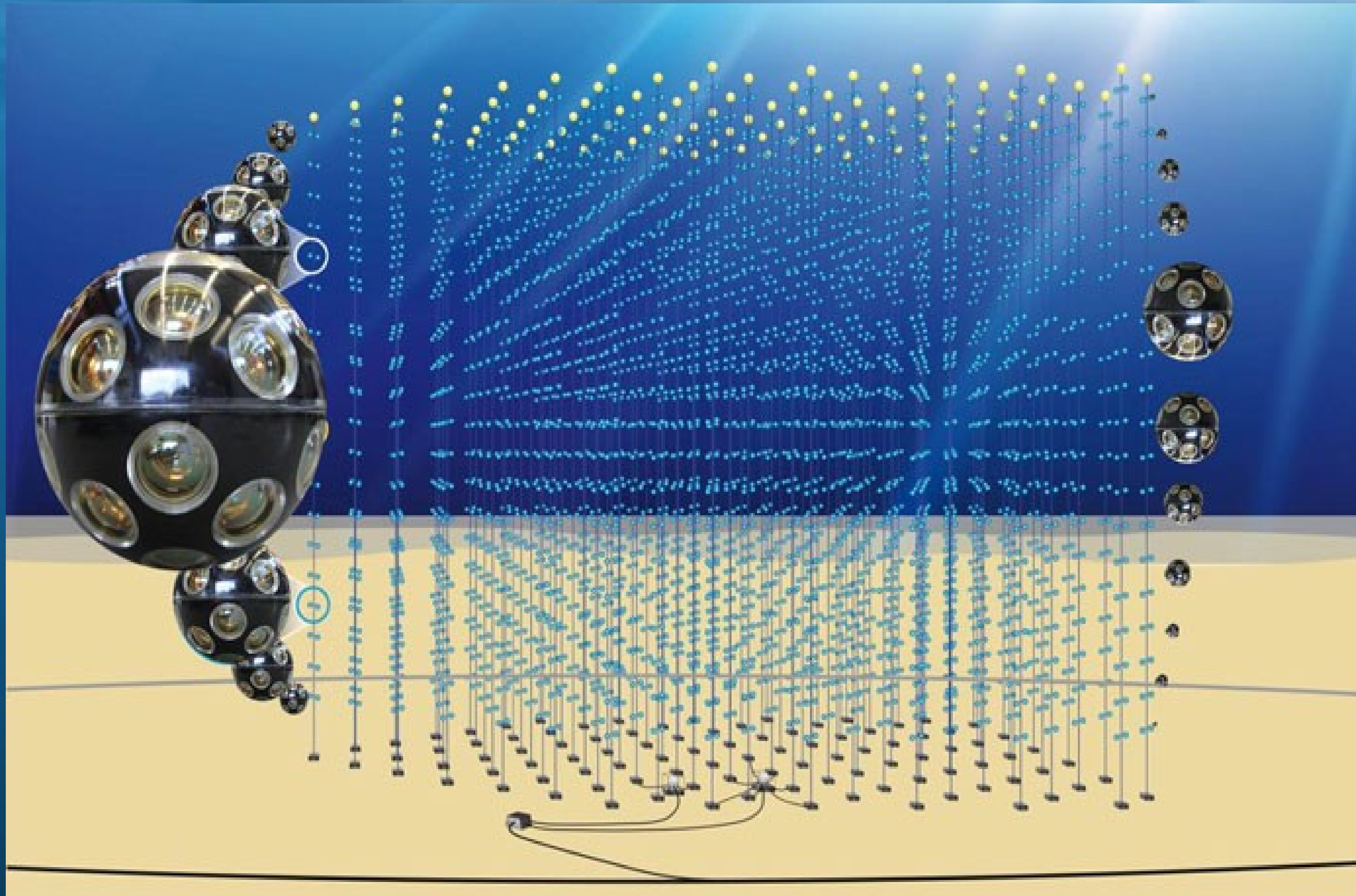
KM3NeT

Under construction
New technology

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

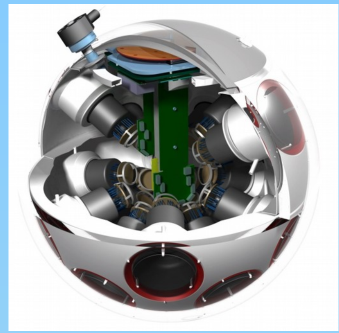
2 blocks in Italy:
ARCA (larger, 1km3)
- HE astrophysics
→ 1 line taking data!

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



KM3NeT detectors:

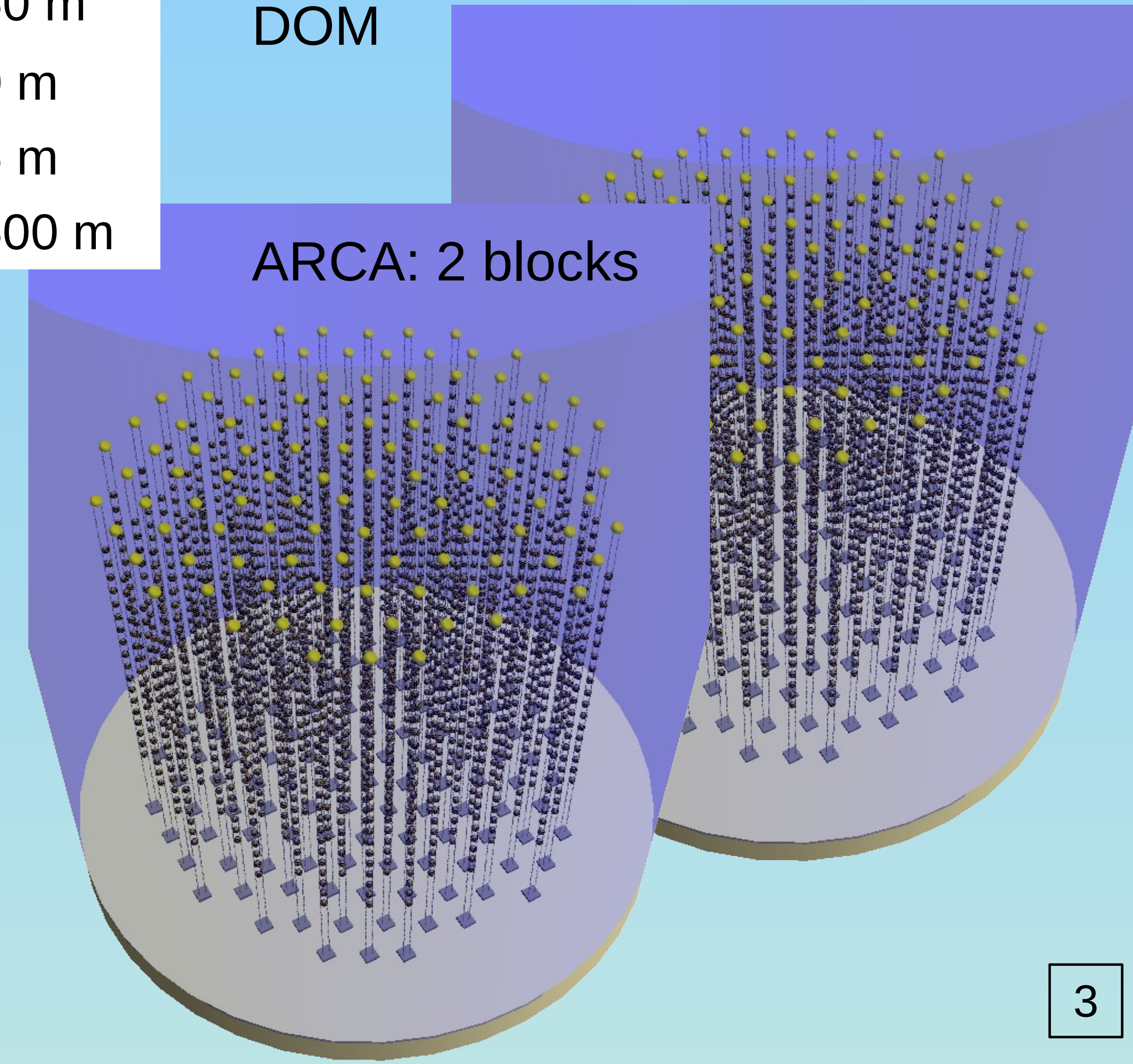
	ANTARES	ORCA	ARCA
Eff. Mass	10 Mt	5.7 Mt	1 Gt
Line length	350 m	200 m	650 m
Inter-line dist	70 m	20 m	90 m
Inter-OM dist	14.5	9 m	36 m
Depth	2450 m	2450 m	3500 m



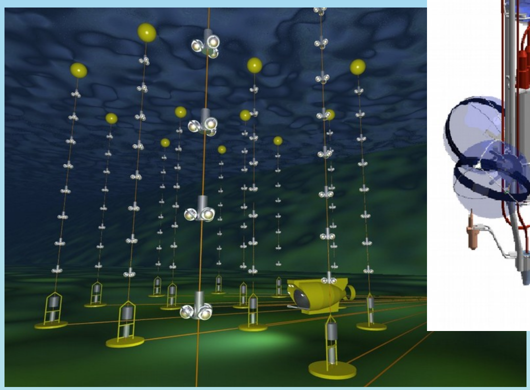
DOM

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

ARCA: 2 blocks

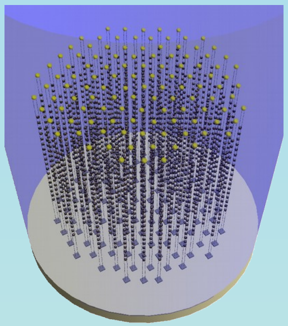


ANTARES



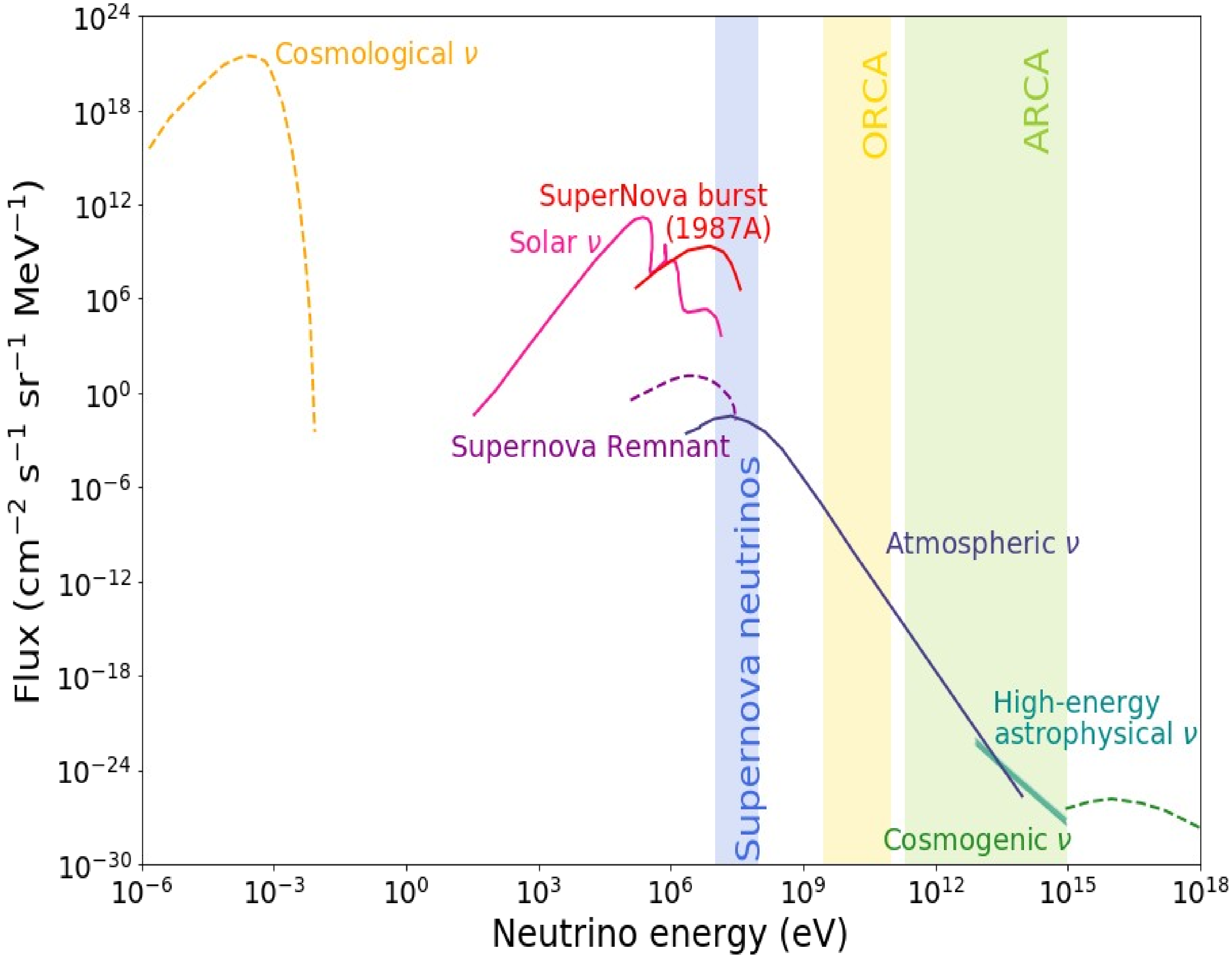
ANTARES storey

ORCA:
1 block



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

Multi-energy neutrino spectrum:



CCSN neutrino detection in water:

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

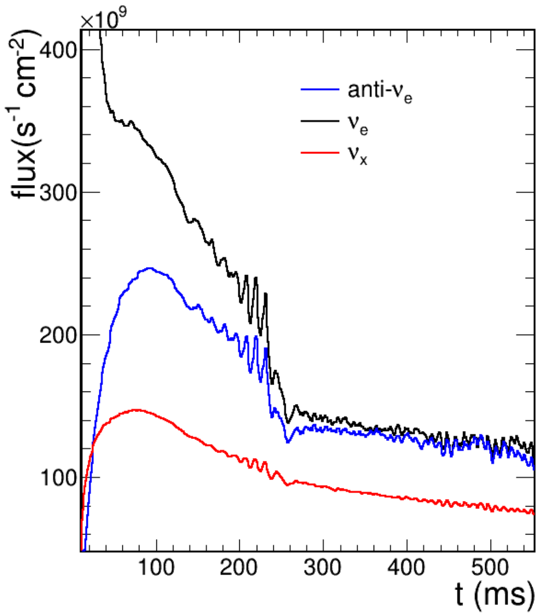
  anti-nue dominate during accretion phase (~500ms)
- Main interaction: anti-nue with protons (IBD), also ES (~3%)
- We expect ~1000-8000 events with double coincidence selection: storage of all data needed (at ms precision)

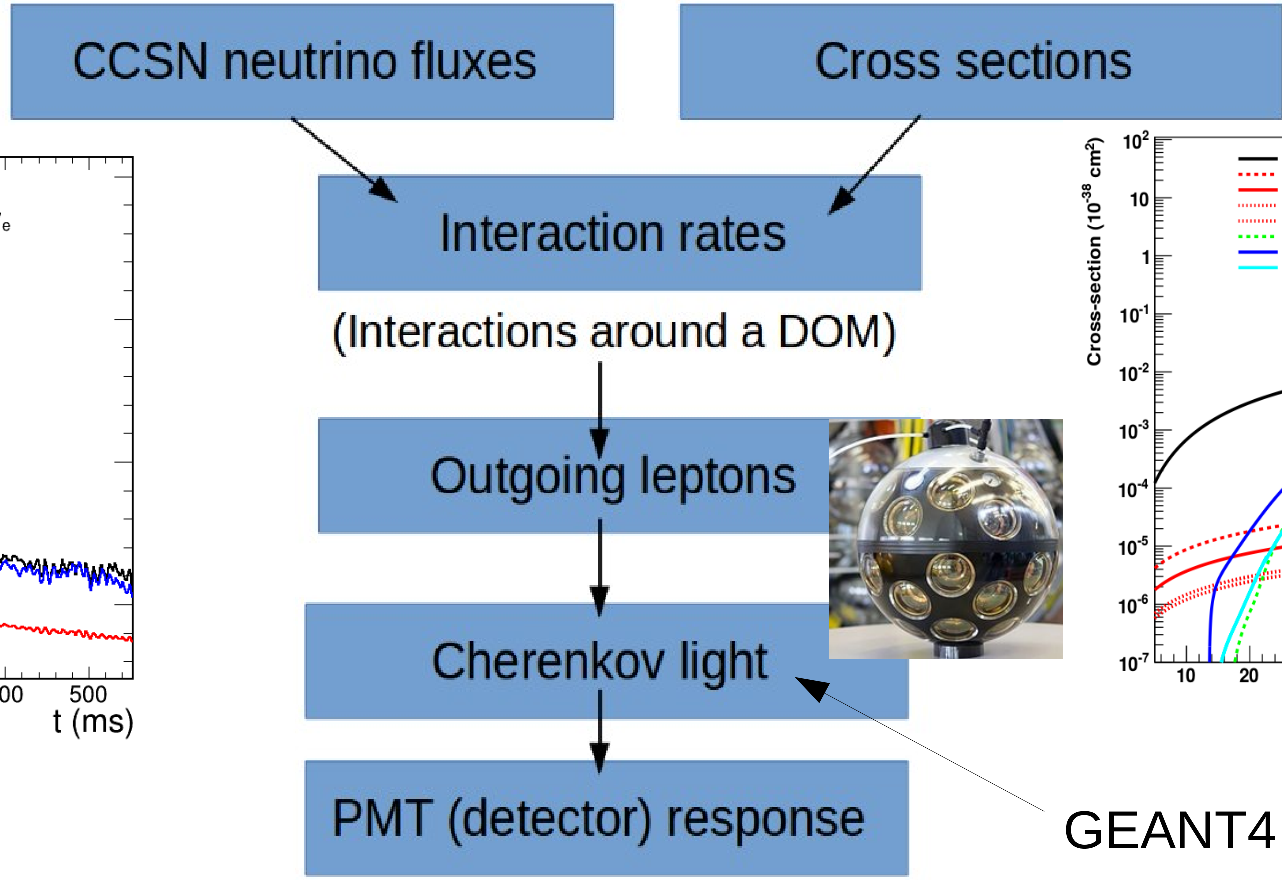
What we do:

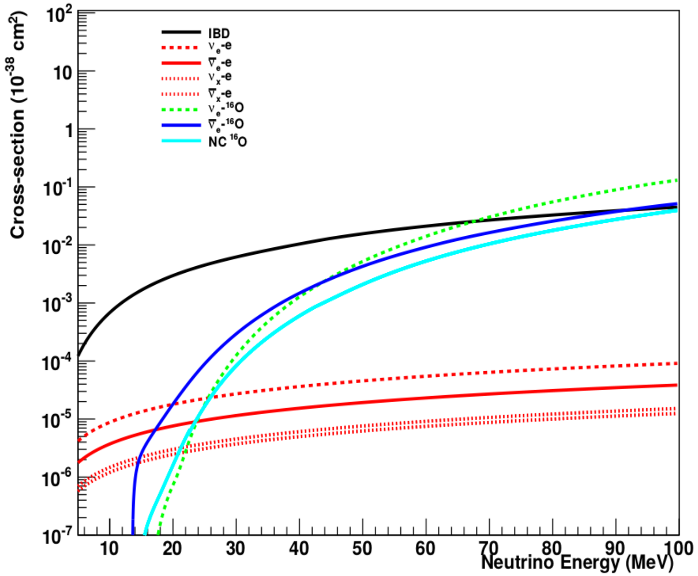
- Detection performance + real-time alerts (See talk by M.Lincetto)
- Time resolution: light-curve physical features + pointing
- Energy resolution: neutrino spectrum

Monte-Carlo simulation in KM3NeT

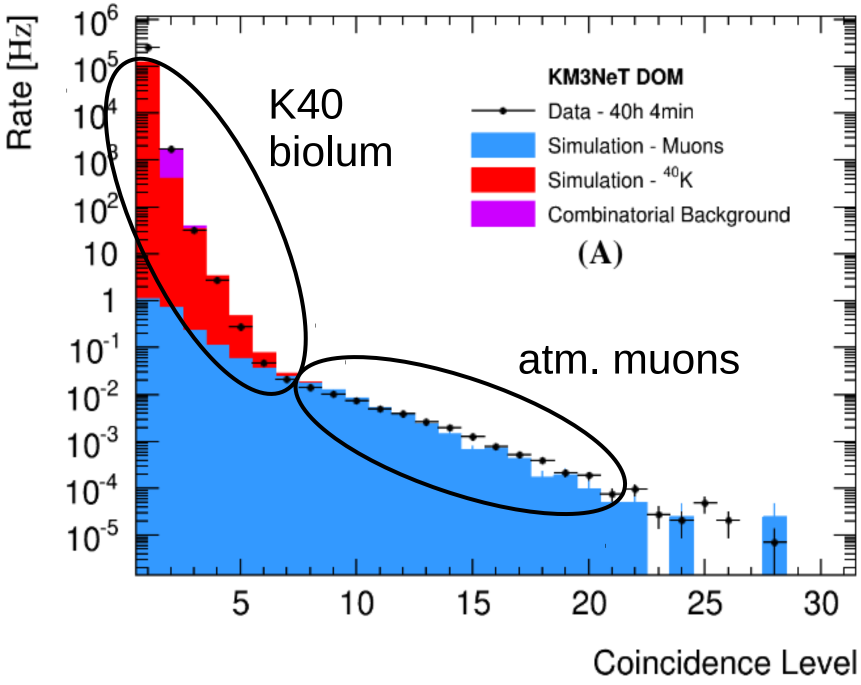
- Development of a low energy MC neutrino generator for KM3NeT.
- Flux from 3D CCSN simulations by Garching Group: 3 energy and time dependent parameters in the model: $L(E_\nu,t)$, $\alpha(E_\nu,t)$ and $<E_\nu>(E_\nu,t)$
- Main interaction channel → Inverse Beta Decay (IBD): $\overline{\nu}_e + p \rightarrow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



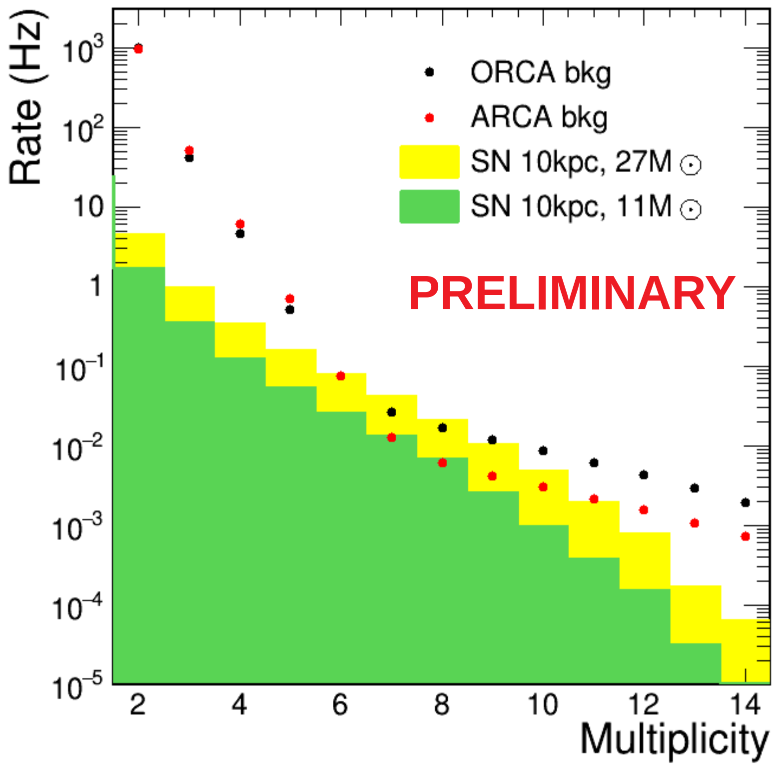




Detection method:



Exploit multi-PMT technology to achieve better performance!



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

Signal and background events:

PRELIMINARY

Multiplicity	1	2	3	4	5	6	7	8	9	10
N_{ev} $27 M_\odot$	1.6e5	5.0e3	1.0e3	3.8e2	1.7e2	88	46	23	12	5
N_{ev} $11 M_\odot$	4.1e4	1.2e3	247	85	38	18	9	5	2	1

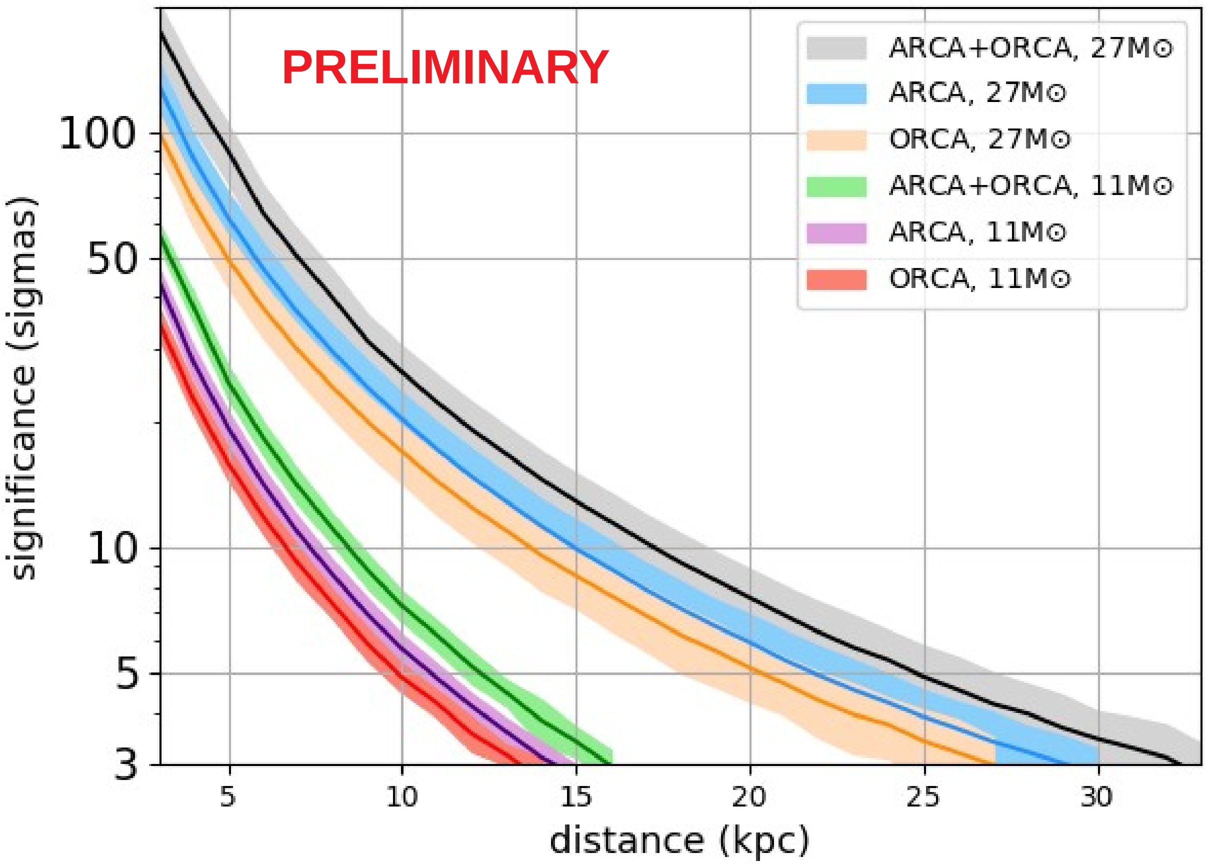
Table: Signal event statistics as a function of the multiplicity

Progenitor mass	Δt (ms)	N_b ORCA	N_b ARCA	N_s
27 $M_\odot$	543	60	98	174
11 $M_\odot$	340	38	61	34

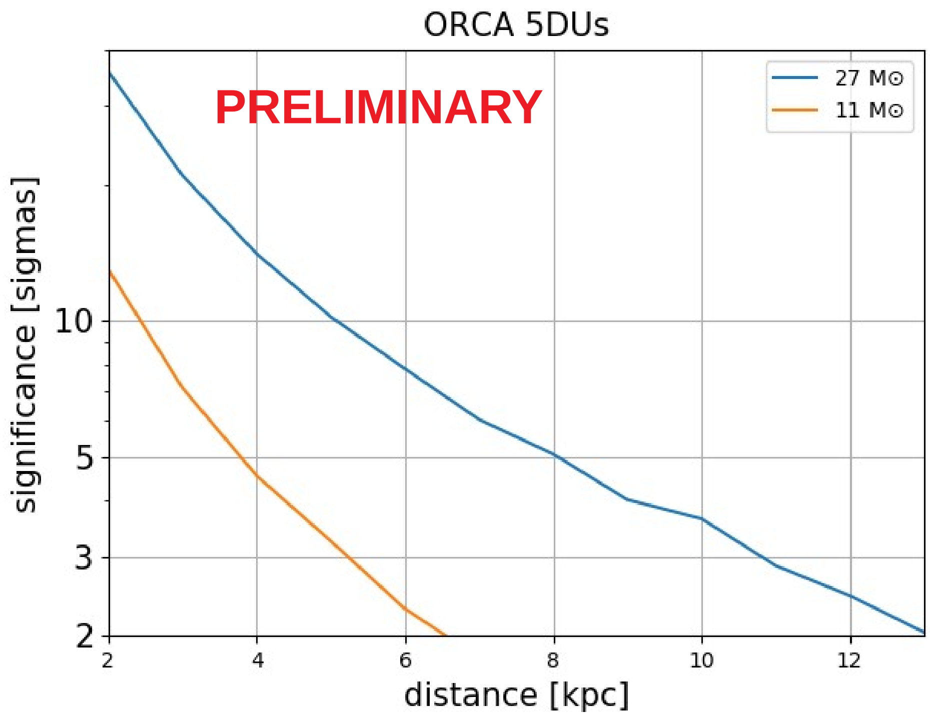
Table: Number of background and signal events in the 6-10 multiplicity cut after the muon filter, per KM3NeT building block in the ORCA and ARCA configurations.

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⊙)



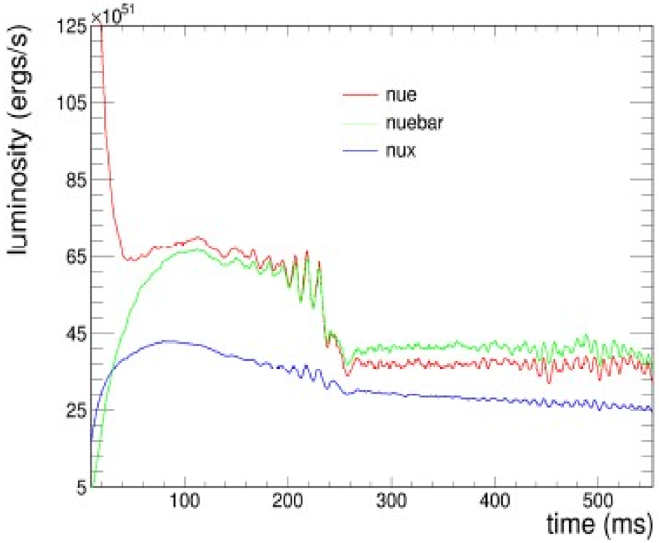
(Time window search used in the analysis: duration of the simulation)

What to learn on CCSN neutrinos?

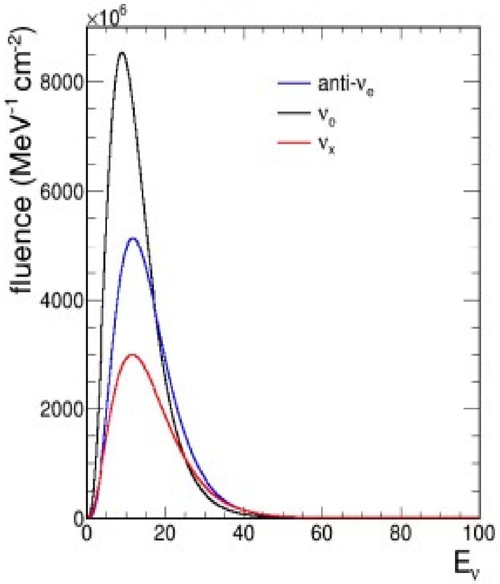
- Multi-PMTs (multiplicity) for optimal sensitivity and energy estimation
- Double coincidences for time information: high statistics (large detector)

Constrain the models!

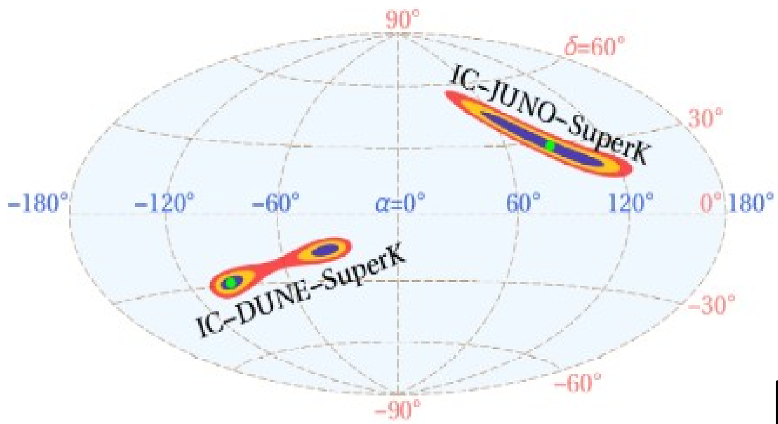
Light-curve
(time profile)



Energy spectrum



Source direction



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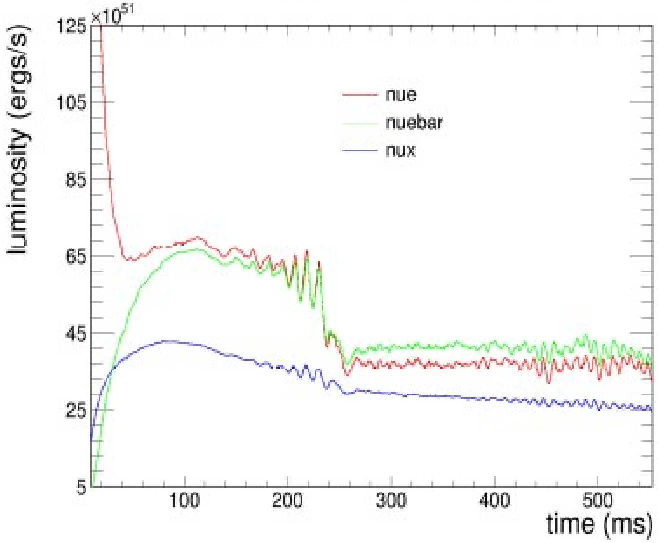
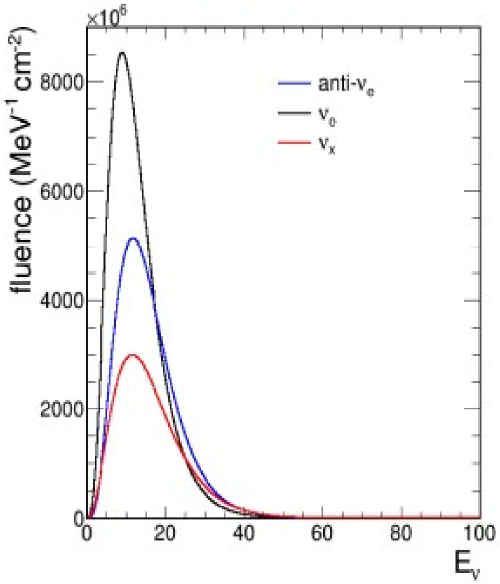


Energy spectrum



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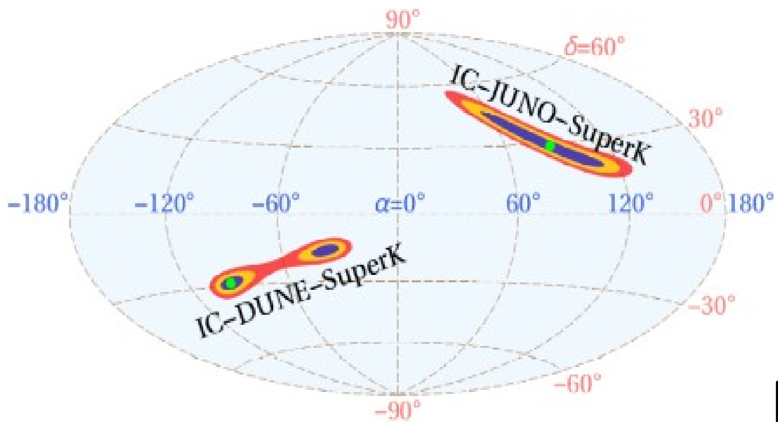
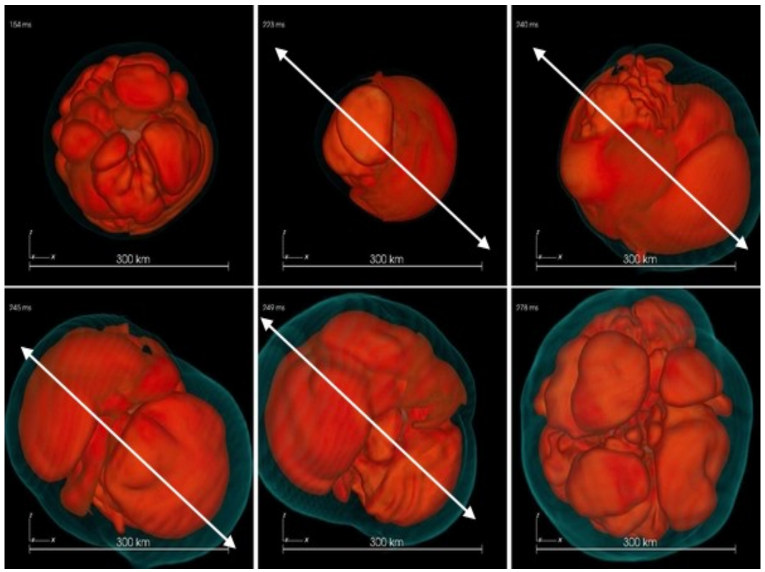
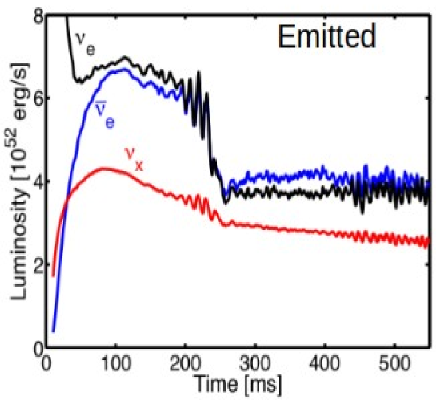
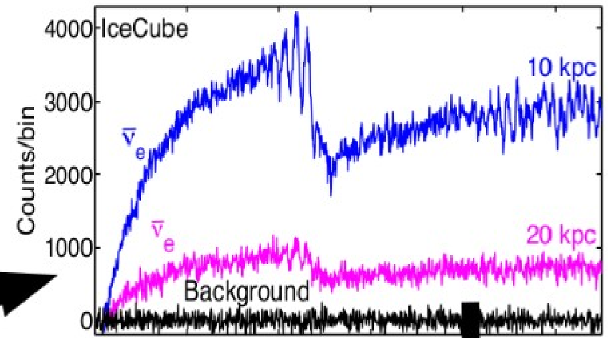


Fast time variations on the neutrino light-curve: SASI

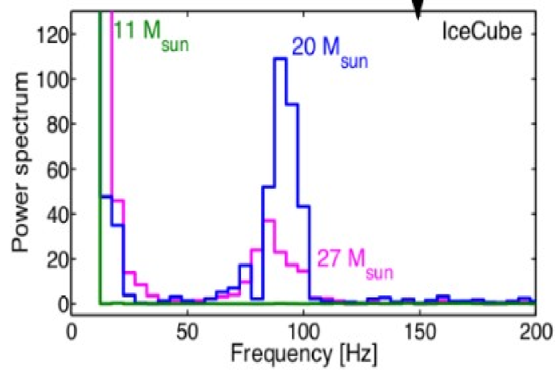
- Standing Accretion Shock Instability (SASI): hydrodynamical instabilities during CCSN predicted by recent 3D simulations → Directional effect
- Footprint: Time variations in the neutrino light-curve around 200ms
- Feature: Characteristic oscillation frequency (80Hz) seen trough Fourier analysis
- Enhances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







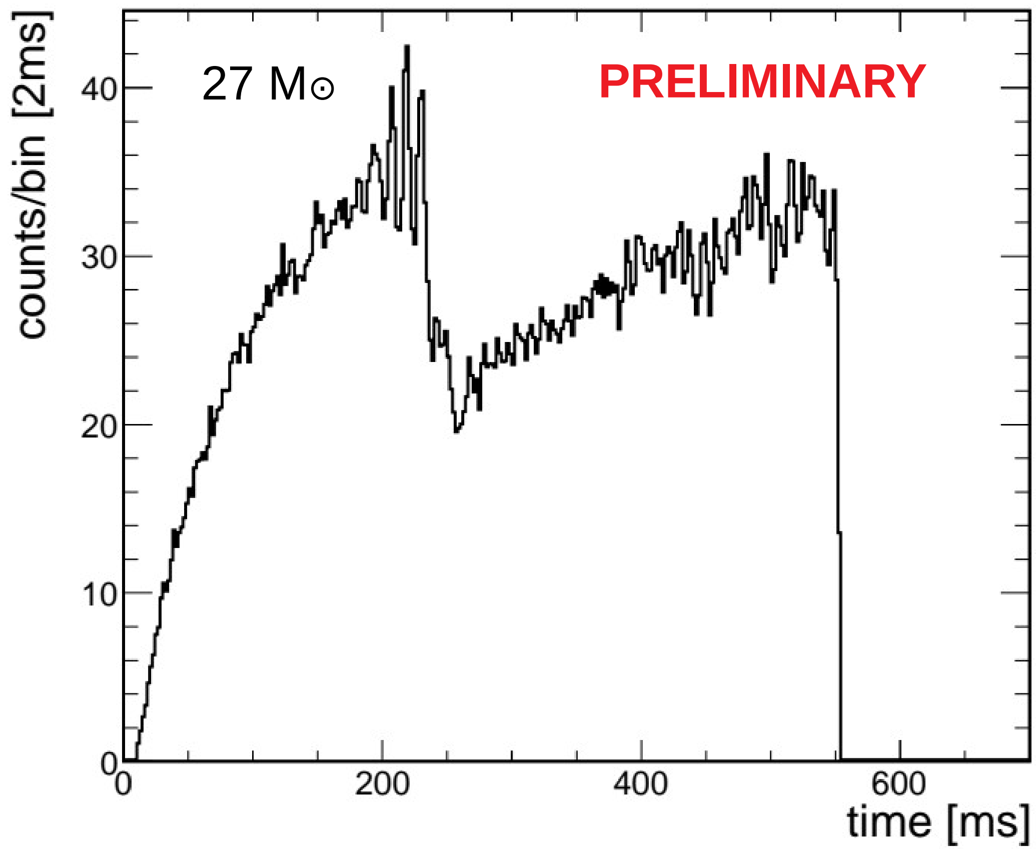
Detected IC signal and bckg

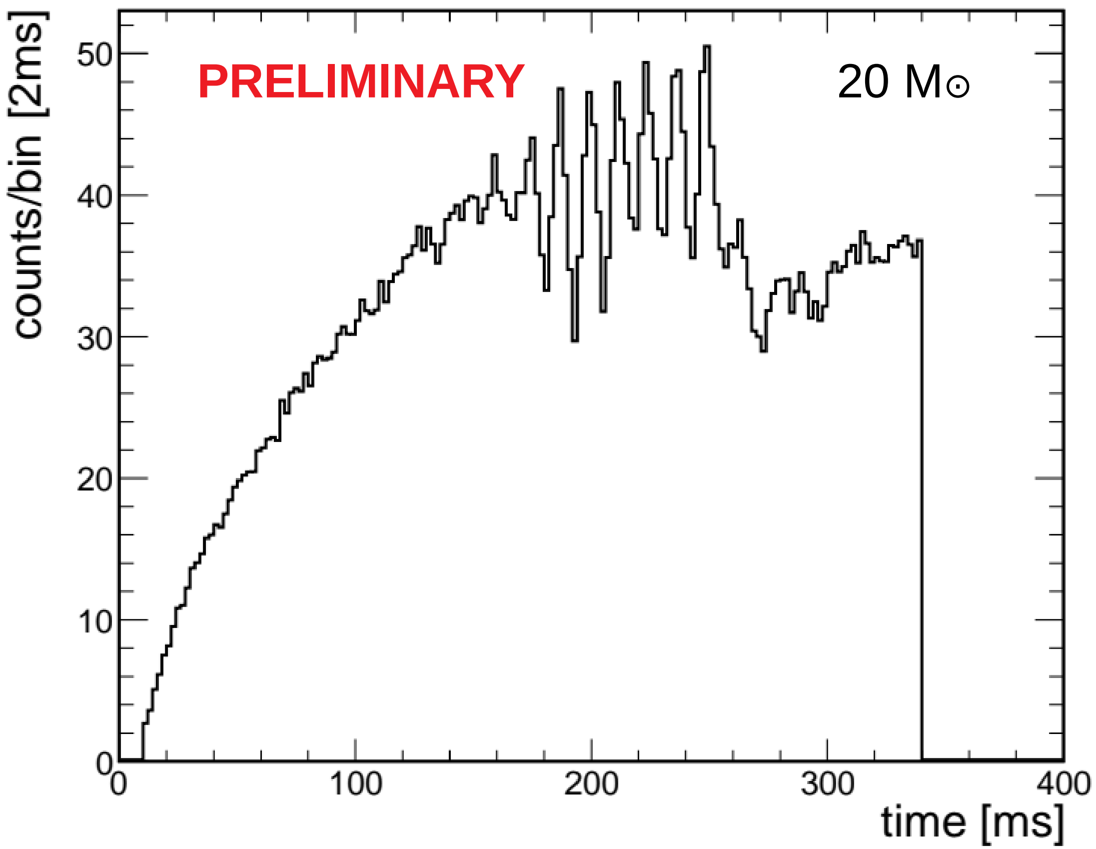


Power spectrum IC

Progenitor models and detector response to CCSN signal time profile

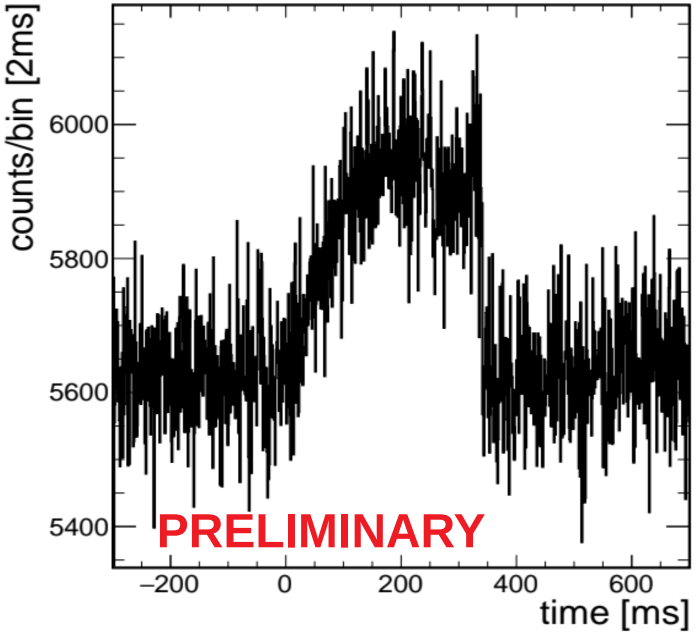
→ We use double (5ns) coincidences (high stats, reduce biolum)
→ Expected signal in 115 detection lines (1 block) @ 10 kpc



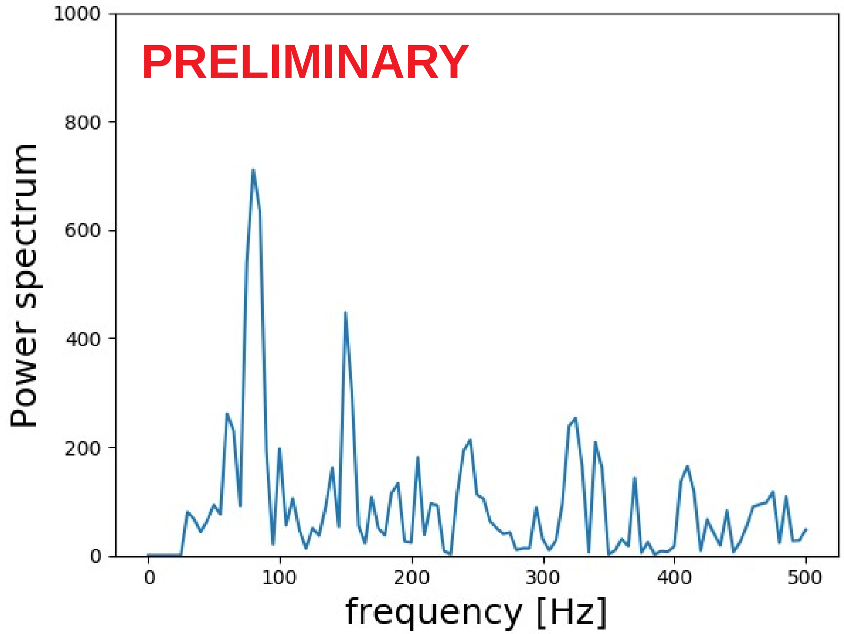


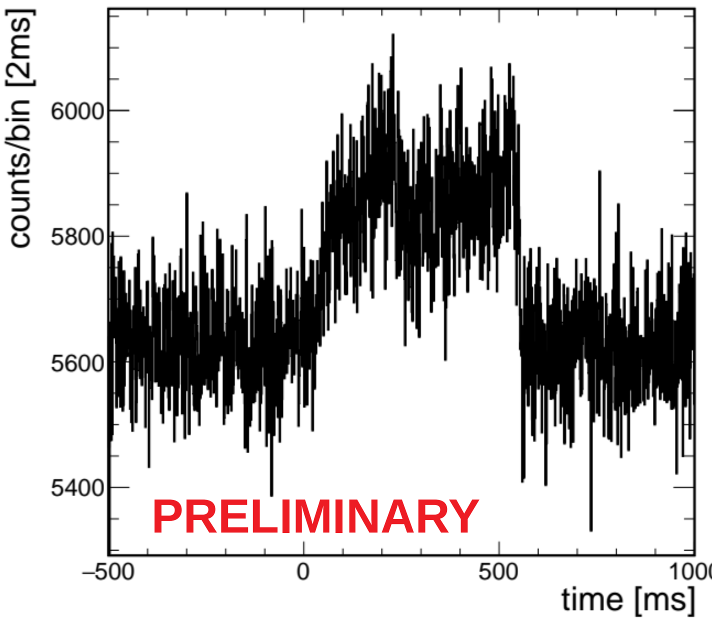
Now, add background and see...

Light-curves and Power Spectrum:

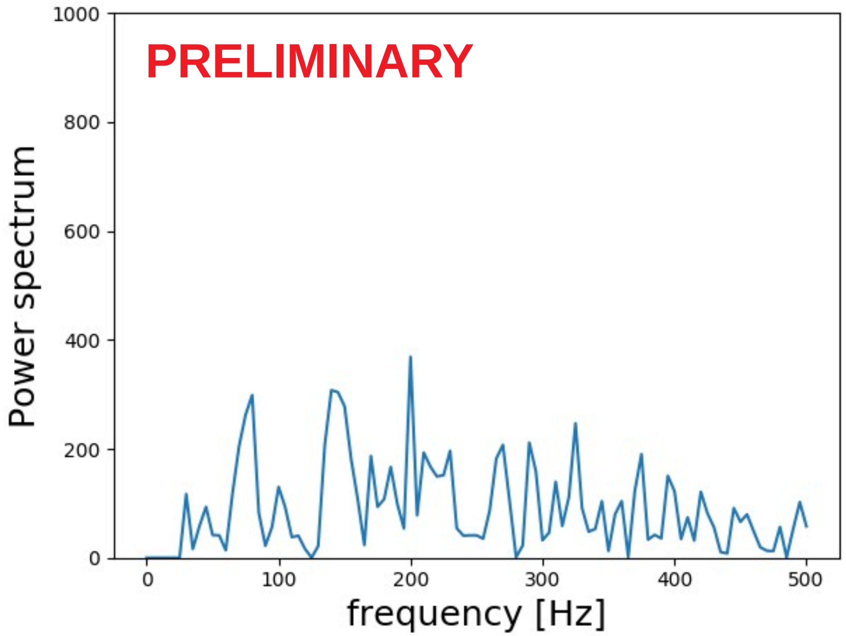


ARCA 20M⊙
@5kpc (with bkg)





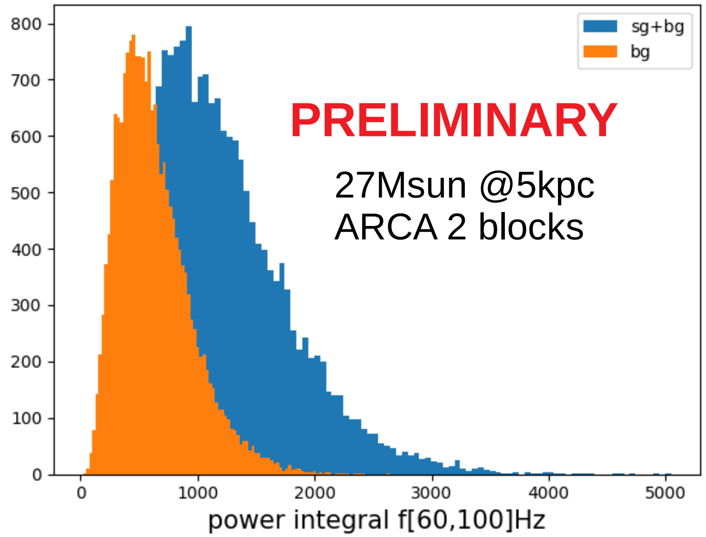
ARCA 27M⊙
@5kpc (with bkg)



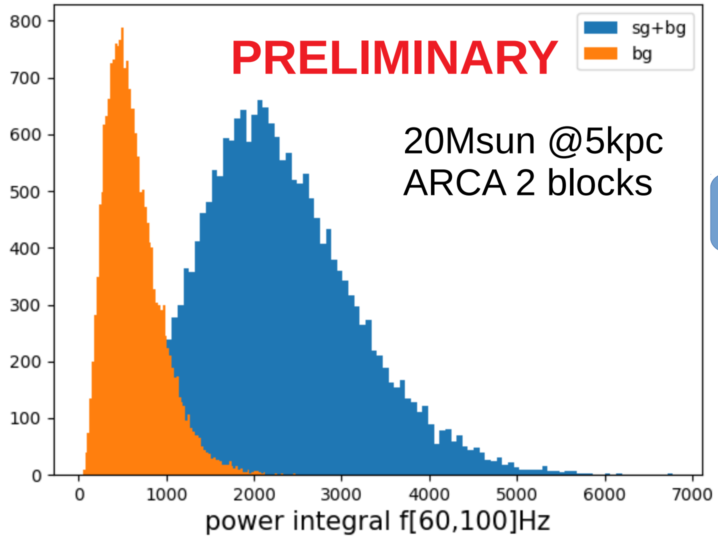
Analysis method & preliminary results:

Model dependent approach:

Look for a significant power excess around the expected SASI frequency



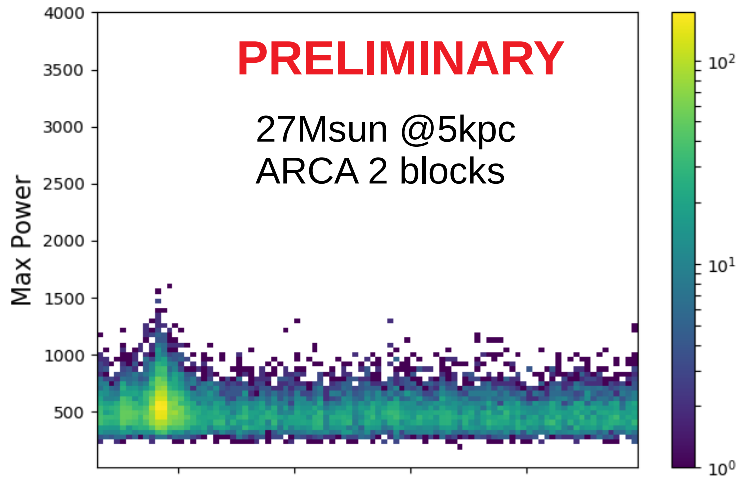
2σ



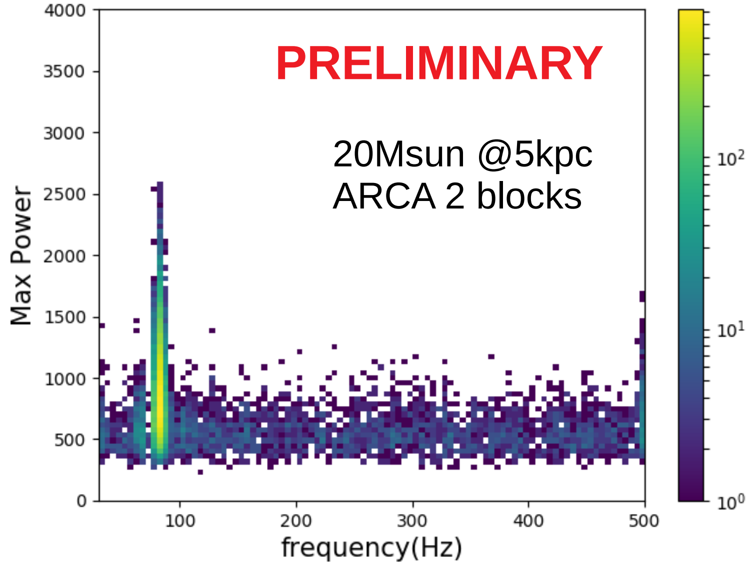
3.5σ

Model independent approach:

Look for a significant peak on the Power Spectrum at any frequency



1.1σ



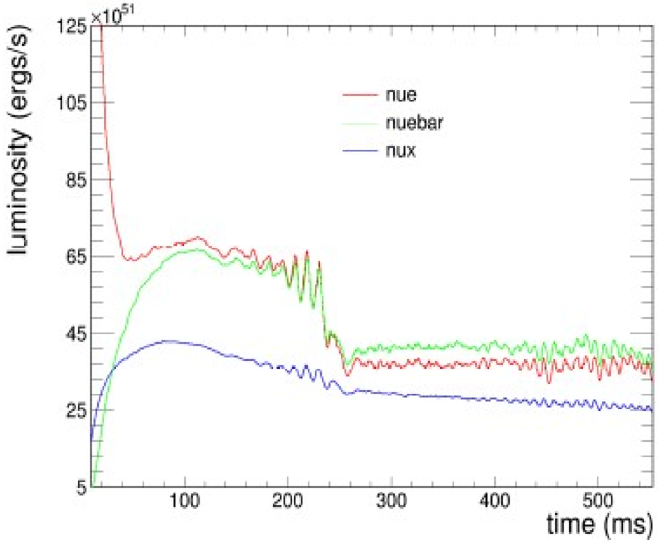
2.5σ

What to learn on CCSN neutrinos?

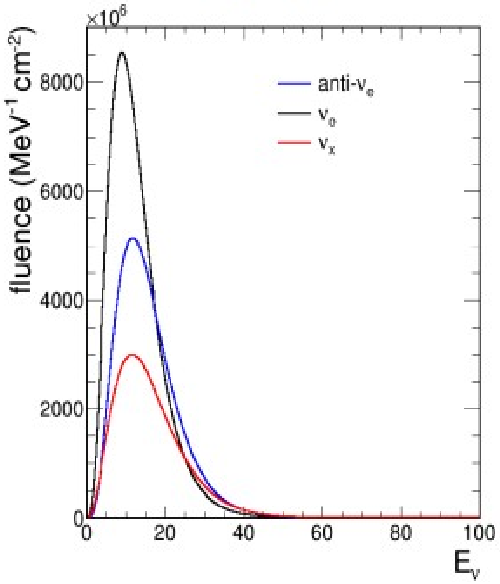
- Multi-PMTs (multiplicity) for optimal sensitivity and energy estimation
- Double coincidences for time information: high statistics (large detector)

Constrain the models!

Light-curve
(time profile)



Energy spectrum



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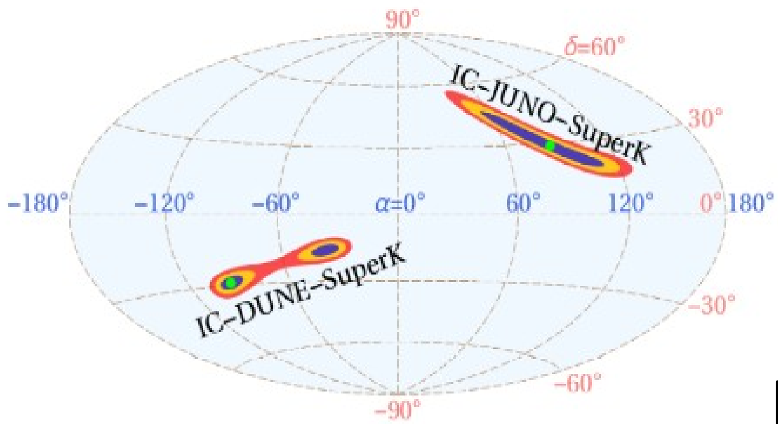


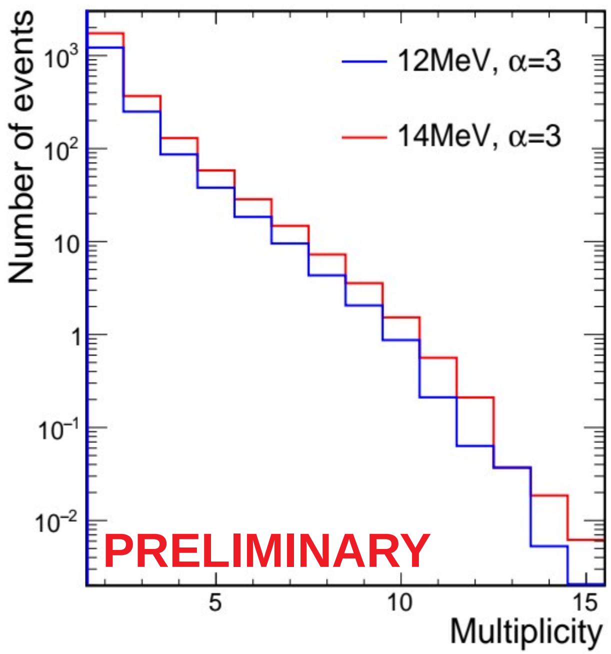
Determining the mean energy of CCSN neutrinos

- 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:

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



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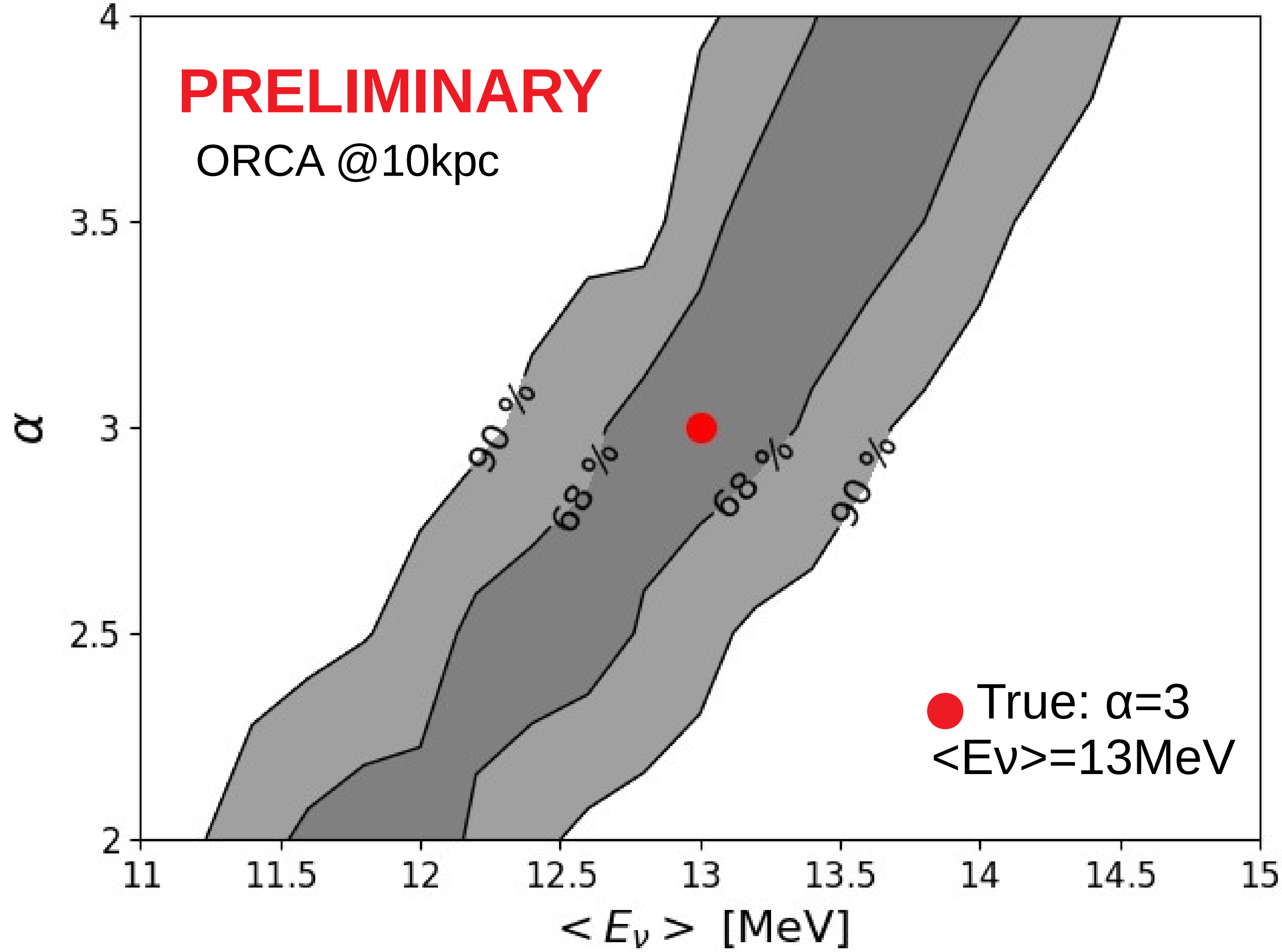


Degeneracy between α and <Eν> in the 2D parameter space

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

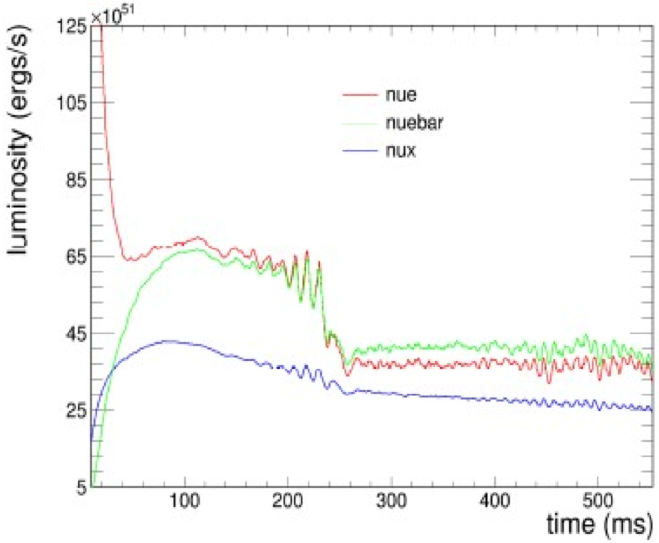
(Conservative ν flux, close to 11Msun values)

What to learn on CCSN neutrinos?

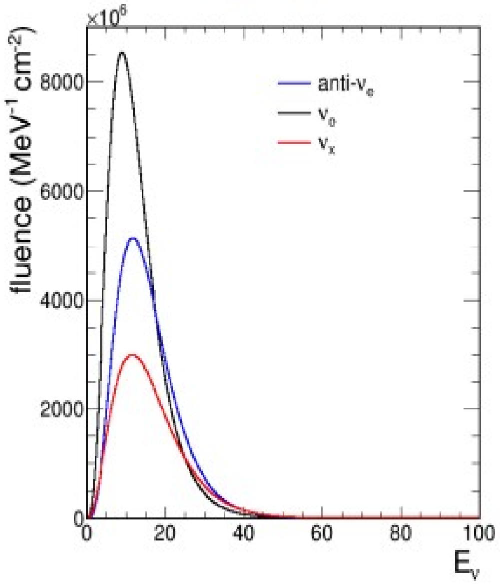
- Multi-PMTs (multiplicity) for optimal sensitivity and energy estimation
- Double coincidences for time information: high statistics (large detector)

Constrain the models!

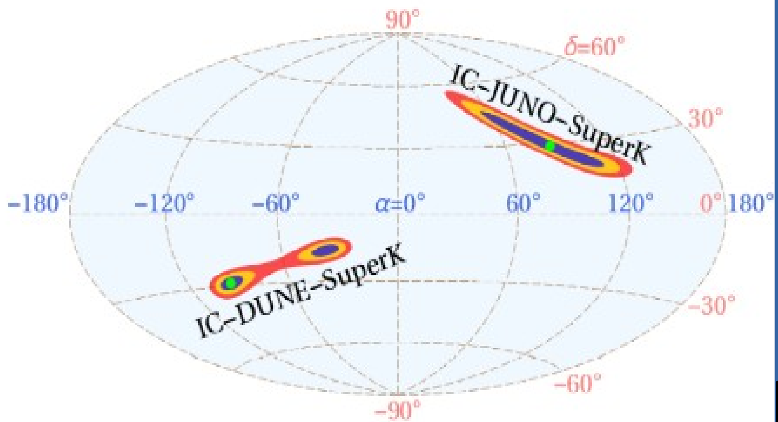
Light-curve
(time profile)



Energy spectrum



Source direction



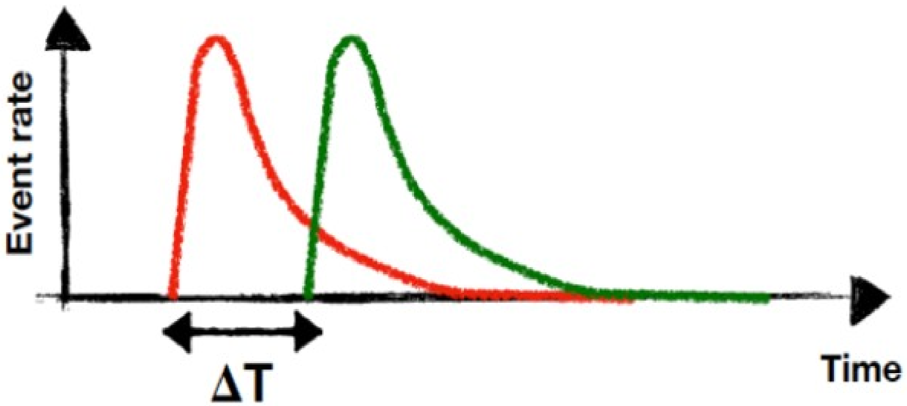
Determination of the neutrino arrival at the different detectors

Panel I: Discussion

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

Combining light-curve information

Panel I: Discussion

What can we by gain exhanging experimental light-curves?

- Comparison of observed signal with expected signal: requires precise models + distance and progenitor information
- It can be used for more than pointing: constrain the physics
- No need to specify a particular time point
- PROBLEM: Can we use this when different detection channels?

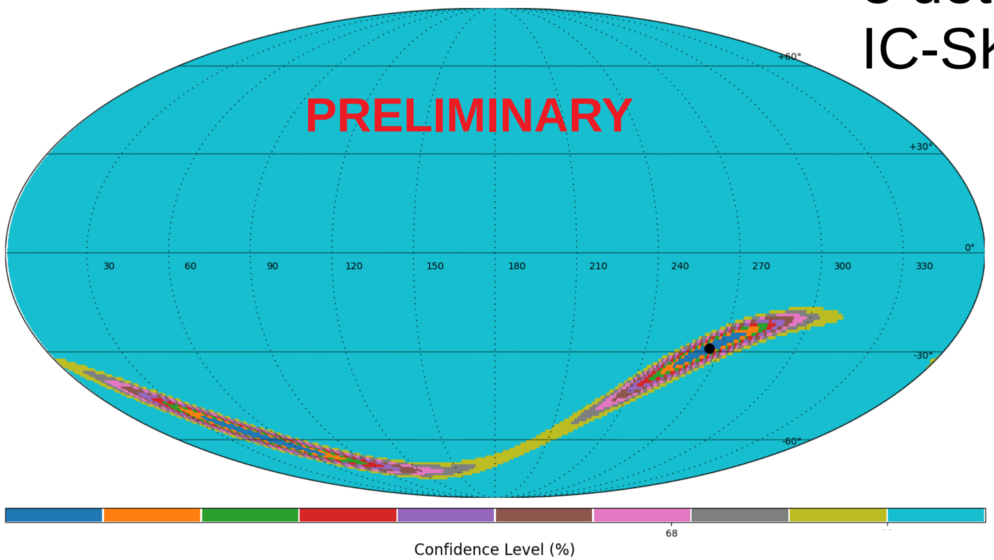
Preliminary results with KM3NeT and IC data:

- Combined preliminary result IC+ARCA @10 kpc: δt=7ms

  → No worst results than only experiment T0 fit
  (to be verified with other experiments data)
  → Helps improving resolution for background dominated experiments: more detectors can enter the game

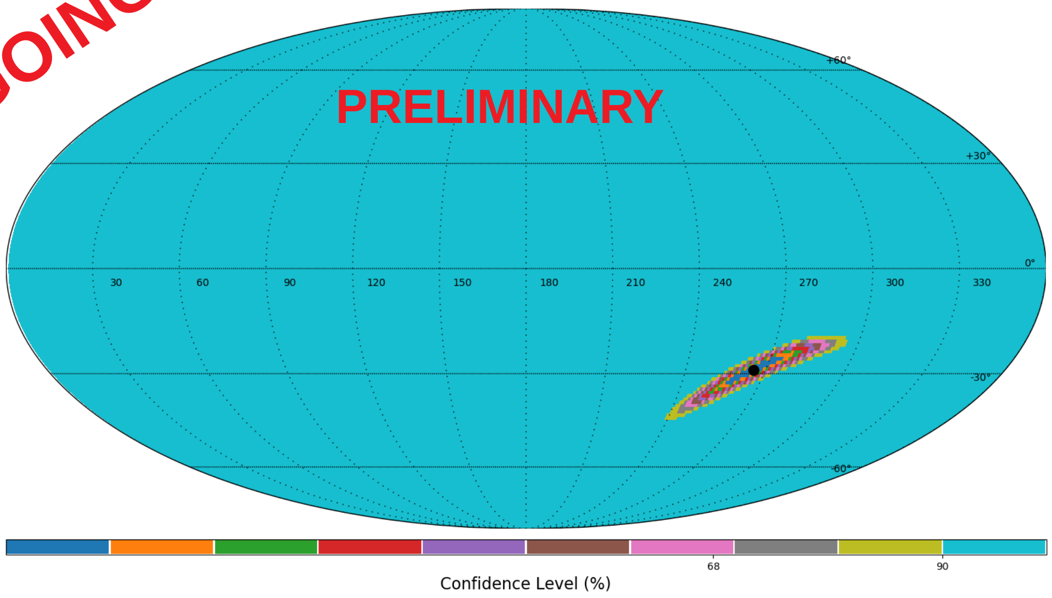
Pointing to CCSN with neutrinos:

3 detectors:
IC-SK-KM3NeT



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

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!