Core Collapse Supernova neutrino detection with KM3NeT

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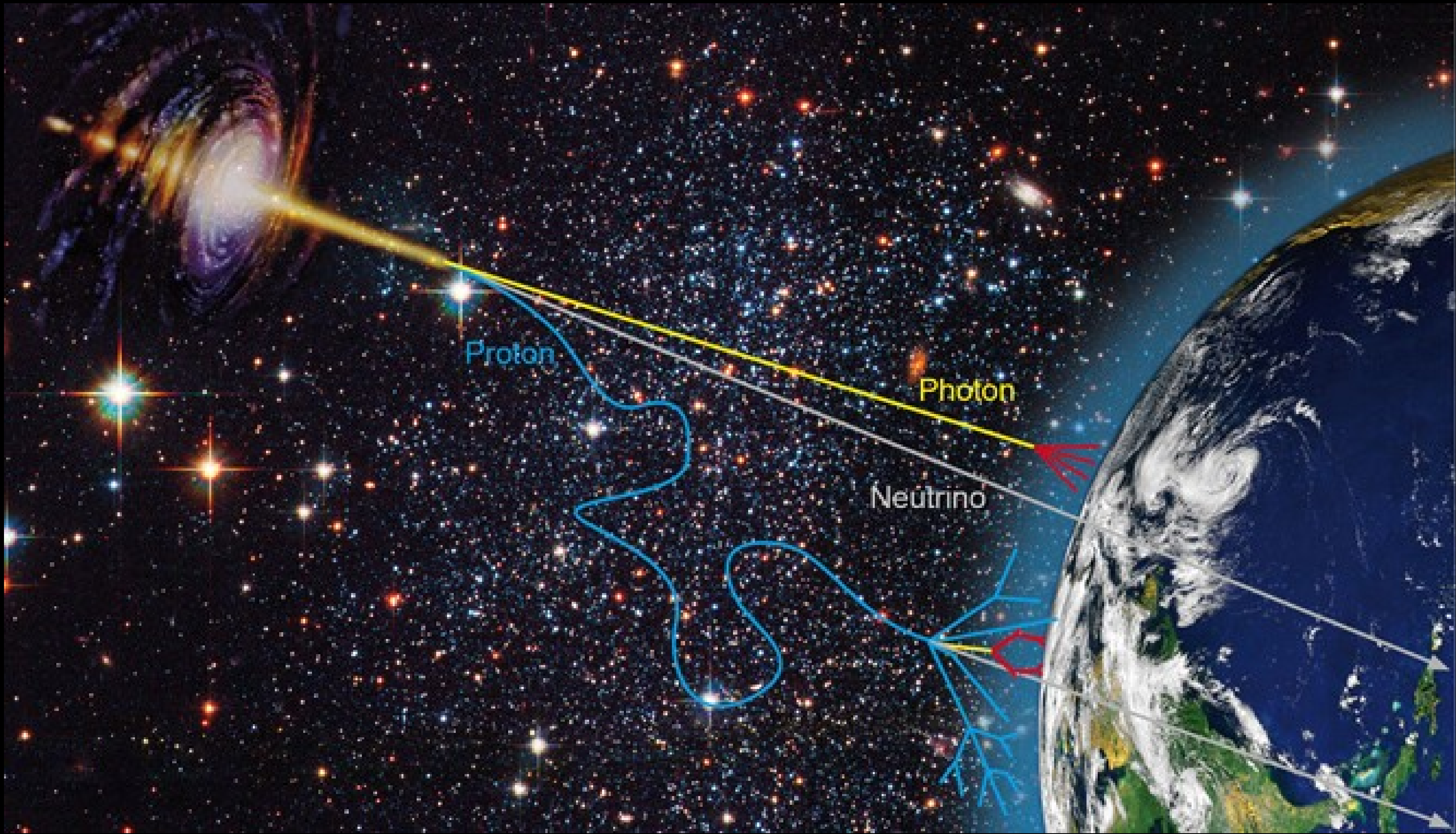
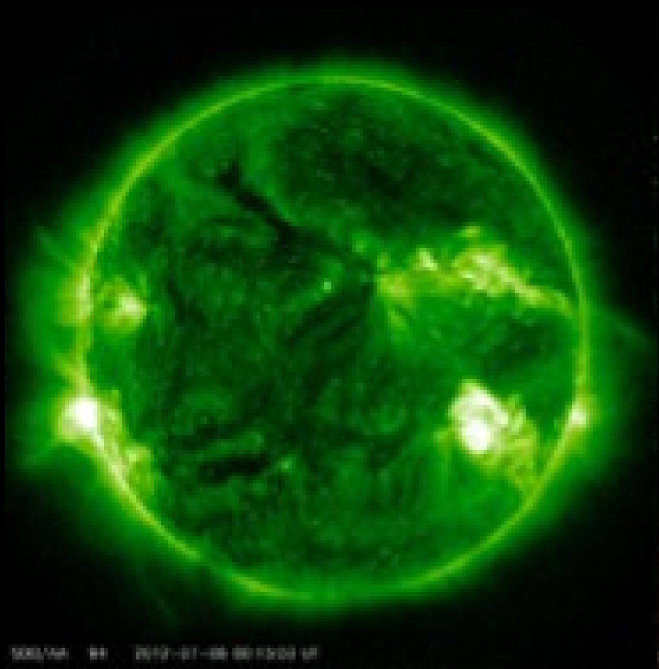
PhD Seminar
IFIC, Valencia
11 December 2019

Astronomy with neutrinos, why?



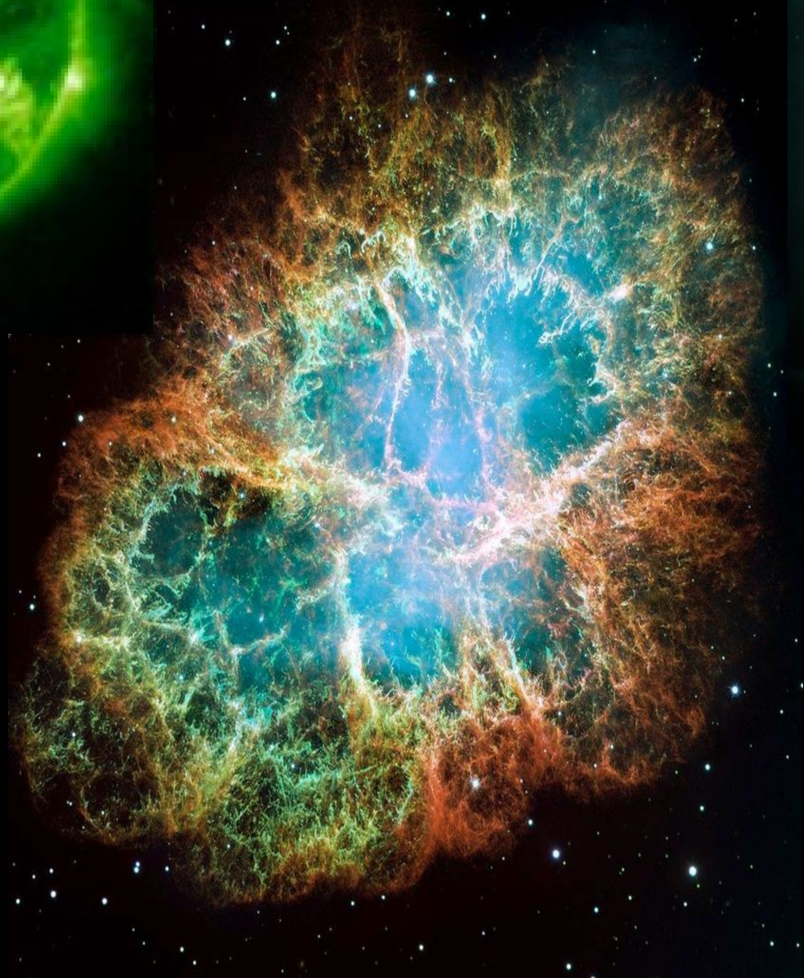
- Don’t (weakly) interact on their way
- Point directly to the source!
- Additional information on astrophysical process

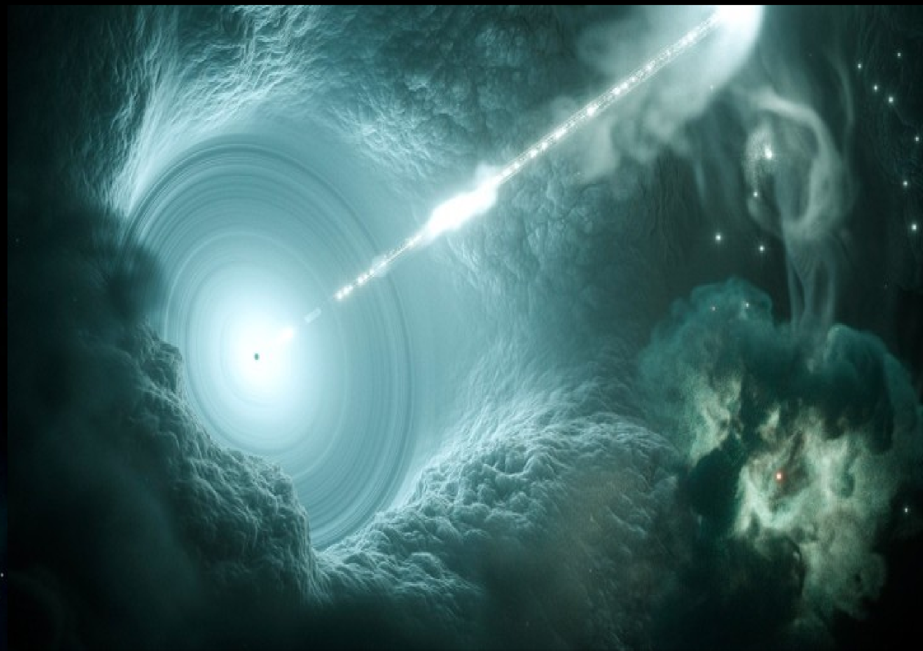
3 identified sources of neutrinos:



Sun

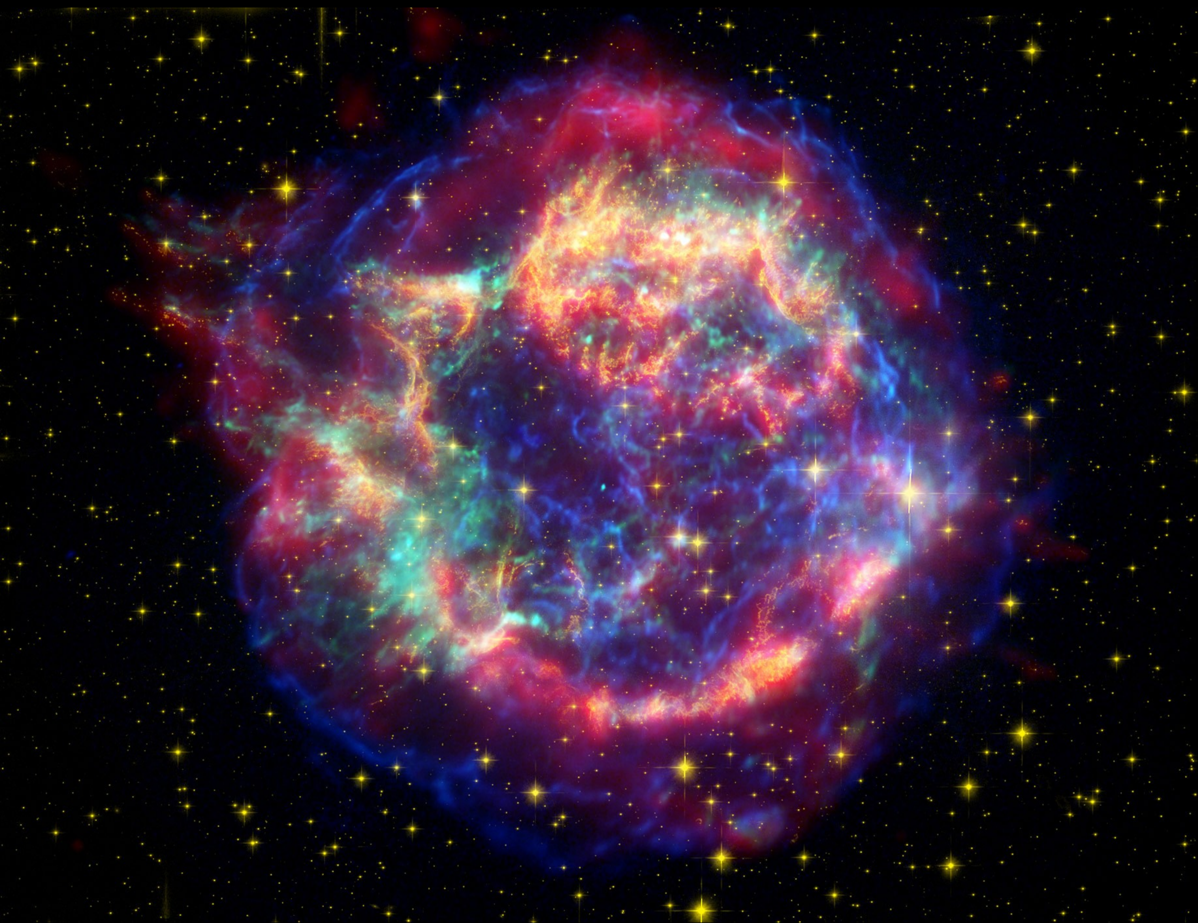
SN1987A





TXS 0506+056

Core-Collapse Supernova neutrinos:



Motivation:

- Only observation: SN1987A
→ 25 neutrinos detected
- Prove the explosion mechanism: neutrinos play a major role
- Constrain the theoretical models
- Neutrino properties measurements
- Extreme environment:
  → New physics

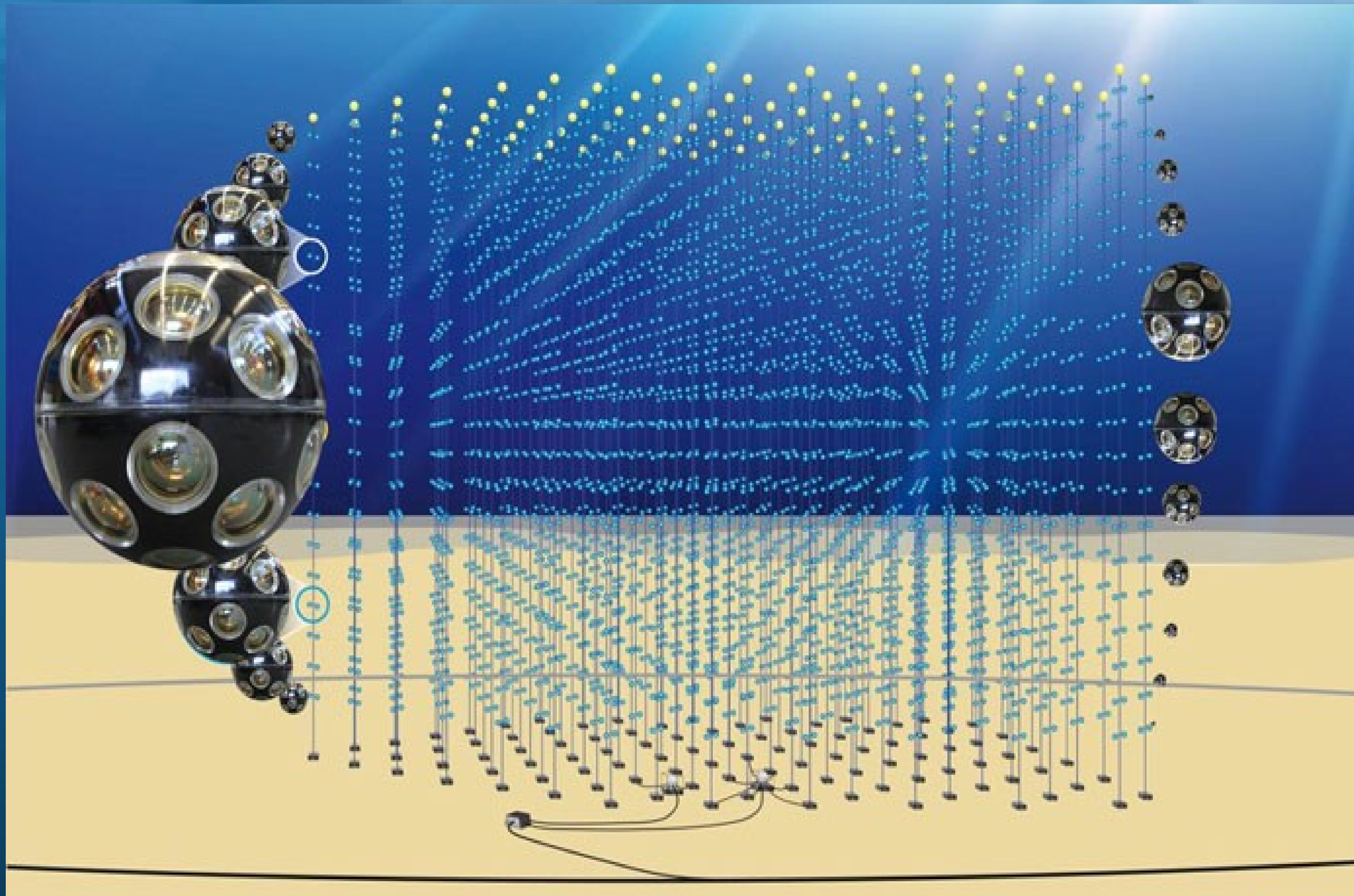
KM3NeT

Under construction
New technology

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

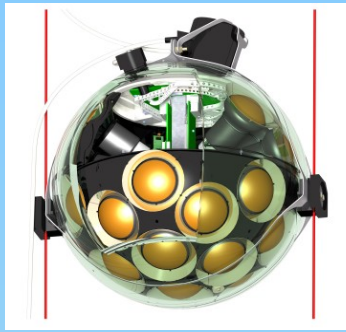
2 blocks in Italy:
ARCA (larger, 1km3)
- HE astrophysics
→ 1 line taking data!

1 block in France:
ORCA (denser)
-Neutrino oscillations
→ 4 lines taking data!



KM3NeT detectors:

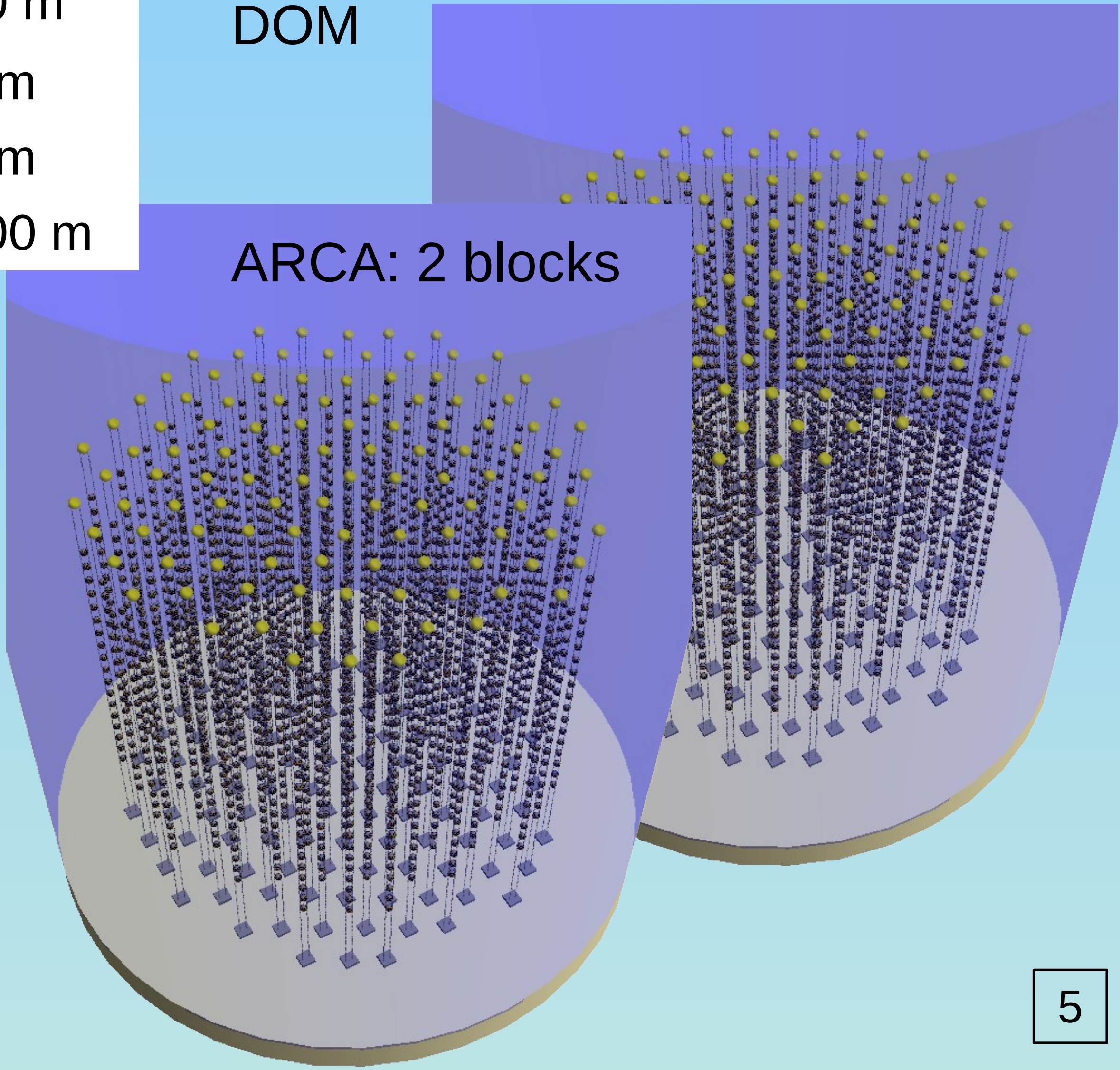
	ANTARES	ORCA	ARCA
Eff. Mass	10 Mt	5.7 Mt	1 Gt
Line length	350 m	200 m	650 m
Inter-line dist	70 m	20 m	90 m
Inter-OM dist	14.5	9 m	36 m
Depth	2450 m	2450 m	3500 m



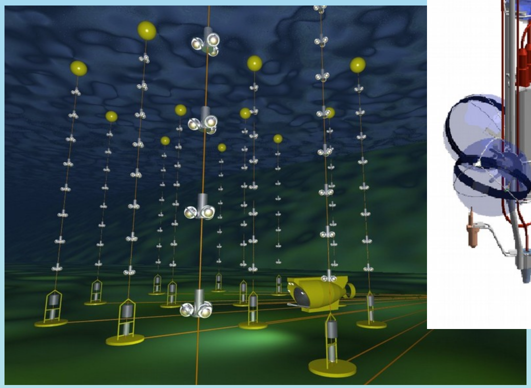
DOM

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

ARCA: 2 blocks



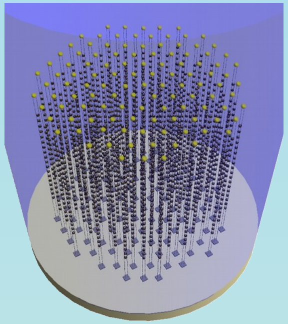
ANTARES



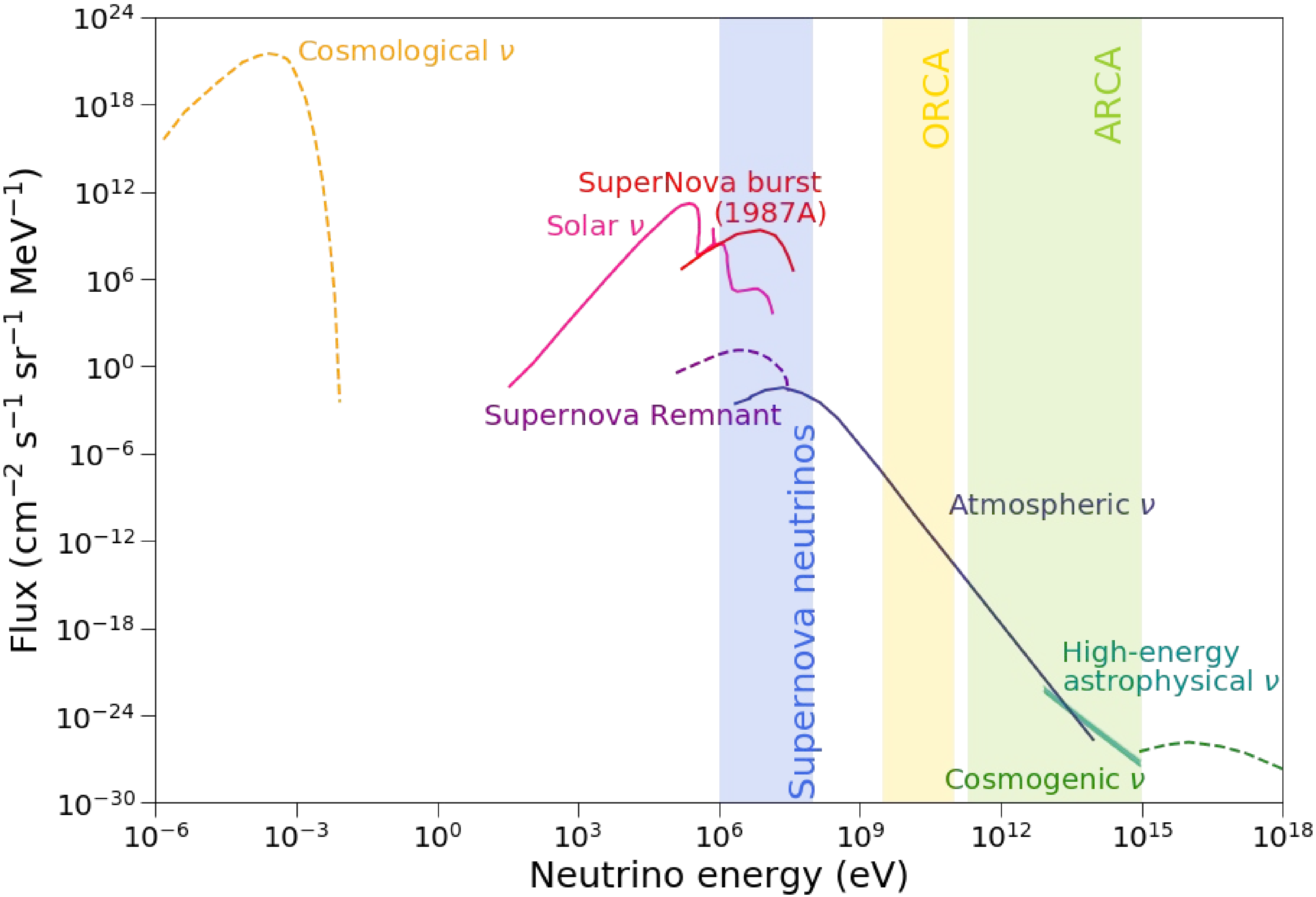
ANTARES storey

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

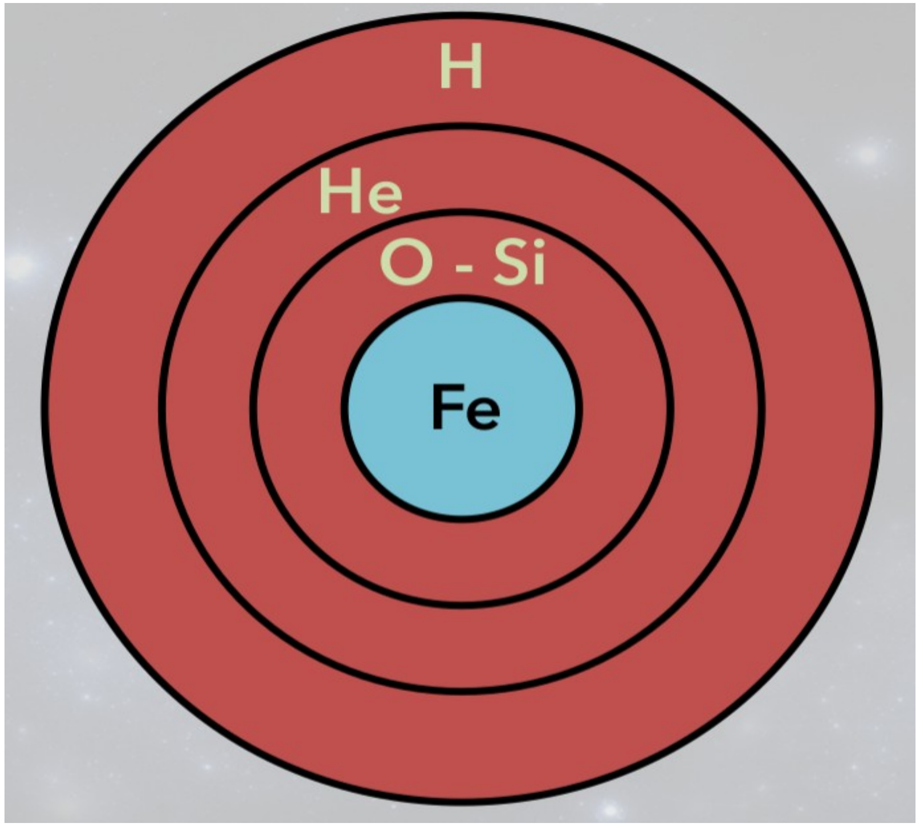
ORCA:
1 block



Multi-energy neutrino spectrum:

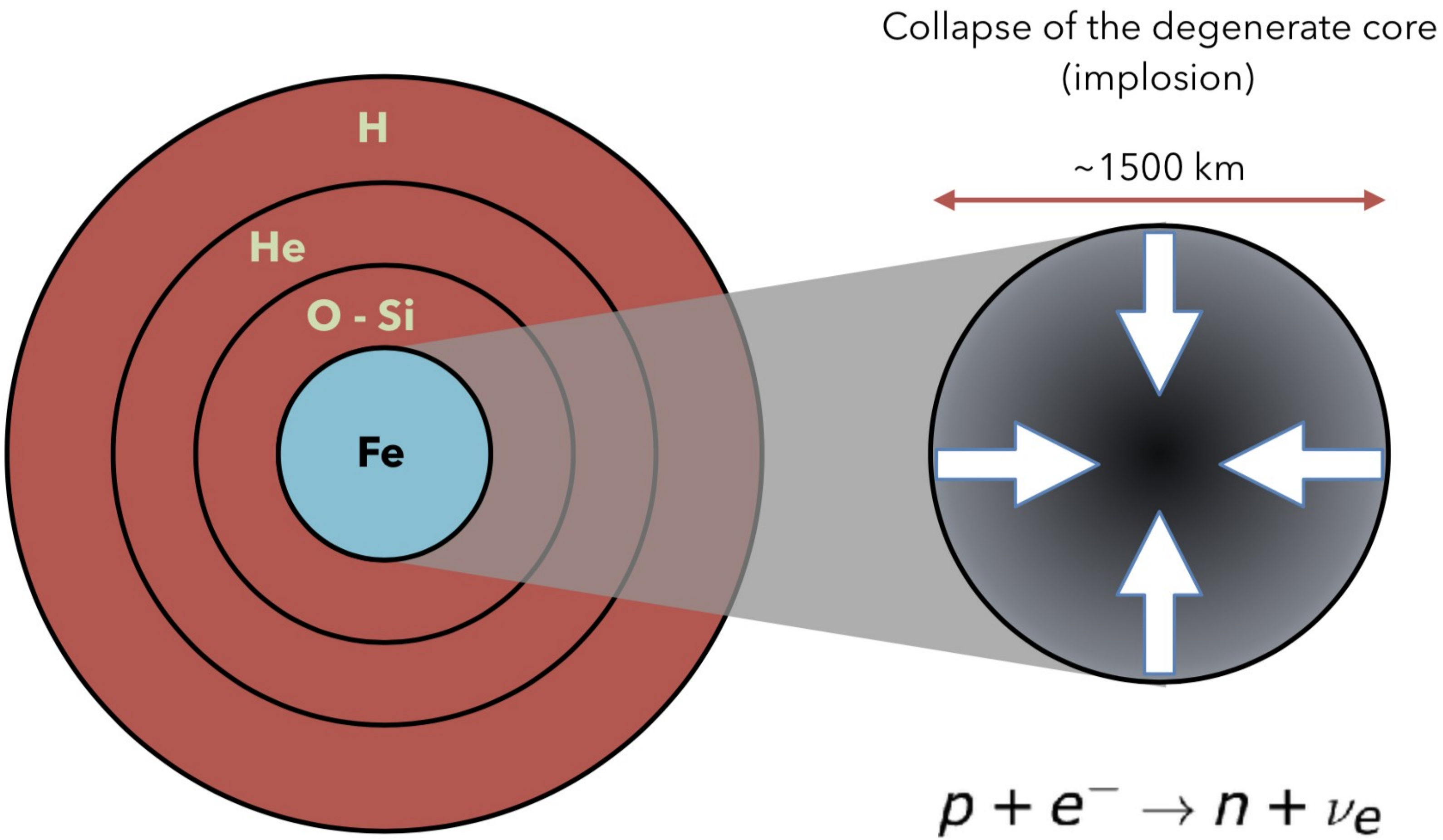


Core Collapse Supernova: The explosion mechanism



- Massif stars (>10Msun)
- Onion structure
- Gravity: Compress matter
- Temperature and pressure increase
- Nuclear force: Burns H and He
- Competition between gravity and nuclear force
- In the end, it runs out of fuel (H, He): no more nuclear reactions

Core Collapse Supernova: The explosion mechanism

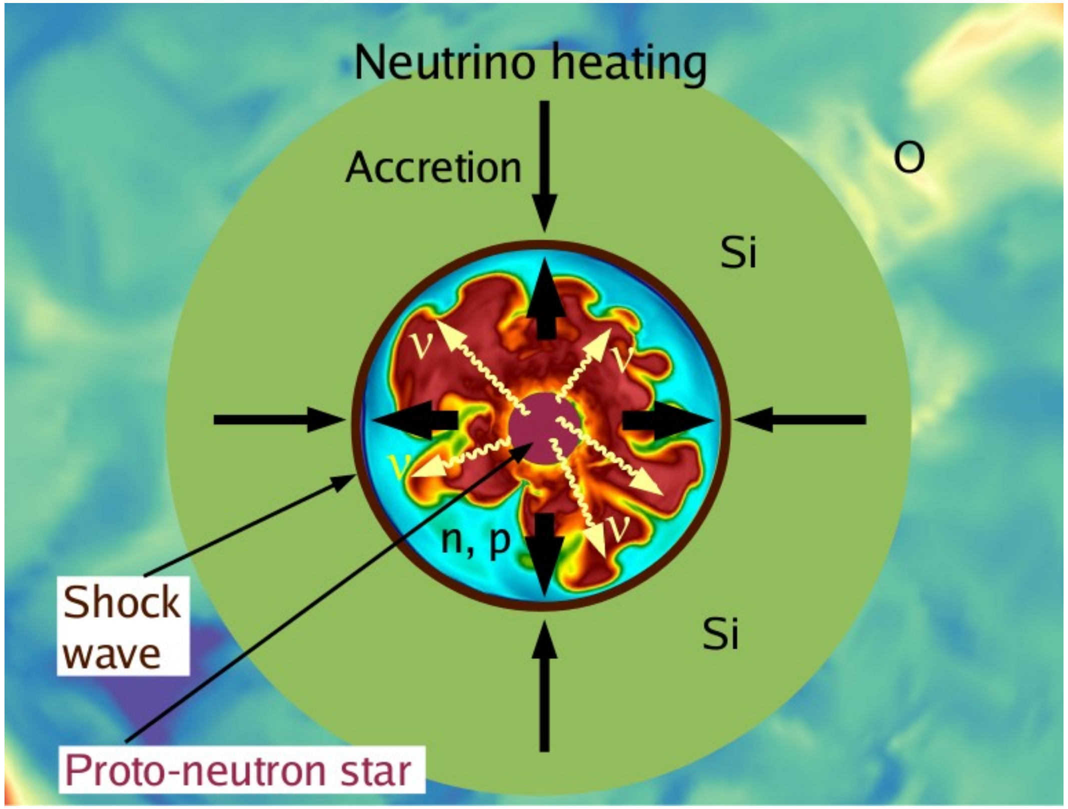


$$p + e^- \rightarrow n + \nu_e$$

Massive star M ≳ 10$M_\odot$
Onion structure

As M_{core} ~ M_{Chand}, pressure of degenerate relativistic electrons decreases due to electron capture and becomes insufficient to resist gravity ➜ collapse

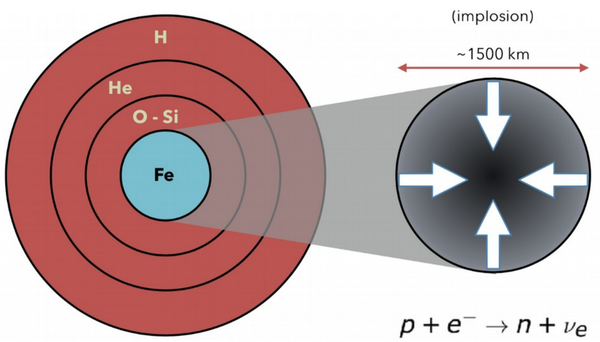
Core Collapse Supernova: The explosion mechanism

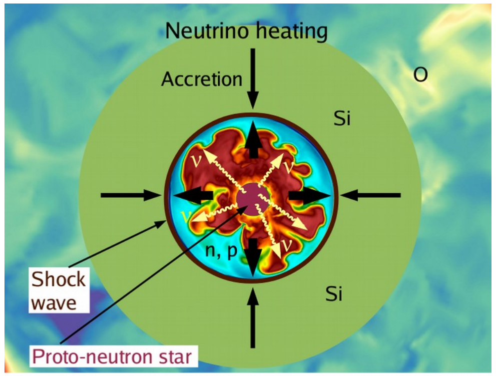


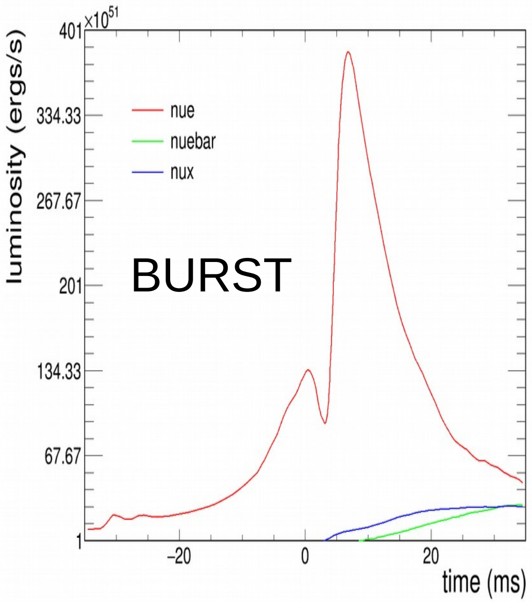
T.Hanka (2017) arXiv:1702.08825

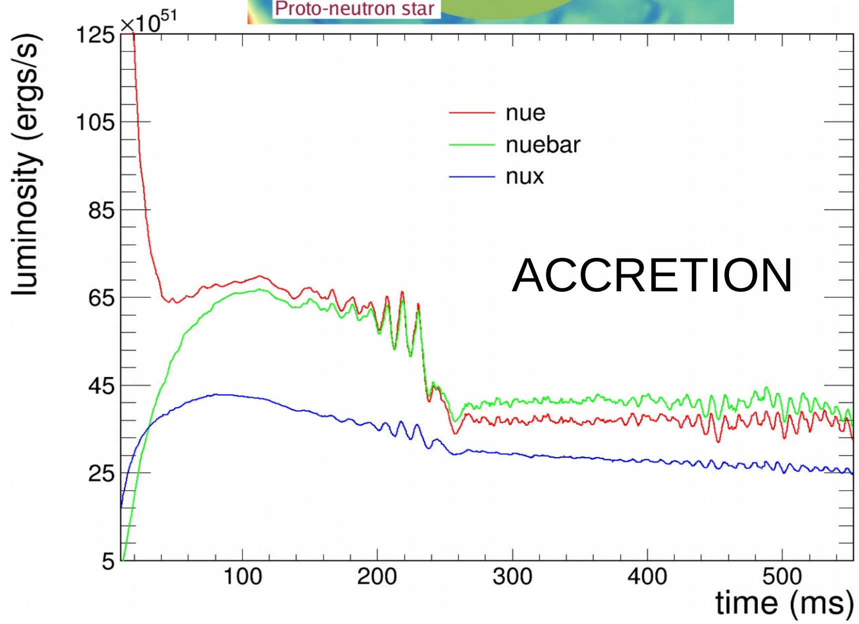
- Nuclear reactions: Huge amount of neutrinos emitted
- Shock wave formation: it propagates until it stalls.
- Neutrinos revive the shock (neutrino heating) by energy deposition and allow for:
  - The final explosion
  - Stellar nucleosynthesis of heavy nuclei
- 99% of the gravitational binding energy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

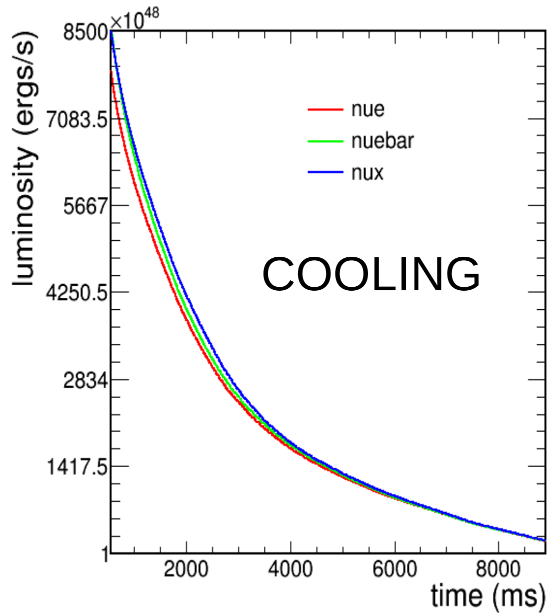
Phases of a Core Collapse Supernova:











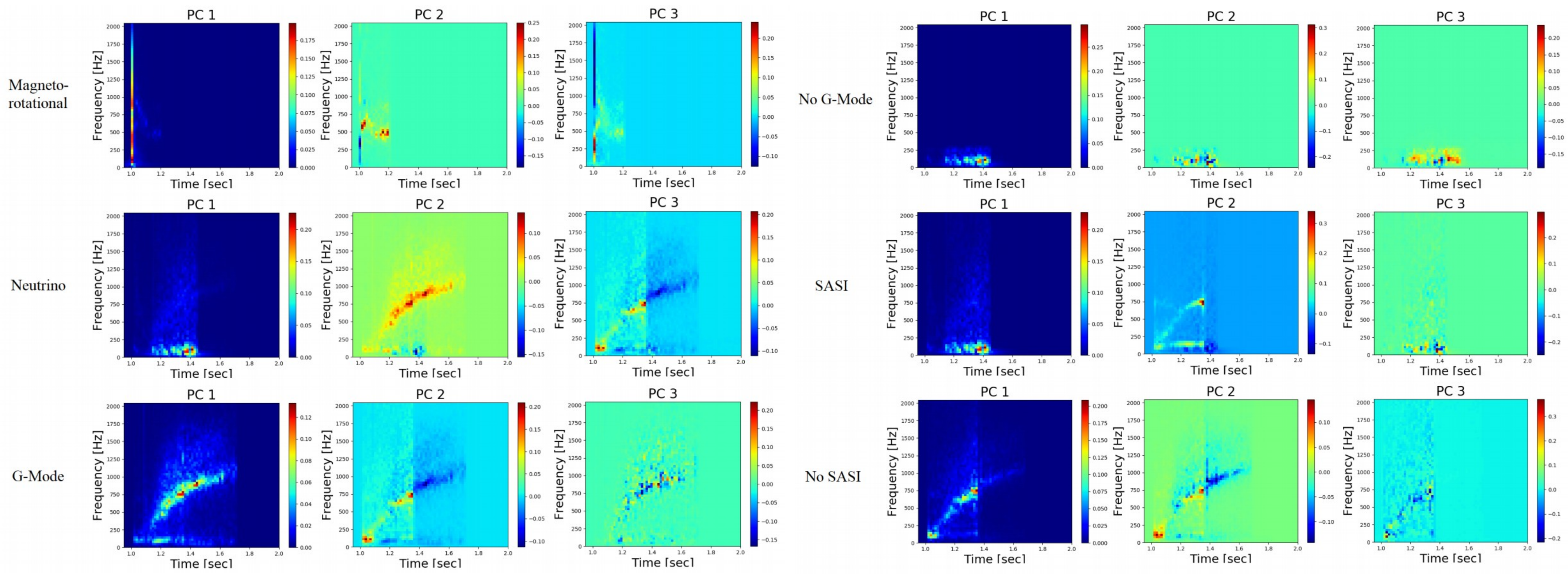
- Shock bounce
- Electron capture
- Birth of remaining compact object

- Hydrodynamical instabilities/convection
- Neutrino heating
- Shock revival

- Neutrino pair production
- Nucleosythesis
- Explosion

CCSN, neutrinos and GWs:

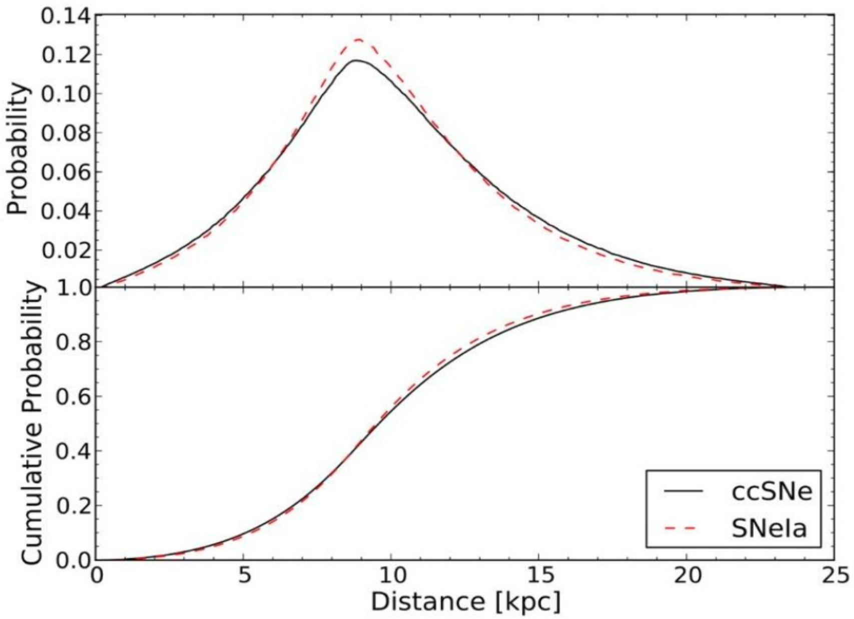
Non-spherical mass-energy dynamics (quadrupoles or higher order contributions)
→ **Gravitational Wave emission**
Such asymmetric magnetohydro-dynamics are expected to be present in CCSN
→ Unkown model for the GW signal form...



https://arxiv.org/pdf/1901.08692.pdf

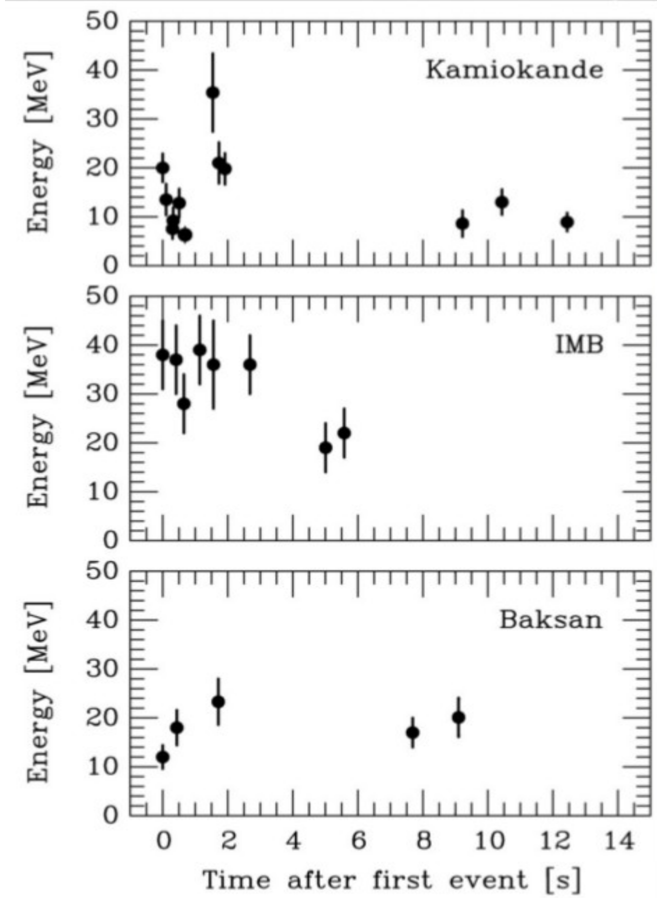
What is really happening?

- 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…



Scott M. Adams et al. (2013) ApJ (778)

T. Foglizzo (2015) arXiv:1501.01334



Annu. Rev. Nucl. Part. Sci. (1999)

CCSN neutrino detection in water:

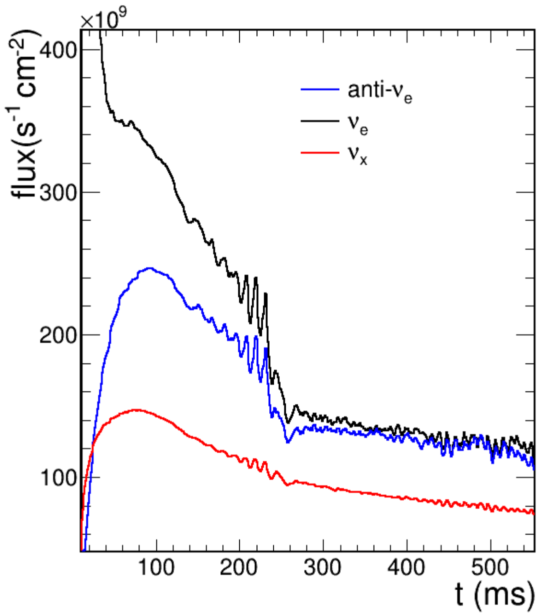
- Large amount (~3e53 erg/s) of 1-100 MeV neutrinos emitted:
  $\overline{\nu}_e$ dominate during accretion phase (~500ms)
- Main interaction: $\overline{\nu}_e$ with protons, IBD (~97%) : $\overline{\nu}_e + p \to e^+ + n$
  also ν_e with electrons, ES (~3%): $\nu_e + e^- \to \nu_e + e^-$
- We expect ~1000-8000 events @10kpc in 1 detection block:
  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

Interaction rates

(Interactions around a DOM)

↓

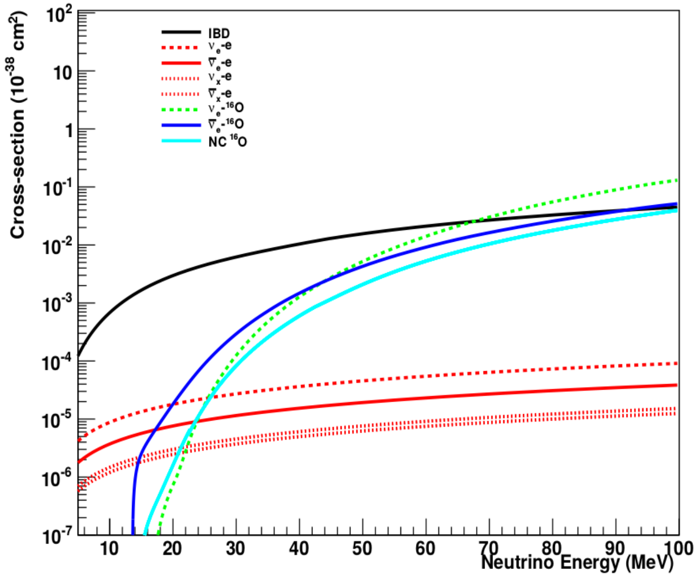
Outgoing leptons

↓

Cherenkov light ← GEANT4

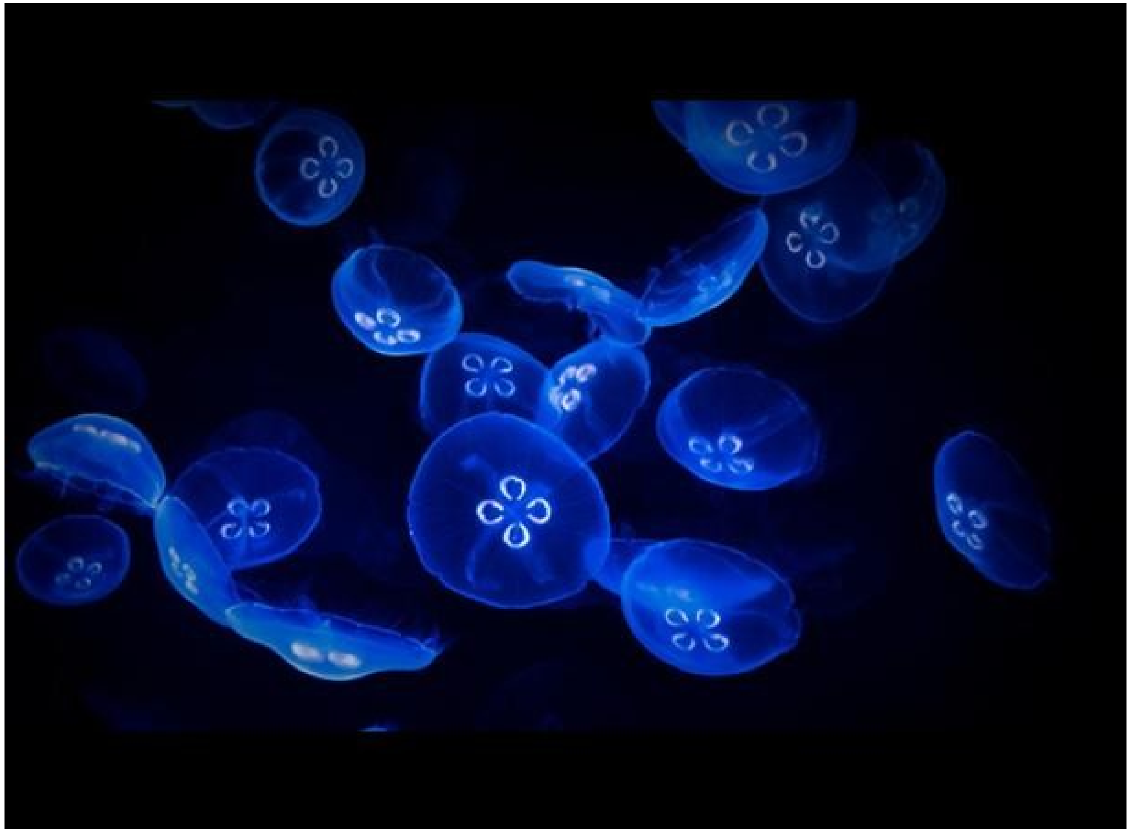
↓

PMT (detector) response

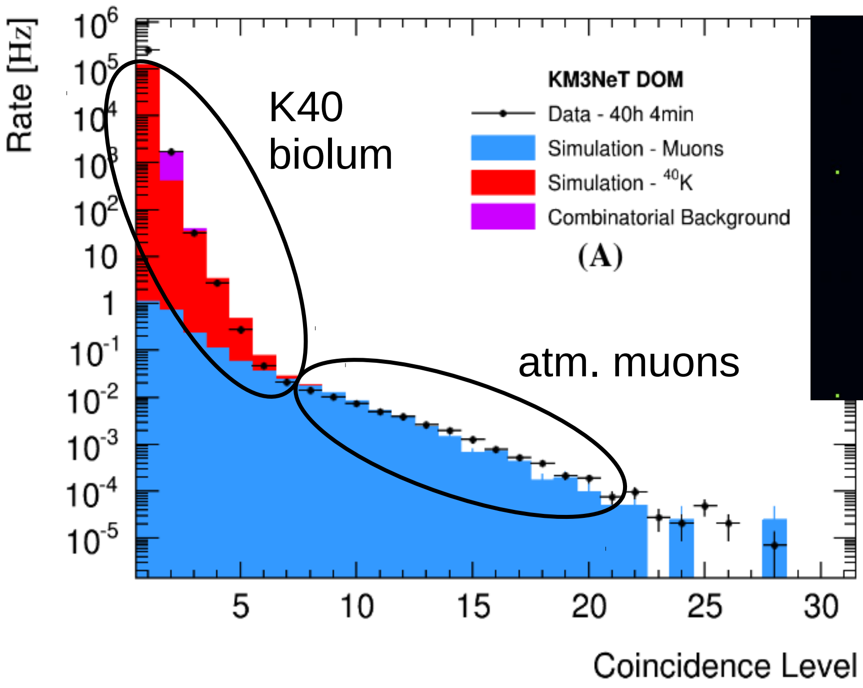


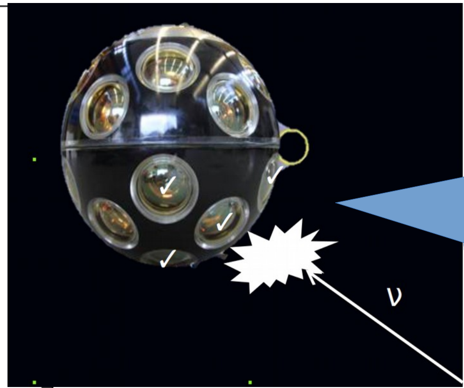
What other things produce light in sea water? (Background)

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

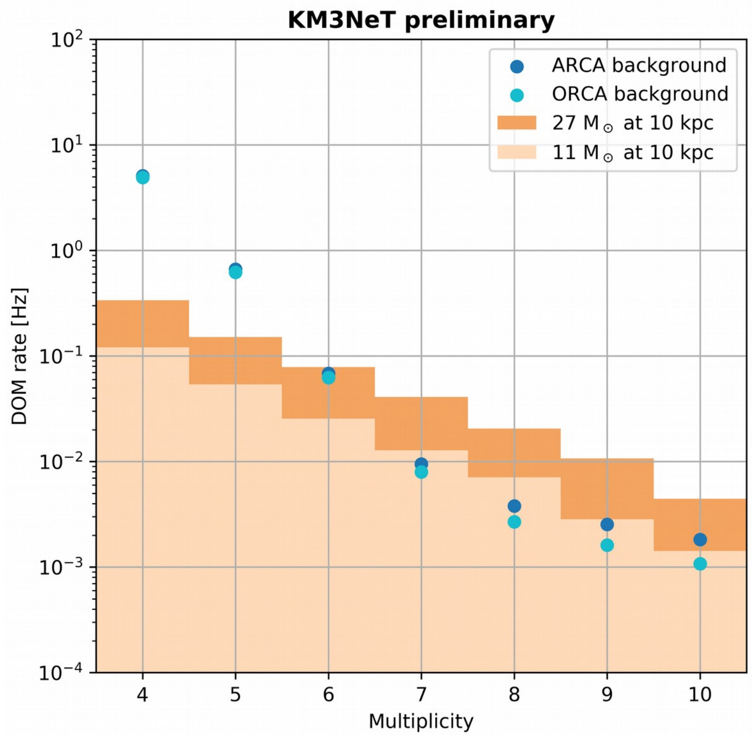


Detection method:

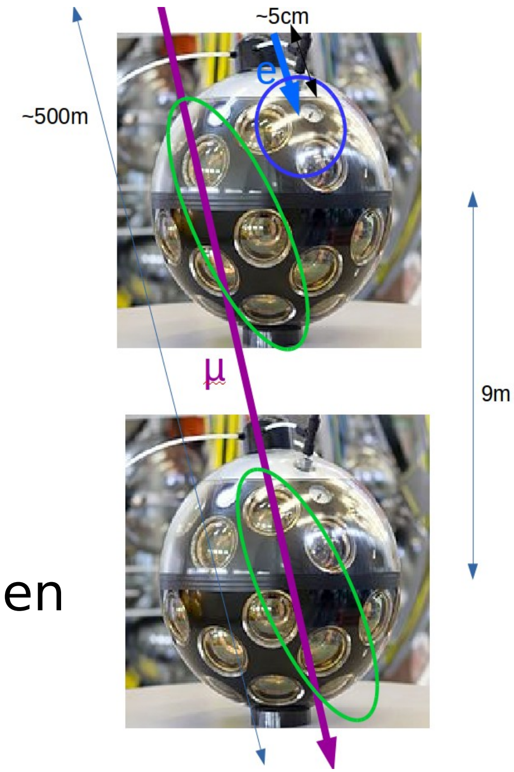




Exploit multi-PMT technology to achieve better performance!



- Signal = Overall increase of detected PMT rates over baseline
- **Multiplicity**: number of PMTs in a DOM receiving a photon in **10 ns**
- Multiplicity selection for optical background reduction!
- Muon veto: μs coincidences between DOMs to identify atm. muons



KM3NeT event statistics

Events in 1 detection block, @10 kpc:

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

Table: Signal event statistics as a function of the multiplicity

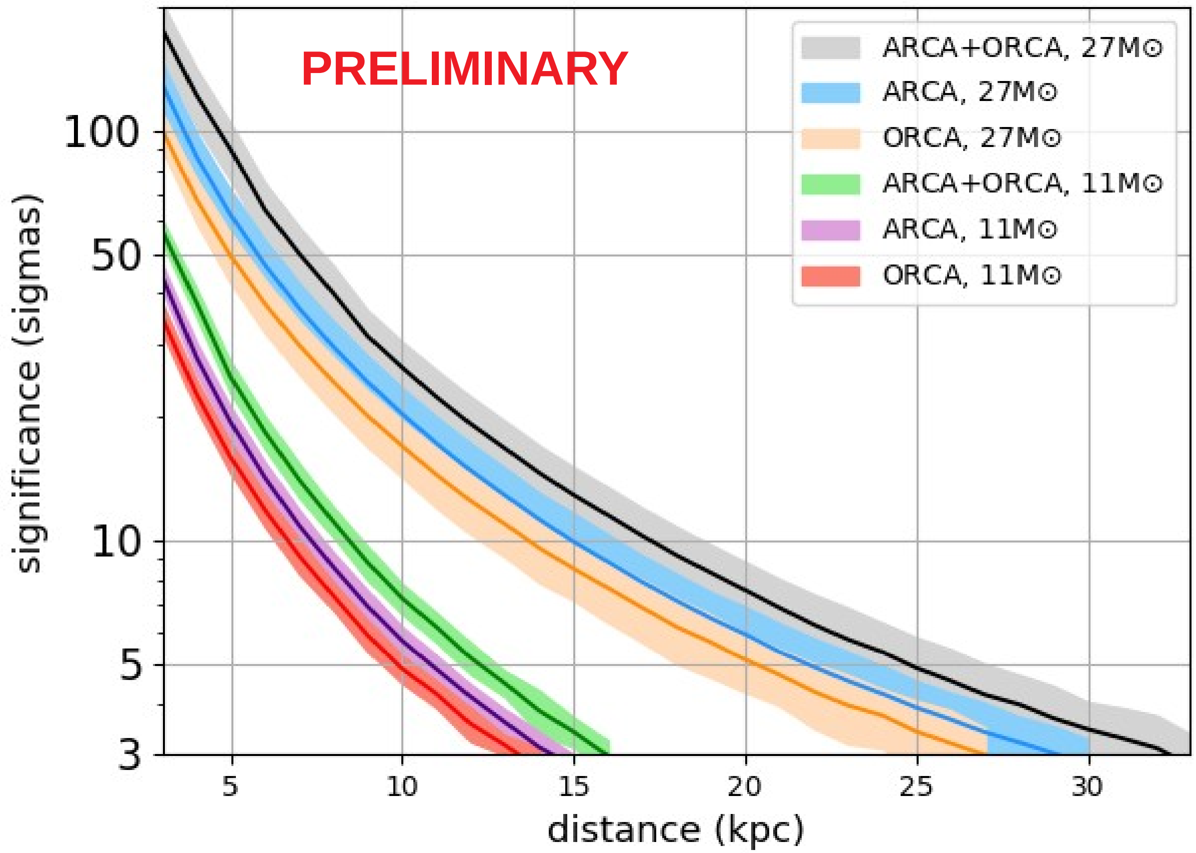
Progenitor mass	**Δt (ms)**	N_b **ORCA**	N_b **ARCA**	N_s
27 $M_\odot$	543	60	98	174
11 $M_\odot$	340	38	61	34

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.

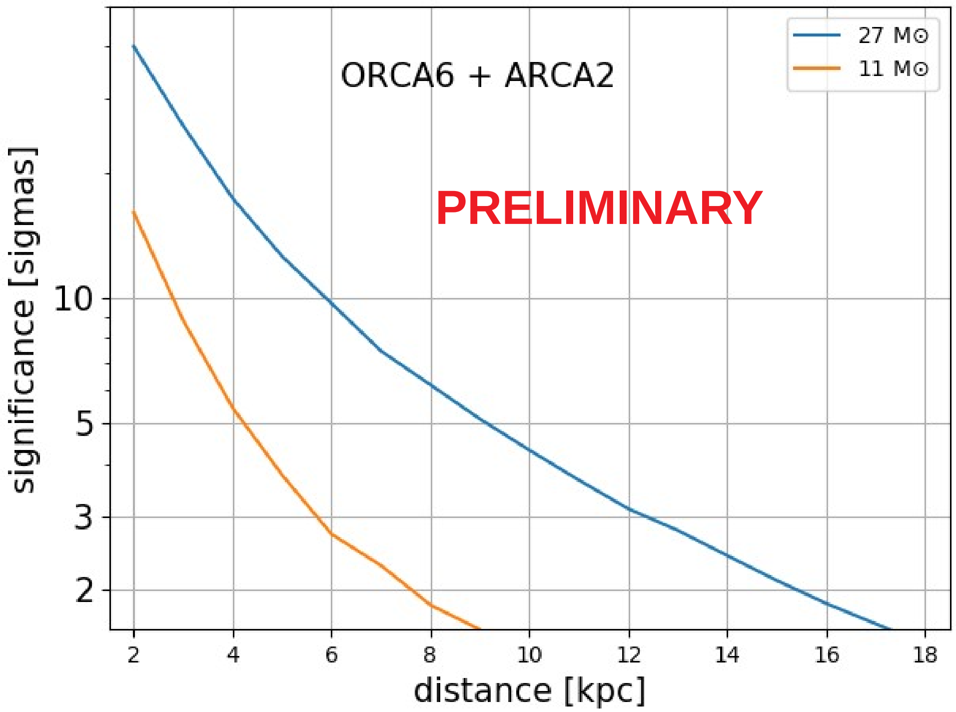
Significance of the detection

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

M.Colomer PoS(ICRC2019)857



With 6DUs ORCA + 2DUs ARCA, 5σ up to: 9kpc (4.2kpc) for 27M⊙ (11M⊙)

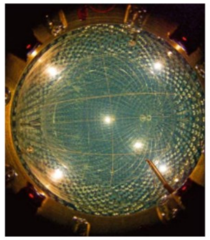


(Time window search used in the analysis: duration of the simulation)

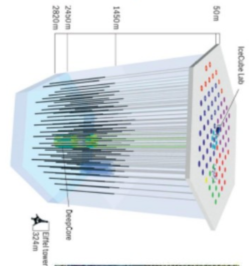
Current and future detectors:

	Detector	Events (@10kpc)	Channel	5σ distance
Running	IceCube	~300.000	IBD	SMC (70kpc)
	Super-K	~7000	IBD, ES	SMC (70kpc)
	Borexino	~100	IBD	Galaxy (25kpc)
	KamLAND	~300	IBD	Galactic Center
	NOvA	~4000	IBD	Galactic Center
	LVD	~300	IBD	Galaxy (25kpc)
Future	Hyper-K	~11.000	IBD, ES	1-2 Mpc
	JUNO	~6000	IBD, proton ES	SMC (70kpc)
	DUNE	~3000	ES	Galaxy (25kpc)

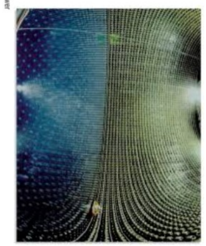
Liquid Scintillators
- Borexino
- KamLAND
- Juno
- ...



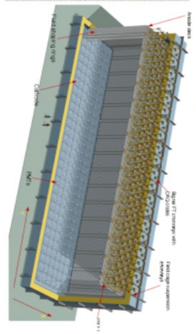
Long-String Cherenkov detectors
- IceCube
- KM3NeT



Water Cherenkov detectors
- Super-K
- Hyper-K



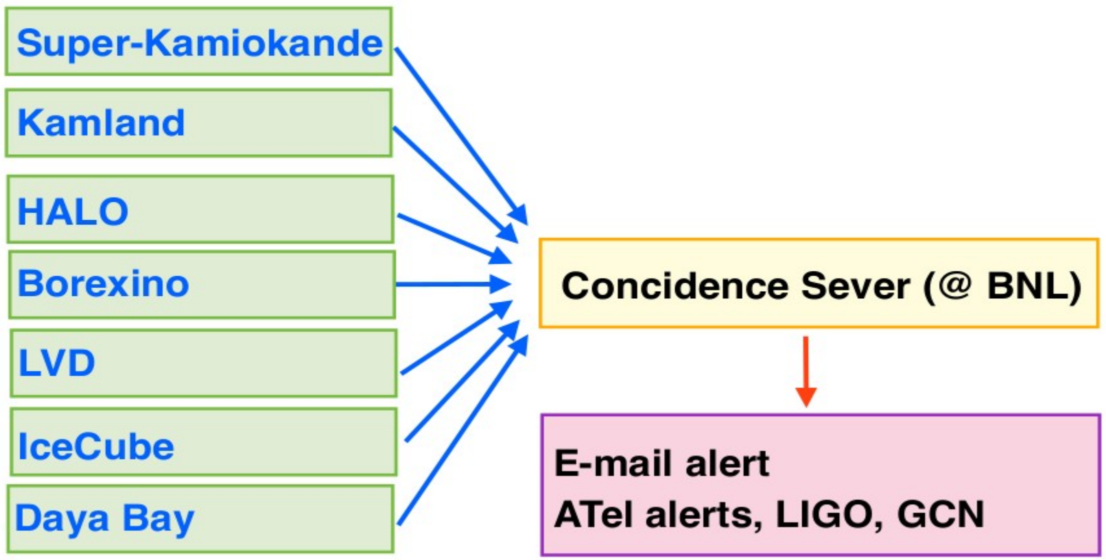
Argon detectors
- DUNE



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 (10s)
- KM3NeT is now part of the network!

SuperNova Early Warning System (SNEWS)

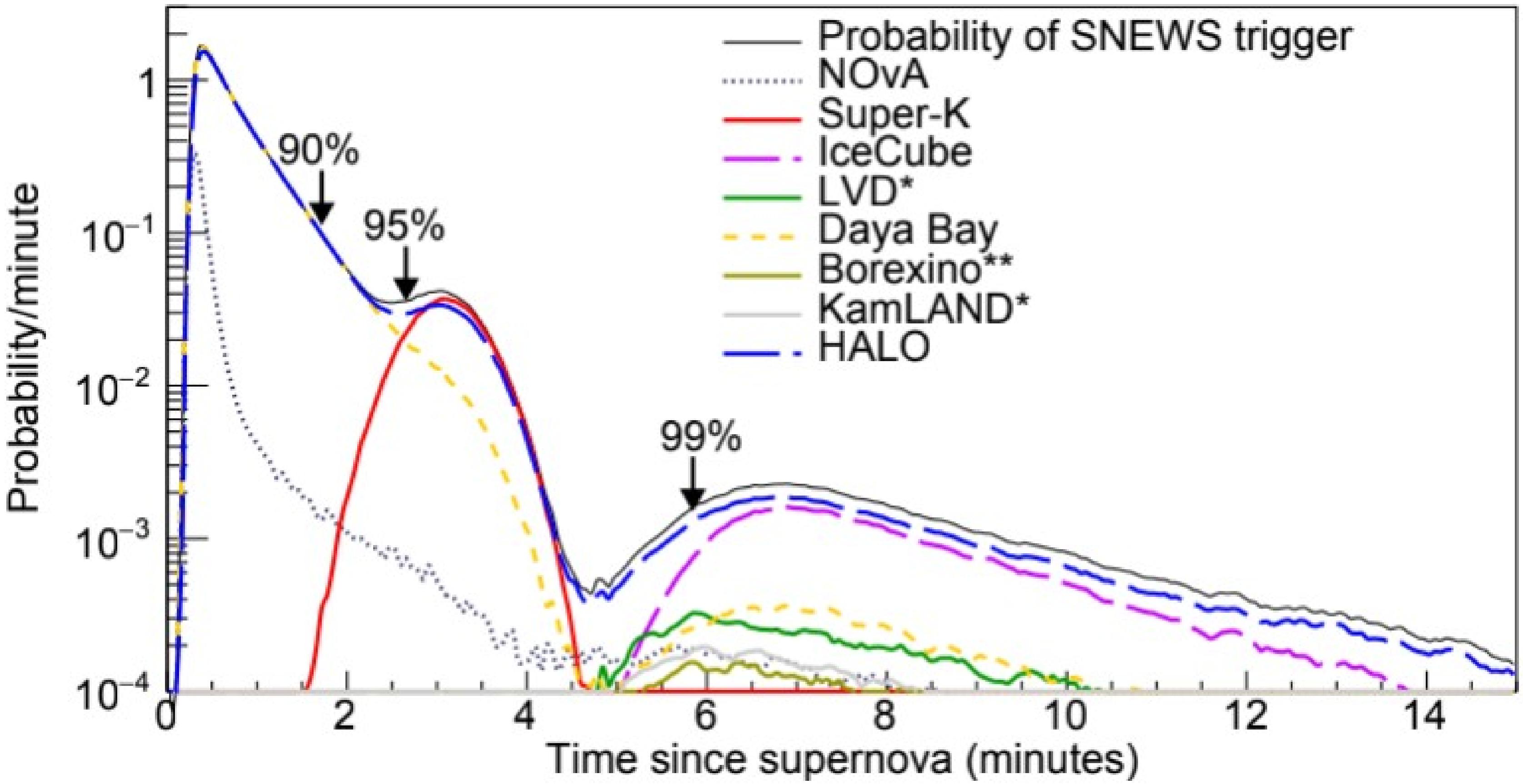


SNEWS 2.0

- ORCA can trigger beyond the Galactic Center!
- Online SN monitoring working stable for almost 1yr now!
- Combined real-time trigger ORCA+ARCA

Real-time alerts: SNEWS

- Current latency of SNEWS participants: some min
- KM3NeT latency with combined trigger: ~15sec!

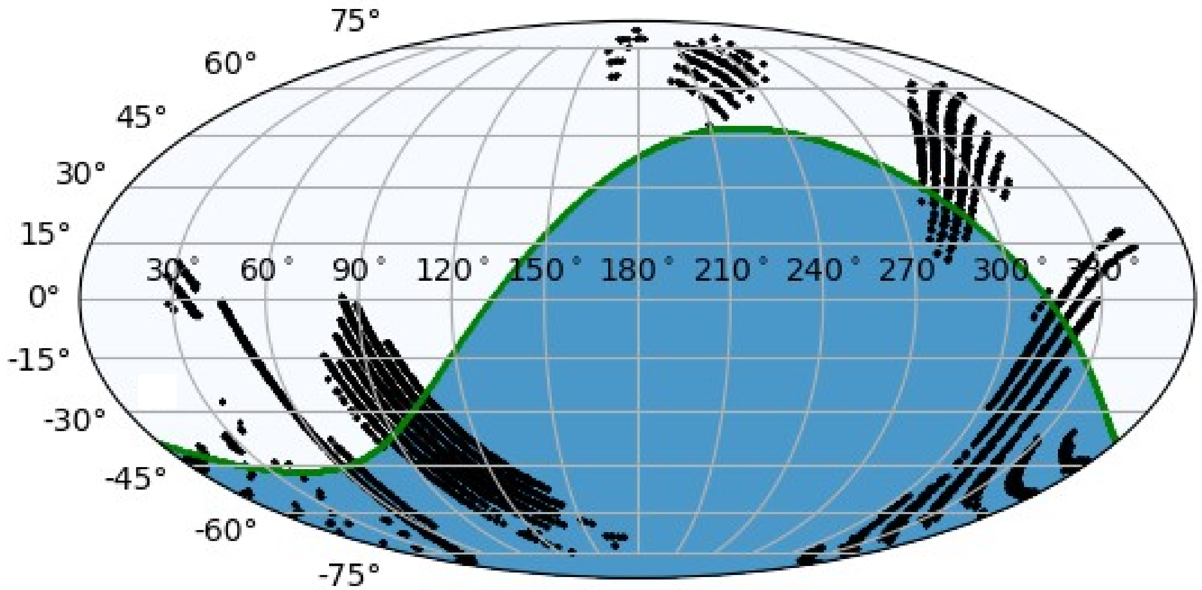


→ KM3NeT is ready to start sending and receiving alerts!

K. Scholberg (2008) arXiv:0803.0531

First real-time results: GW follow-up

Unmodelled burst GW candidate S191110af (GCN #26222) : RETRACTED



→ Potential close-by CCSN candidate

KM3NeT follow-up using online SN trigger with 4 ORCA lines:

NO TRIGGER over 400ms search (GCN #26249) → Constraints at 90% CL

Lower limits on the CCSN distance:

- 27 M⊙ : 11.4 kpc
- 11 M⊙ : 5.7 kpc

Upper limit on the total energy emitted in neutrinos @10kpc :

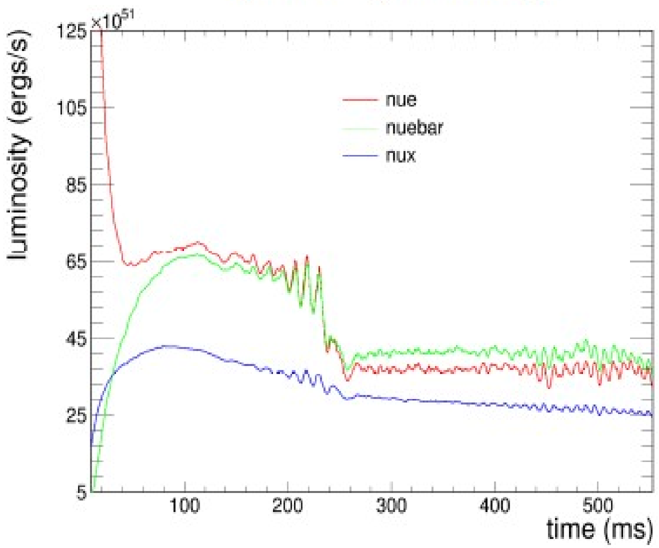
E < 2.8e53 erg (<Eν> = 15MeV)

What to learn on CCSN neutrinos?

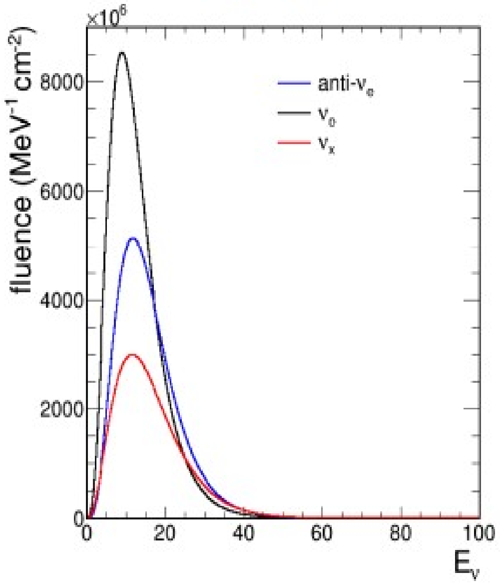
- Multi-PMTs (multiplicity) for optimal sensitivity and energy estimation
- Double coincidences for time information: high statistics (large detector)

Constrain the models!

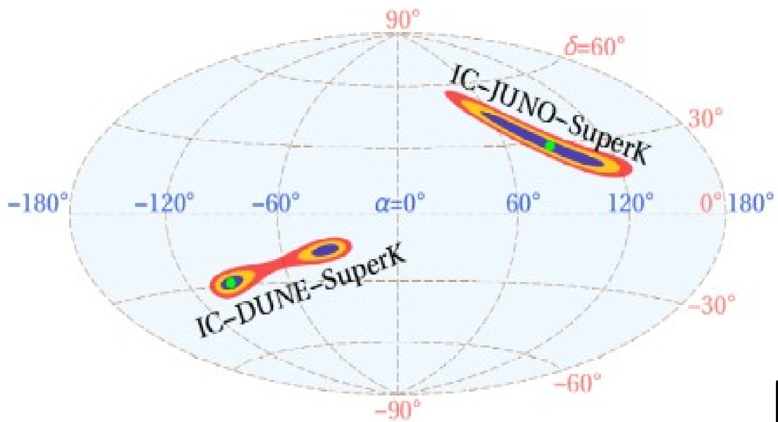
Light-curve
(time profile)



Energy spectrum



Source direction



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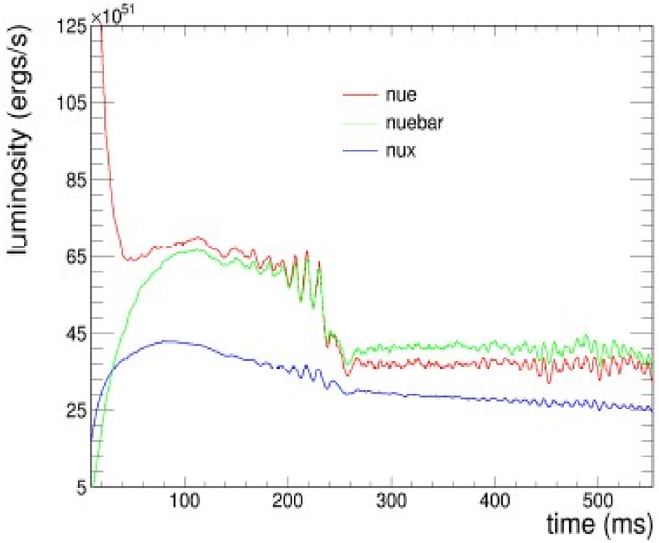
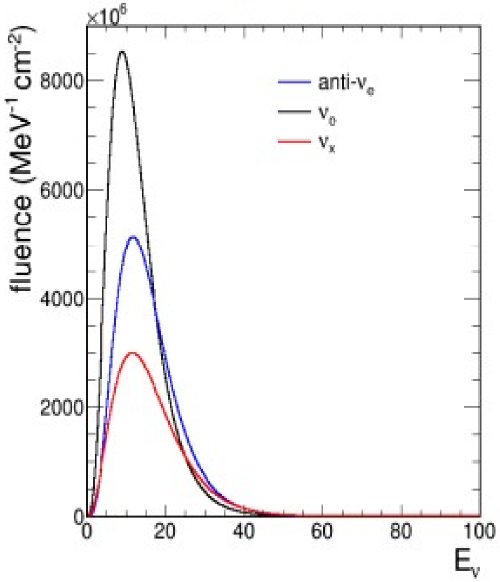
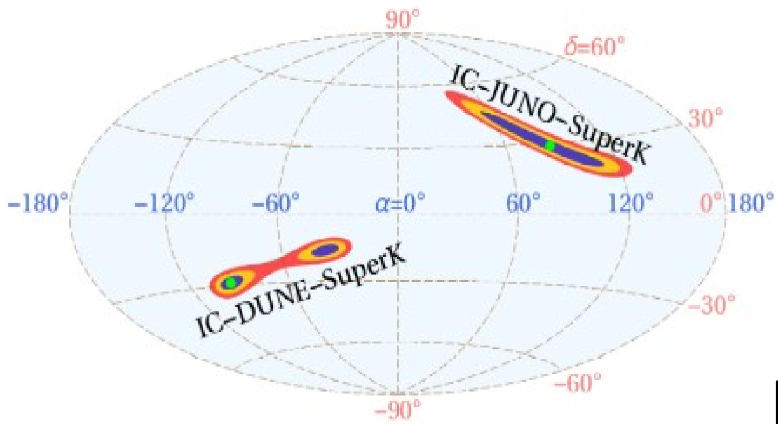


Energy spectrum

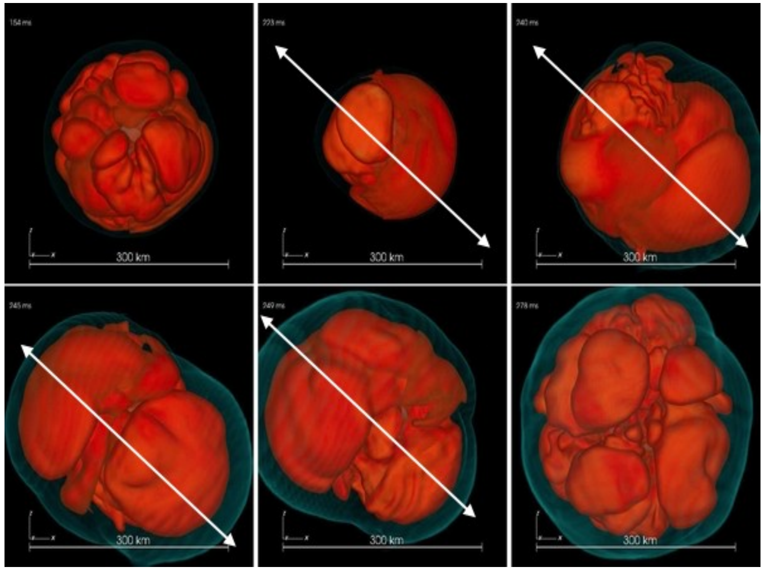


Source direction



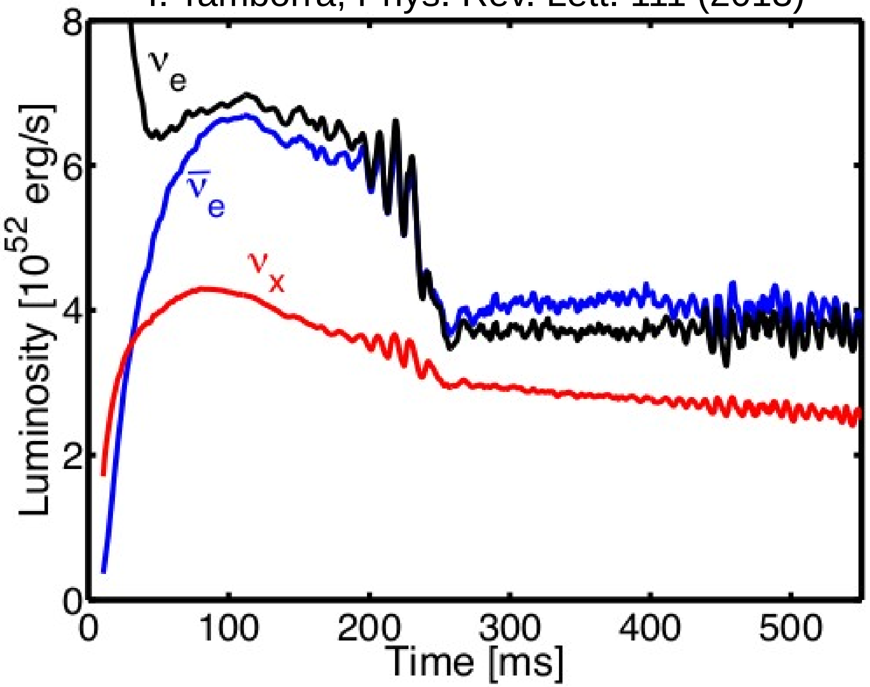
Fast time variations on the neutrino light-curve: SASI

- 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 through Fourier analysis
- Enhances the neutrino heating favoring the explosion:
  → can help understanding the mechanism!
- Potentially correlated with GW emission!



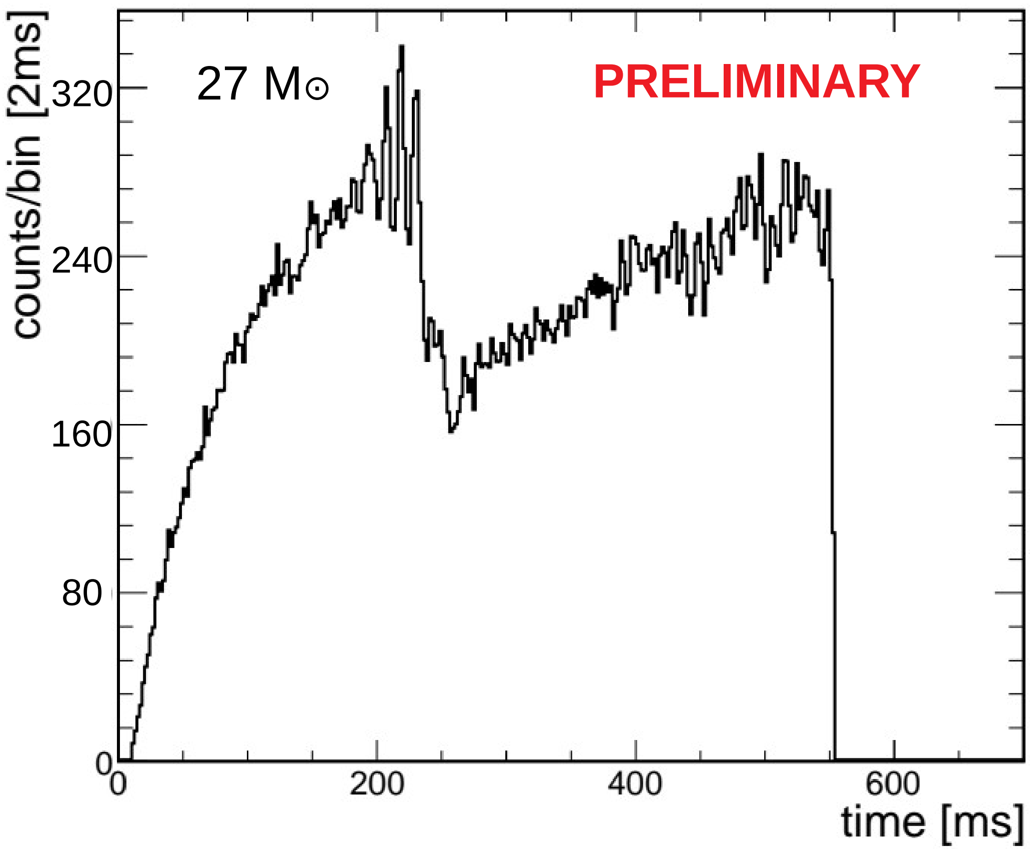
T.Hanka (2017) arXiv:1702.08825

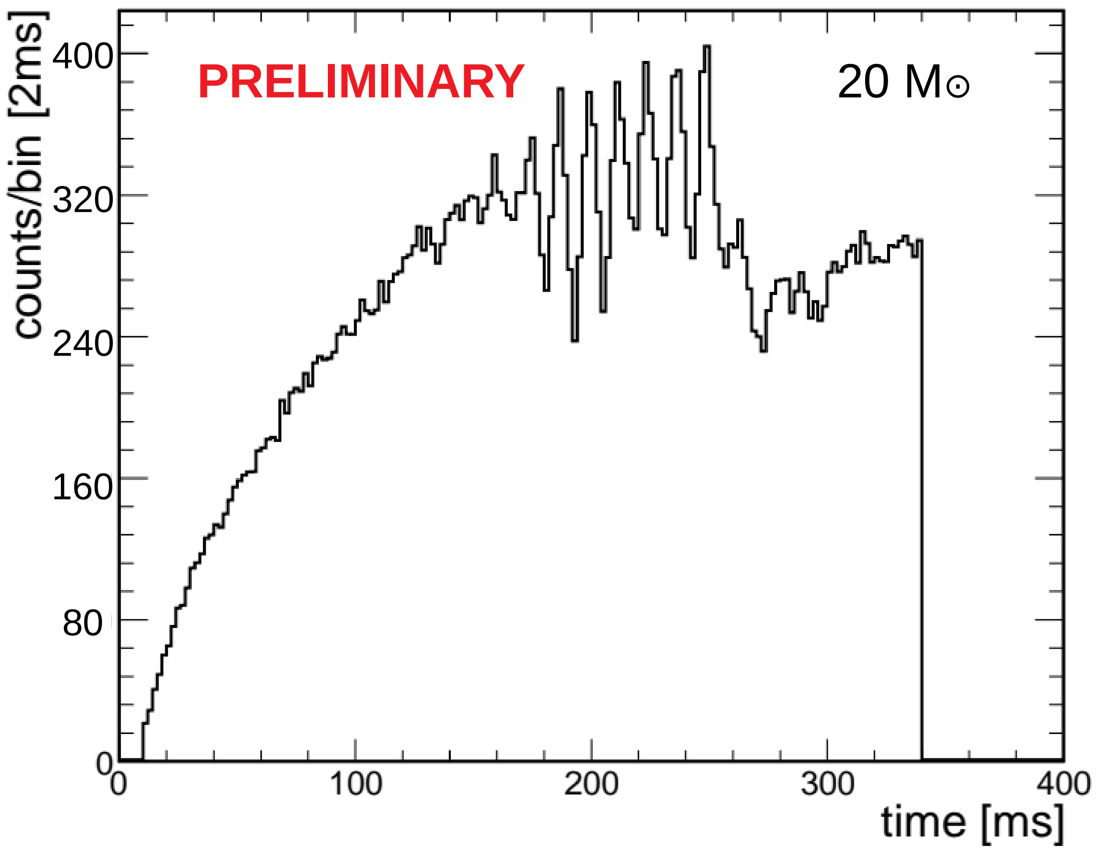
I. Tamborra, Phys. Rev. Lett. 111 (2013)



Progenitor models and detector response to CCSN signal time profile

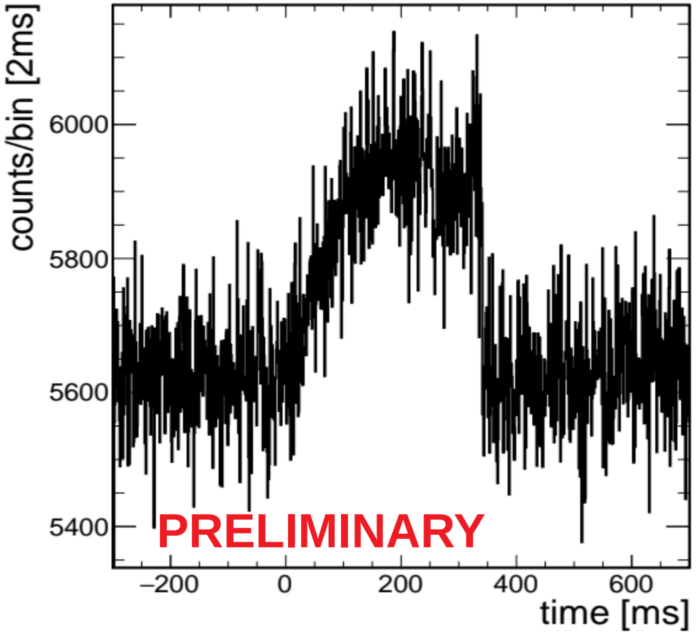
→ We use double coincidences (high stats, reduce biolum)
→ Expected signal in full ARCA detector @ 5 kpc



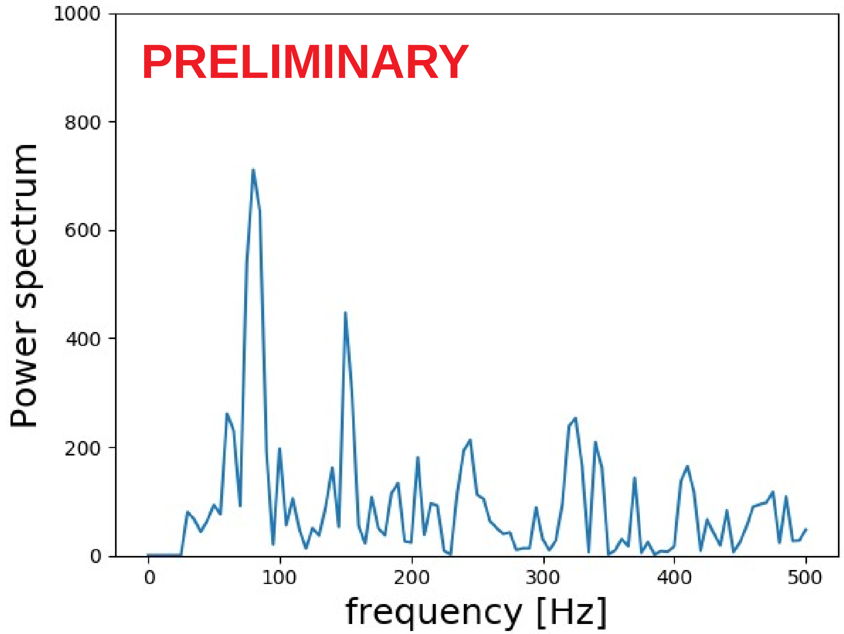


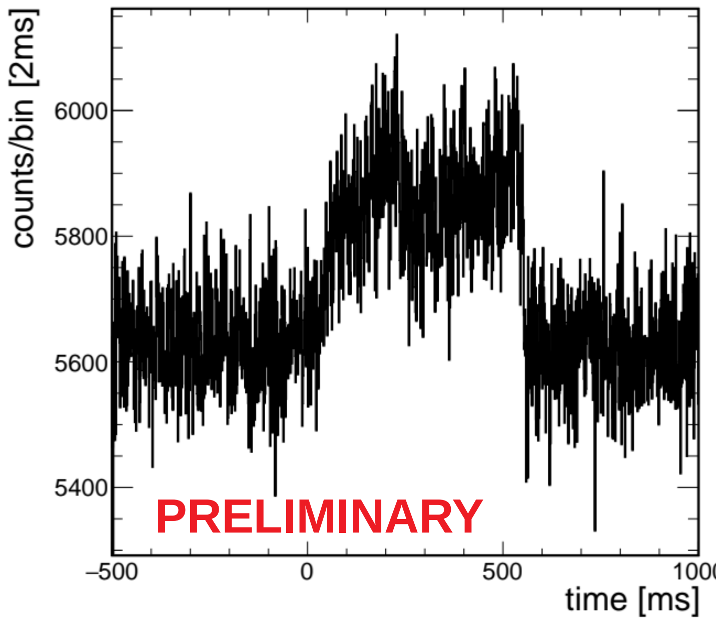
Now, add background and apply FT...

Light-curves and Power Spectrum:

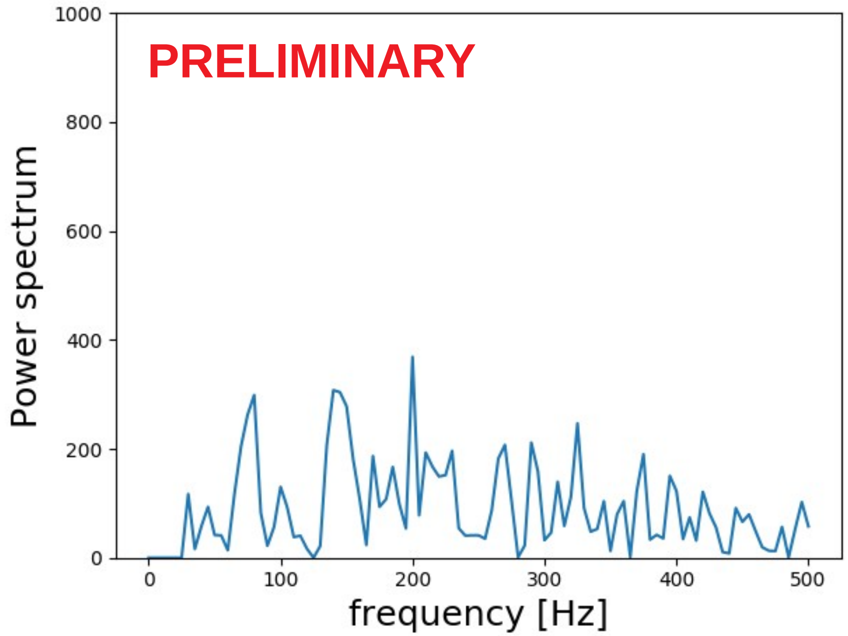


ARCA 20M⊙
@5kpc (with bkg)



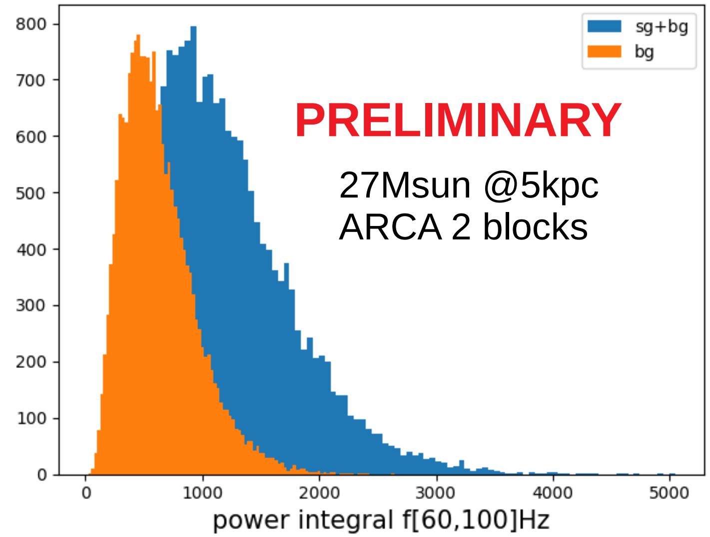


ARCA 27M⊙
@5kpc (with bkg)

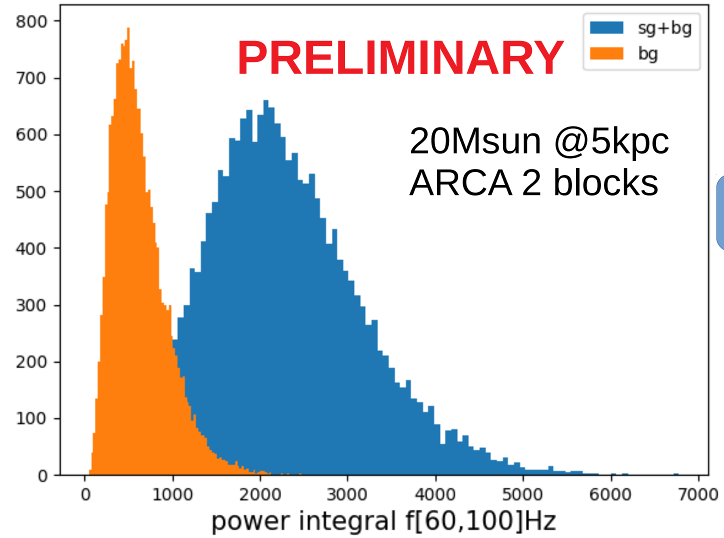


Analysis method & preliminary results:

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

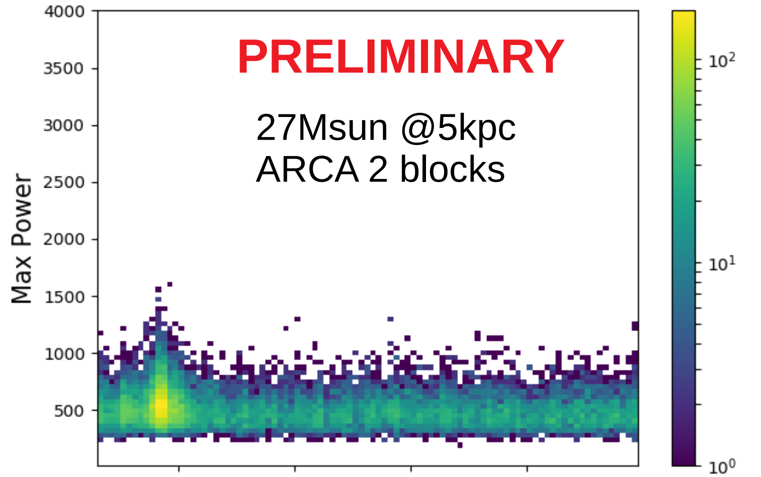


2σ

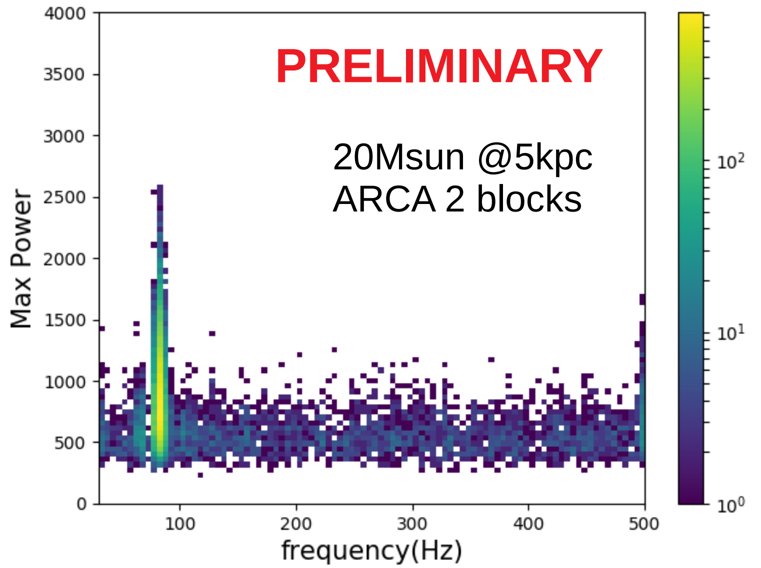


3.5σ

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



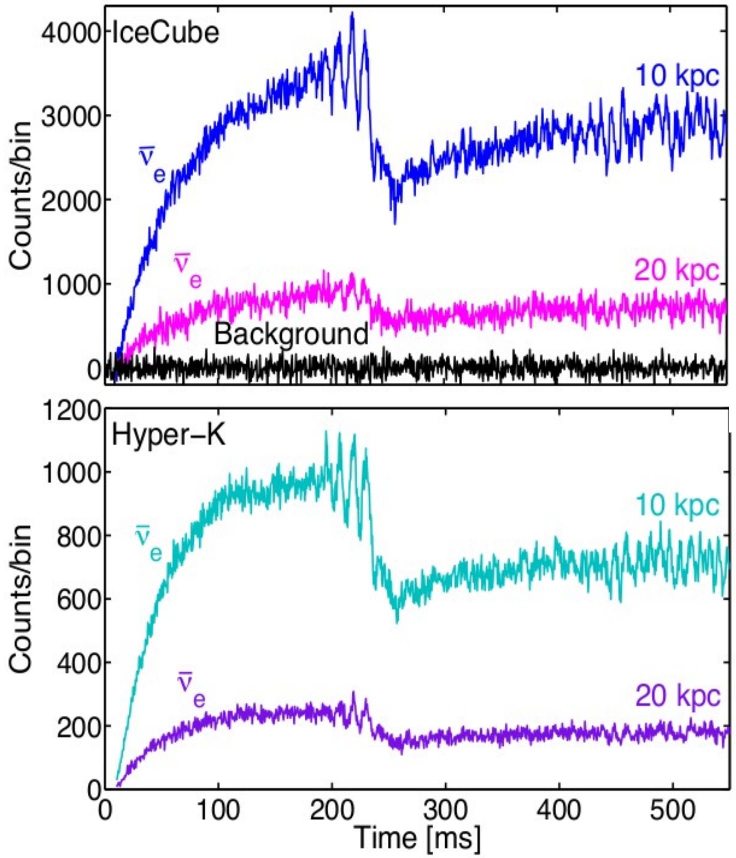
1σ

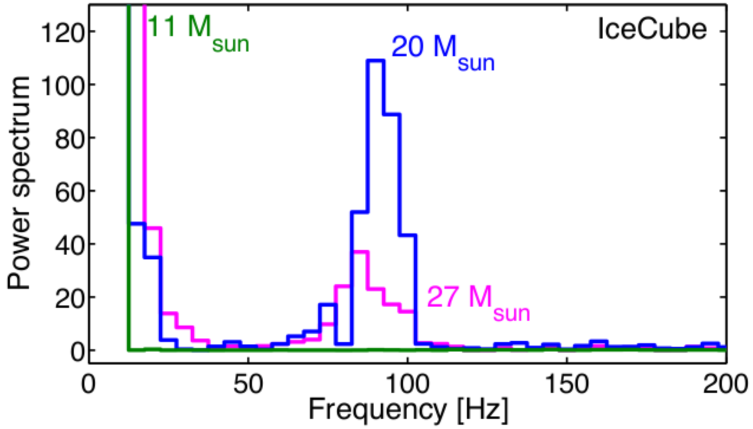


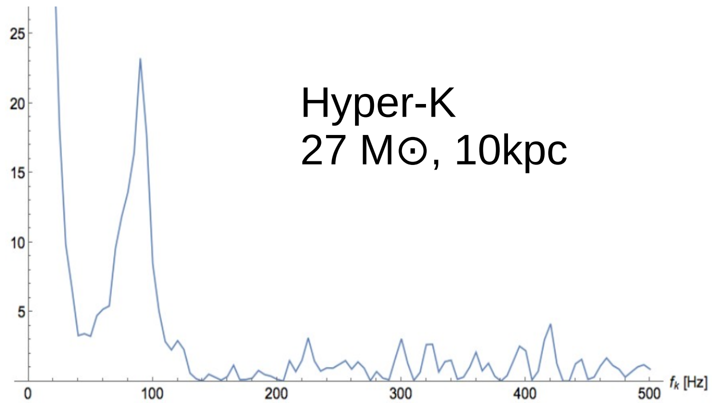
2.5σ

Sensitivity to SASI: state of the art

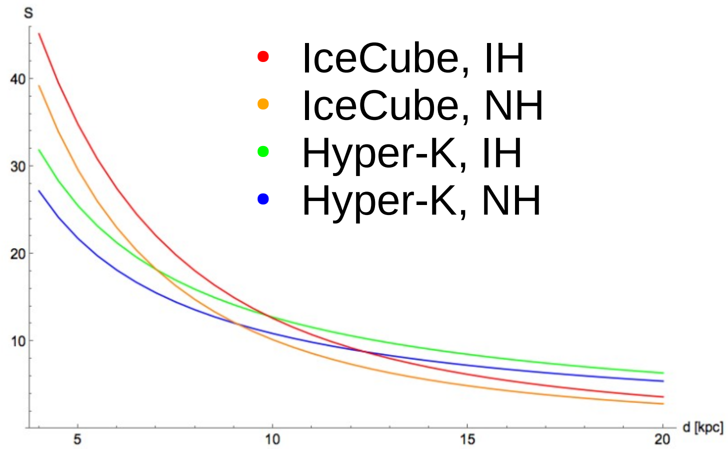
Observed light-curve → Power Spectrum: FT → Detection sensitivity







27 M⊙, 10kpc

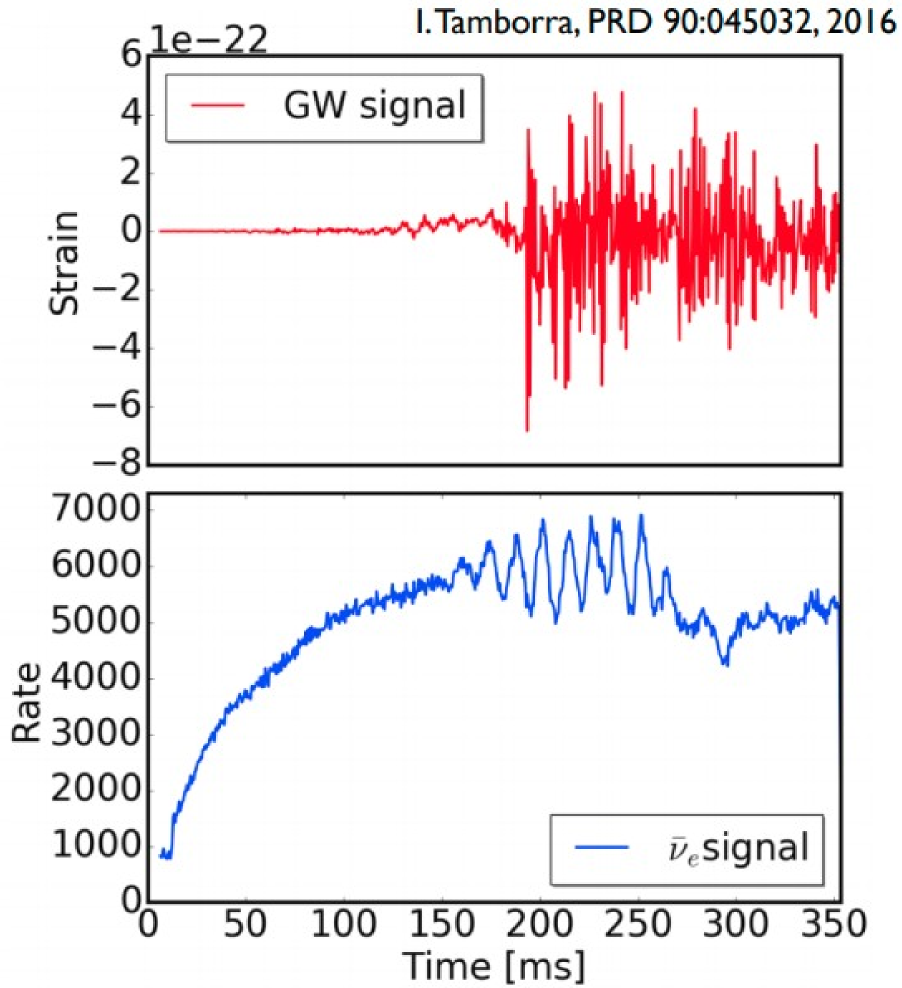


→ IceCube and Hyper-K can see the SASI oscillations up to ~20kpc

I. Tamborra, Phys. Rev. Lett. 111 (2013); J. Miganda (2016) arXiv:1609.04286

SASI and GW emission:

- Enhanced SASI oscillations correlated with GW emission
- Precise light-curve measurements → imprint short time-scale phenomena

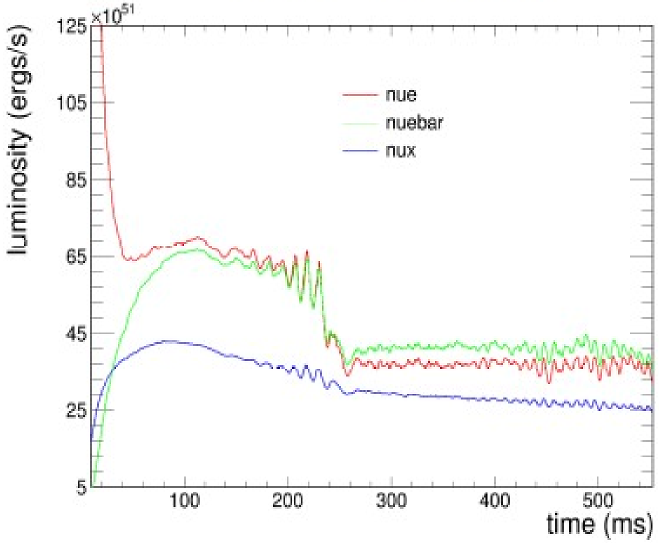


What to learn on CCSN neutrinos?

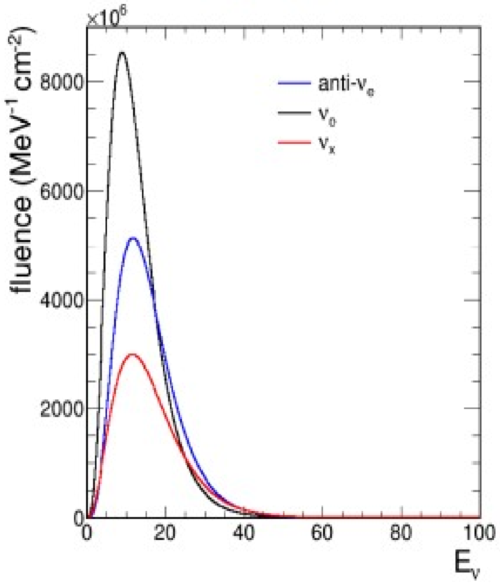
- Multi-PMTs (multiplicity) for optimal sensitivity and energy estimation
- Double coincidences for time information: high statistics (large detector)

Constrain the models!

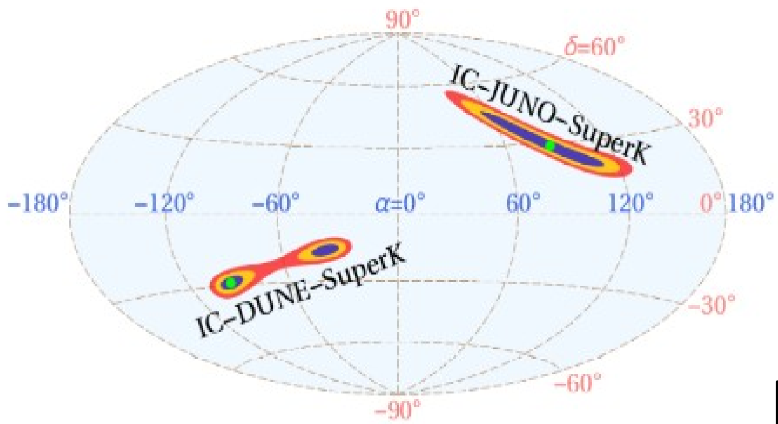
Light-curve
(time profile)



Energy spectrum



Source direction



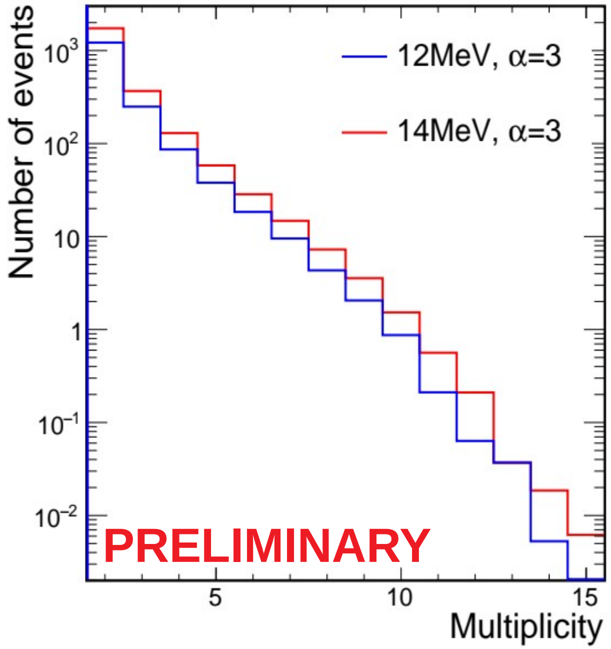
Determining the mean energy of CCSN neutrinos

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

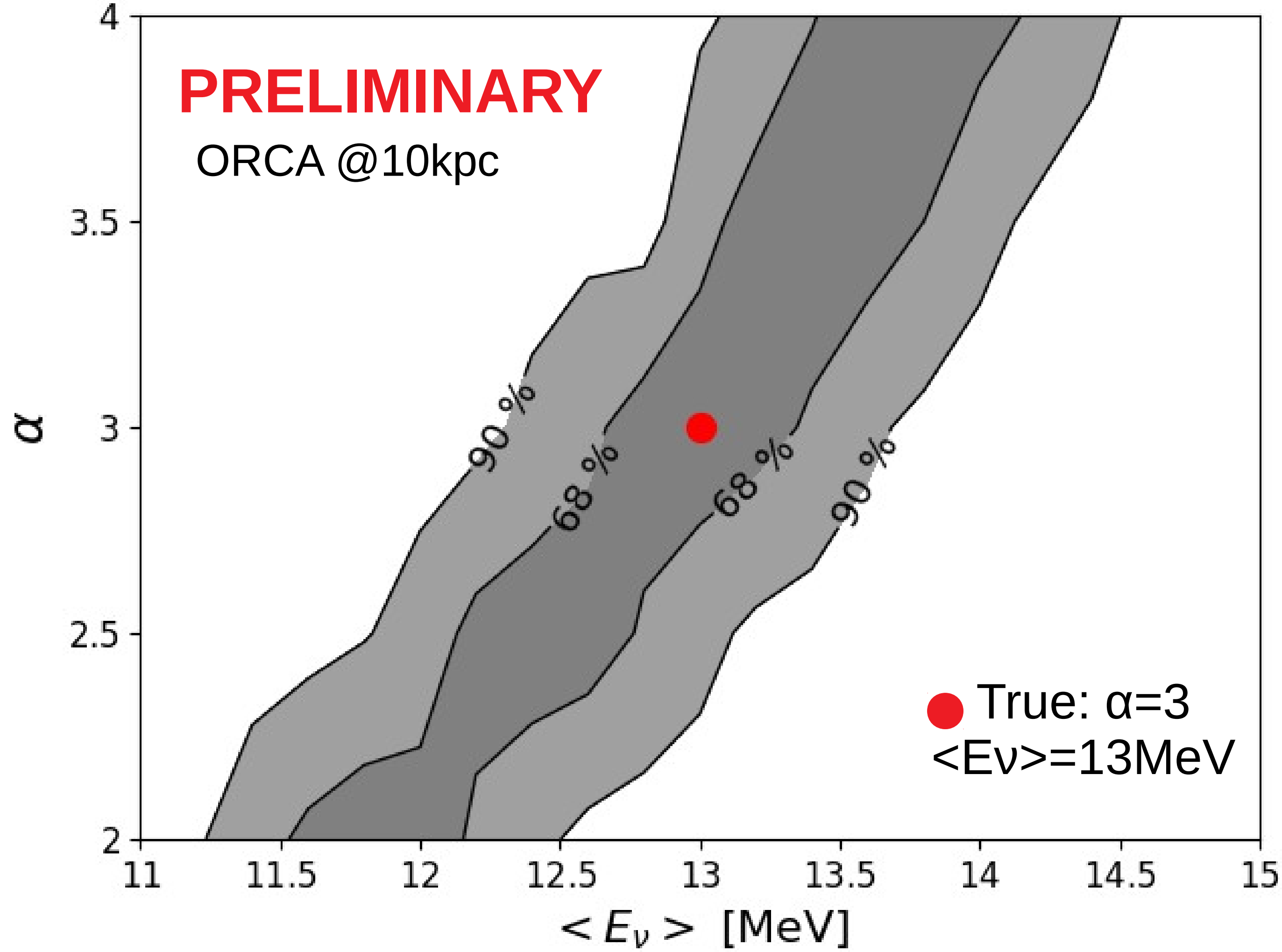
$$f_\nu^{SN} \propto \frac{1}{4\pi d^2} \times \frac{E_\nu^\alpha exp(-(\alpha+1)\frac{E_\nu}{<E_\nu>})}{<E_\nu>}$$

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

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



Constraining the mean energy of CCSN neutrinos: KM3NeT



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

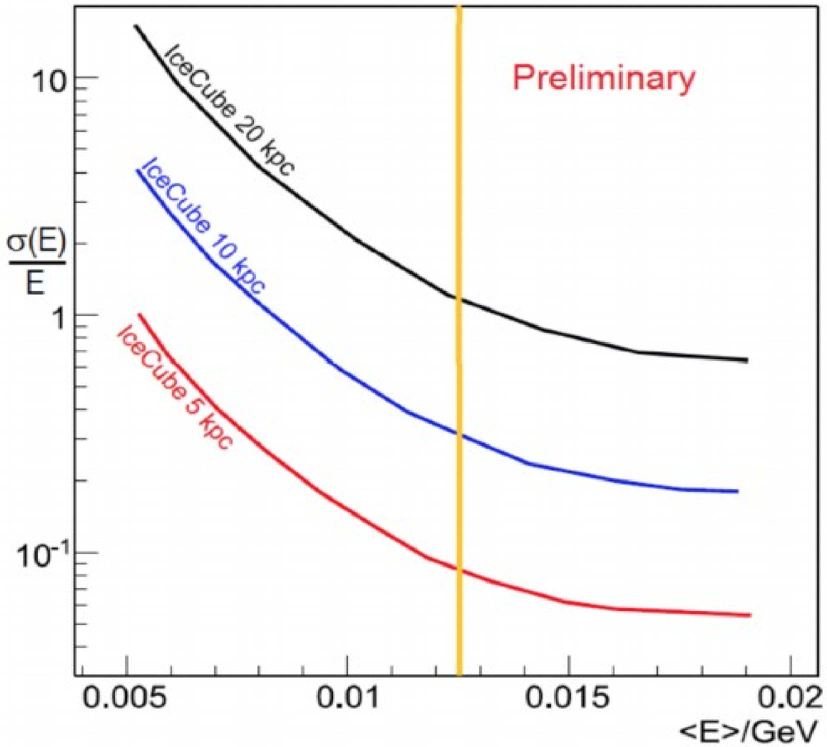
Scan over <Eν> and fixed α plane yields: σ(Eν)/<Eν> ~ 2-3%

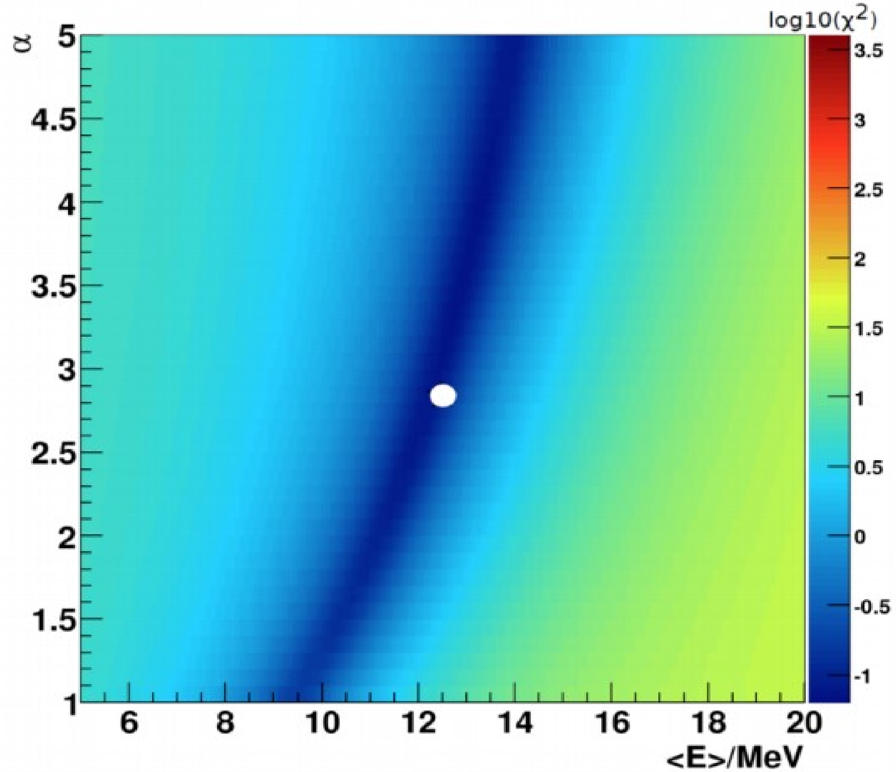
(Conservative ν flux, close to 11Msun values)

Constraining the mean energy of CCSN neutrinos: IceCube

- Coincident hit distributions depend on shape of energy spectrum. Use χ^2 method to produce 2D constraints in $\langle E_\nu \rangle$ and pinch parameter α.
- Assumes 8.8 $M_\odot$ O-Ne-Mg core collapse. Energy resolution is ~30%.

Lutz Köpke, 8th Int. Symp. on Large TPCs (Dec. 2017)





What to learn on CCSN neutrinos?

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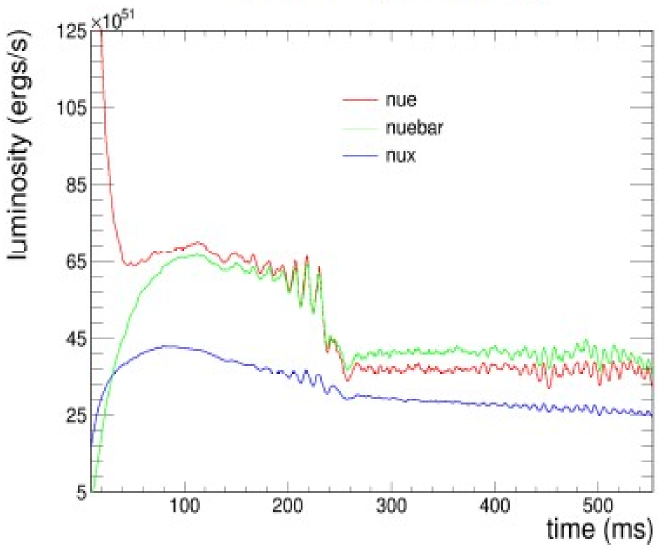
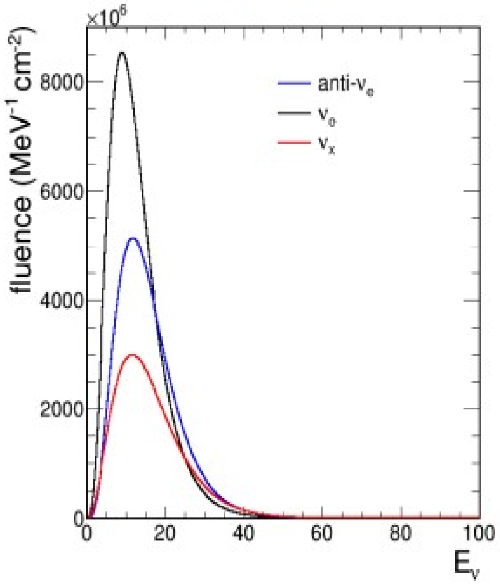
- Double coincidences for time information: high statistics (large detector)

Constrain the models!

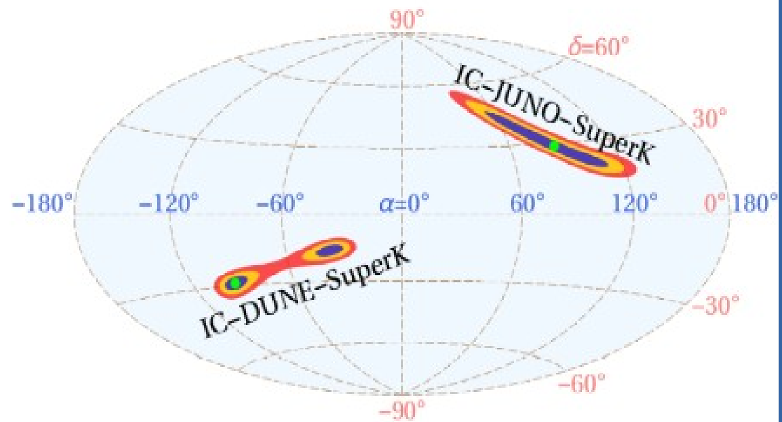
Light-curve
(time profile)



Energy spectrum



Source direction

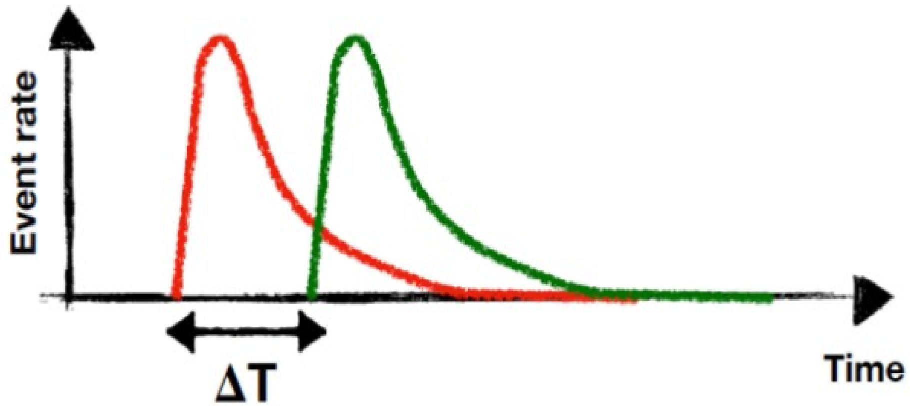


Determination of the neutrino arrival at the different detectors

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
- NOTE: Only detectors sensitive to the same channel and with enough signal statistics can be combined

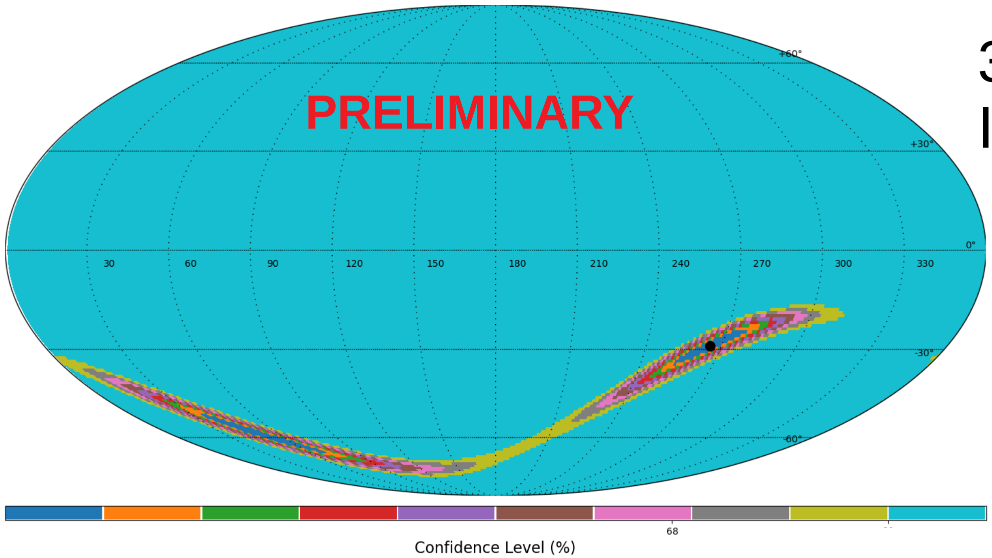


How?

- Chi2: fit time delay between signal in two light-curves
- Normalized cross-correlation

Pointing to CCSN with neutrinos:

→ Good time resolution needed for good localization performance!

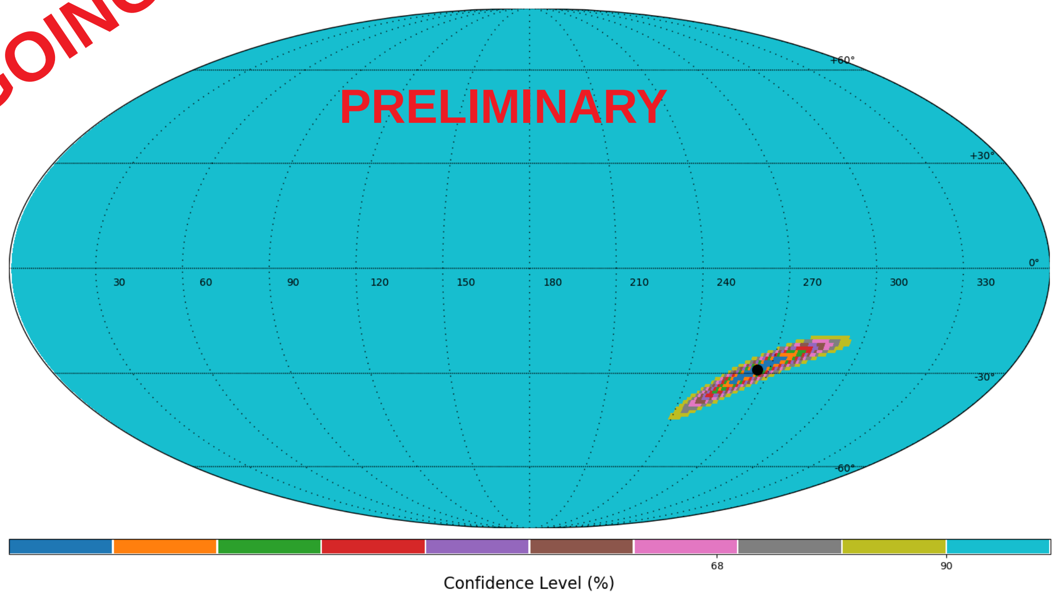


3 detectors:
IC-SK-KM3NeT

(and several detectors taking data!)

ONGOING WORK...

4 detectors:
IC-SK-KM3NeT-JUNO

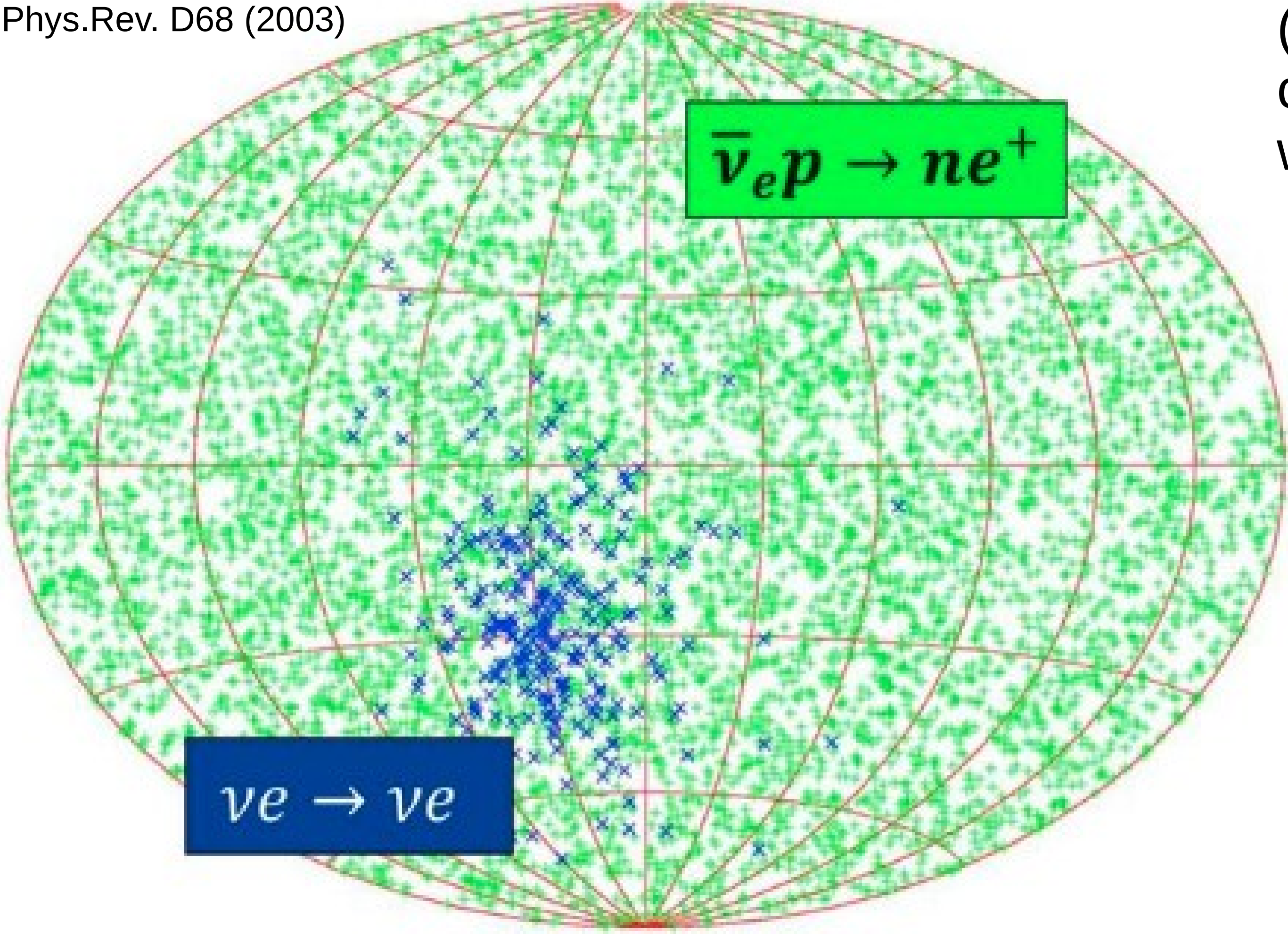


Assumptions:

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

Pointing to CCSN with neutrinos: Super-K

R.Thomas; Super-K
Phys.Rev. D68 (2003)

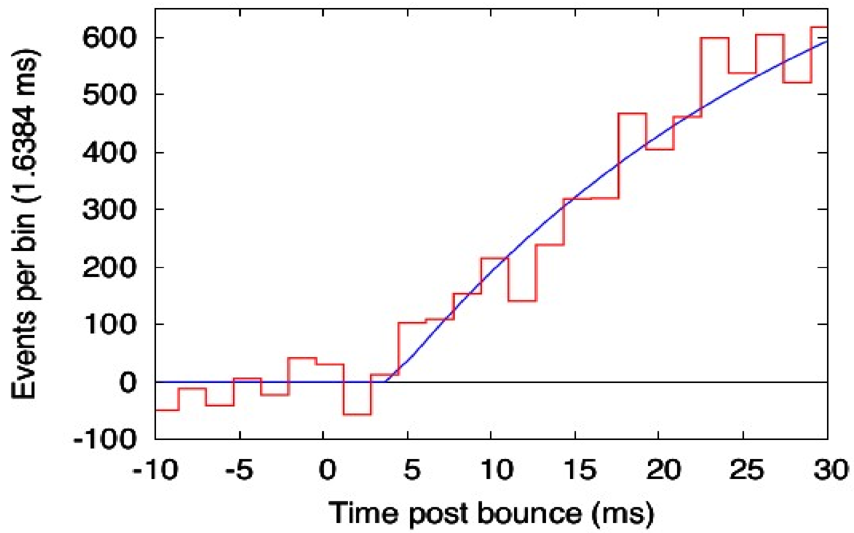


(At the moment, they cannot do precise pointing with fast enough delay)

Neutron tagging efficiency		
None	90 %	
7.8°	3.2°	SK
1.4°	0.6°	SK × 30
95% CL half-cone opening angle		

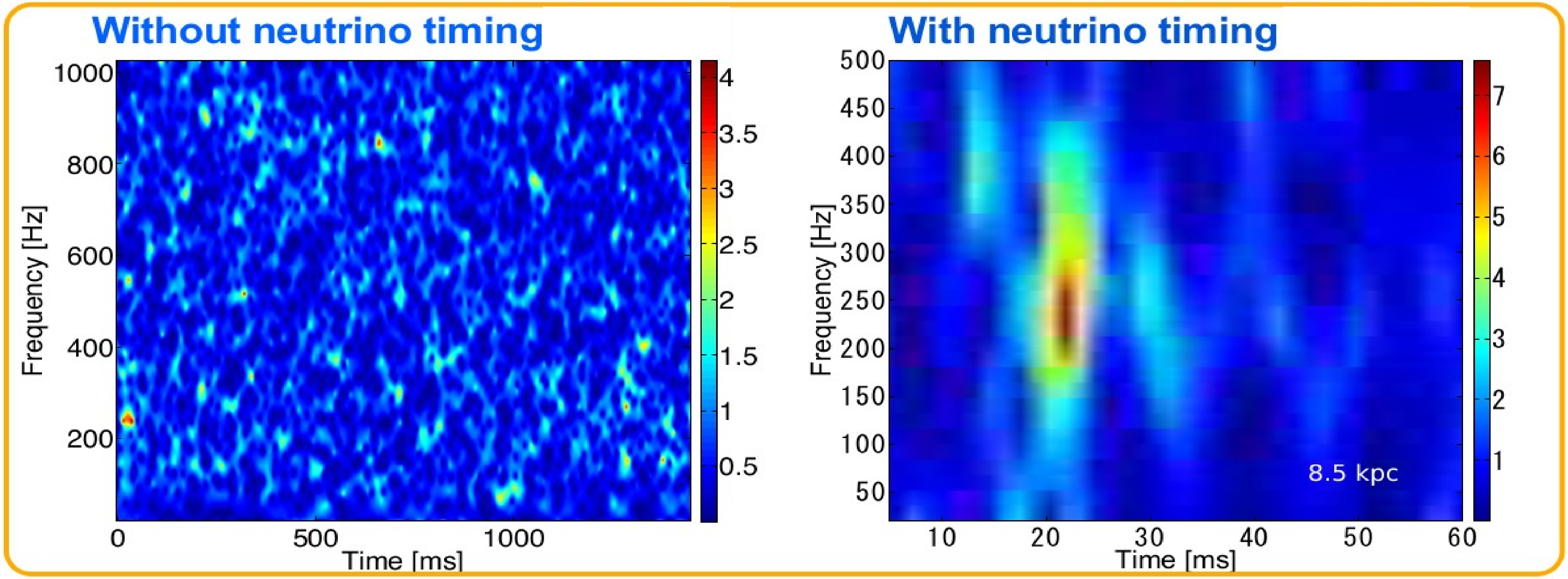
→ Identify elastic scattering interaction for directional information!

SN neutrino timing and GW identification



Probe core bounce time with neutrinos.

Timing for gravitational wave detection.



Pagliaroli et al., PRL (2009), Halzen & Raffelt PRD (2009). Nakamura et al., MNRAS (2016)

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
- Looking forward for the results with ORCA6+ARCA2 beginning of next year!