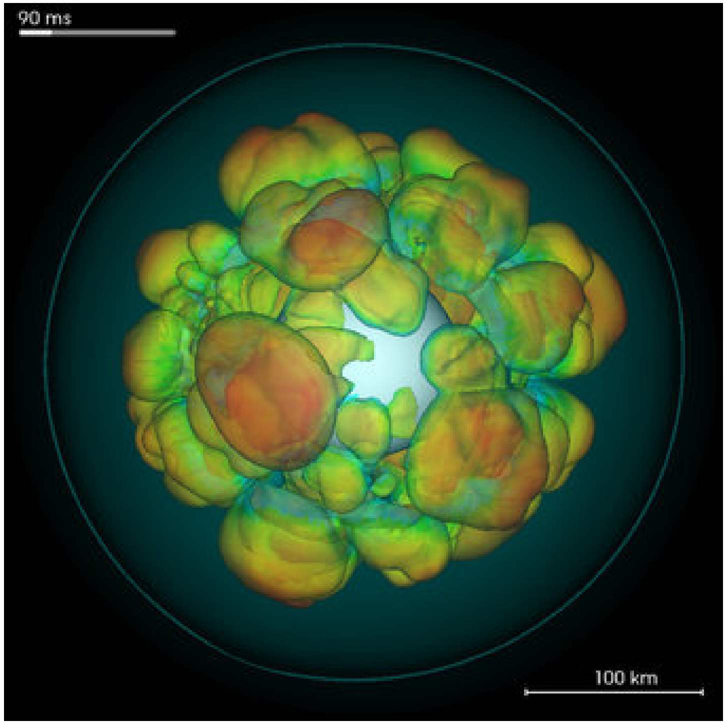
Detection of Core-Collapse Supernova neutrinos in DS20K and ARGO

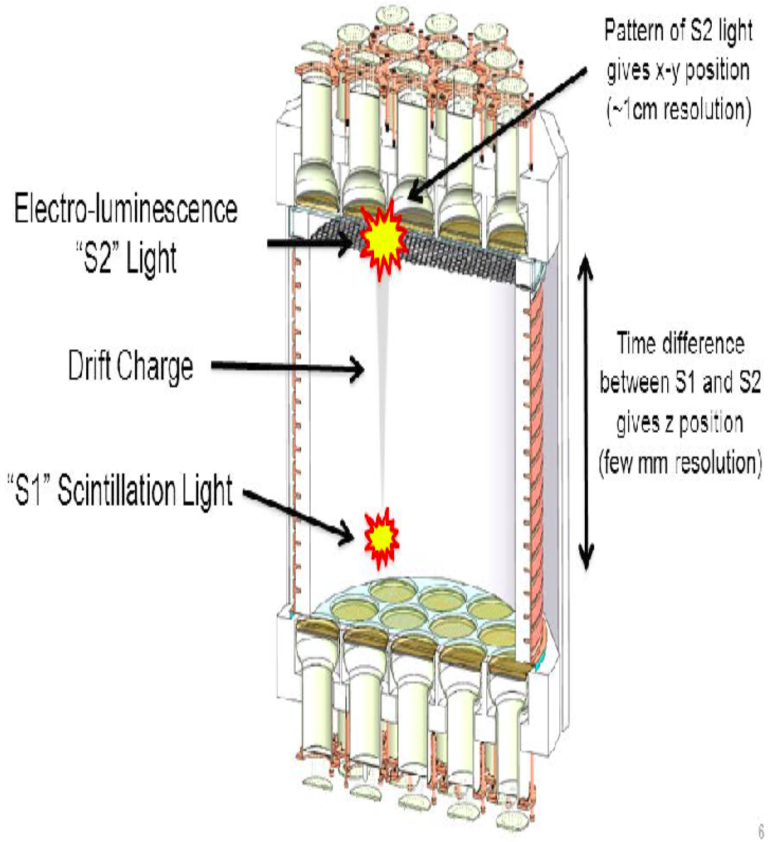


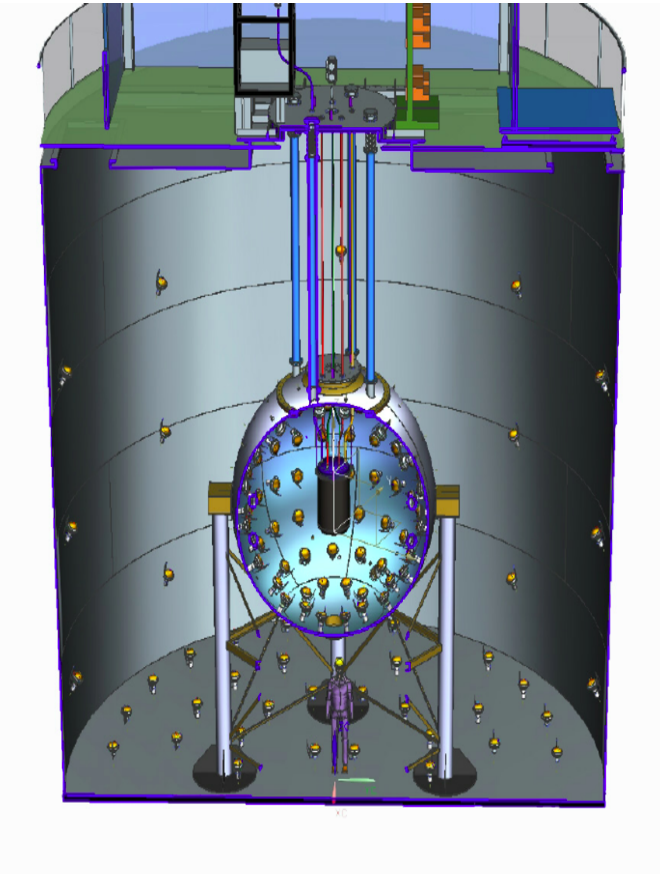
P. Agnes, W. Bonivento, D. Franco,
M. Lai, A. Renshaw, Z.Ye

On behalf of DarkSide Collaboration

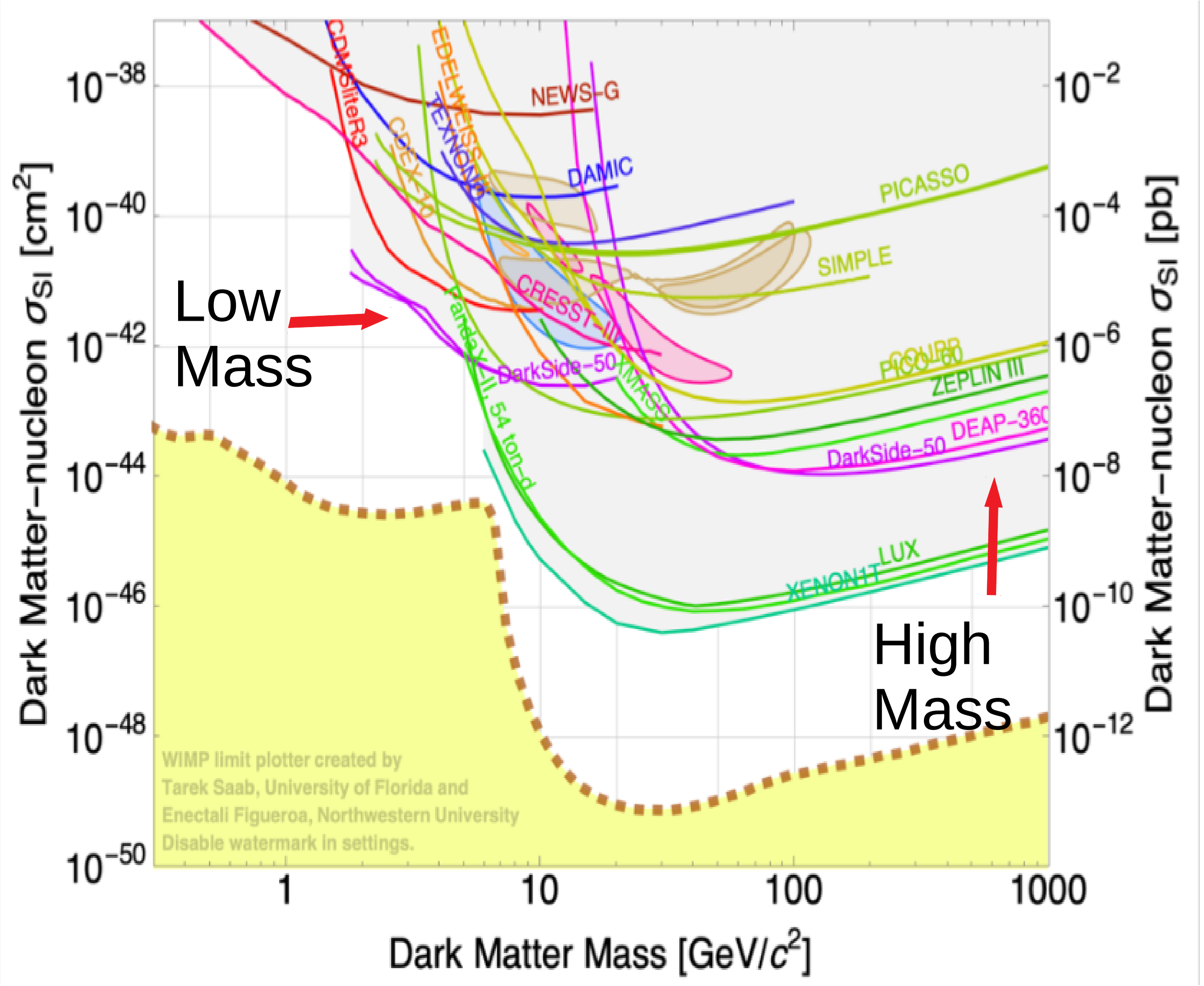
DarkSide: Direct Dark Matter Detection in Liquid Argon

Looks at the light from WIMPs (Weakly Interacting Massive Particles) interactions with Liquid Argon nucleus.





WIMPs exclusion limits



Best exclusion limit with DS50 in the **low mass region**

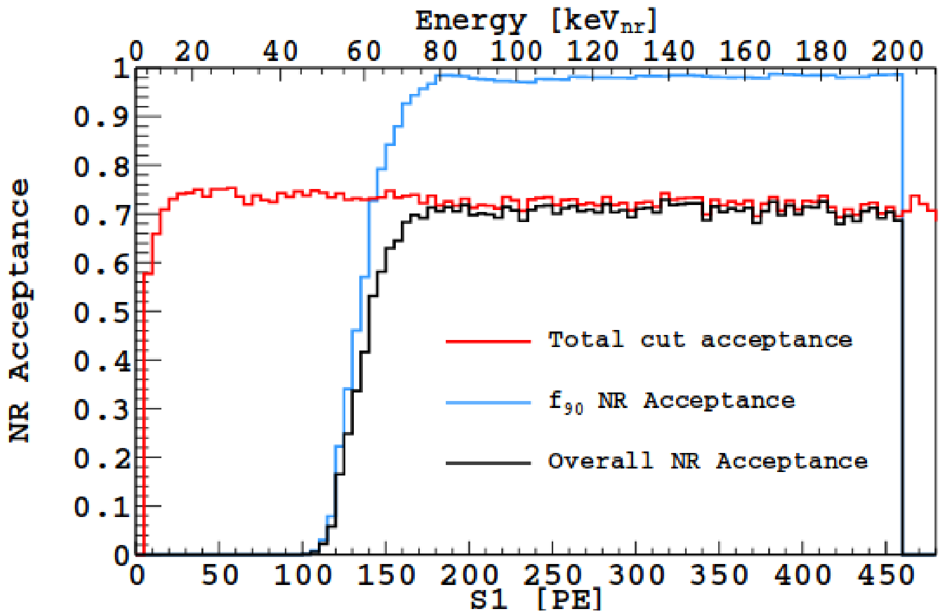
High Mass WIMPs

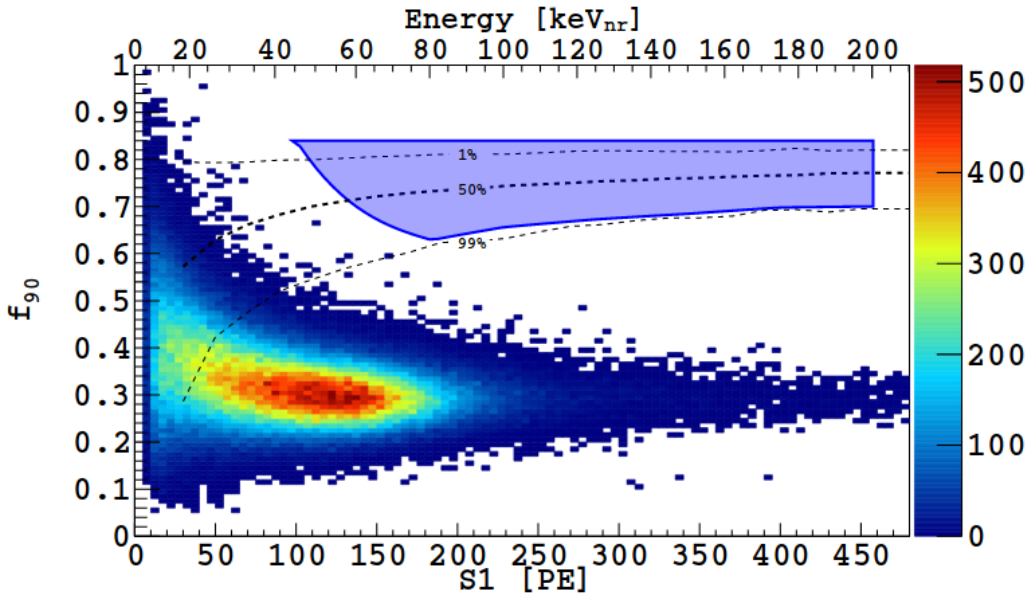
$$M_{WIMP} > 20\,GeV/c^2$$

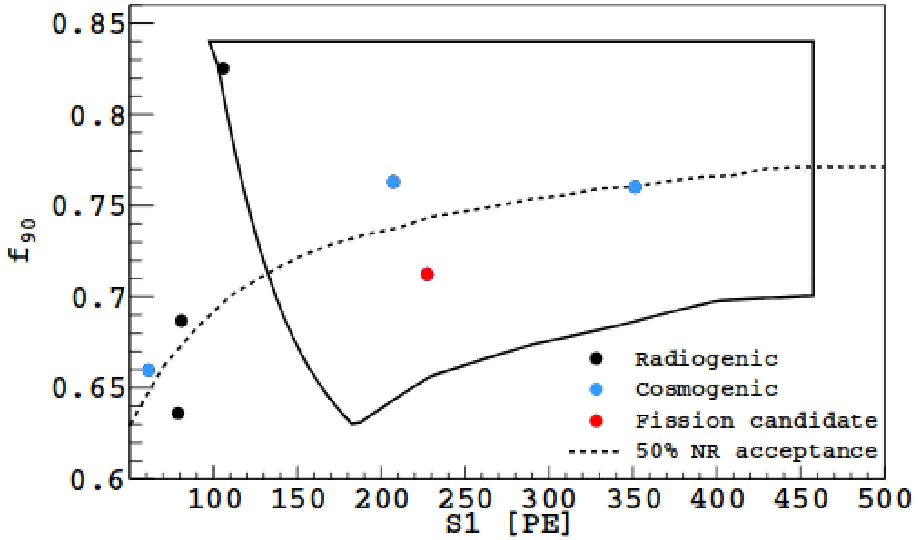
$$E_{REC} \in \left(45\,keV_{NR} - 200\,keV_{NR}\right)$$

Background free analysis (< 0.1 events)

Excellent Pulse Shape Discrimination







https://arxiv.org/pdf/1802.07198.pdf

Low mass analysis

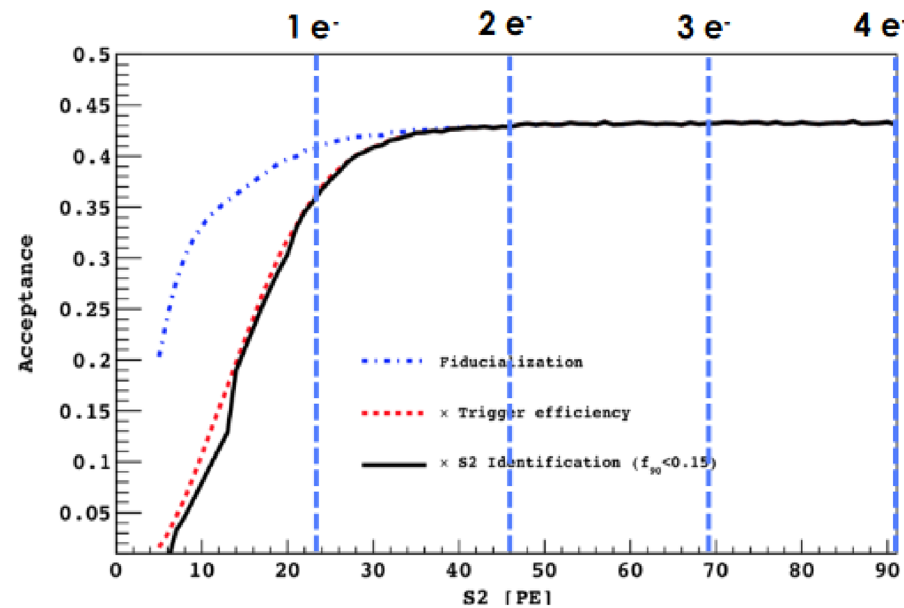
$$M_{WIMP} \in \left(1.8\, GeV/c^2, 20\, GeV/c^2\right)$$

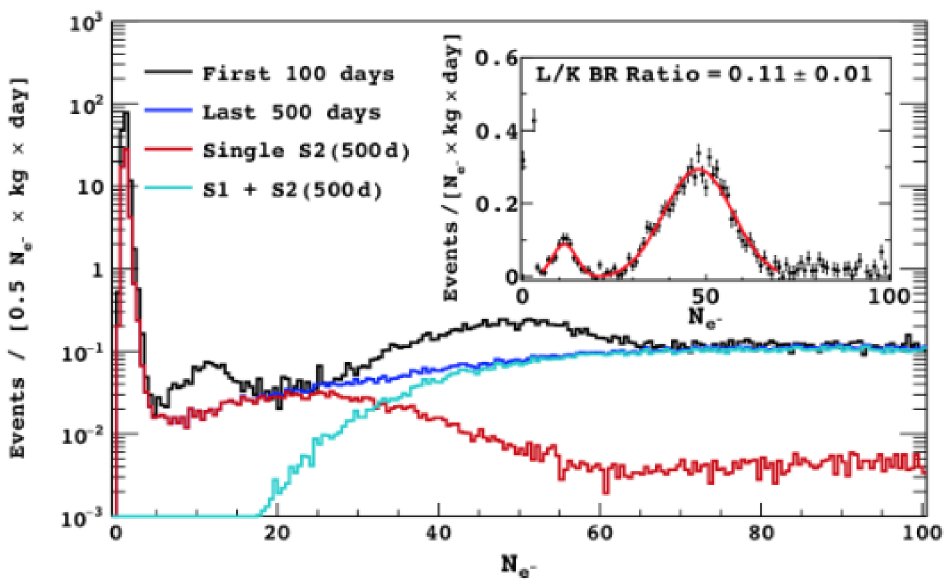
$$E_{REC} \in \left(0.6\, keV_{NR}, 15\, keV_{NR}\right)$$

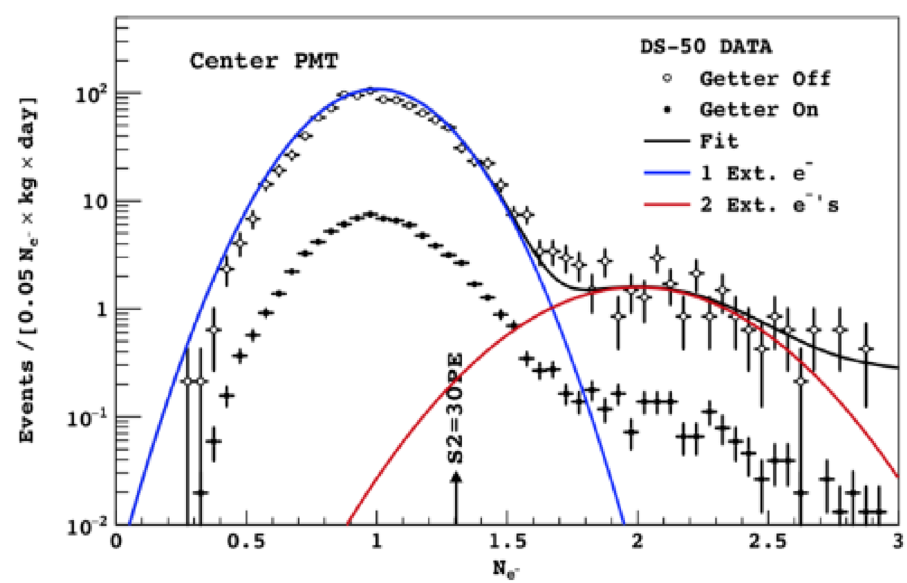
Very **low background**, almost all known

Calibration of S2-only response for both electron recoils and nuclear recoils

Calibration of the **ionization yield** down to 0.6 keV_{NR}



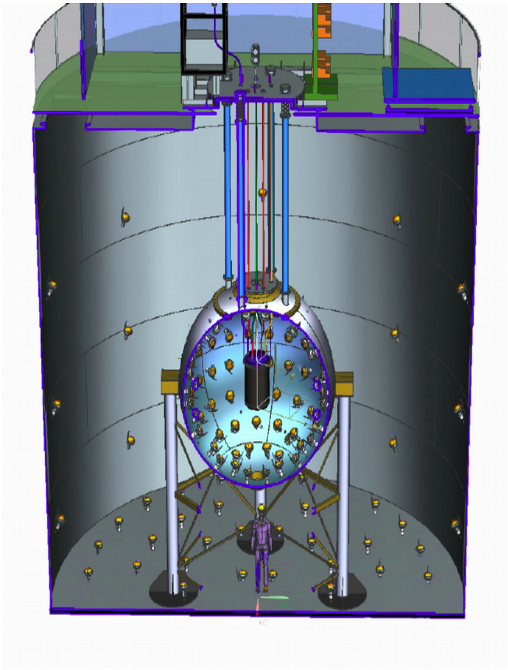




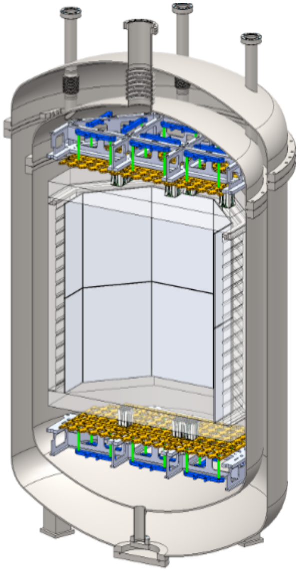
https://arxiv.org/pdf/1802.06994.pdf

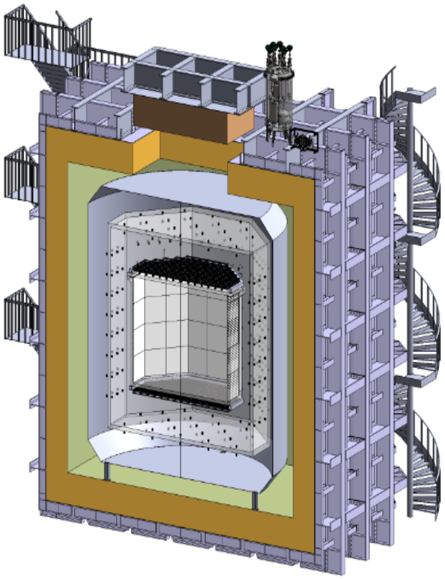
DarkSide project

A Multi-Stage Experiment: three upcoming detectors



Proto-0





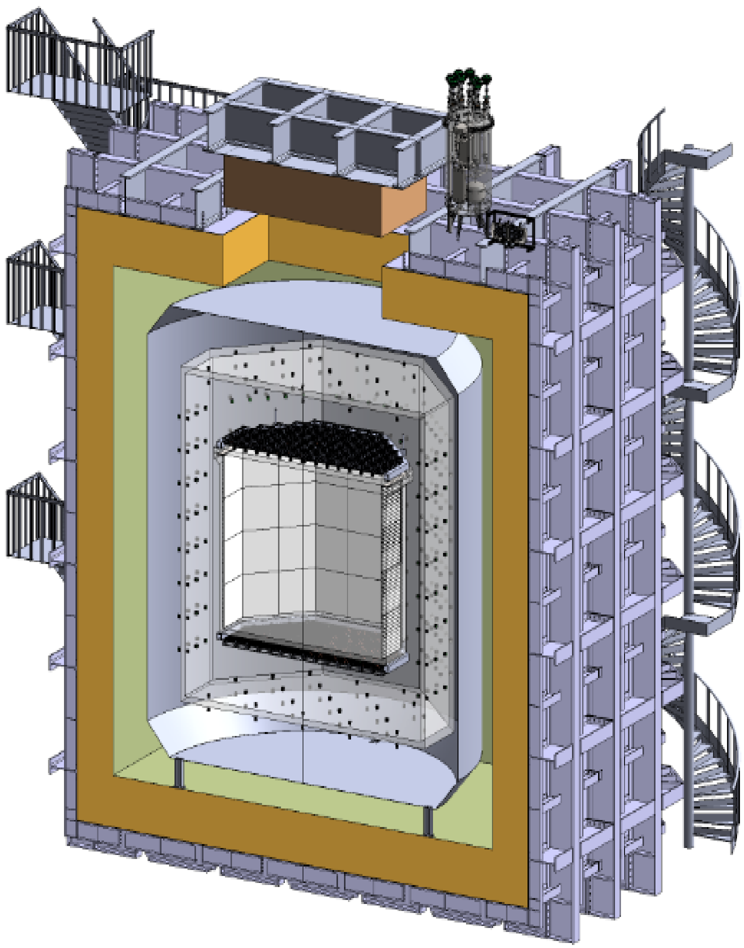
ARGO (300 ton)

DS50 (50kg)

DS-Low Mass (1 ton)

DS20K (38.6 ton)

From DS50 to DS20K and ARGO

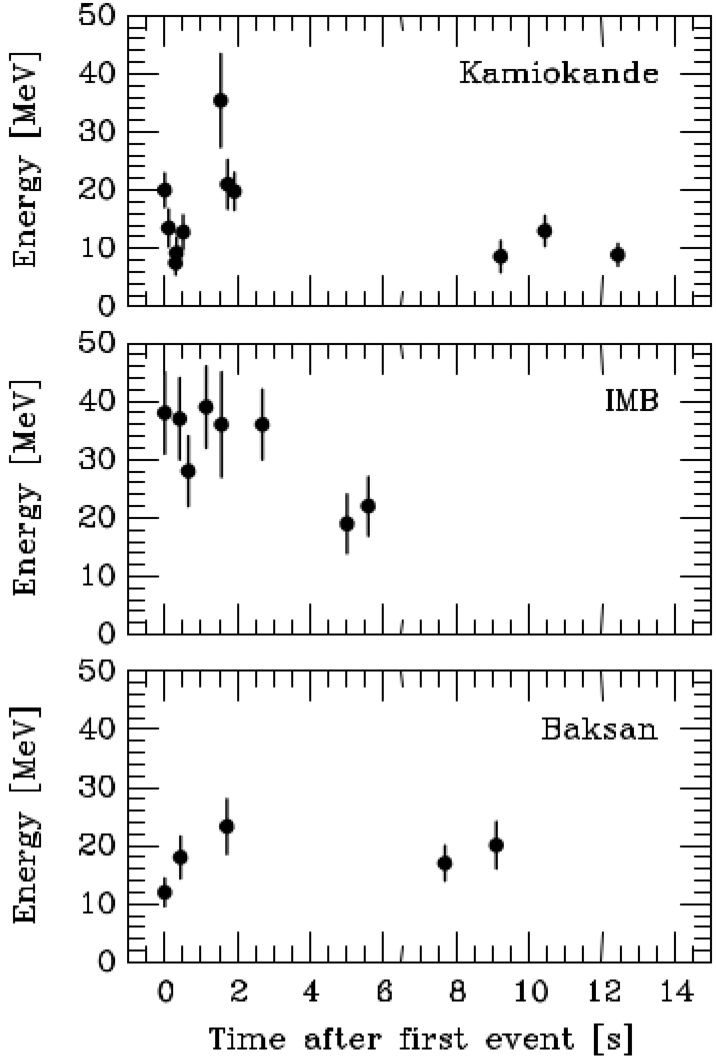


DS20K design:
-TPC filled with **38.6 ton of UAr**
-Outer active veto of AAr (300 ton), with a layer of acrylic loaded with Gadolinium
-Plastic panels in a stainless steel array
-Set 3.800 m.w.e, in Hall C of LNGS.
-Read out via ~8000 SiPMs

ARGO design :
-TPC filled with **300 ton of UAr**
-Same shields of DS20K
-Set 6,000 m.w.e., at SNOLab

Why should we use our dark matter detectors for core-collapse Supernova neutrinos?

Core-collapse Supernova: what we know



Explosion mechanism of Type II Supernova

Colgate and White, 1966:
99% of the SN energy released via neutrinos

Confirmed by the observation of SN 1987A,
50 kpc far (LMC)

Galactic rate ~ 2/3 per century

Duration time ~ 10 s

Energy released = 3 x 10^{46} J via:
-Gravitational Waves
-Electromagnetic Waves
-Neutrinos

Average neutrino energy ~ **10 MeV**

What can we learn from Supernova neutrinos

"Neutronization burst" Neutrino emission

Role of neutrinos during the accretion phase

Detection of neutrinos from a core-collapse Supernova

Average neutrinos energy and total energy of the supernova

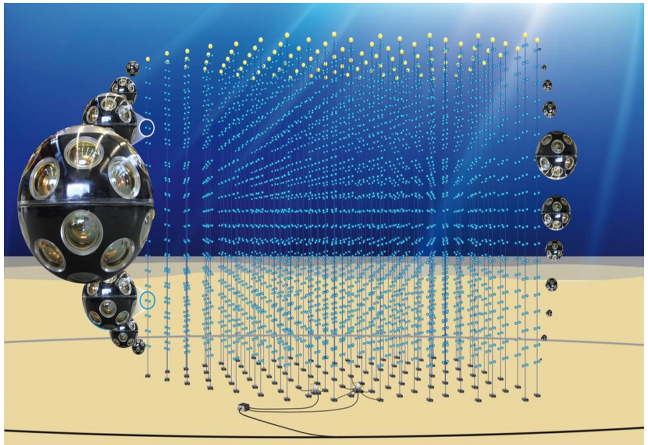
Non-spherical symmetric phenomena (i.e. Convection, SASI, LESA)

Neutrino Mass Hierarchy

Beyond Standard Model physics from cooling phase

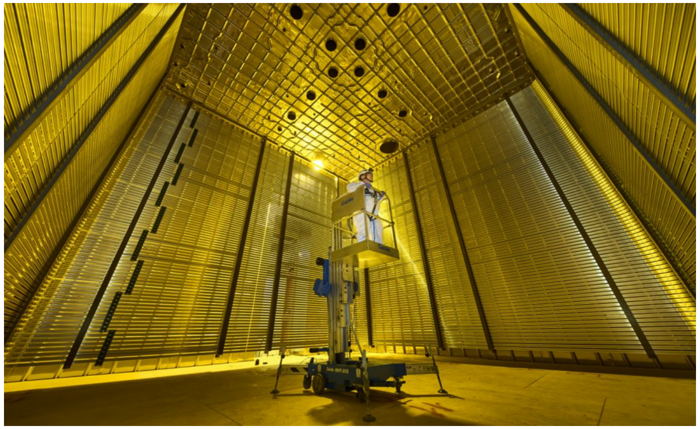
Complementarity with neutrino detectors

KM3NT/ORCA



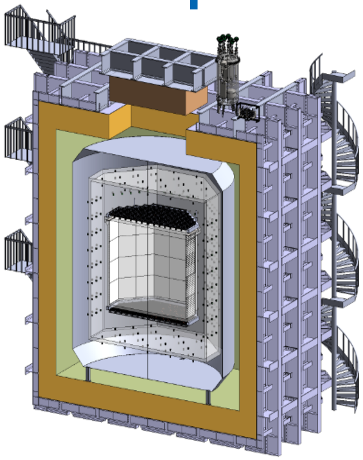
Mainly via Elastic scattering
High time resolution
Low energy resolution

DUNE



Mainly via Charged Current (CC)
Huge target mass
Low time resolution

See Molla -Lincetto at https://www.epj-conferences.org/articles/epjconf/pdf/2019/12/epjconf_vlvnt2018_05007.pdf

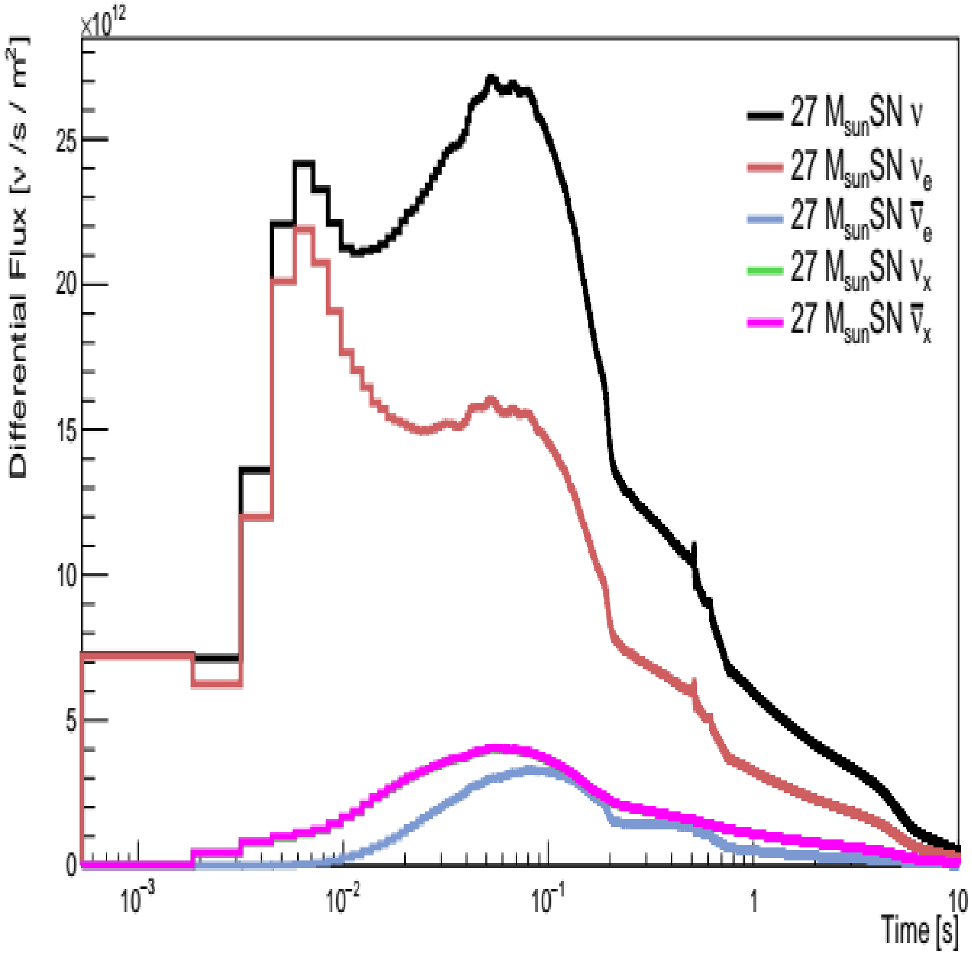


Mainly via CevNS
Low time resolution
High energy resolution

Core collapse supernova model

1D simulation[1] of 11 M_{sun} and 27 M_{sun} progenitor Supernovae, 10 kpc far, EoS LS220K

Assumed Normal Mass Ordering



$$f_0(E_\beta,t)=\frac{L_\beta(t)}{4\pi d^2}\frac{\phi_\beta(E,t)}{\langle E_\beta(t)\rangle}$$

$$\phi_\beta(E,t)=\frac{1}{\langle E_\beta\rangle}\left(\frac{E}{\langle E_\beta\rangle}\right)^\alpha \exp\left[(1+\alpha)\frac{E}{\langle E_\beta\rangle}\right](1+\alpha)^{1+\alpha}\frac{1}{\Gamma(1+\alpha)}$$

Total emitted neutrinos:

7.91 x 10^{15} **ν**/m² from 11 M_{sun}SN

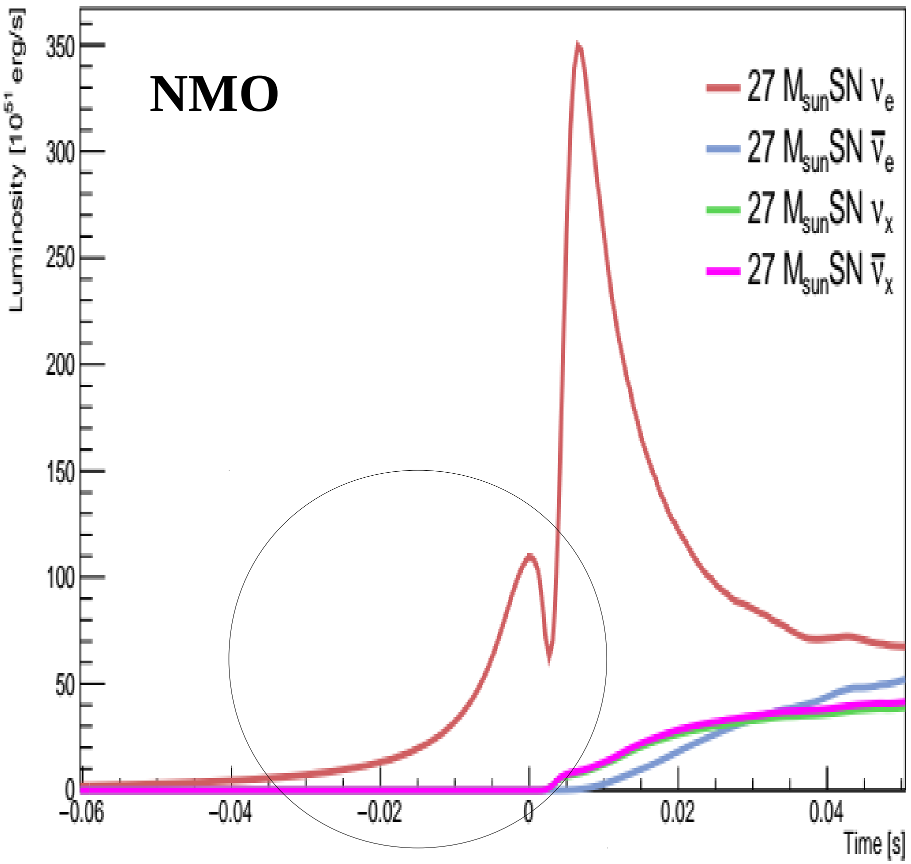
13.71 x 10^{15} ν/m² from 27 M_{sun}SN

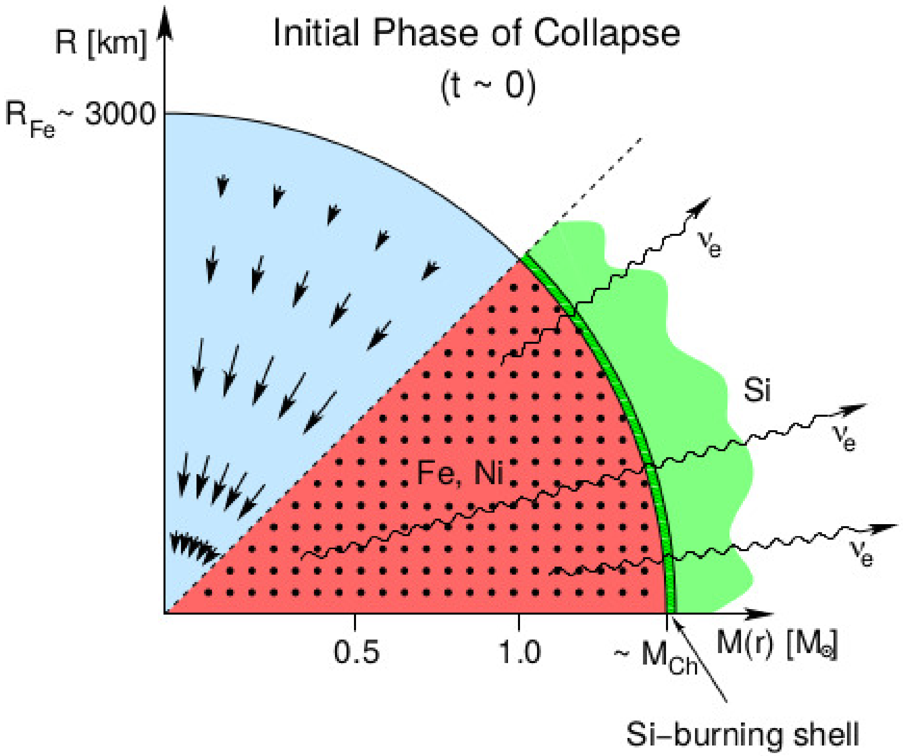
Three phases:

- -Neutronization (~50 ms)
- -Accretion (~1 s)
- -Cooling (~9 s)

[1] special thanks to Prof A. Mirizzi (Garching group)

Onset of the collapse

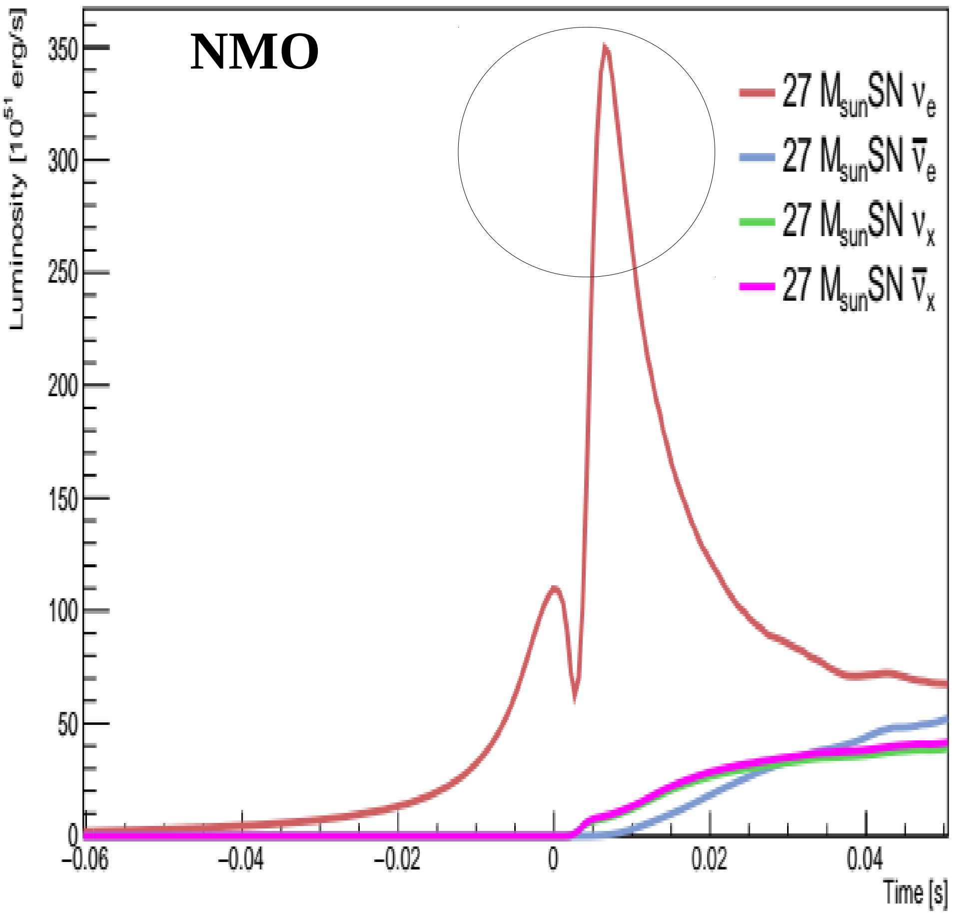


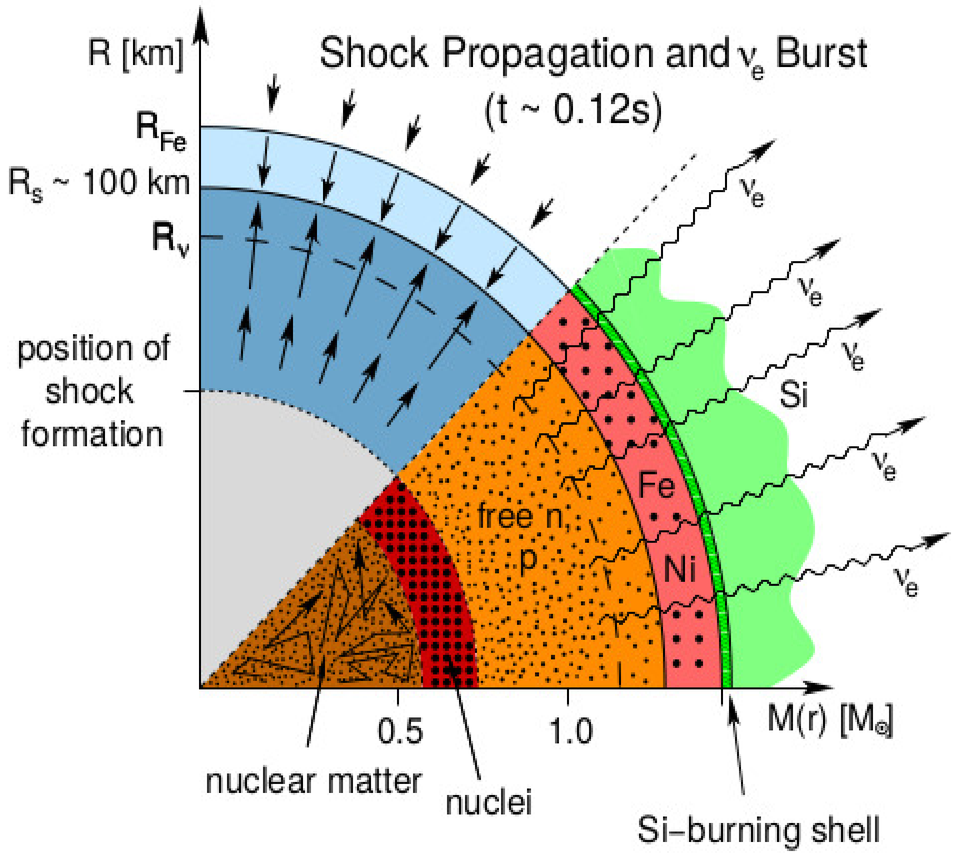


Release of electron neutrinos from the core, until they get trapped, due to the increase of the local density ~ 10^{11} g/cm^3

Neutronization phase

Almost **not depending on the progenitor mass**

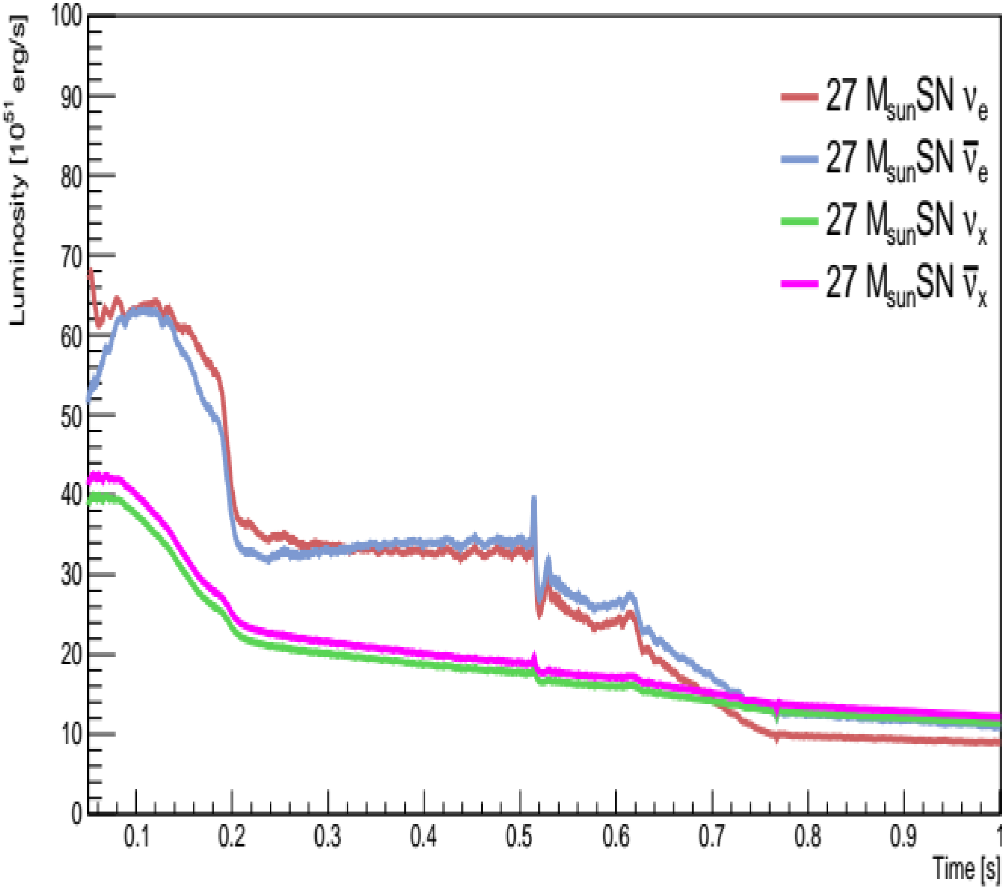


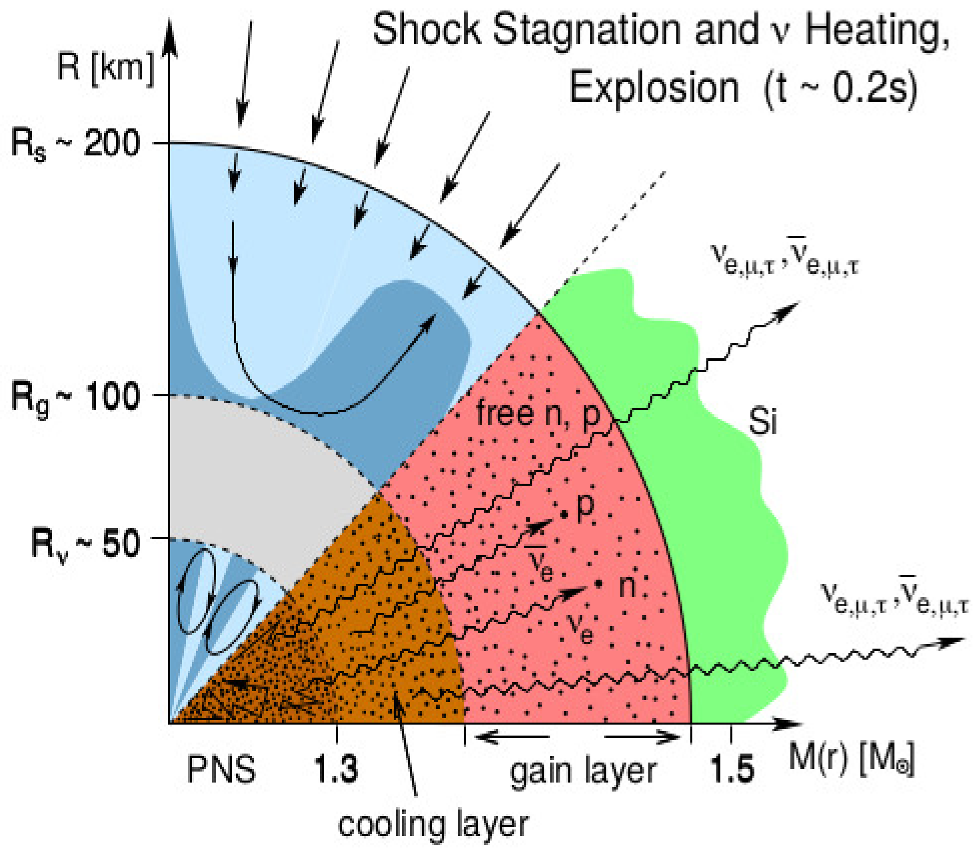


Characteristic peak of electron neutrinos set free by the shock wave

Accretion phase

Supernova explosion **artificially** set at 0.5 s

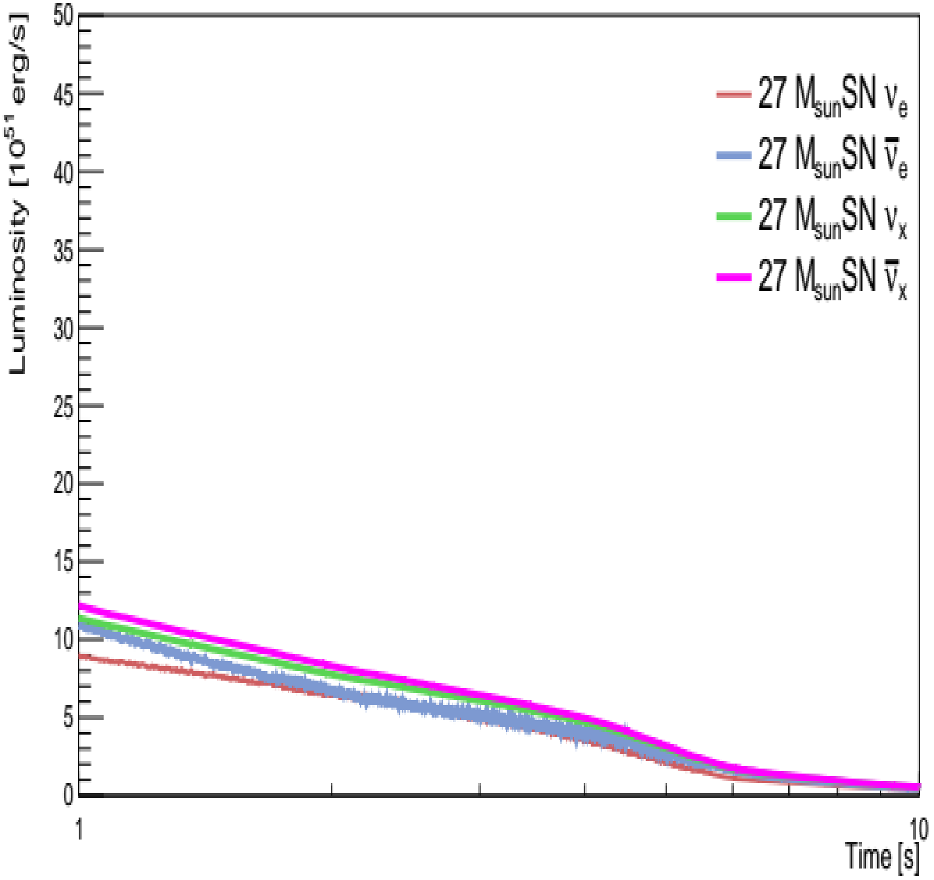


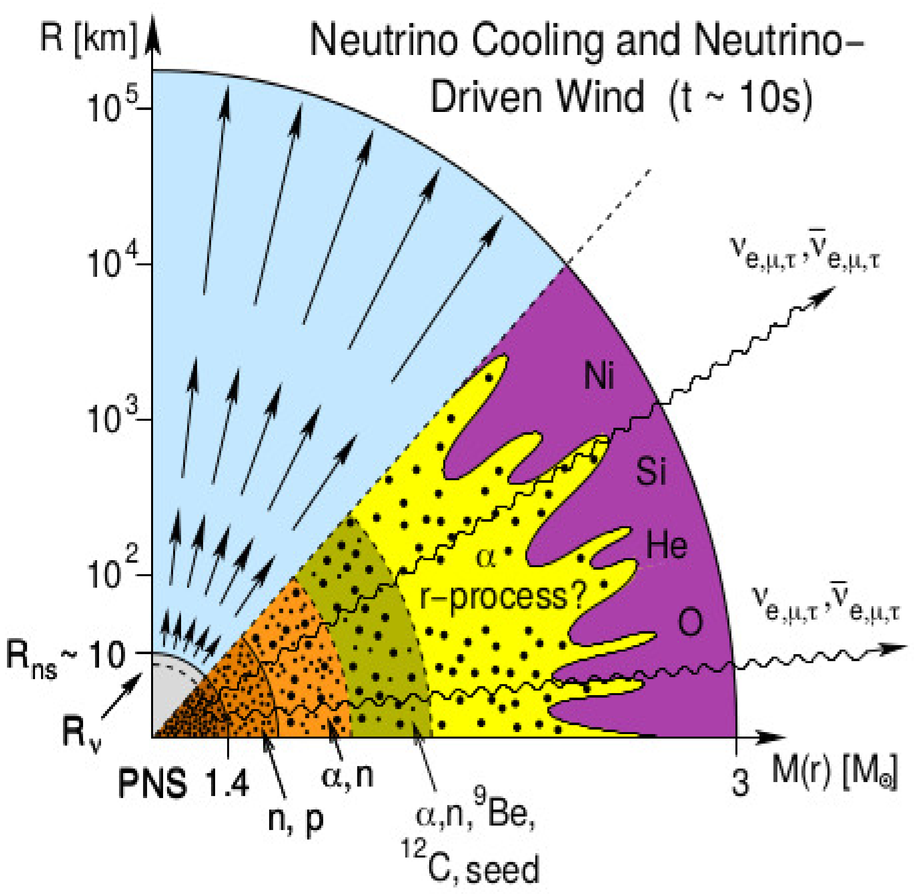


Contribution to the neutrino emission from the accretion disk

Cooling phase

Longest lasting phase, **strongly dependent on the progenitor mass**

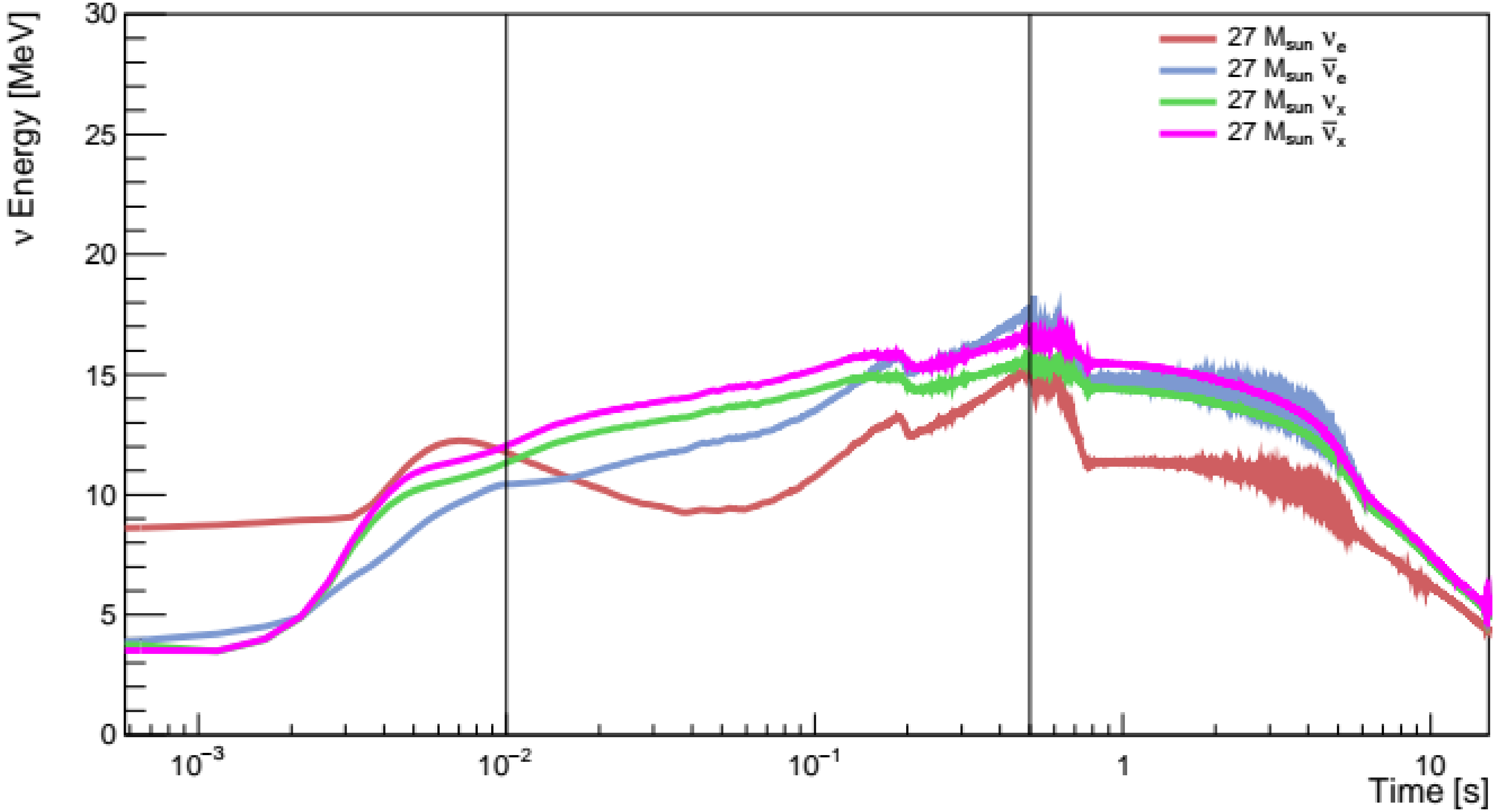




Release of neutrinos of all flavors as the proto-neutron star cools and deleptonizes

Neutrino Average energy

Average neutrino energy $< E > \sim 10$ MeV



How can DS20K and ARGO detect neutrino signal from a core-collapse supernova ?

Coherent Elastic neutrino- nucleus Scattering (CEνNS)

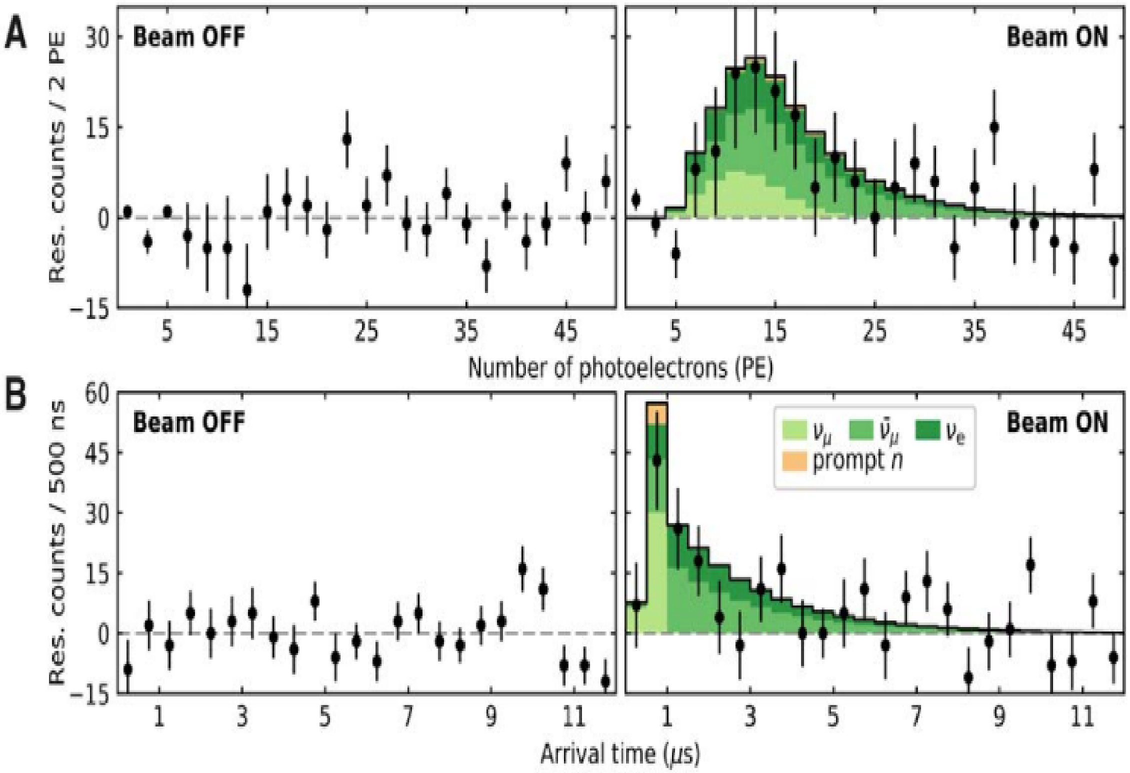
First observation by **COHERENT (2017)**

$$\frac{d\sigma}{dE_R}=\frac{G_F m_N}{4\pi}\left[A-Z\left(1-4\sin^2\theta_W\right)\right]^2\left(1-\frac{m_N E_R}{E_\nu^2}\right)F^2(E_R)$$

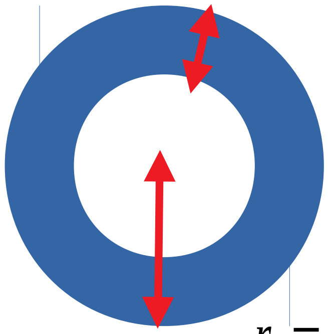
Helm form factor

$$F(E_R)=\frac{3\,j_1(q r_n)}{q r_n}e^{\frac{-q s^2}{2}}$$

$$q=\sqrt{2 m_N E_R}$$



$s=0.9\,fm$ $\quad$ $c=1.23\,A^{1/3}-0.60\,fm$

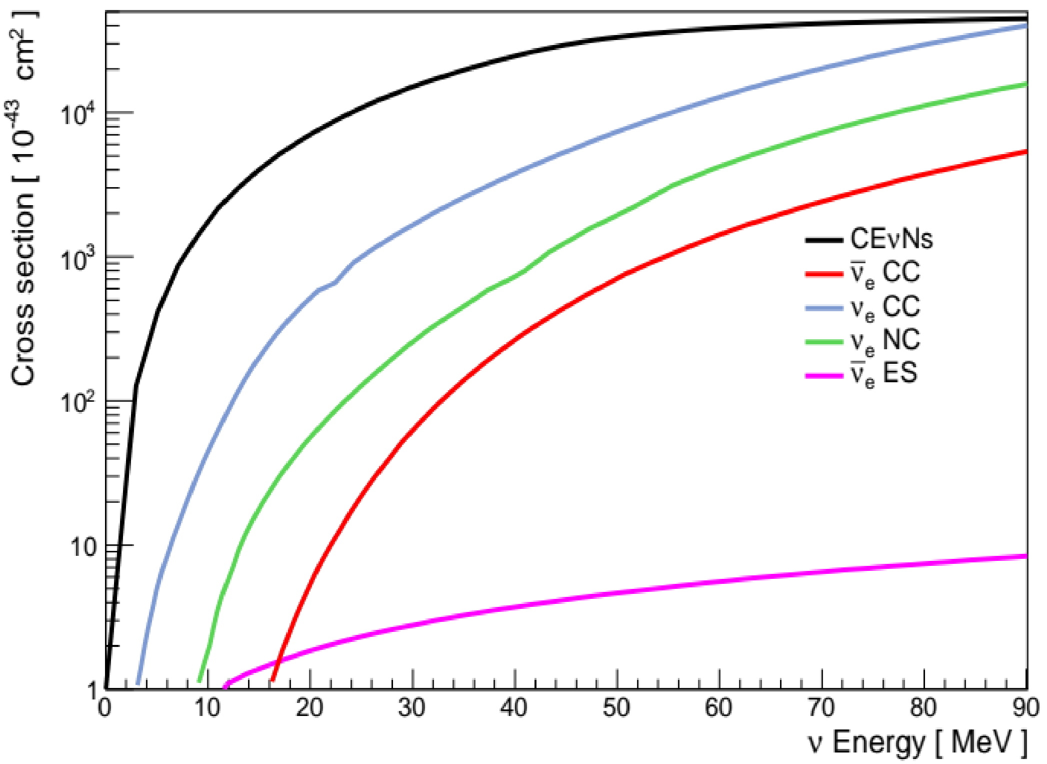


$a=0.52\,fm$

$$r_n=\sqrt{c^2+\frac{7}{3}\pi^2 a^2-5 s^2}$$

Detecting core-collapse supernova neutrinos

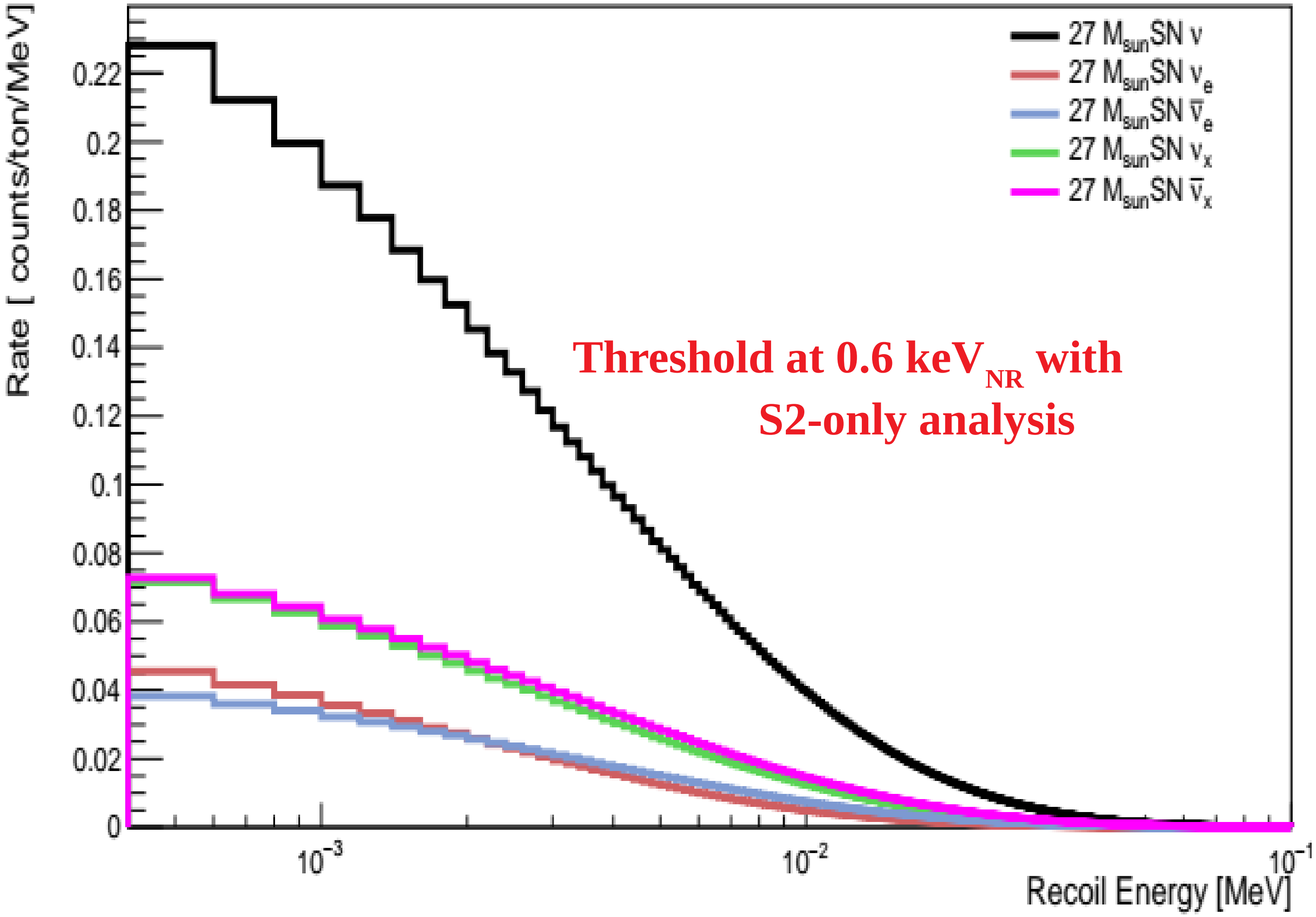
Experiment	Mass [ton]	ν flavor	CS	# events 27 M_{sun}
DS20K	38.6	All	CEνNS	~300
ARGO	300	All	CEνNS	~2000
DUNE	~4 x 10^4	$\bar{\nu}_e$	Mostly CC	~3000
HK	~4 x 10^5	ν_e	Mostly CC	~50000



CEνNS cross section:
- Low threshold
- Flavor insensitive

The Cross section compensates for the small target mass

SN Signal in a Liquid Argon TPC



Toy MonteCarlo pseudo-experiment

1) Event generation:
- SN signal: recoil energy and time dependence for each ν flavor
- Background: recoil energy and time dependence

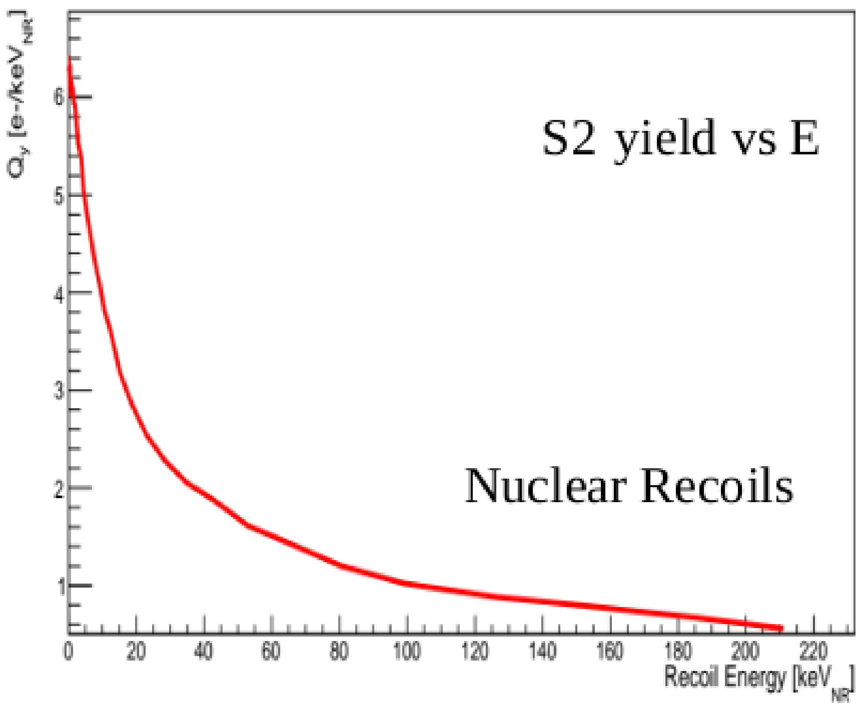
2) Detector effects:
- S2 yield: converting ER and NR in number of electrons
- Drift time, in agreement with the detector drift length,
  DS20k: 2.6 m
  ARGO: 3.5 m

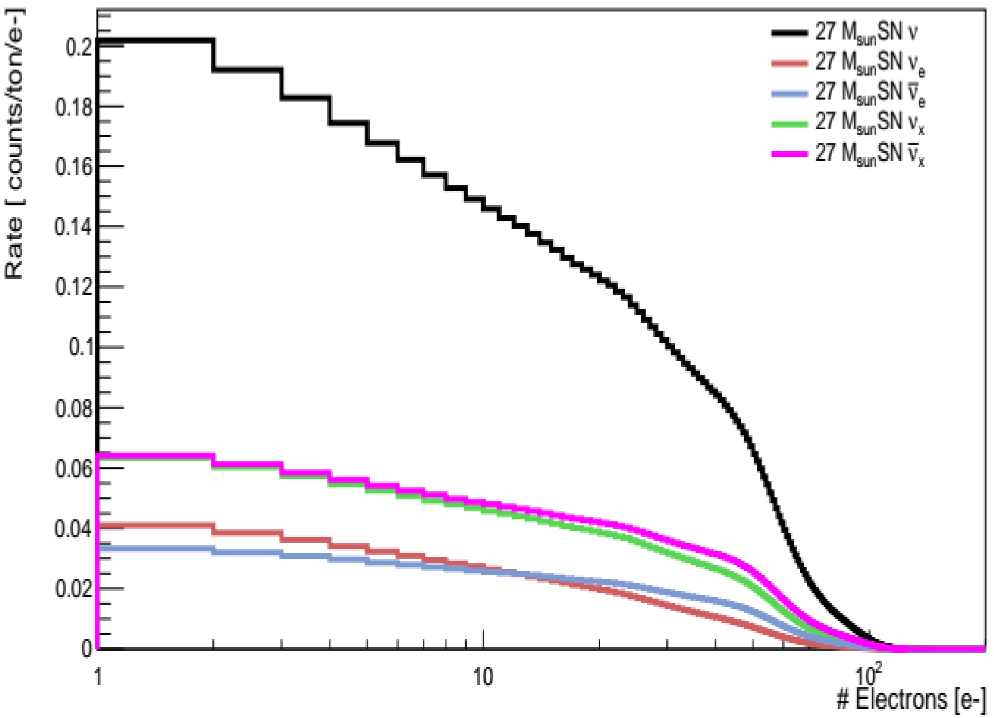
3) Pseudo-experiments based on Poisson statistics

4) Analysis on each pseudo-experiment

5) Iteration on ~5000 pseudo-experiments

S2 only response

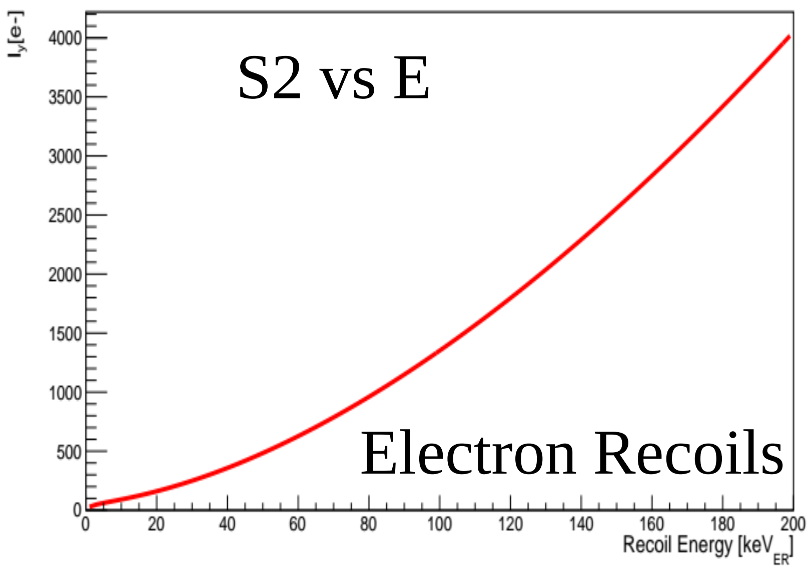




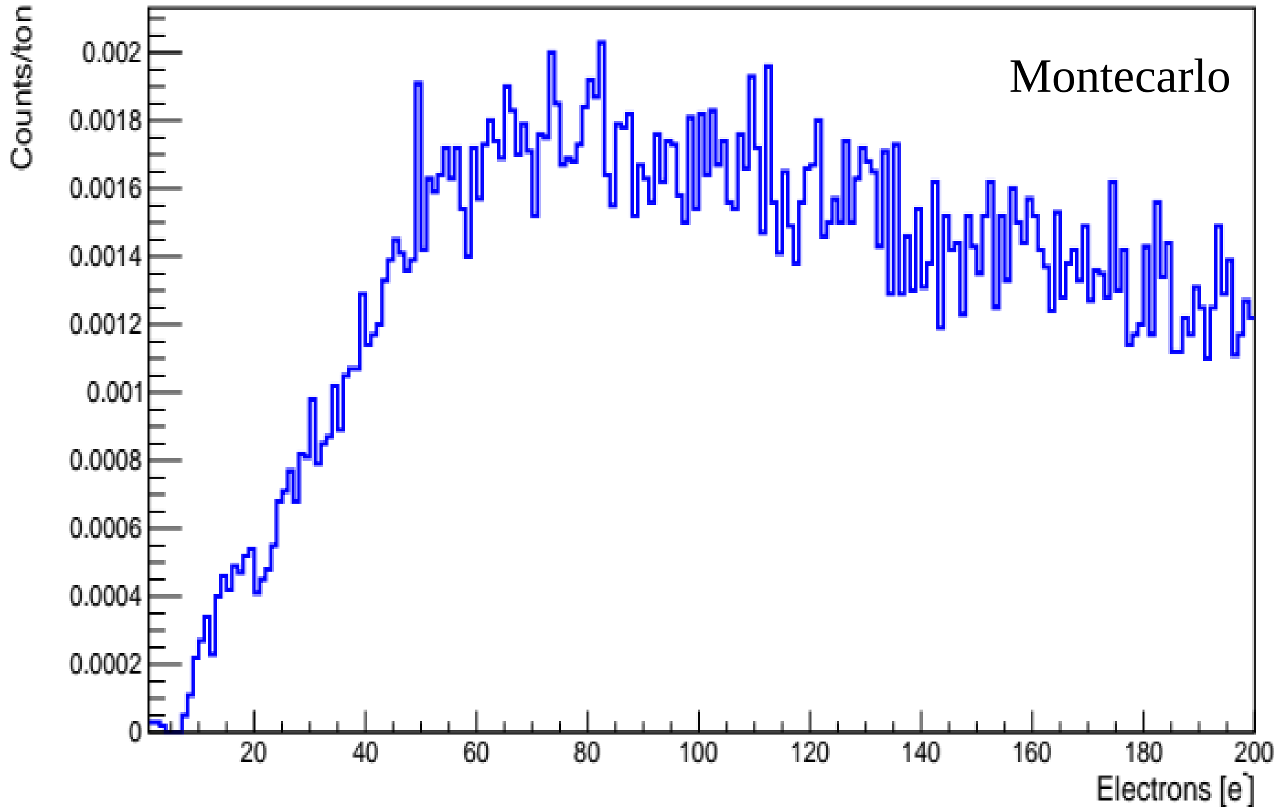
Energy recoil → # ionization electrons

Expected backgrounds

Source	Rate	Rejection
Cryostat α /γ	0 (assumed negligible, work in progress)	Fiducialization in xy and multiple scatter
^{39}Ar	0.7 mBq/kg	Constrained before and after the SN
Single electron	Measured from DS50 and scaled up by the volume	Constrained before and after the SN

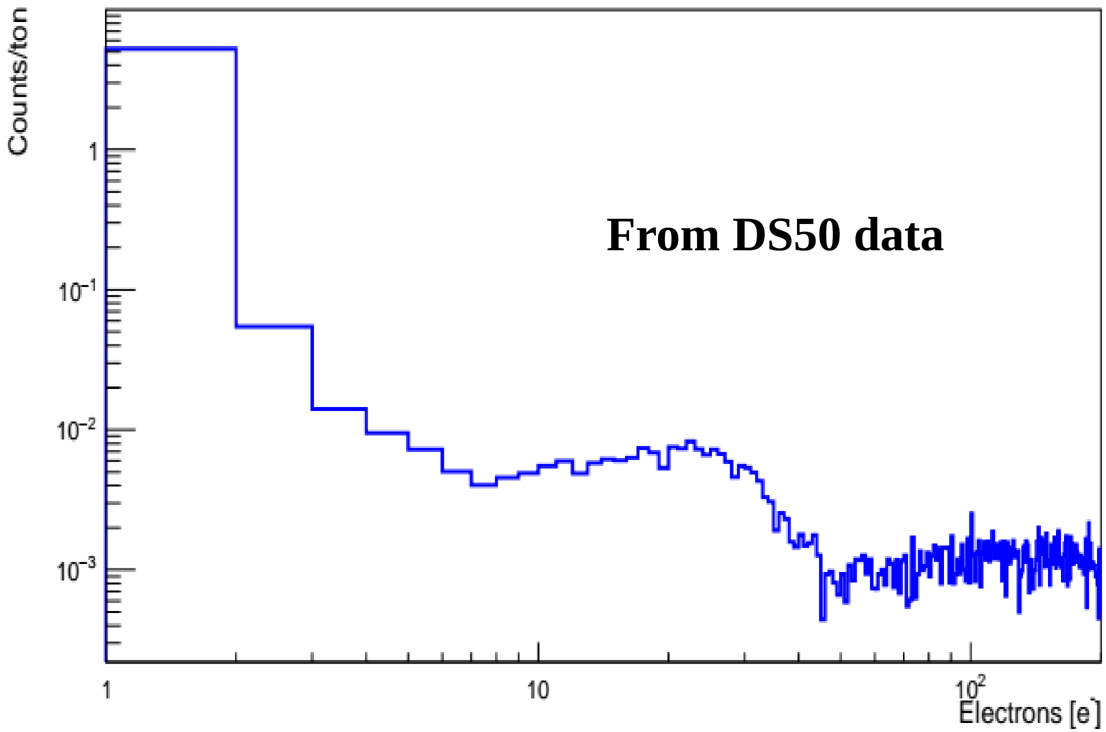


39 Argon



Experiment	Mass[ton]	^{39}Ar events in $\Delta t = 10$ s	ν events 11 M_{sun} SN	ν events 27 M_{sun} SN
DS20K	38.6	20	150	270
ARGO	300	100	1200	2110

Impurities

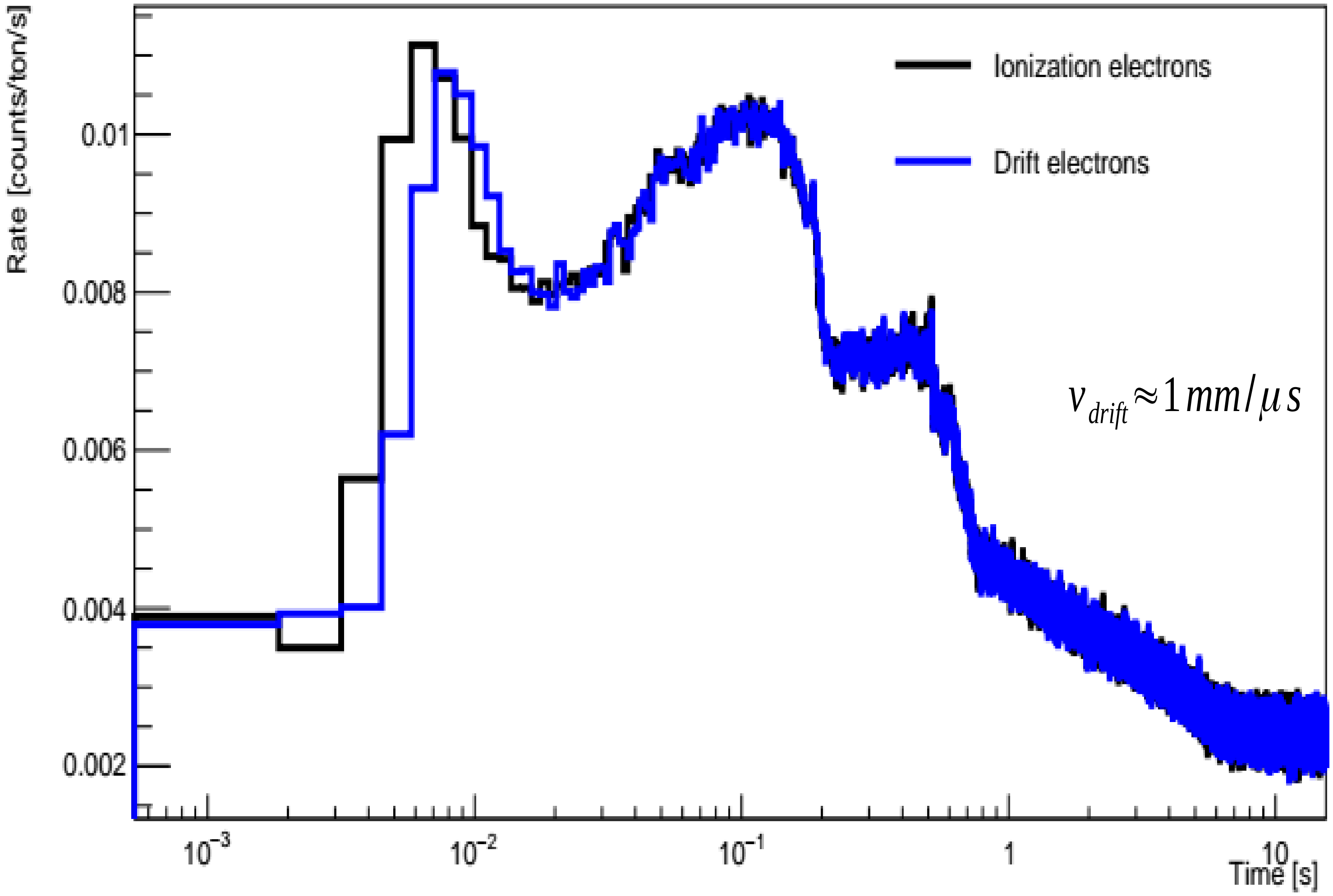


From 532-days DS50 analysis:
-central PMT data
-f90< 0.15
-single event
-single pulse

Experiment	Mass [ton]	Impurities events in Δt = 10 s	ν events 11 M_{sun} SN	ν events 27 M_{sun} SN
DS20K	38.6	**680**	150	270
ARGO	300	**5290**	1200	2110

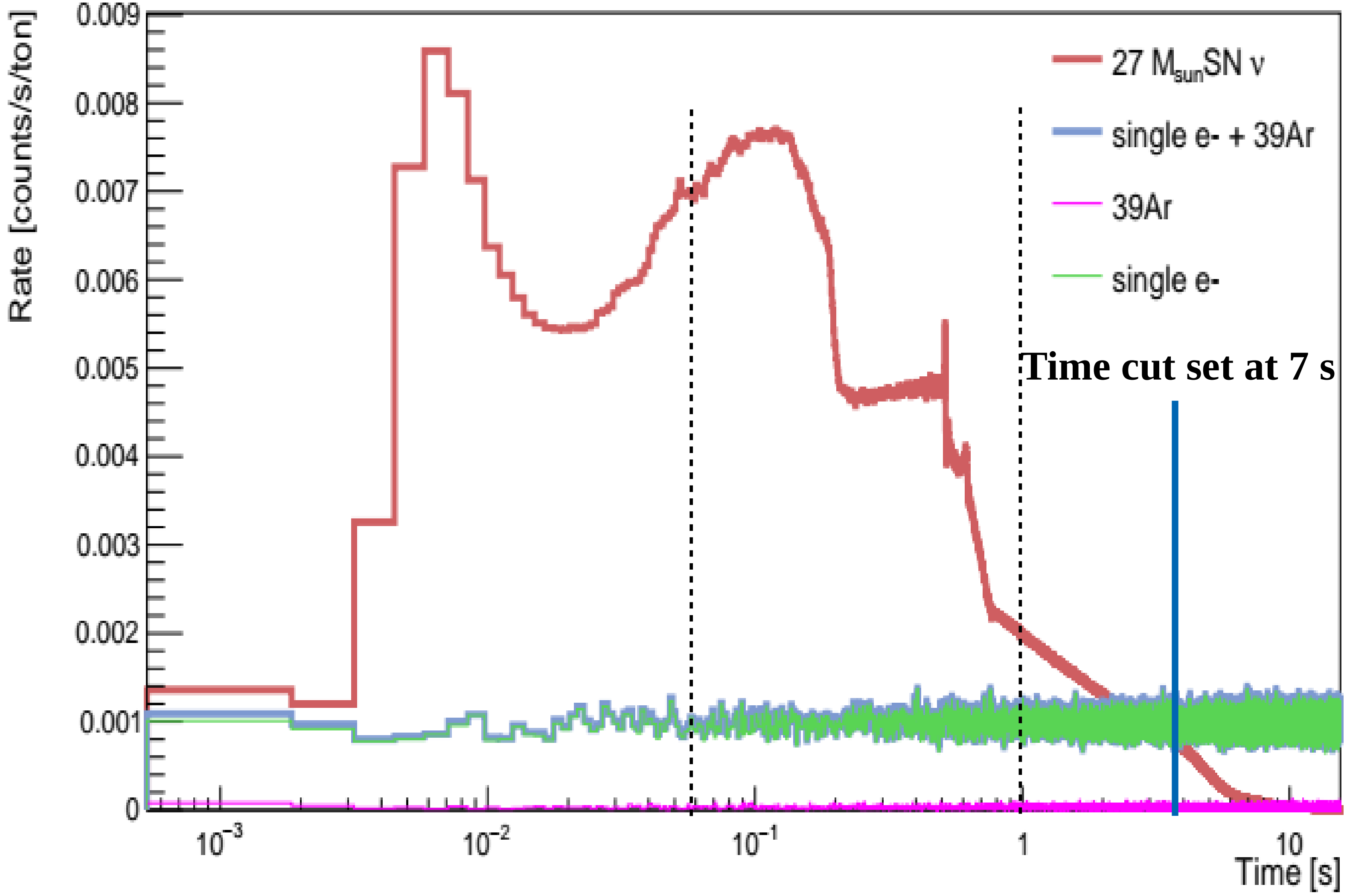
Too much background
Threshold needed !

Electron drift through the TPC



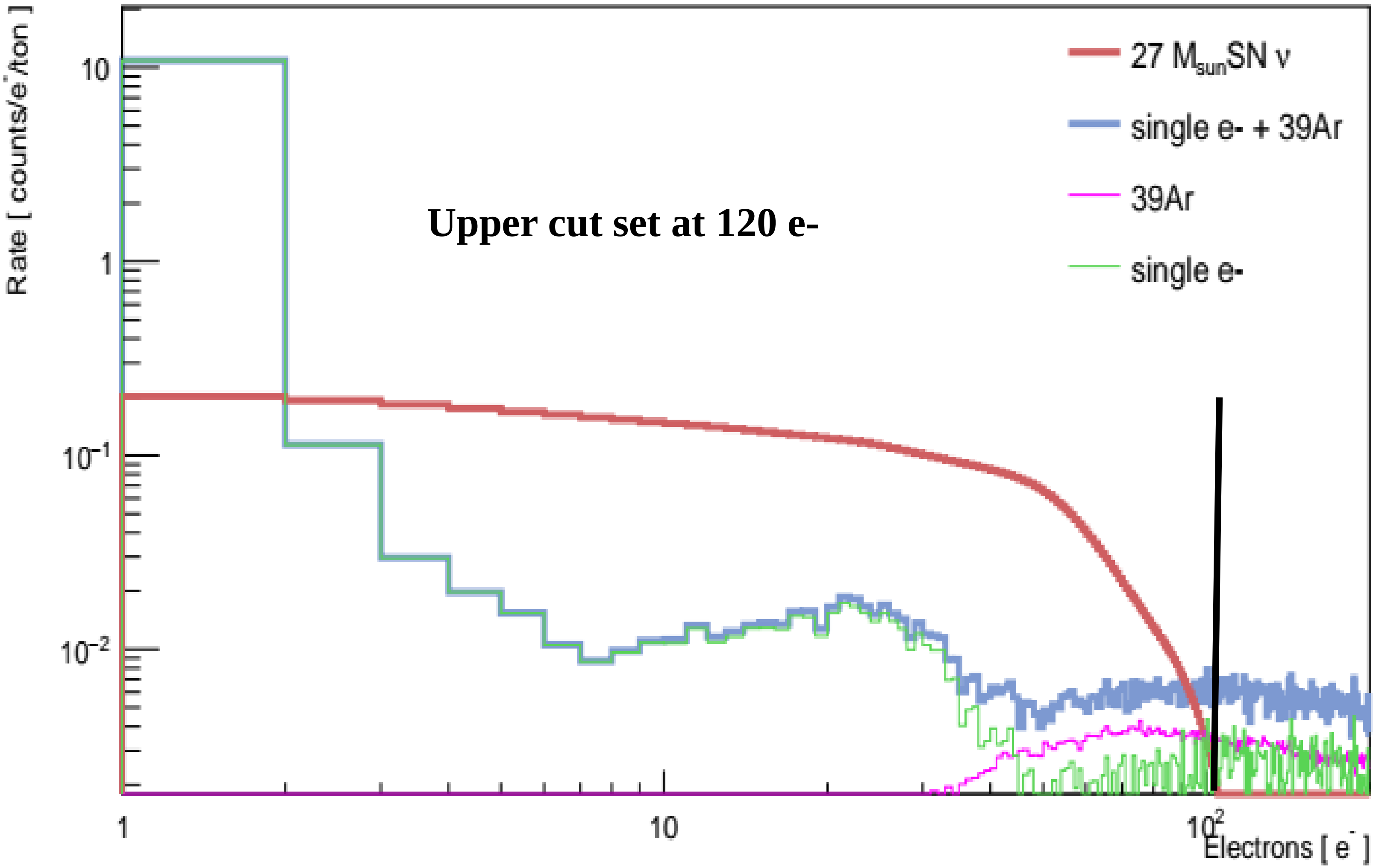
The delay due to the drift time does not affect the shape of the signal

Time cut

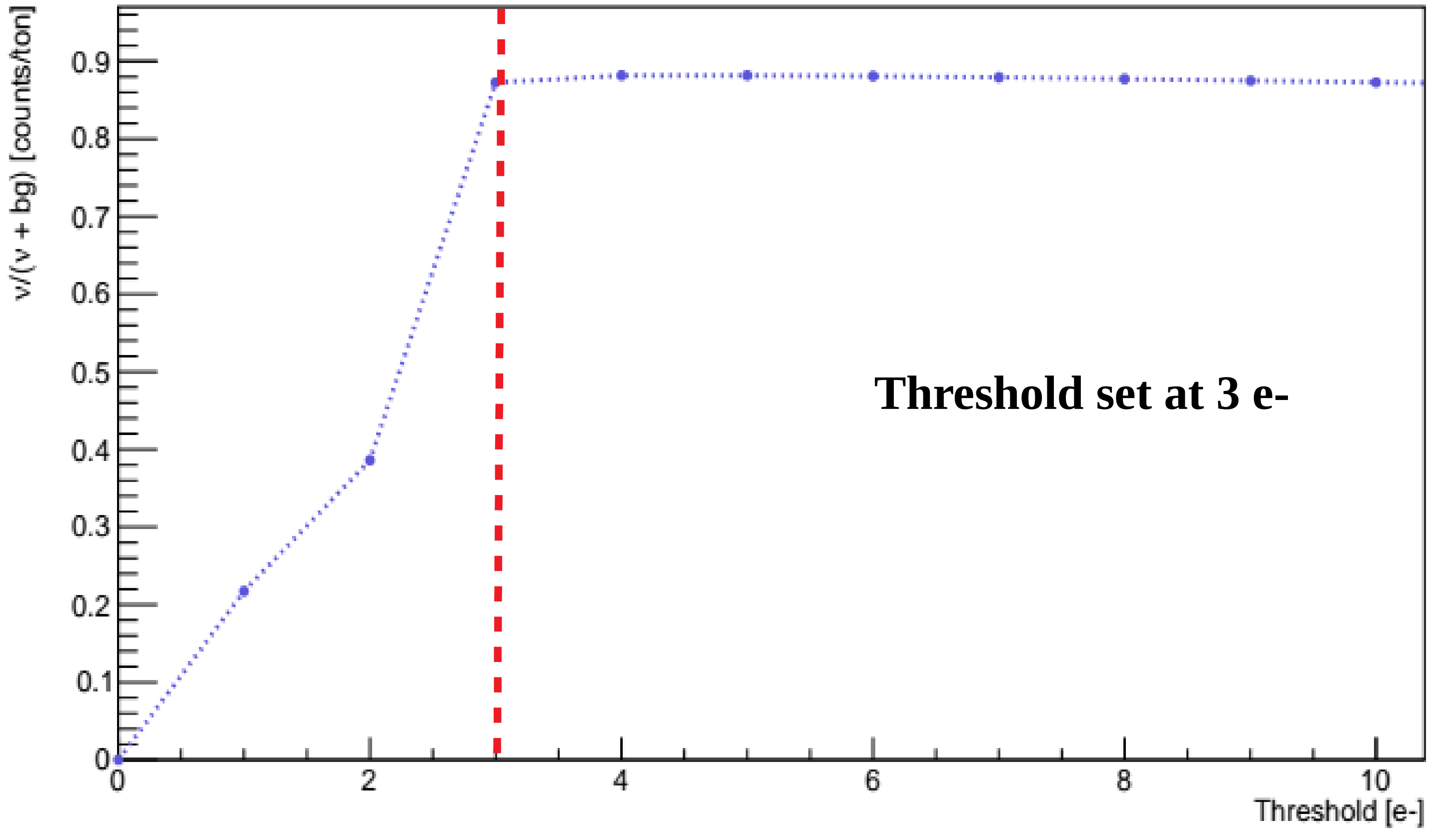


High Signal to background ratio during neutronization and accretion phase

Electron cuts

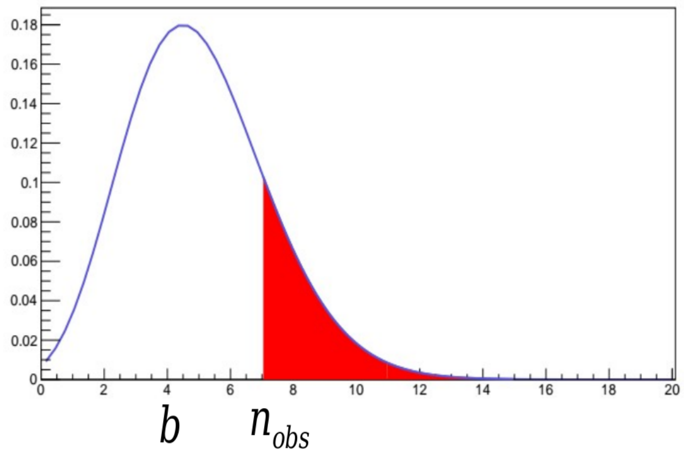


Electron threshold

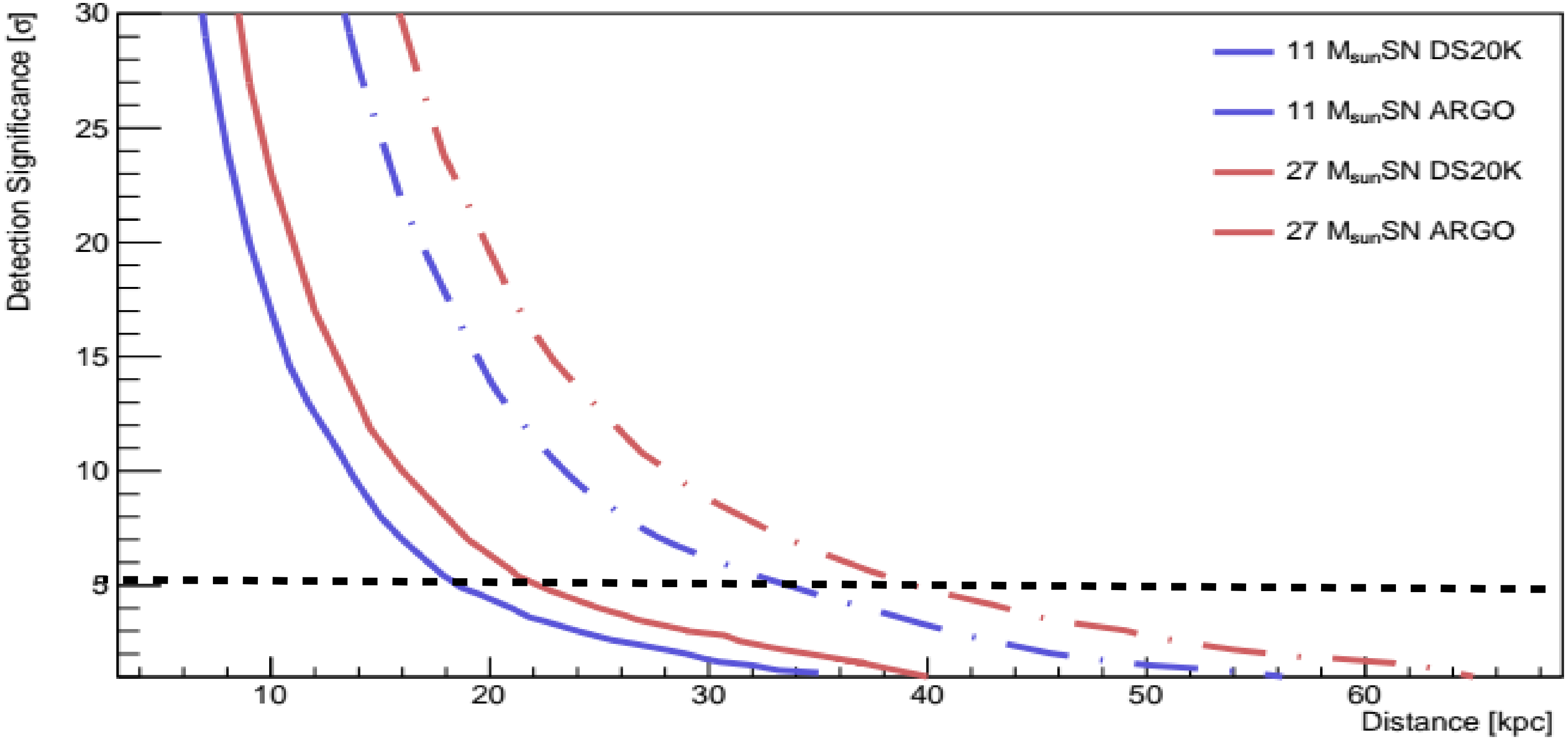


Experiment	Mass [ton]	^{39}Ar events in Δt = 7 s	Impurities events in Δt =7 s	ν events 11 M_{sun} SN	ν events 27 M_{sun} SN
DS20K	38.6	5	**12**	150	270
ARGO	300	40	**100**	1200	2110

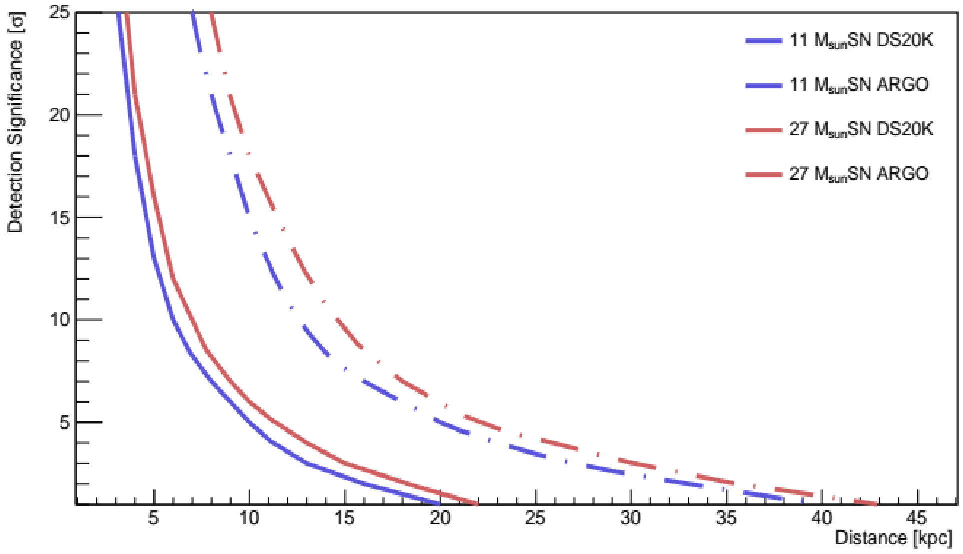
Discovery potential



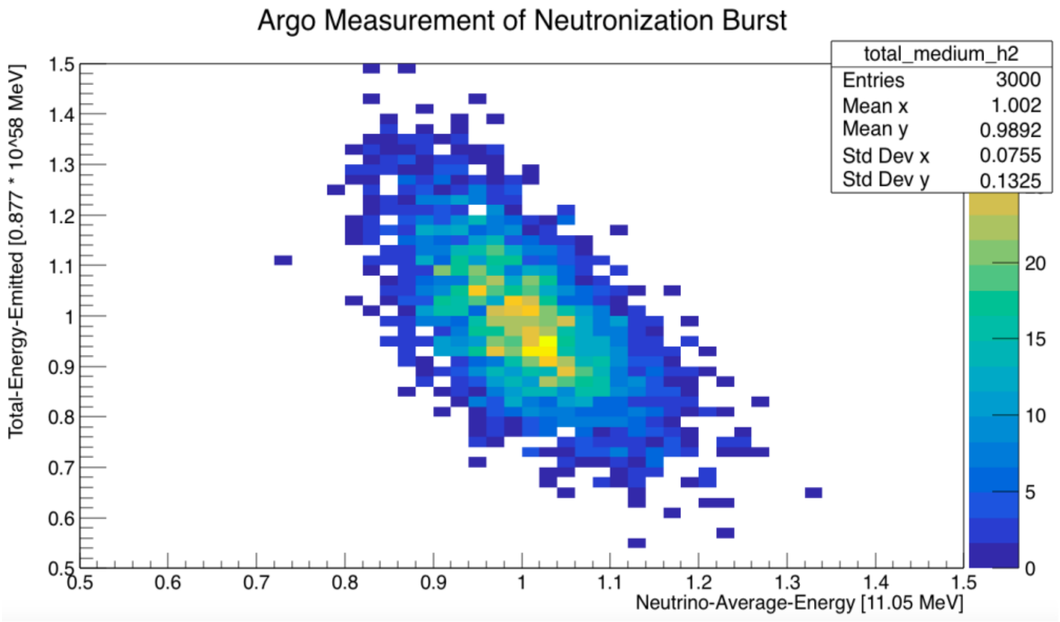
Counting experiment, assuming
-negligible background uncertainty
-Poisson statistic



SN and neutrino physics from the neutronization burst

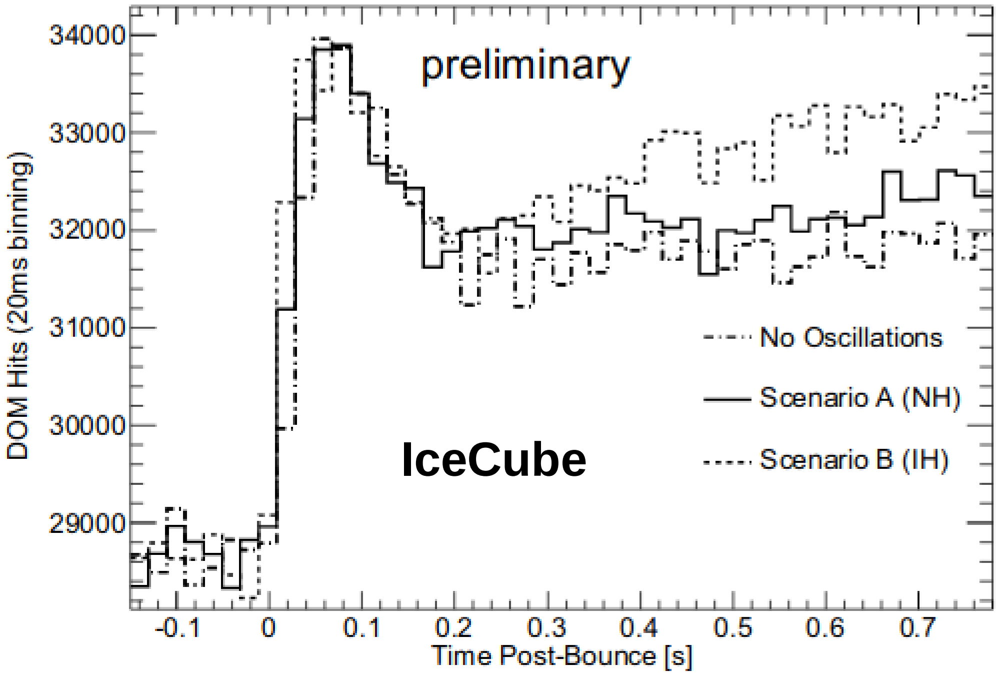


The high Signal to background ratio compensates for the short integration time

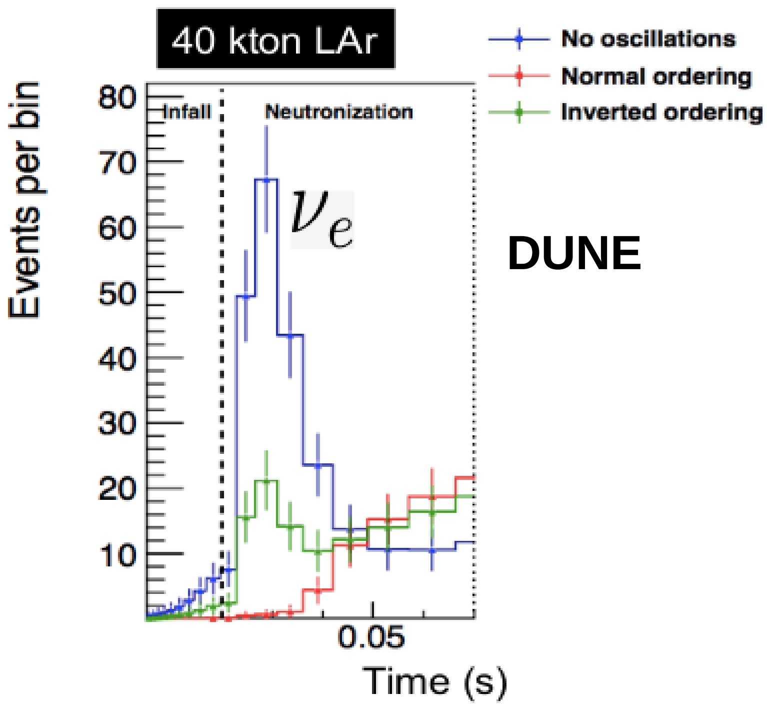


Good reconstruction of the **total energy** emitted and the **neutrino average energy**

Neutrino mass ordering from the neutronization burst



https://arxiv.org/pdf/1106.6225.pdf0



https://arxiv.org/pdf/1804.01877.pdf

The comparison with DS20K and ARGO will allow for setting a limit on the neutrino mass ordering from the survival probability of electronic neutrinos released during the neutronization burst

$$f_i \approx \frac{E_{TOT}}{<E>_i} \qquad \frac{f_e}{f_{tot}} = P_{ee}$$

$$P_{ee}^{NMO} \approx 0.022 \qquad P_{ee}^{IMO} \approx 0.297$$

Conclusion

Thanks to the

-High (and flavor insensitive) cross section
-Very low background level due to WIMP haunt

DS20K and ARGO are going to achieve

-**5σ** discovery for any galactic core-collapse supernova
-Reconstruction of total energy released via neutrinos
-Reconstruction of the average neutrino energy
-Inspection on the neutrino mass ordering (comparison with CC detection)

And so are going to be inserted in **SNEWS-2.0**

Back-up

Any question?

FBK NUV-HD SiPM

- Strict collaboration with *Fondazione Bruno Kessler (FBK)*: development of specific SiPM for LAr (50 PDM under way)
- The FBK technology on transfer to *LFoundry* for mass production (starting April 2019)
- Packaging of 240,000 SiPMs at *NOA*, a facility funded at LNGS

	DS-20k requirement	SiPM tile (PDM)	
Surface	5x5cm^2	24cm^2 prototype 25cm^2 final PDM	✓
Power dissipation	<250mW	~170mW	✓
PDE	>40%	$50\% \cdot \varepsilon_{geom} = 45\%$	✓
Noise Rate	<0.1cps/mm^2	0.004cps/mm^2	✓
Time Resolution	O(10ns)	16ns	✓
Dynamic Range	>50	~100	✓