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Search for neutrino signals from failed supernovae using BUST Data

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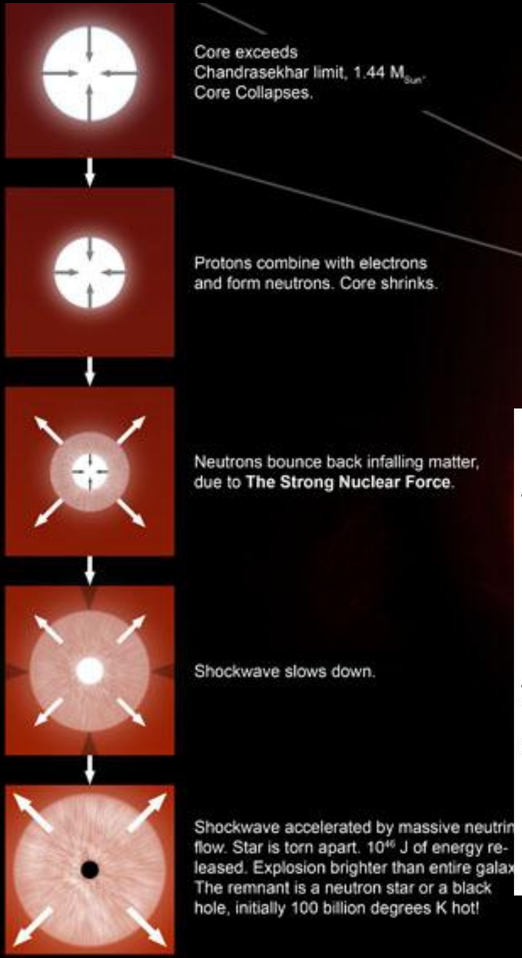
on behalf of BUST collaboration

DLNP JINR
BNO INR RAS

23 August 2025

Neutrino signal from the core-collapse supernova



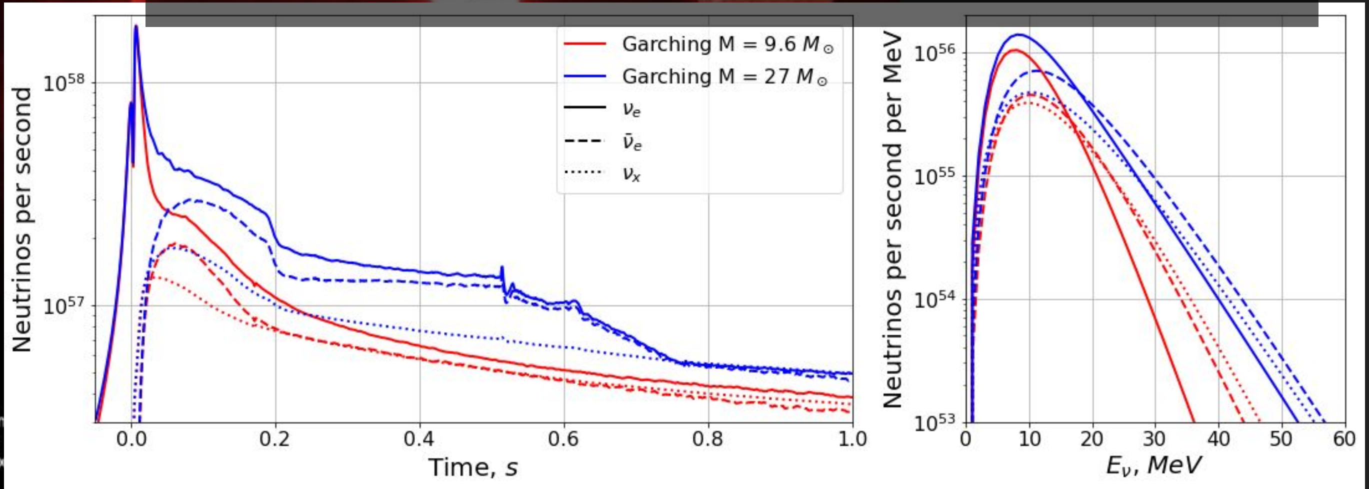
Type II SN radiates ~**99%** of the collapse energy in neutrinos:

~10^{58} neutrinos: **E_ν~10-60 MeV** within **T ~10s**

Neutrino signal: probe of

- Neutrino properties
- Supernova properties

arXiv:1508.00785 [astro-ph.HE]

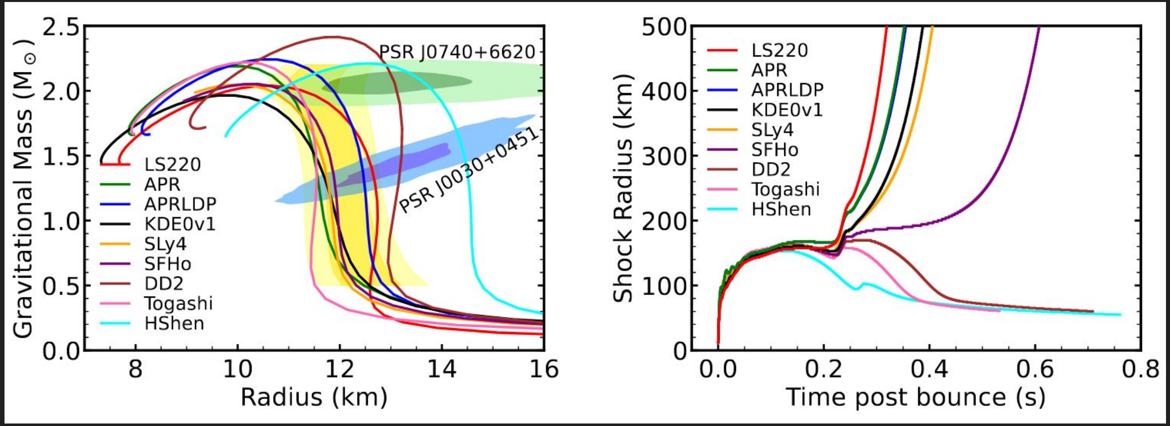


Explosion vs. failed supernova

Historically, the idea was that explodability depend on the progenitor mass:

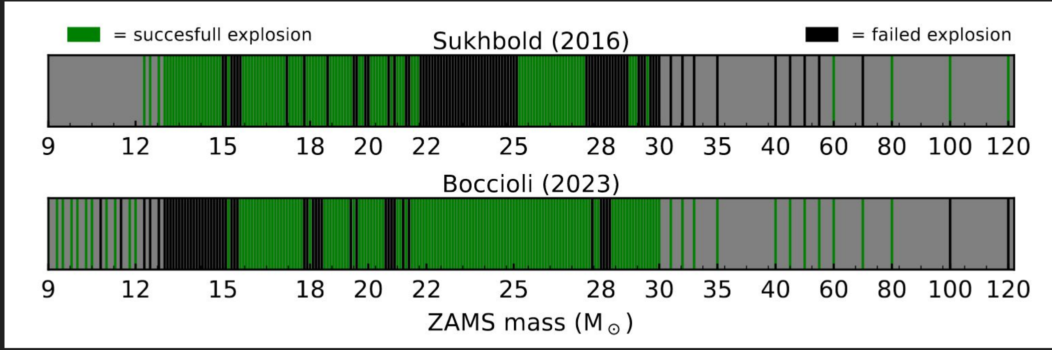
- $M \lesssim 20\ M_\odot$ - explode and form neutron stars
- $M \gtrsim 20\ M_\odot$ - lead to failed supernovae and form black holes.

Current 3D simulations show that “explodability” depends on many effects.



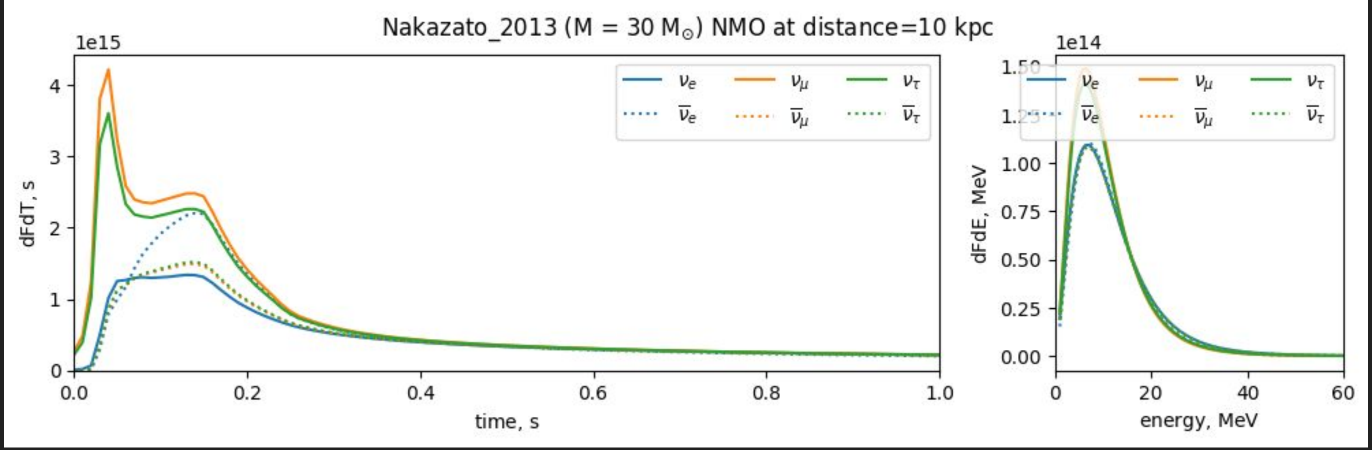
Star with the same mass, but different EOS

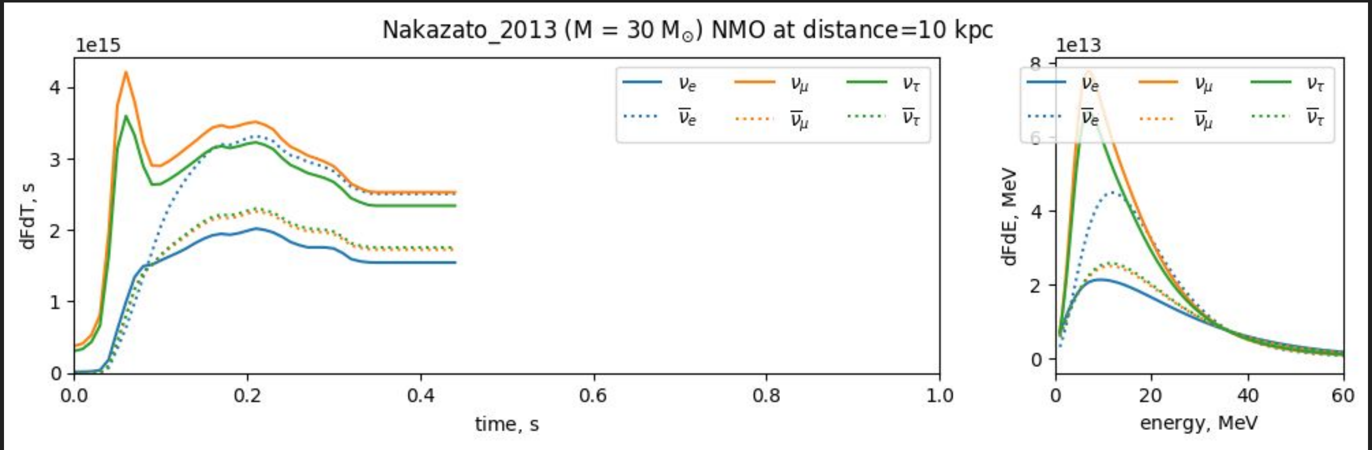
- Recent simulation show the “islands of explodability”
- These islands differ for different simulations



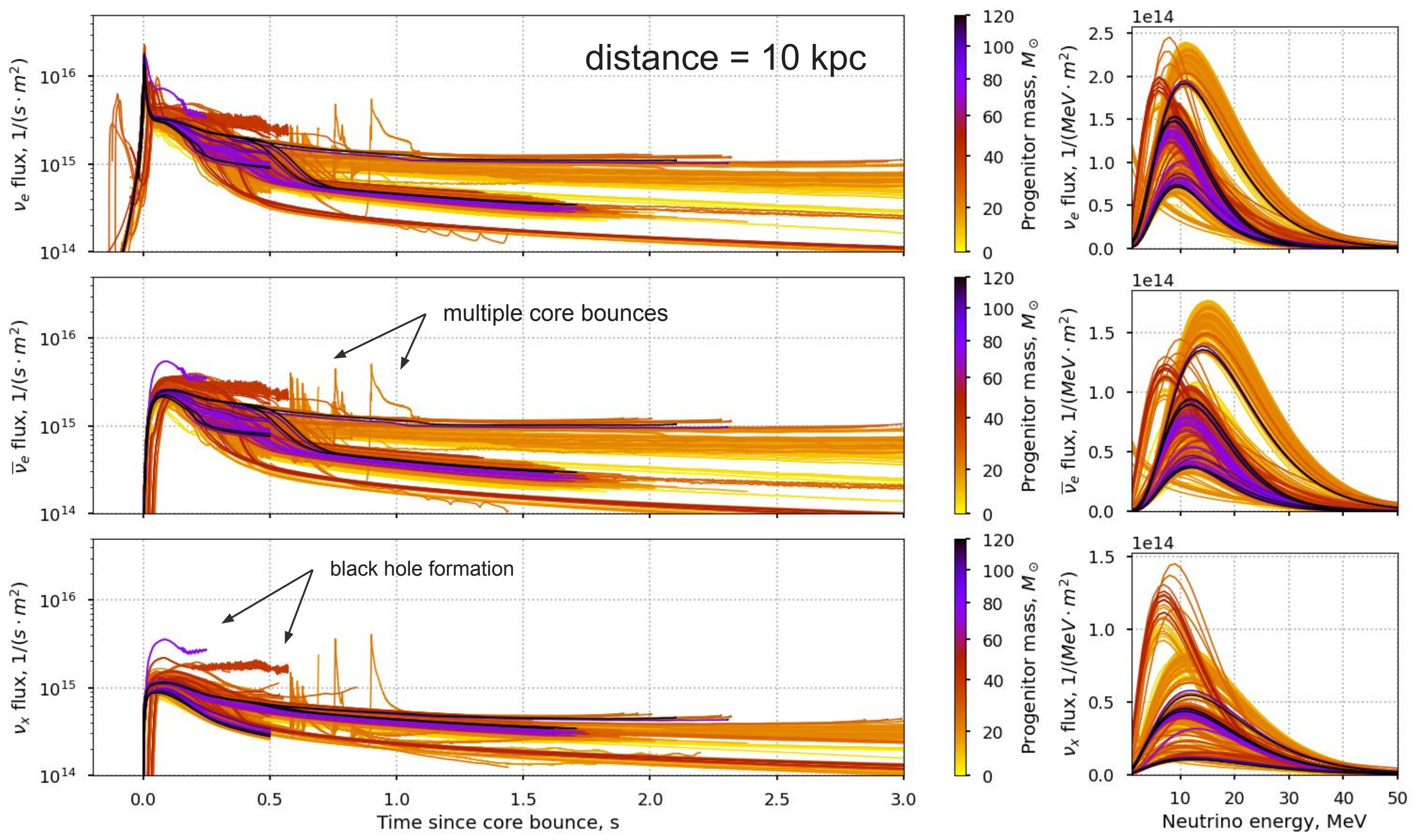
http://arxiv.org/abs/2403.12942

Explosion vs. failed supernova: neutrino flux





How well do we know the expected signal?

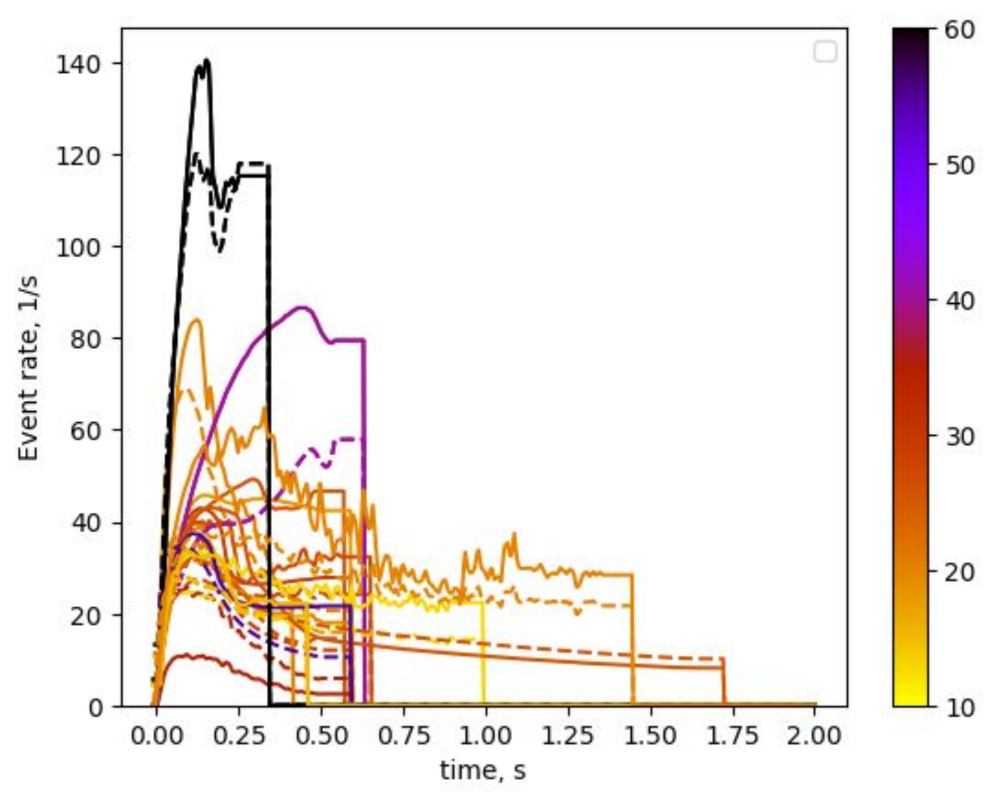


About 850 models from many sources in snewpy package

Parameters:

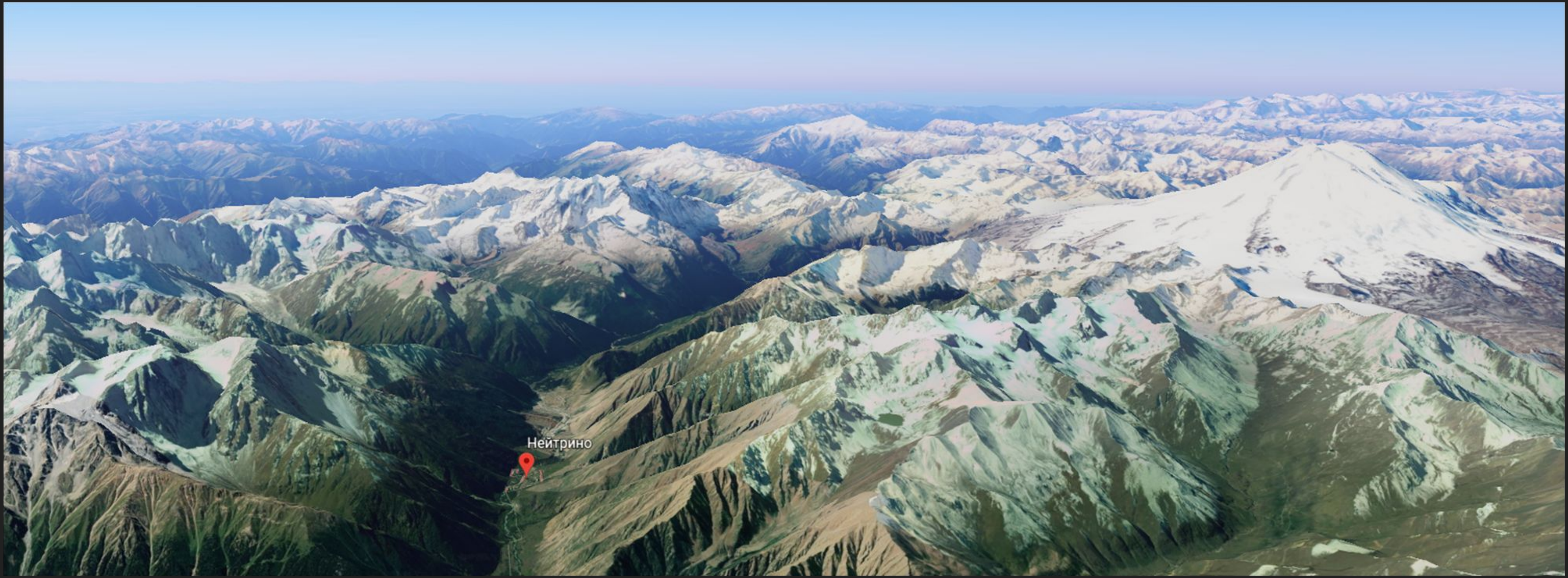
- Mass
- EOS
- direction
- $t_{revival}$
- additional physics…

IBD events from failed supernovae



- Signal is similar to the exploding one, but truncated
- The length of signal can be from ~0.25s to ~2.0s (depends on many parameters and processes)
- Experimental search should be similar to the usual CCSN search, but with short time windows.

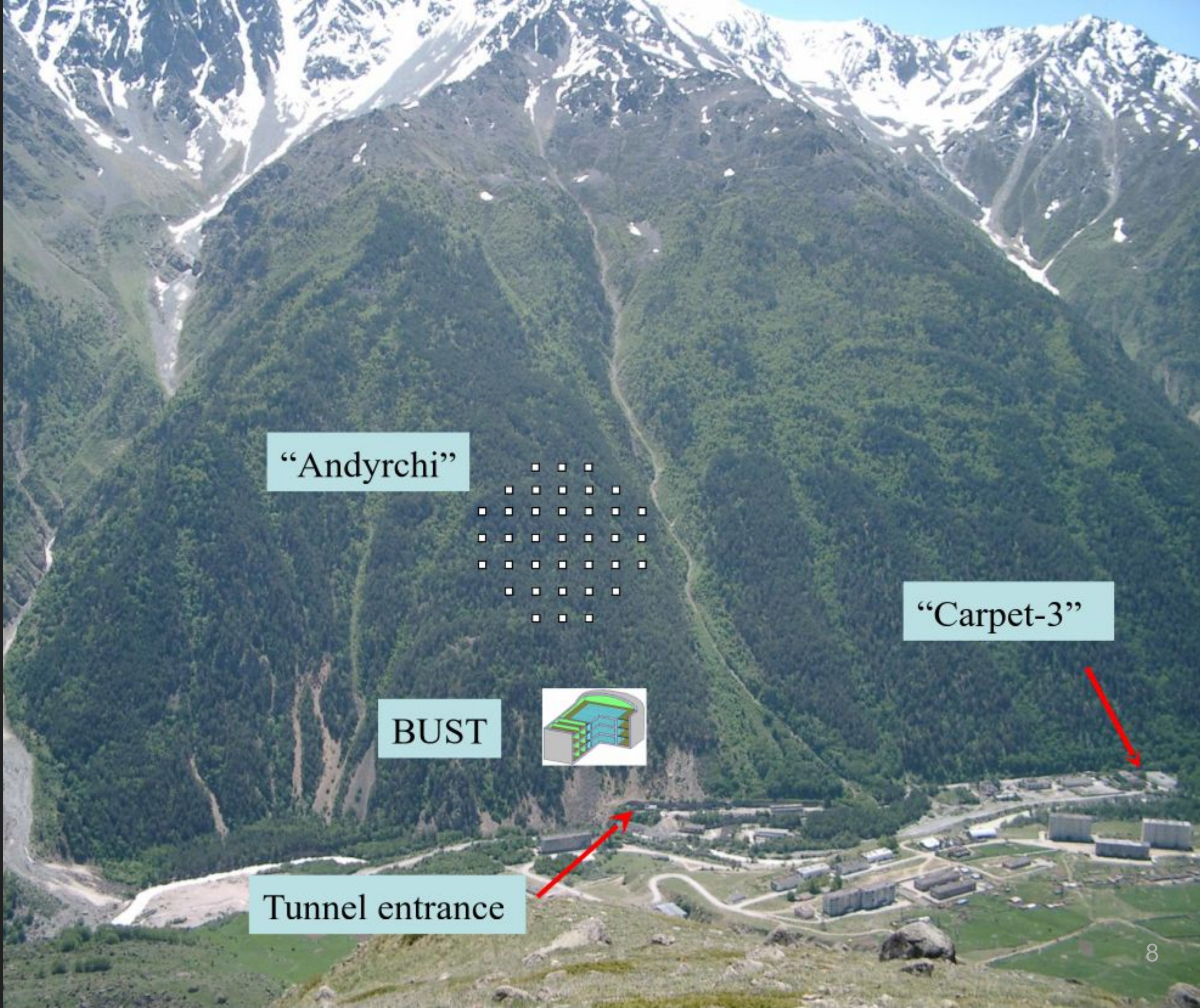
Baksan Neutrino Observatory



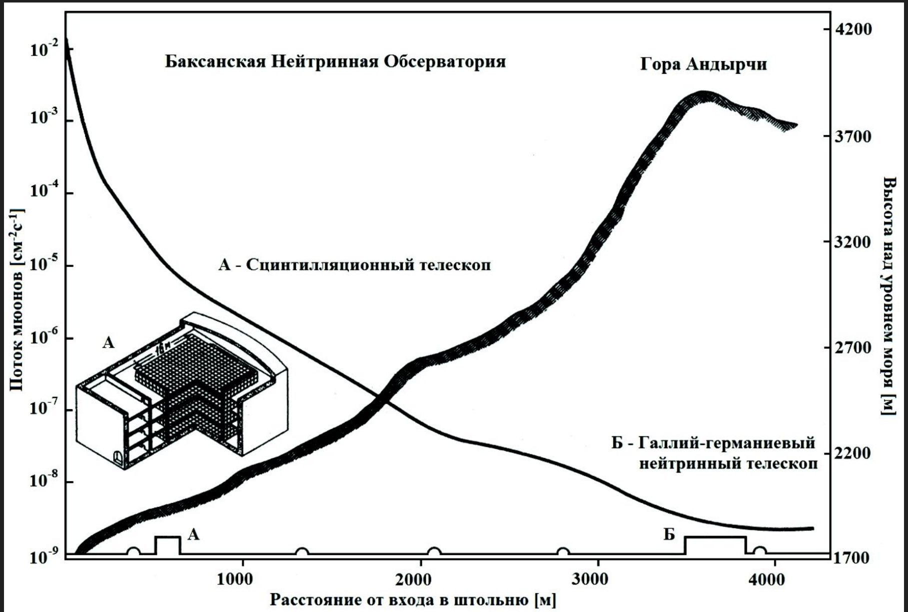
Located in Baksan river valley, 20km from mt. Elbrus

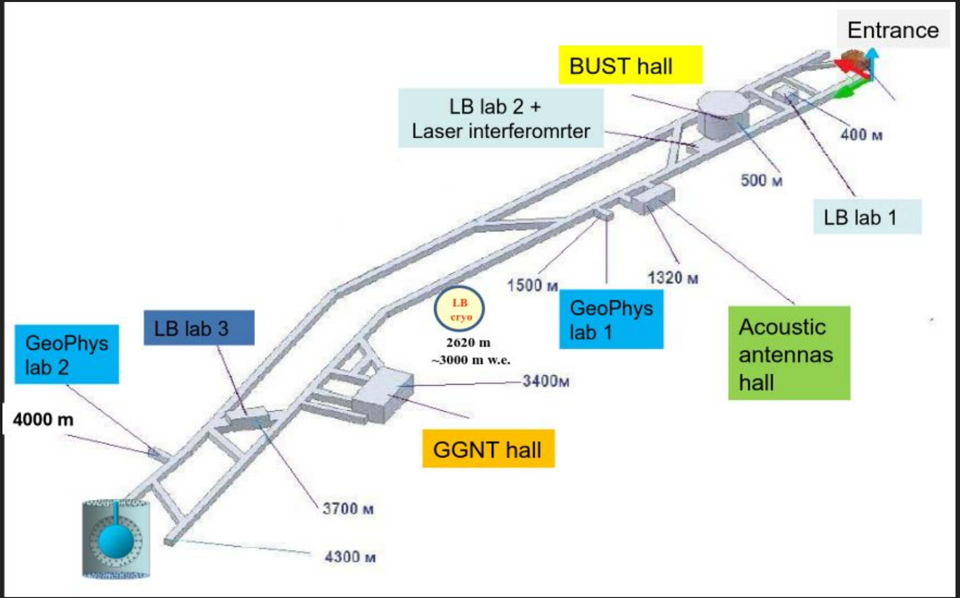
Baksan Neutrino Observatory

A unique complex of surface and underground facilities built for fundamental research in fields ranging from neutrino astrophysics to geophysics.

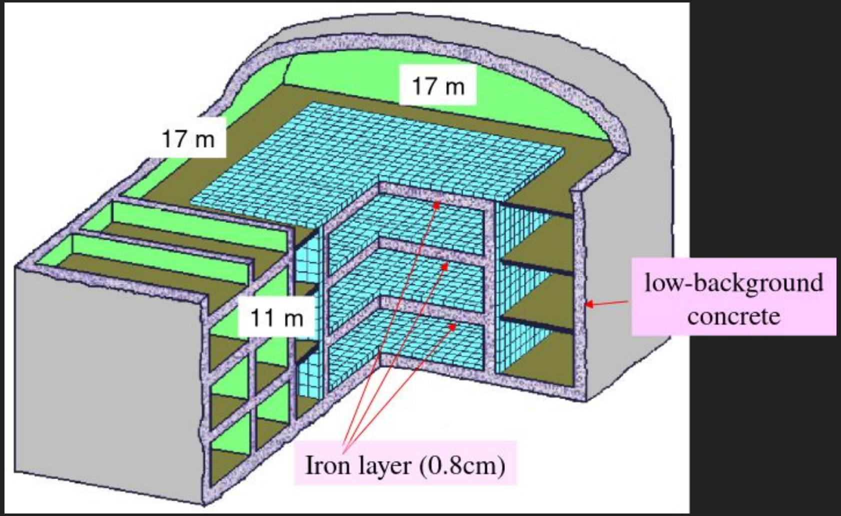


BNO Underground facilities

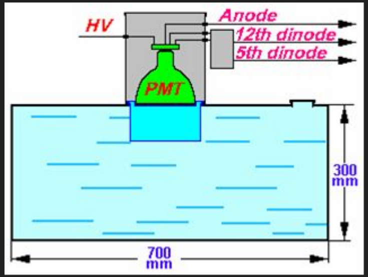




Baksan Underground Scintillation Telescope

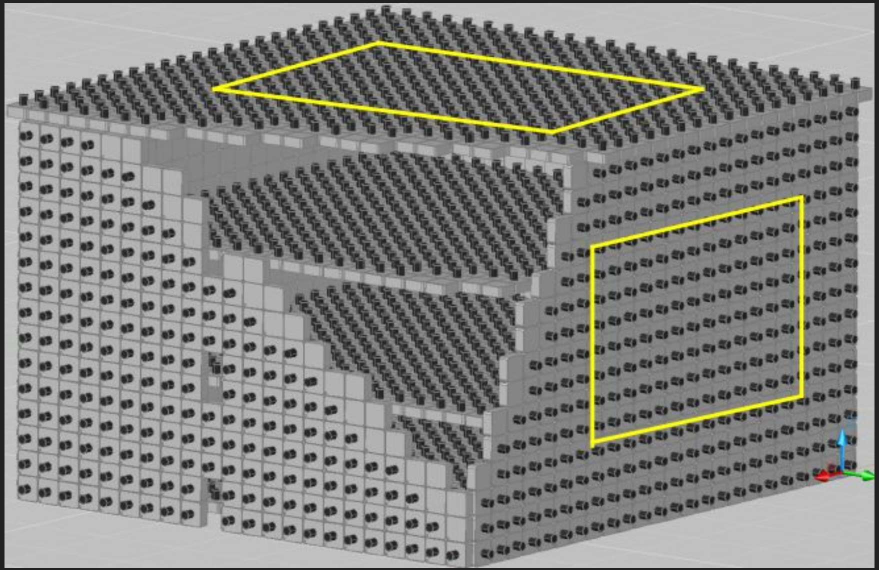


- 850 m.w.e overburden
- 330 ton of LS: C_nH_{2n+2} (n≈9)
- dimensions: 17 * 17 * 11 m^3



- number of counters: 3180
- tank size: 70 * 70 * 30 cm^3

Two parts of BUST: separate detectors



- External planes: 1980 counters, 1.4 sec^{-1}
- D1: 1200 counters (130 tons), 0.0207 sec^{-1}
- D2: 1030 counters (112 tons), 0.12 sec^{-1}

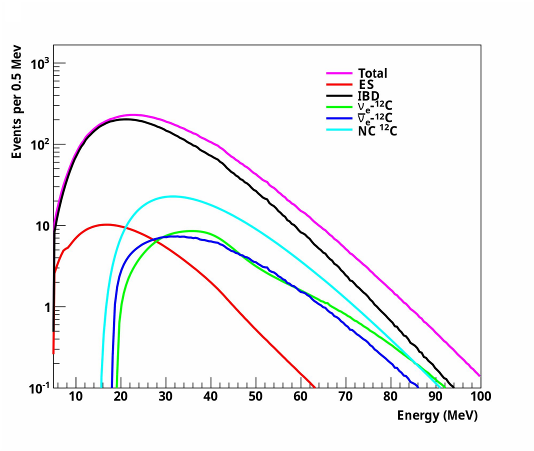
Each counter has:

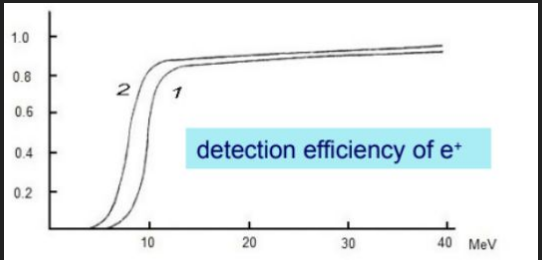
- pulse channel: used for triggering, if Edep>8 MeV (D1) or 10 MeV (D2)
- anode: measure Edep up to 2.5 GeV
- logarithmic: measure Edep

Data Aquisition:

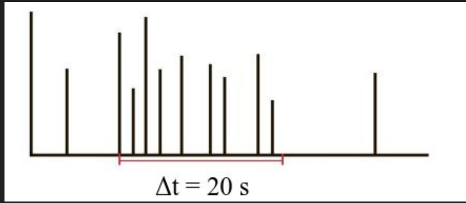
- July 1980 - March 2001
- March 2001 - current time
    - upgraded DAQ system
    - lowered the energy threshold for horizontal planes

Supernova neutrino detection



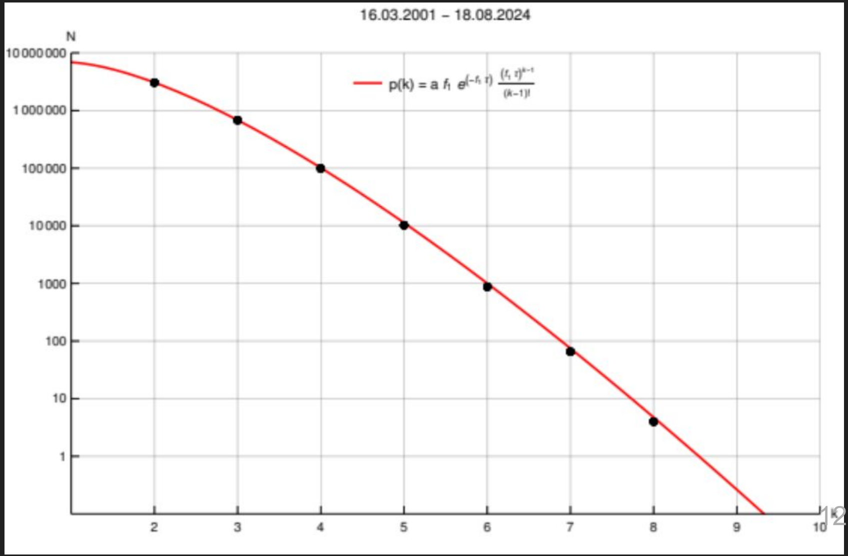


- IBD channel provides more than 88% of interactions
  - Can be used for conservative estimation
- IBD positron deposits energy in a single counter
  - Using only single events for analysis
  - Multi-counter events are background (muons, showers)

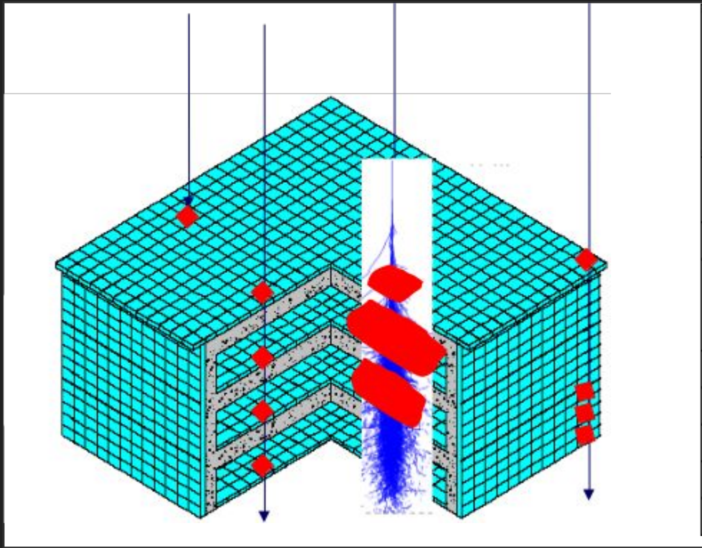


- Signal is a series of single events within a time window

Background follows Poisson distribution



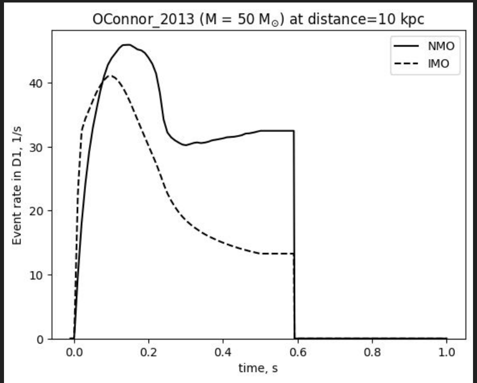
Muon induced background: isotopes deexcitation

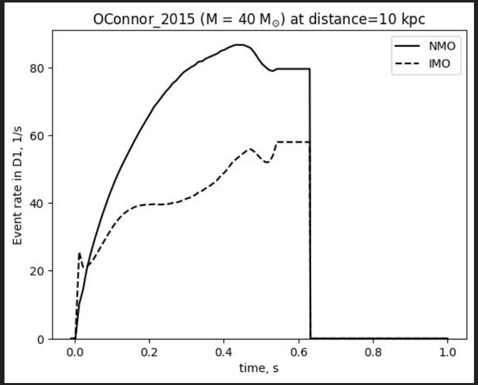


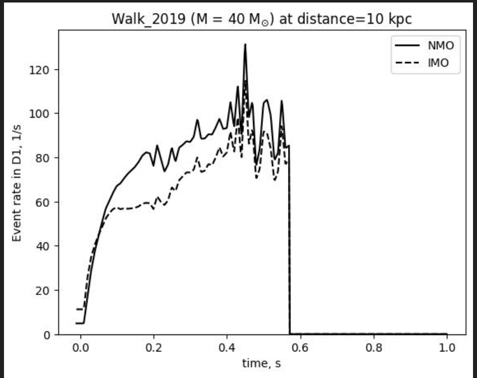
Изотоп	Время жизни, τ	Q, МэВ	Тип распада	Максимальное энерговыделение, с учётом аннигиляции позитрона	Основная реакция	Конечное состояние
^{12}N	15.9 ms	16.38	β+	17.38	^{12}C(p,n)	стаб. (^{12}C)
^{12}B	29.1 ms	13.4	β-	13.4	^{12}C(n,p)	стаб. (^{12}C)
^{8}He	171.7 ms	10.7	β-	10.7	^{12}C(π,n3p)	^{8}Li (84%), остальные – стаб.[2]
^{9}C	182.5 ms	16.5	β+	17.5	^{12}C(π^+,^{3}H)	стаб.[2]
^{9}Li	257.2 ms	13.6	β-	13.6	^{12}C(π^-,^{3}He)	стаб.[2]
^{8}B	1.11 s	18.0	β+	19.0	^{12}C(π^+,^{2}H^{2}H)	стаб.[2]
^{8}Li	1.21 s	16.0	β-	16.0	^{12}C(n,pα)	стаб.[2]
^{11}Be	19.9 s	11.5	β-	11.5	^{12}C(n,2p)	стаб.[2]

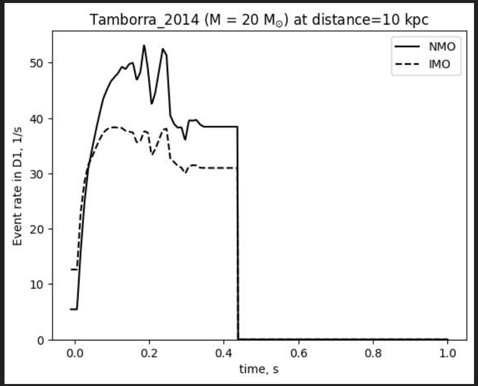
- Clusters from such processes can be tagged by proximity of the energetic events in the past.

Searching for failed supernovae in BUST









Smaller windows for clusters search

- Impossible to predict the exact signal shape and length
- We consider time windows [0.1..1.0]s
- Exact limits on the failed supernova rates will be model-dependent

Status of the data analysis

Processing of phase2 data (since 2001) is in progress.

A preliminary analysis of the total livetime of **13.68 years for**
for time windows [0.1, 0.2 , … 1] s

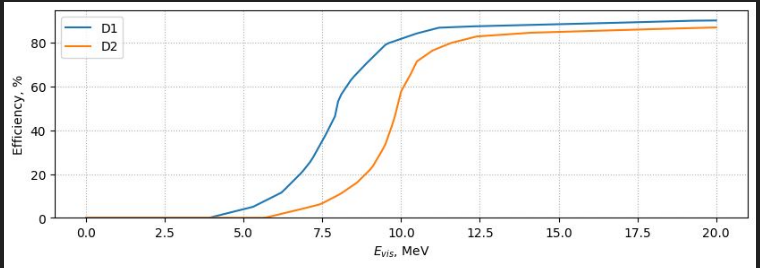
- 0.1 s - 0.4 s time windows show clusters with multiplicity **n=[2,3]**
- 0.5 s - 1.0 s time windows show clusters with multiplicity **n=[2, 3, 4]**.

Random background coincidence predict:

- in 0.1s time window: n=4 clusters are expected 1/1038 years
- in 0.4s time window: n=4 are 1/16 years, n=5 are 1/7887 years
- in 1.0s time window: n=5 are 1/204 years

So far we observe no significant candidates for the core-collapse neutrino bursts.

Probe the sensitivity with simulation:



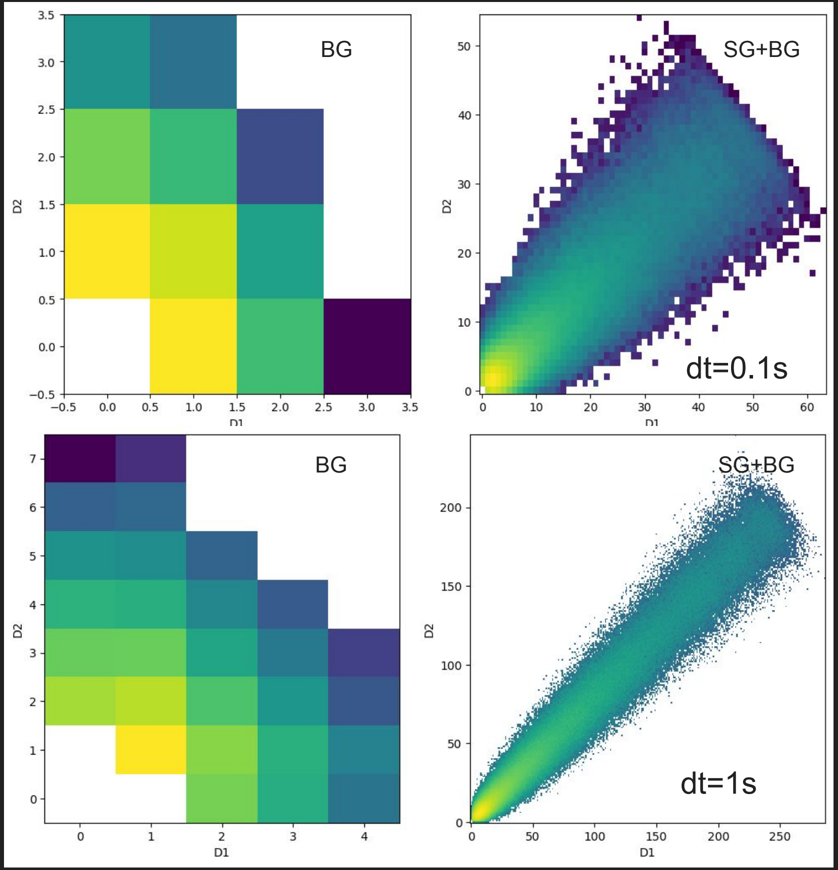
- Simulation based on expected rate: B+S(t)
  - Background: Poisson, independent for [D1,D2]
  - Signal: expected rate based on D1,D2 efficiency
- Random events in D1, D2: event timestamps
- Apply the deadtime (1ms after each event)

Analysis:

- Find clusters of events (events connected within dt<=1s)
- Find the signal start: scan with 0.5s window (maximum point)
- Count events in [0.1… 1]s time windows after signal start

Perform MC for background and signal+background

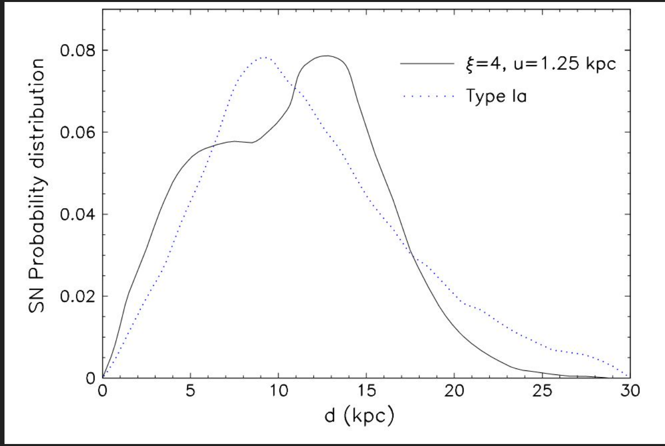
Using two detectors D1 and D2



We can use both detectors to better suppress the background clusters.

Simulation produces PDFs for cluster multiplicity in both detectors.

Simulation of signal clusters is done with the distribution of SN candidates in the galaxy

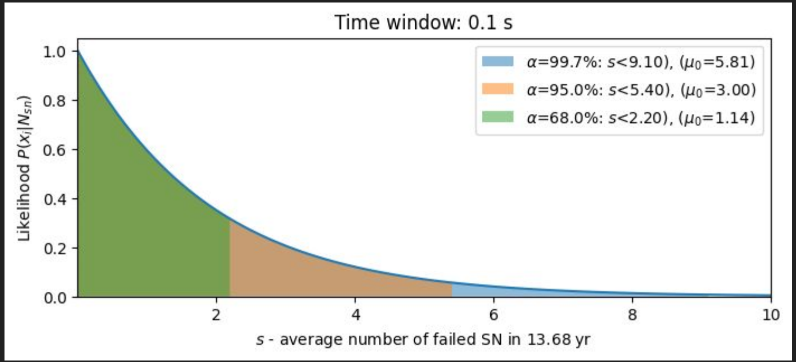


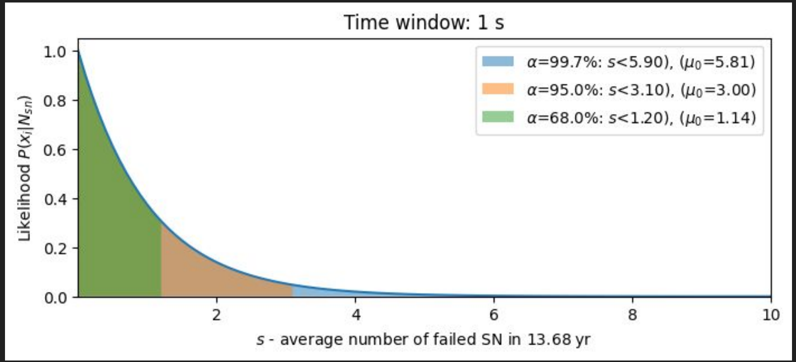
Statistical analysis: estimating the sensitivity

It's possible to calculate likelihood of observing given dataset, using PDFs for signal and background clusters.

$$P(\{x_i\}|b,s) = P(N|b+s)\cdot\prod_{i=1}^{N}\frac{b\cdot p_b(x_i)+s\cdot p_s(x_i)}{b+s} = \frac{e^{-(b+s)}}{N!}\cdot\prod_{i=1}^{N}\left[b\cdot p_b(x_i)+s\cdot p_s(x_i)\right]$$

We can estimate the limits on the failed supernova rate, on a MC background sample consistent with our live time





Summary

- Failed supernova explosions produce black holes instead of explosions
    - Can be hard to detect apart from neutrino bursts
    - Truncated neutrino signal, compared to exploding supernovae
    - Many simulations predict very different neutrino signals
- BUST is one of the neutrino detectors with the longest operation live time
    - Performs a search for SN neutrino signal since July 1980
    - Collected data can be analyzed to limit the failed supernova rate in our galaxy
- Preliminary data analysis shows no significant data clusters, compatible with a supernova neutrino burst
- Preliminary statistical analysis based on simulation is performed to define the sensitivity limits
    - The results are model-dependent