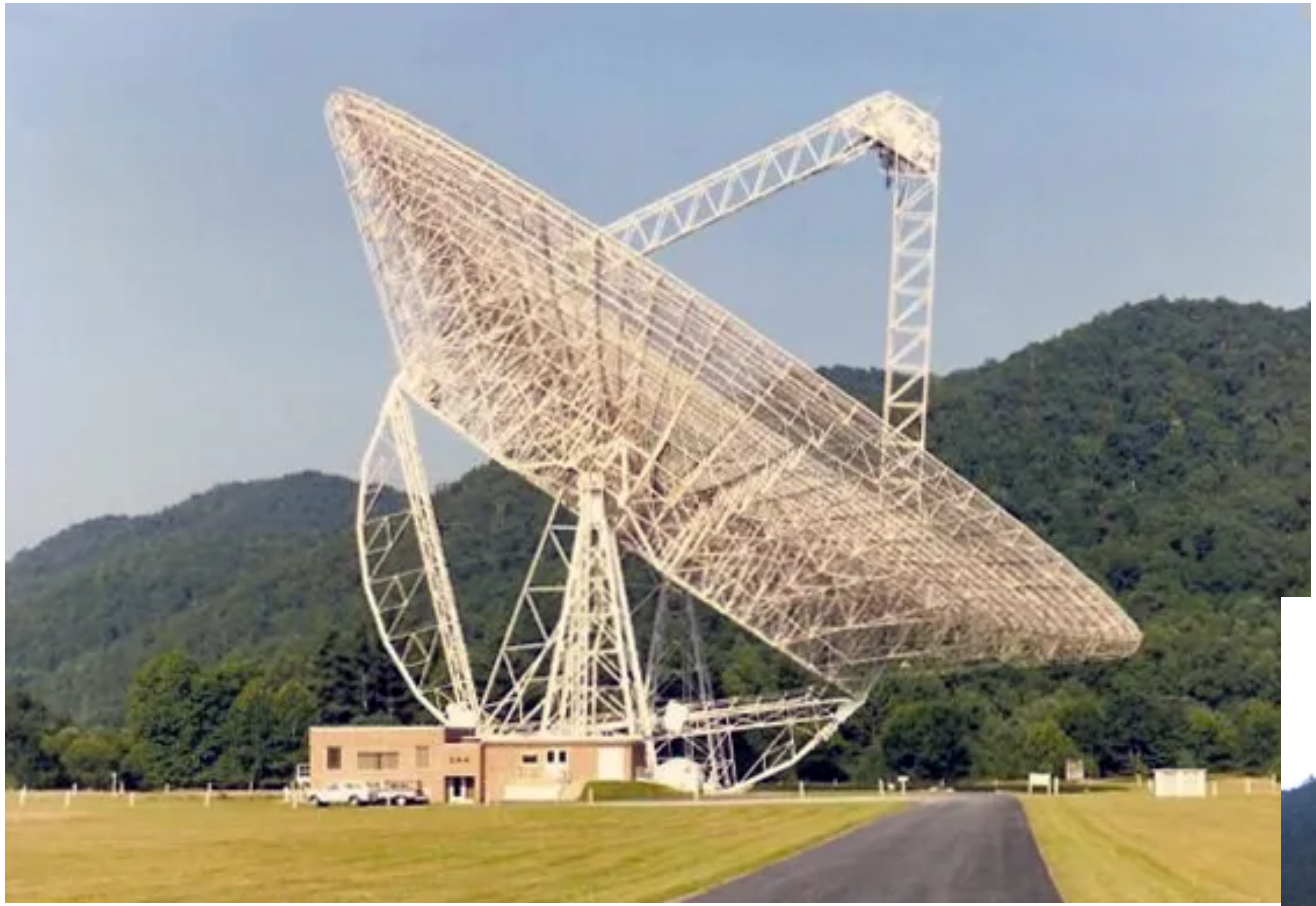
Nuclear physics of supernovae

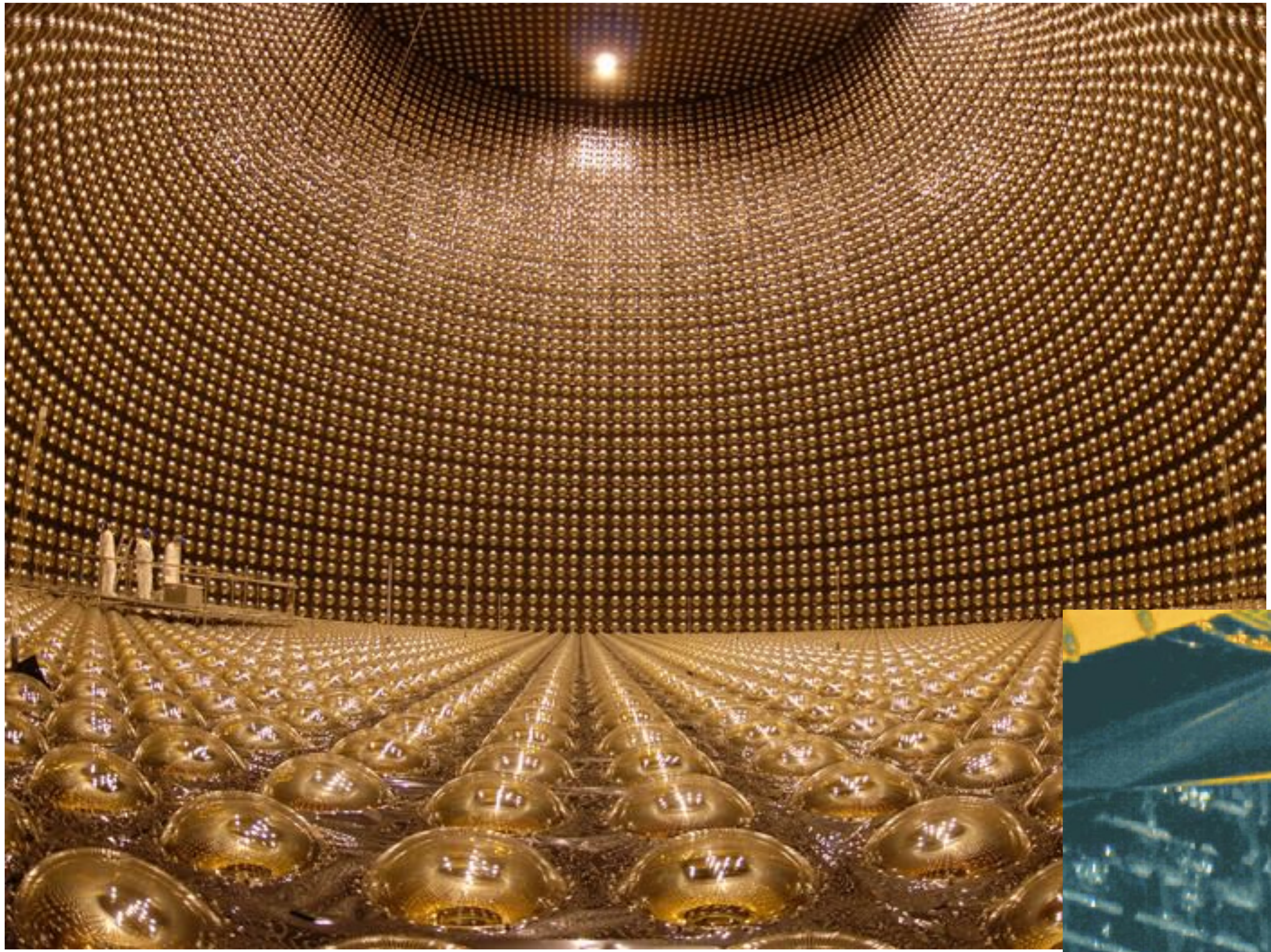
- During my career, astronomers have won the cosmic lottery, *twice.*
- **Supernova SN1987a**: Giant explosion of massive star that radiated huge burst of “ghost particles” called **neutrinos**.
- **Neutron star merger GW170817**: Titanic collision of two extreme stars that shook up space and time itself to radiate burst of **gravitational waves**.
- These events and gigantic new detectors promise an **exciting future**.

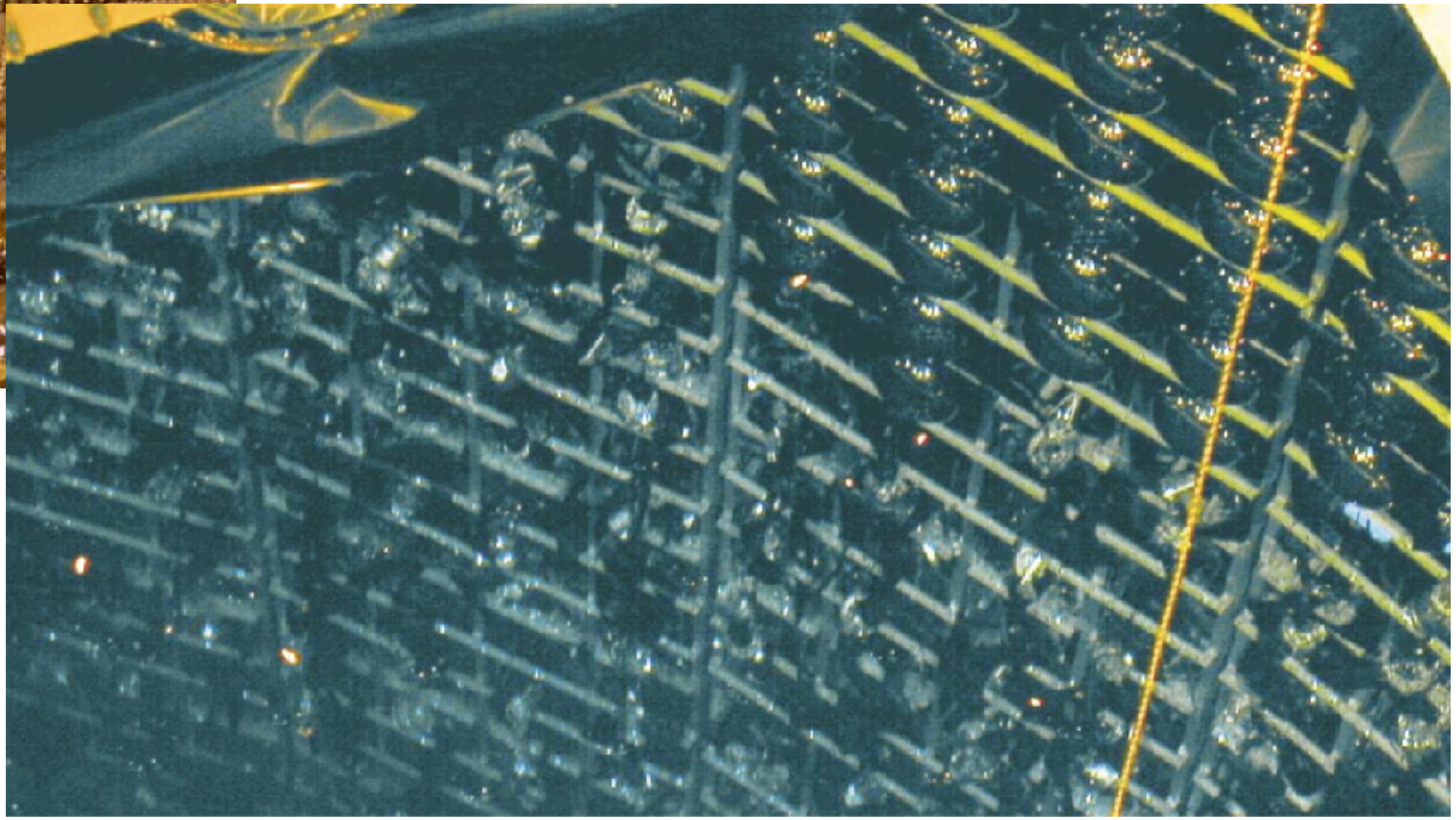


300 ft Green Bank Telescope

Lecture 1 neutron stars

Lecture 2 Supernovae





Super-Kamikande neutrino detector
“imploded” on 11/12/2001

Pairing

- Neutron stars (Horowitz): Rotational glitches and cooling.
- Nuclear structure (Stroberg): Low density of states in even-even nuclei.
- Nucleosynthesis (Schatz): Even Z elements more abundant than odd Z.
- Fundamental symmetries (Cirigliano): Double beta decay occurs because of pairing.
- QCD (Rajagopal): Color superconductors
- Quantum information science (Savage): Pairing is entanglement? Superfluids and superconductors have macroscopic quantum phases.
- Nuclear reactions (Nunes): Pairing can impact the transfer of a nucleon.
- AI/ML (Li): AI will now give a much better version of this lecture.

Cooper Pairs

- Particles near Fermi surface are effectively two dimensional. States deeper in sea are blocked.

- One dimensional and 2-D quantum systems have bound states for arbitrarily weak attractive interactions.

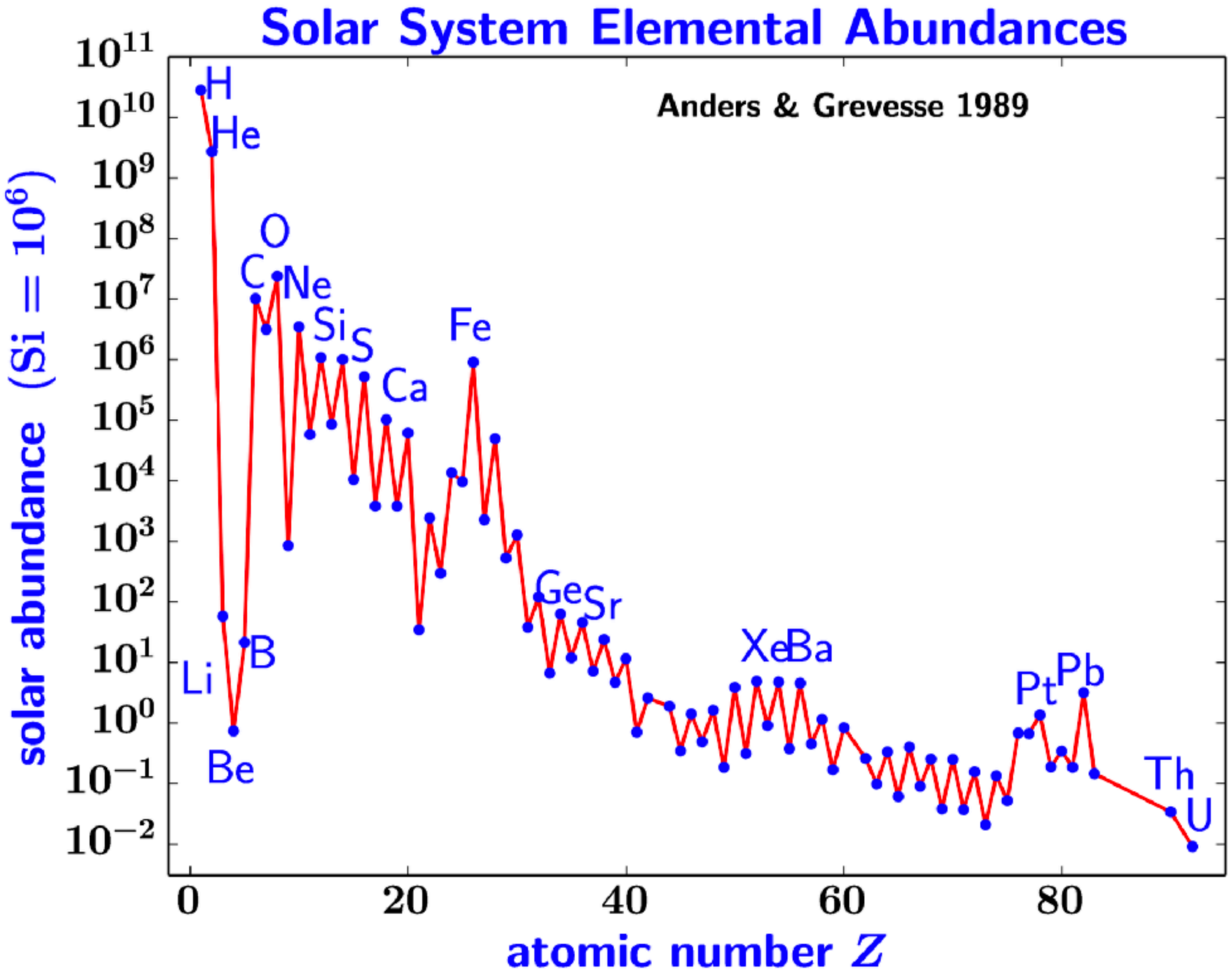
- Two protons or two neutrons in 3-D free space are unbound even though interaction is attractive.

- Two n near Fermi surface in neutron matter can form a Cooper pair with a binding E of order 1 MeV. This corresponds to a critical T ~ 10^{10} K -> superfluid or superconductor in neutron stars.

- Conventional superconductor: one electron can polarize lattice and then second electron is attracted to polarized lattice. Producing very weak effective attraction and a low critical temperature.

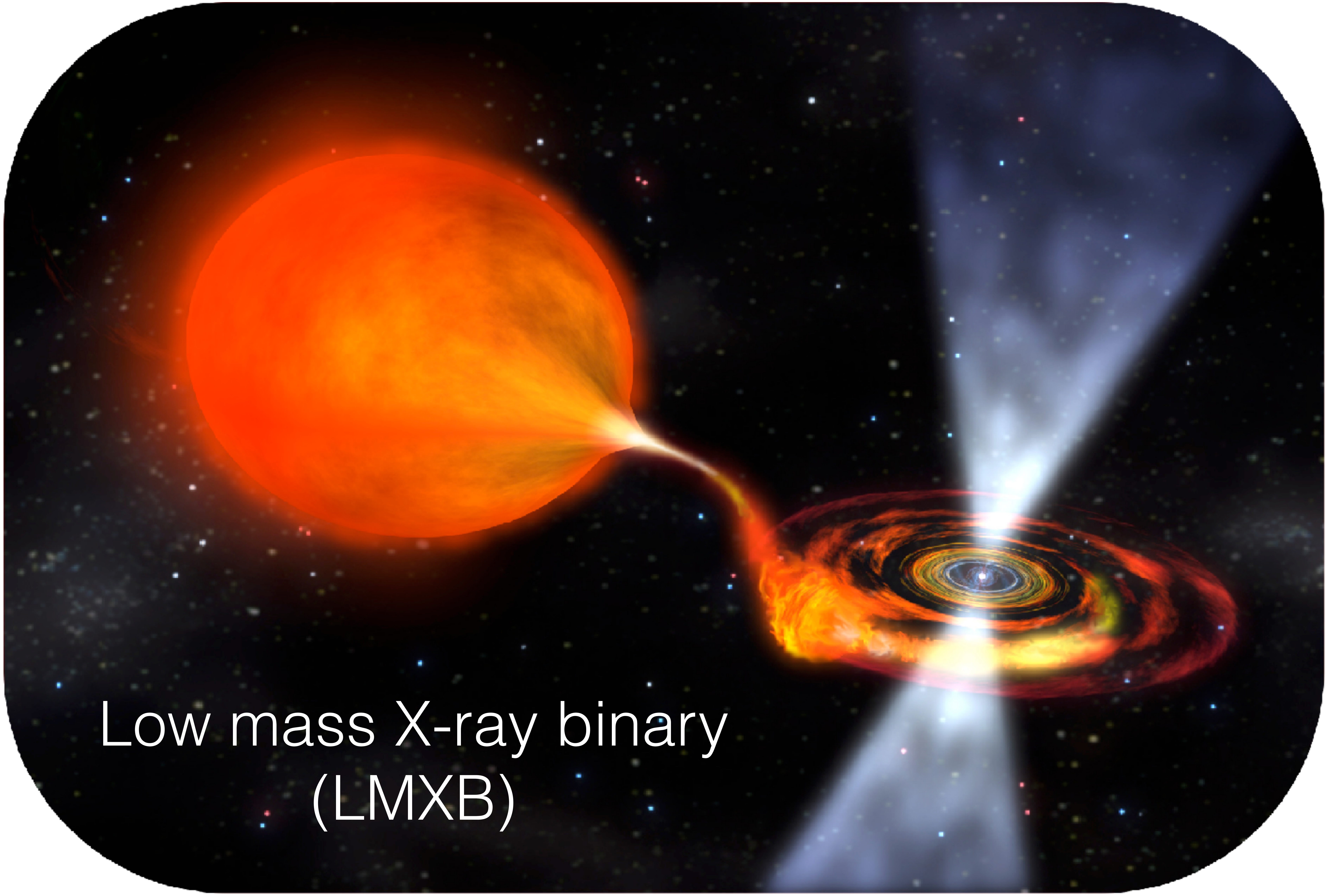
Nucleosynthesis

- An odd-odd nucleus can beta decay and gain pairing energy—> There are no stable odd-odd nuclei heavier than ^{14}N.
- Even Z elements can have stable even N and odd N isotopes. Odd Z elements only have stable even N isotopes.
- Even Z elements are more abundant than odd Z elements.
- **Double Beta Decay:** ^{48}Ca with 28 n and 20 p is too n rich to be stable. However pairing stabilizes ^{48}Ca against beta decay. Only decay mode available is double beta decay.



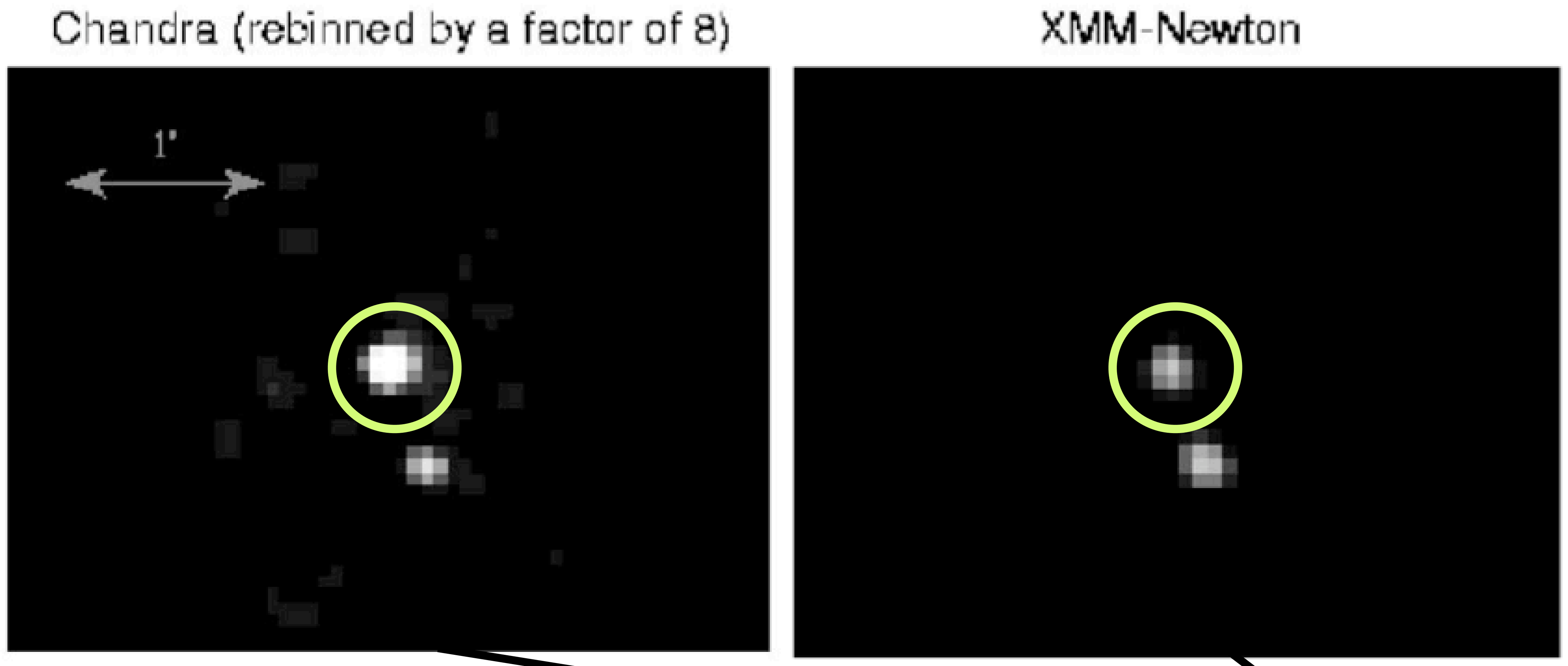
Cold Dense Quark Gluon Plasma

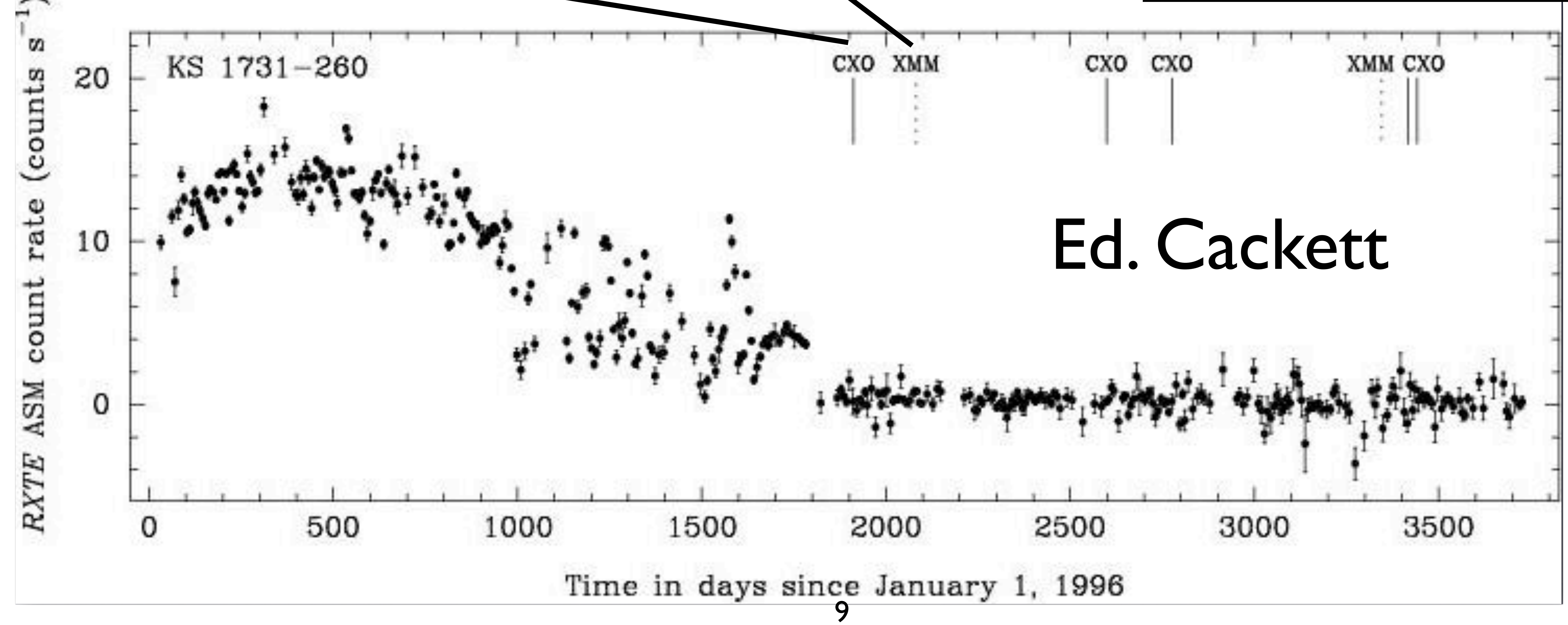
- At very high Fermi momenta interactions become weak leaving a nearly free quark Fermi gas.
- However, one gluon exchange between quarks is attractive for some spin flavor and color states. Therefore no matter how high the Fermi momentum and how small the running coupling constant, there will still be bound Cooper pairs of quarks for some spin, flavor and color states.
- In the limit of very high densities, the ground state of cold QCD is a color superconductor.



Low mass X-ray binary
(LMXB)

Cooling of crust of KS 1731-260





Ed. Cackett

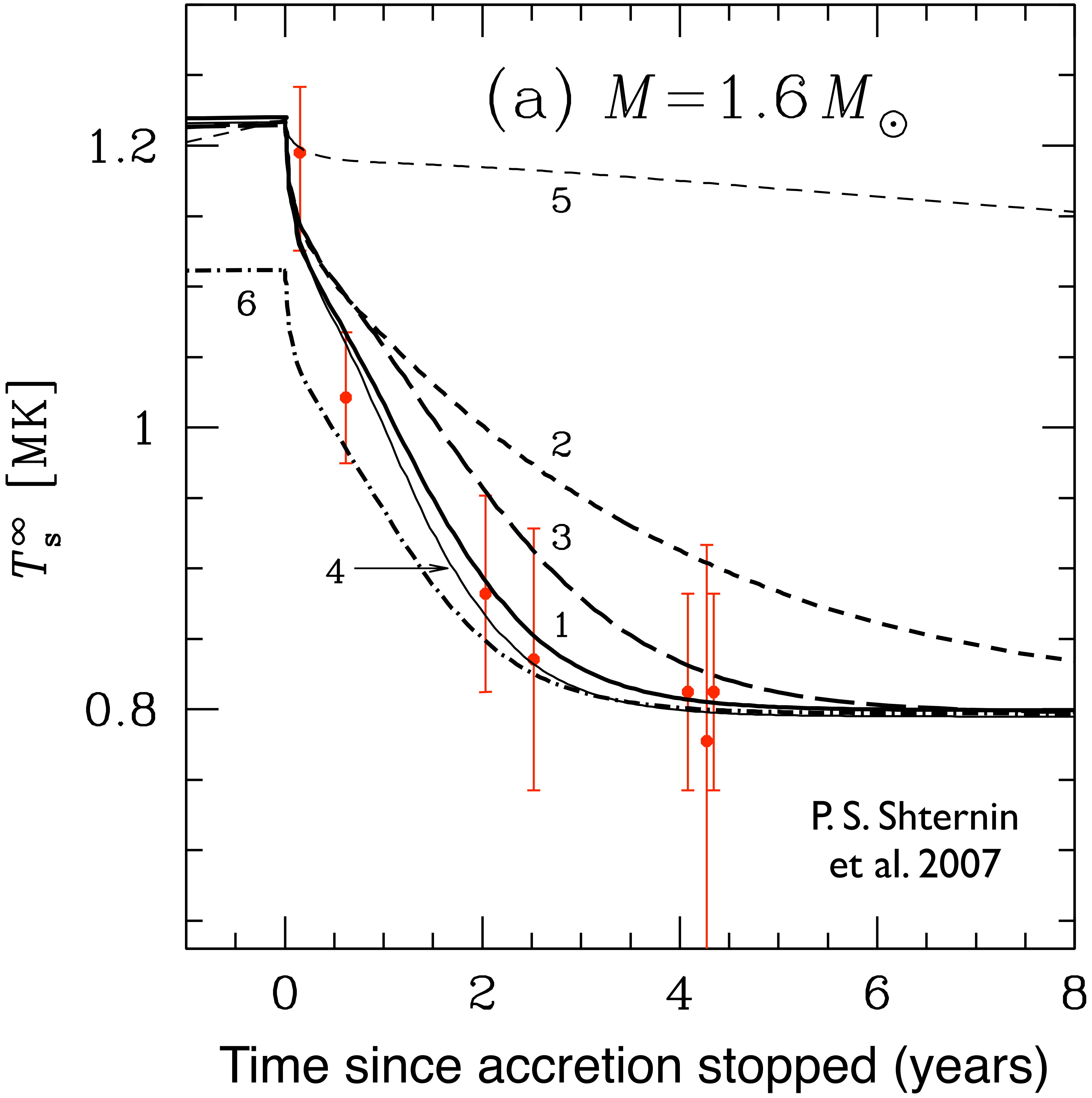
Cooling of KS 1730-260 After Extended Outburst

Curves 1-4 use high crust thermal conductivity (regular lattice) while 5 uses low conductivity (amorphous)

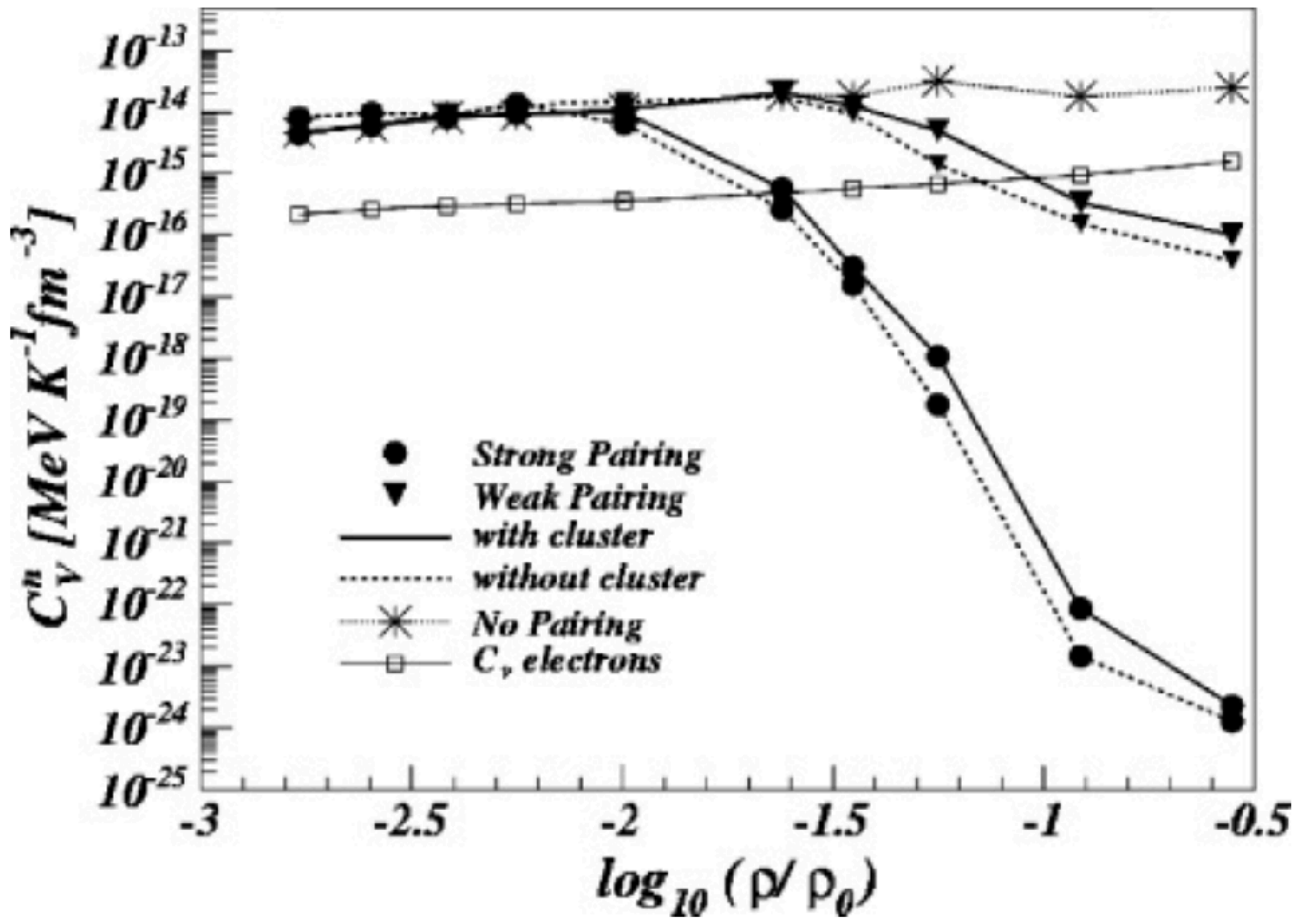
Rapid cooling strongly suggests crust is a clean crystalline solid with high thermal conductivity.

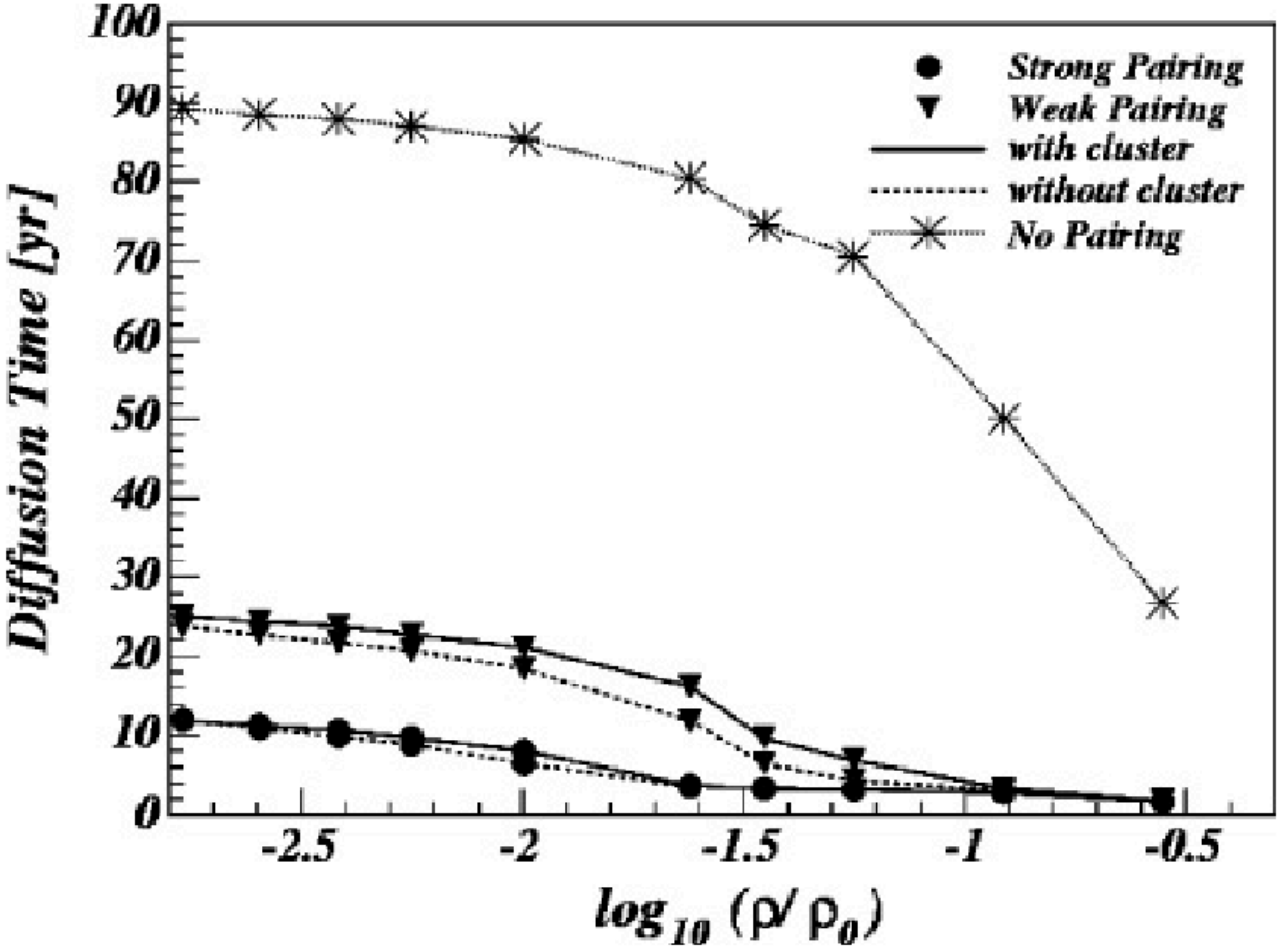
Heat capacity of dripped n gas in crust can be high. This would slow cooling.

Rapid cooling also suggests n gas is superfluid with small heat capacity for T < gap.



P. S. Shternin et al. 2007

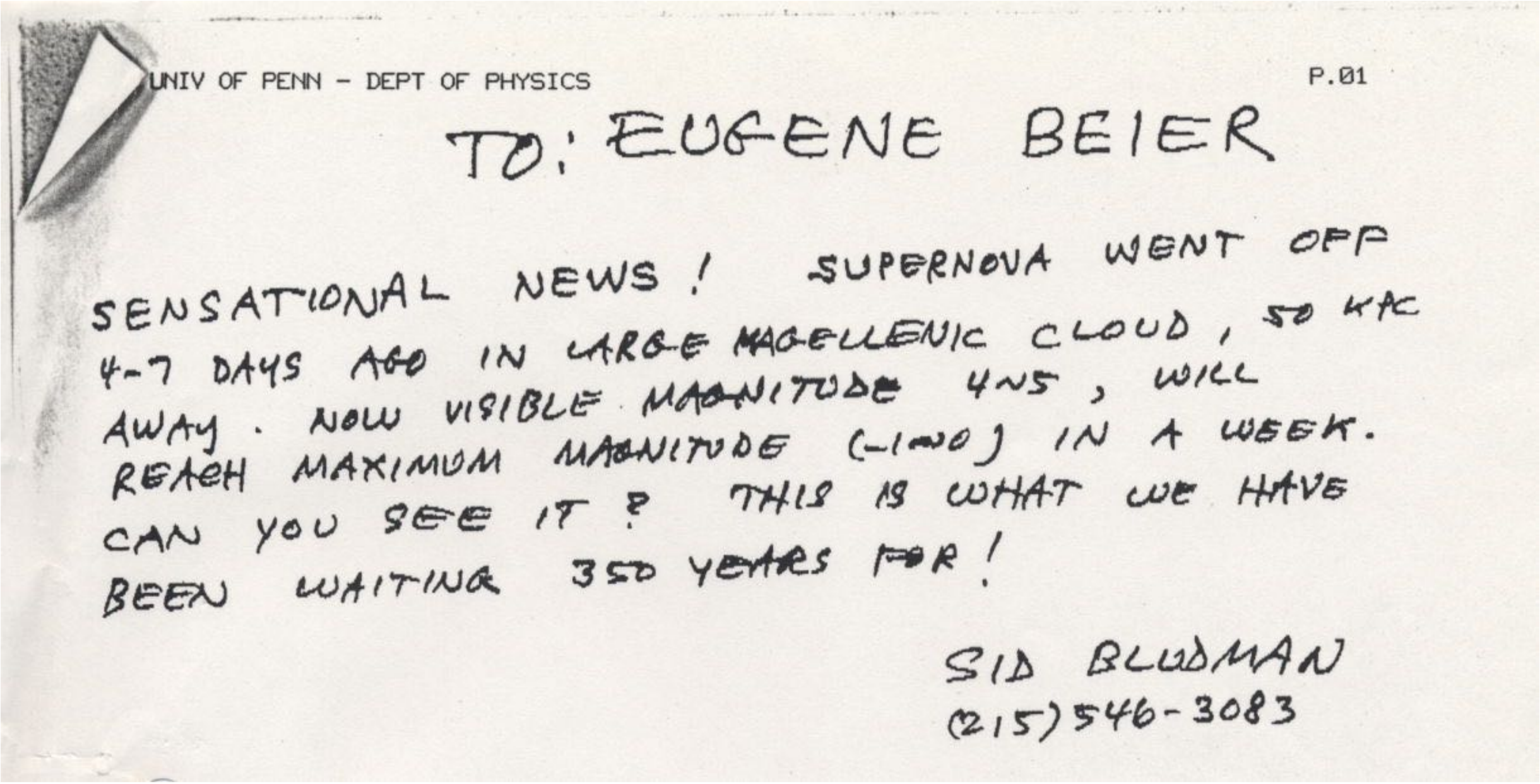

C_V^n [MeV K^{-1} fm^{-3}]
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
-3
-2.5
-2
-1.5
-1
-0.5
$\log_{10}(\rho/\rho_0)$
Strong Pairing
Weak Pairing
with cluster
without cluster
No Pairing
C_v electrons


Diffusion Time [yr]
100
90
80
70
60
50
40
30
20
10
0
-2.5
-2
-1.5
-1
-0.5
$\log_{10}(\rho/\rho_0)$
Strong Pairing
Weak Pairing
with cluster
without cluster
No Pairing

Rotational glitches in pulsars

- Rotational glitches are sudden, small increases in their rotational frequency, typically on the order of 1 part in a million.
- Caused by the interaction between a neutron superfluid inside the star and its rigid solid crust.
- Superfluids carry angular momentum in rotational vortices.
- The superfluid “rotation rate” is related to the number of vortices and need not be the same as the solid crust.
- Vortices can pin to the crust lattice and keep the superfluid spinning at a different rate from the crust.
- Many vortices can unpin all at once leading to small change in the rotation rate of the star, say 1 part in a million. This is a glitch and provides evidence of a superfluid.

Supernovae



UNIV OF PENN - DEPT OF PHYSICS P.01

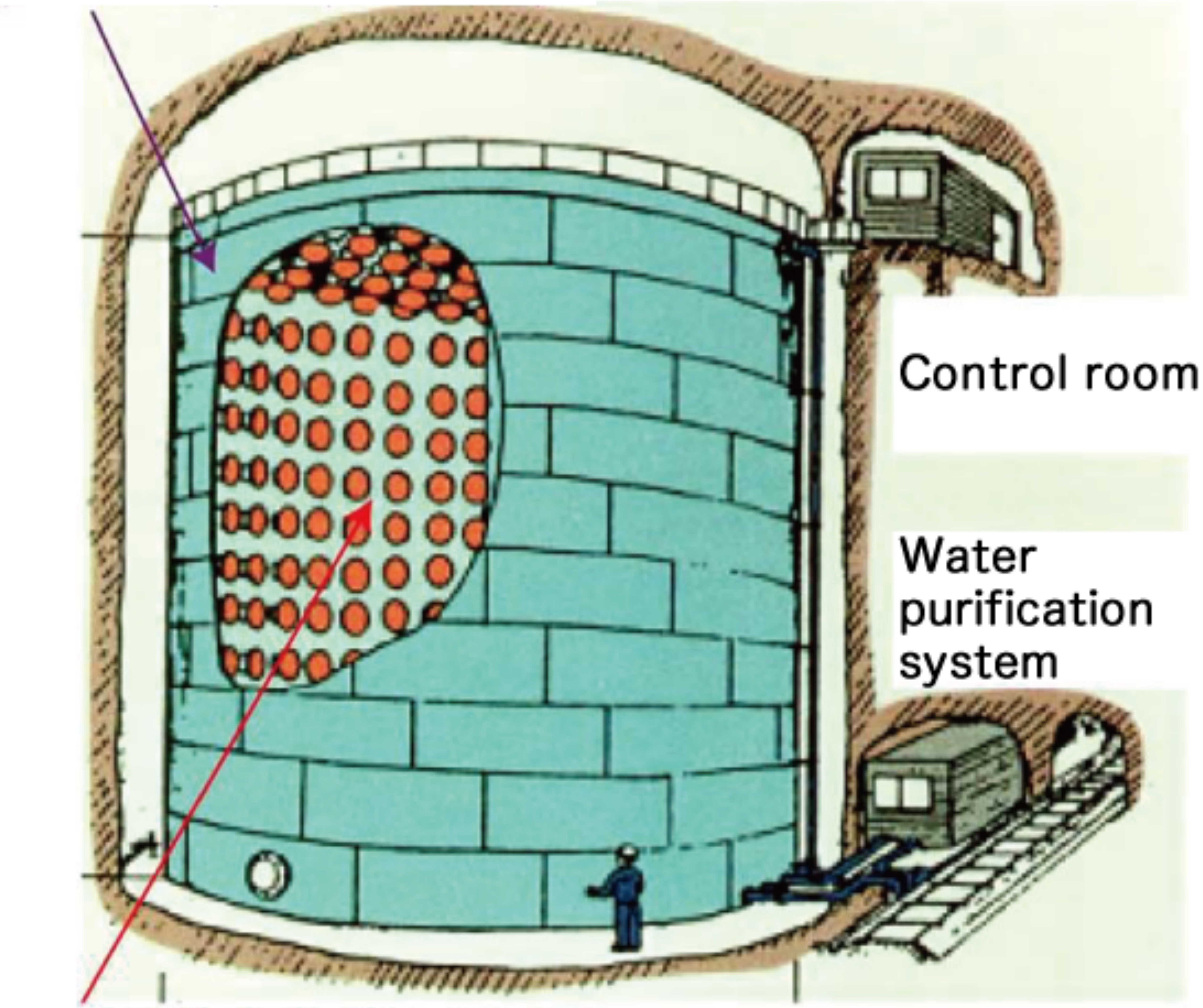
TO: EUGENE BEIER

SENSATIONAL NEWS! SUPERNOVA WENT OFF
4-7 DAYS AGO IN LARGE MAGELLENIC CLOUD, 50 KPC
AWAY. NOW VISIBLE MAGNITUDE 4~5, WILL
REACH MAXIMUM MAGNITUDE (-1~0) IN A WEEK.
CAN YOU SEE IT? THIS IS WHAT WE HAVE
BEEN WAITING 350 YEARS FOR!

SID BLUDMAN
(215) 546-3083

Fax sent Feb. 25, 1987 from U. Penn to U. Tokyo (SN1987a discovered Feb. 23)

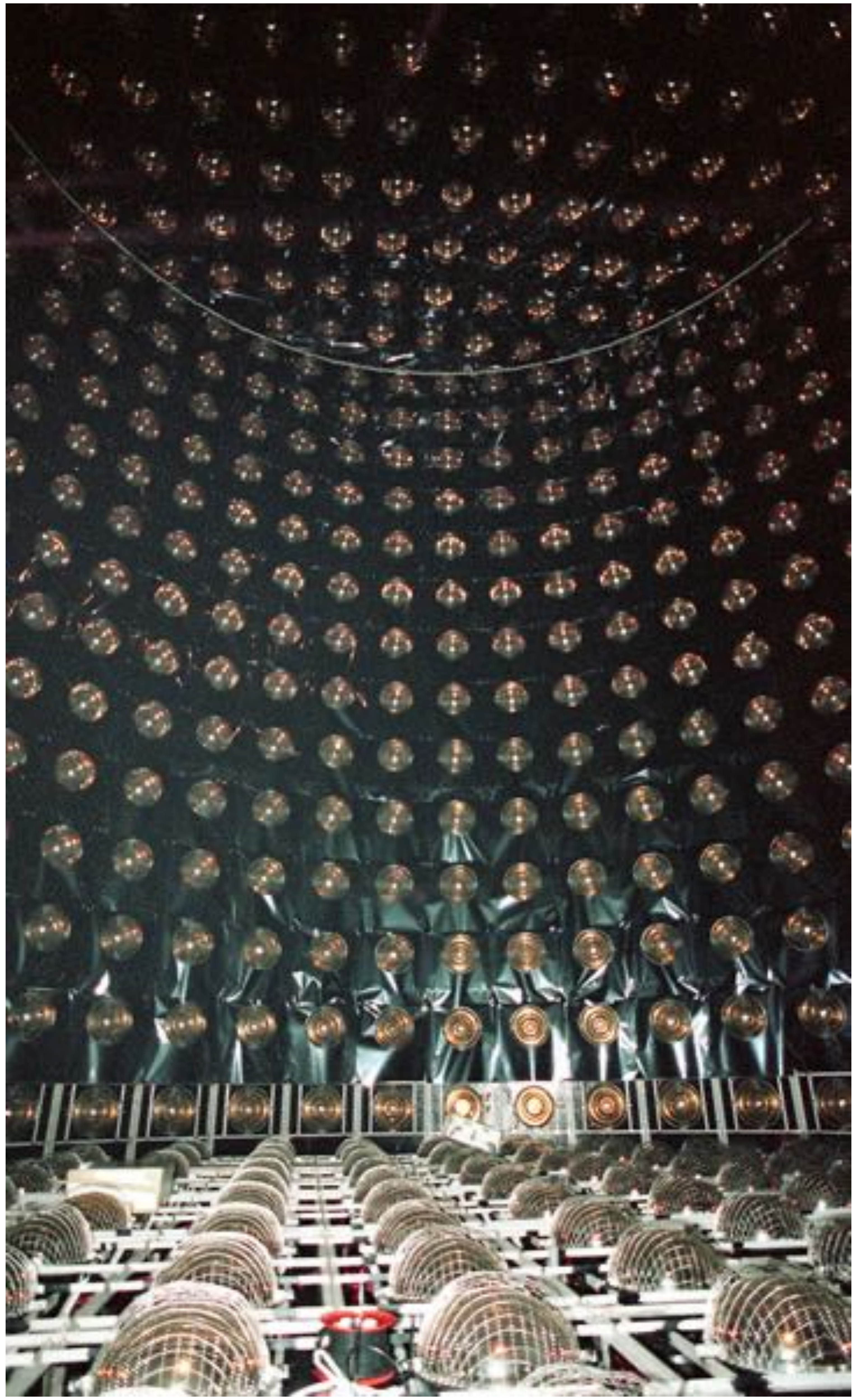
Water tank
Diameter 16 m
Height 16 m



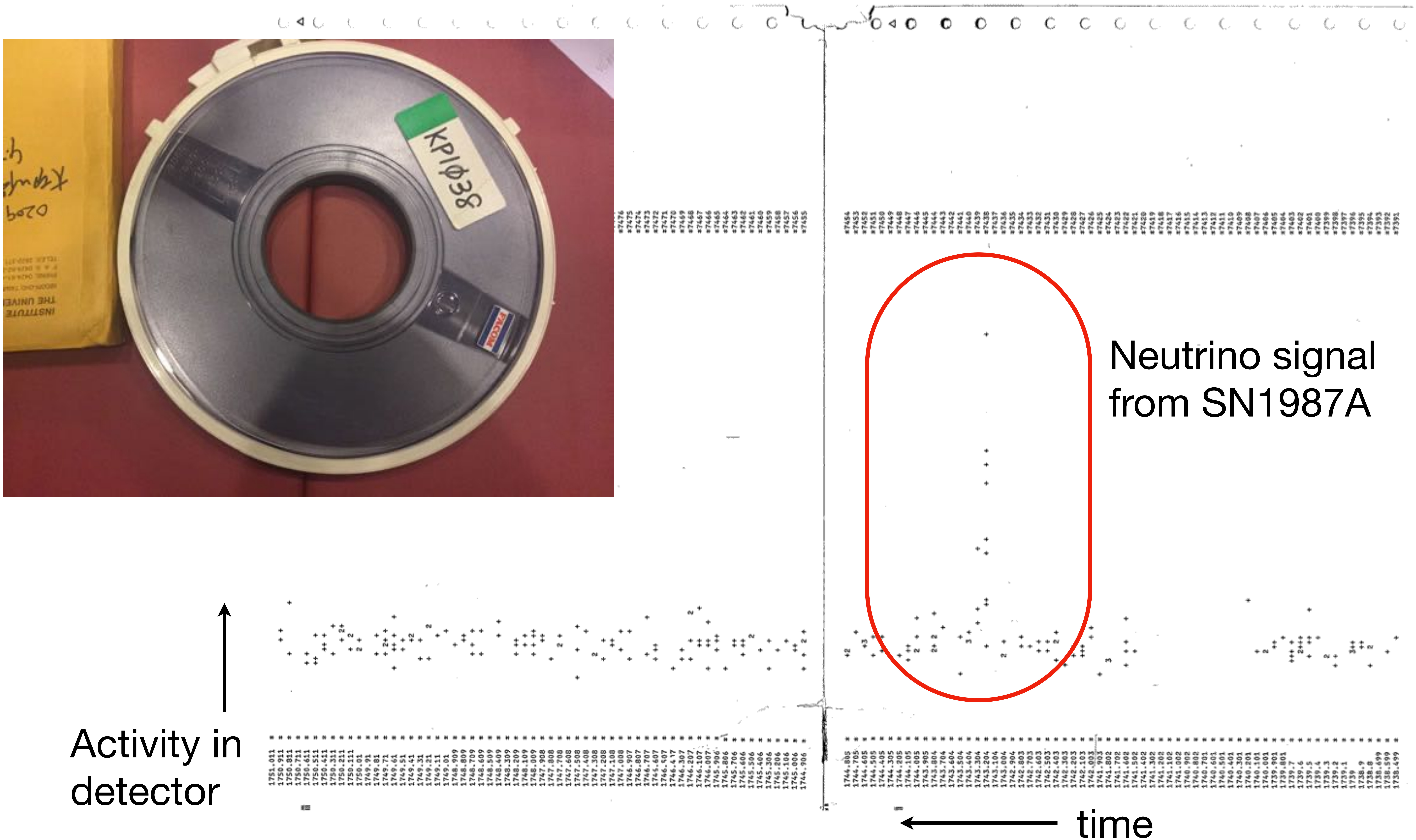
Control room

Water
purification
system

1000 20 inch
Photomultiplier Tubes



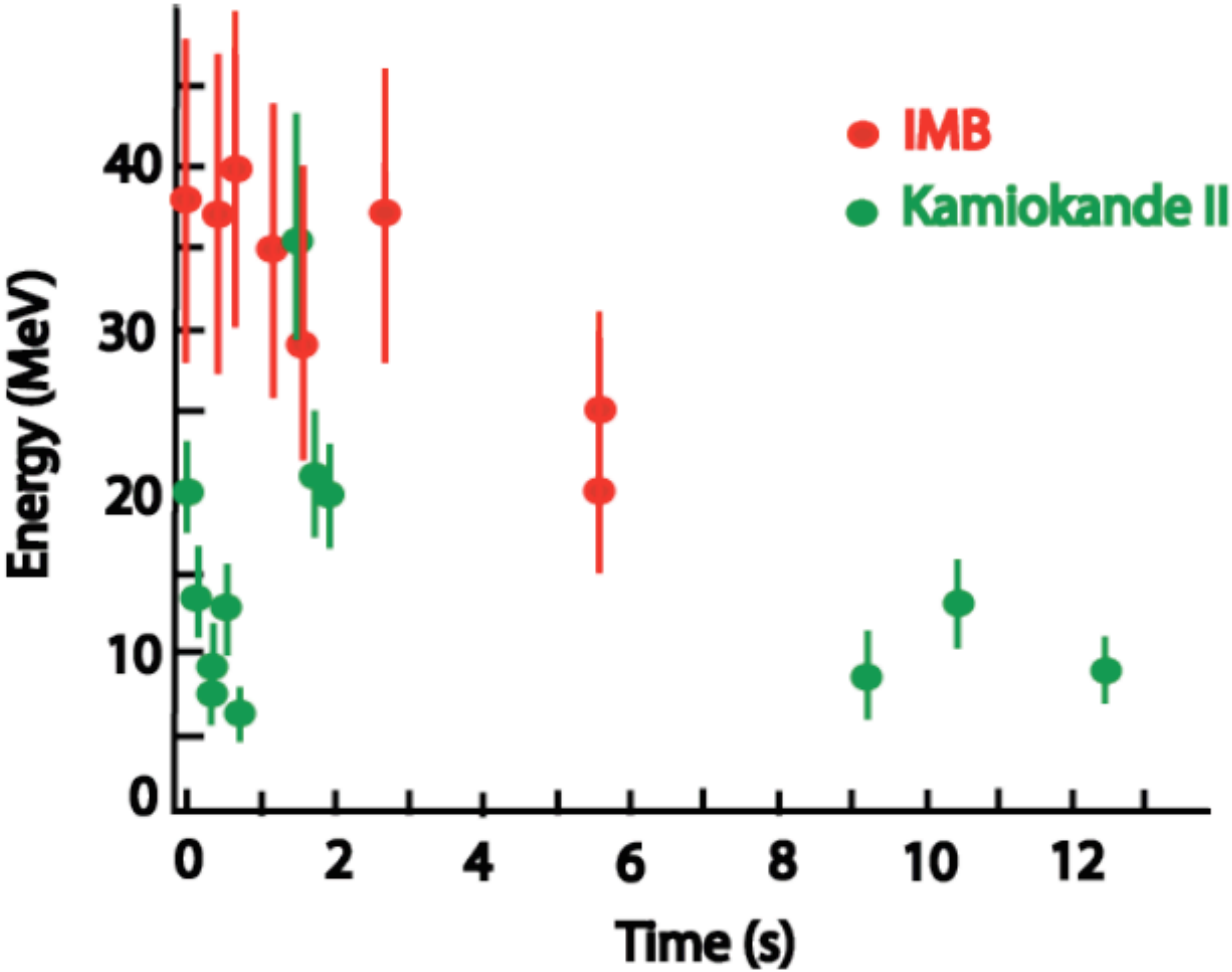
Kamiokande Detector 1000 m underground



Neutrino signal from SN1987A

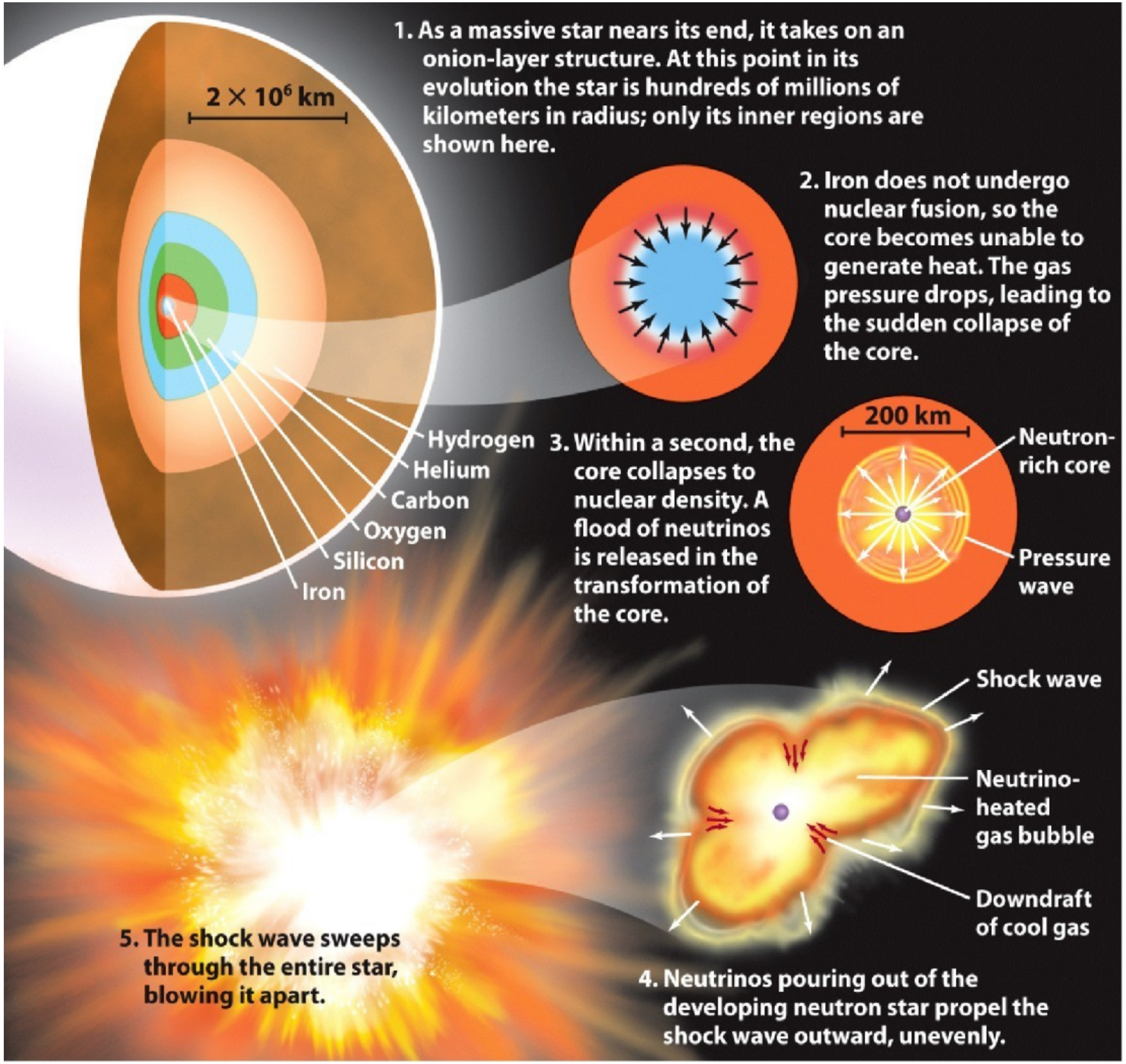
Activity in detector

time


IMB
Kamiokande II
Energy (MeV)
40
30
20
10
0
Time (s)
0
2
4
6
8
10
12

Core collapse Supernova

- Planet sized core of massive star runs out of nuclear fuel and collapses in ms all the way to nuclear density to form proton-neutron star.
- Nuclear incompressibility starts a shock wave which is reenergized by intense neutrino emission.
- Gravitational binding energy of NS ~$0.3 M_{sun} c^2$ radiated as 10^{58} neutrinos.
- Shock wave may eject outer 90% of star to form supernova
- Failed SN: if shock fails to eject rest of start may collapse on proto-NS and form black hole. Black hole formation abruptly ends neutrino emission.



1. As a massive star nears its end, it takes on an onion-layer structure. At this point in its evolution the star is hundreds of millions of kilometers in radius; only its inner regions are shown here.

2. Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, leading to the sudden collapse of the core.

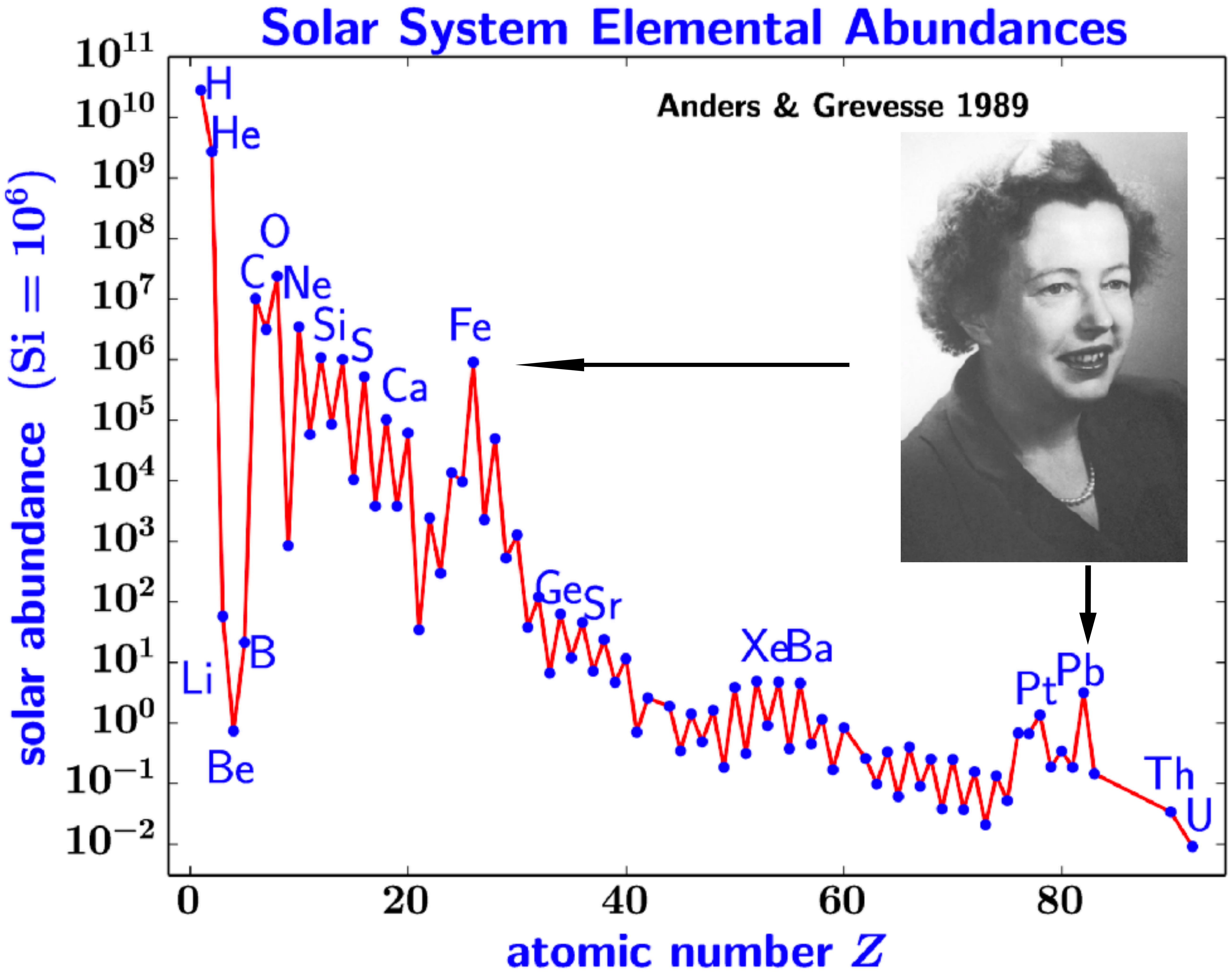
3. Within a second, the core collapses to nuclear density. A flood of neutrinos is released in the transformation of the core.

4. Neutrinos pouring out of the developing neutron star propel the shock wave outward, unevenly.

5. The shock wave sweeps through the entire star, blowing it apart.

Nucleosynthesis

- **Marie Curie,** Nobel 1903: radioactive decay
- **Maria Goeppert Mayer**, Nobel 1963 Nuclear Shell Model. Nuclei with closed neutron or proton shells are particularly stable (like noble gases).
- Supernovae make ^{56}Ni with N=Z=28 (closed shell). This beta decays twice to ^{56}Fe and powers SN light curve.
- About half of the elements heavier than ^{56}Fe, including Au and U, are made in r-process where seed nuclei rapidly capture several neutrons.
- Many textbooks claim r-process in SN.



Supernova light curves

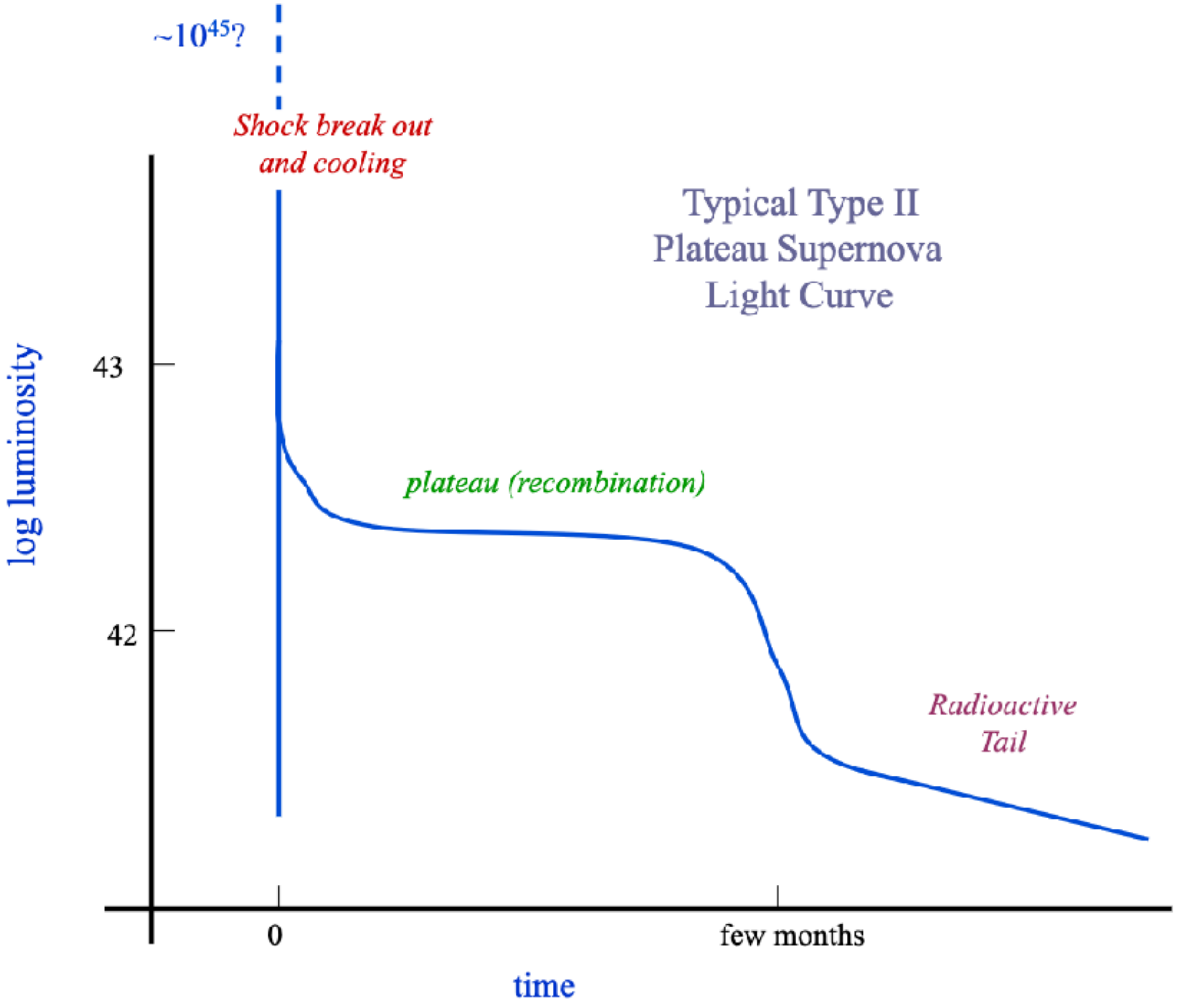
- Are powered by radioactive decay e+^{56}Ni -> ^{56}Co + v with 6 day half-life followed by e+ ^{56}Co -> ^{56}Fe v with 77 day half-life.

- Core collapse SN (such as SN II) are explosions of massive stars that make neutron stars (and some ^{56}Ni).

- Thermonuclear SN (SN Ia) are explosions of white dwarfs that make more ^{56}Ni and no compact objects. SN Ia brighter than SN II

- $E_v \sim 10^{53}$ ergs, $E_{kinetic} \sim 10^{51}$ ergs >> E_{light}

- The light curve will vary depending upon the mass of the envelope, radius of the pre-SN star, energy of the explosion, and mass of ^{56}Ni produced.



Supernova: Macroscopic changing of generations

- Total E of neutrinos radiated = Binding E of NS ~ 3/5 GM^2/R ~ 3×10^{53} ergs
- Average E of each ν $\langle E_\nu \rangle$ ~ 3T ~ 15 MeV
- Total # ν radiated 3e53ergs/15MeV =10^{58}.
- NS has Y_e~0.1 so SN radiates ~10^{57} more ν_e than anti-ν_e.
- Electron Fermi E in NS rises above muon mass producing muon Fermi gas. $k_{fe}=\mu_e=\mu_\mu=(k_{f\mu}{}^2+m_\mu{}^2)^{1/2}$

	Stellar core	ProtoNS during SN	NS
Neutrinos radiated	0	10^{58}	0
Baryon number	10^{57}	10^{57}	10^{57}
Electron number	10^{57}	10^{57}->10^{56}	10^{56}
Muon number	0	0->10^{55}	10^{55}
Tau number	0	0->10^{54}->0	0
Strangeness	0	?	?

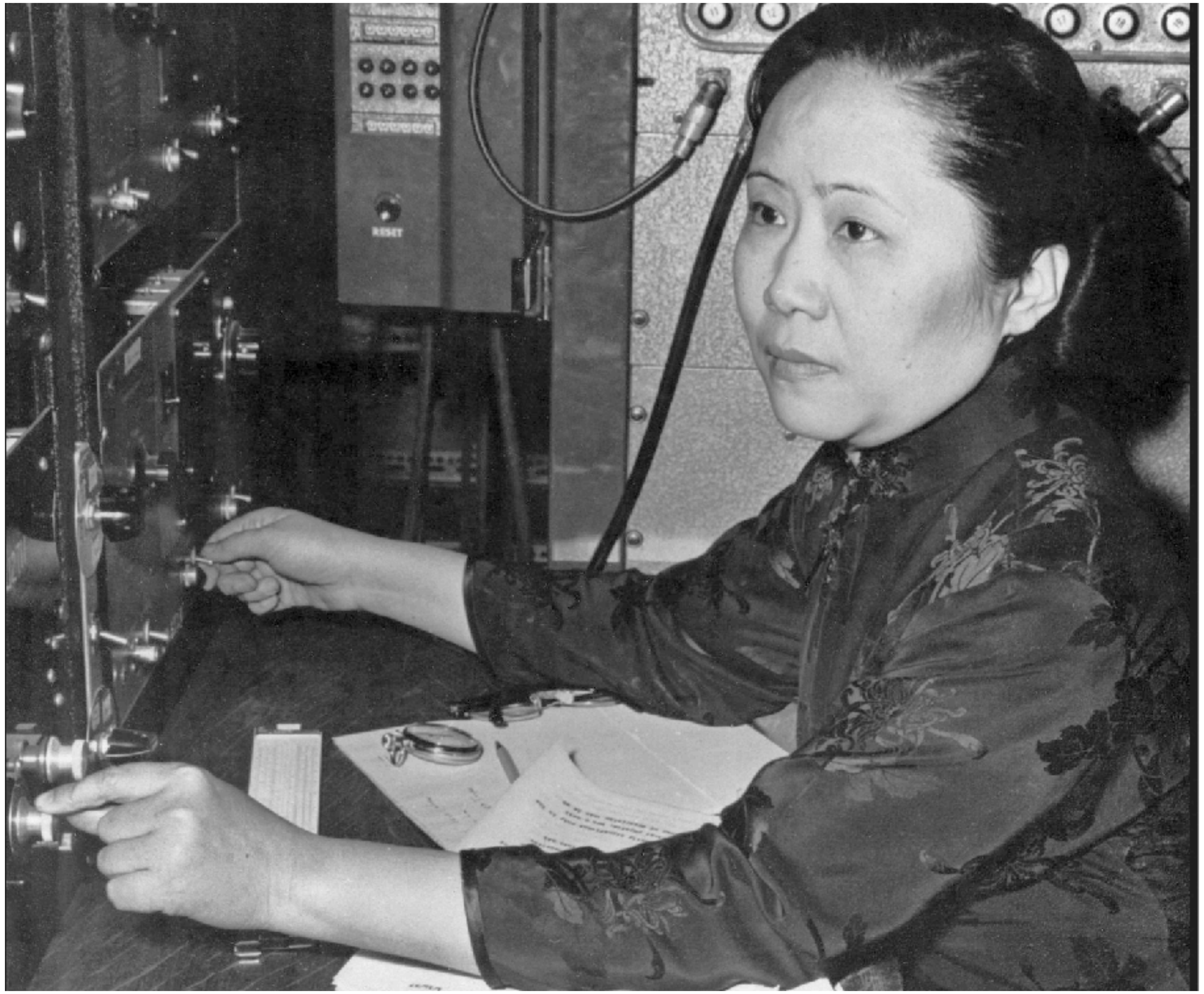
Parity Violation

- **Chien-Shiung Wu** observed that *neutrinos are left-handed* (Lee + Yang won Nobel). Antineutrinos are right-handed.

- Given CP is approximately conserved, P violation -> *C violation*. [This may help explain lack of r-process in SN]

- DUNE (Deep Underground Neutrino Experiment) looks for differences in oscillations of neutrinos and antineutrinos (CP violation)

- Why is Universe made of matter and not anti-matter?



C violation and weak magnetism

- ν-nucleon cross-section for ν energy k << nucleon mass is same for ν and anti-ν

$$\frac{d\sigma_0}{d\Omega} = \frac{G_F^2 k^2}{4\pi^2}[c_v^2(1+\cos\theta) + c_a^2(3-\cos\theta)]$$

$$J_\mu = c_v\gamma_\mu + F_2\frac{i\sigma_{\mu\nu}q^\nu}{2M}$$

- Vector current has weak magnetism part involving F_2. Axial is $c_A\gamma_\mu\gamma_5$

- Cross section to first order in e=k/m is 20% larger for ν(+) than anti-ν (-)

$$\frac{d\sigma}{d\Omega} \approx \frac{d\sigma_0}{d\Omega}\left[1 + \left(\pm\frac{4c_a(c_v+F_2)}{c_v^2(1+x)+c_a^2(3-x)} - 3\right)e(1-x)\right]$$

Example: k=25 MeV, k/M=0.025

$\sigma=\sigma_0$(1+/- 4*0.025) = 1+/- 10%

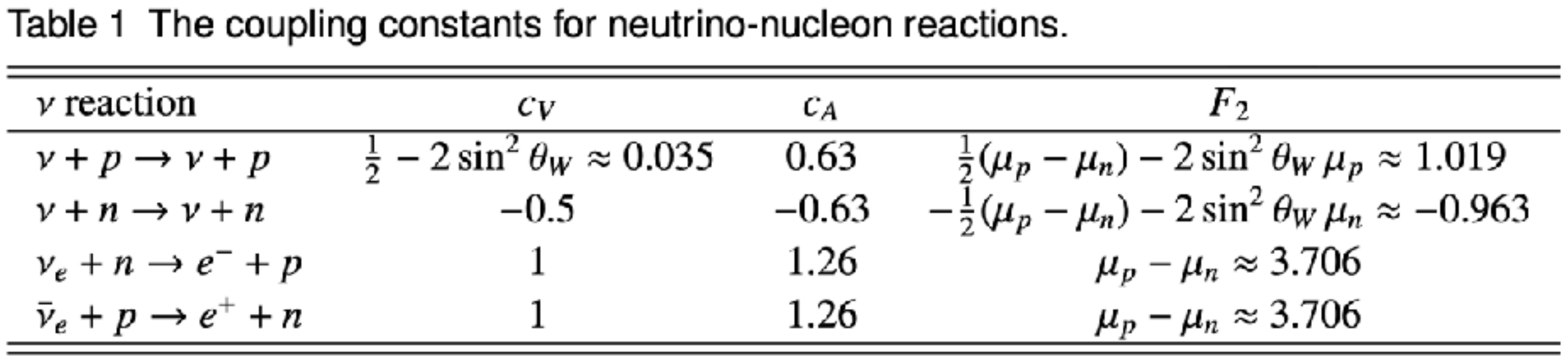


Table 1 The coupling constants for neutrino-nucleon reactions.

ν reaction	c_V	c_A	F_2
$\nu + p \to \nu + p$	$\frac{1}{2} - 2\sin^2\theta_W \approx 0.035$	0.63	$\frac{1}{2}(\mu_p - \mu_n) - 2\sin^2\theta_W\,\mu_p \approx 1.019$
$\nu + n \to \nu + n$	-0.5	-0.63	$-\frac{1}{2}(\mu_p - \mu_n) - 2\sin^2\theta_W\,\mu_n \approx -0.963$
$\nu_e + n \to e^- + p$	1	1.26	$\mu_p - \mu_n \approx 3.706$
$\bar{\nu}_e + p \to e^+ + n$	1	1.26	$\mu_p - \mu_n \approx 3.706$

Tau number during a SN

- Equal #s of tau and anti-tau neutrinos are produced in for example $e^+ + e^- \rightarrow \nu_\tau$ + anti-ν_τ
- Anti-ν have smaller cross sections on nucleons than do ν so they escape the star faster.
- This leaves the star neutrino rich with a nonzero tau number while the proto-NS is hot.
- This tau number escapes the star when the proto-NS cools off.

PLB **443** (1998) 58

Nucleosynthesis in nu driven wind

- Intense neutrino wind blows nucleons off of proto-neutron star.
- Ratio of neutrons to protons in wind set by rates of nu and anti-nu capture.
- Weak magnetism makes neutrino cross section 20% larger than anti-nu cross section.
- This prevents wind from being n rich enough for r-process synthesis of heaviest elements [Gang Li + CJH, PRL **82**, 5198]
- => Gold, Uranium not made in SN.

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

$$\bar{\nu}_e + p \longrightarrow n + e^+$$

Supernova as 10^{58} qubit quantum computer

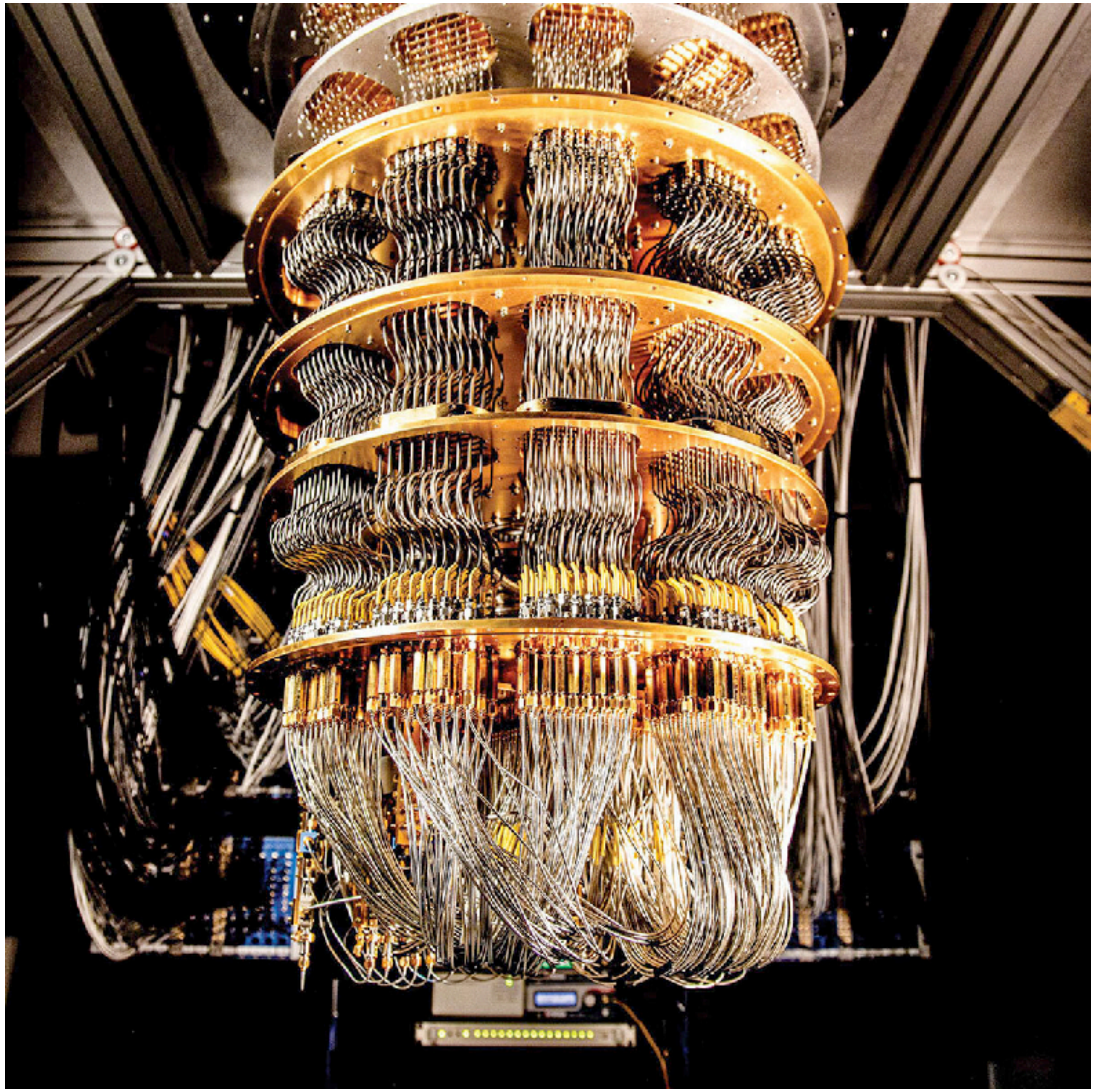
- Bare electrons (spin up or down) make poor qubits because they interact strongly with surroundings. Neutral atoms have weaker interactions and may make better qubits.

- Neutrinos with very weak interactions may make perfect qubits! They have spin and flavor (e, mu, tau) degrees of freedom. Supernova radiates 10^{58} neutrinos.

- Neutrinos interact with other neutrinos and may change flavor -> Neutrino oscillations. These oscillations are non-linear because they depend on flavor of other neutrinos which are also oscillating.

- Some simulations of SN nu oscillations run on present modest quantum computers.

- How to "read out quantum computing results" ie detect neutrino flavors on earth?



Supernova neutrino detectors

- **Anti-ν_e detectors** (events SN / 10 kpc)
  - Super-K H_20+Gd ~7,000
  - JUNO $(CH_2)_n$ ~7,000
  - Hyper-K H_20 ~53,000

$$\bar{\nu}_e + p \rightarrow n + e^+$$

(Inverse beta decay)

- **ν_e detectors**
  - DUNE Ar ~3,000

ν_e + Ar -> e + X

- **Coherent ν_x detectors (dark matter)**
  - Darwin Xe ~1000
  - DarkSide 20k Ar ~300
  - PandaX-4T Xe ~100 …

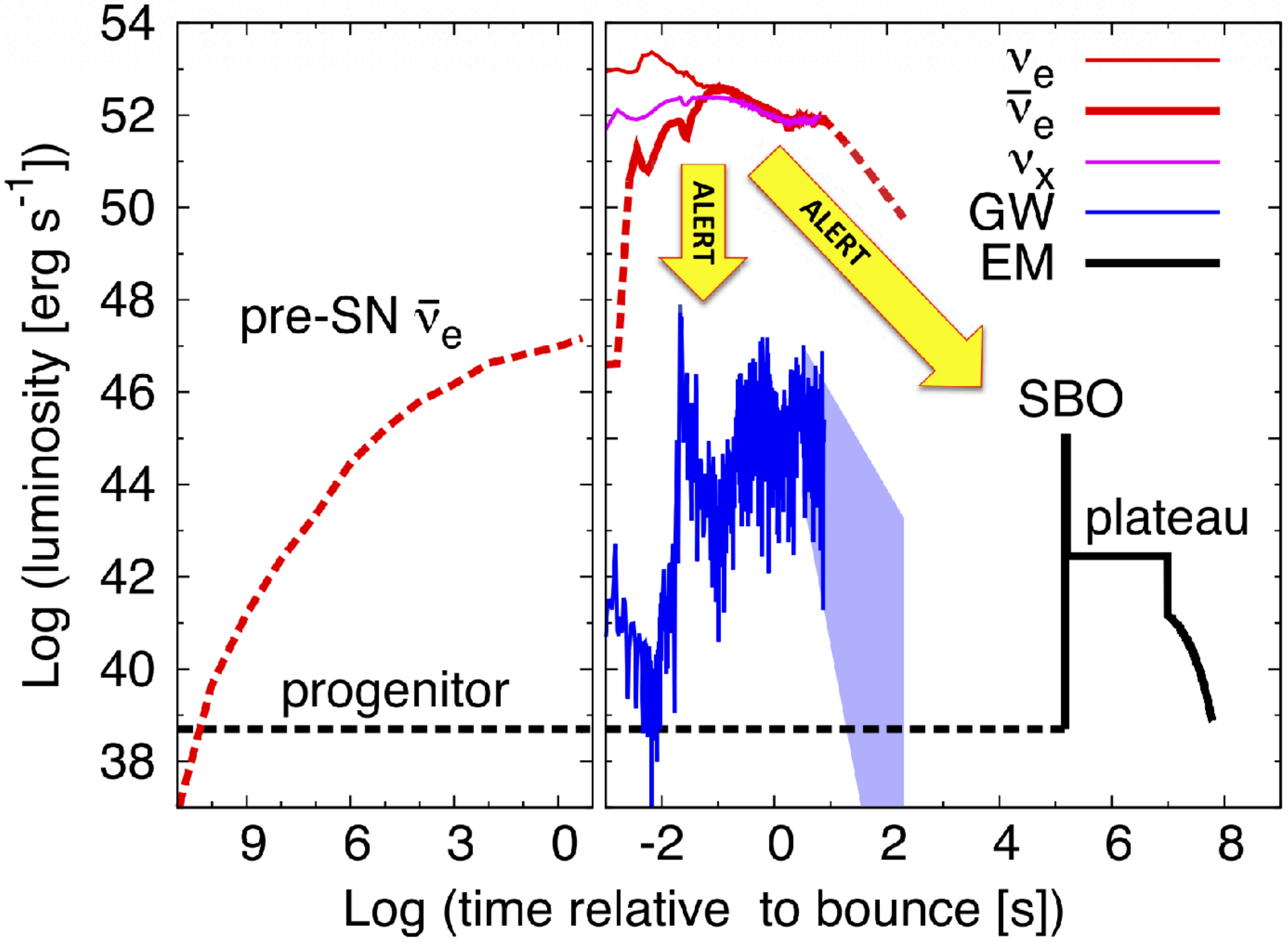
ν_x + A -> ν_x + A

- Coherent neutrino-nucleus scattering (Rex Tayloe at SNS …) detect low energy nuclear recoil.
  - Large cross section ~N^2
  - All nu flavors x 6 compared to IBD
  - All detector mass (not just H) x 9 compared to H_2O
- ==> Tens of **events per ton** compared to hundreds of **events per kiloton**. [CJH, K Coakley, D McKinsey PRD **68**, 023005]

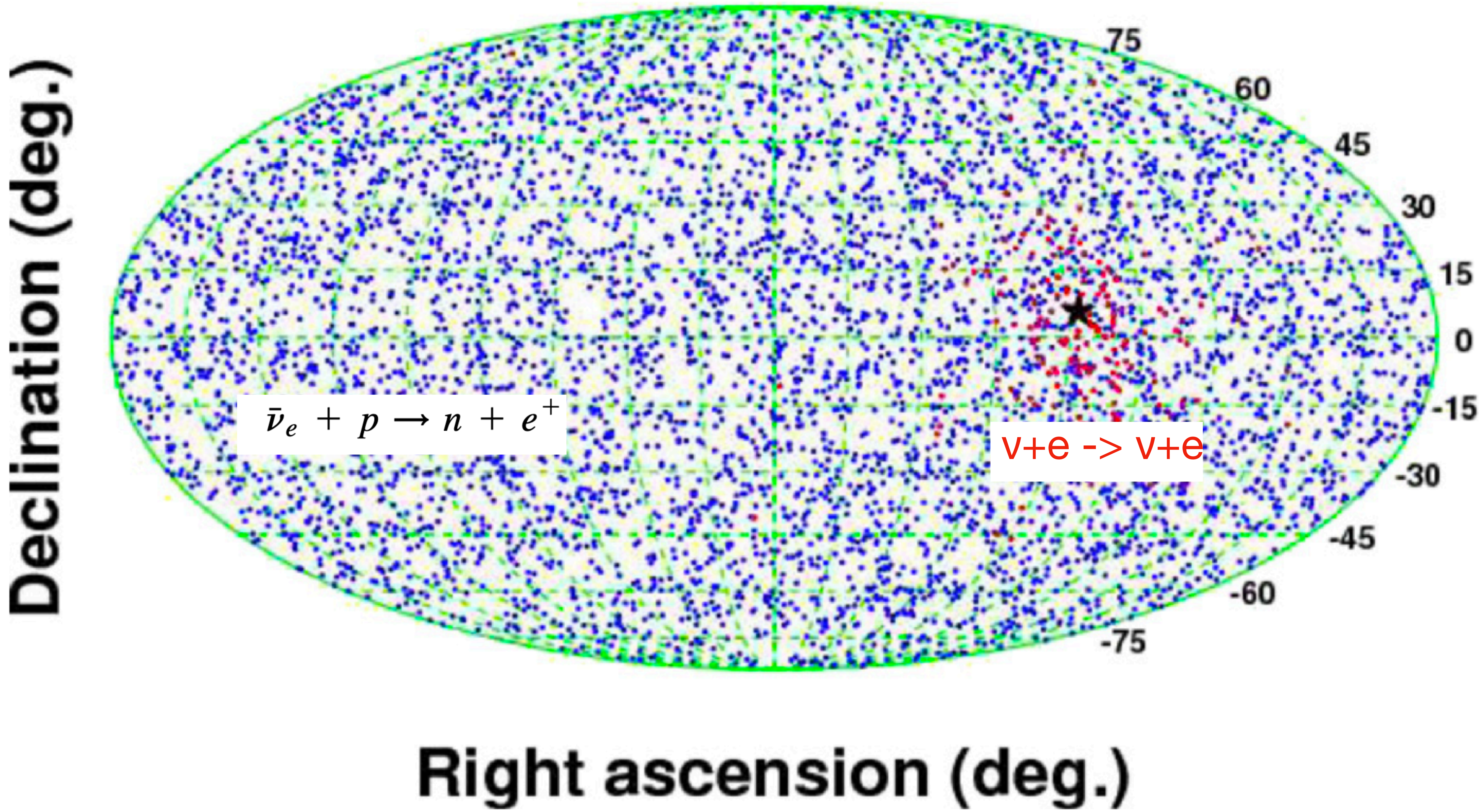
Supernova Neutrino Early Warning System

- SNEWS: Network of neutrino detectors that sends an alert if a neutrino burst is seen in two or more detectors.
- **In 21st century there have been no alerts.**
- Supernovae are rare in our galaxy.
- Set limits on *silent* supernovae

Kate Scholberg is (im)patiently waiting


Log (luminosity [erg s^{-1}])
54
52
50
48
46
44
42
40
38
Log (time relative to bounce [s])
9
6
3
0
-2
0
2
4
6
8
pre-SN $\bar{\nu}_e$
progenitor
ALERT
ALERT
ν_e
$\bar{\nu}_e$
ν_x
GW
EM
SBO
plateau

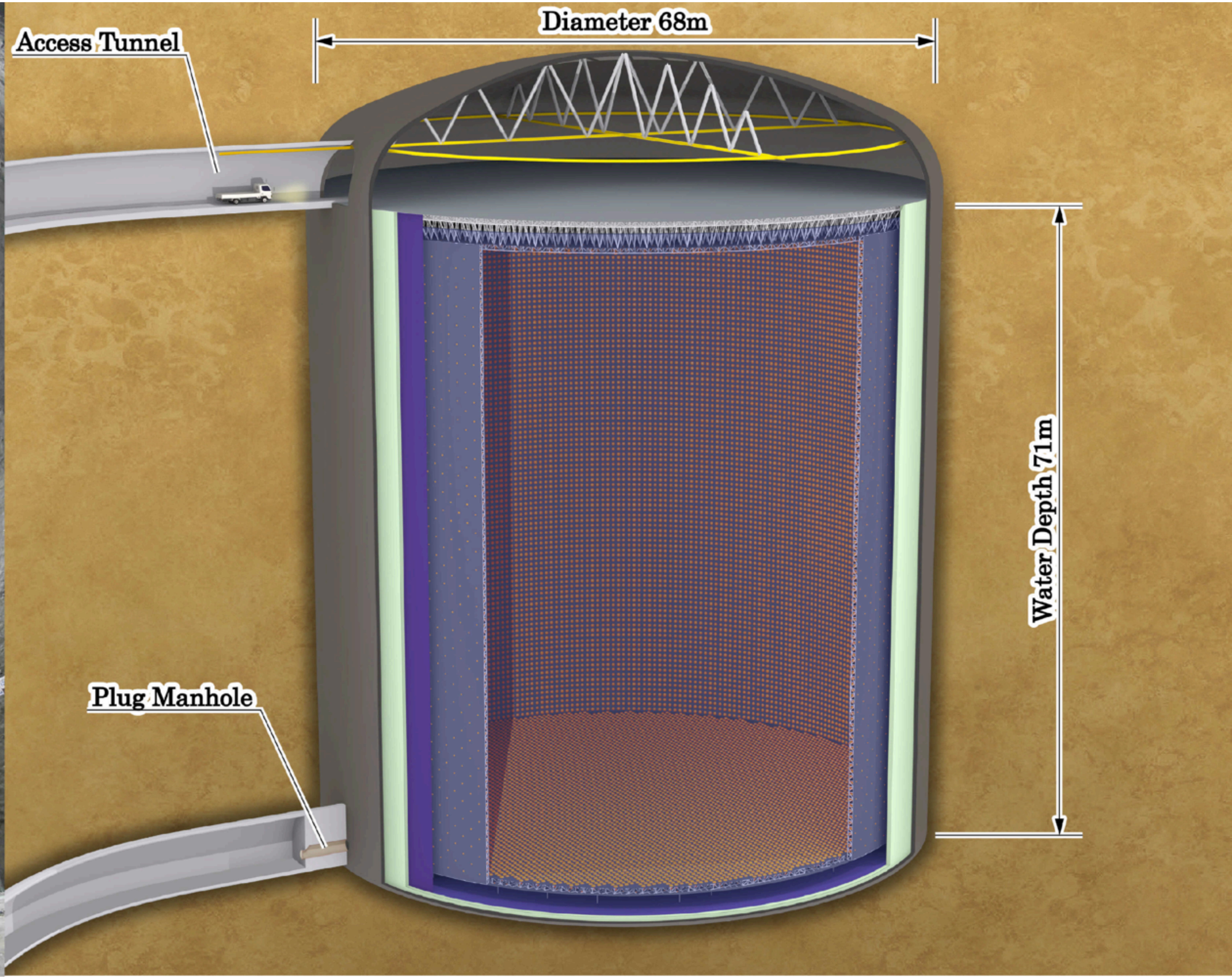
Pointing to Supernova with Neutrinos

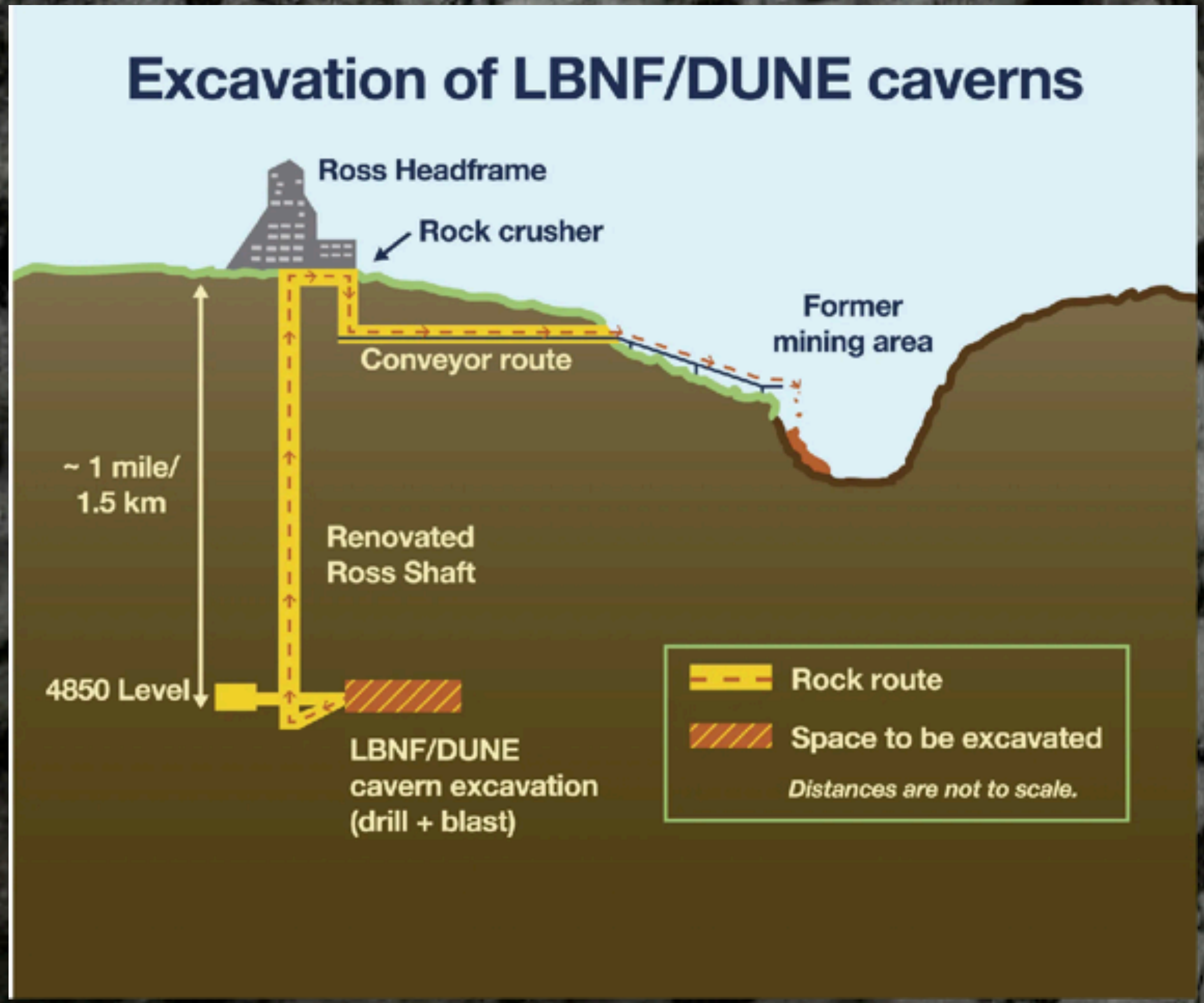


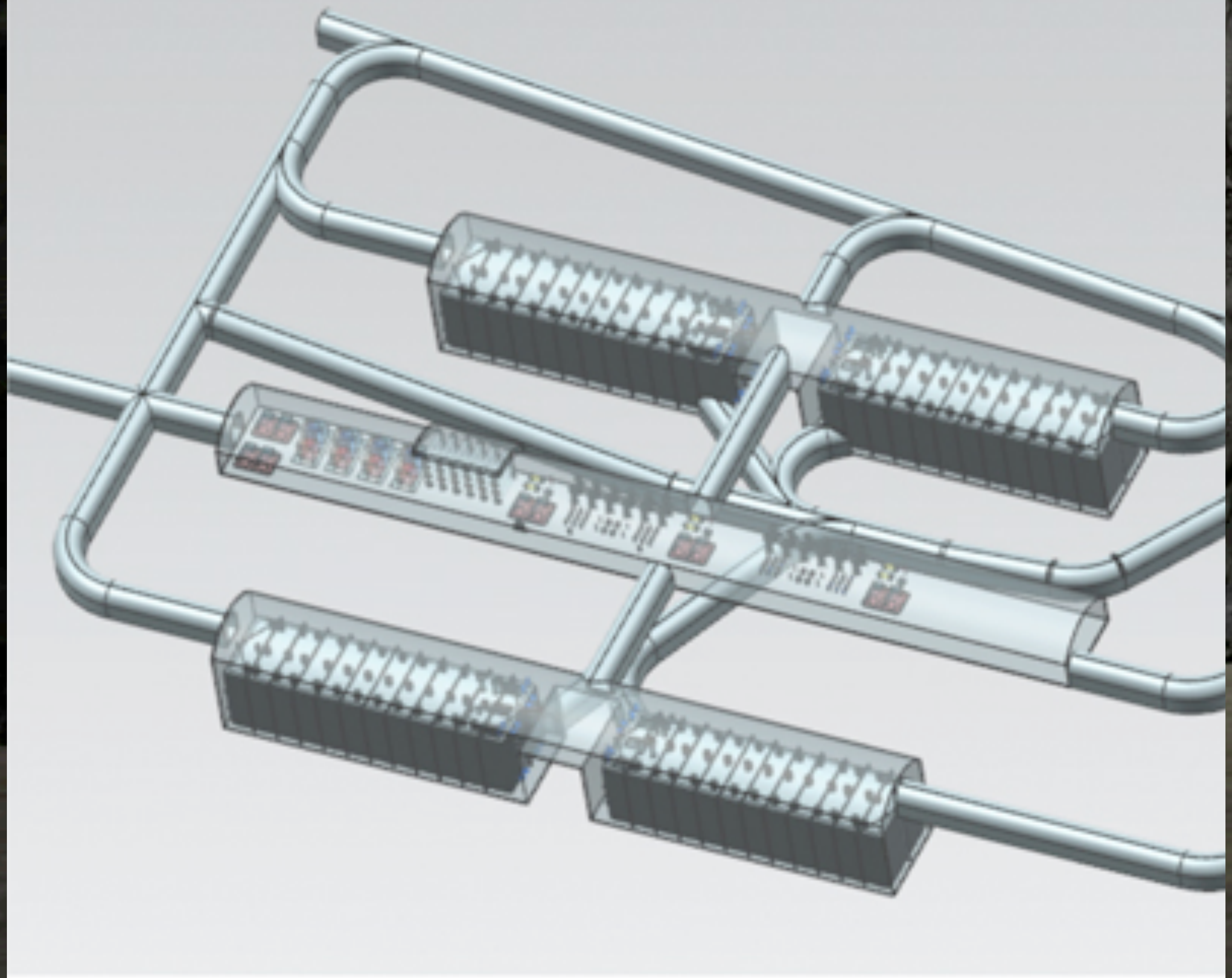
$\bar{\nu}_e + p \rightarrow n + e^+$

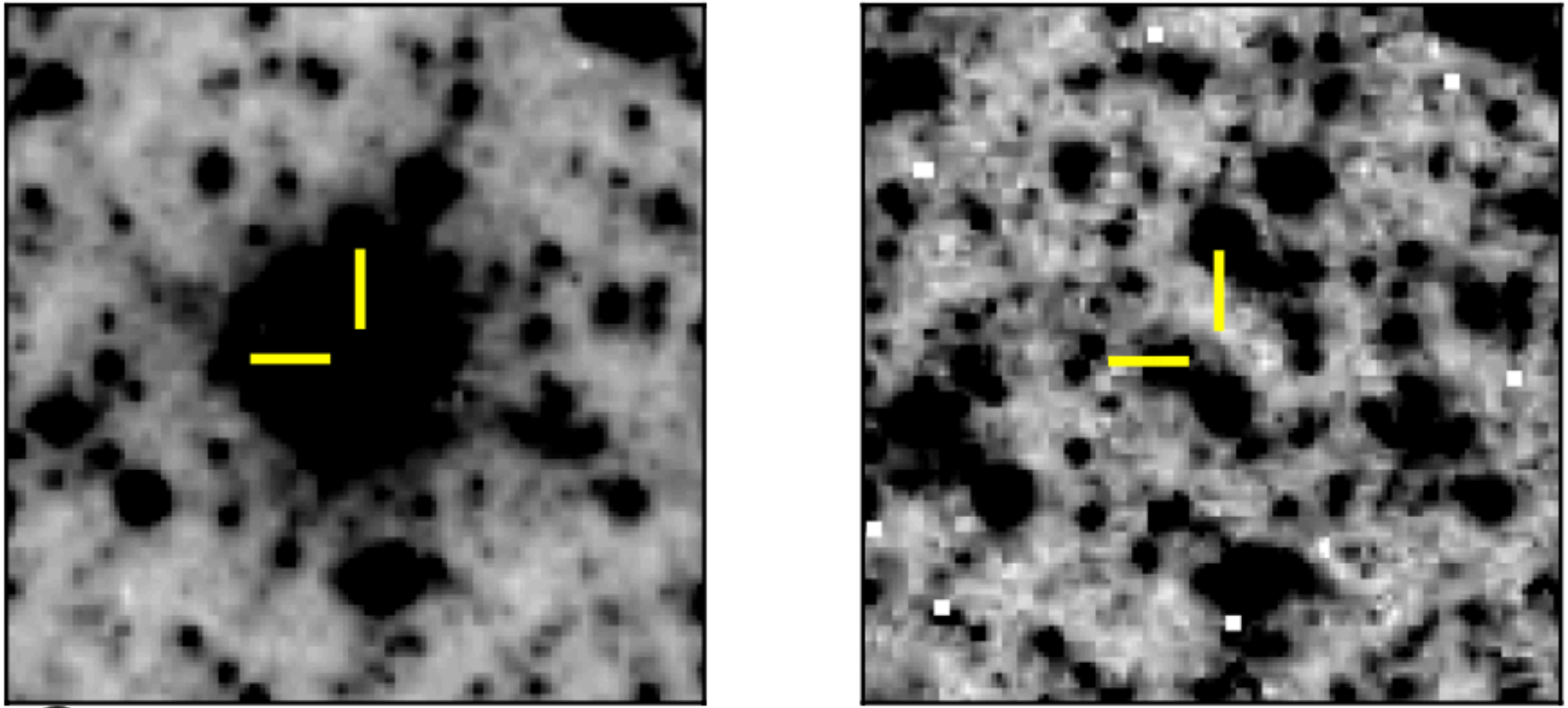
v+e -> v+e

Simulated events in Super-K showing v+e -> v+e (red) pointing to SN and IBD blue


Access Tunnel
Diameter 68m
Water Depth 71m
Plug Manhole


Excavation of LBNF/DUNE caverns
Ross Headframe
Rock crusher
Former mining area
Conveyor route
~ 1 mile/ 1.5 km
Renovated Ross Shaft
4850 Level
LBNF/DUNE cavern excavation (drill + blast)
Rock route
Space to be excavated
Distances are not to scale.





G HST 2012 (0.8 µm)

H HST 2022 (0.8 µm)

Disappearance of a massive star in M31 galaxy

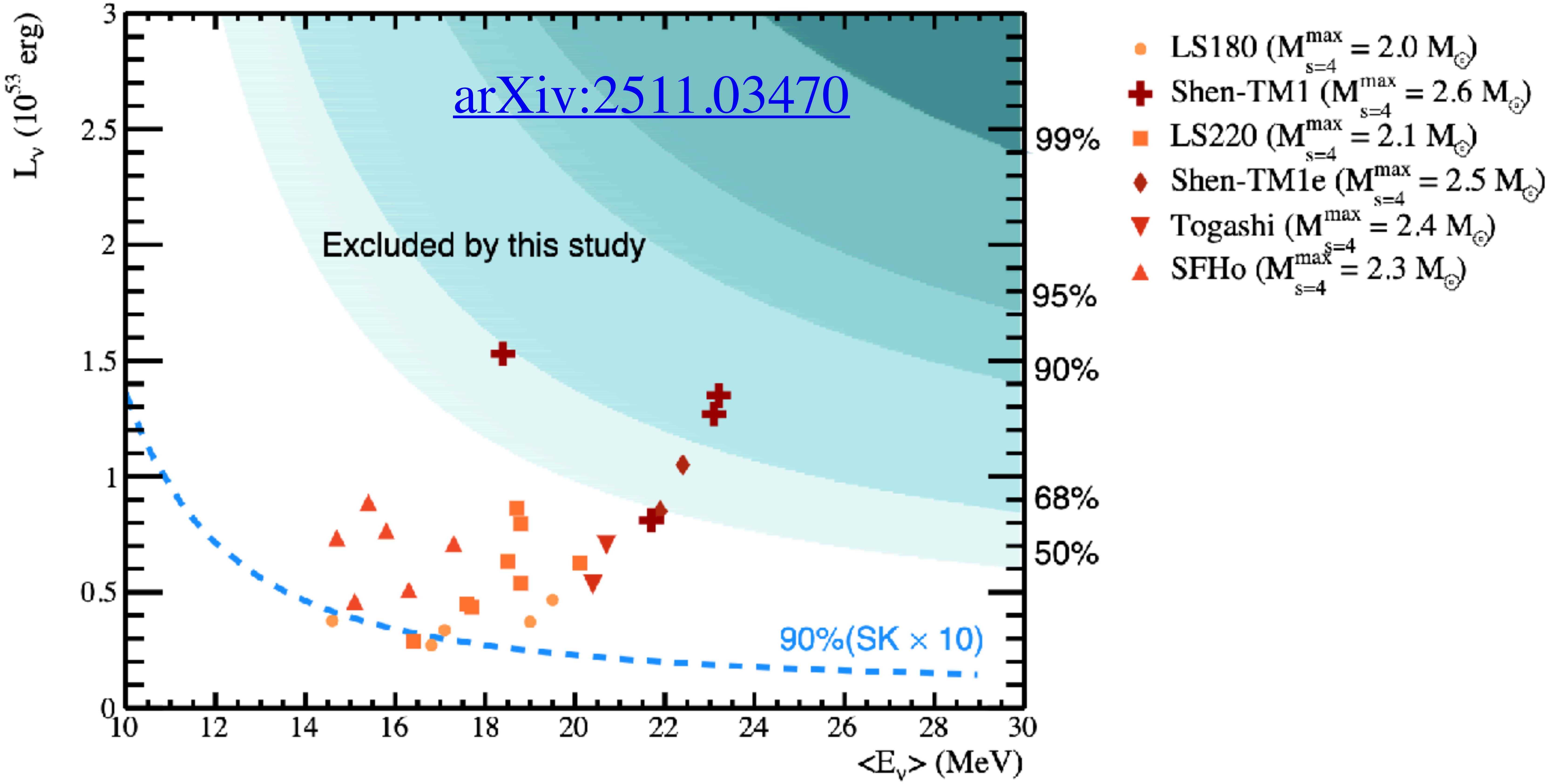


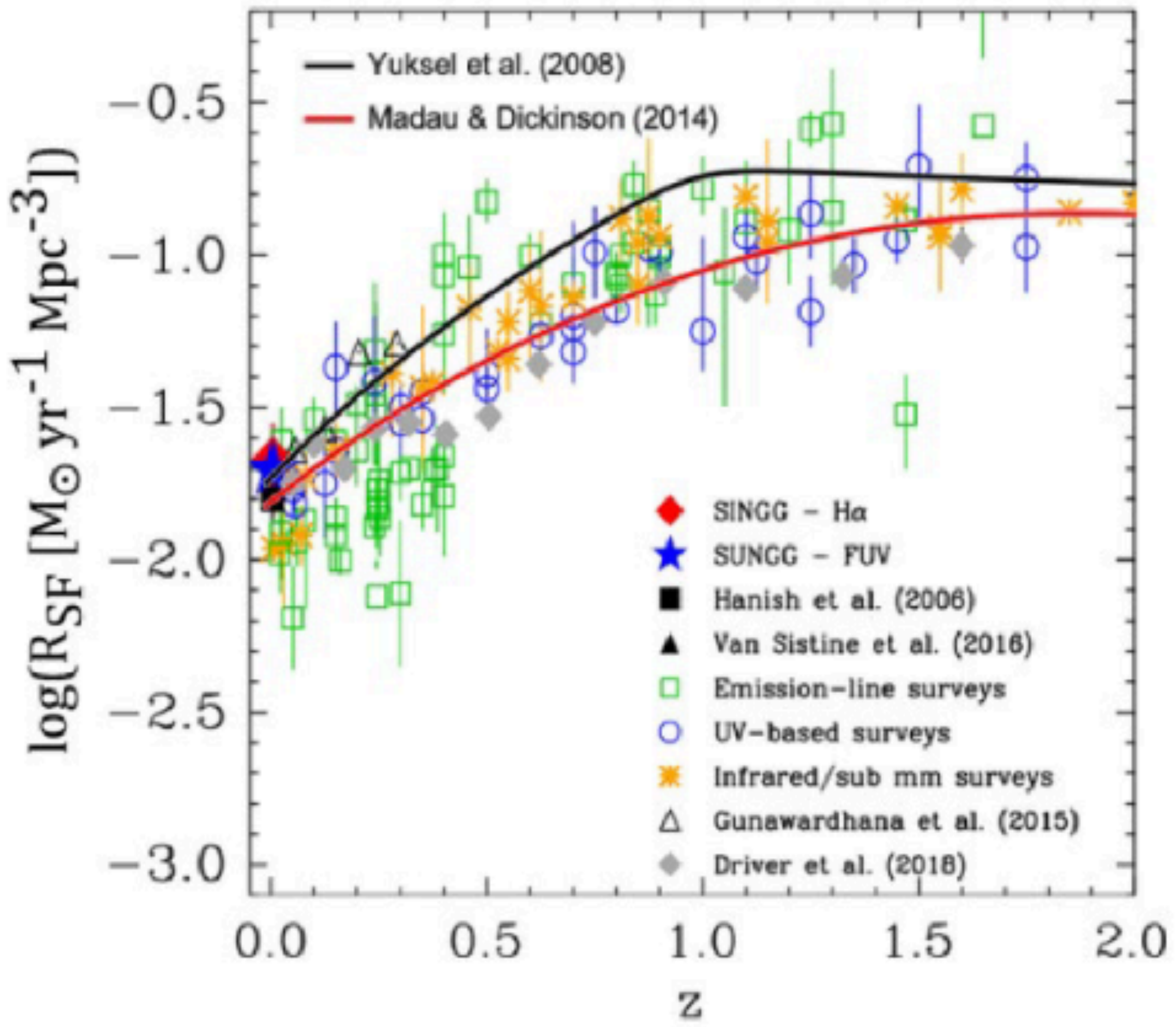
Figure 4. Electron antineutrino luminosity L_ν versus mean energy $\langle E_{\bar{\nu}_e} \rangle$. Shaded regions (light to dark cyan) represent the probability contours (50%, 68%, 90%, 95%, and 99%) for detecting at least two correlated events in SK, based on Poisson statistics for a source located at 770 kpc. The regions above these bands are excluded based on the nondetection of time-clustered events in SK. Filled markers show individual simulation results for six nuclear equations of state (EOS): LS180, LS220, SFHo, Togashi, Shen-TM1e, and Shen-TM1. Each model corresponds to Figure 1 and Table 1 in Y. Suwa et al. (2025). The blue dashed line indicates the 90% probability contour for a detector with ten times the fiducial mass of SK, assuming Poisson statistics for a source at the distance of 770 kpc.

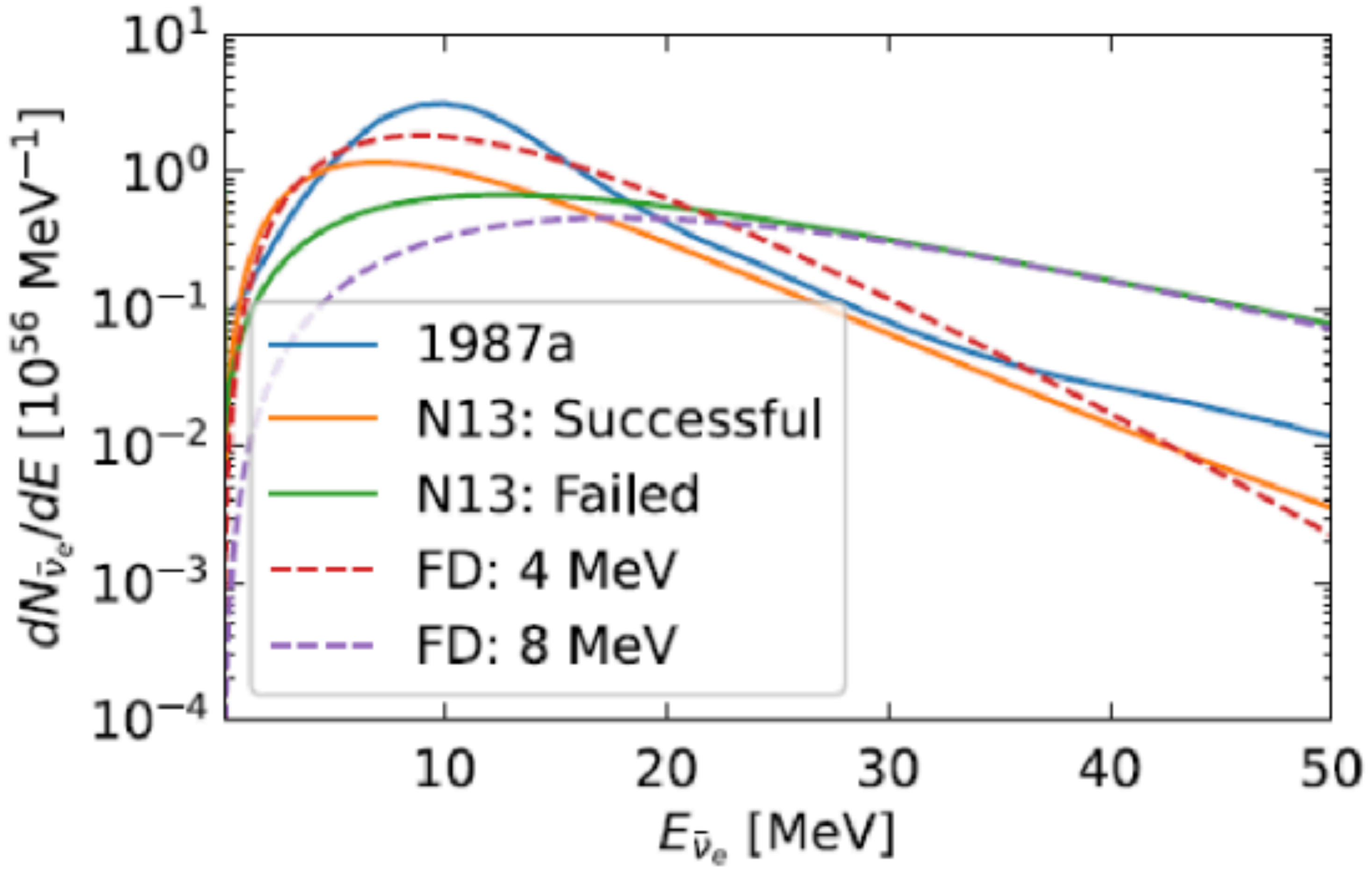
Diffuse Supernova Neutrino Background

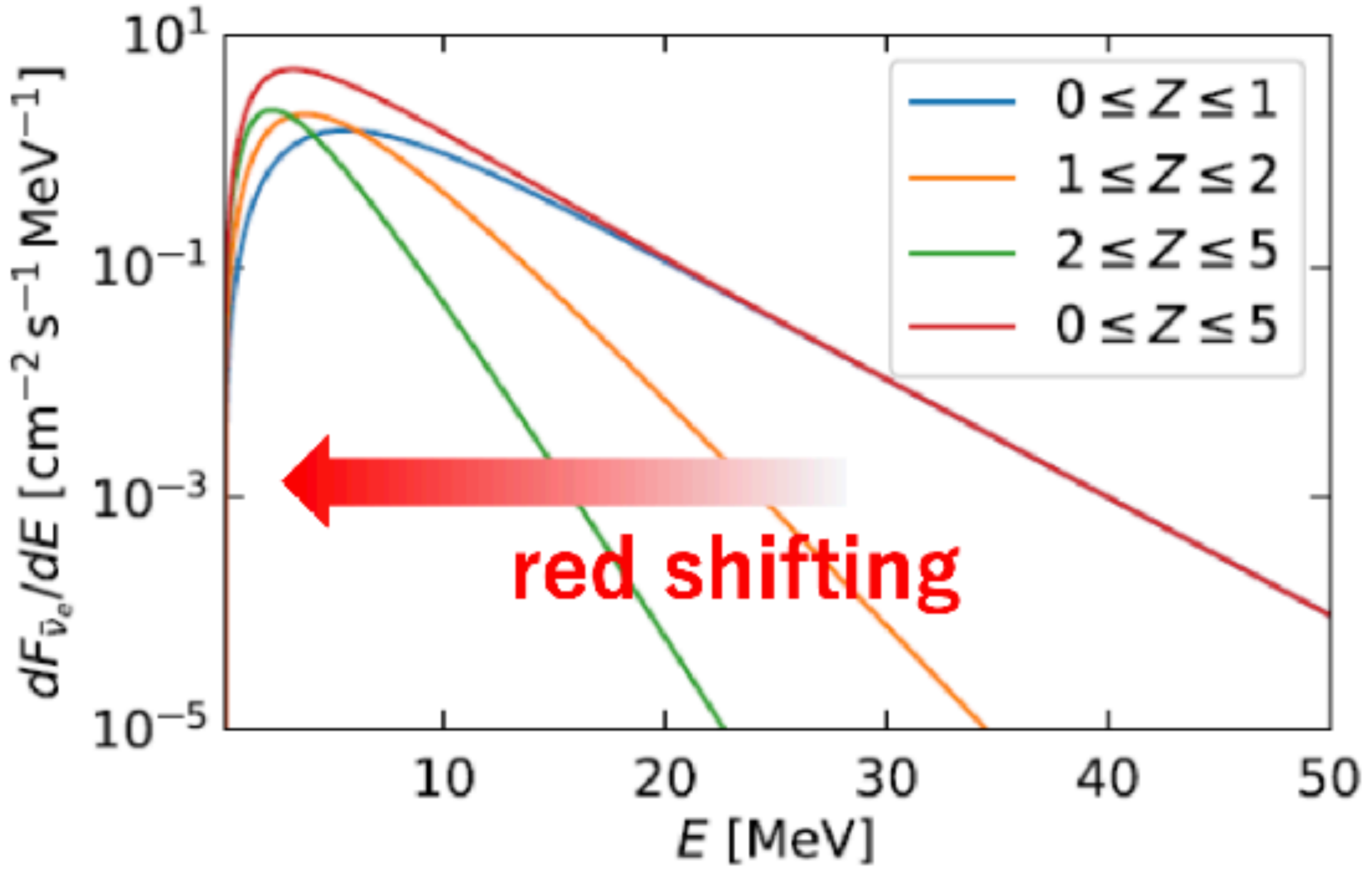
Hiroyuki Sekiya
on behalf of the Super-Kamiokande Collaboration
NEUTRINO Conference 2026@UCI
June 25, 2026

$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z_{\max}} R_{\mathrm{SN}}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

SN rate at z **(averaged)SN spectrum** **Red shift**







S.Ando et al., Proc. Jpn. Acad., Ser. B, Phys. 99 (2023) 10

Access to

- ✓ **Star formation rate**
- ✓ **BH formation rate**
- ✓ **Binary interaction effect**
- ✓ **Mechanism of the supernova explosion**

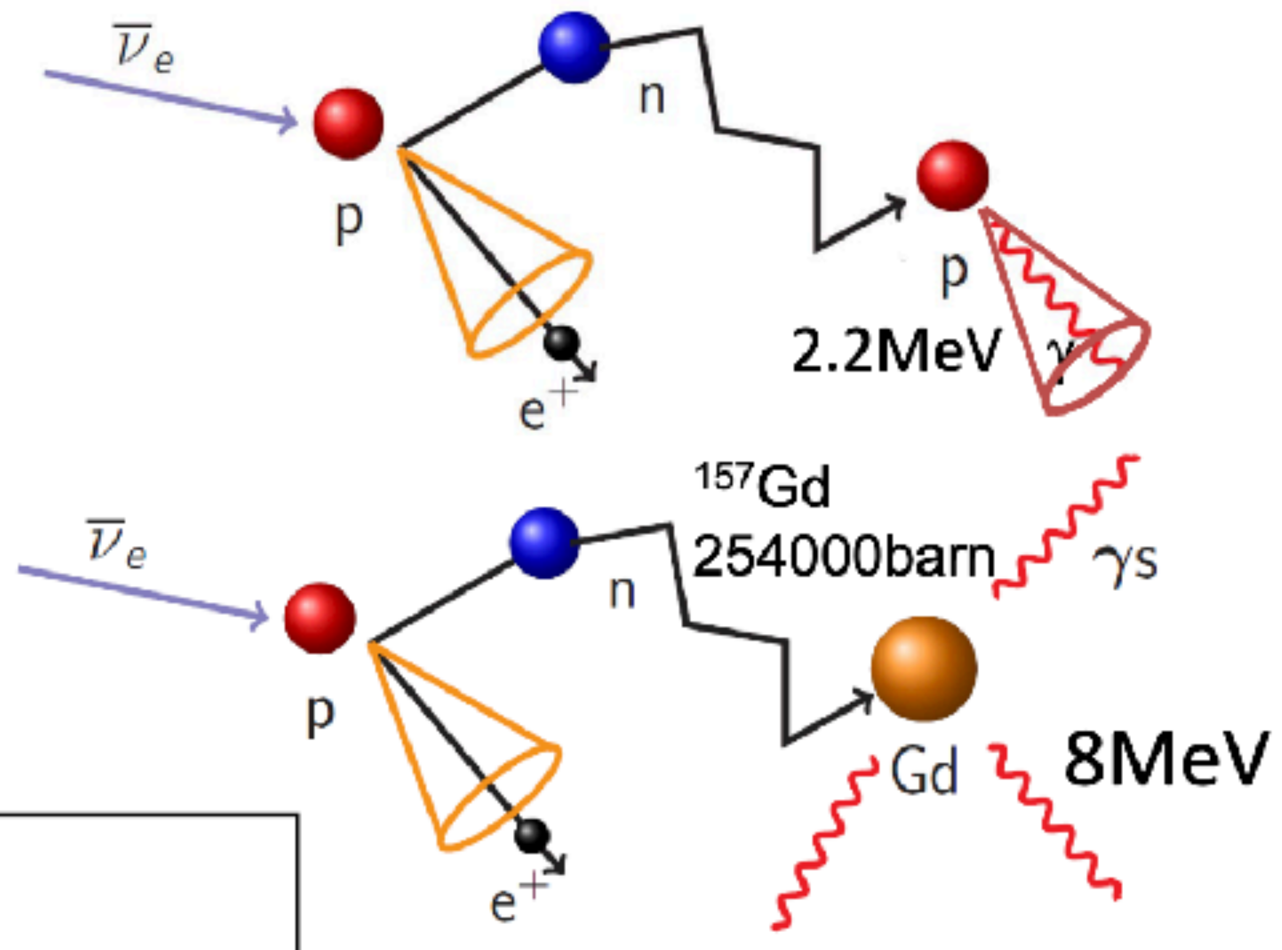
+ Particle physics
- ✓ **ν Mass Ordering**
- ✓ **exotic process (ex ν-decay)**

The Gd-loading to SK

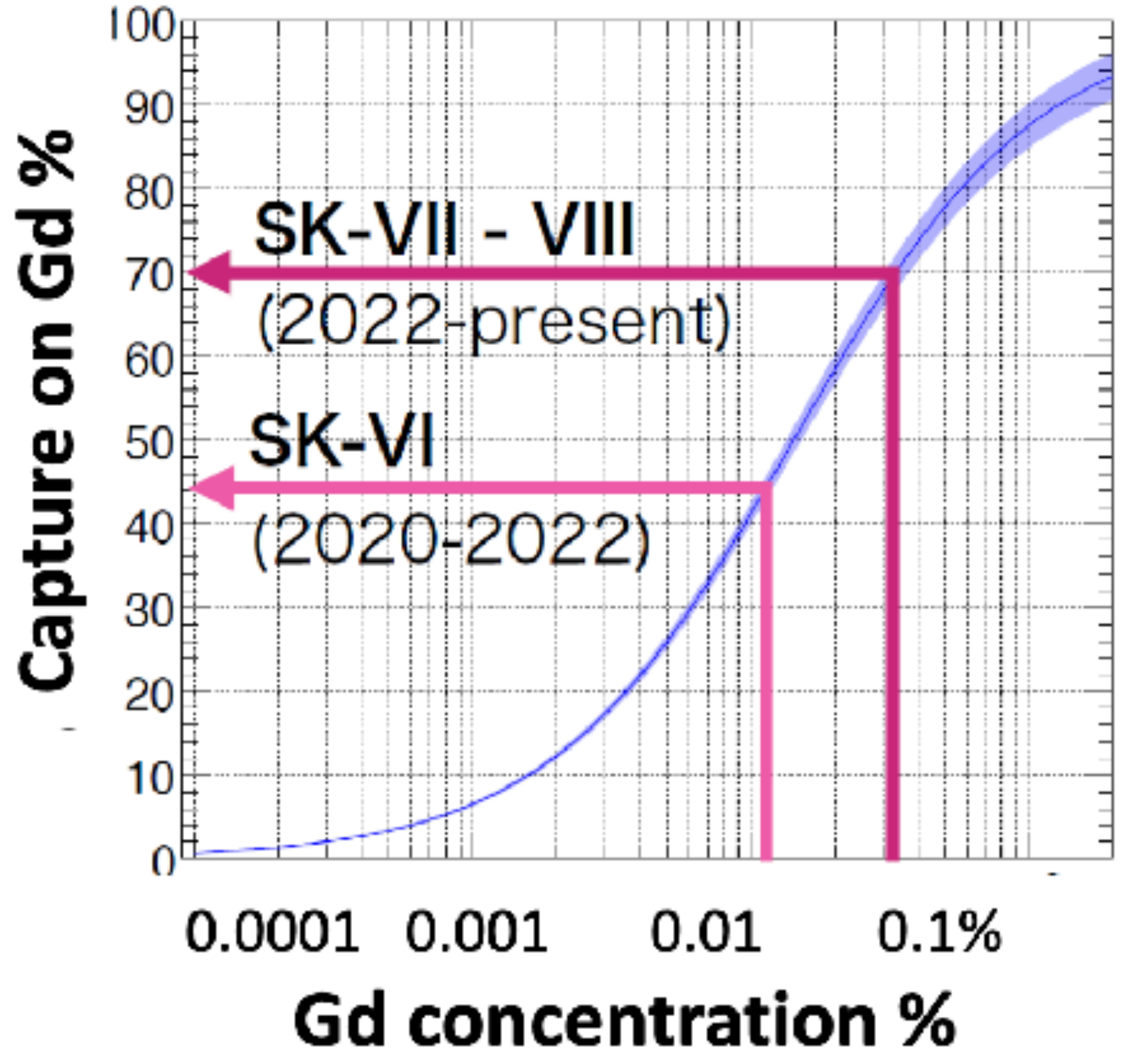
Beacom, J.F., and Vagins, M.R. PRL. 93 (2004) 171101

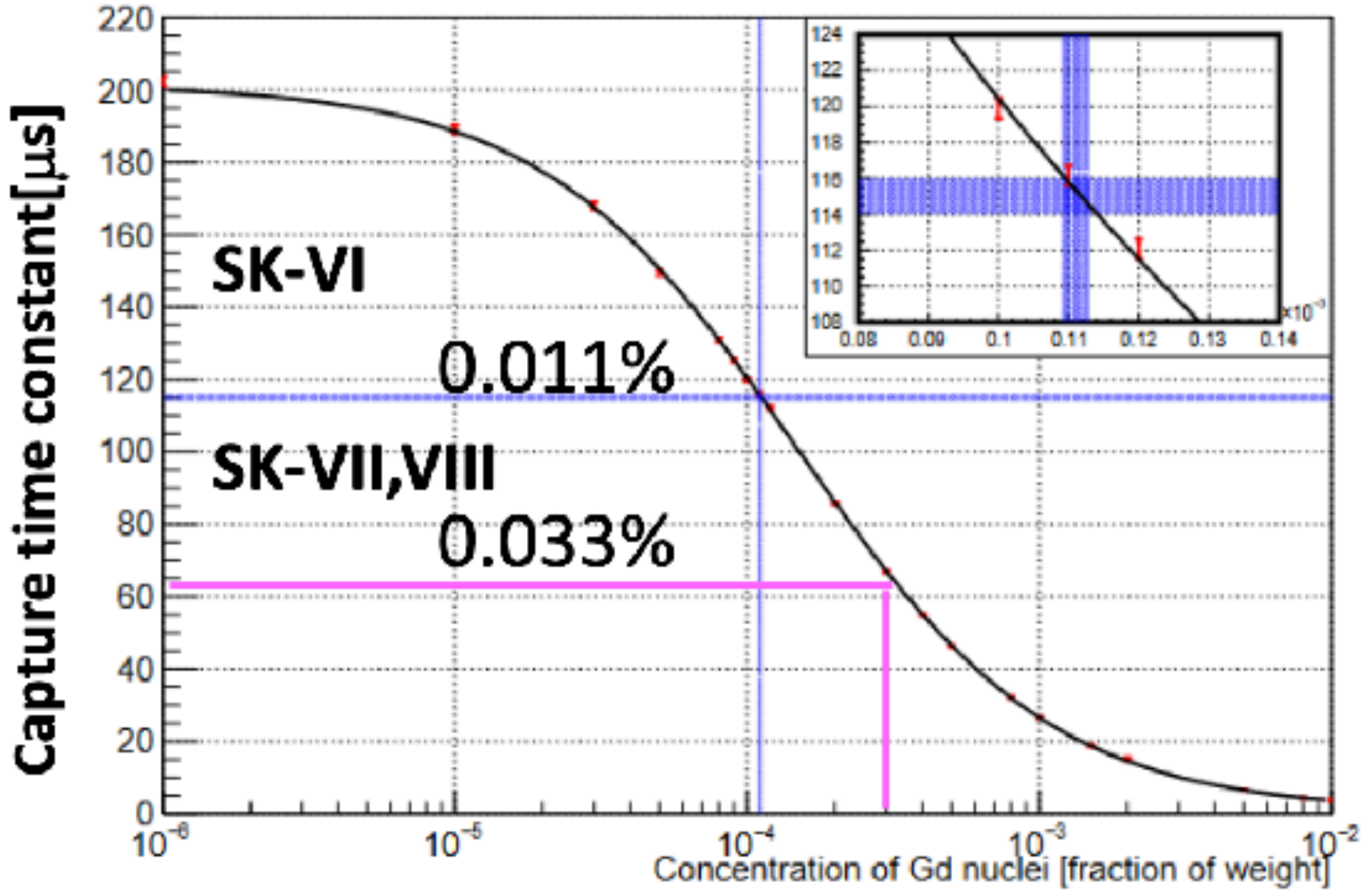
NIM A 1027 (2022) 166248 PTEP (2025) 013C01

- **Neutron tagging for interaction (especially IBD) identification**
  - Originally only by delayed coincidence with 2.2MeV gamma from p-capture
  - **Gd-loading** significantly enhances its efficiency by Gd(n,g)



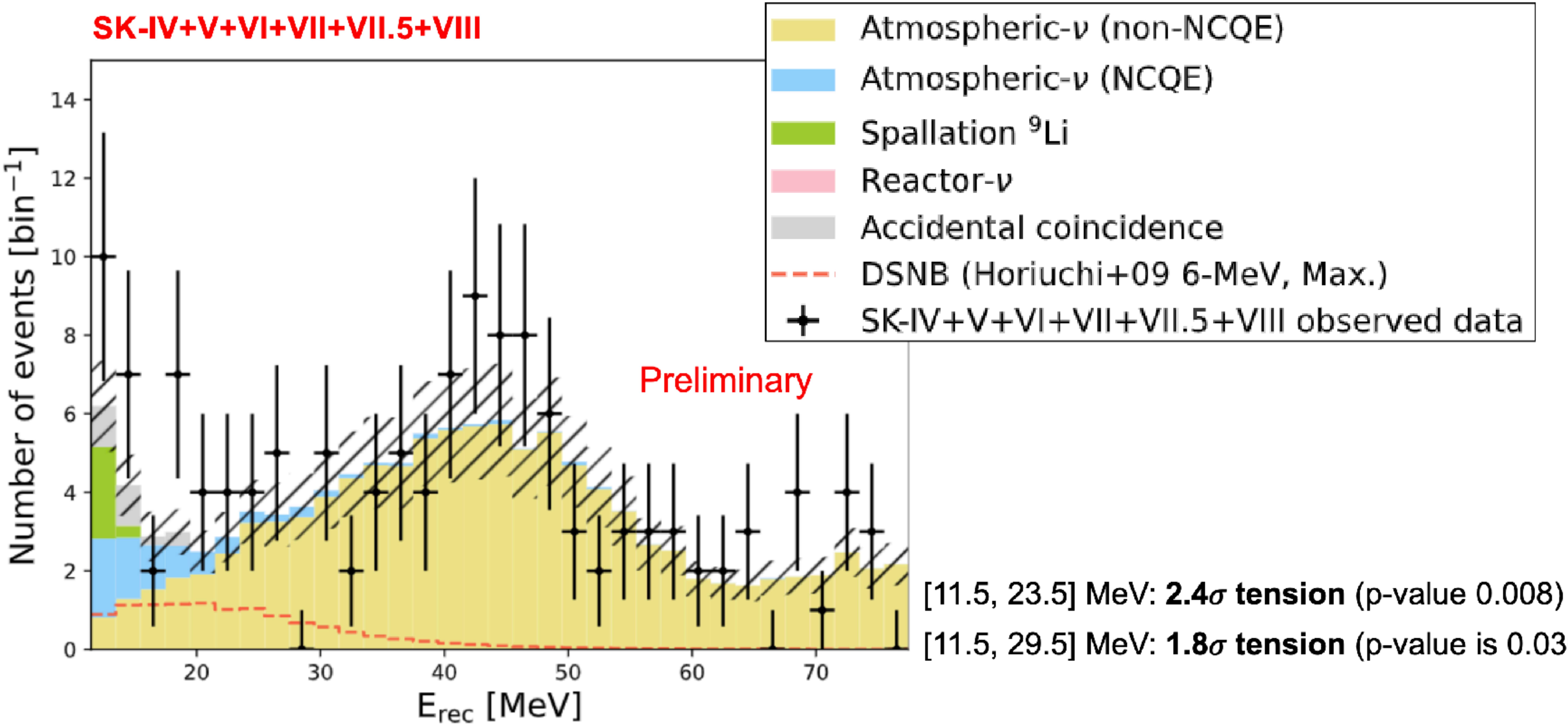
Since July 5, 2022, 39 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$ in SK
= 16.2 tons of Gd(0.033 w%)
→ ~70% Gd neutron capture efficiency





Separating IBD from BG improves sensitivity to low-energy signals such as DSNB.
Separating ES from IBD improves the SN direction-pointing accuracy.

Model-independent binned analysis result



[11.5, 23.5] MeV: **2.4σ tension** (p-value 0.008)

[11.5, 29.5] MeV: **1.8σ tension** (p-value is 0.036)

General tension with a BG-only hypothesis, with greater tension at lower energies.

Summary DSNB

Hiroyuki Sekiya
on behalf of the Super-Kamiokande Collaboration
NEUTRINO Conference 2026@UCI
June 25, 2026

- Since the introduction of Gadolinium, Super-Kamiokande has successfully accumulated over **1,650 days** of continuous observation data.

- We are fully prepared for the next galactic supernova. We have upgraded our real-time alert infrastructure using GCN Kafka and are advancing collaborations with electromagnetic telescopes to catch the Shock Breakout signals.

- Our real-time reconstruction capabilities are highly robust. For a typical supernova at 10 kpc, based on the Nakazato model, we can achieve a **pointing accuracy of $3.8^{\circ}(1\sigma)$** and a **distance-estimation precision of $\pm 12\ \%\ (1\sigma)$**

- **SK observed the first indication of the DSNB**. **The best-fit DSNB signal flux** obtained from a joint fit of SK-Ntag era phases (SK-IV, V, VI, VII, VII.5, VIII) is **$3.6\ {+1.6}/{-1.5}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$** **($4.8\ {+2.2}/{-2.0}$ events yr^{-1}) for $E\ > 13.3$ MeV**, assuming the Horiuchi+09, 6 MeV, max model. This corresponds to a **2.6σ tension with a null hypothesis (5×10^{-3} one-sided p-value)**. Similar significance was obtained for two other DSNB models with varying spectral shapes.

- Similar conclusions we can draw from the binned analysis. Depending on the binning, **the binned analysis shows tension with the BG-only hypothesis at the 1.8- 2.4σ level.**

Next Galactic Supernova

- Measure neutrino fluence -> neutrinos/cm^2
- Assume distance to SN (probably determined via E+M observations??) and isotropic angular distribution -> Infer total number of neutrinos radiated and total energy in neutrinos.
- Binding energy of NS ~3/5 GM^2/R ~ 3x10^{53} ergs for 1.4M$_{sun}$ 12 km star.
- What if measured total E is 1x10^{53} ergs?
- What if measured E is 6x10^{53} ergs?

Some open SN questions

- What are the observed spectra of different flavor neutrinos? What is the impact of neutrino oscillations?
- What are the mass, initial spin, and magnetic field of proto-NS? Is a millisecond Magnetar produced? (Crab period 33 ms, fastest known NS 1.4 ms)
- How does total E in nu compare to binding E of NS?
- What is the GW signal? How does this depend on spin?
- Are there signatures of new physics such as axions? Or what limits can we place on new physics?
- Can we observe collapse to a black hole (abrupt end of nu signal)? For how long can we rule out collapse?

SN1987A