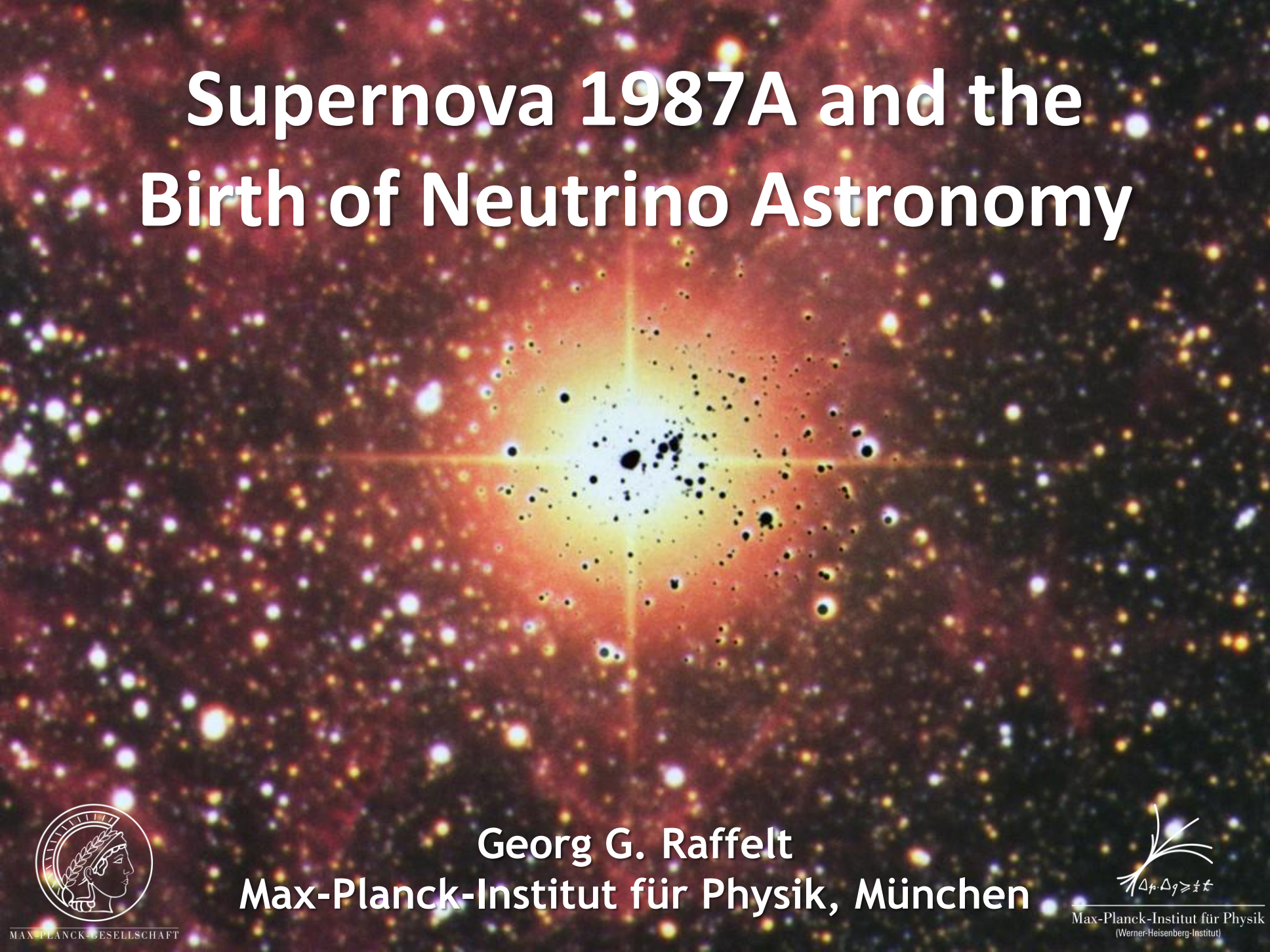
Supernova 1987A and the Birth of Neutrino Astronomy



Georg G. Raffelt
Max-Planck-Institut für Physik, München

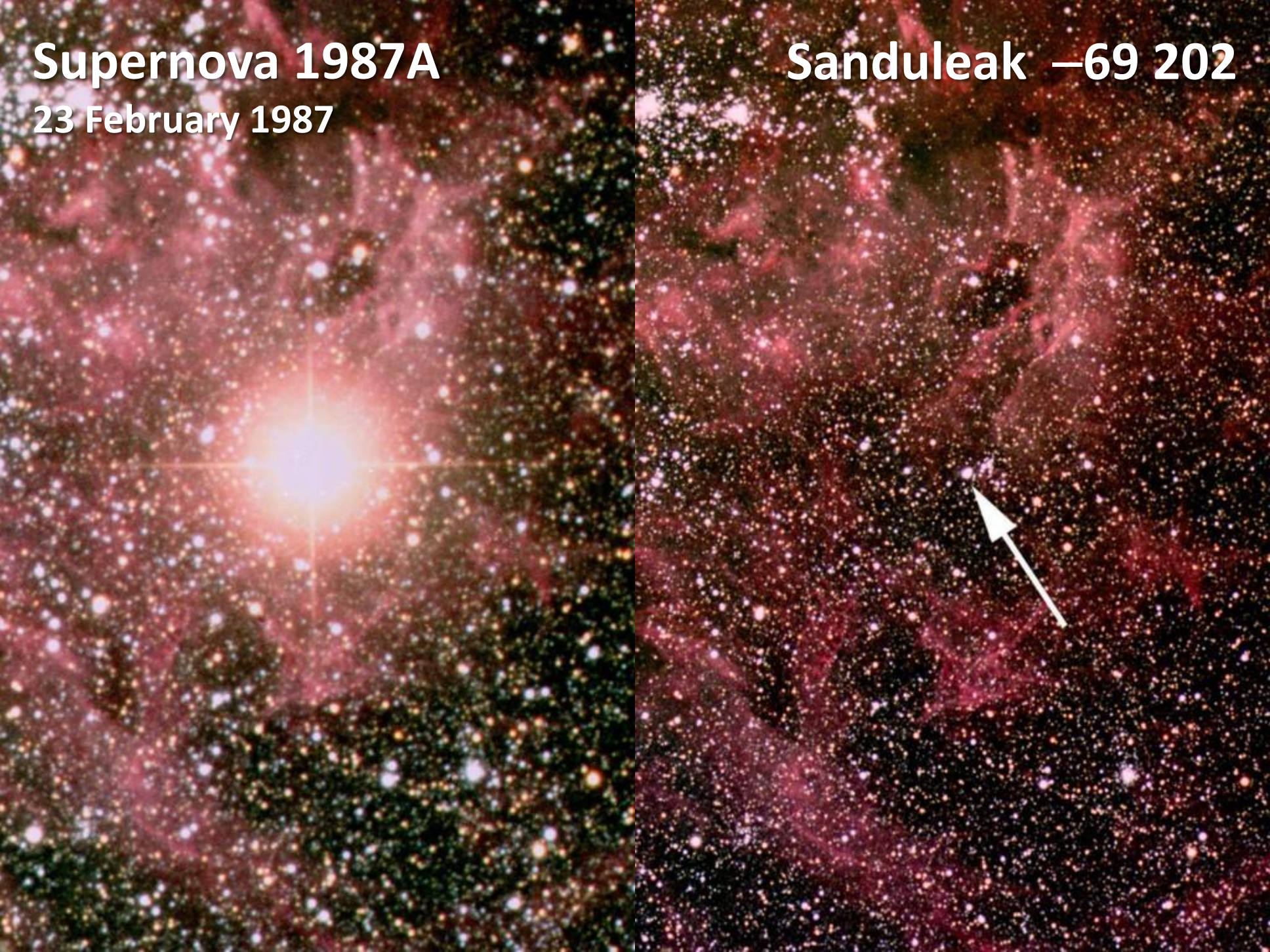
MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)


Large Magellanic Cloud
Distance 50 kpc
(160.000 light years)

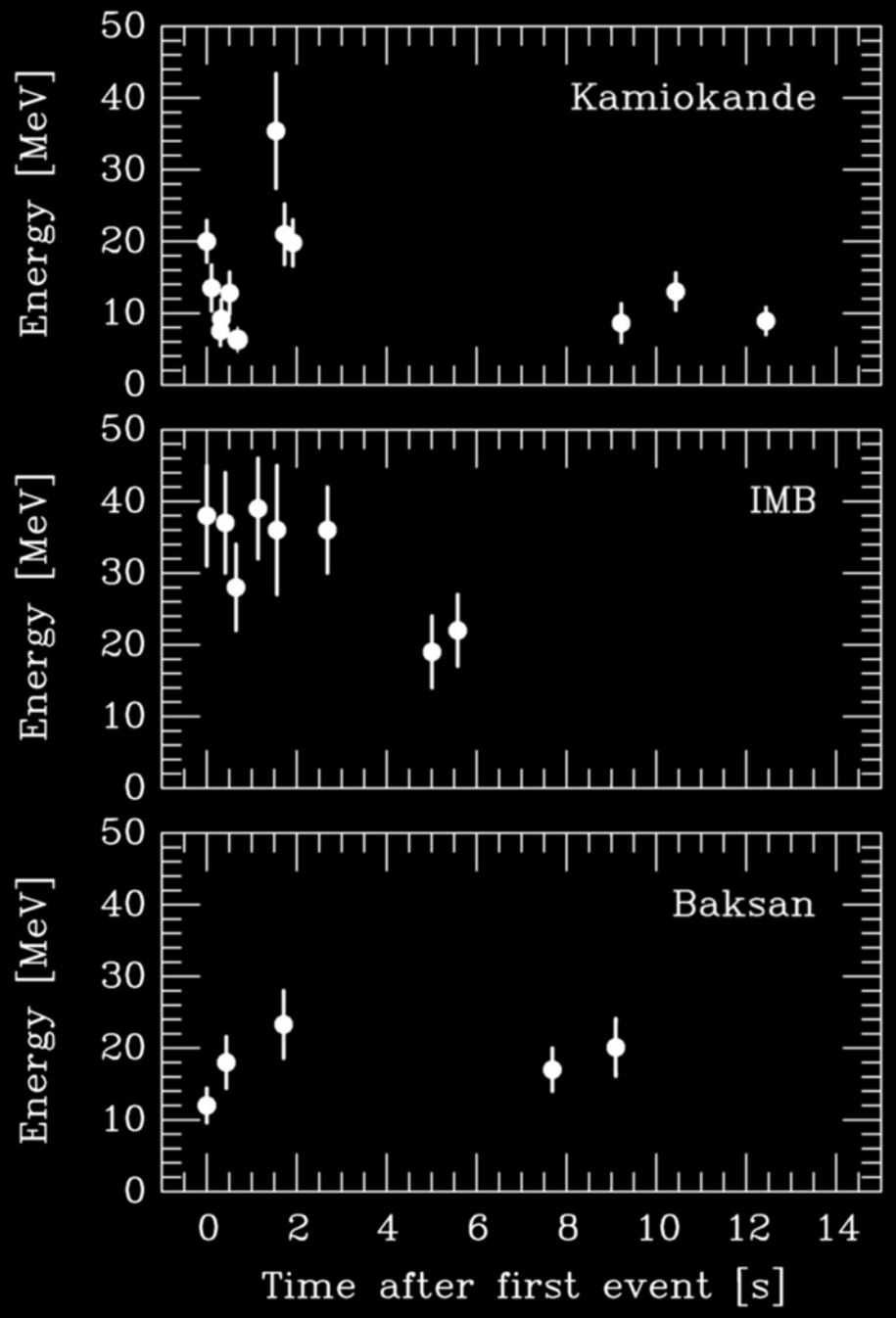

Tarantula Nebula


Sanduleak –69 202


Supernova 1987A
23 February 1987
Sanduleak –69 202

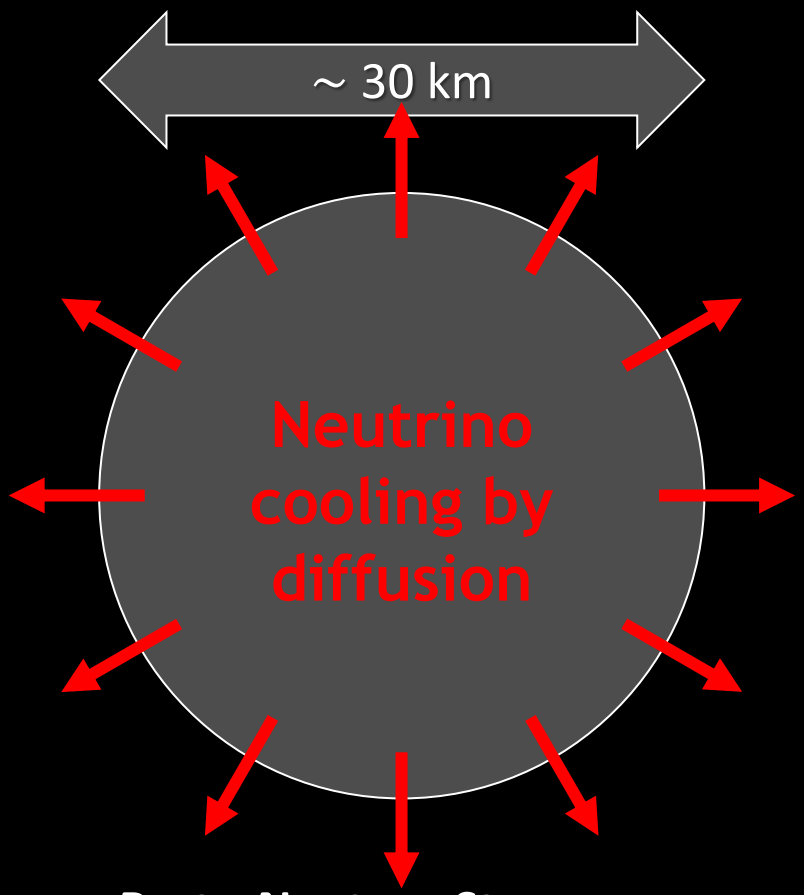
Supernova 1987A

23 February 1987



Neutrinos from Core Collapse Supernovae

Newborn Neutron Star



Proto-Neutron Star

$\rho \sim \rho_{nuc} = 3 \times 10^{14}$ g cm^{-3}

T ~ 10 MeV

Gravitational binding energy

$$E_b \approx 3 \times 10^{53} \text{ erg} \approx 17\% \, M_{SUN} \, c^2$$

Showing up as

99%	Neutrinos
1%	Kinetic energy of explosion
0.01%	Photons, outshine host galaxy

Neutrino luminosity

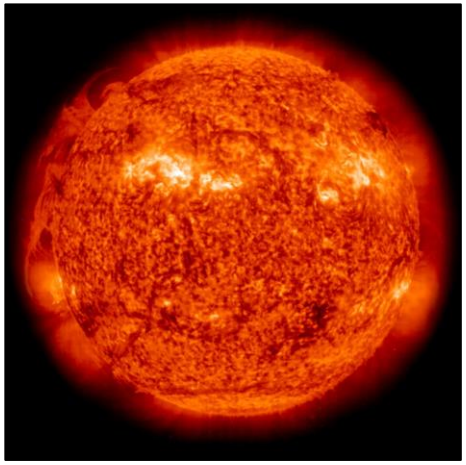
$$L_\nu \sim 10^{53} \text{ erg/sec} \sim 3 \times 10^{19} \, L_{SUN}$$

While it lasts, outshines the universe

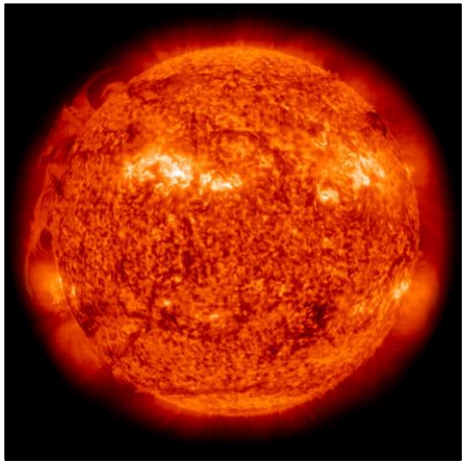
Diffuse SN neutrino background (DSNB)

- Comparable to EBL
- 10% of cosmic radiation density
- Dominant cosmic neutrino radiation (big bang nus are hot dark matter)

Sun Glasses for Neutrinos?

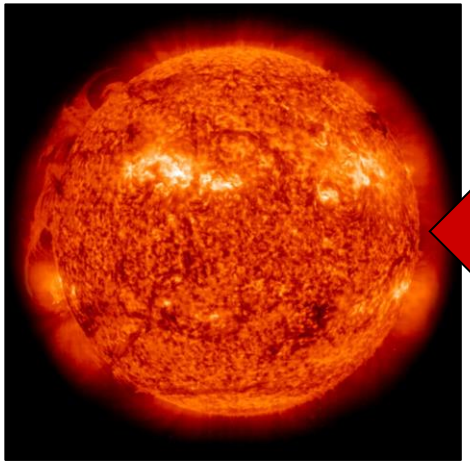


Sun Glasses for Neutrinos?



Several light years of lead needed to shield solar neutrinos

Sun Glasses for Neutrinos?



8.3 light minutes

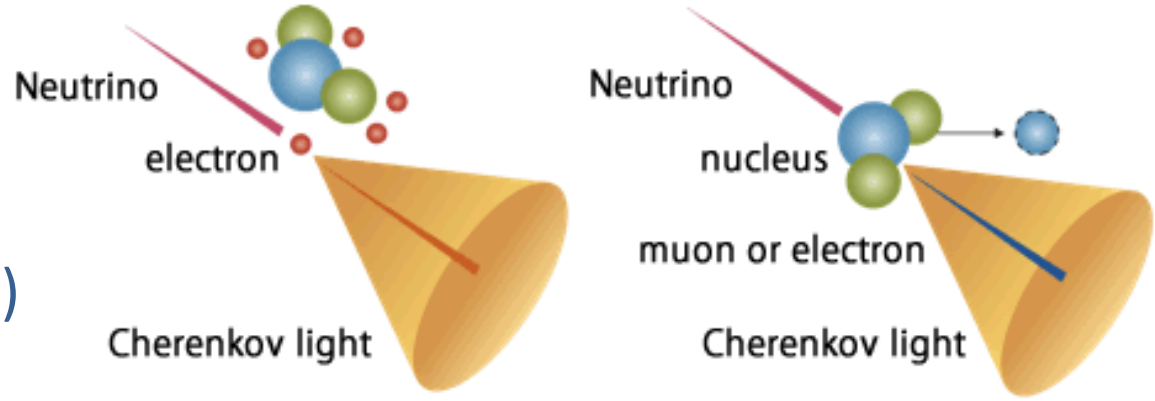
Several light years of lead needed to shield solar neutrinos

May There Be Light

Cherenkov Radiation

Charged particle with
"superluminal" speed
in a medium (water, air, …)

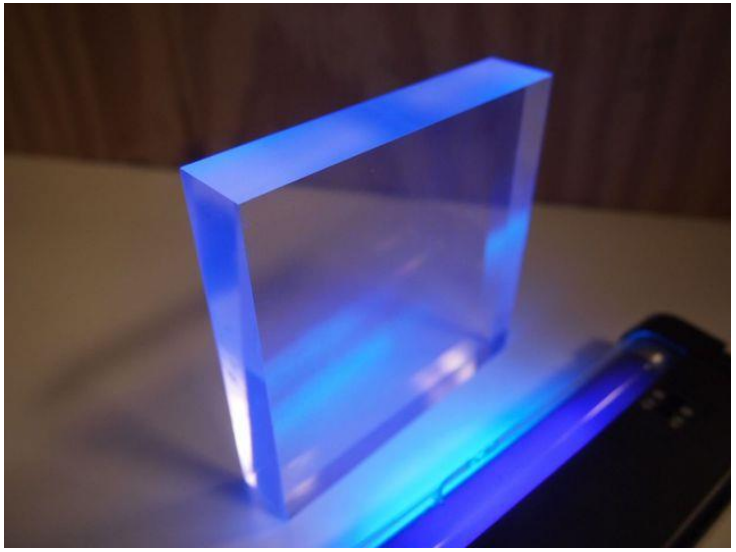
- Directional information



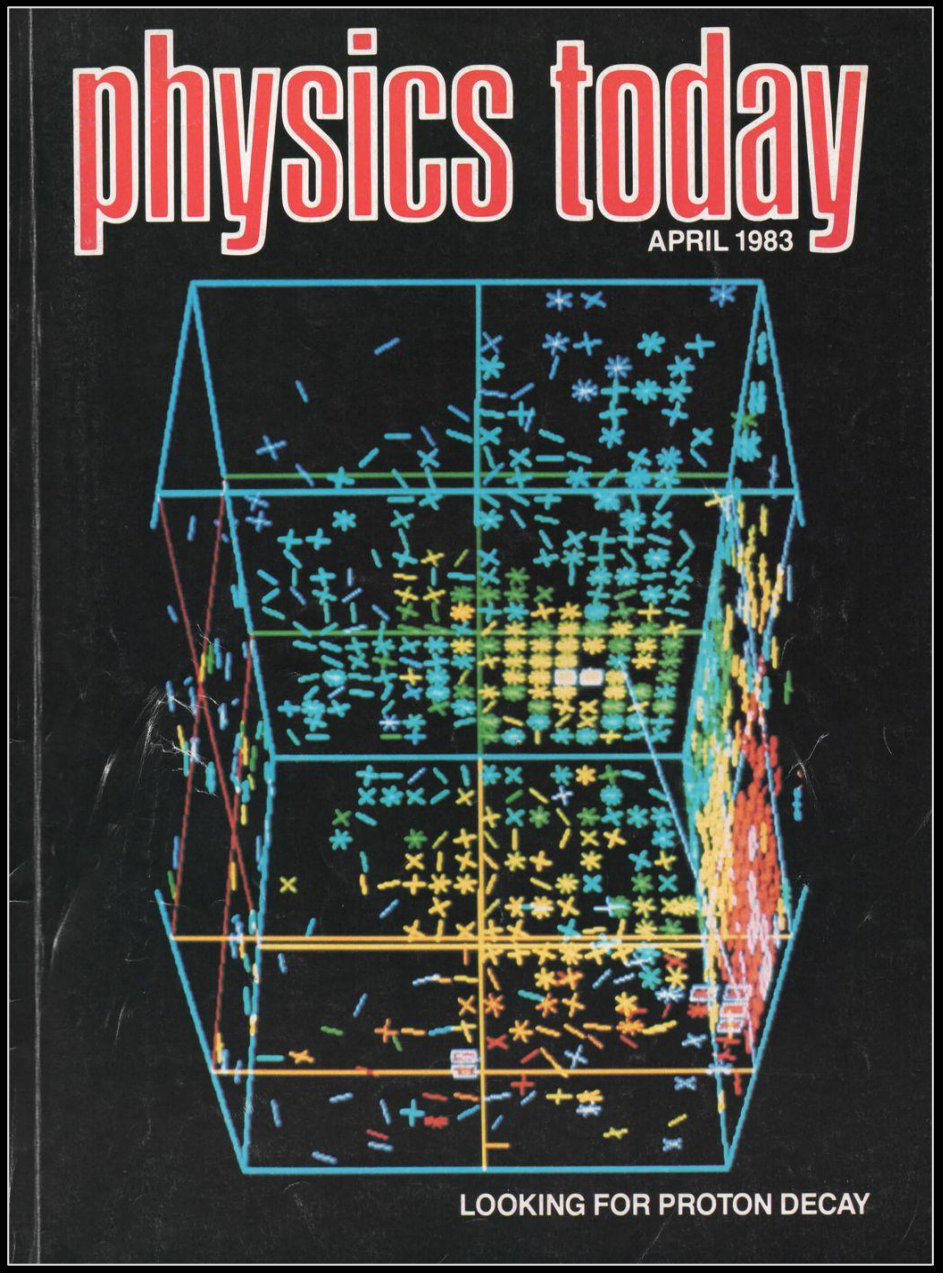
Scintillation Light

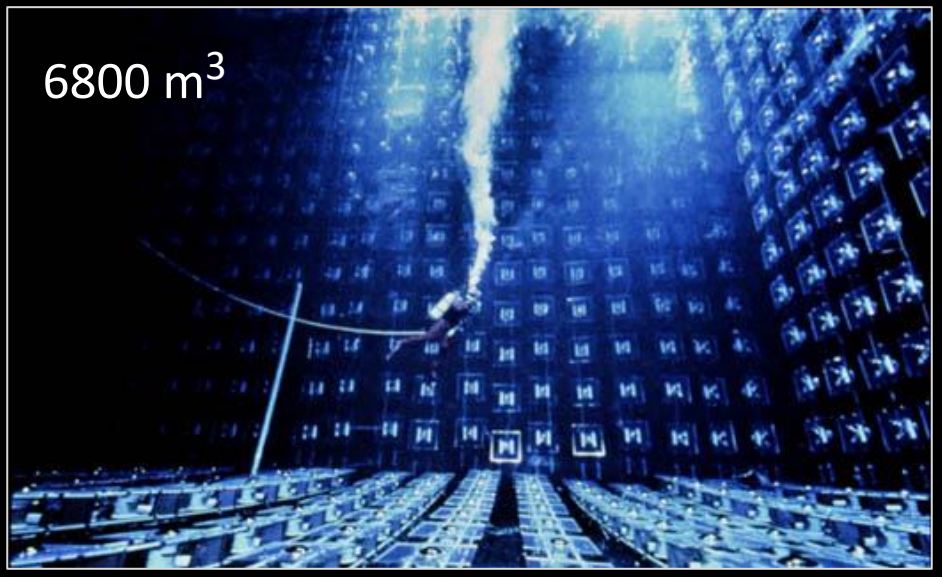
Charged particles excite certain
transparent materials
(e.g. organic compounds dissolved
in mineral oil → large volume)

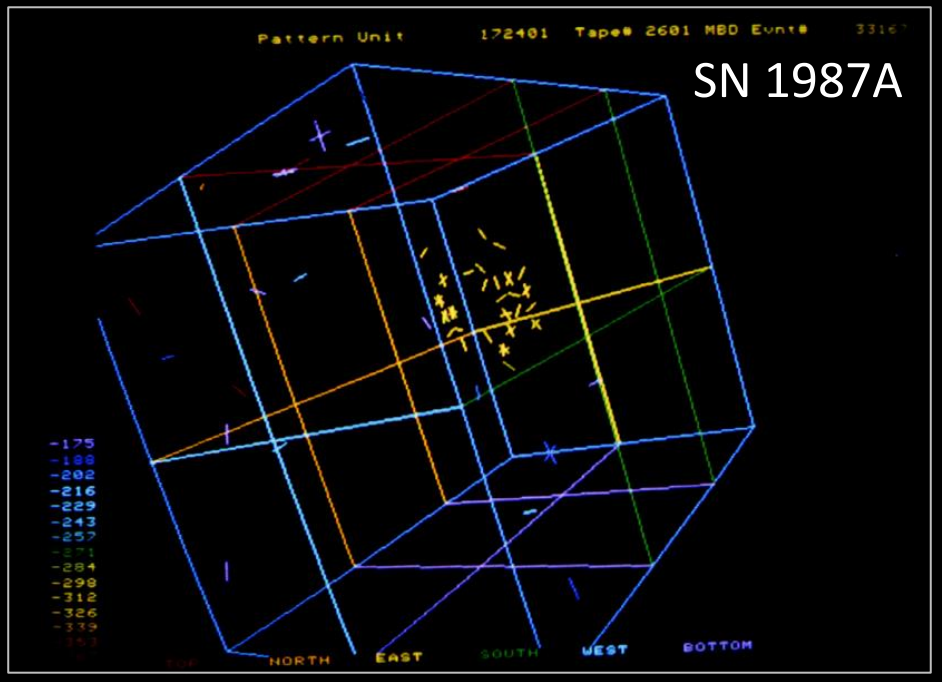
- More light (lower threshold)
- No directional information



Irvine-Michigan-Brookhaven (IMB) Detector

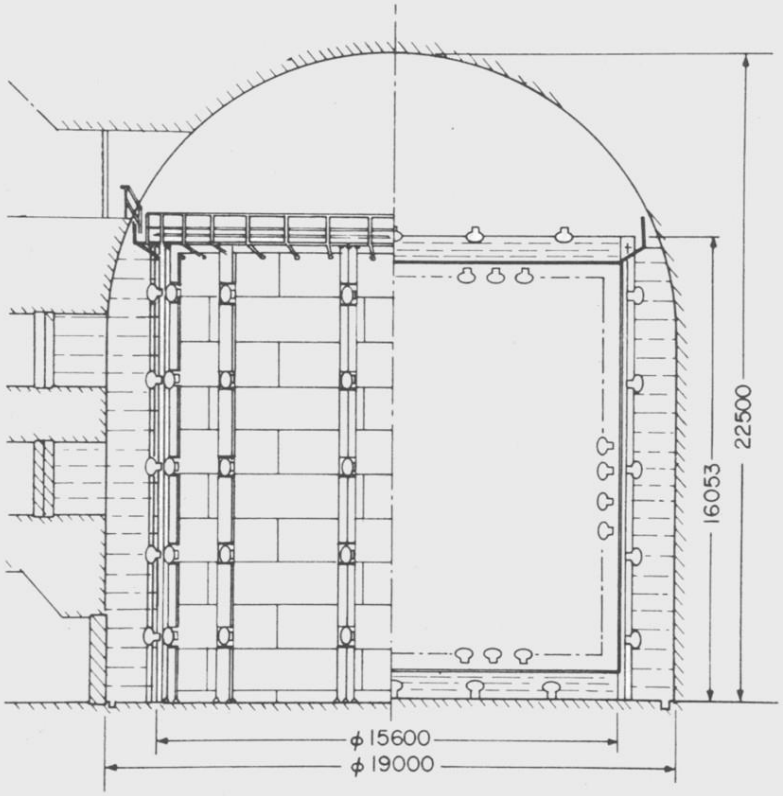


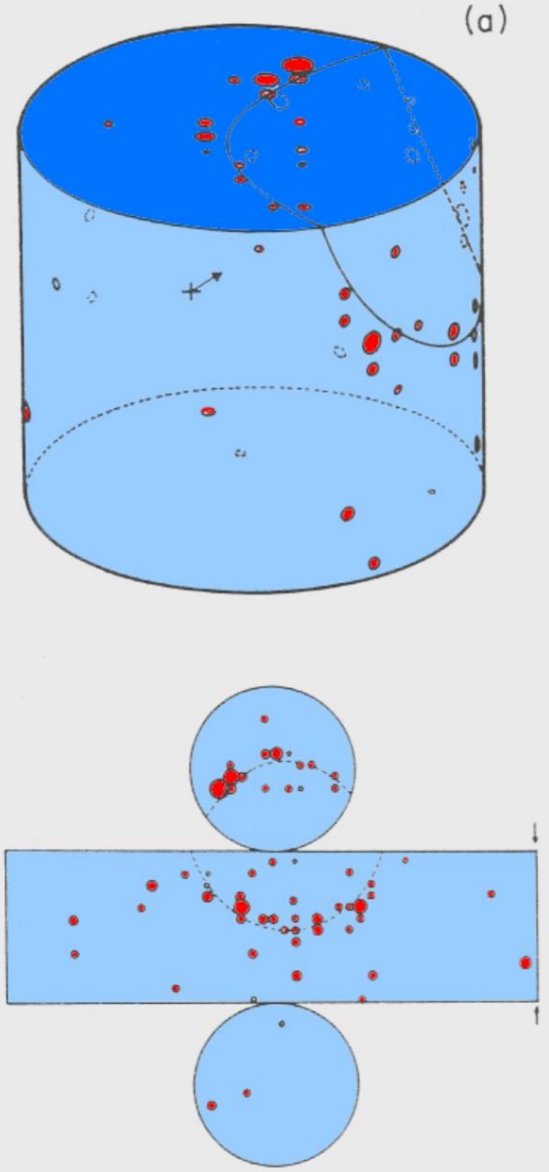




SN 1987A Event No.9 in Kamiokande

Kamiokande-II Detector
(2140 tons of water)

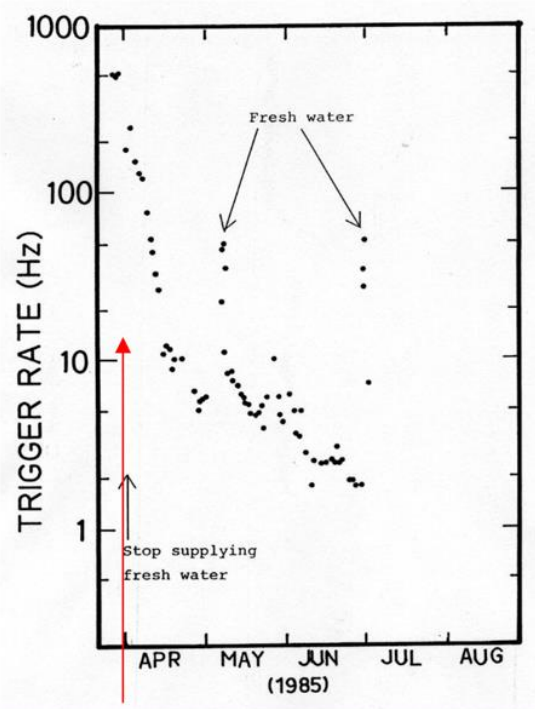




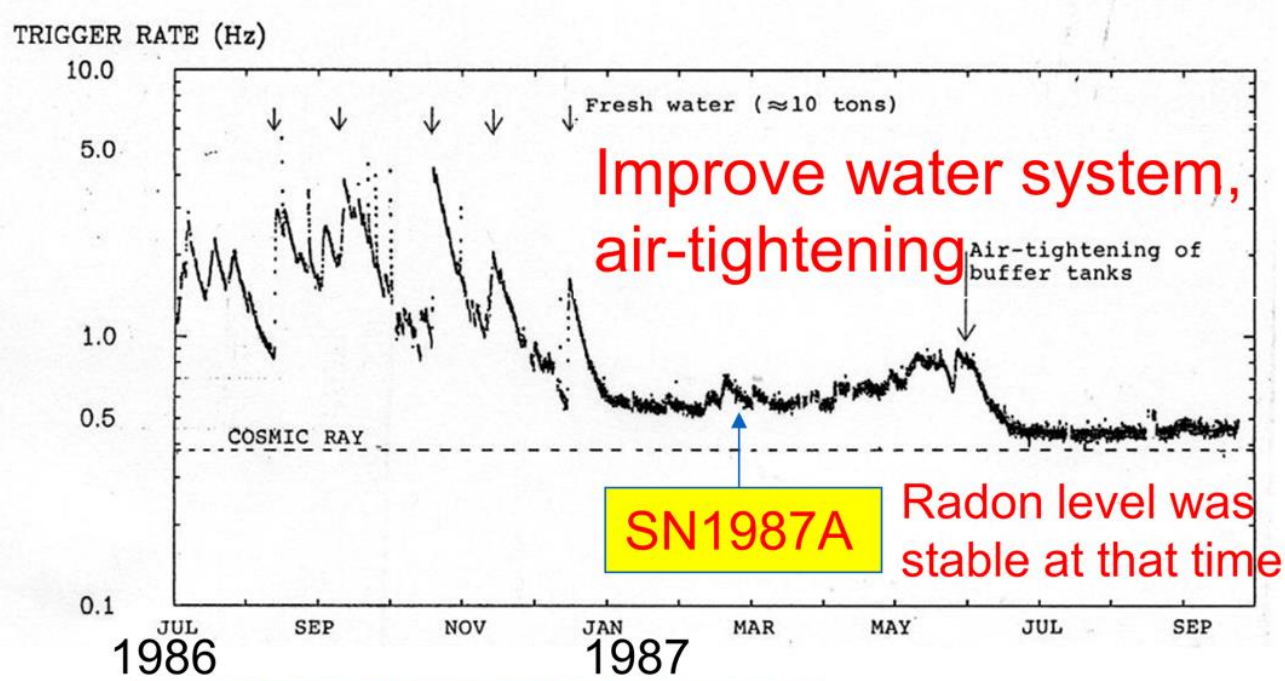
Hirata et al., PRD 38 (1988) 448

Battle against Radon(1985 →)

$^{222}Rn \rightarrow {}^{218}Po \rightarrow {}^{214}Pb \rightarrow {}^{214}Bi \rightarrow \beta$ (3.26MeV)



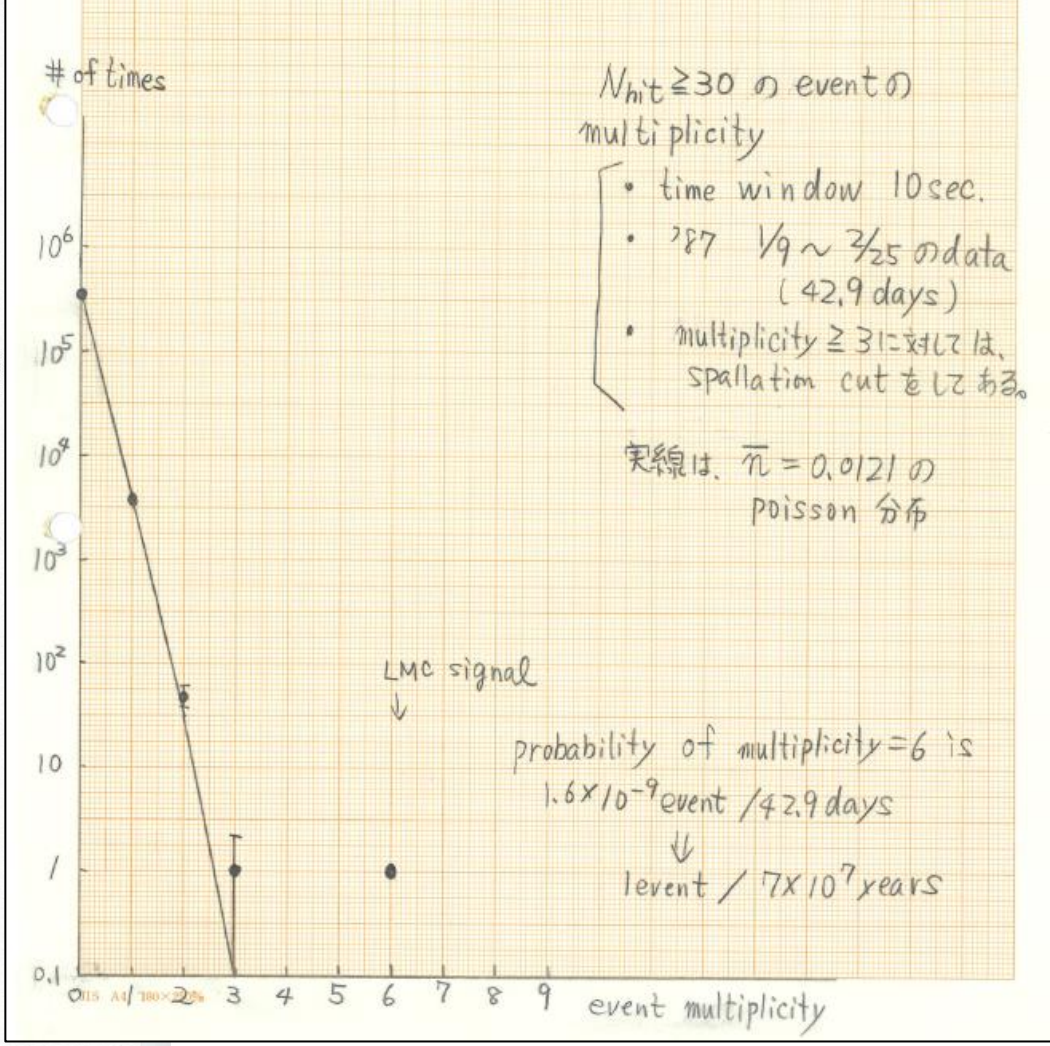
Fresh water supply mode →recirculation mode (1985 April)



Improve water system, air-tightening

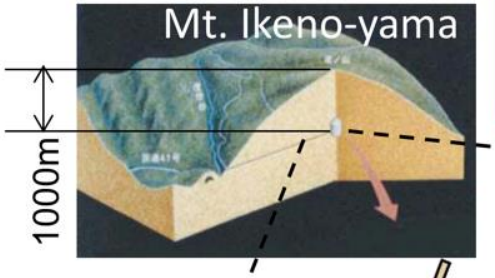
Radon level was stable at that time

Air-tightening the tank

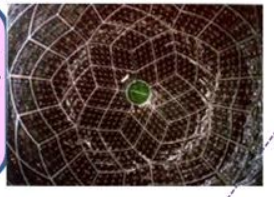


M.Nakahata's notes after the analysis
(now director of Kamioka Observatory)

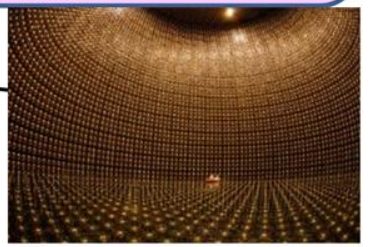
Kamioka Underground Today



KamLAND (Tohoku Univ.)
1000 ton liquid scintillator detector
Reactor, geo neutrinos
^{136}Xe double beta decay



Super-Kamiokande
50,000 ton water Cherenkov detector
Atmospheric, solar, supernova neutrinos
Proton decay, indirect dark matter search
Far detector for T2K



Kamiokande was here

KamLAND

CANDLES
CaF_2 scintillation detector
for ^{48}Ca double beta decay

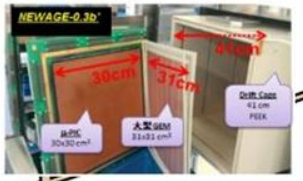
Gravitational-wave
CLIO 100m x 100m prototype
Geo-physics 100m x 100m
Laser strainmeter

Lab.A
Super-K dome
clean room
Lab.E/IMPU
Lab.2
water system
IMPU
Lab.1
100m
Atotsu entrance

XMASS
Direct dark matter search experiment

EGADS
200t Gd test tank

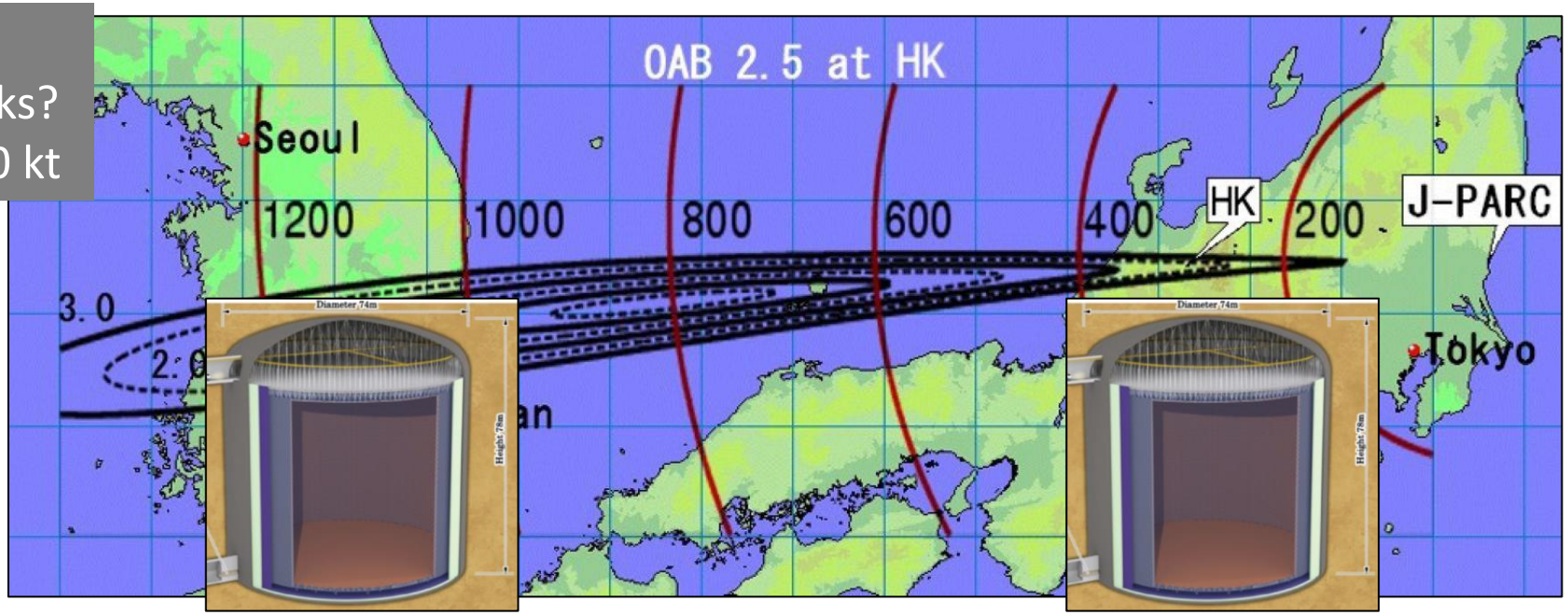
NEWAGE
Directional dark matter experiment



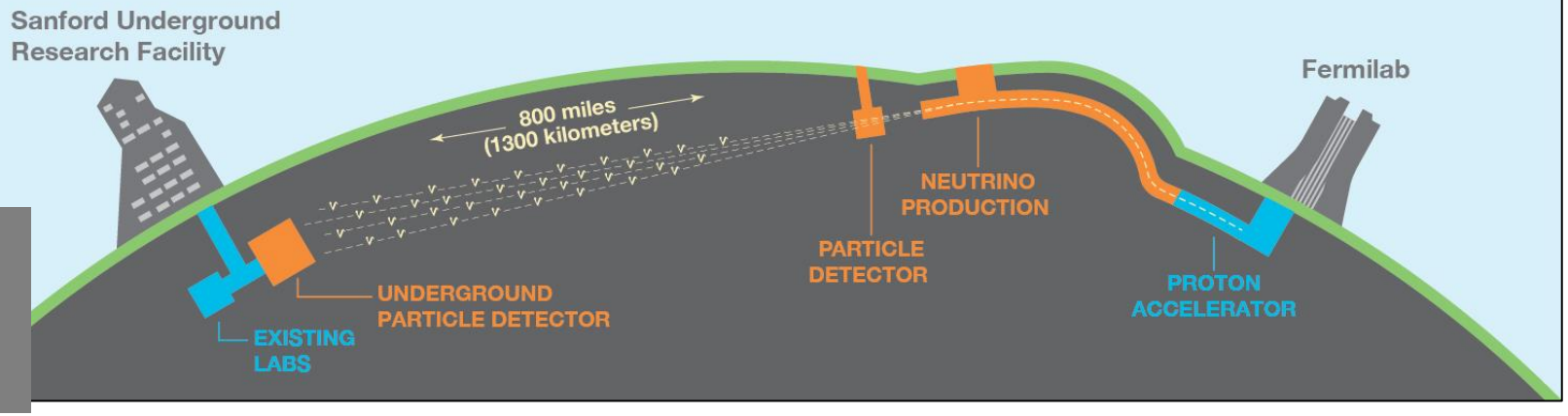
Adapted from M. Nakahata (Tokyo, February 2017)

Long-Baseline Neutrino Oscillation Projects (2025+)

Hyper-K
Two Tanks?
Each 220 kt

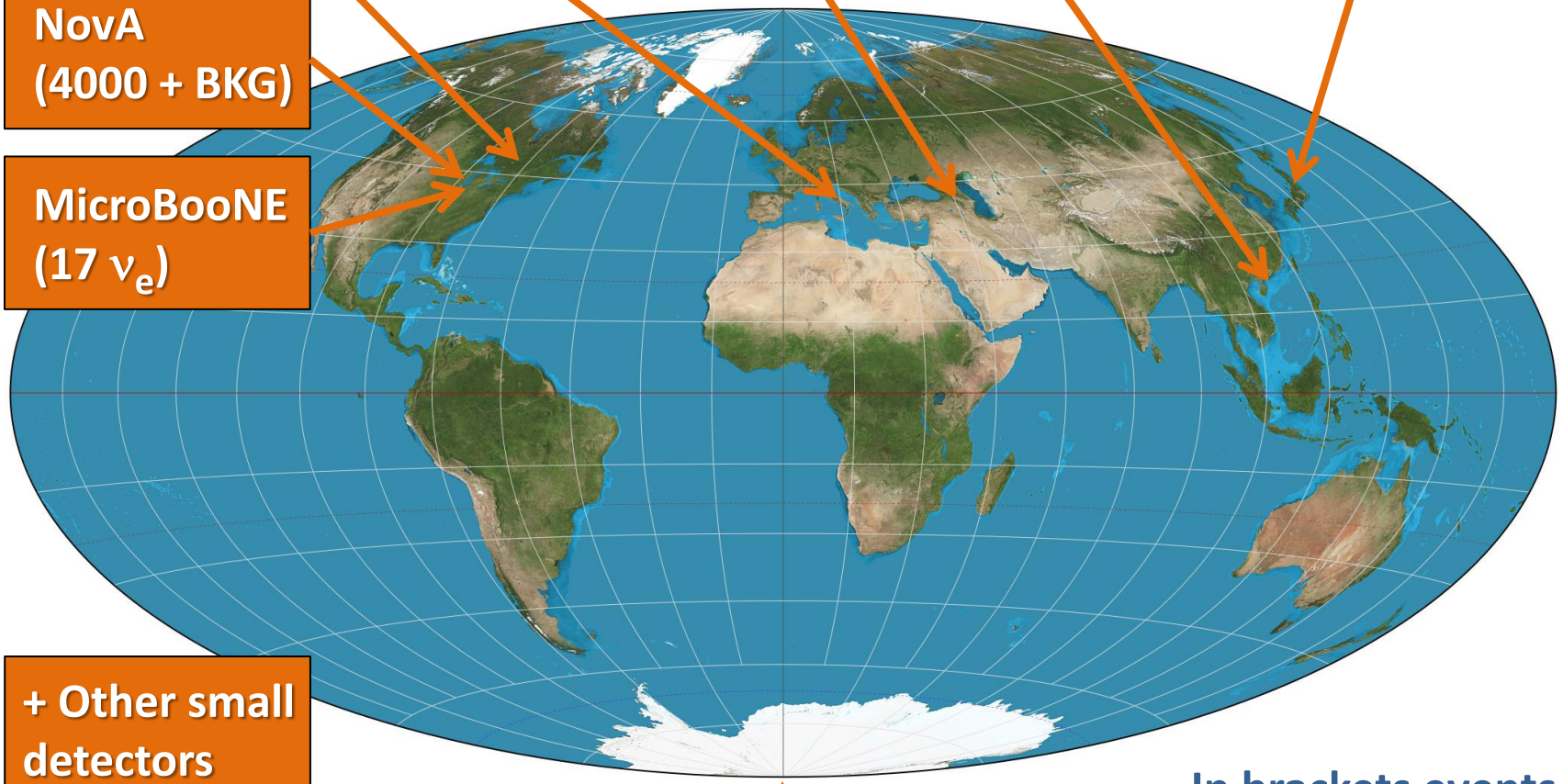


DUNE (Fermilab → Homestake in US), Liquid Argon Detector



Liquid Ar:
Measure ν_e
from SN

Operational Detectors for Supernova Neutrinos



HALO (30)
SNO+ (300)

LVD (400)
Borexino (100)

Baksan (100)

Daya Bay (100)

Super-K (4000)
KamLAND (400)

NovA (4000 + BKG)

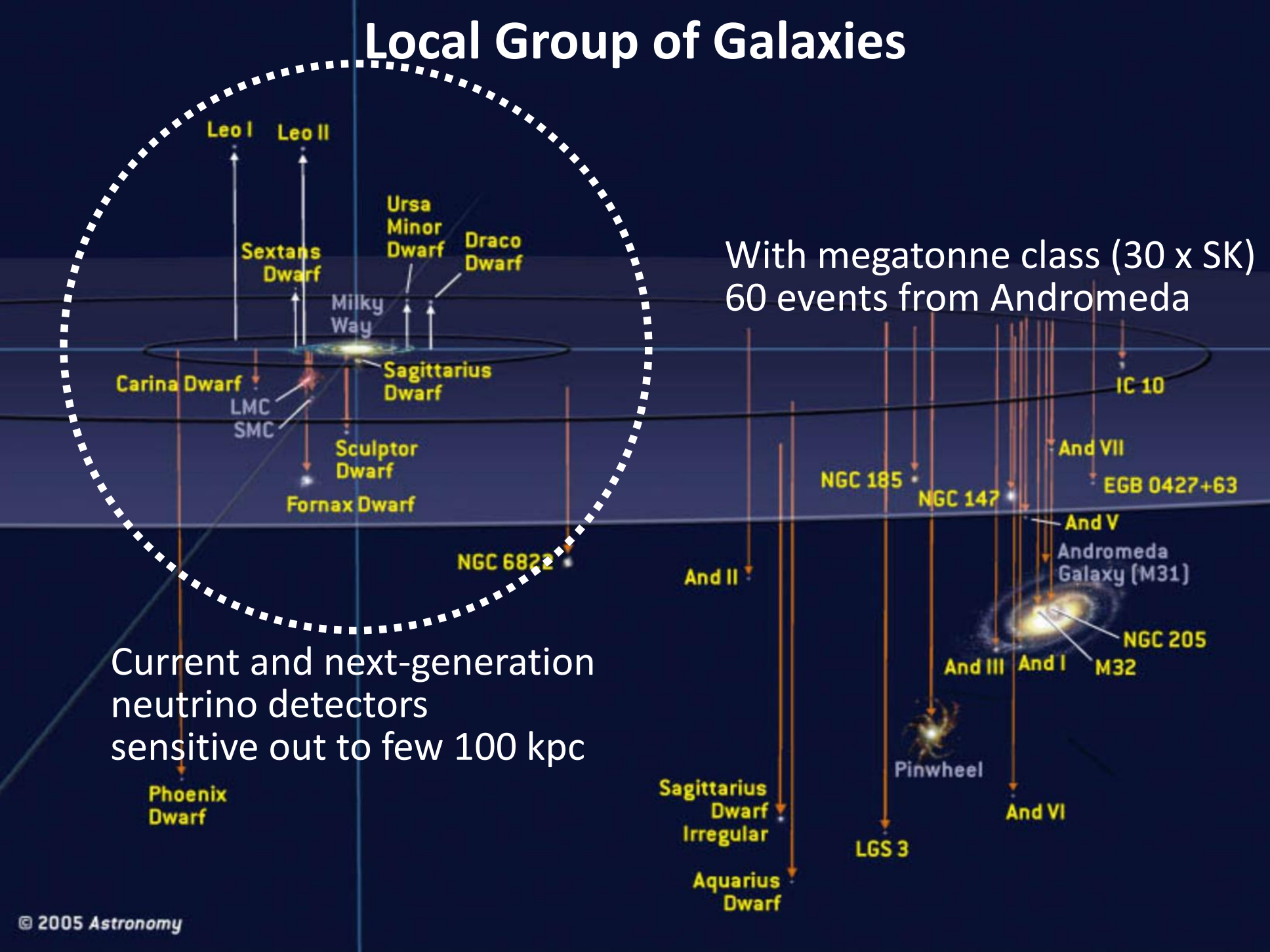
MicroBooNE (17 ν_e)

+ Other small detectors with some SN sensitivity

IceCube (10^6)

In brackets events for a "fiducial SN" at distance 10 kpc

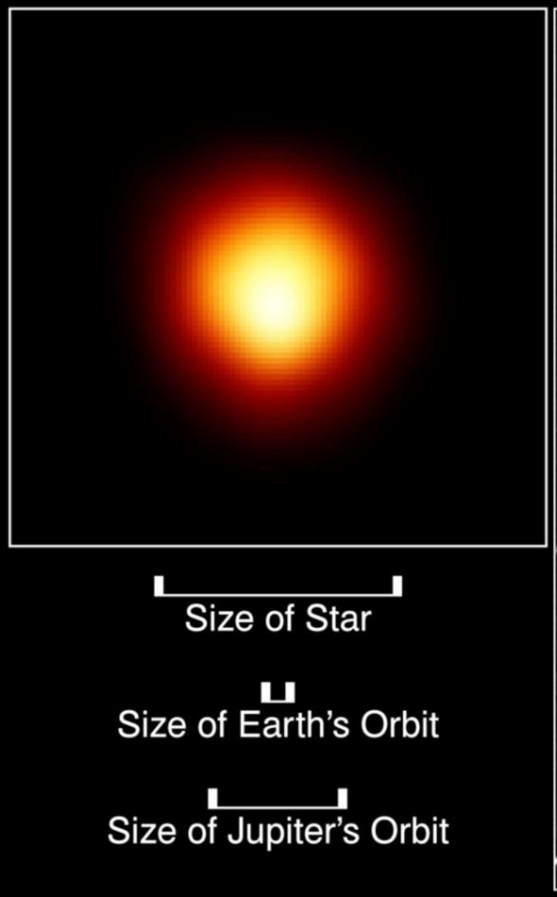
Local Group of Galaxies

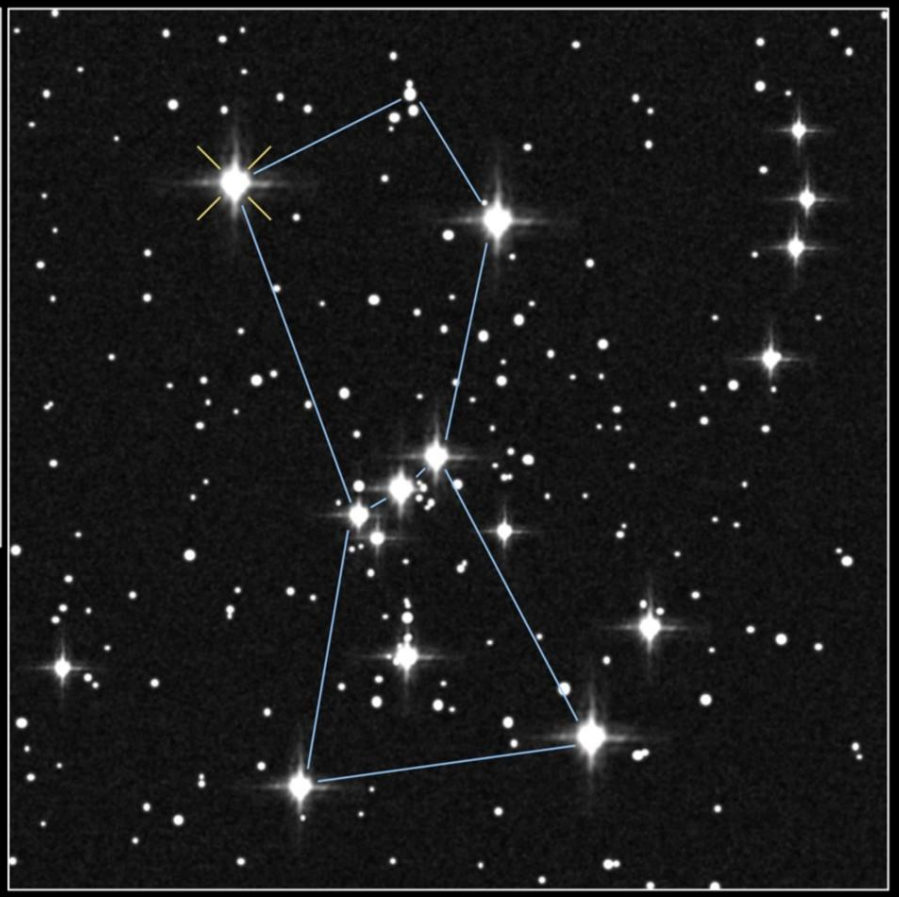


With megatonne class (30 x SK)
60 events from Andromeda

Current and next-generation
neutrino detectors
sensitive out to few 100 kpc

The Red Supergiant Betelgeuse (Alpha Orionis)





First resolved image of a star other than Sun

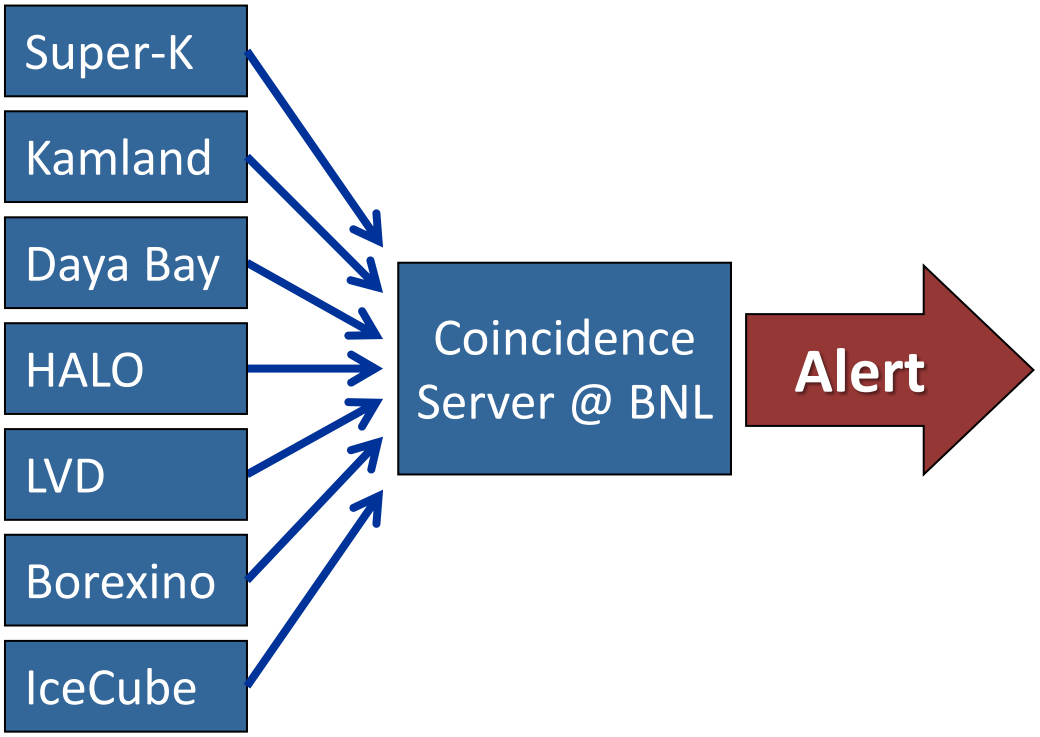
Distance (Hipparcos) 130 pc (425 lyr)

If Betelgeuse goes Supernova:

- 60 million neutrino events in Super-Kamiokande
- 2400 neutrons/day from Si burning phase (few days warning!) [Odrzywolek, Misiaszek & Kutschera, astro-ph/0311012]

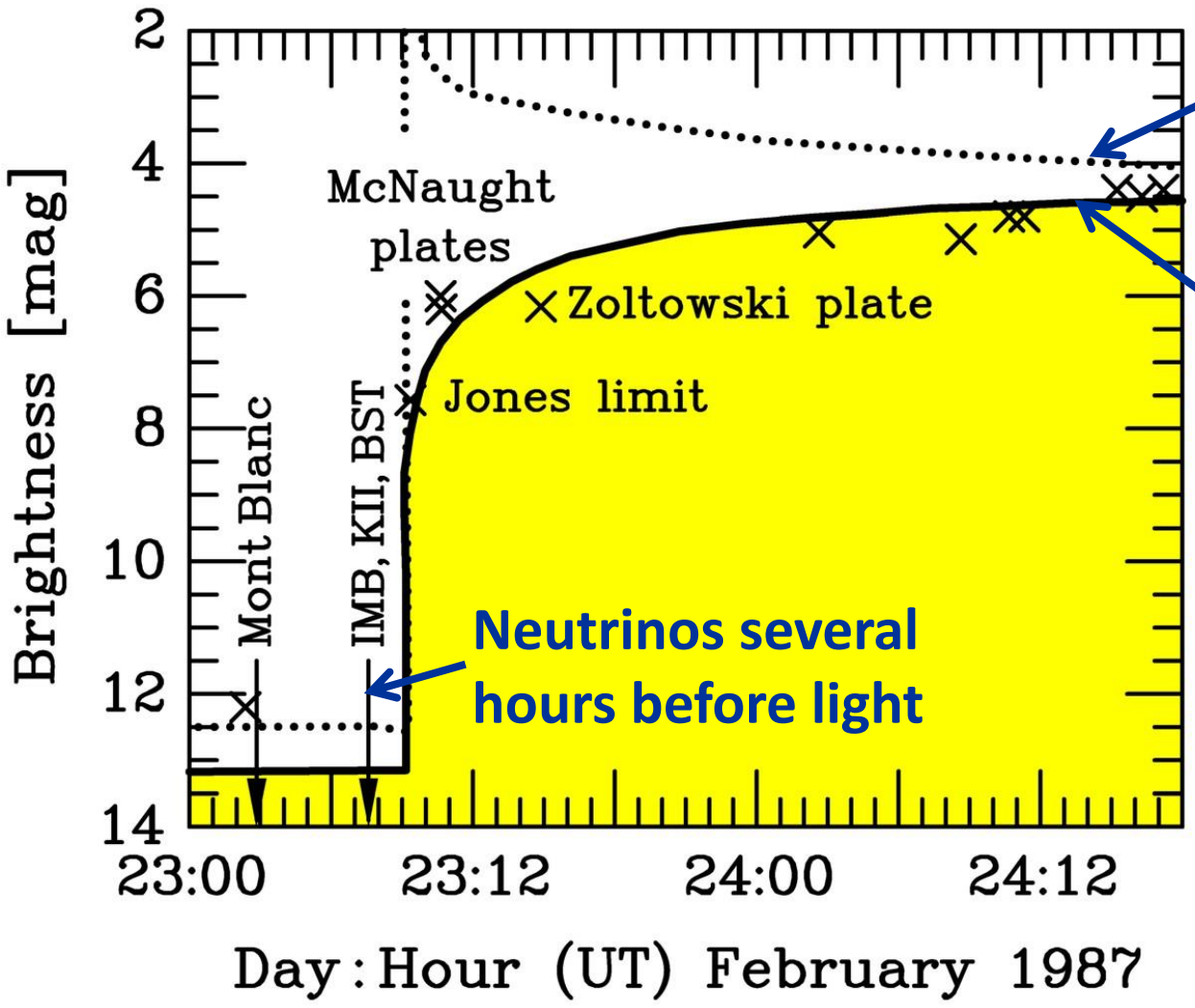
SuperNova Early Warning System (SNEWS)

http://snews.bnl.gov



- Neutrinos arrive several hours before optical outburst
- Issue alert to astronomical community
- Trigger to LIGO, NOvA, GCN

Early Lightcurve of SN 1987A

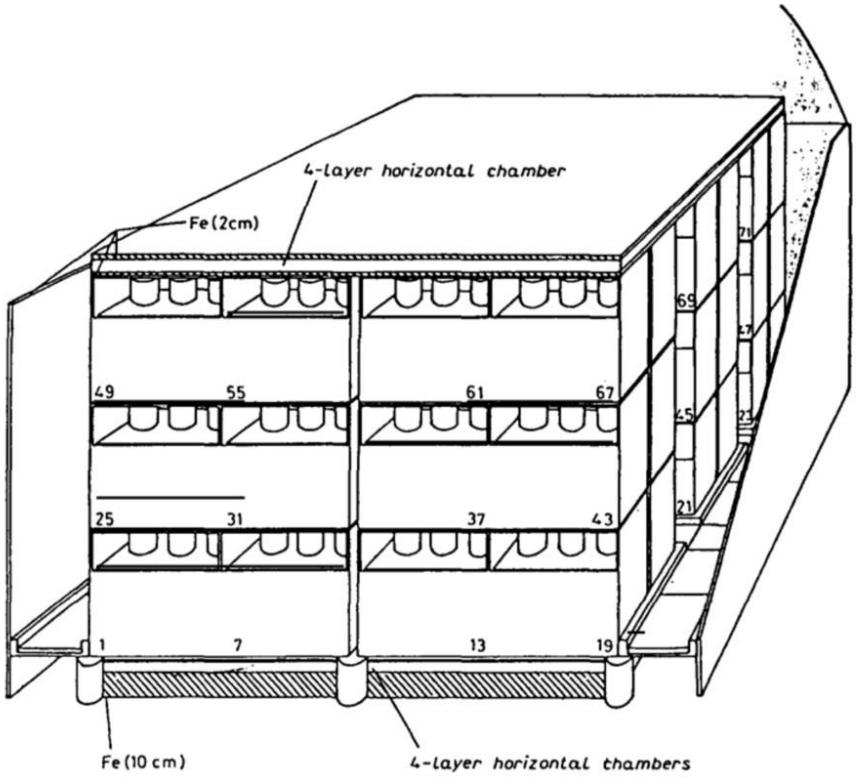


Expected bolometric brightness evolution

Expected visual brightness evolution

Adapted from
Arnett et al.,
ARAA 27 (1989)

May a Supernova Bang Twice?



LSD (Liquid Scintillator Detector)
in the Mont Blanc Tunnel
(Oct. 1984 – March 1999)
Supernova monitor for our galaxy
90 tons scintillator
200 tons iron (support structure)

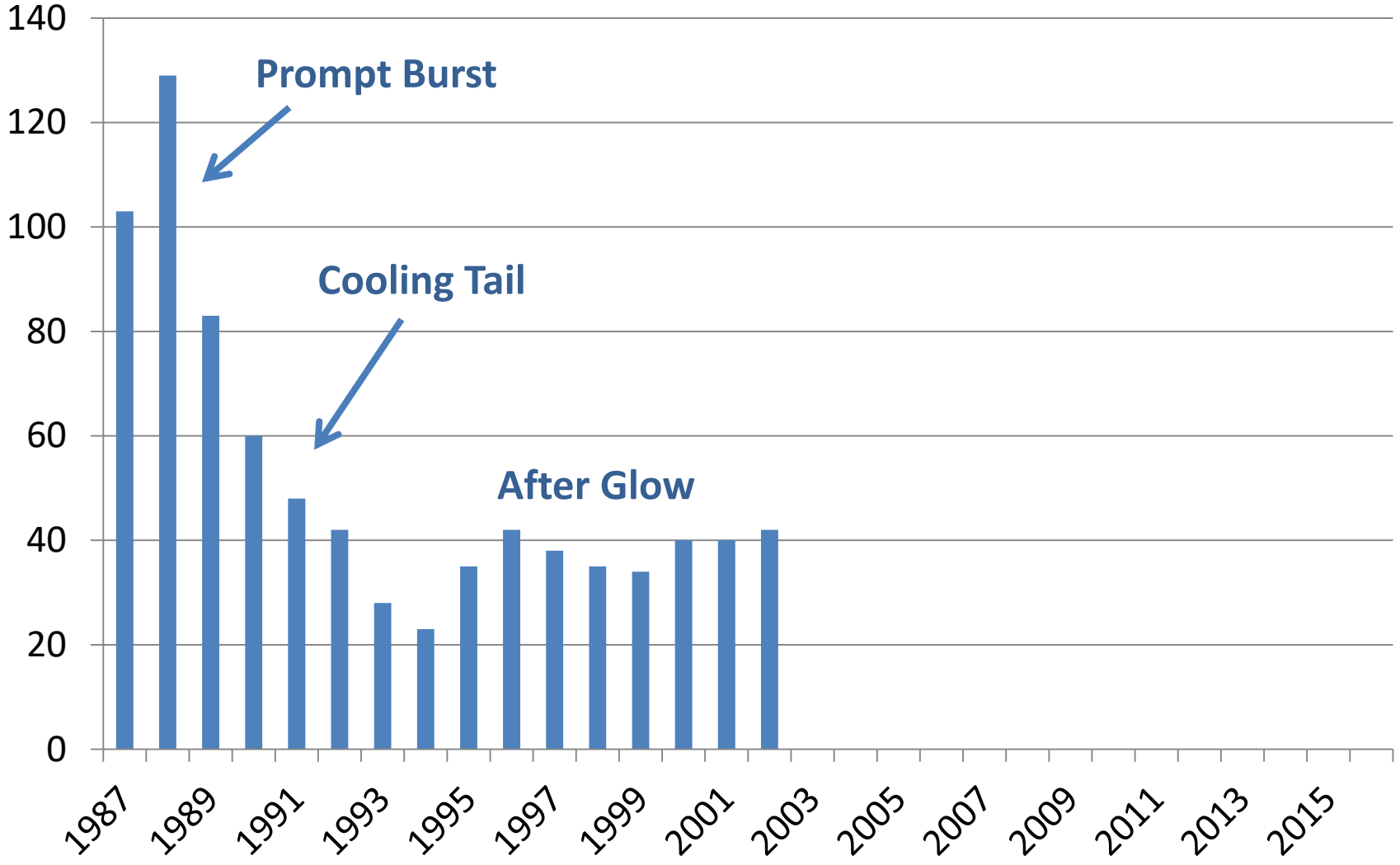
- Observed a 5-event cluster (7 sec) 4.72 hours before IMB/Kam-II
- Triggered autmatic SN alert
- Statistical fluctuation very unlikely
- No significant signal in IMB/Kam-II at LSD time
- No significant LSD signal at IMB time

- One interpretation as “double bang”: Huge ν_e flux (~ 40 MeV) at LSD time
- LSD signal caused by interactions in iron of support structure
- Second bang ordinary multi-flavor signal

(Imshennik & Ryazhskaya,
“A rotating collapsar and possible interpretation of the LSD neutrino signal from SN 1987A”, astro-ph/0401613)

SN 1987A Burst of Neutrino Papers

inSPIRE: Citations of the papers reporting the neutrino burst



SN 1987A Burst of Neutrino Papers

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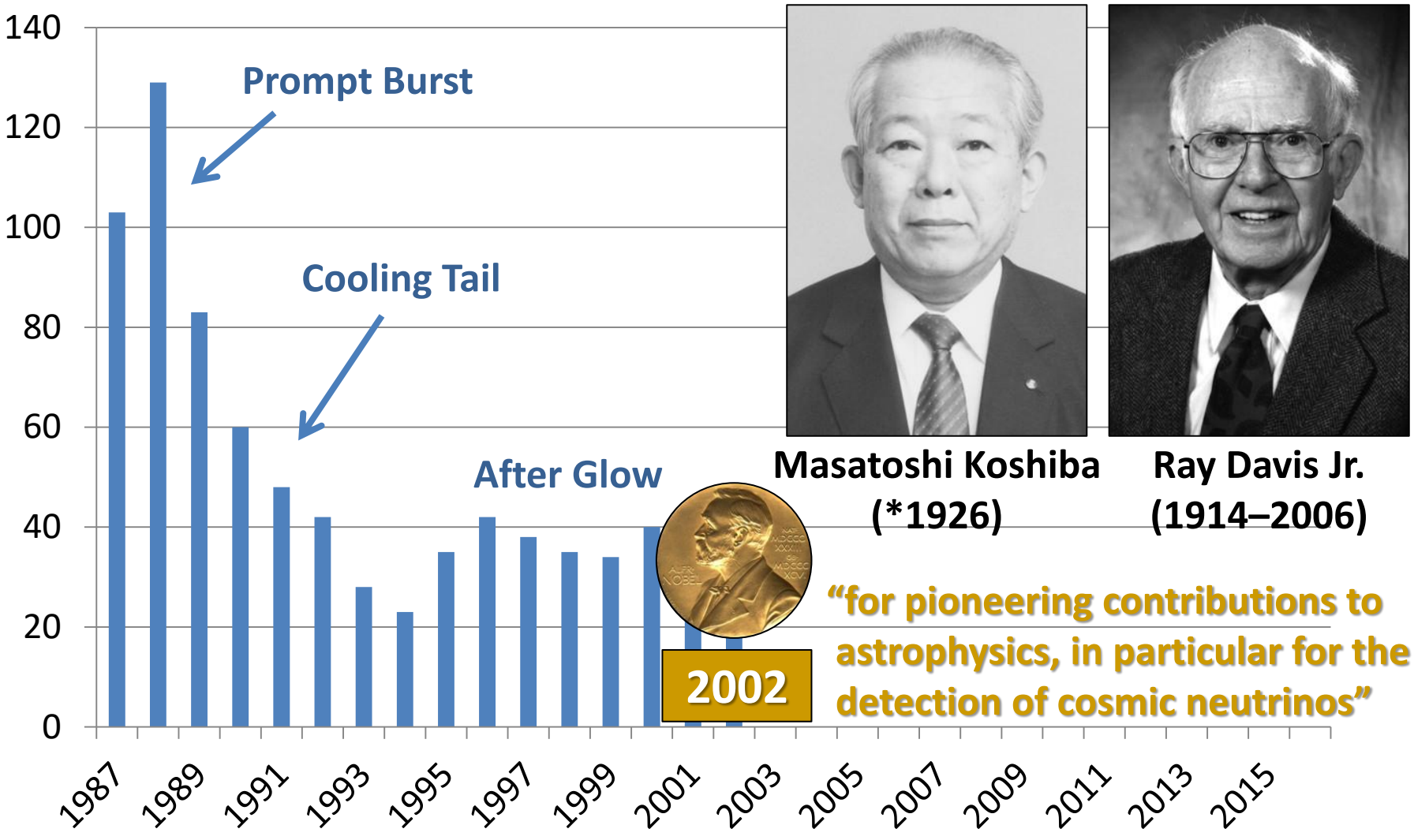


Masatoshi Koshiba
(*1926)

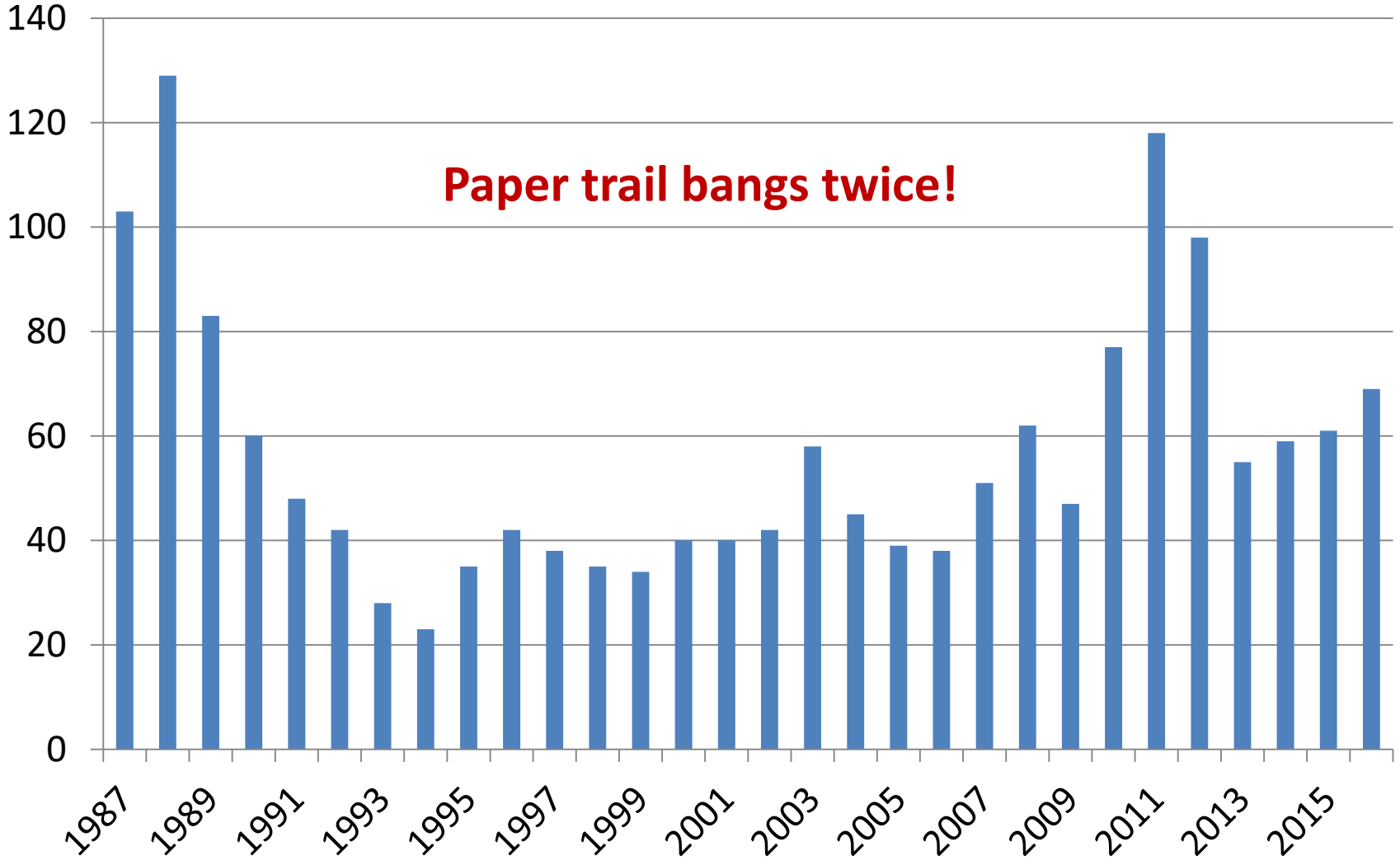
Ray Davis Jr.
(1914–2006)

2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

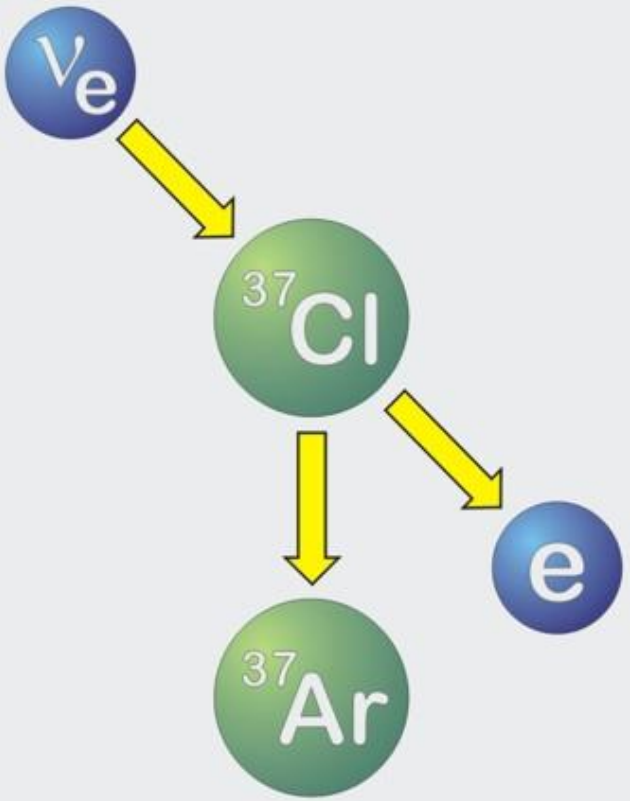
SN 1987A Burst of Neutrino Papers

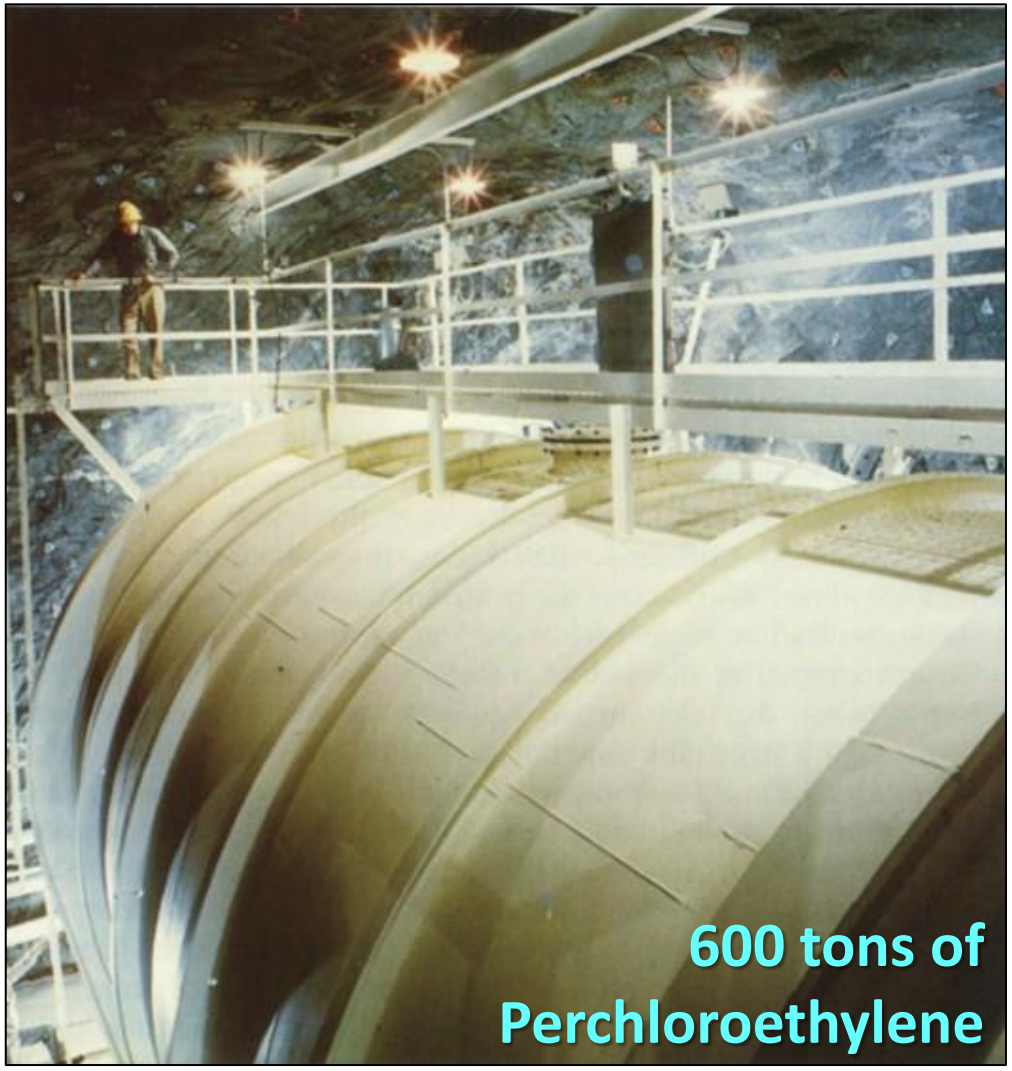
inSPIRE: Citations of the papers reporting the neutrino burst



First Measurements of Solar Neutrinos

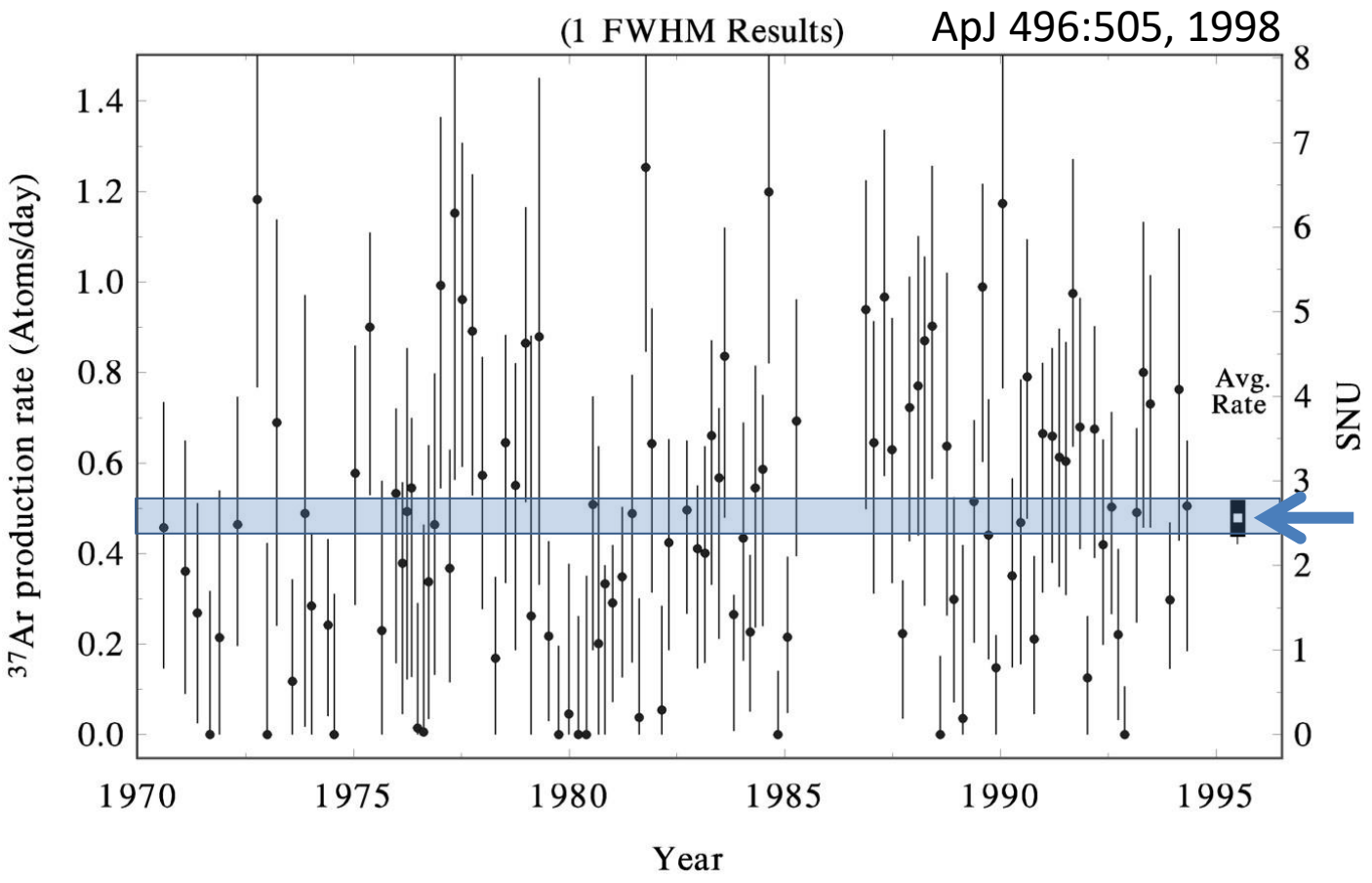
Inverse beta decay of chlorine





Homestake solar neutrino observatory (1967–2002)

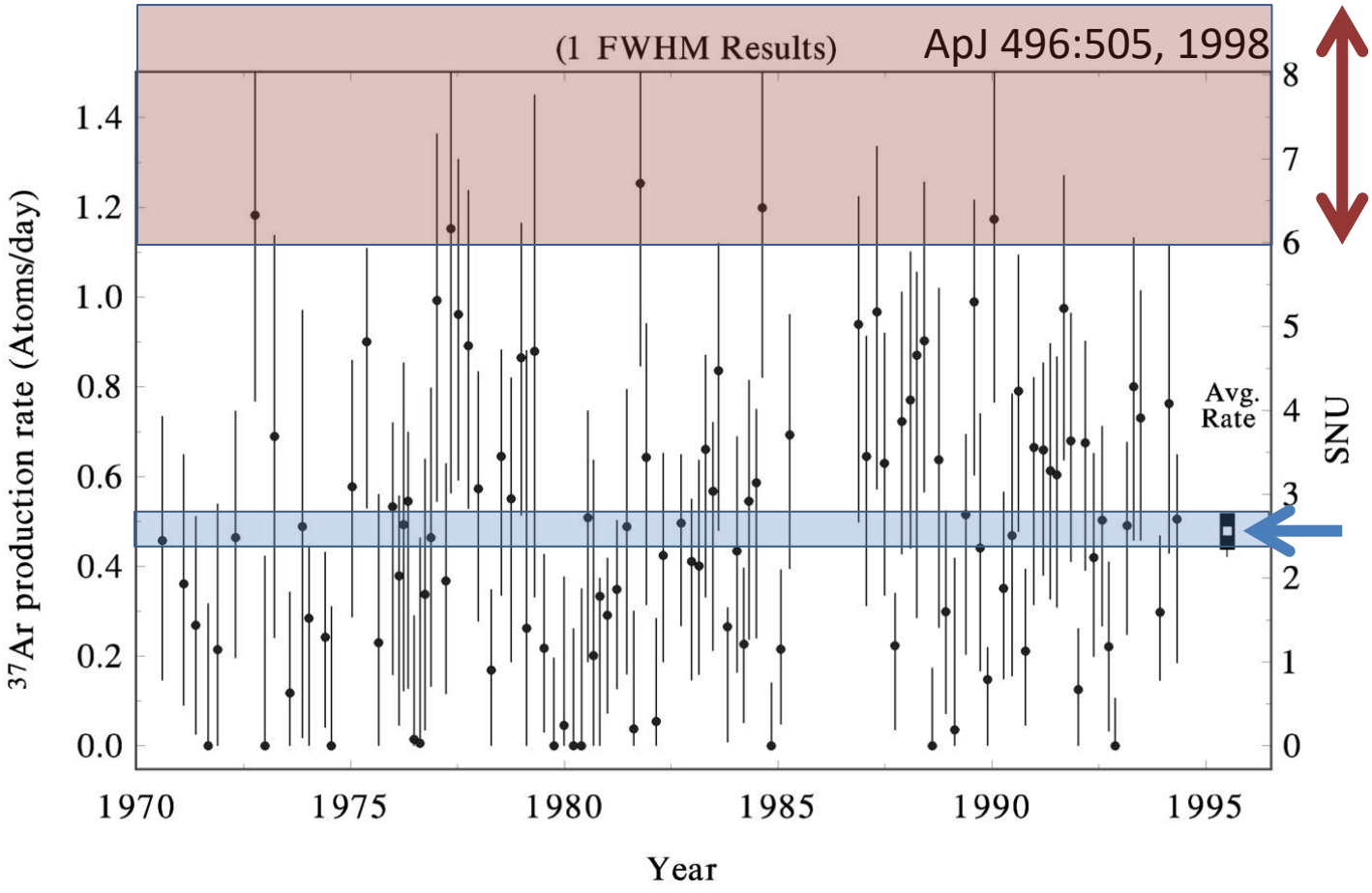
Results of Chlorine Experiment (Homestake)



Average (1970–1994) $2.56 \pm 0.16_{stat} \pm 0.16_{sys}$ SNU

(SNU = Solar Neutrino Unit = 1 Absorption / sec / 10^{36} Atoms)

Results of Chlorine Experiment (Homestake)



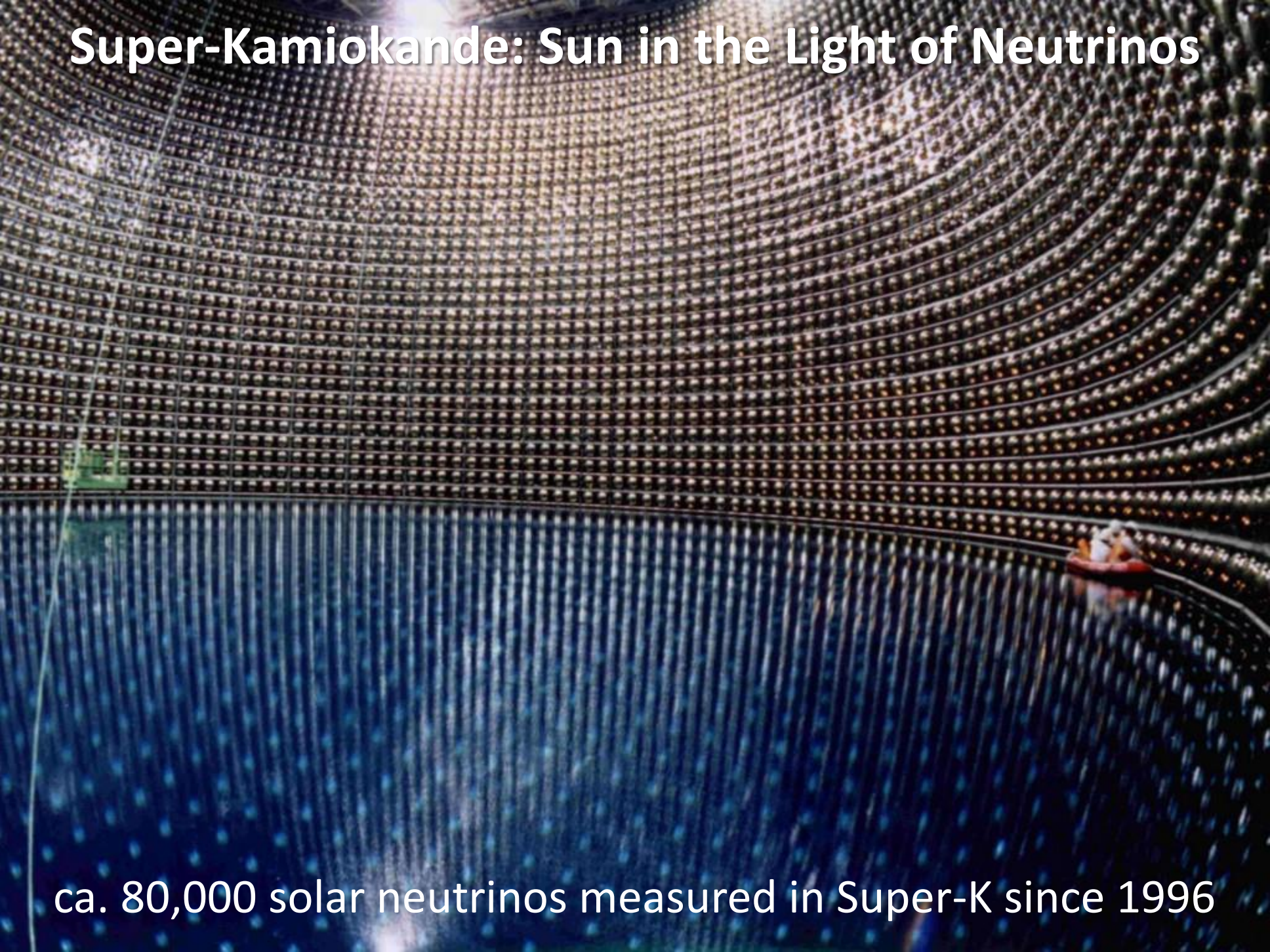
Average (1970–1994) $\mathbf{2.56 \pm 0.16_{stat} \pm 0.16_{sys}}$ **SNU**

(SNU = Solar Neutrino Unit = 1 Absorption / sec / 10^{36} Atoms)

Theoretical Prediction 6–9 SNU

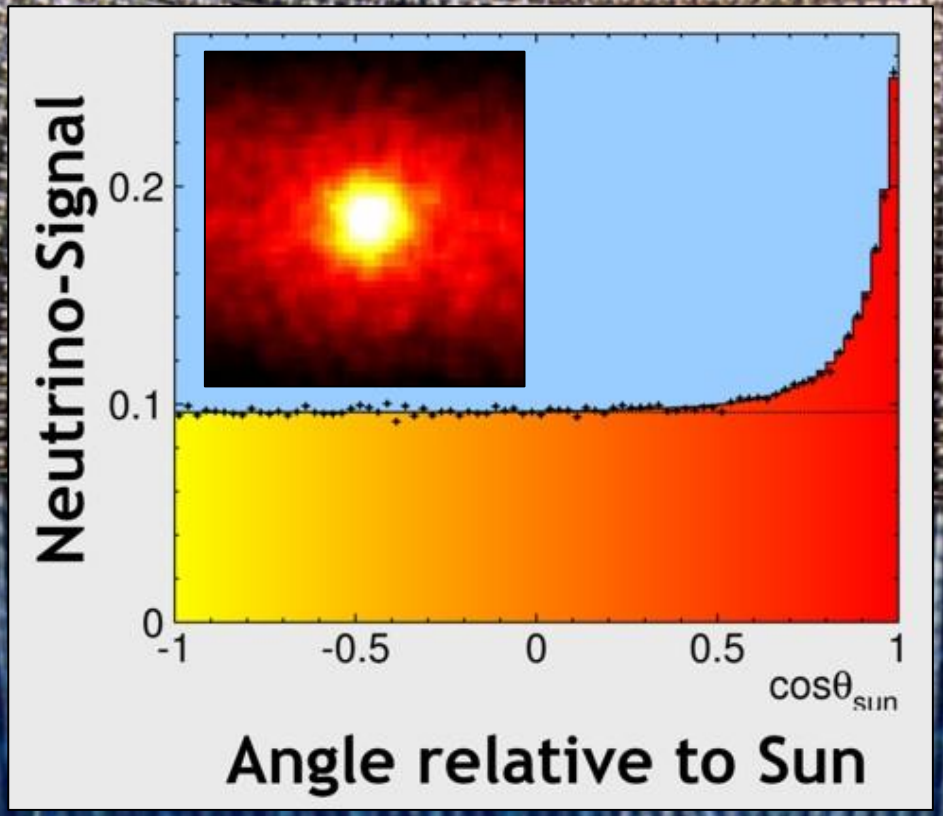
"Solar Neutrino Problem" since 1968

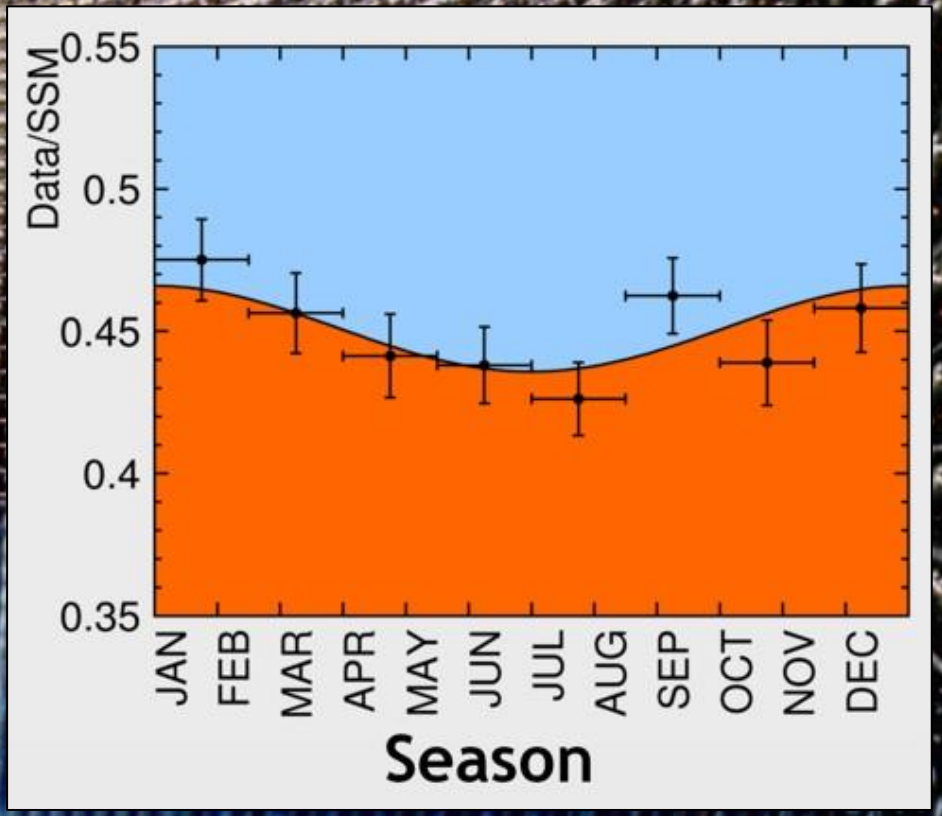
Super-Kamiokande: Sun in the Light of Neutrinos



ca. 80,000 solar neutrinos measured in Super-K since 1996

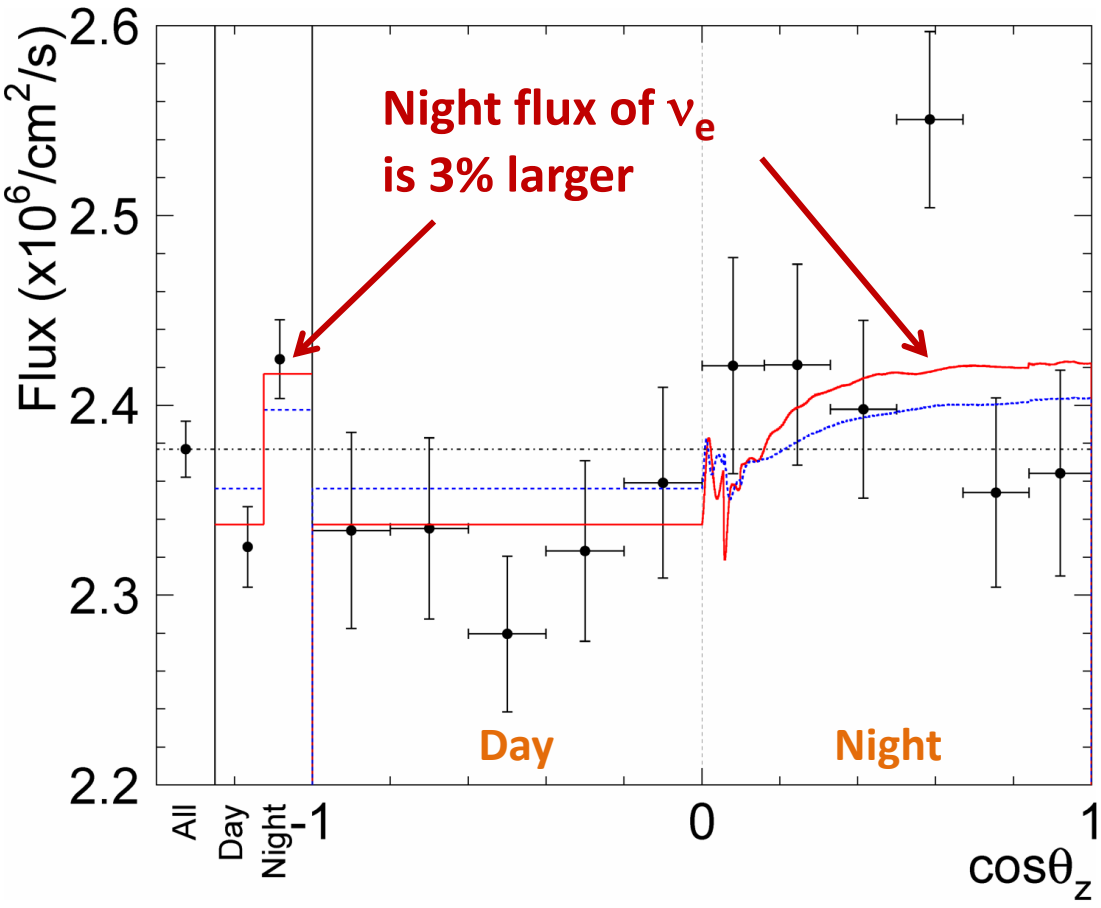
Super-Kamiokande: Sun in the Light of Neutrinos



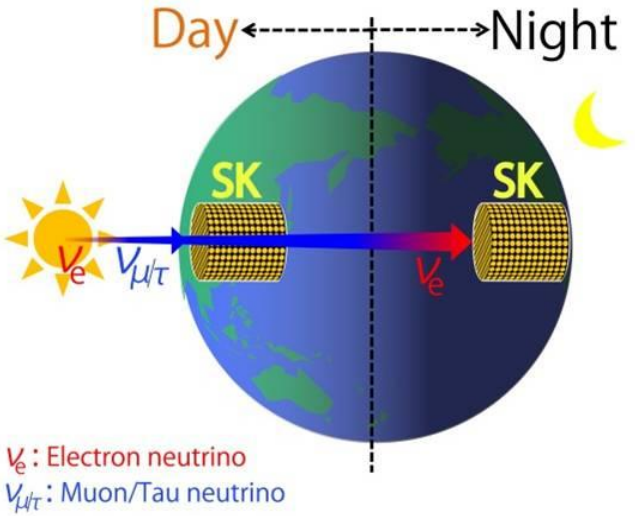


ca. 80,000 solar neutrinos measured in Super-K since 1996

Sun Shining Brighter at Night



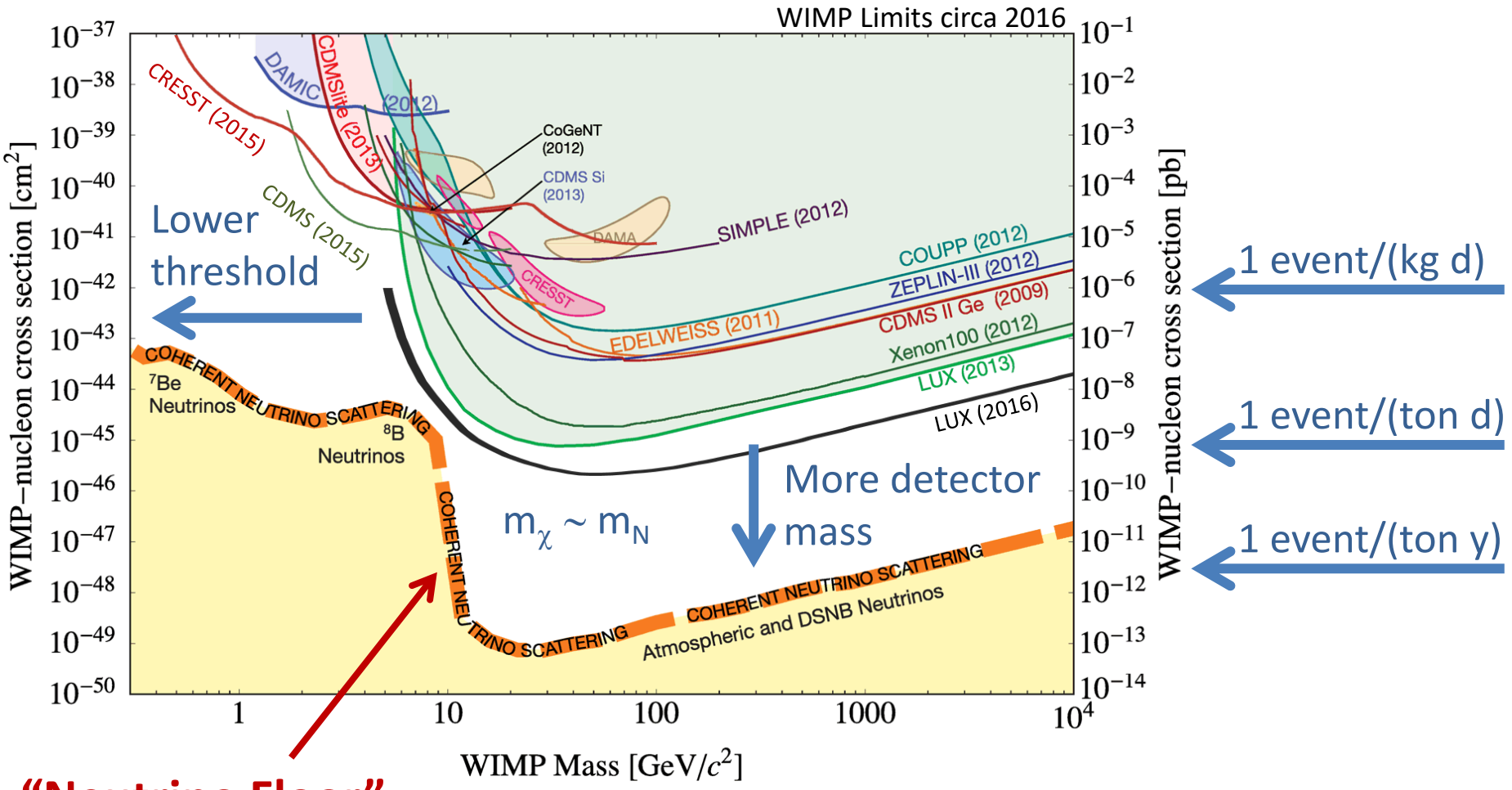
ν_e regeneration by propagating through matter of Earth



Renshaw et al. (Super-Kamiokande Collaboration), arXiv:1312.5176

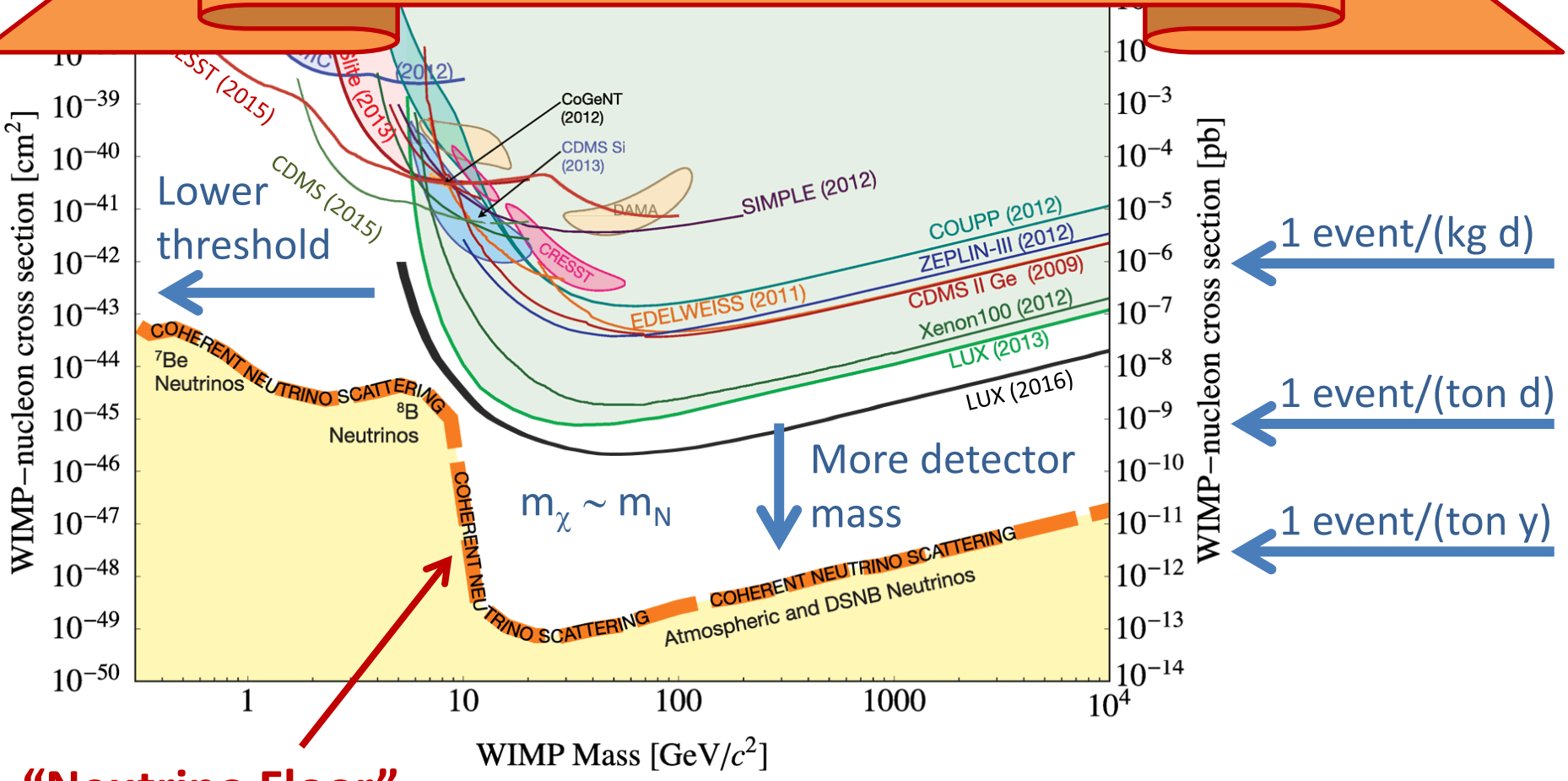
WIMP Limits: Race to the Bottom

Searchig weakly interacting massive particles (~heavy neutrinos) in direct detection experiments

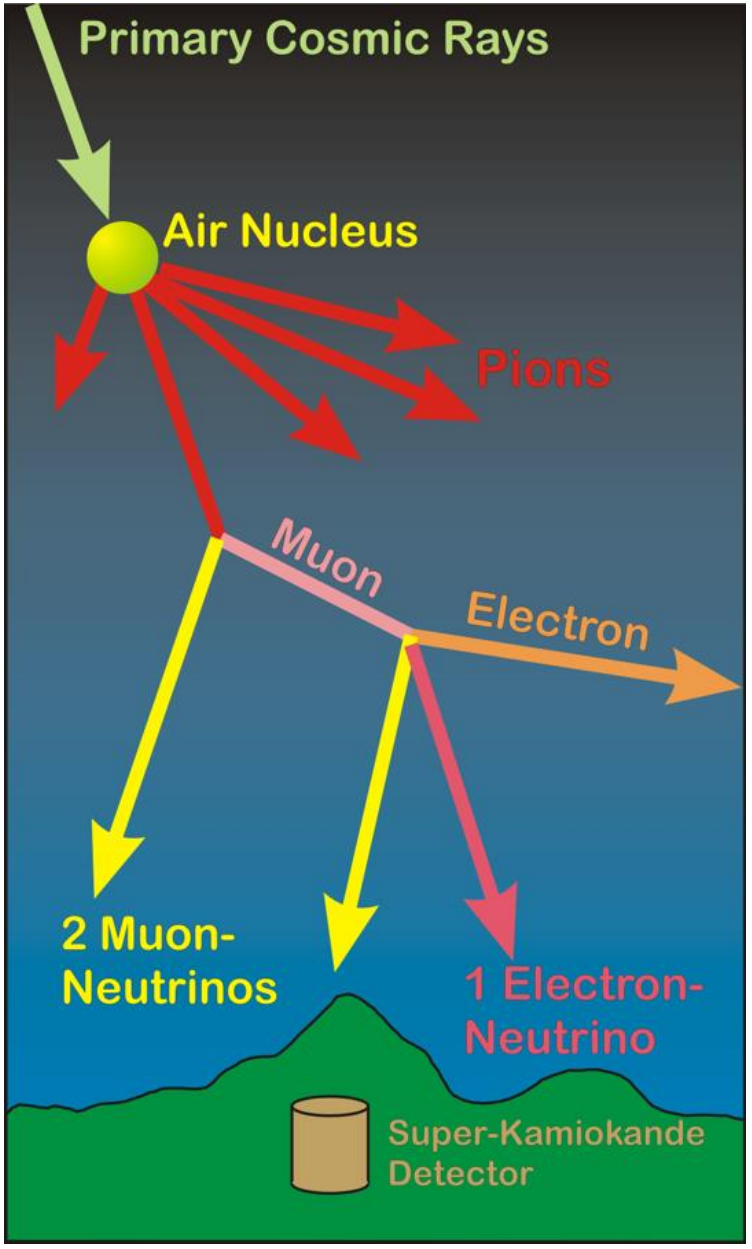


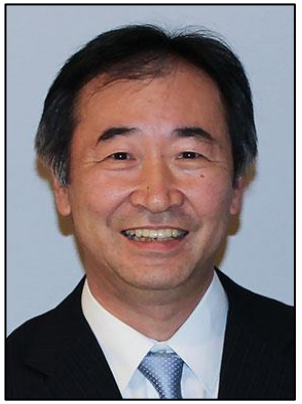
Search

Yesterday's sensation
is today's calibration *—R.Feynman*
… and tomorrow's background *—V.Telegdi*



Atmospheric Neutrinos



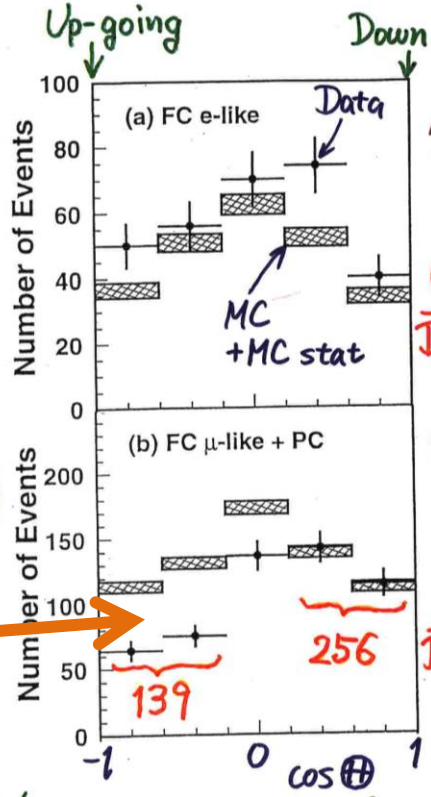


T. Kajita
Univ. Tokyo

2015

Neutrino 1998
Takayama, Japan

Zenith angle dependence
(Multi-GeV)



(e) χ^2(shape) = 2.8/4 dof

$\frac{Up}{Down} = 0.93^{+0.13}_{-0.12}$

(μ) χ^2(shape) = 30/4 dof

$\frac{Up}{Down} = 0.54^{+0.06}_{-0.05}$ (6.2σ !!)

※ Up/Down syst. error for μ-like

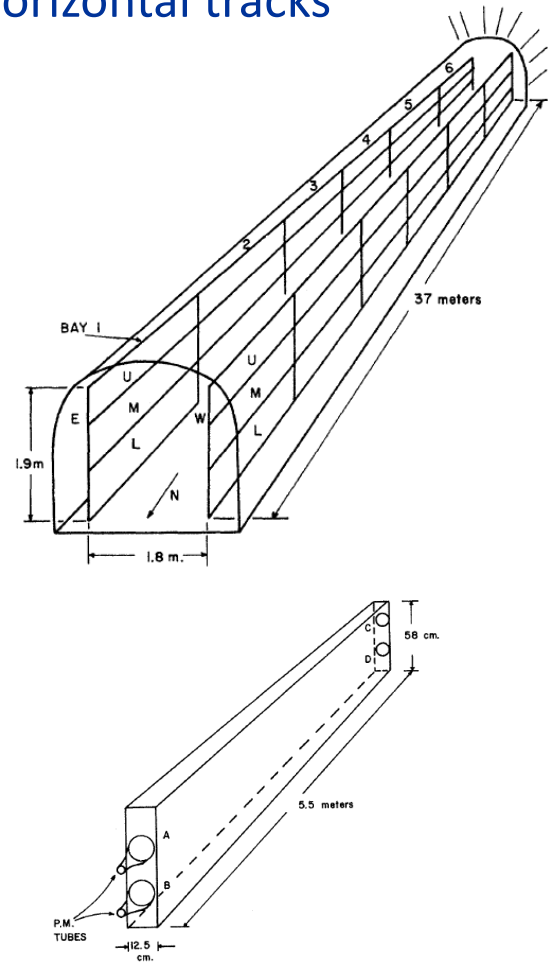
Prediction (flux calculation ····· ≲1%, 1km rock above SK ···· 1.5%) 1.8%

Data (Energy calib. for ↑↓ ···· 0.7%, Non ν Background ····· < 2%) 2.1%

Detection of First Atmospheric Neutrinos 1965

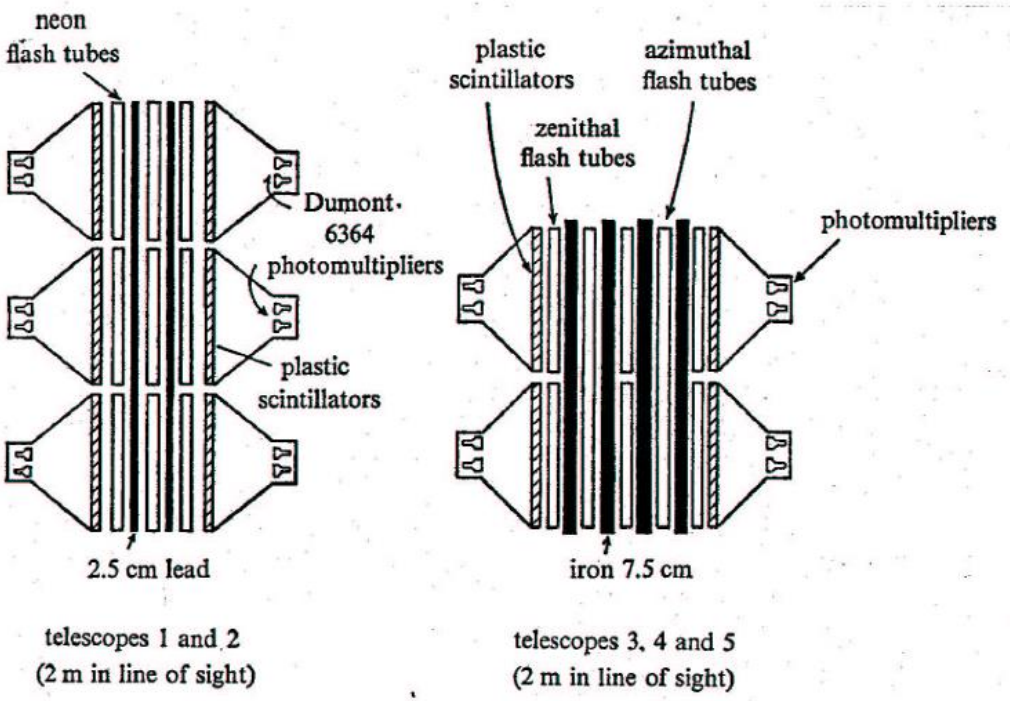
Chase-Witwatersrand-Irvine (CWI) Coll.
Mine in South Africa, 8800 mwe

- Liquid scintillator
- Horizontal tracks



Kolar Gold Field (KGF) Collaboration
(Japan-India-UK group), 7500 mwe

- Plastic scintillator
- Flash tubes



CASE

E.R.P.M.

WITS

DETECTION OF THE FIRST NEUTRINO IN NATURE
ON
23RD FEBRUARY 1965
IN
EAST RAND PROPRIETARY MINE

THIS DISCOVERY TOOK PLACE IN A LABORATORY SITUATED
TWO MILES BELOW THE SURFACE OF THE EARTH ON
76 LEVEL OF EAST RAND PROPRIETARY MINE, MANNED
BY A GROUP OF PHYSICISTS FROM THE CASE INSTITUTE OF TECHNOLOGY U.S.A.
AND THE UNIVERSITY OF THE WITWATERSRAND JOHANNESBURG.

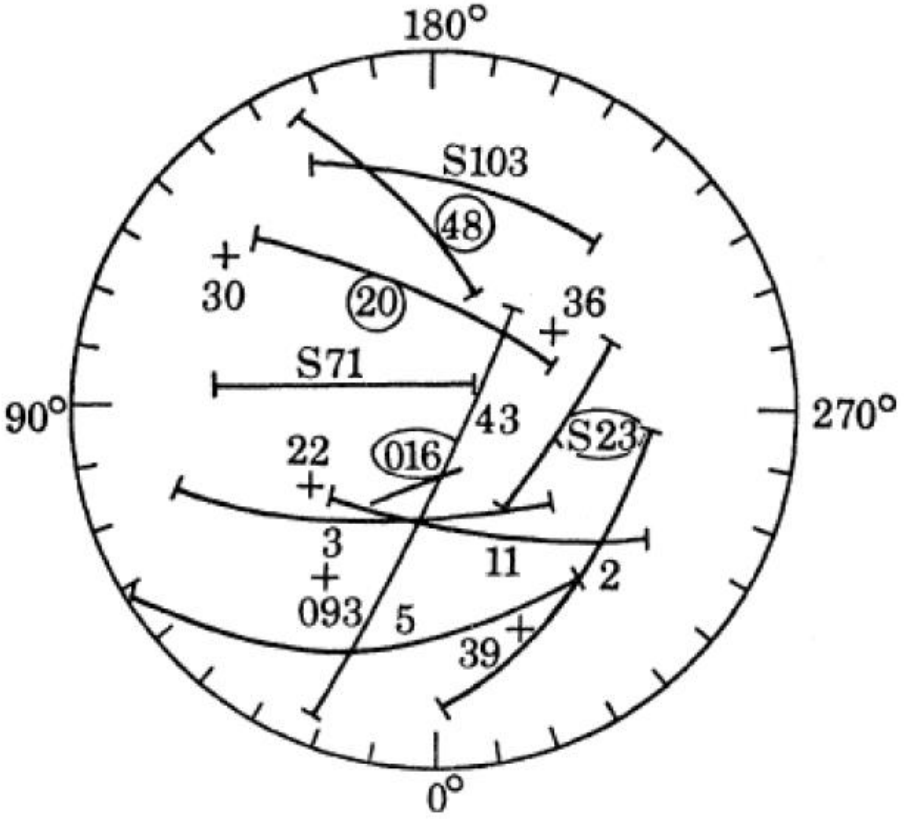
THE PROJECT WAS SPONSORED BY :-
UNITED STATES ATOMIC ENERGY COMMISSION
E.R.P.M. AND RAND MINES GROUP
CASE INSTITUTE OF TECHNOLOGY
UNIVERSITY OF THE WITWATERSRAND
TVL. & O.F.S. CHAMBER OF MINES
AND CONVERTED FROM PROPOSAL TO REALITY
WITH THE HELP OF THE OFFICIALS AND MEN
OF THE HERCULES SHAFT OF E.R.P.M.
6TH DECEMBER 1967

SCIENTIFIC TEAM : F. REINES J.P.F. SELLSCHOP M.F. CROUCH
AND F.T. JENKINS W.R. KROPP H.S. GURR B. MEYER A.A. HRUSCHKA B.M. SHOEMER

First Neutrino Sky Map

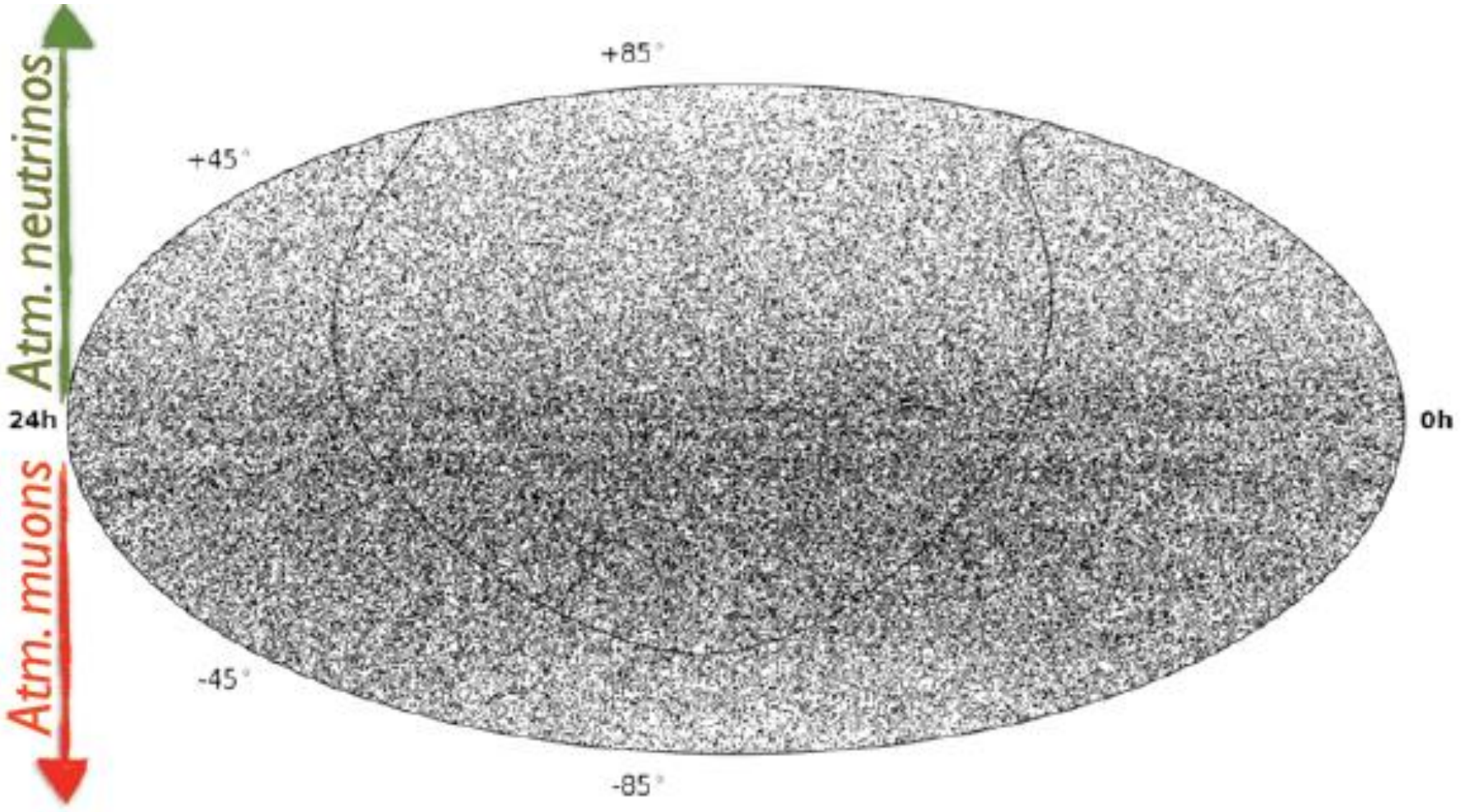
The first neutrino sky map with the celestial coordinates of 18 Kolar Gold Field neutrino events

(Krishnaswamy et al. 1971)



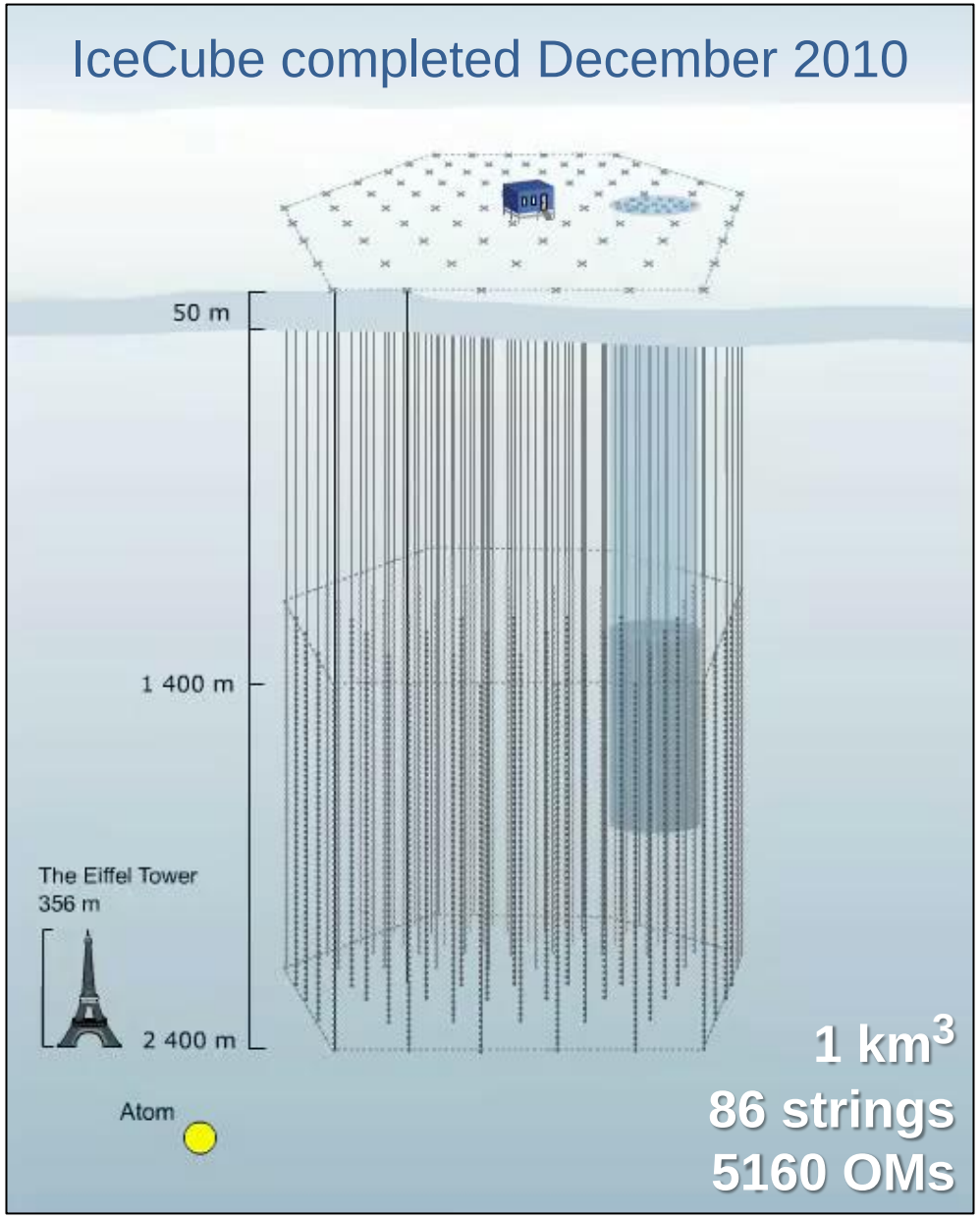
Due to uncertainties in the azimuth, the coordinates for some events are arcs rather than points. The labels reflect the numbers and registration mode of the events (e.g. S for spectrograph). Only for the ringed events the sense of the direction of the registered muon is known.

IceCube (40 & 59 strings) Skymap



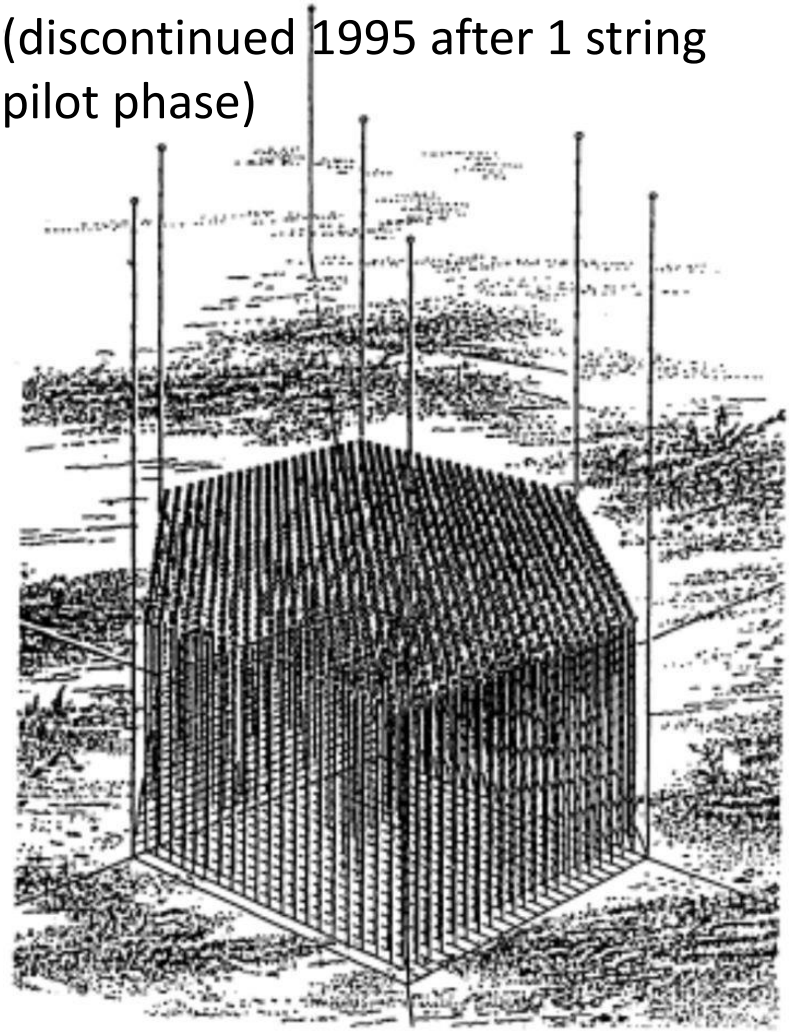
Total events: 43339 (upgoing) and 64230 (downgoing)
Livetime: 348 days (IC59) and 375 days (IC40)

IceCube Neutrino Telescope at the South Pole

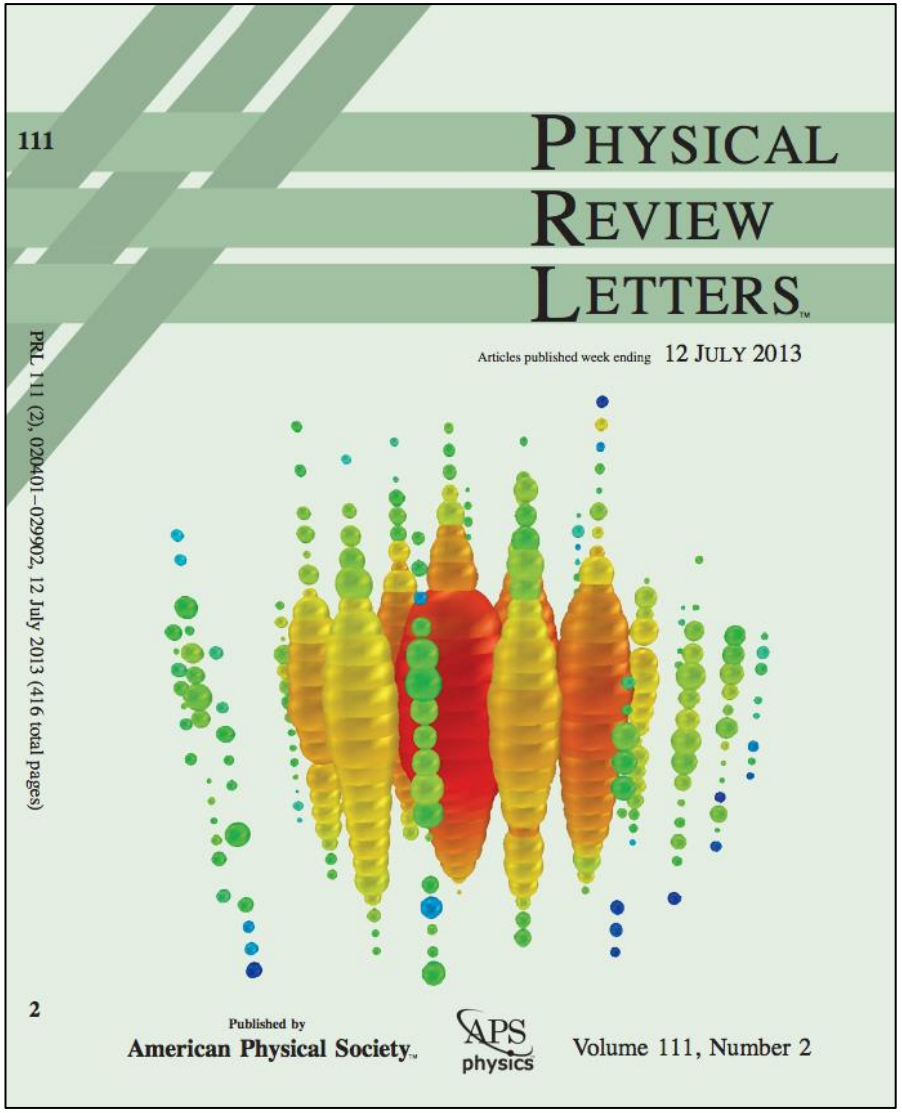


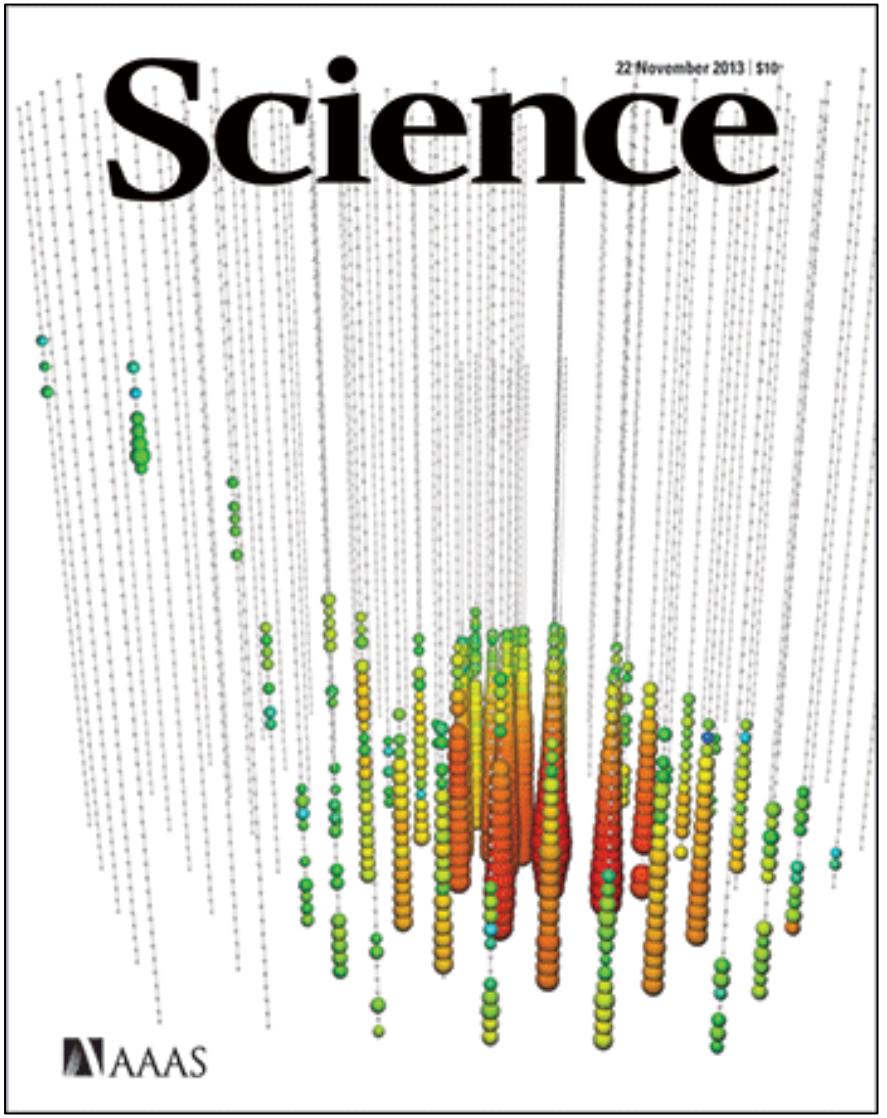
Idea for DUMAND under sea Cherenkov detector (1978)

1.26 km^3, 22 698 Optical Modules (discontinued 1995 after 1 string pilot phase)

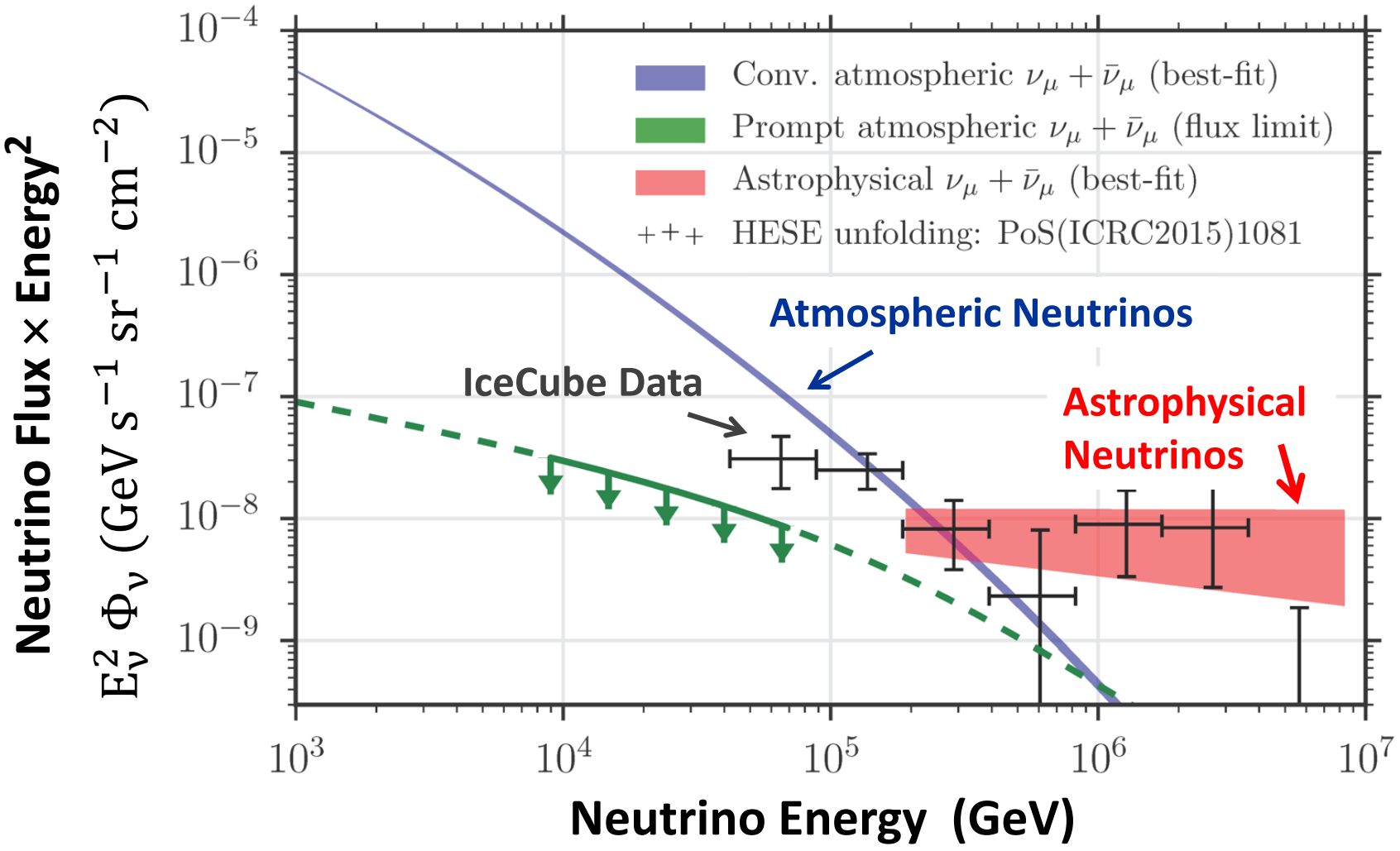


Detection of The Year (2013)



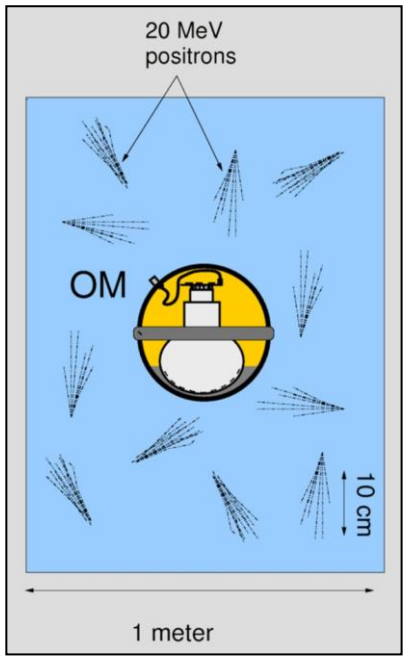


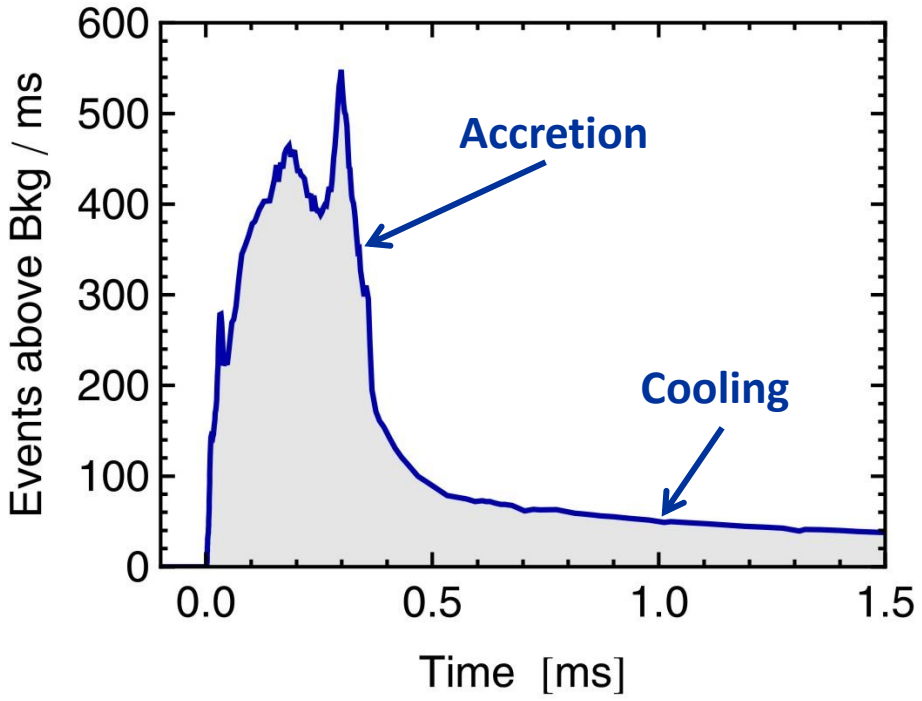
Diffuse Astrophysical High-Energy Neutrinos



IceCube Collaboration, arXiv:1702.05244

IceCube as a Supernova Neutrino Detector



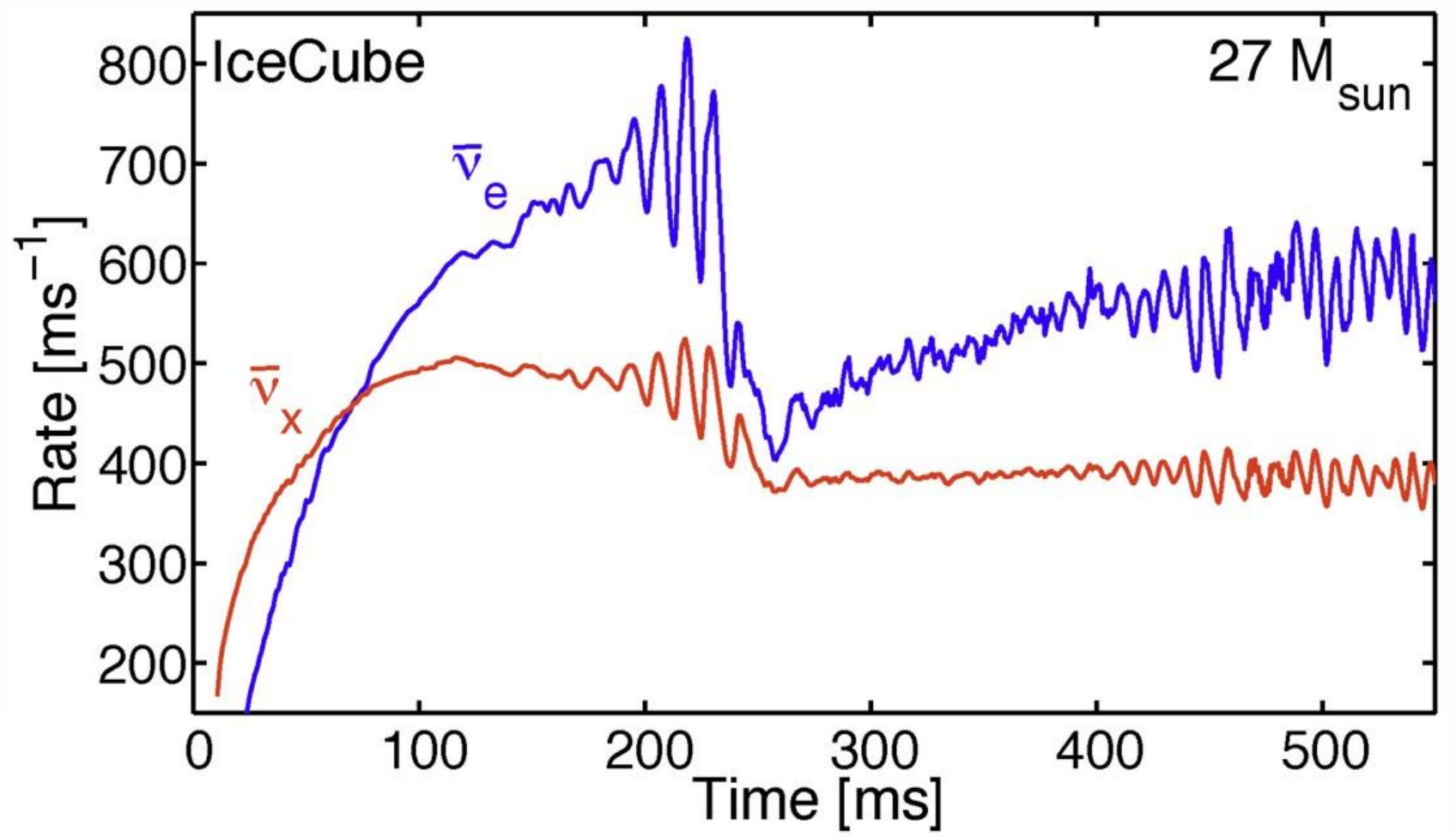


SN signal at 10 kpc
10.8 M_{sun} simulation
of Basel group
[arXiv:0908.1871]

- Each optical module (OM) picks up Cherenkov light from its neighborhood
- ~ 300 Cherenkov photons per OM from SN at 10 kpc, bkgd rate in one OM < 300 Hz
- SN appears as "correlated noise" in ~ 5000 OMs
- Significant energy information from time-correlated hits

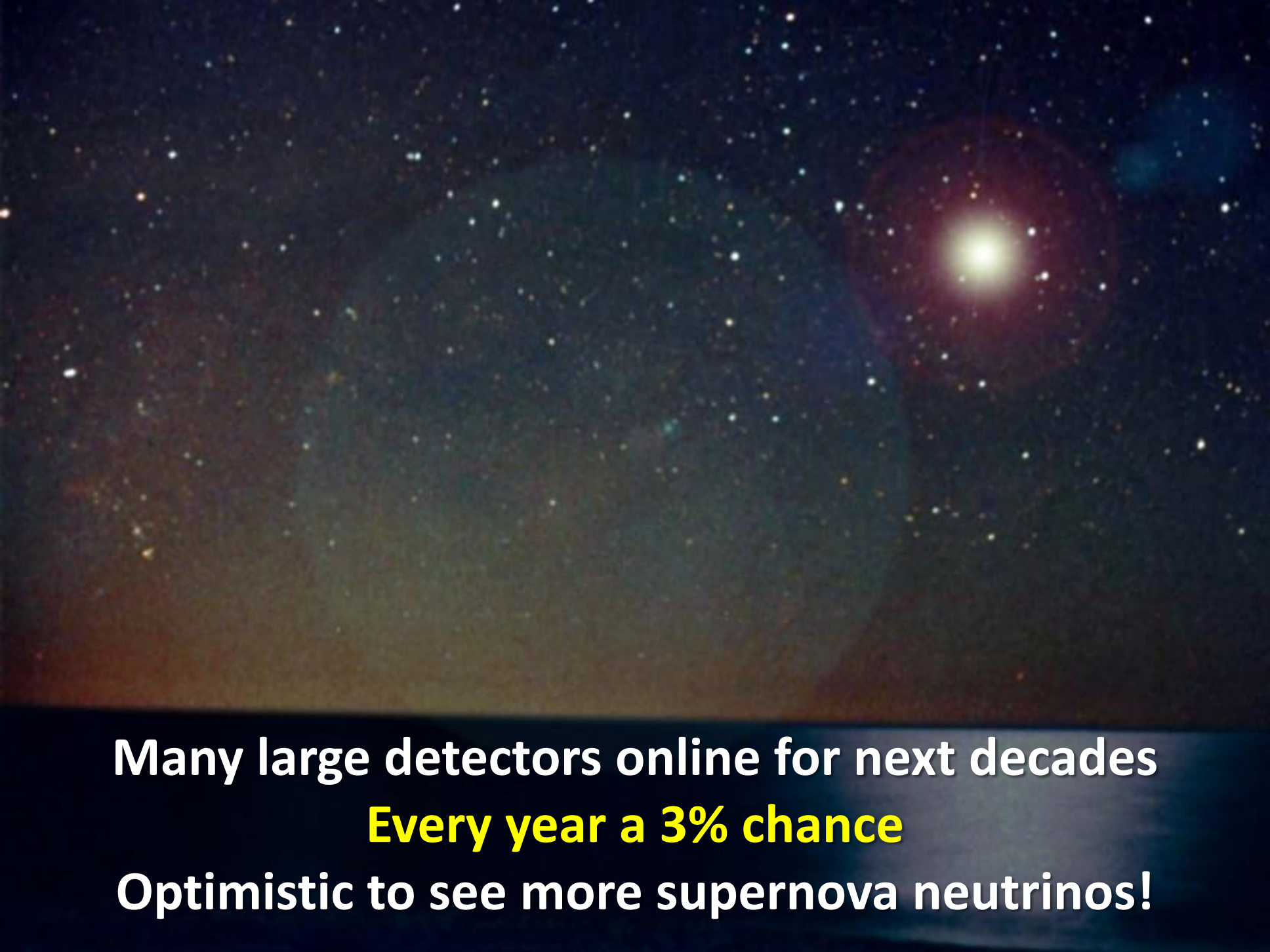
Pryor, Roos & Webster, ApJ 329:355, 1988. Halzen, Jacobsen & Zas, astro-ph/9512080. Demirörs, Ribordy & Salathe, arXiv:1106.1937.

SASI Mode in Neutrinos (3D Model)



Tamborra, Hanke, Müller, Janka & Raffelt, arXiv:1307.7936

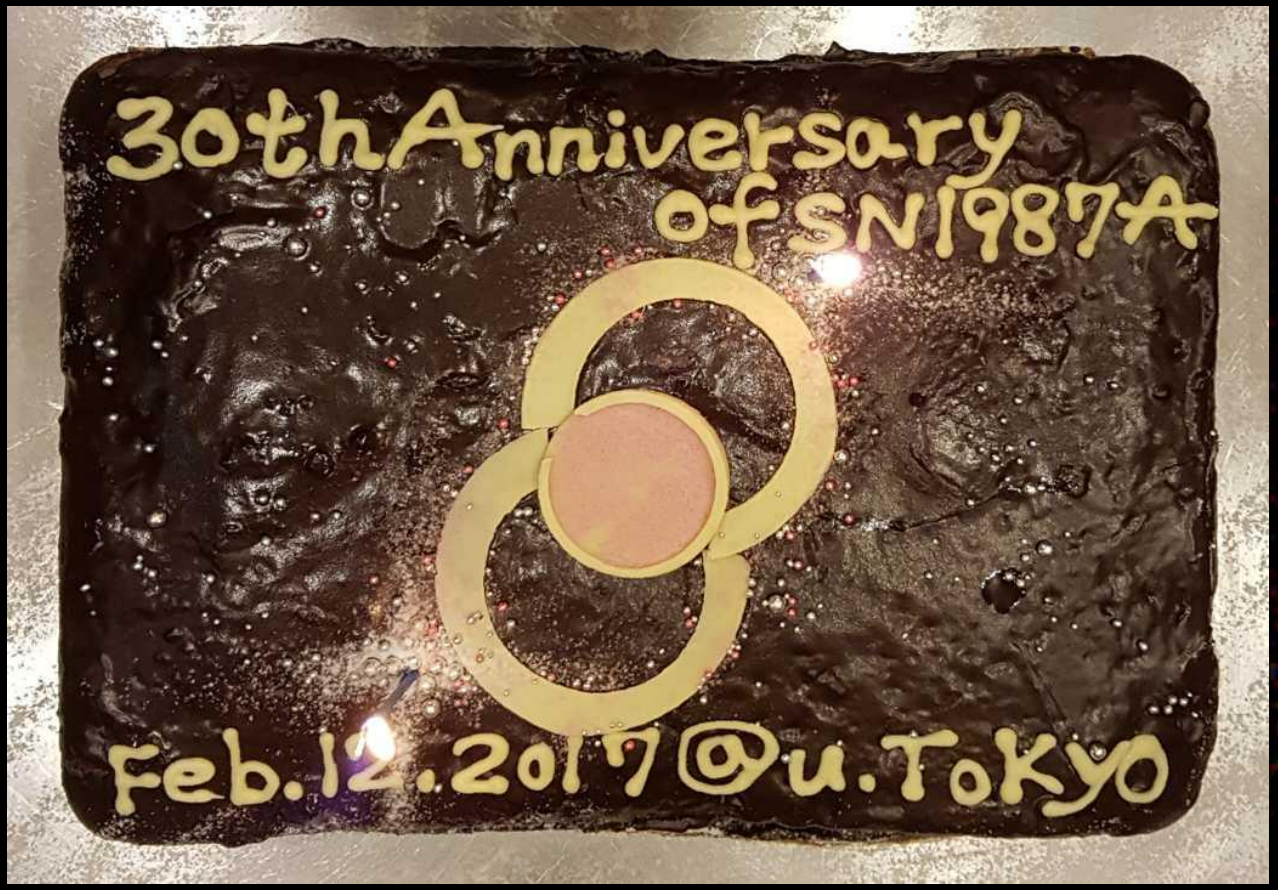
See also Lund, Marek, Lunardini, Janka & Raffelt, arXiv:1006.1889



Many large detectors online for next decades

Every year a 3% chance

Optimistic to see more supernova neutrinos!


30th Anniversary
of SN1987A
Feb.12.2017@u.Tokyo