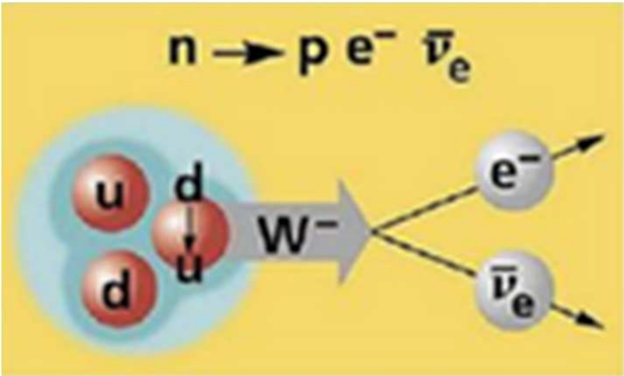
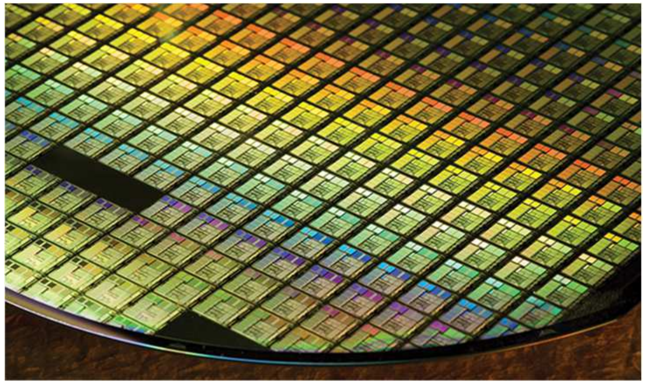
From Neutrino to Semiconductor

A journey of Learning and Research that Started from Physics



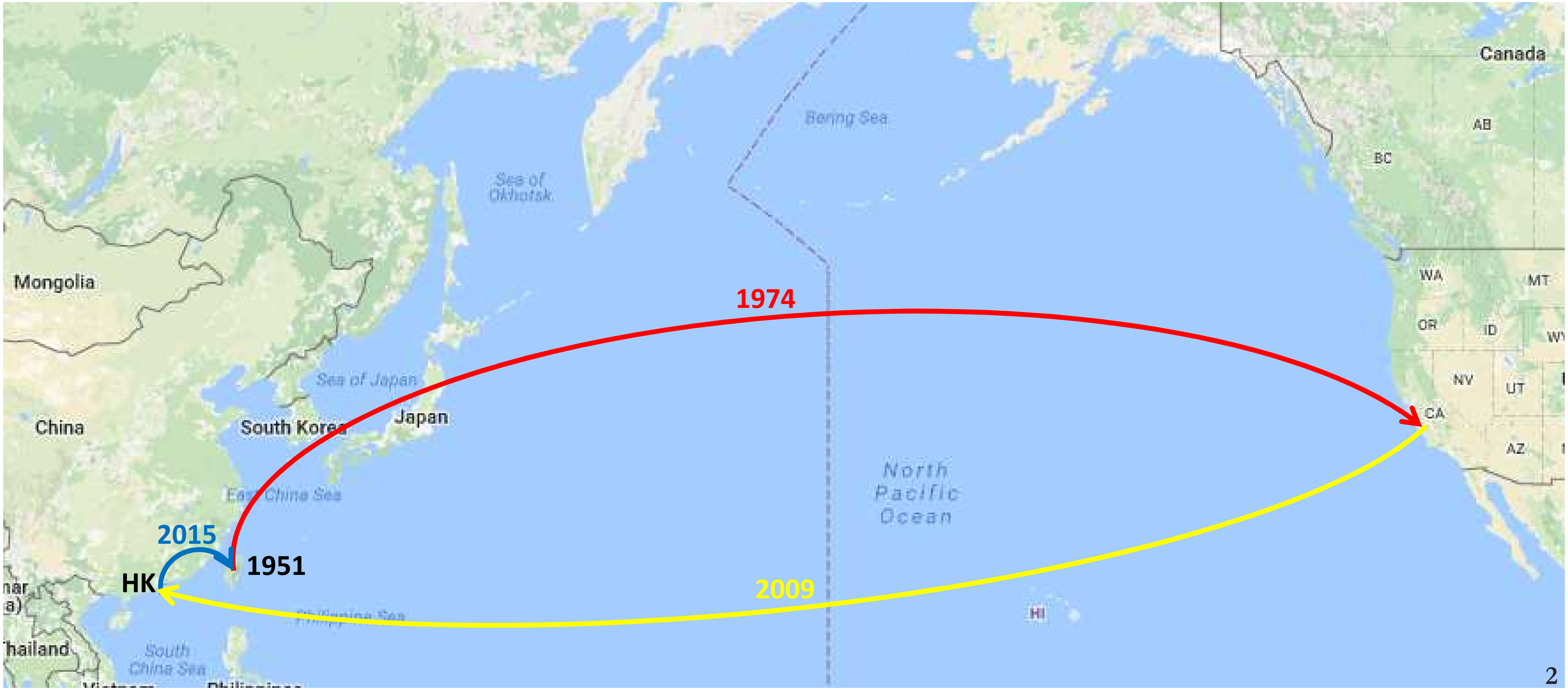


KC Wang（王克中）

Macronix (旺宏電子)

Joint AS IOP Colloquium and PG2023 General Talk on 6/1/2023

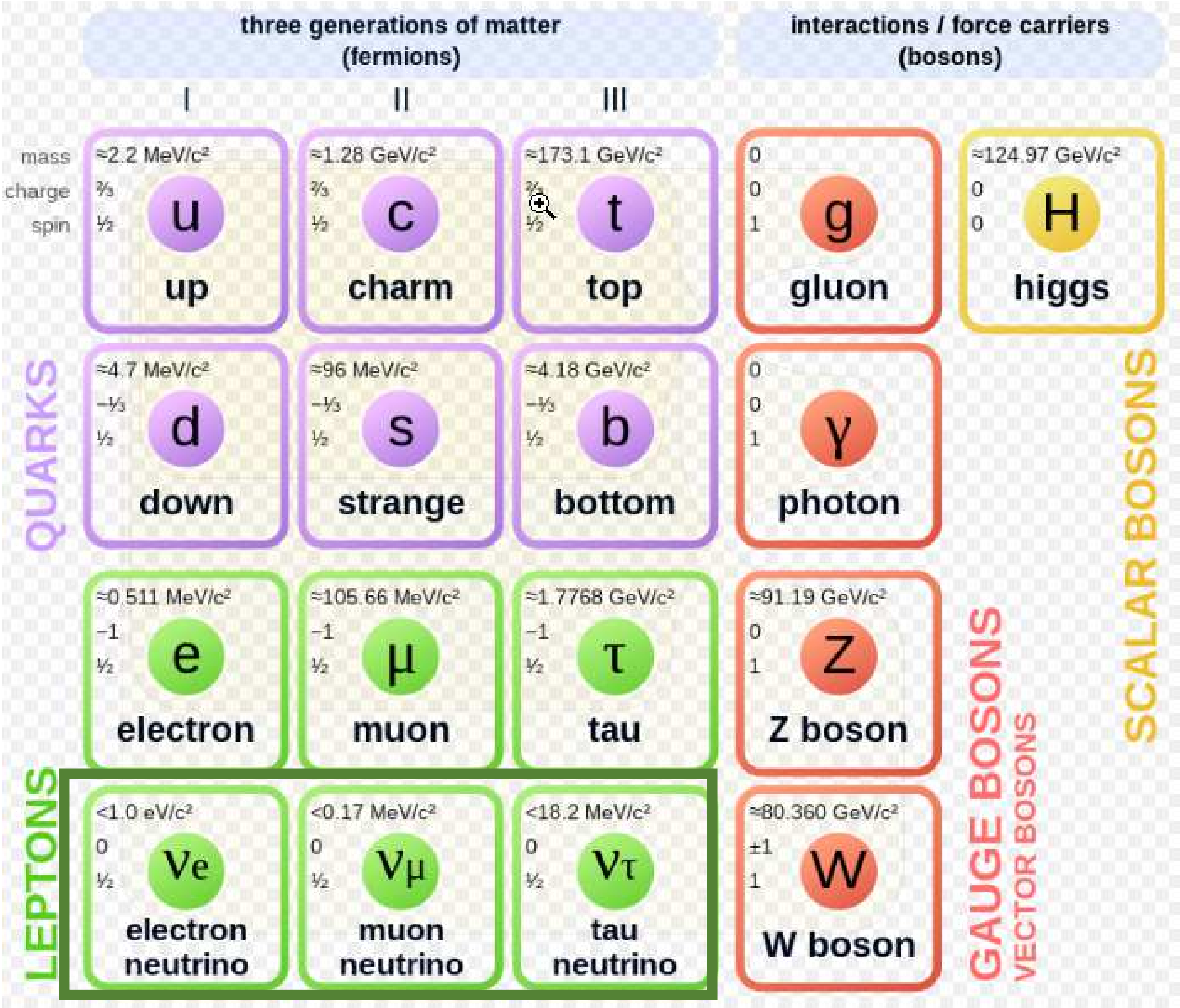
A Fulfilling Journey



Outline

- Introduction
- Experience Sharing
  - Some Stories of Neutrino
  - GaAs Heterojunction Bipolar Transistor (HBT) and ICs
  - Semiconductor Memories
- Conclusion Remarks

Elementary Particles of Standard Model

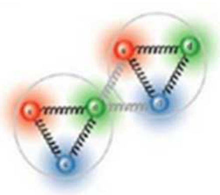


There are 3 flavors of neutrinos and their anti-particles

Source: https://en.wikipedia.org/wiki/Fundamental_interaction#/media/File:Standard_Model_of_Elementary_Particles.svg

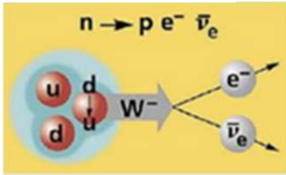
Fundamental Interactions

1. Strong



2. Electromagnetic

3. Weak



4. Gravitation

Interaction	Current theory	Mediators	Approximate relative strength	Long distance behavior (potential)	Range (m)
Strong	QCD	gluons	1	~r	10^{-15}
EM	QED	photons	10^{-2}	1/r	infinite
Weak	Elecroweak theory	W and Z bosons	10^{-6} to 10^{-7}	$1/r\ e^{-m_{W,Z}\,r}$	10^{-18}
Gravity	General relativity	gravitons	10^{-39}	1/r	infinite

https://en.wikipedia.org/wiki/Fundamental_interaction
http://hyperphysics.phy-astr.gsu.edu/hbase/Forces/couple.html

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The Origin of Neutrino Concept

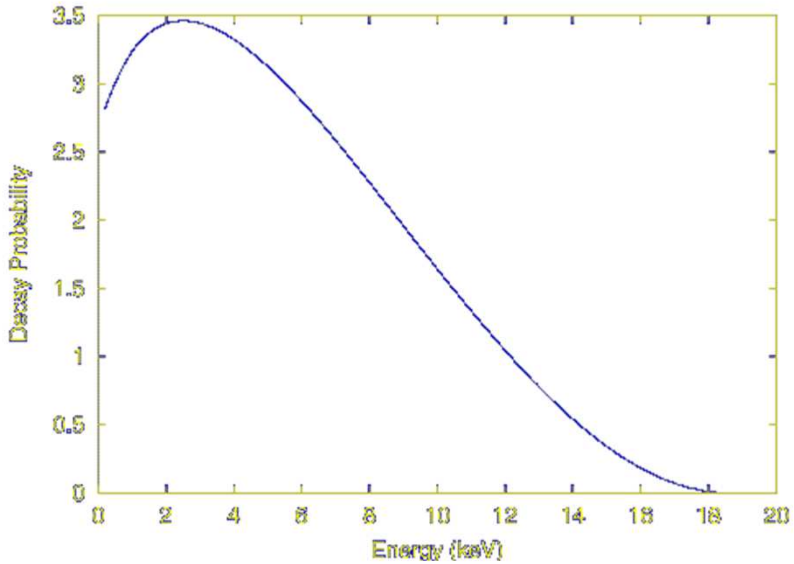
Puzzle of Beta Decay

When a neutron converts to a proton and electron, The electron should have single energy

However, the observed spectrum of electron was continuous.

N1 → N2 + e^-

$E_{e-} = E_{N1} - E_{N2}$



In 1930, Wolfgang Pauli proposed an idea of neutrino to save the law of conservation of energy

Discovery of Neutrino

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

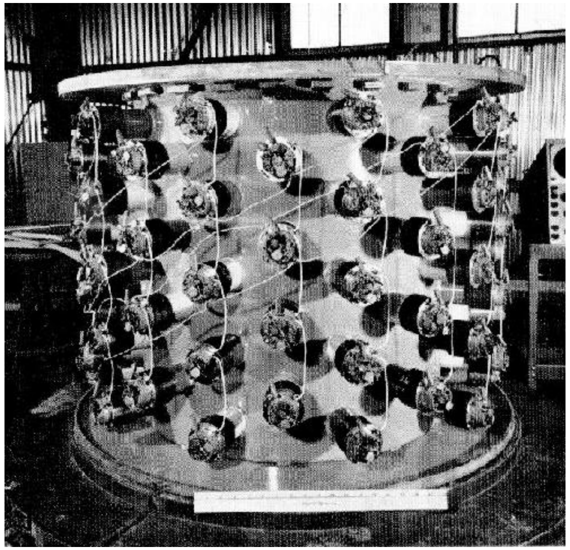
Energy >1.8 MeV

$$e^+ + e^- \rightarrow 2\gamma$$

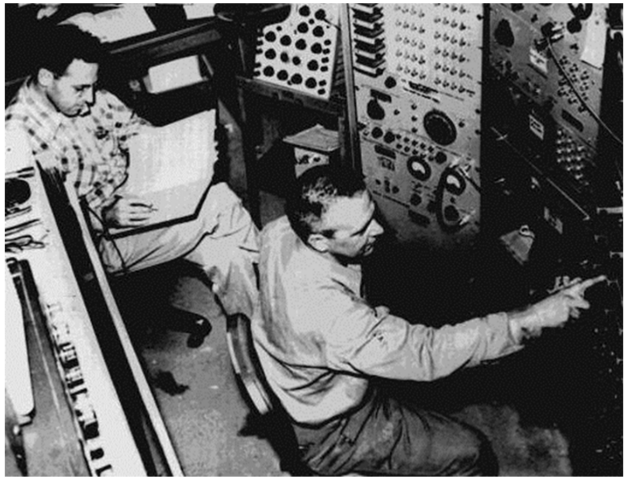
$$n^o + \text{Cd} \rightarrow (\text{several})\,\gamma$$

8 MeV

0.5MeV

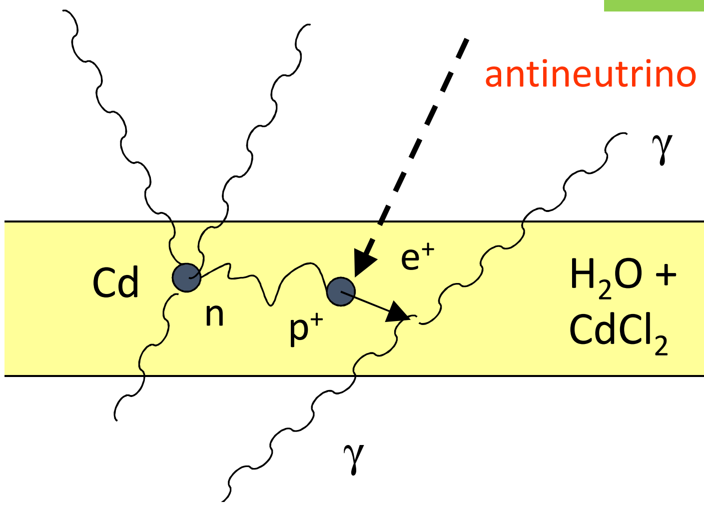


300-liter liquid scintillator with Cadmium salt using 90 PMTs



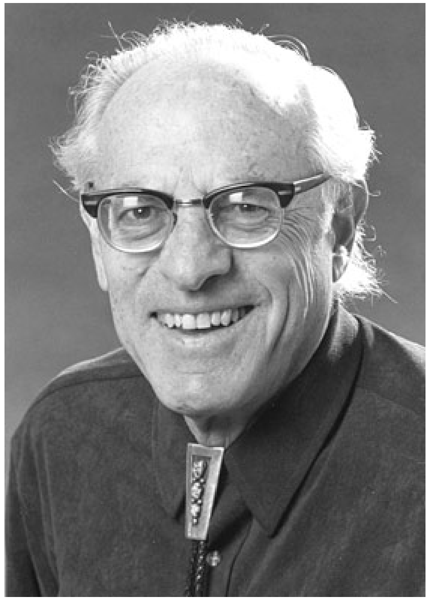
Signal 2γ, then several γ ~few μs later

Experiment attempted at Hanford in 1953, too much background. Repeated at Savannah River in 1956. [Flux: 1.2 x 10^{12} neutrinos/(cm^2 s)]



Cowan passed away in 1974
In 1995, Reines was awarded the Nobel Prize in Physics

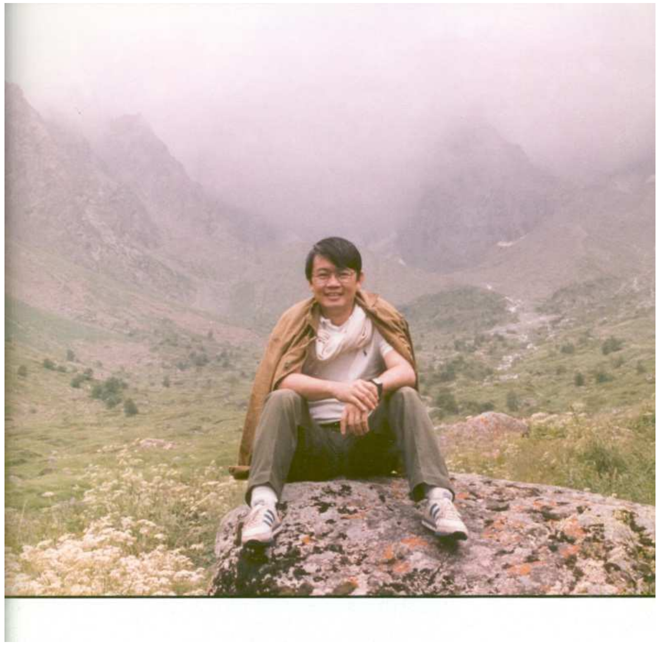
Clyde Cowan



Fred Reines

Herbert H. Chen (陳華生) – An Exceptional Neutrino Physicist

- Born in Chunking, China in 1942 and immigrated to US in 1955
- B.S. from Caltech and Ph.D. from Princeton U.
- Joined UC Irvine in 1968, Associate Prof. in 1974, Prof. in 1980
- Led UCI-LANL ν_e - e elastic scattering experiment
- Designed and initiated Sudbury Neutrino Observatory (SNO) experiment
- Pioneered development of Liquid Argon TPC
- Chaired an NSF committee on "Computing for Particle Physics by Network" which led to NSFNET that soon merged with ARPANET which eventually became Internet
- Passed away in 1988



https://en.wikipedia.org/wiki/Herbert_H._Chen

ν_e - e Elastic Scattering Experiment

Feynman Diagram for $\nu_e + e^- \to \nu_e + e^-$

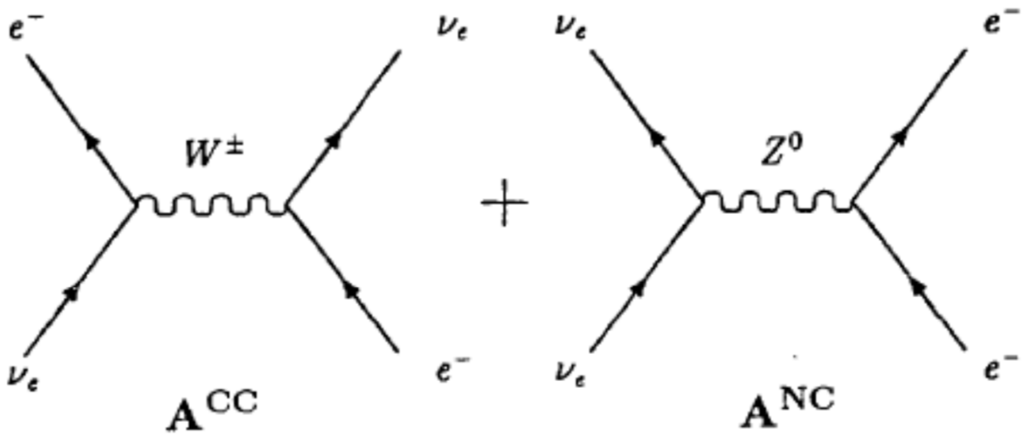


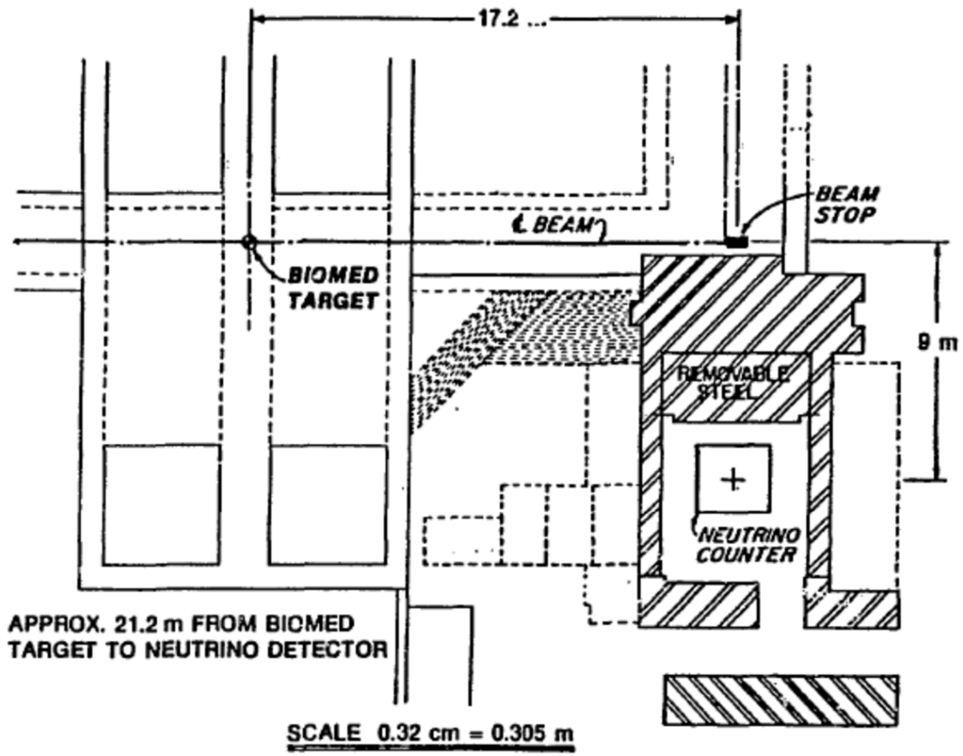
FIGURE 1: Feynman diagram for $\nu_e + e^- \to \nu_e + e^-$ showing the weak charged and neutral current amplitudes.

Los Alamos Meson Physics Facility (LAMPF)

- Opened in 1972
- Has an 800-m long, 800 MeV, 1mA proton linear accelerator
- Now, it is Los Alamos Neutron Science Center (LANSCE)_

https://lansce.lanl.gov/facilities/index.php

LAMPF Beam-Stop Neutrino Source and Experimental Area



LAMPF beam stop neutrino facility layout.

FIGURE 6: Overhead view of LAMPF beam-stop neutrino source and experimental area.

Source: LAMPF

Energy Spectrum of Neutrinos at LAMPF

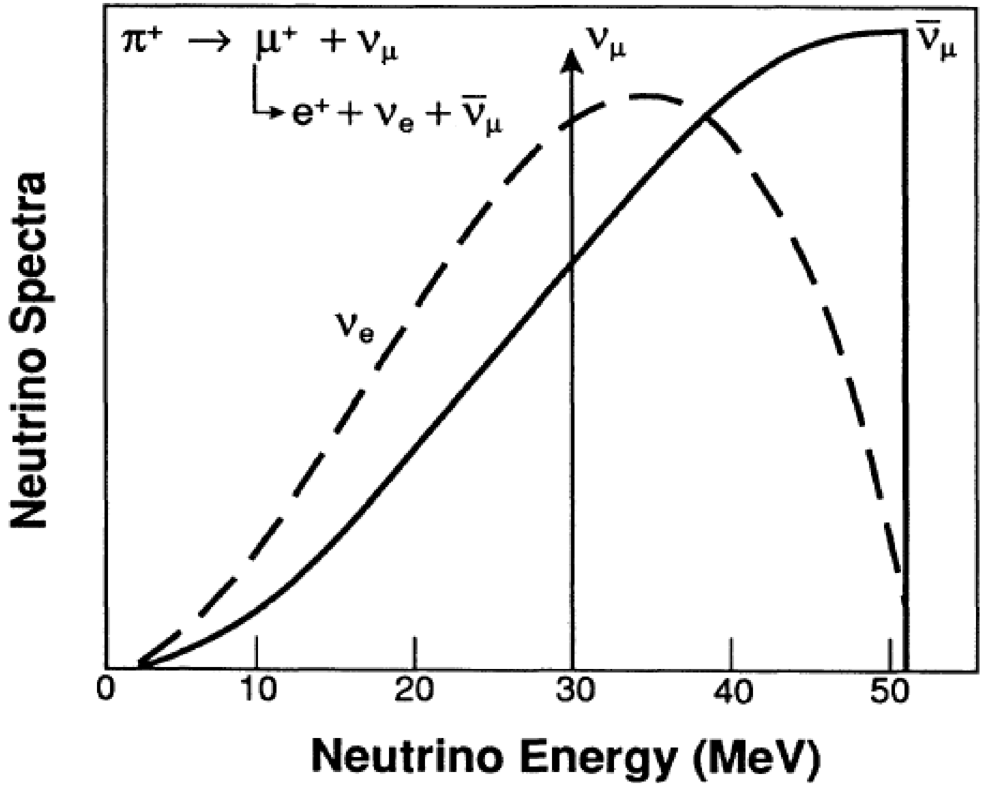


FIG. 3. Energy spectrum of neutrinos produced by π and μ decay at rest in the proton beam stop. Spectra for all three neutrinos are shown.

R.C. Allen, et al., Physical Review D, Vol. 47, No. 1, 1993

Neutrino-Electron Elastic Scattering Detector

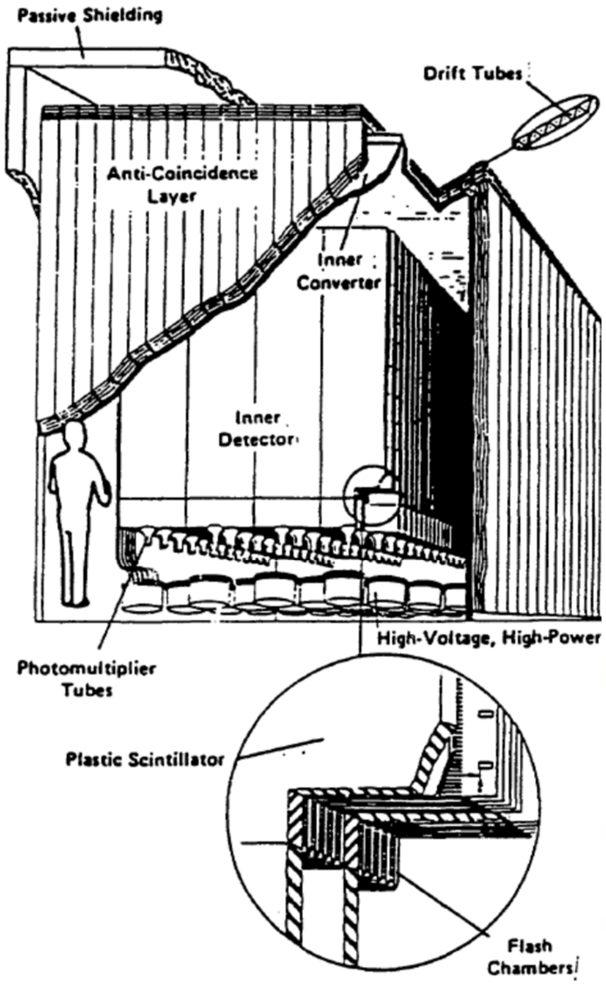


FIGURE 7: Cutaway view of the neutrino detector showing how the central detector was placed within the anticoincidence shield and cosmic-ray shielding. Insets show details of the central detector's FCM and scintillation counter stacking and details of the MWPC wire arrangement.

Source: UCI-LANL Neutrino Collaboration

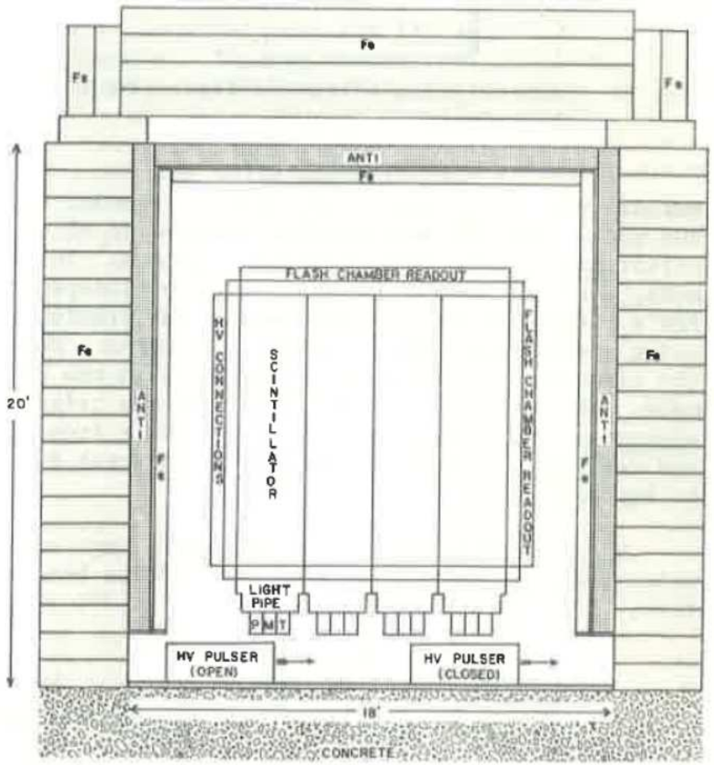


Fig. 1b. End view of the UCI/LASL neutrino detector.

End View

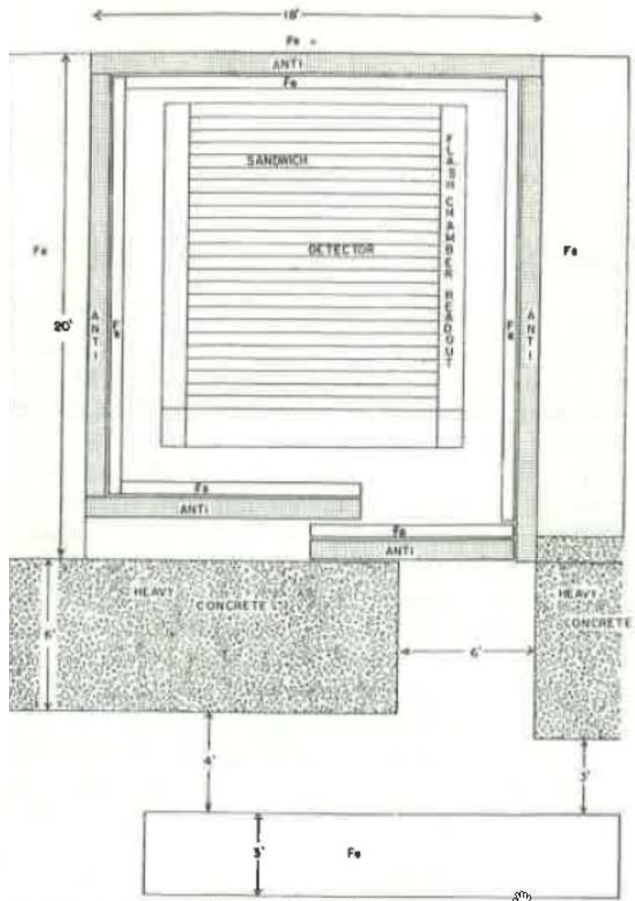


Fig. 1a. Top view of the UCI/LASL neutrino detector.

Top View

K. C. Wang and H. H. Chen, IEEE Tran. on Nuclear Science, Vol. NS-28, No. 1, 1981

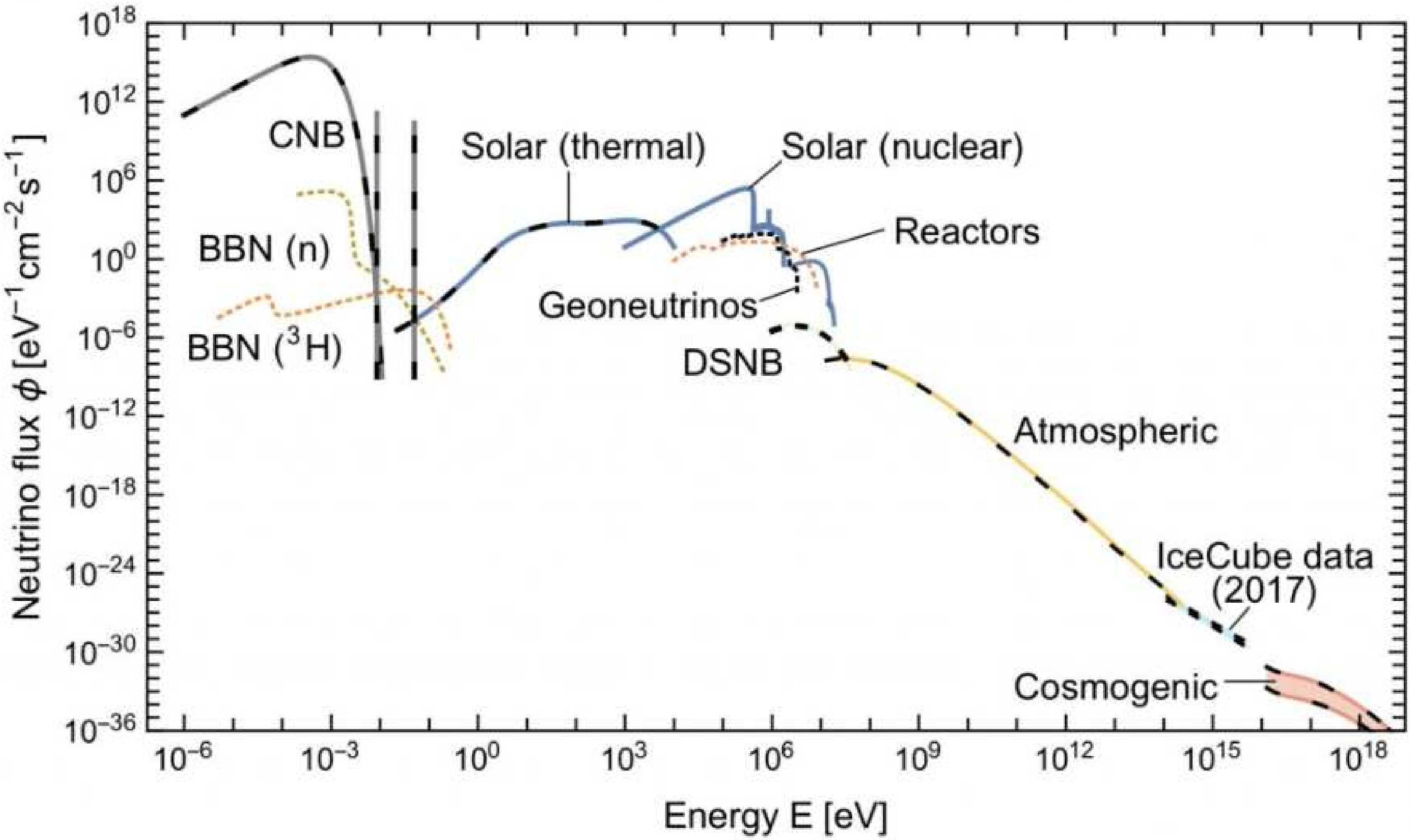
Key υ_e e → υ_e e Results

- Observed 236 ± 35 υ_e e → υ_e e events
- Determined total elastic scattering cross-section to be $10.0 \pm 1.5(stat) \pm 0.9(syst) \times 10^{-45}$ cm$^2 \times [E_\upsilon$ (MeV)]
- The results showed that the interference of weak charged and neutral currents was destructive with a strength of $I = -1.07 \pm 0.21$
- It agreed well with the standard model (SM) prediction of $I = -1.08$

Ref: Physical Review D, Vol. 47, No. 1, pp. 11-28, 1993.

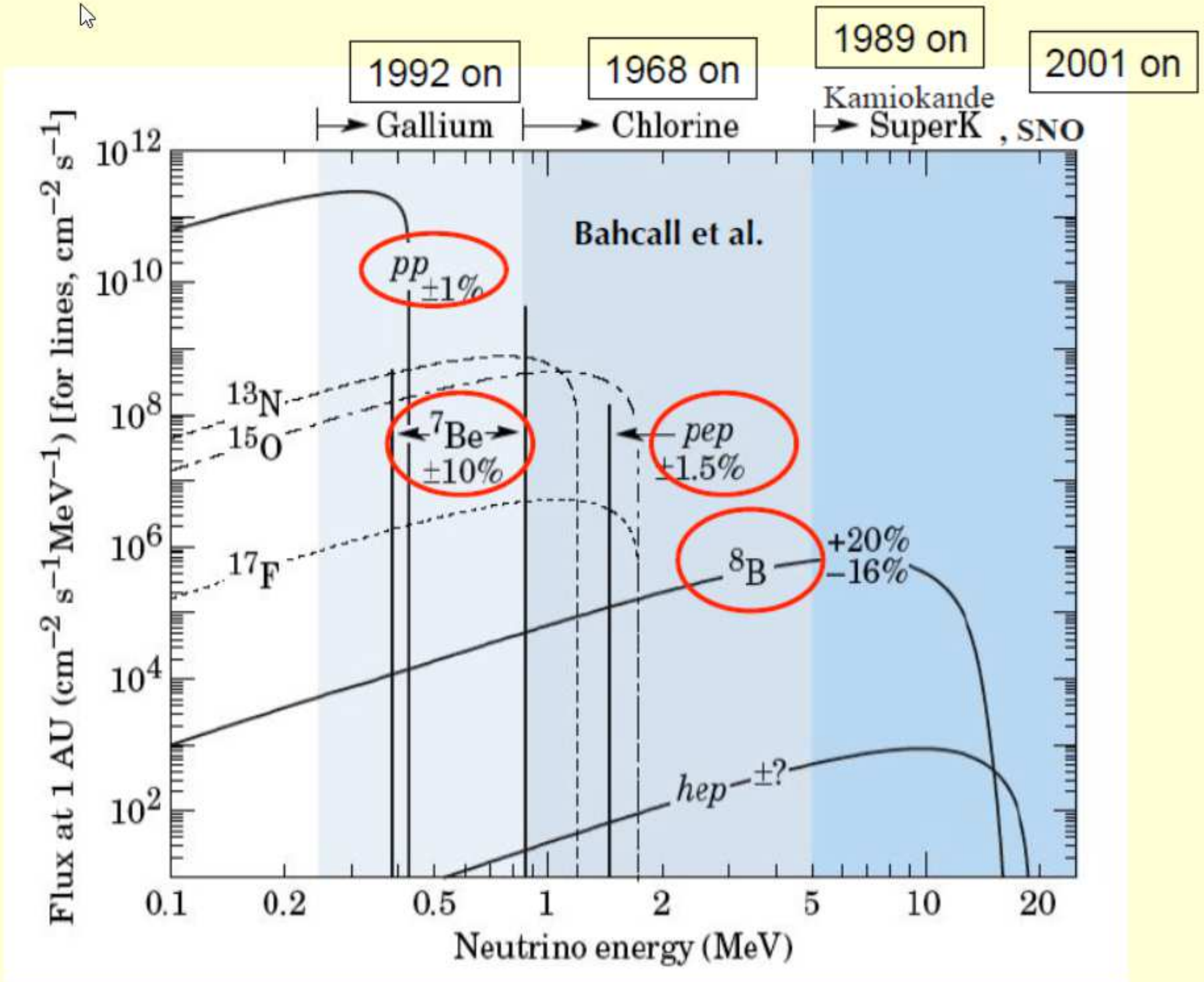
Neurtino Sources and Flux on Earth

- Grand Unified Neutrino Spectrum



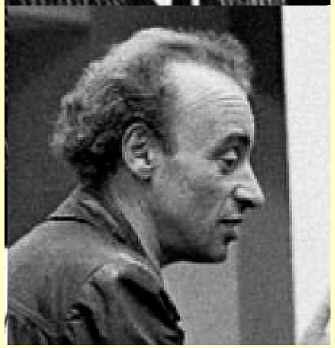
E. Vitagliano, I. Tamborra, G. Raffelt, Rev. Mod. Phys. 92 (2020) 45006; arXiv:1910.11878
https://neutrino-history.in2p3.fr/introduction-to-neutrino-sources/

Including other solar neutrino measurements



Source: Art McDonald, Queen's University, for SNO Collaboration

Pioneers of Solar Neutrino Physics: Davis, Bahcall, Pontecorvo & Gribov



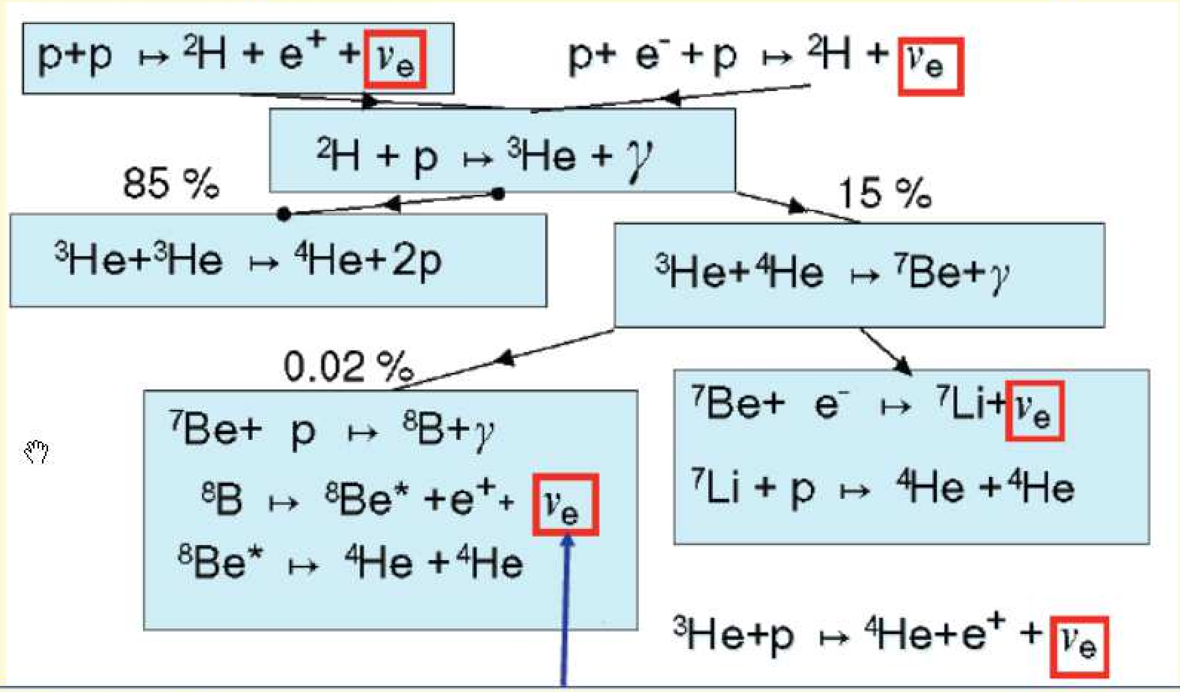
1968: Davis' Measurements of electron neutrinos with Chlorine-based detector show 3 times fewer than Bahcall's calculations.

Ray Davis: Nobel Laureate 2002

1969: Gribov and Pontecorvo suggest flavor change (oscillation) of electron neutrinos to muon neutrinos as a possible reason.

Source: Art McDonald, Queen's University, for SNO Collaboration

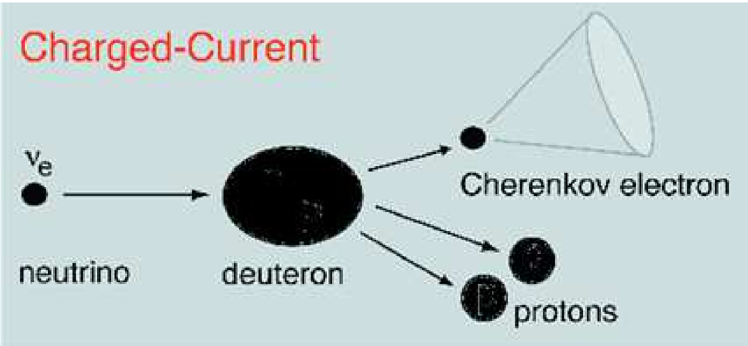
SOLAR FUSION CHAIN

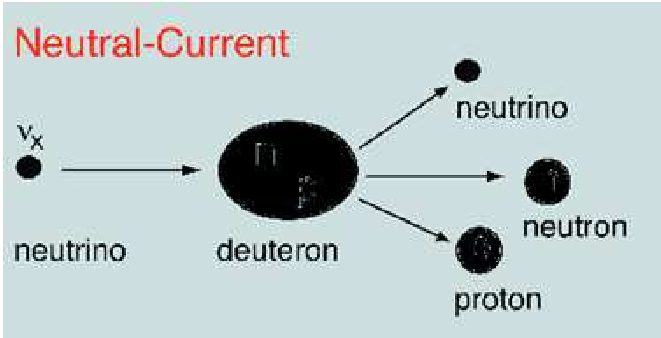


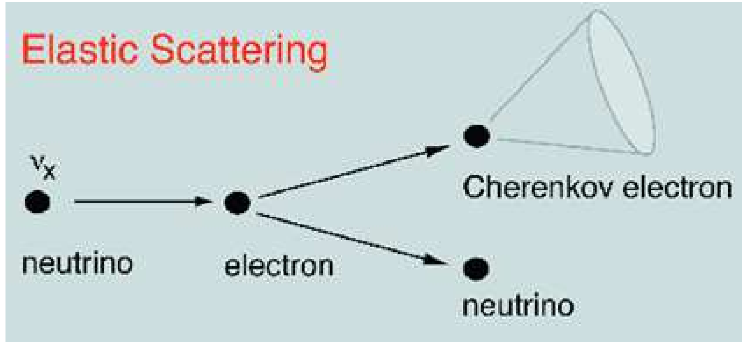
1984: Herb Chen proposes heavy water to search for direct evidence of flavor transformation for neutrinos from ^{8}B decay in the Sun. Electron neutrinos and all active neutrinos are measured separately to show flavor change independent of solar model calculations. SNO collaboration is created with Chen and George Ewan as Spokesmen.

Source: Art McDonald, Queen's University, for SNO Collaboration

Herb Chen's Idea (1984): Using Heavy Water







VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

Direct Approach to Resolve the Solar-Neutrino Problem

Herbert H. Chen
Department of Physics, University of California, Irvine, California 92717
(Received 27 June 1985)

A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu + d \rightarrow \nu + p + n$ and the charged-current reaction $\nu_e + d \rightarrow e^- + p + p$, is suggested for this purpose.

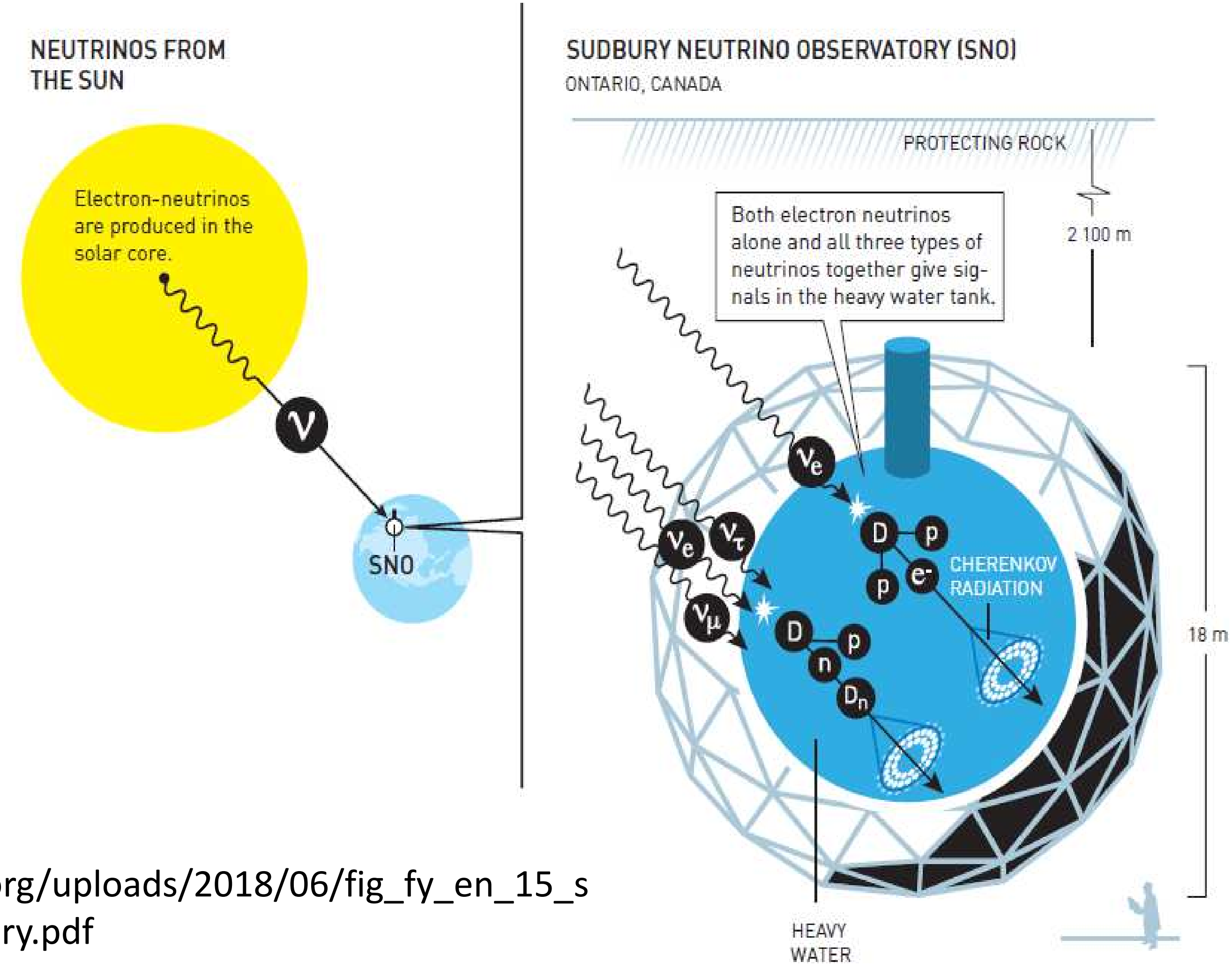
PACS numbers: 96.60.Kx, 14.60.Gh

SNO Collaboration Meeting, Chalk River, 1986

PROPOSAL TO BUILD A NEUTRINO OBSERVATORY IN SUDBURY, CANADA
D. Sinclair, A.L. Carter, D. Kessler, E.D. Earle, P. Jagam, J.J. Simpson, R.C. Allen, H.H. Chen, P.J. Doe, E.D. Hallman, W.F. Davidson, A.B. McDonald, R.S. Storey, G.T. Ewan, H.-B. Mak, B.C. Robertson Il Nuovo Cimento C9, 308 (1986)

Source: Art McDonald, Queen’s University, for SNO Collaboration

Sudbury Neutrino Observatory



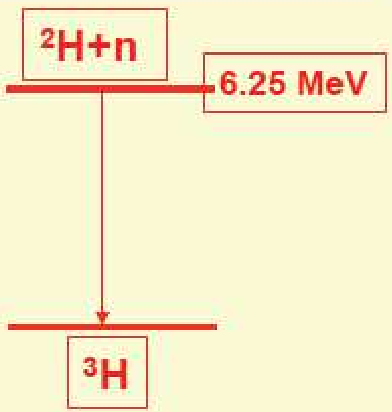
https://www.nobelprize.org/uploads/2018/06/fig_fy_en_15_sudburyneutrinoobservatory.pdf

3 neutron (NC) detection methods (systematically different)

Phase I (D_2O)

Nov. 99 - May 01

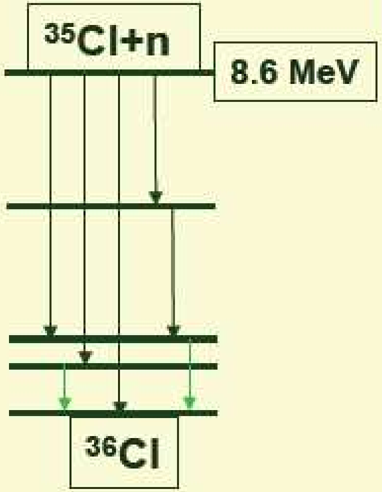
n captures on
$^{2}H(n, \gamma)^{3}H$
Effc. ~14.4%
NC and CC separation by energy, radial, and directional distributions



Phase II (salt)

July 01 - Sep. 03

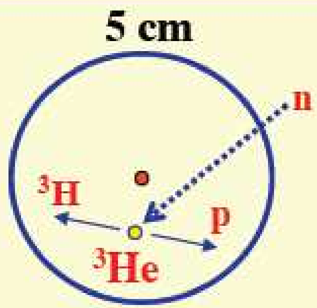
2 tonnes of NaCl
n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
Effc. ~40%
NC and CC separation by event isotropy



Phase III (^{3}He)

Nov. 04-Dec. 06

400 m of proportional counters
$^{3}He(n, p)^{3}H$
Effc. ~ 30% capture
Measure NC rate with entirely seperate detection system.

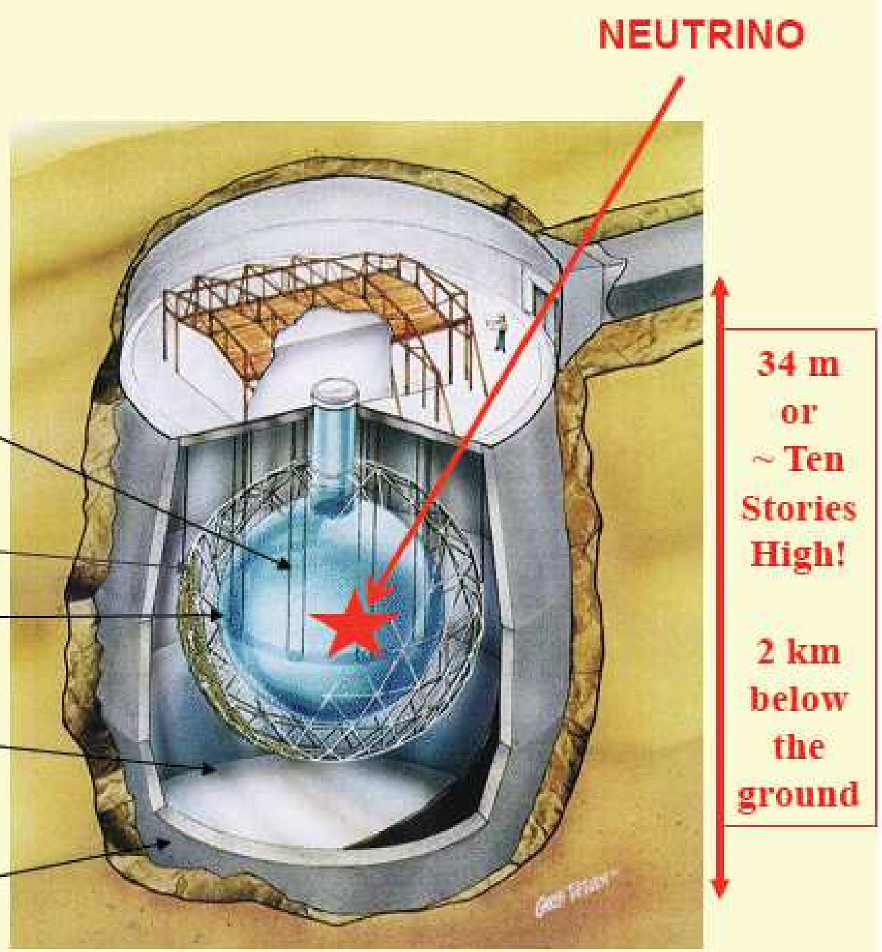


$$n + {}^{3}He \rightarrow p + {}^{3}H$$

Source: Art McDonald, Queen's University, for SNO Collaboration

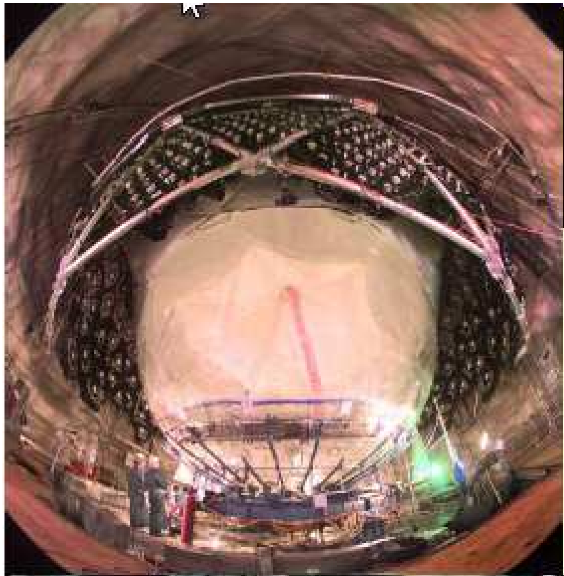
Sudbury Neutrino Observatory (SNO)

Neutrinos are very difficult to detect so our detector had to be very big with low radioactivity, deep underground.

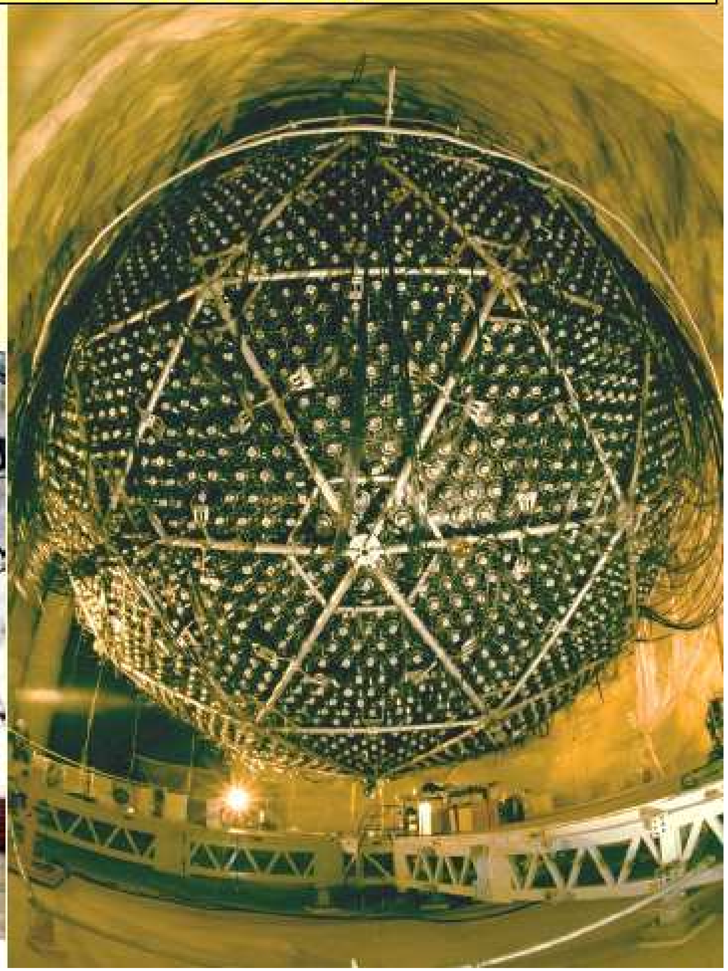


Source: Art McDonald, Queen's University, for SNO Collaboration

SNO: One million pieces transported down in the 3 m x 3 m x 4 m mine cage and re-assembled under ultra-clean conditions. Every worker takes a shower and wears clean, lint-free clothing.



70,000 showers during the course of the SNO project

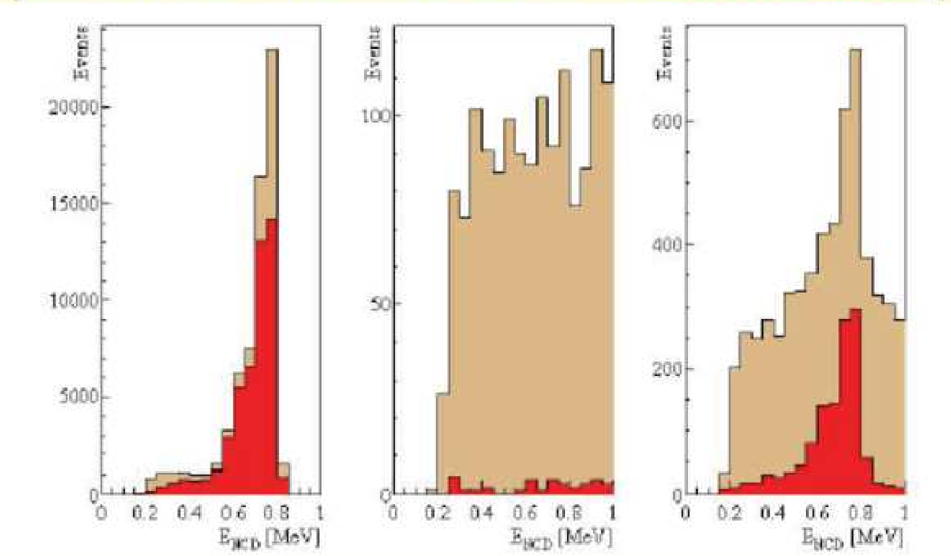


Source: Art McDonald, Queen’s University, for SNO Collaboration

Final Complete Analysis of SNO solar data

The SNO Collaboration (B. Aharmim et al) Phys. Rev. C 88, 025501 (2013)

NCD pulse shape analysis to identify neutron events



^{3}He detectors: neutron source

^{4}He detectors: alpha backgnd

^{3}He detectors: neutrino data

$$CC/NC = 0.317 \pm 0.016(stat) \pm 0.009(syst)$$

implies flavor change at far more than 7 σ and shows that θ_{12} is non-maximal by more than 5 σ.

Full joint analysis of solar data from all three phases provides best sensitivity with all correlations, backgrounds, systematic uncertainties included.

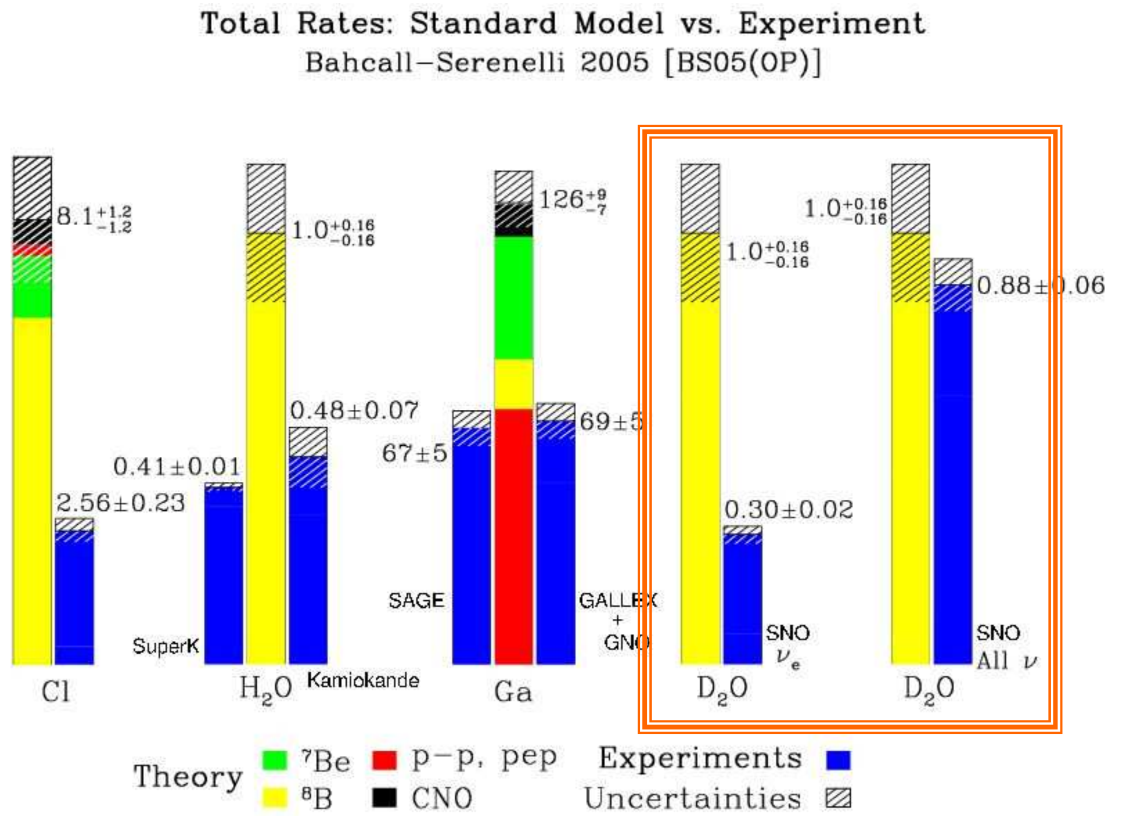
Individual results from all three phases are very consistent within uncertainties

$$\Phi_{^8B} = 5.25 \pm 0.16 \ {}^{+0.11}_{-0.13}$$

More accurate than current solar models and lying between the fluxes predicted for two values of metallicity in the sun

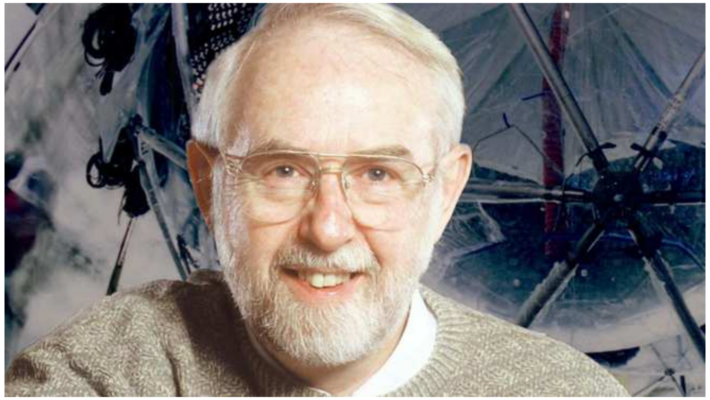
Source: Art McDonald, Queen's University, for SNO Collaboration

Experimental Results of Solar ν Experiments



Final SNO results (2013): Total ν flux = 5.25 ± 0.16 (stat) $^{+0.11}_{-0.12}$(sys) $\times 10^6 cm^{-2} s^{-1}$
In very good agreement with theory

Arthur B. McDonald and Takaaki Kajita were awarded Nobel Prize in Physics in 2015 for "for the discovery of neutrino oscillations, which shows that neutrinos have mass"



Arthur B. McDonald

Takaaki Kajita

6 Neutrino Experiments Won Nobel Prizes

1. 1988 Leon Lederman, Melvin Schwartz, and Jack Steinberger (at Brookhaven National Lab., USA)
2. 1995 Frederick Reines (at Savannah River Nuclear Reactor, USA)
3. 2002 Raymond Davis, Jr. (at Homestake Gold Mine, USA)
4. 2002 Masatoshi Koshiba (at Kamioka Observatory, Japan)
5. 2015 Takaaki Kajita (at Super Kamiokande, Japan)
6. 2015 Arthur B. McDonald (at Sudbury Neutrino Observatory, Canada)

And more are coming…

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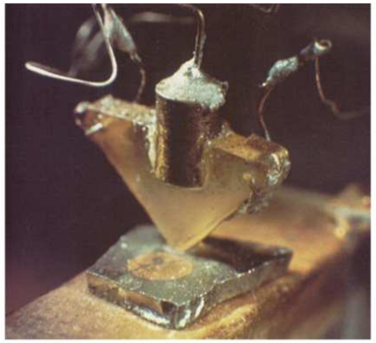
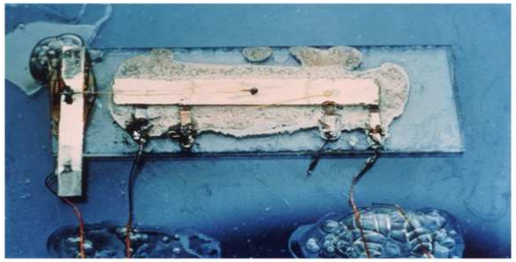
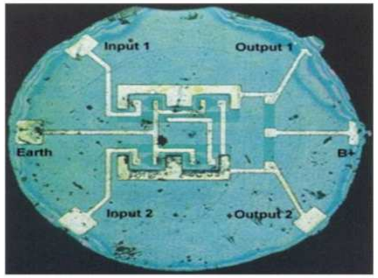
First Transistor and ICs



The 1st Transistor -1947



The 1st IC -1958



The 1st planar IC - 1960

William Shockley, John Bardeen, Walter Brattain

Nobel Prize Winner, 1956

Jack Kilby

Nobel Prize Winner, 2000

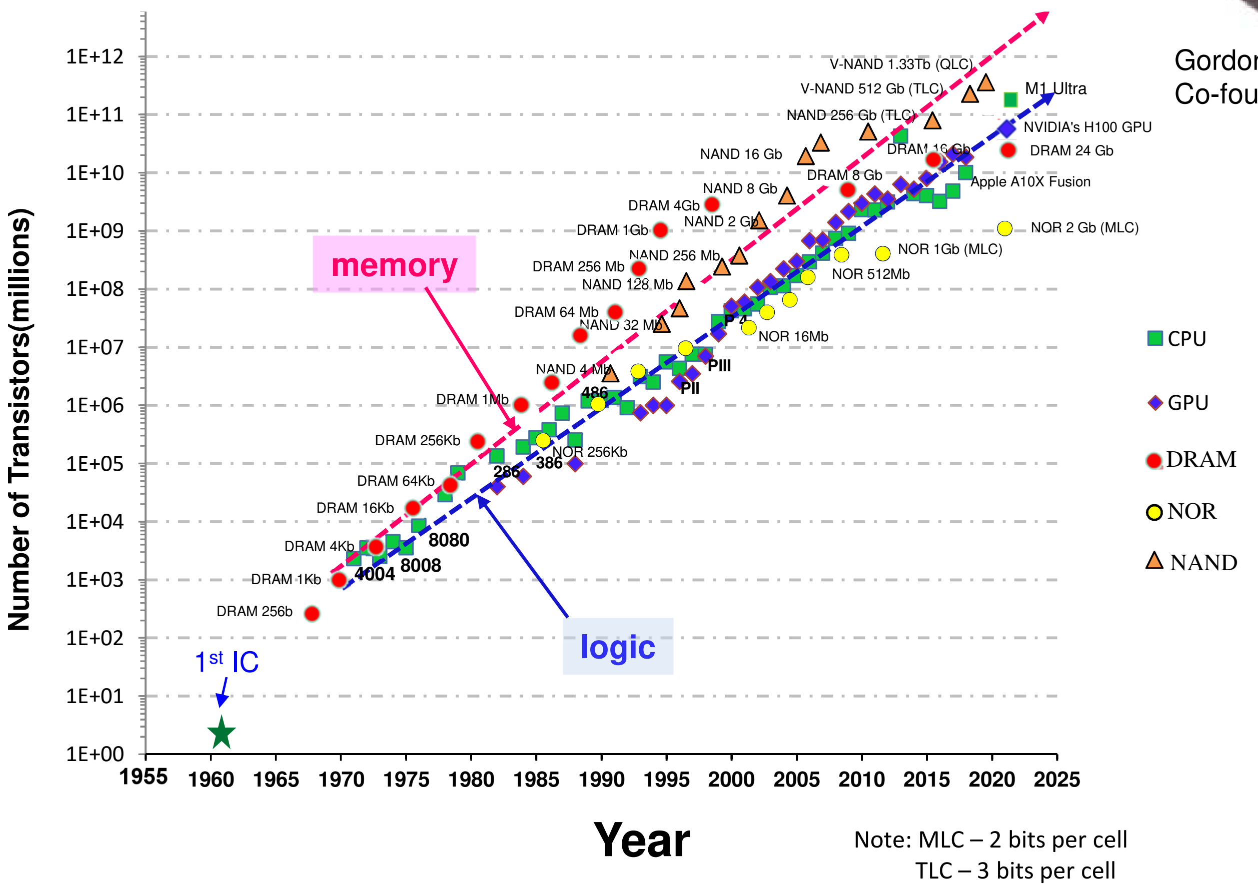
Robert Noyce

Images from Wikipedia

Moore's Law

The number of transistors per chip doubles each 18~24 months *

Gordon Moore
Co-founder of Intel 1968

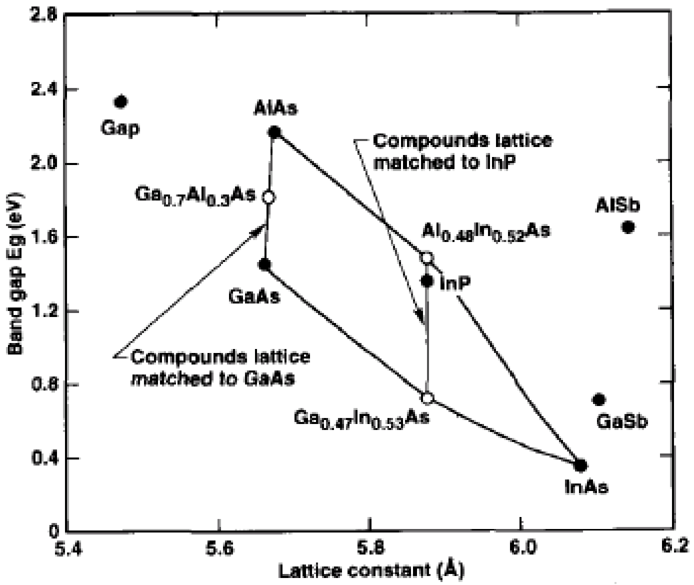


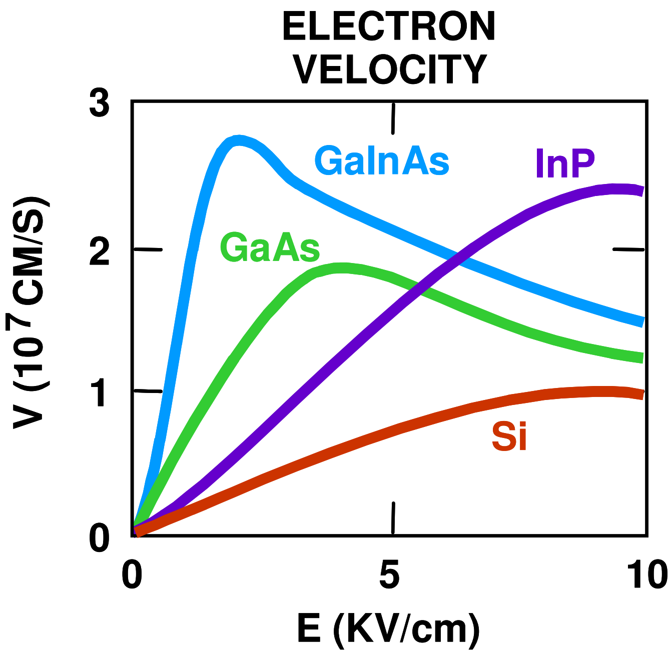
Note: MLC – 2 bits per cell
TLC – 3 bits per cell
QLC – 4 bits per cell

Data source: https://en.wikipedia.org/wiki/Transistor_count
https://en.wikipedia.org/wiki/Random-access_memory
https://en.wikipedia.org/wiki/Flash_memory#NAND_flash
* https://en.wikipedia.org/wiki/Moore%27s_law#cite_note-26

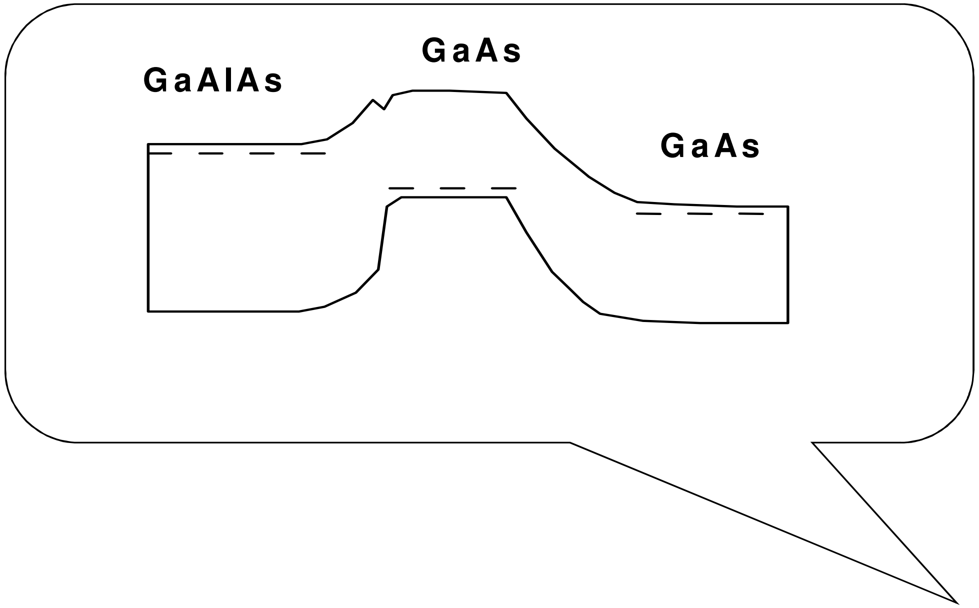
III-V Compound Semiconductors for High-speed Electronics

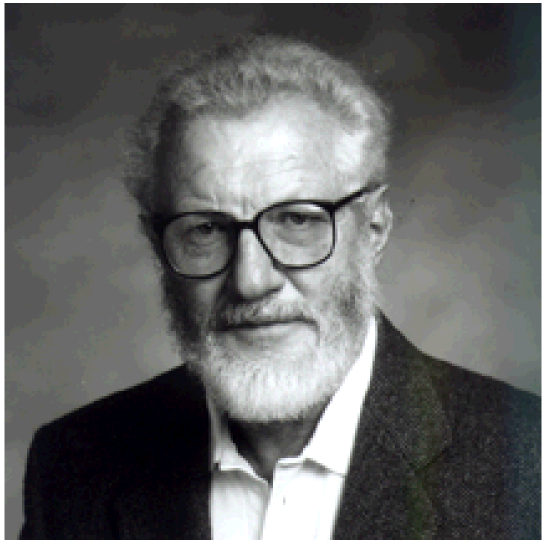
I	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*
Li	Be	B	C	**N**	O	F	Ne
Na	Mg	**Al**	Si	**P**	S	Cl	Ar
K	Ca	**Ga**	Ge	**As**	Se	Br	Kr
Rb	Sr	**In**	Sn	**Sb**	Te	I	Xe





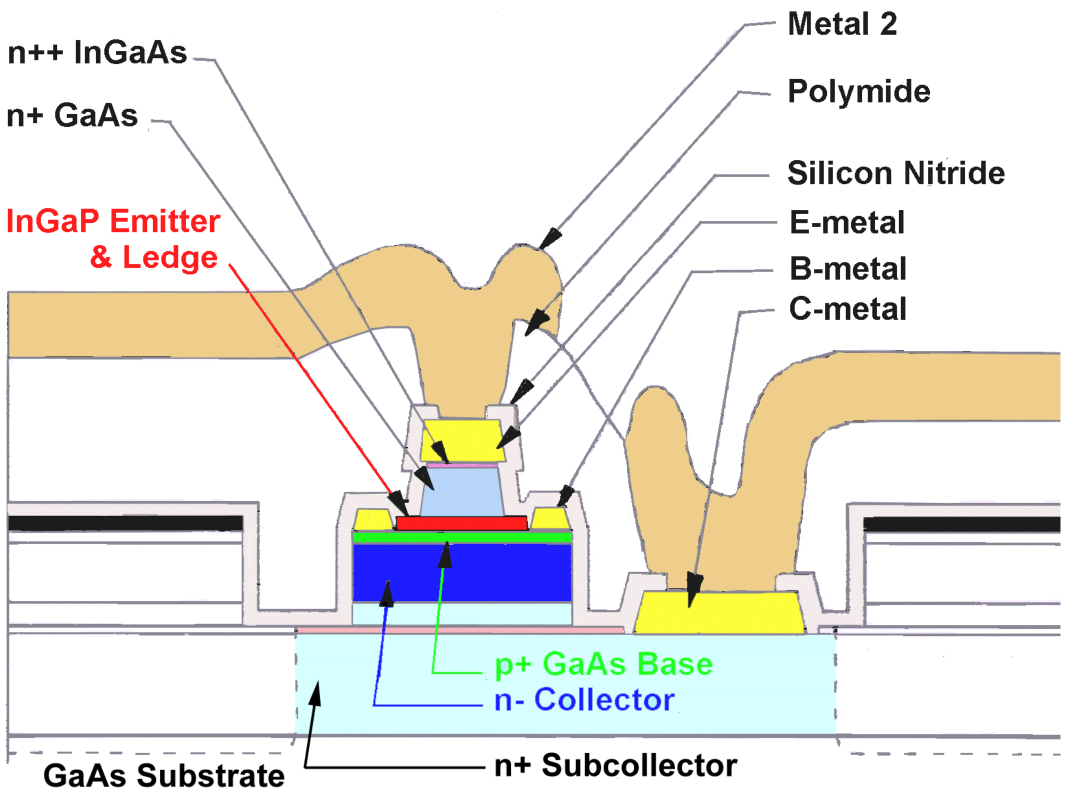
An Enthusiastic HBT Promoter



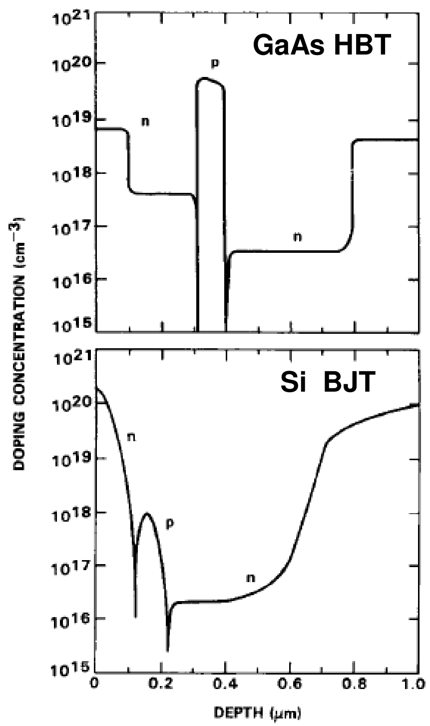


Herb Kroemer
2000 Nobel Laureate in Physics

InGaP/GaAs HBT



DOPING



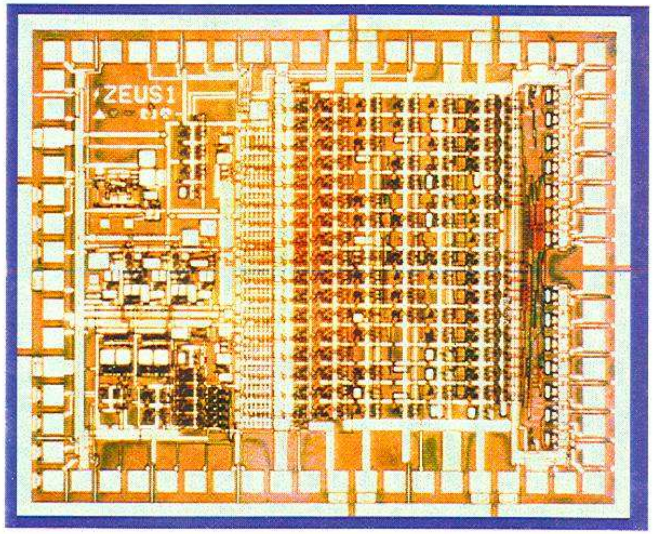
Source: Peter Asbeck, UCSD

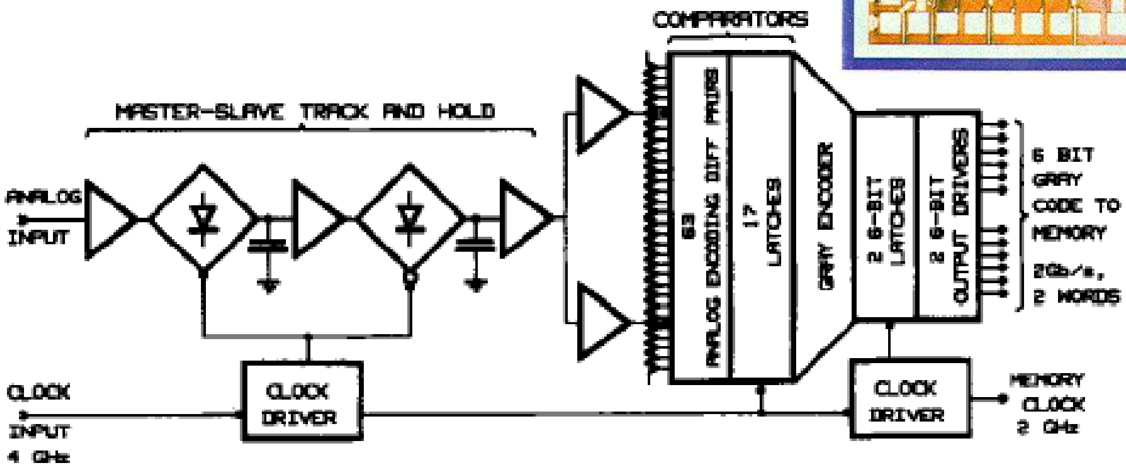
HBT Power Amplifiers Enhanced Mobile Communications

https://www.skyworksinc.com/About/-/media/SkyWorks/Documents/Downloads/skyworks_overview.pdf

6-Bit 4 GS/s ADC with AlGaAs/GaAs HBTs

- **Supported by AFWL**
- **6-Bit ADC with on-chip 1:2 demux**
- **1.8 GHz analog BW at 4GS/s**
- **6 W power**



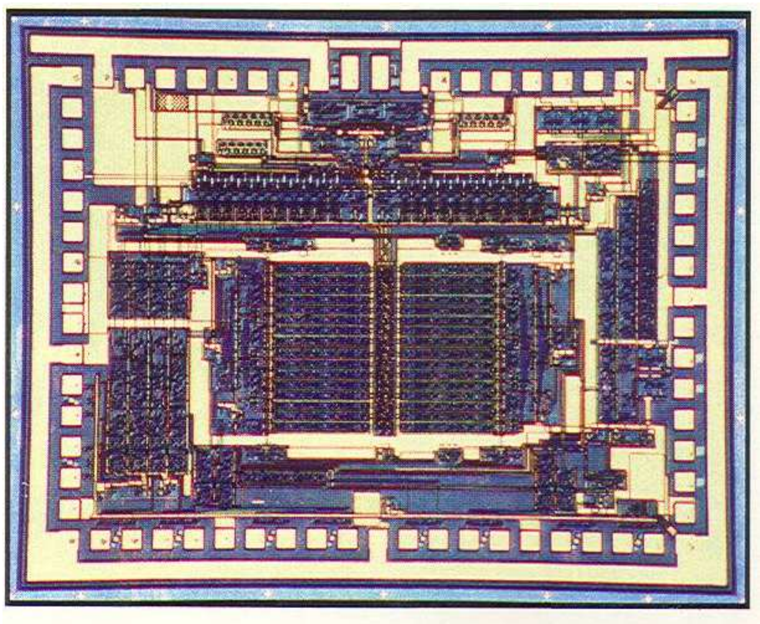


Source: Rockwell & Agilent

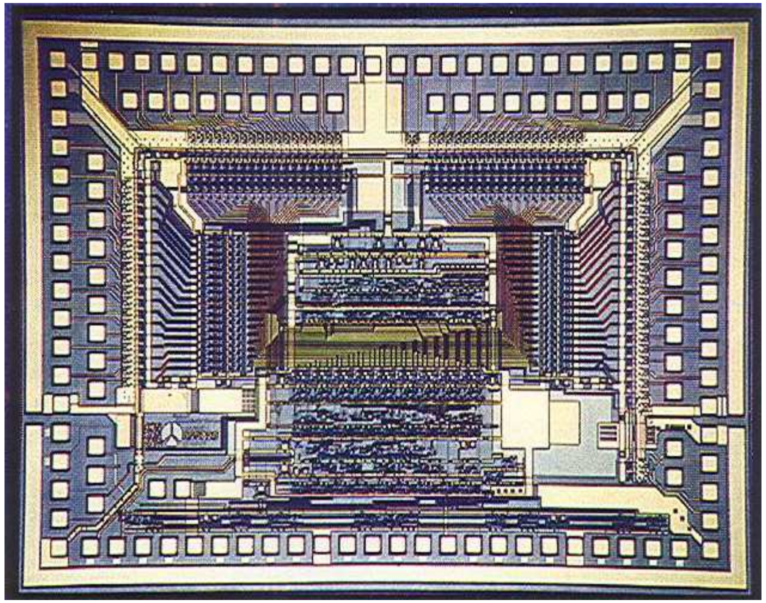
Rockwell Science Center

8-Bit 2-Gs/s ADC and 8:64 DEMUX

- 2.5GS/s sampling rate
- 3 GHz analog input BW
- IQ Folding and Interpolation architecture
- 5 W power

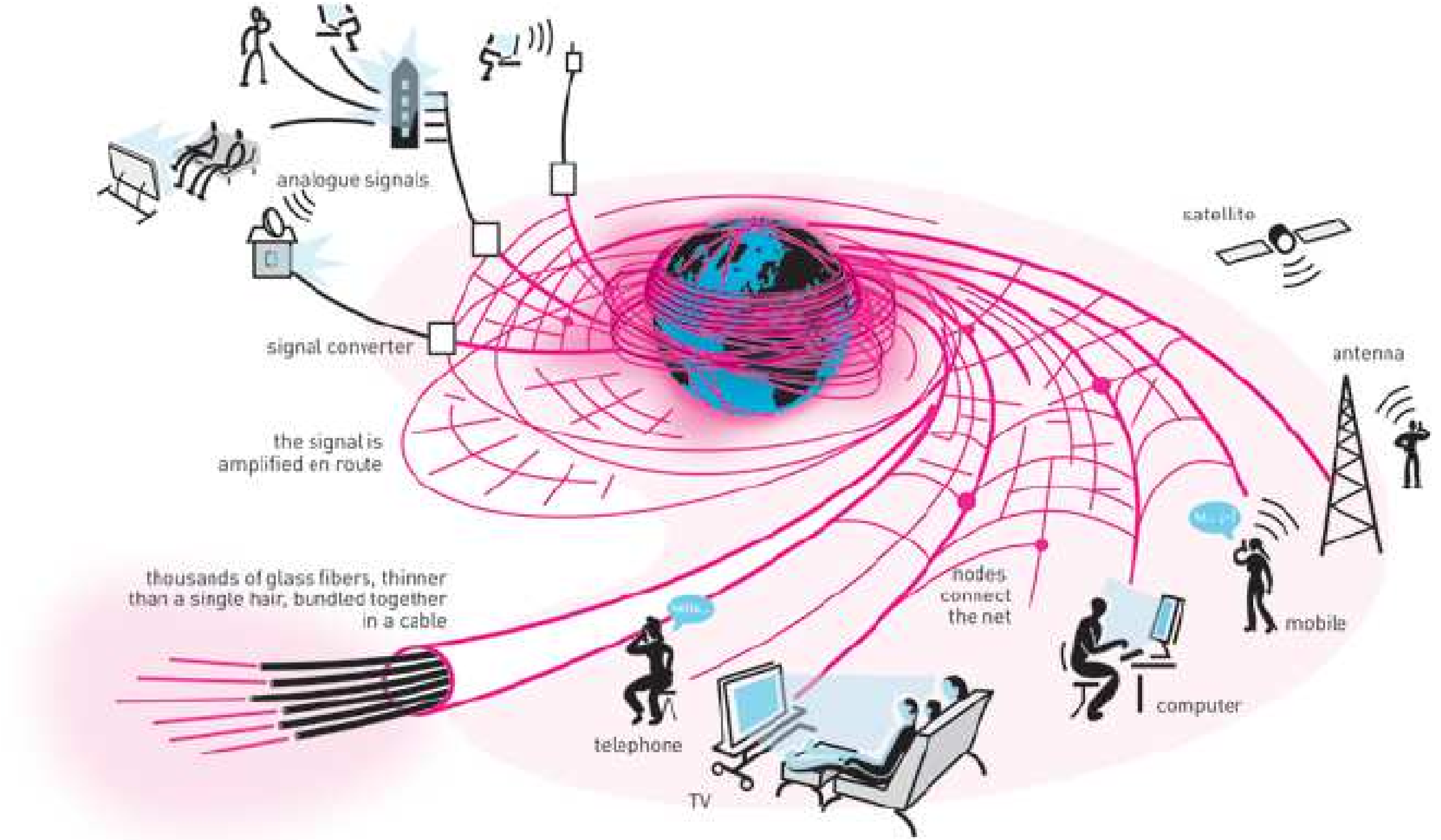


- Gray to Binary converter
- 3 GB/s
- BIST PRN generator
- 3 W power



Rockwell Science Center

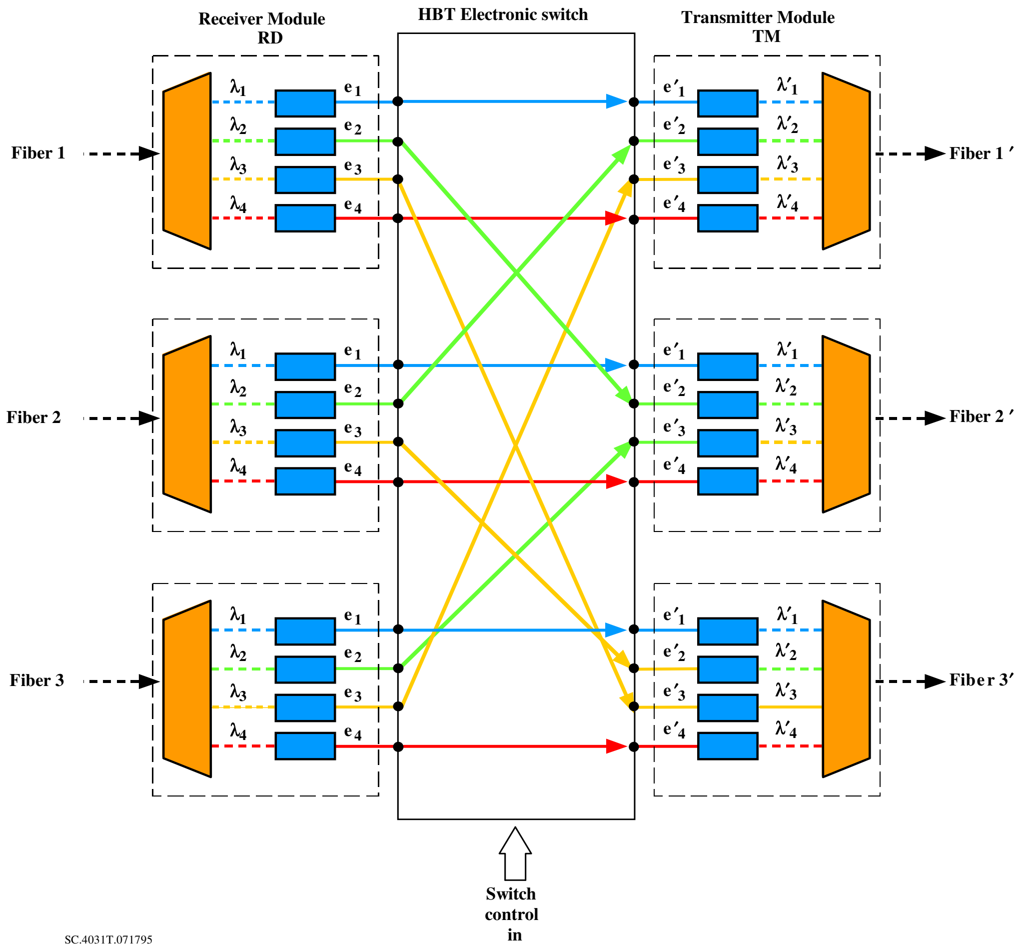
Artistic View of Global Communication



Sources: The Royal Swedish Academy of Sciences.

WDM with Electronic Switch Technology (WEST)

WEST Optoelectronic 3 x 3 WDM Switch



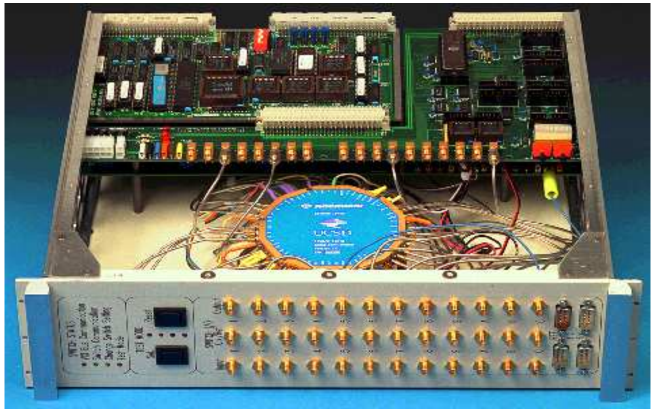
- Low risk
- Fast reconfiguration
- Clock and data regeneration
- Minimum crosstalk
- Flexible switching (Wavelength translation)
- Low cost

WDM: Wavelength Division Multiplexing
WEST Consortium: DAARPA, Rockwell, Ortel, Caltech/JPL, UCSB, UCSD

Source: Rockwell Science Center

12x12 VXI Switch Module

Feature Highlights

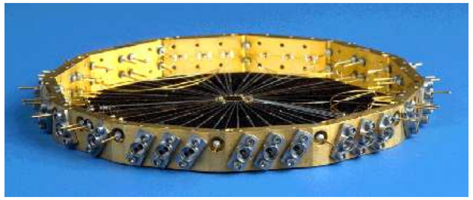


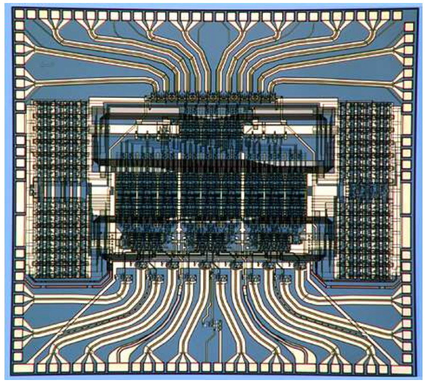
Switch Module Features:

- 120 Gb/s data throughput
- Twelve 10 Gb/s channels
- VXI Management and Control

High Speed Package Features:

- Clean high speed interface
- High Isolation
- Thermal management





Switch Chip Highlights:

- Suitable for larger switching fabrics
- GaAsAlGaAs HBT
- Low crosstalk & jitter generation
- Die size: 4.8 x 5.1 mm^2
- 4600 transistors
- P_{diss}: 7.4 W

10Gb/s

Source: Rockwell Science Center

WEST Demonstration

Source: Rockwell Science Center

WEST Team

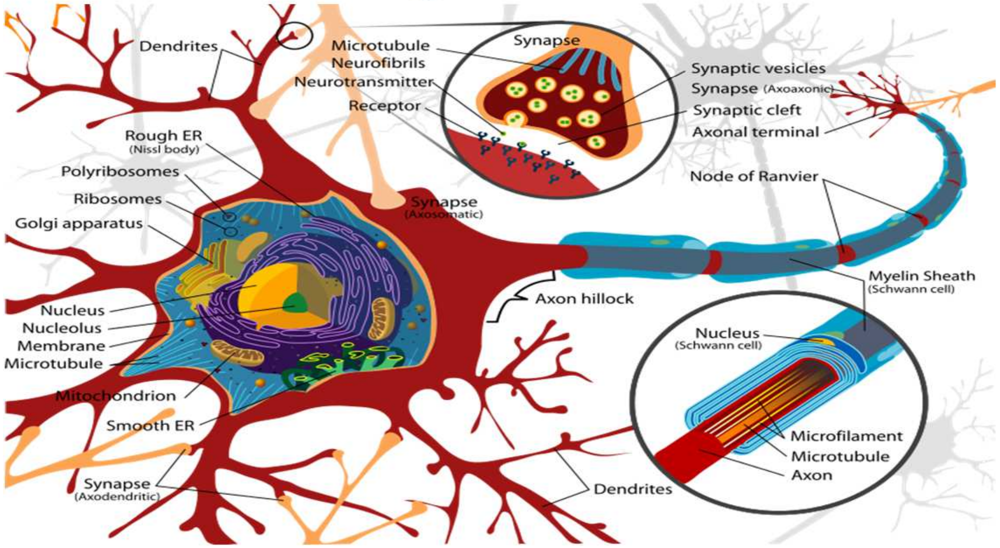
Source: Rockwell Science Center

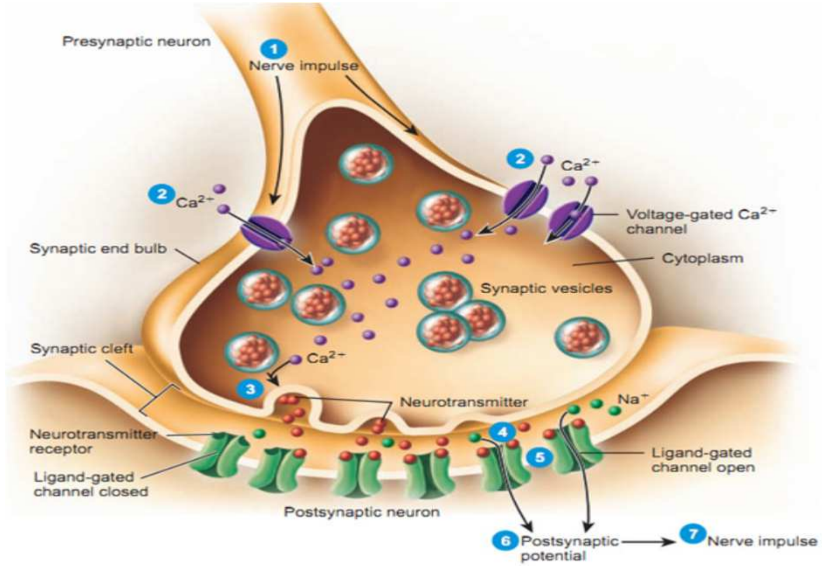
Outline

- Introduction
- Experience Sharing
  - Some Stories of Neutrino
  - GaAs Heterojunction Bipolar Transistor (HBT) and ICs
  - Semiconductor Memories
- Conclusion Remarks

An Amazing Nature Memory

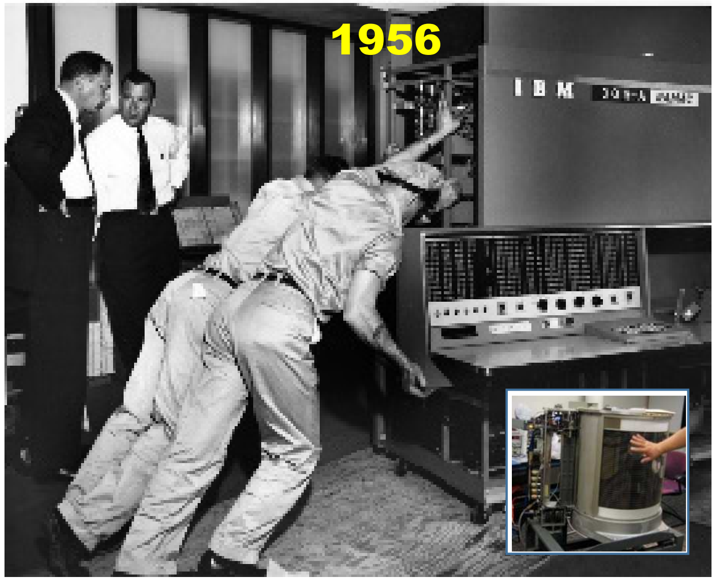
- Fits in a shoe box
- Runs on a tuna sandwich and a cup of water
- Ultra-low power and always on
- 86B neurons, 16B in cerebral cortex, Most of the 16 B neurons have ~10K synapses each
- 1.5Kg (1.2Kg in cerebral cortex)





A brain keeps information and processes it

The Power of Semiconductor Technology



IBM 350 Disk Storage Unit

Storage Capacity: 5 million characters (3.75 MB)

Weight: over 1 ton

Leased: $750 per month

One GB capacity needs more than **308 sets** IBM 350.
The total rent for one GB storage memory per month is $ 231,000.

2022

2 TB Solid State Drive

Solid State Drive

Storage Capacity: 2 TB

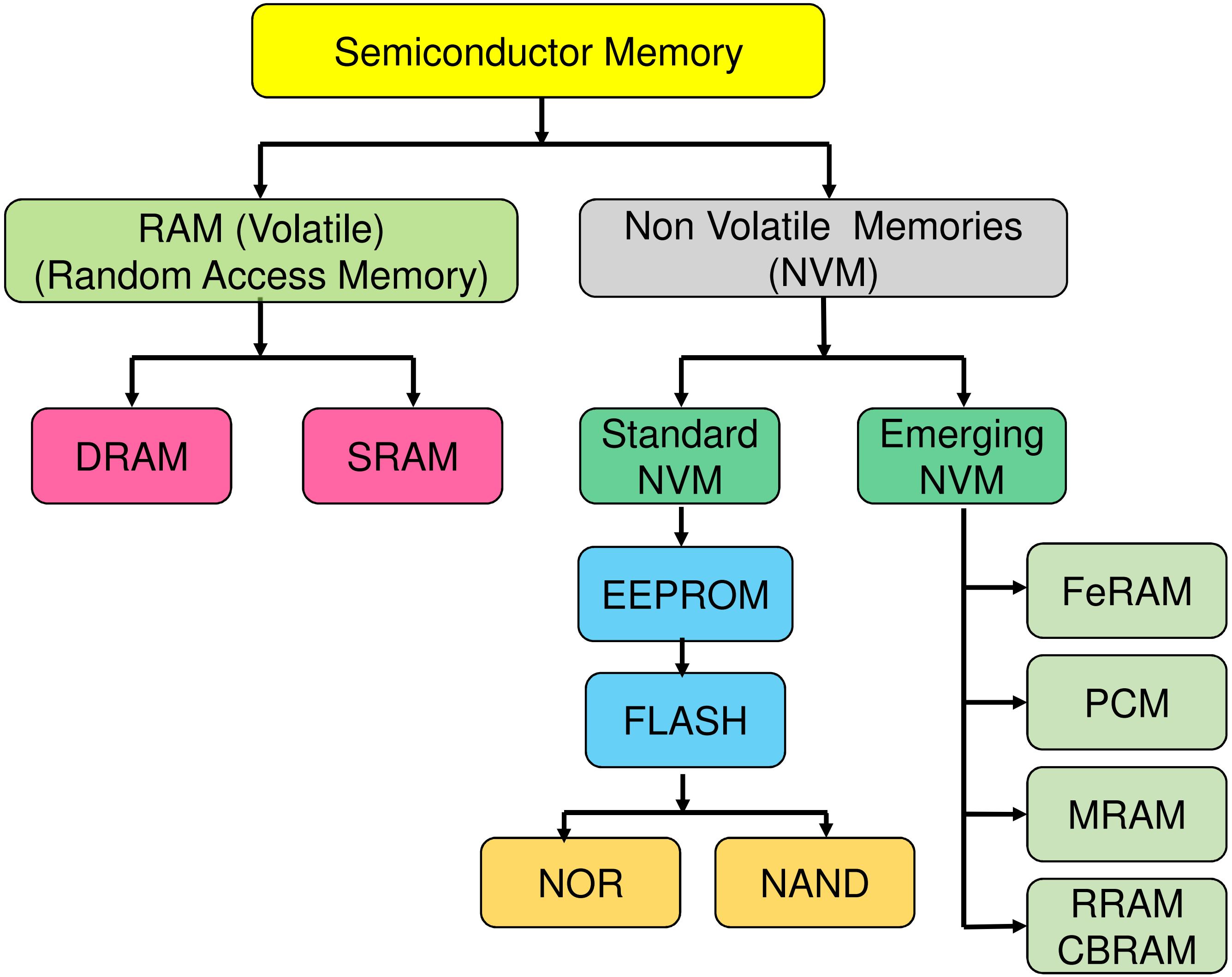
Weight:~ 80 g

Price: $250 (~ per GB costs $ 0.125)

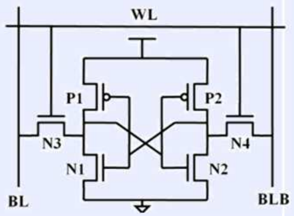
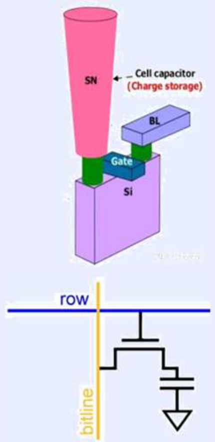
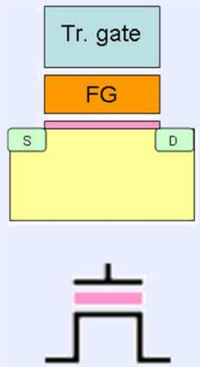
The price drops to 6 order magnitudes

https://www.computerhistory.org/storageengine/first-commercial-hard-disk-drive-shipped/
https://www.engadget.com/samsungs-2tb-980-pro-ssd-drops-to-a-new-low-of-250-132013127.html

Semiconductor Memory Family

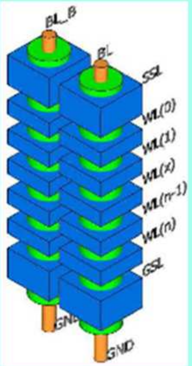


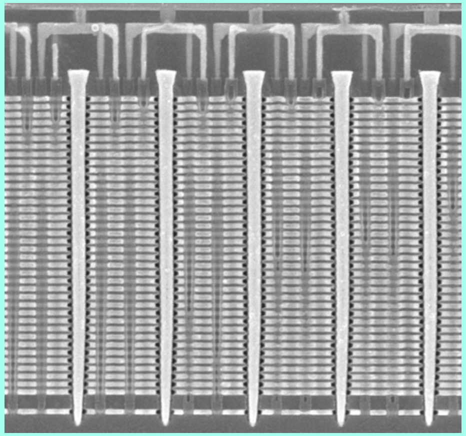
Mature Semiconductor Memory Devices

Features	SRAM	DRAM	FLASH
Density	Low	High	High
Speed	Very Fast	Fast	Slow
Leak Power	Low	Medium	Low
Non-volatile	No	No	Yes
Device	6T	1T1C	1T
Cell Structure			

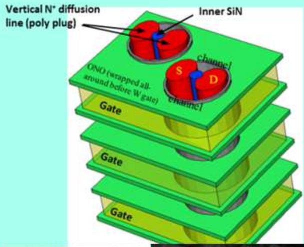
Landscape of Non-Volatile Memories

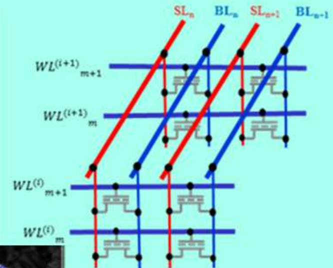
3D NAND Flash

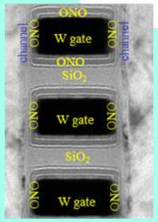


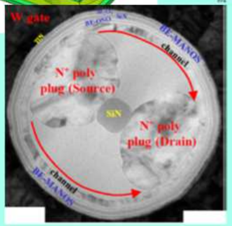


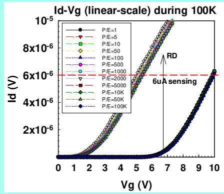
3D NOR Flash (in R&D)





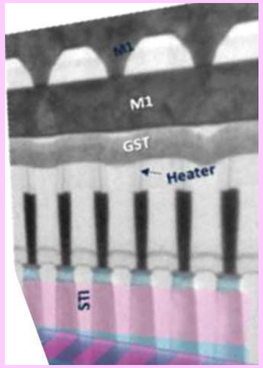




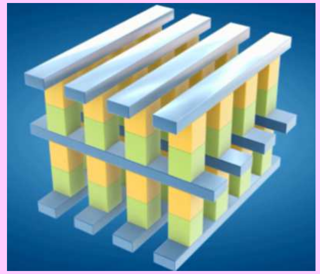


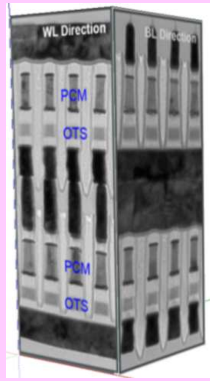
Phase-Change Memory and 3DXP

1T1R



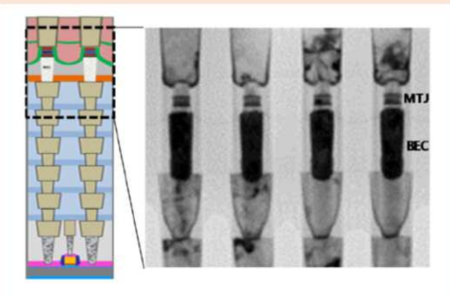
3D Cross-Point with selector



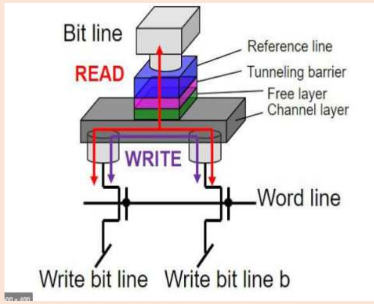


MRAM

STT

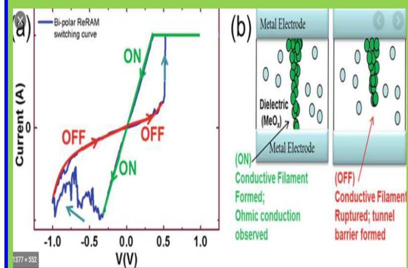


SOT

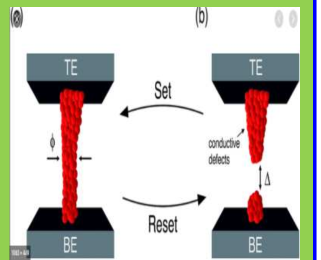


ReRAM

Metal Oxide

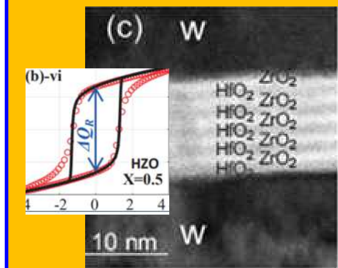


Conductive-Bridge

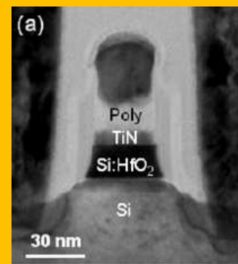


Ferroelectric RAM

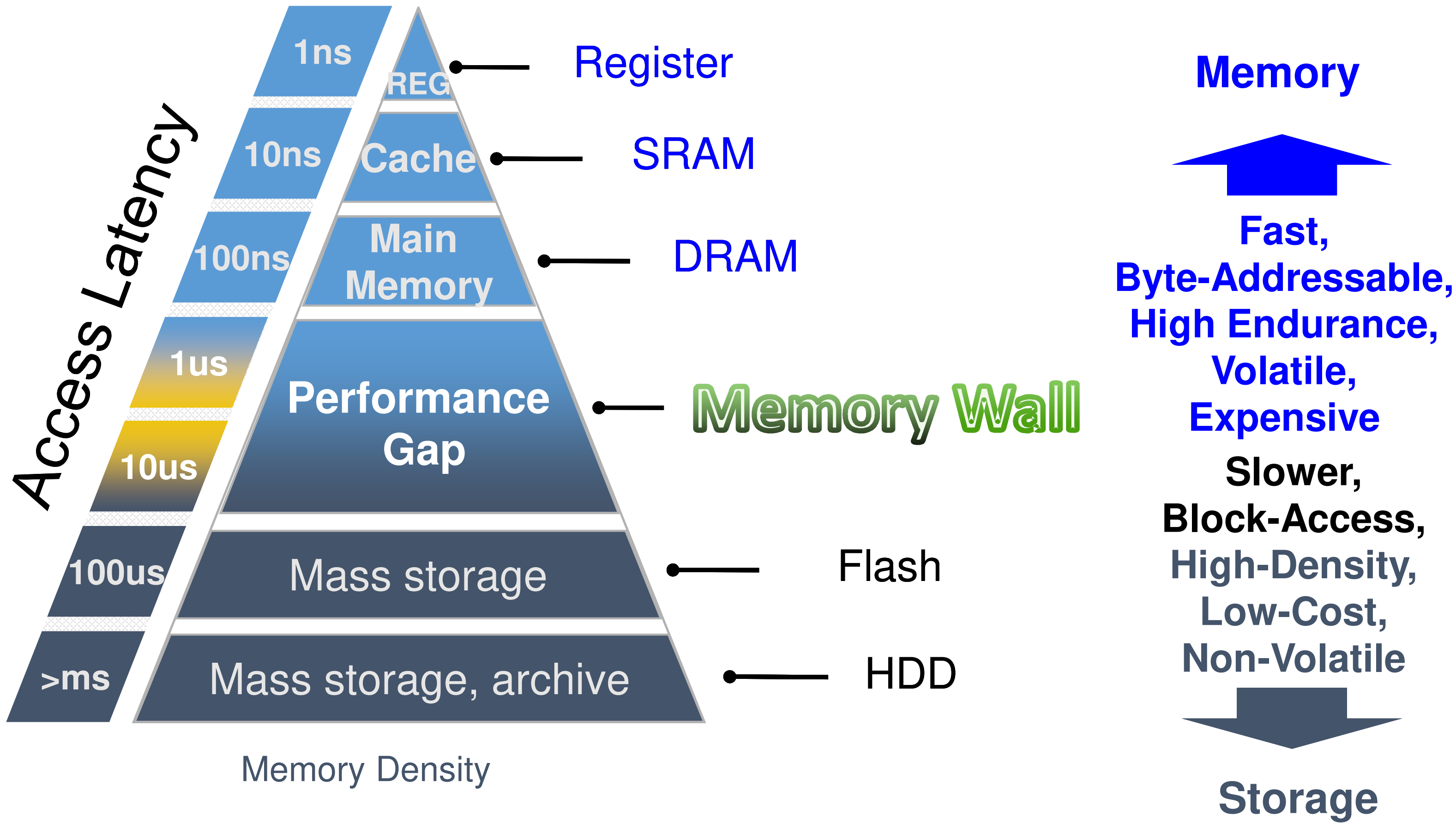
1T1C or 2T2C



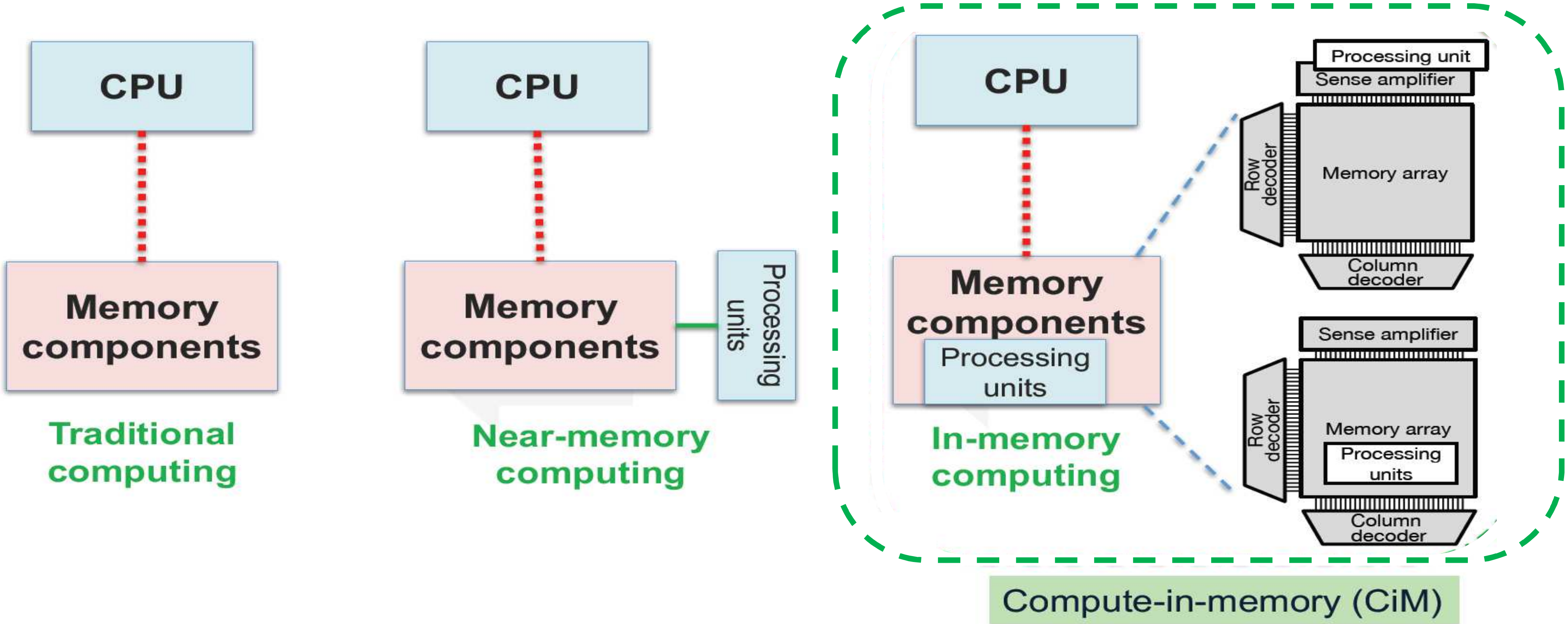
1T FeFET



Memory Hierarchy



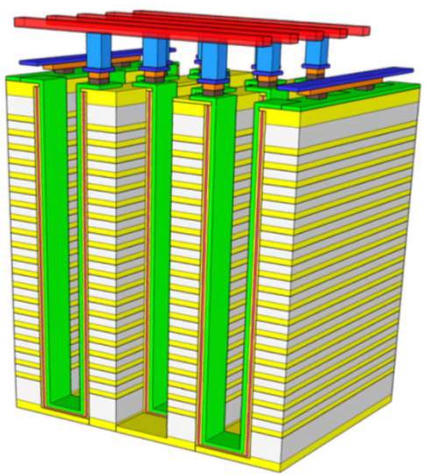
Memory-Centric Computing is Emerging to Complement Process-Centric Computing

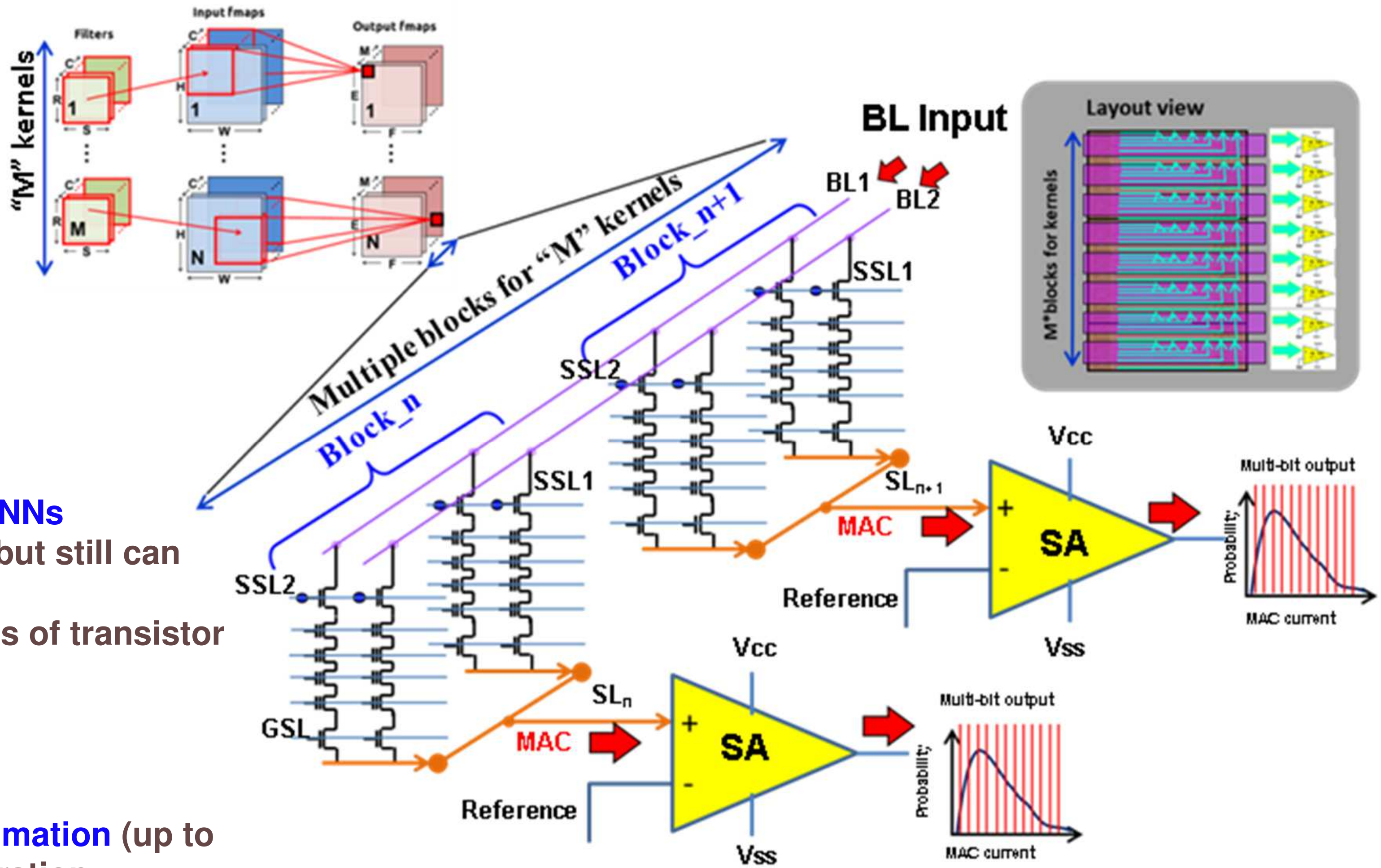


1. **Processing units can be simple logic/arithmetic operations or more complex operation sequences**
2. **"Memory components" can be SRAM, DRAM, NAND, NOR, PCM, ReRAM, MRAM, FeRAM, HDD, etc. depending on applications**

X. Sharon Hu, U. of Norte Dame, NVMSA 2019

In-Memory Computing Using 3D NAND





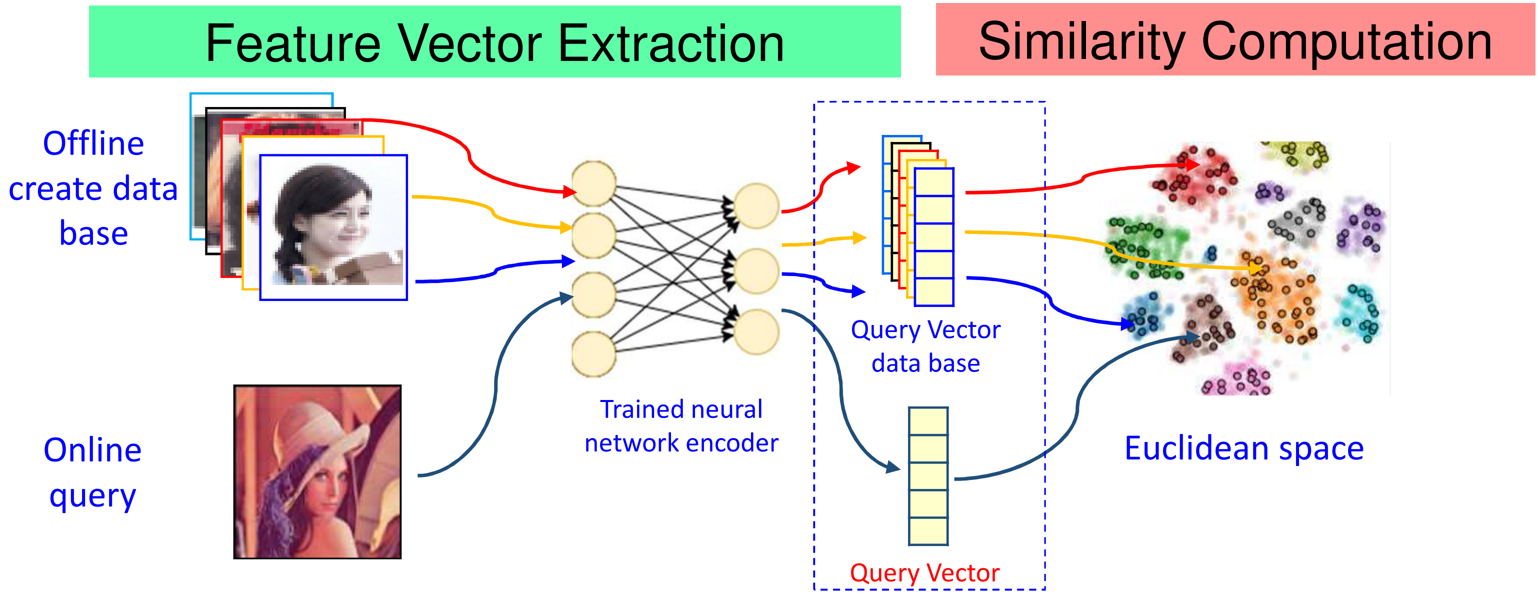
Key features:

1. High capacity (>64Gb) for **large NNs**
2. SLC storage for best reliability, but still can provide multi-bit MAC operation
3. The large ON/OFF ratio >4 orders of transistor Icell
4. Low Icell ~nA
5. Tight Vt distributions

➡ Enable **large and parallel summation** (up to ~10,000) to enhance the MAC operation bandwidth

Hang-Ting Lue, et al., Macronix, IEDM 2019 38.1

In-Memory Search Technology



An in-memory search engine can be embedded in a data search system as a memory module (device)

- ✓ **nvTCAM: Non-volatile Ternary Content-Addressable Memory**
- ✓ **Similarity search with Cosine Similarity or Hamming Distance sorter**

Source: Macronix

In-Memory Search with Flash Memories

- Key Advantages
  - High capacity 512Gb per NAND, 4Gb per NOR
  - Non-volatility, Low cost, Low power (a few 100mW),
  - low read disturbance (> 1G) + refresh

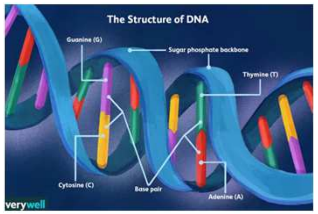
- Key Dis-advantages
  - Slow read for NAND (~50us), NOR (~120ns)
  - Limited endurance for NAND (~1e4), NOR (~1e5)

- Some Example Applications

Face Recognition

Large Language Model

Car Localization



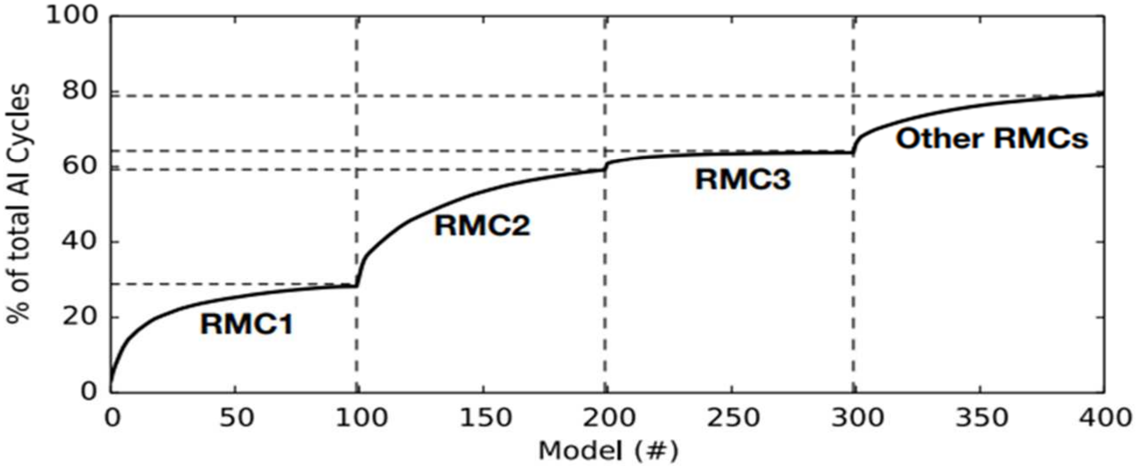
DNA Mapping

Recommendation

Source: Macronix

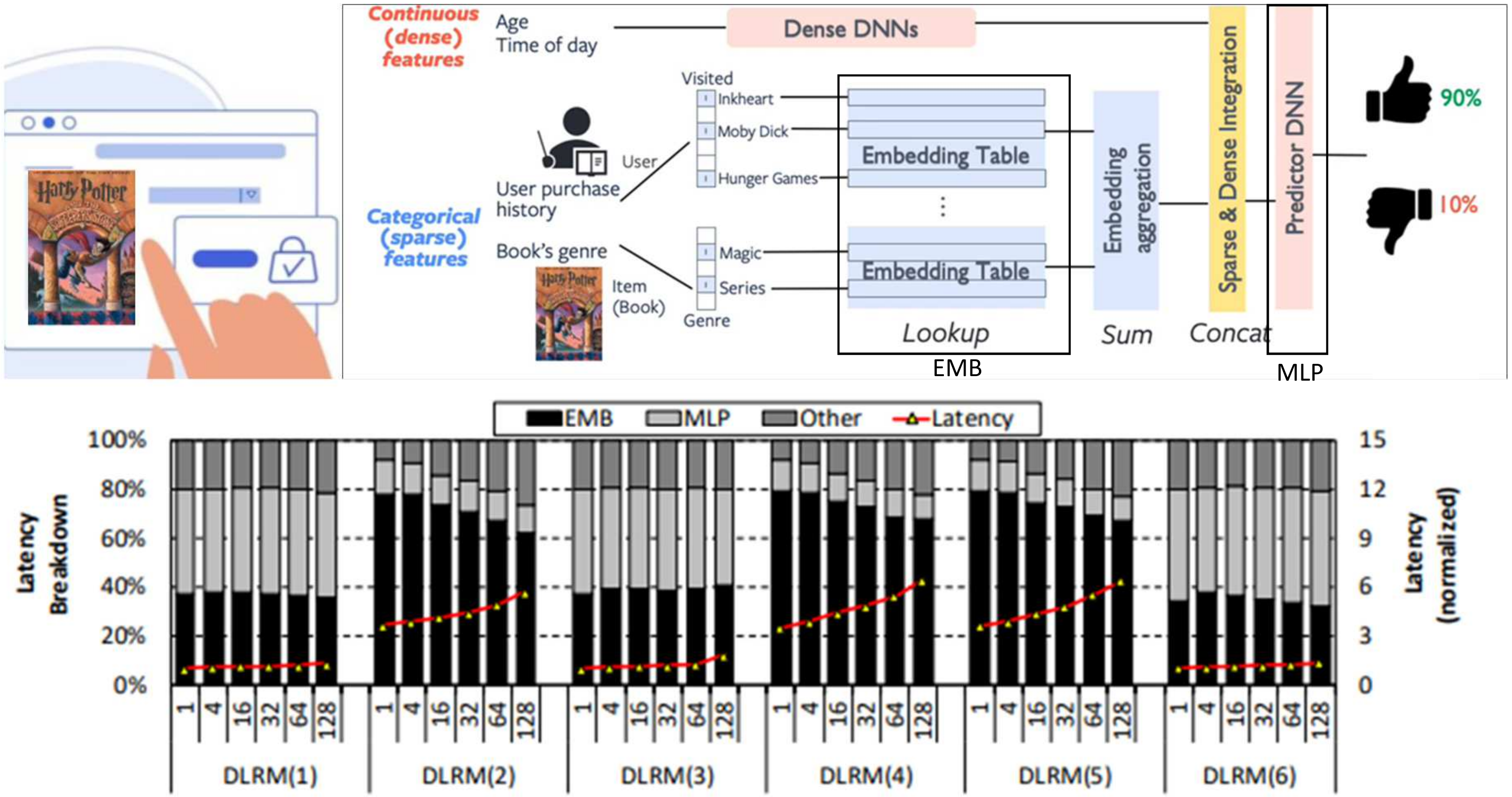
Recommendation (1)

- DNN-based personalized recommendation models comprise up to 79% of AI inference cycles in a production-scale data center



U. Gupta, et al. "The Architectural Implications of Facebook's DNN-based Personalized Recommendation" (HPCA2020)

Recommendation (2)

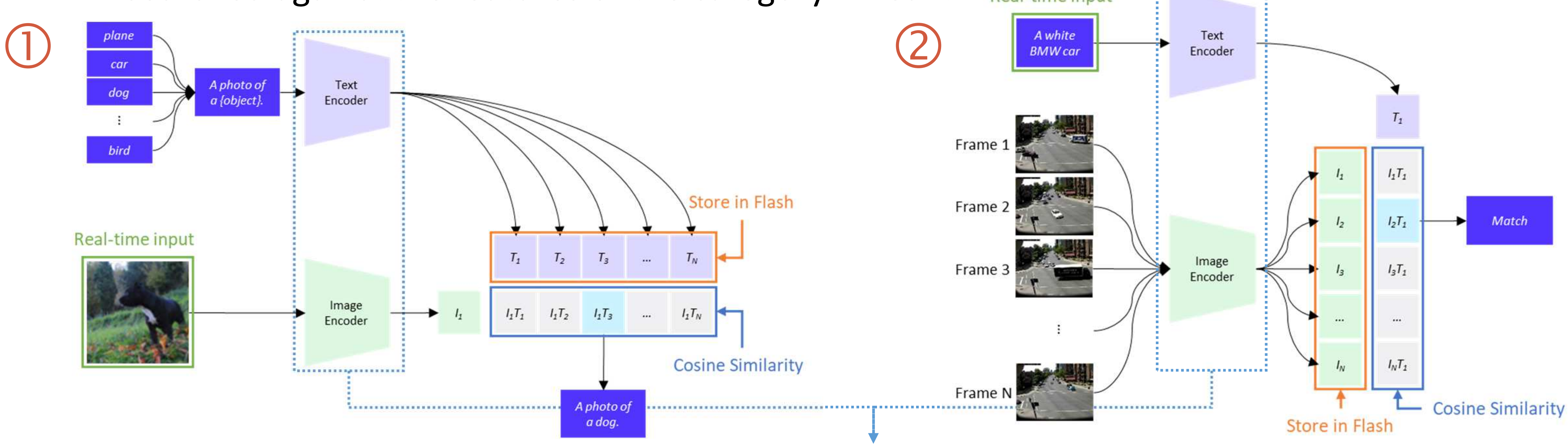


R. Hwang et al. "Centaur: A Chiplet-based, Hybrid Sparse-Dense Accelerator for Personalized Recommendations," *(ISCA2020)*

Surveillance (1)

CLIP (Contrastive Language-Image Pre-Training)

- CLIP is trained to match images with the corresponding captions and vice versa. Therefore, there are two ways to use CLIP
  1. A bunch of categories are given and encoded as features. The input image is encoded and searched against the features of the categories in real time.
  2. Given a bunch of images, encode them into features. The text you want to find is encoded and searched against the features of the category in real time.



CLIP is a really powerful neural network proposed by OpenAI. It is trained with 400 million (image, text) pairs collected from the internet.

https://openai.com/blog/clip/
https://arxiv.org/abs/2103.00020\

Surveillance (2)

CLIFS: Contrastive Language-Image Forensic Search

- CLIFS is a proof-of-concept for free text searching through videos for video frames with matching contents.
- The searching is done by first extracting features from video frames using the CLIP image encoder and then getting the features for the search query through the CLIP text encoder.
- The features are then matched by cosine similarity and the top results are returned, if above a set threshold.

A truck with the text "odwalla"

A white BMW car

A truck with the text "JCN"

A bicyclist with a blue shirt

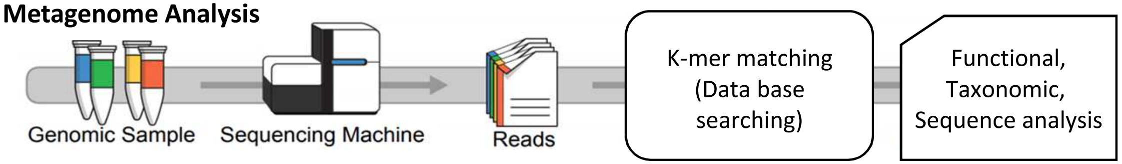
A blue SMART car

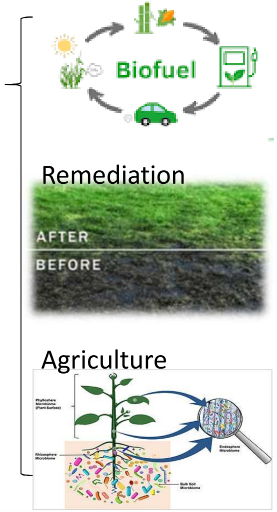
- Scenario: There are about 15,000 surveillance camera in Taipei City. Each video will be saved for 1 month.
  - Each frame is embedded to a 512 dimension FP32 feature: 2KB/feature
  - For each second, suppose that one frame is encoded and stored. Then 2,592,000 features will be stored for one month of video.
  - Total storage requirement: 2KB/feature * 2,592,000 features/month * 15,000 surveillance camera = 72.4 TB

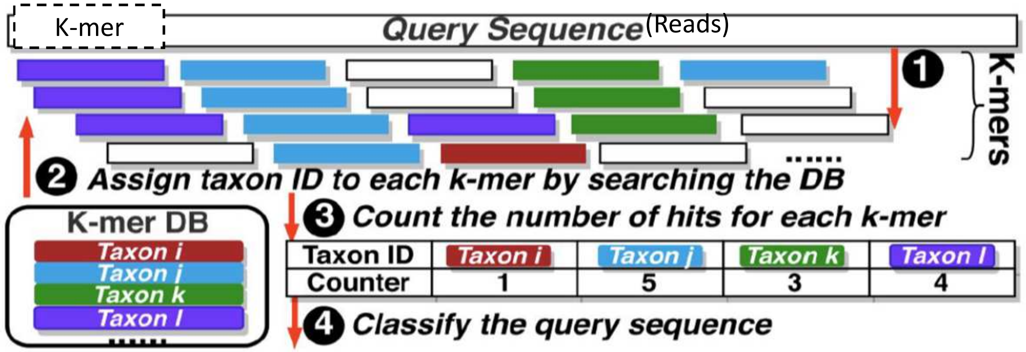
https://github.com/johanmodin/clifs
https://news.ltn.com.tw/news/society/paper/1510190

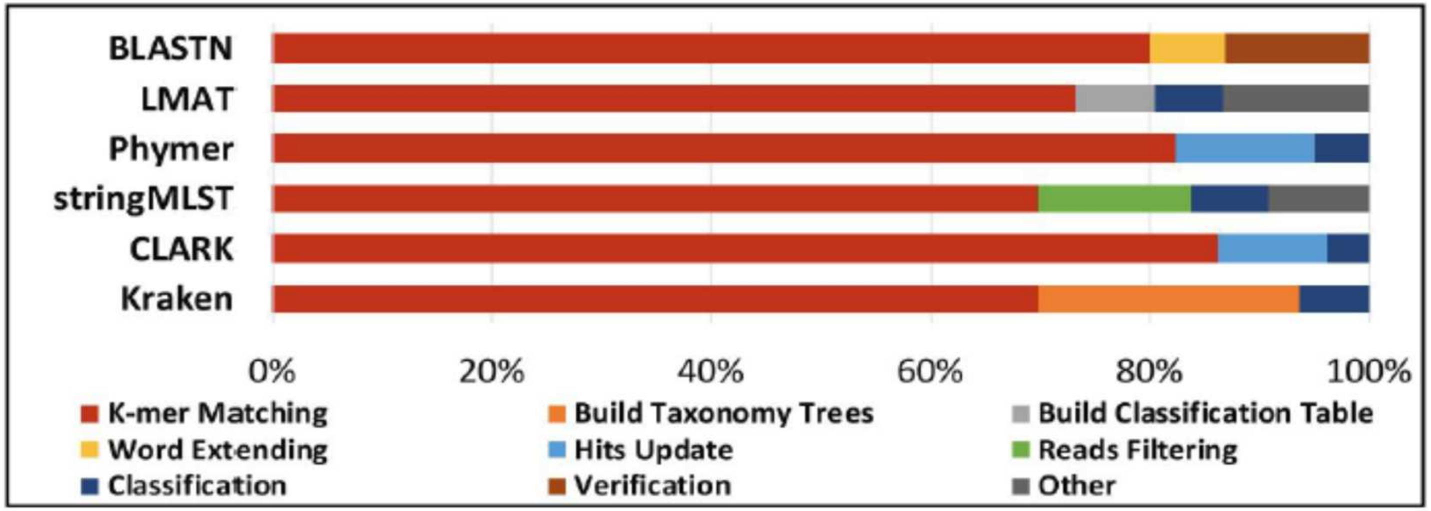
Genomic Analysis

Metagenome Analysis







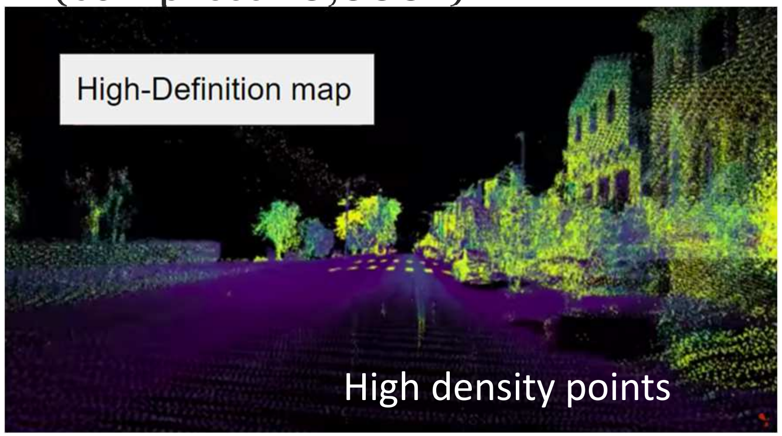


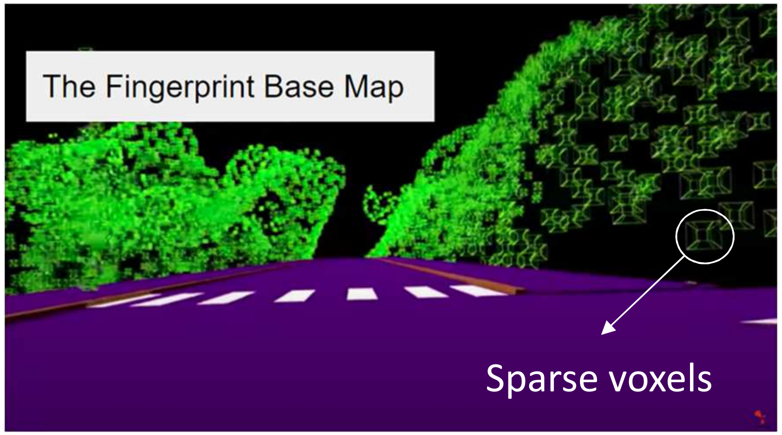
Wu, Lingxi, et al. "Sieve: Scalable in-situ dram-based accelerator designs for massively parallel k-mer matching." *(ISCA 2021)*

Car Localization

Civil Maps' The Fingerprint Base Map™

- A high-definition map (HD map) is a highly accurate map used in **localization** for autonomous driving.
- Civil Maps' The Fingerprint Base Map™ is an edge-based map for real-time localization
  - Each voxel contains its unique fingerprint.
  - It allows **a dictionary lookup** of the location in **0.1 second** and achieves **15 cm – 20 cm** accuracy at high speed.
  - A HD map of San Francisco, which is about 4,000 kilometers, can take up to **4 terabytes**, and Base Map of only **~400 megabytes** for that same region (compress 10,000x)





Source: www.civilmaps.com

Outline

- Introduction
- Experience Sharing
  - Some Stories of Neutrino
  - GaAs Heterojunction Bipolar Transistor (HBT) and ICs
  - Semiconductor Memories
- **Conclusion Remarks**

It is a Privilege Being a Physicist

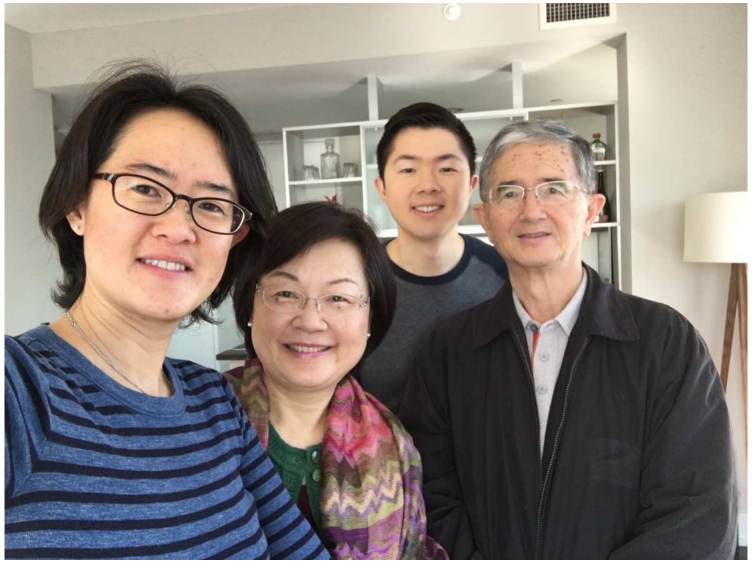
(Victor F. Weisskopf)

- **Studying physics is a lucky, interesting, and practical journey. It trains us to learn new things fast and be leaders of many fields of research and work**
- **Semiconductor industry has been advancing exponentially following Moore's Law since 1960's**
  - It enabled many electronic products that enriched our lives
  - It accelerates developments of AI, IoT, communication, sensing, biomedicine, etc.
  - Memory-centric computing is emerging to complement process-centric computing
- **Neutrino physics research continues to be exciting and important for exploring frontier knowledge of Nature**
- **Competitions in both fields are severe. The keys to success are passion, innovation, and persistence**

Acknowledgement

- 夏期岳先生夫人
- Felix Boehm
- Herb Chen
- Peter Asbeck
- Frank Chang
- Derek Cheung
- Jackson Hu
- Nim Cheung
- C. Y. Lu
- Rich Liu

- Teachers
- Classmates
- Colleagues
- Sponsors
- Customers
- Collaborators
- Friends
- Father
- Wife, Children, Relatives
- …



Thank You!

kcwang@mxic.com.tw