AN INTRODUCTION TO COSMIC NEUTRINOS

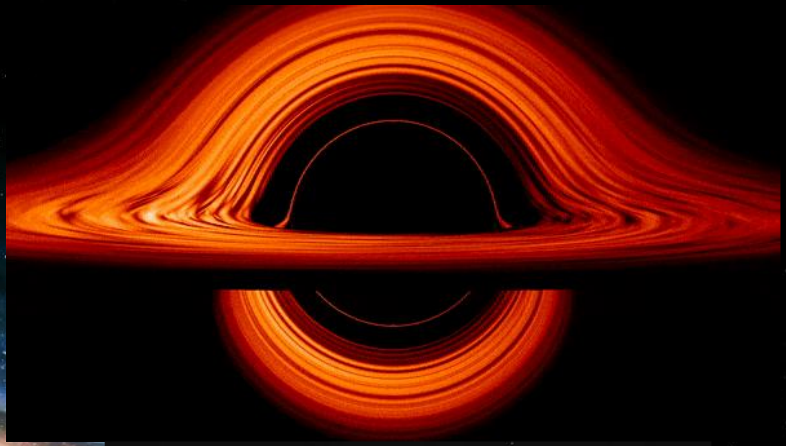
From the edge of the Universe to the Deep Sea

By Saliha Bashir
bashir@agh.edu.pl
D-11 Room 106

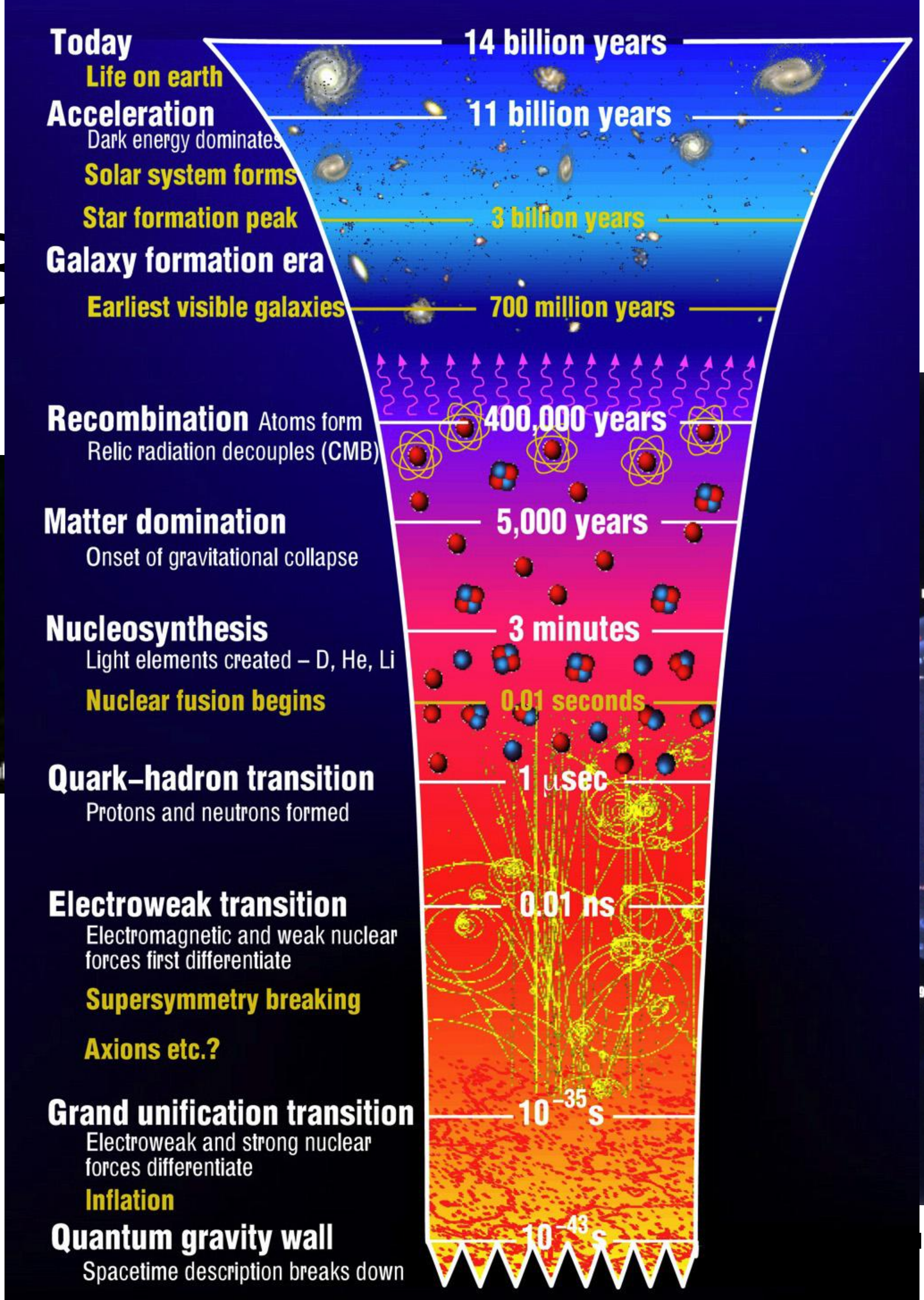
“The Invisible Messengers”

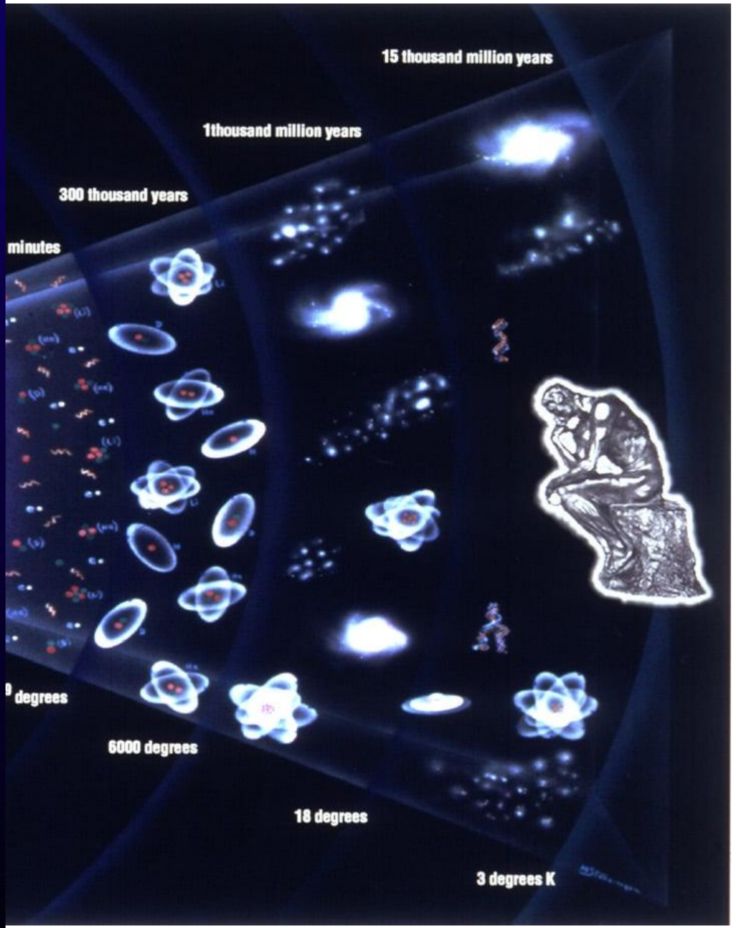
The Universe is full of violent events…

- Black holes devour matter
- Stars explode
- Galaxies accelerate particles beyond anything we can build on Earth



From the Big B





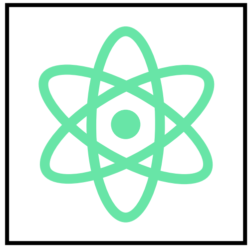
Messengers from the Early Universe

1. Early Universe (Big Bang)

The universe began in an extremely hot, dense state ~13.8 billion years ago.

In the first seconds, fundamental particles formed and interacted intensely.

Neutrinos decoupled from matter about **1 second after the Big Bang**.

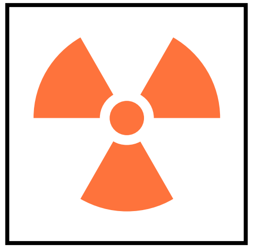


2. Cosmic Neutrino Background

After decoupling, neutrinos streamed freely through the universe.

These relic neutrinos form the **Cosmic Neutrino Background (CvB)**.

They carry information about the **earliest moments of the universe**.



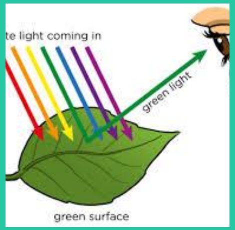
3. Cosmic Microwave Background (CMBR)

Around **380,000 years after the Big Bang**, electrons and protons combined to form neutral atoms.

Photons decoupled from matter and began traveling freely.

These photons are observed today as the **Cosmic Microwave Background**.

Messengers That Cannot Be Stopped

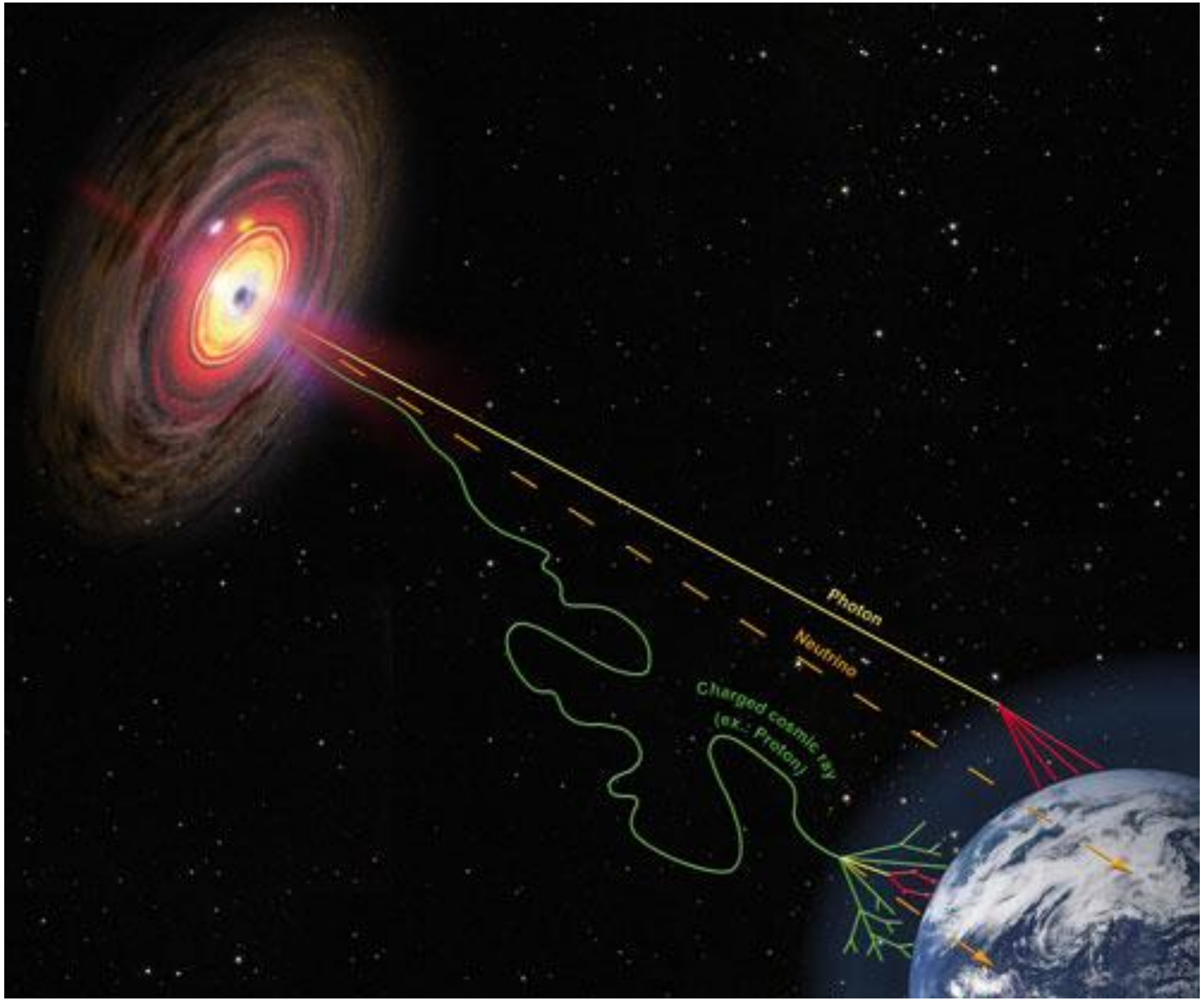


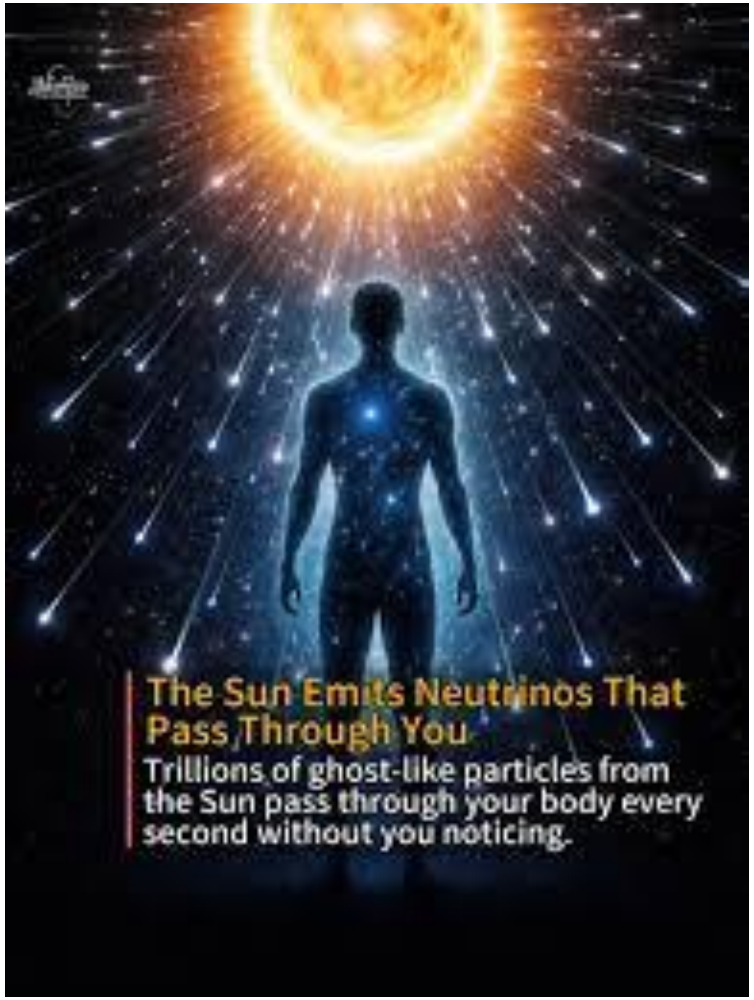
LIGHT CAN BE ABSORBED.

COSMIC RAYS ARE DEFLECTED BY MAGNETIC FIELDS.

BUT **NEUTRINOS TRAVEL STRAIGHT AND ALMOST UNTOUCHED**.

What if we could observe the Universe using particles that pass through entire galaxies without blinking?


Photon
Neutrino
Charged cosmic ray
(ex.: Proton)


The Sun Emits Neutrinos That Pass Through You
Trillions of ghost-like particles from the Sun pass through your body every second without you noticing.

In short...

What Are Neutrinos?

Let's review some properties:

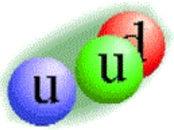
Properties	Neutrinos
Most production places	Stars
Rest mass	Non-zero
Electric charge	No
Speed	$v \approx c$
Reactivity (with matter)	Only through weak interactions
Affection by Magnetic Field	No
Enter/Exit from Earth	Enter from one side exit from other
Number per second (pass through a cm^2 of Earth)	10^{10}
Cross section (TeV)	$\sigma_{\nu N} \sim 10^{-35}\ cm^2$
Detectors Location	Deep underground
Solar neutrino flux	$6 \times 10^{10} cm^{-2} s^{-1}$

Almost impossible to detect

Remember the Standard Model …

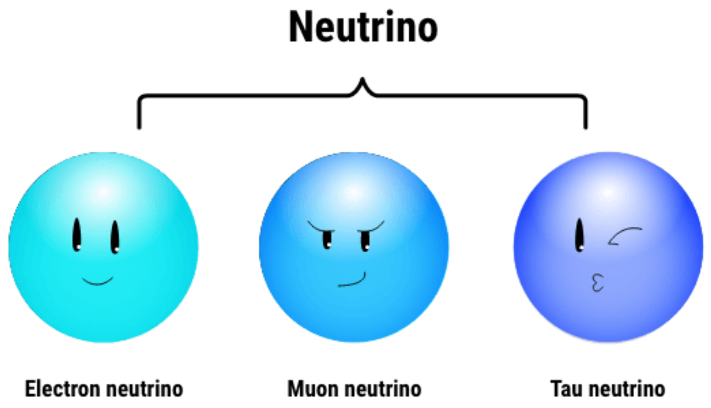
The 3 flavors of neutrinos:

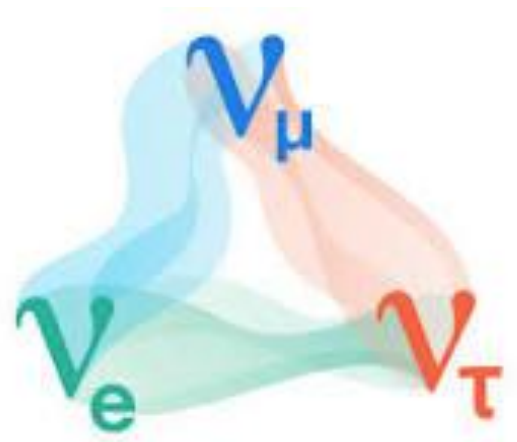
These flavors correspond to their partner particles: the electron, muon, and tau.



The Surprising Discovery: Neutrino Oscillations

- As neutrinos travel through space, they can change from one flavor to another.
- An electron neutrino produced in the Sun can arrive at Earth as a muon or tau neutrino.
- This phenomenon is called "neutrino oscillations".

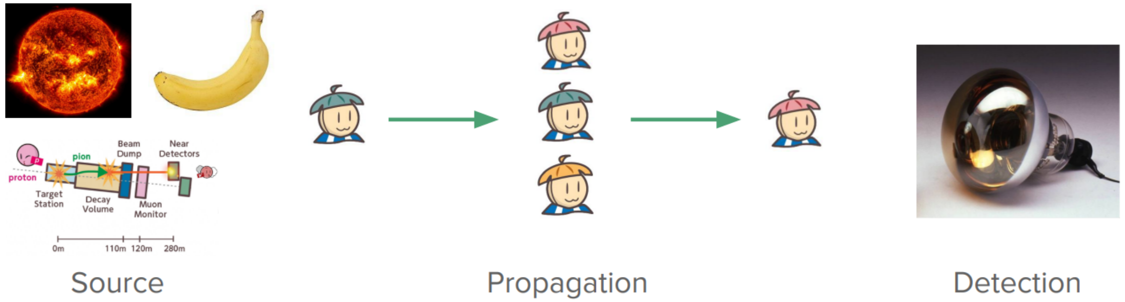




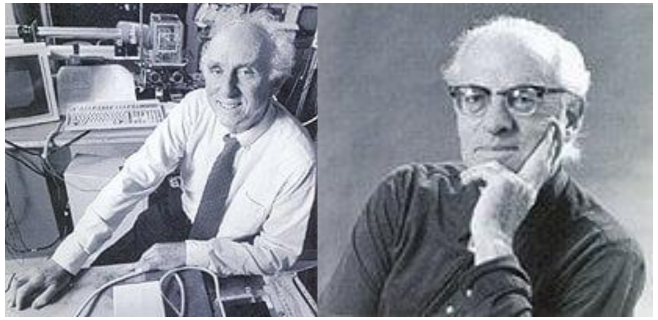
How a particle changes identity?

- **Neutrino oscillations involve all 3 flavors, let's take two for example:**
- **Electron and muon neutrinos are viewed as different particles, so the identity change would seem strange.**
- **But if we view them as quantum mechanical states, then it's a simple consequence of the "Principle of superposition in QM."**

- Neutrinos interact with matter as a definite flavor
- But travel through space as a superposition of all three flavors



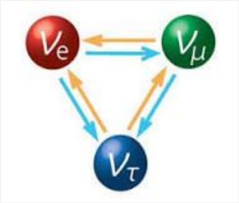
1995 Nobel Prize in Physics



The 1995 Nobel Prize in Physics was awarded to:

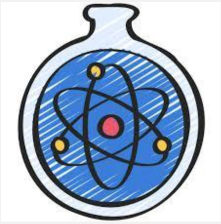
Frederick Reines – for the **detection of the neutrino**

Martin L. Perl – for the discovery of the **tau lepton**



He performed the **first experimental detection of the neutrino in 1956**.

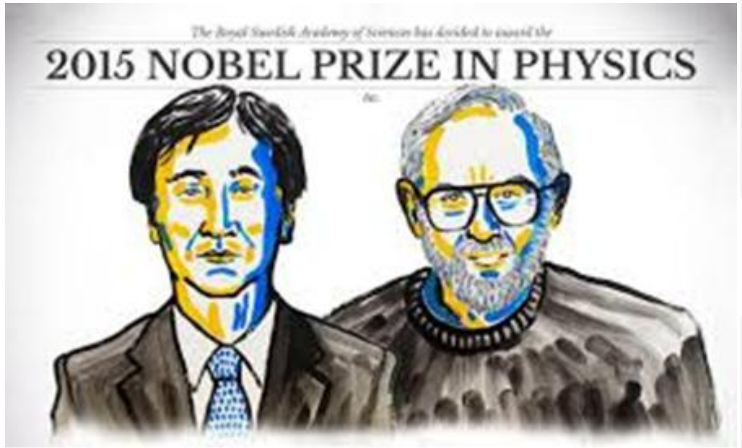
And detected **electron antineutrinos** produced in a **nuclear reactor**.



Their work was based on experiments at:

The experiment used the reaction called **inverse beta decay**, where an antineutrino interacts with a proton to produce a **positron and a neutron**.

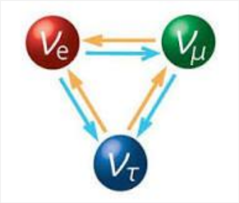
2015 Nobel Prize in Physics



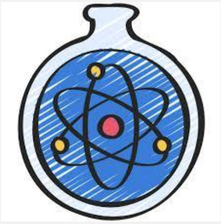
The 2015 Nobel Prize in Physics was awarded to:

Takaaki Kajita

Arthur B. McDonald



For the discovery of **neutrino oscillations**, demonstrating that **neutrinos have mass**.

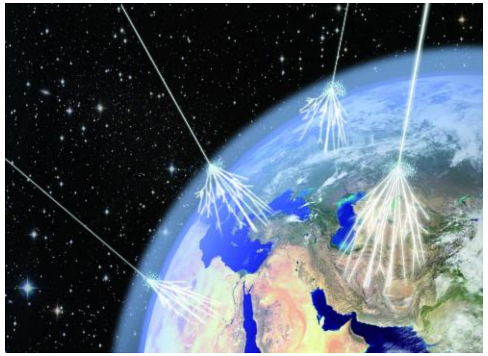


Their work was based on experiments at:

Super-Kamiokande (Japan)

Sudbury Neutrino Observatory (Canada)

The Mystery of Cosmic Accelerators



Observation

- We observe ultra-high-energy cosmic rays.

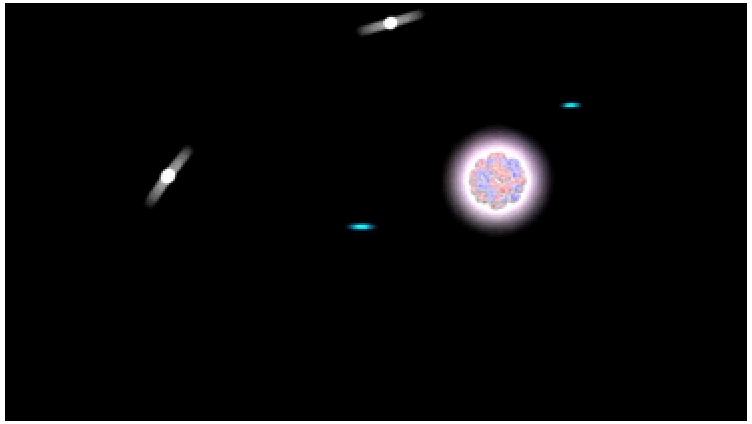
Problem

- They are charged → deflected by magnetic fields → sources unknown.

Solution

- High-energy neutrinos escape from these environments and travel undeflected across the Universe, carrying direct information about their sources.

Why Neutrinos Are Unique Messengers?



Here is where the neutrino properties come in handy… !!!

Neutral → not deflected	Weakly interacting → escape dense environments	Travel cosmological distances

WHY MULTI ?

Because we have multiple signals (messengers):
1) Radiations
2) Gravitational waves
3) Neutrinos
4) Cosmic rays

Mult… observational fiel… tromagnetic radiat… neutrinos, and cosmic rays to study extreme cosmic phenomena.

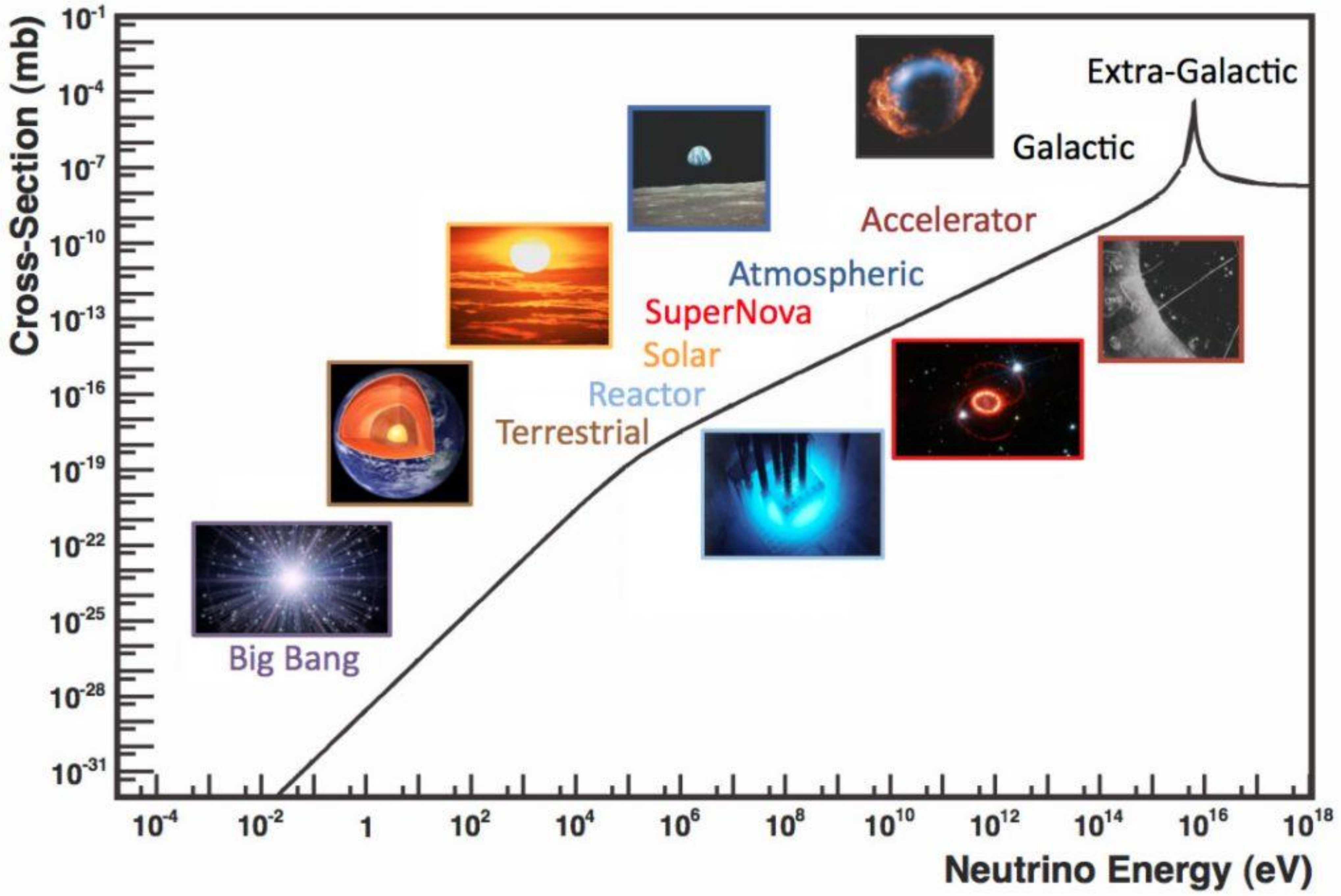
Sources of Astrophysical Neutrinos?

Active galaxies
- TXS 0506+056 (Blazar)
- NGC 1068 (Seyfert galaxy)
- Gamma-Ray Bursts

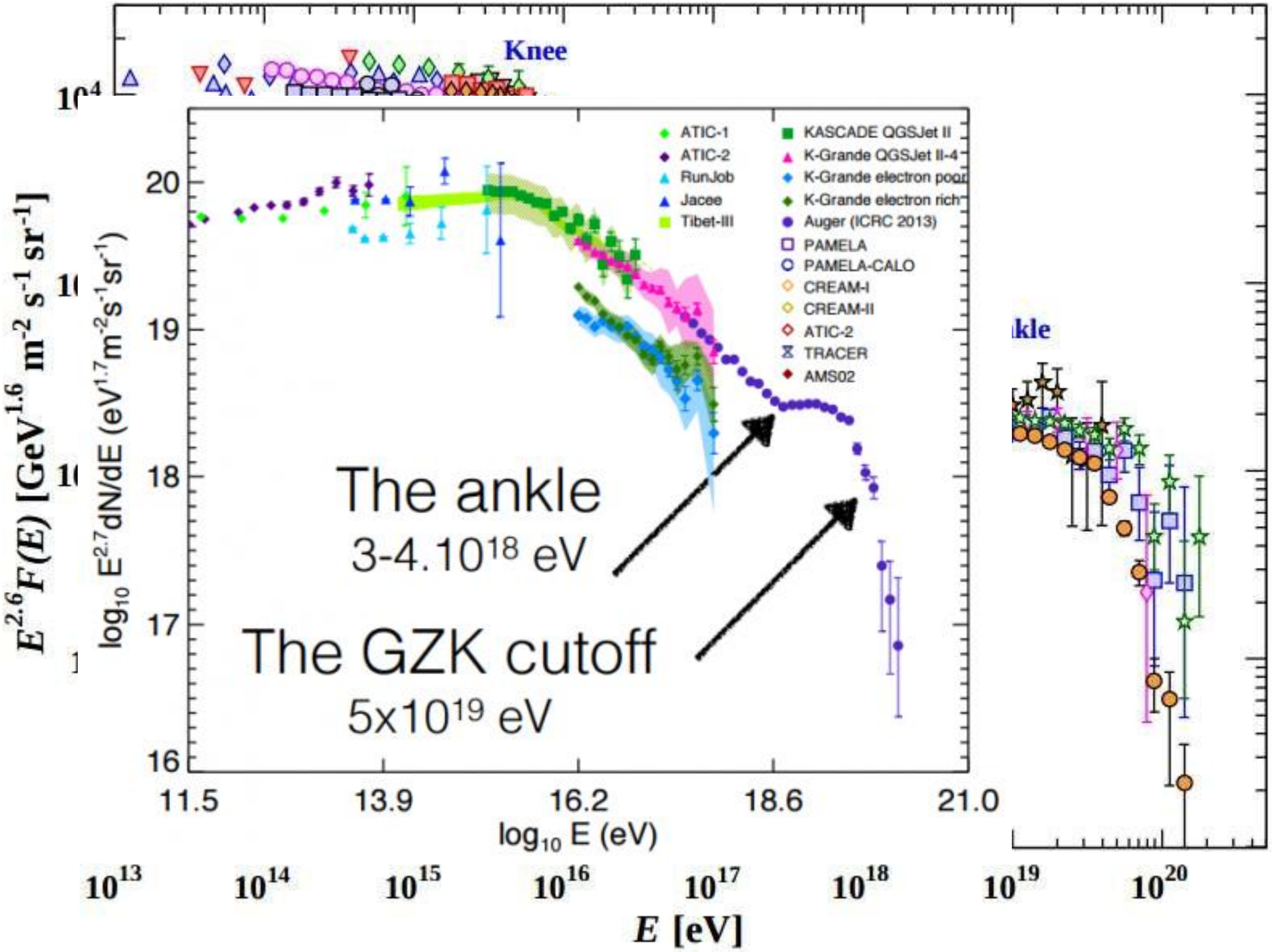
Transient Events
- Core-collapse supernovae
- Tidal disruptive events

Galactic
- Cygnus X-1
- Supernova remnants
- Pulsar wind nebulae

Source	Energy
Solar neutrinos	MeV
Supernova neutrinos	10–50 MeV
Atmospheric neutrinos	GeV–TeV
AGN / Blazars	TeV–PeV
GRBs	PeV–EeV



10.1103/RevModPhys.84.1307



10.1007/s10509-020-03816-3

Extragalactic Sources: TXS 0506+056 (Blazar)

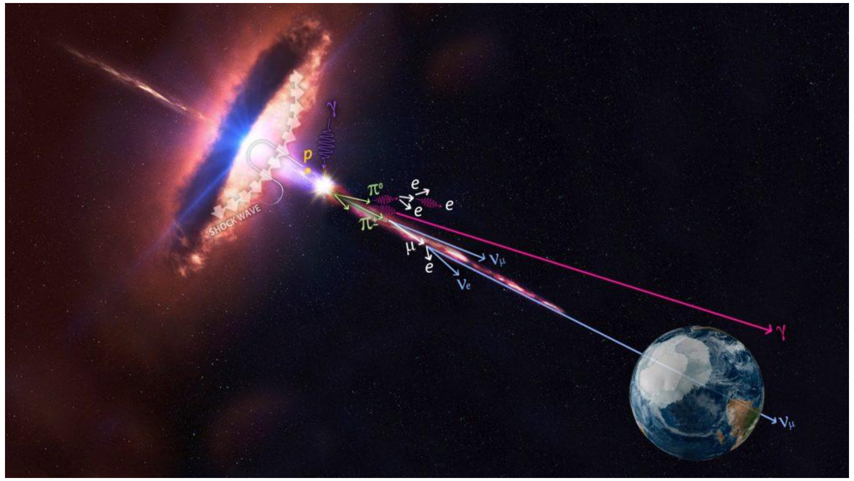
Blazar (Active Galactic Nucleus with jet pointing toward Earth)
Powered by a supermassive black hole
Relativistic jet aligned with our line of sight

First identified high-energy astrophysical neutrino source (2017)
Associated with a ~290 TeV neutrino detected by IceCube
First clear example of multi-messenger neutrino + gamma-ray emission

Proton acceleration in relativistic jet
p–γ interactions inside the jet

$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow \mu^+ + \nu_\mu$$

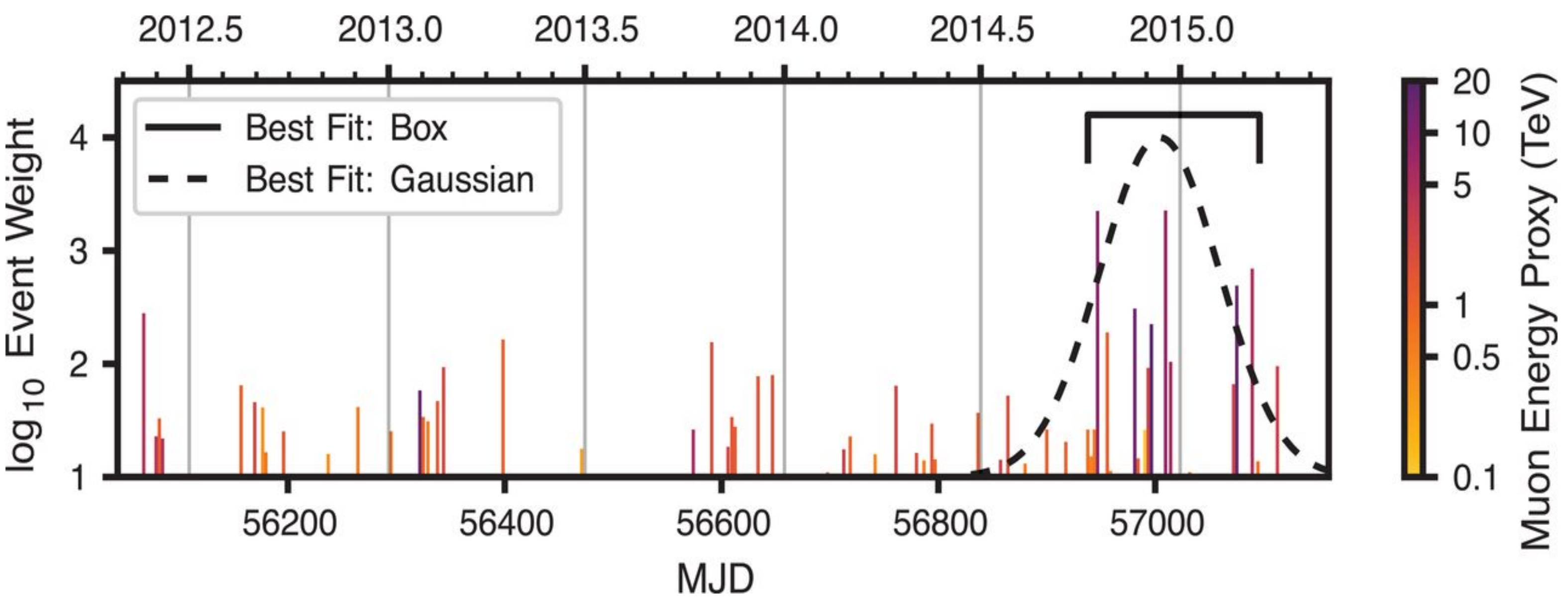
$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu}$$



High-energy neutrinos escape and travel undeflected to Earth

Evidence of the first ν source : TXS 0506+056

neutrino event:	IceCube-170922A
energy:	$E\nu \approx$ 290 TeV
Distance	z = 0.3365
Luminosity distance	$dL\approx$1.8 Gpc
Gamma-ray luminosity	$L\gamma\sim$1047 erg/s



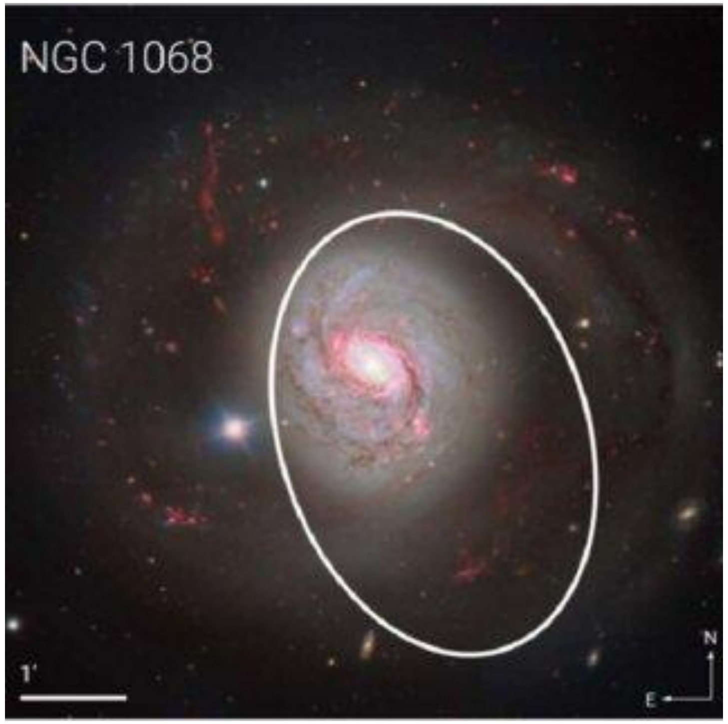
On 22 September 2017 IceCube detected a ~290-TeV neutrino from a direction , as reported by Fermi-LAT on September 28 2017, consistent with the flaring g-ray blazar TXS 0506+056.

Extragalactic Sources: NGC 1068 (Seyfert galaxy)

Seyfert II galaxy (Active Galactic Nucleus)
Contains a supermassive black hole
Obscured central region (dense gas & dust)

Identified as a steady high-energy neutrino source
Evidence for neutrino production in Active Galactic Nuclei (AGN) cores
suggests hadronic processes near the black hole

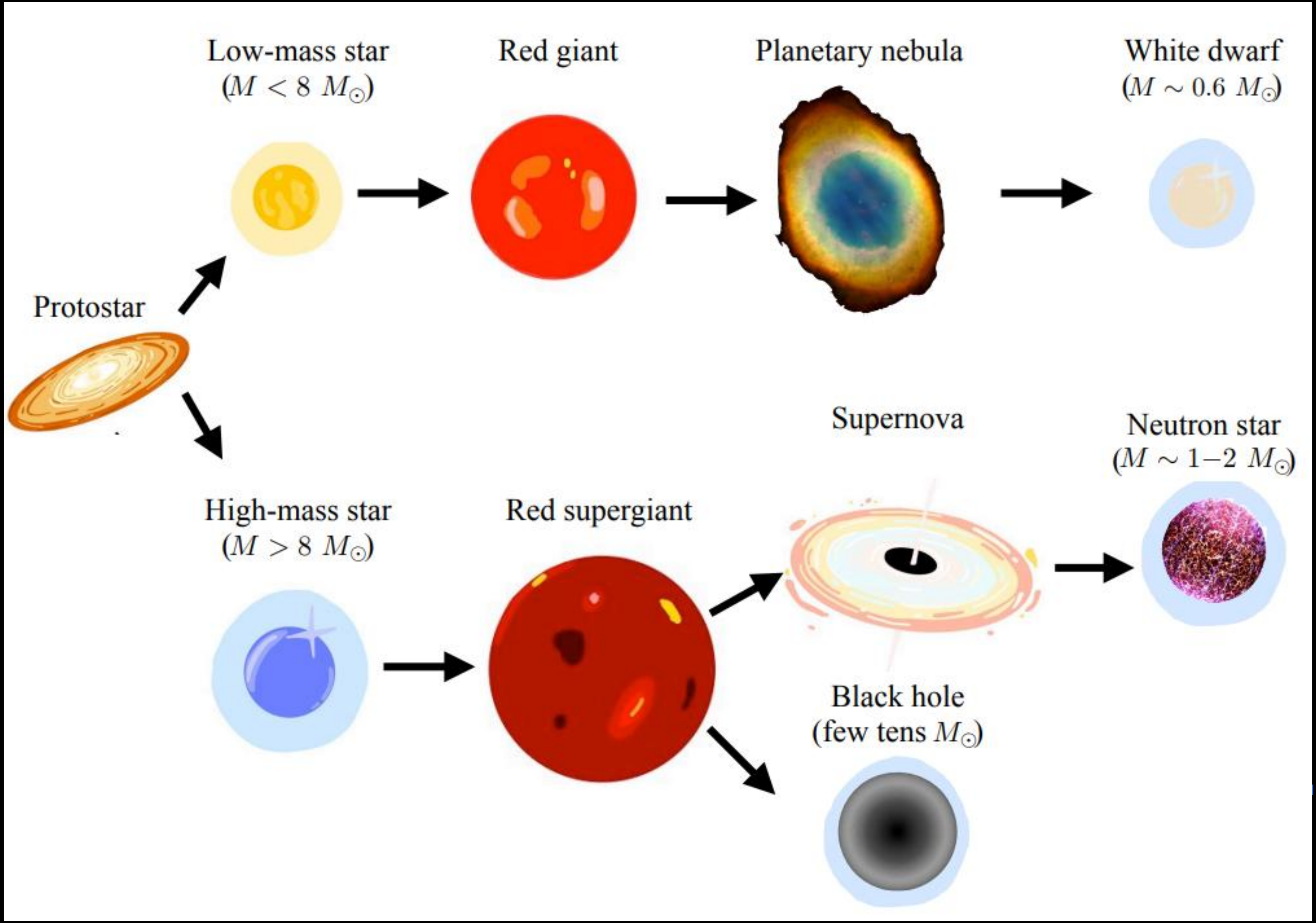
$$p + p \rightarrow \pi^{\pm} \rightarrow \mu^{\pm} \rightarrow \nu_{\mu} + \nu_{e}$$



Difference between Blazar and Syfert

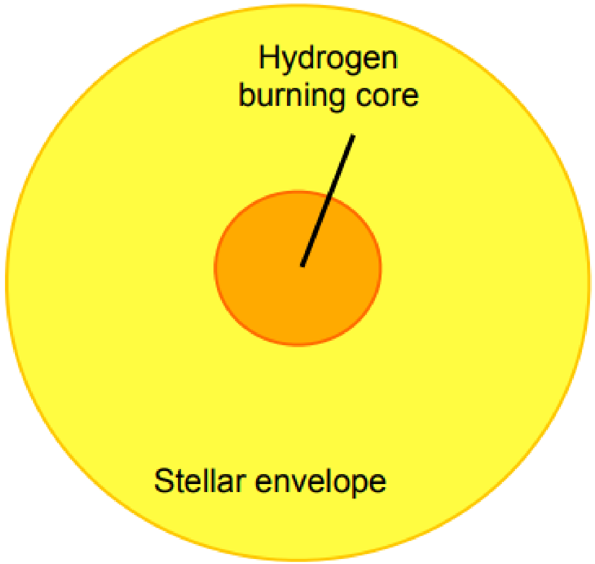
Feature	Seyfert Galaxy	Blazar
Jet orientation	Not pointed toward Earth	Jet aimed almost directly at Earth
Host galaxy	Usually spiral	Often giant elliptical
Variability	Moderate	Extremely rapid
Emission	Strong optical emission lines	Strong radio, X-ray, gamma rays
Brightness boosting	None or small	Strong relativistic beaming

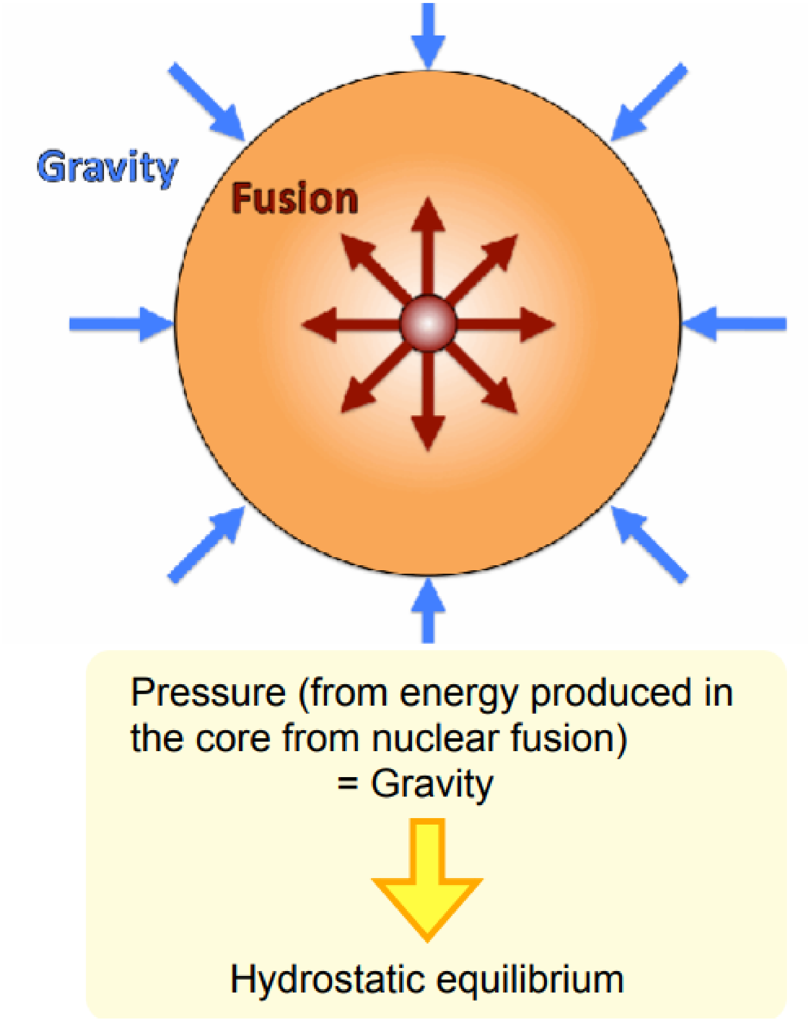
Life cycle of a star



Sun-like star

A young star fuses hydrogen into helium (keeps burning until it runs out of hydrogen).

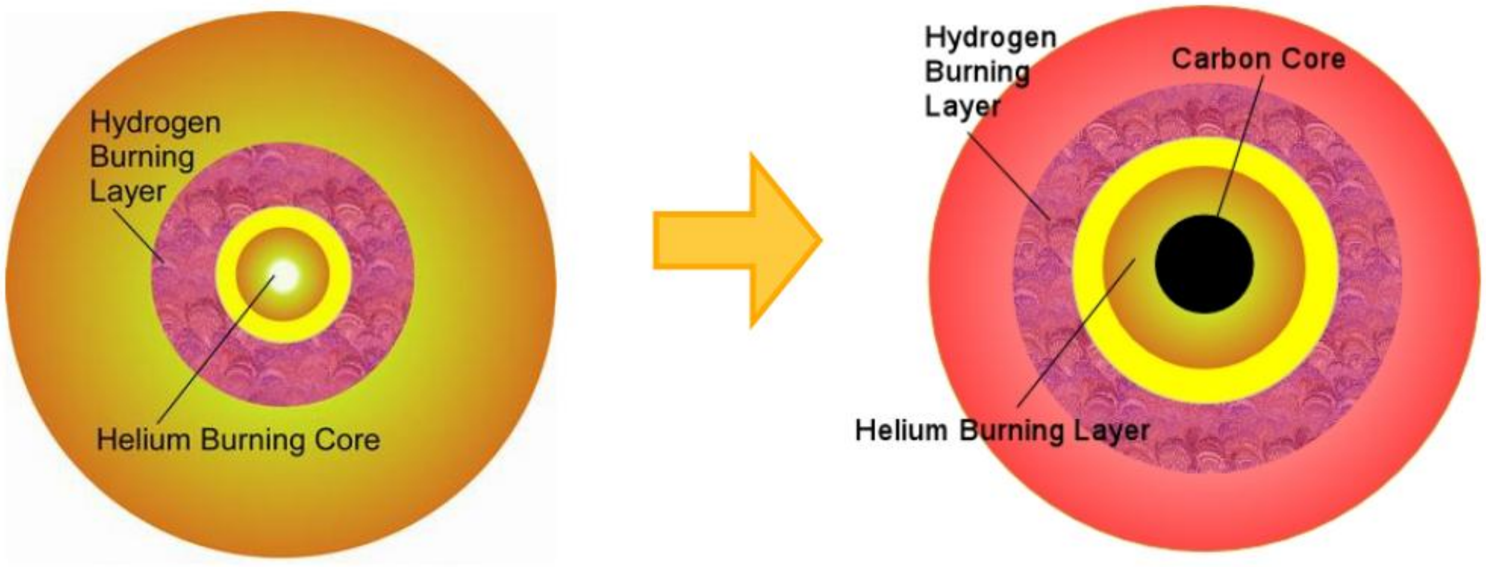




Life cycle of a massive star

When iron is formed, no more temperature raising occurs, no more counter pressure.
Core collapses by gravitation and an explosion occurs. Core-collapse supernova.

When the star exhausts hydrogen, the core drops its pressure. Gravity compresses the core and the latter heats up. Helium burning starts. It continues for all elements up to Iron.



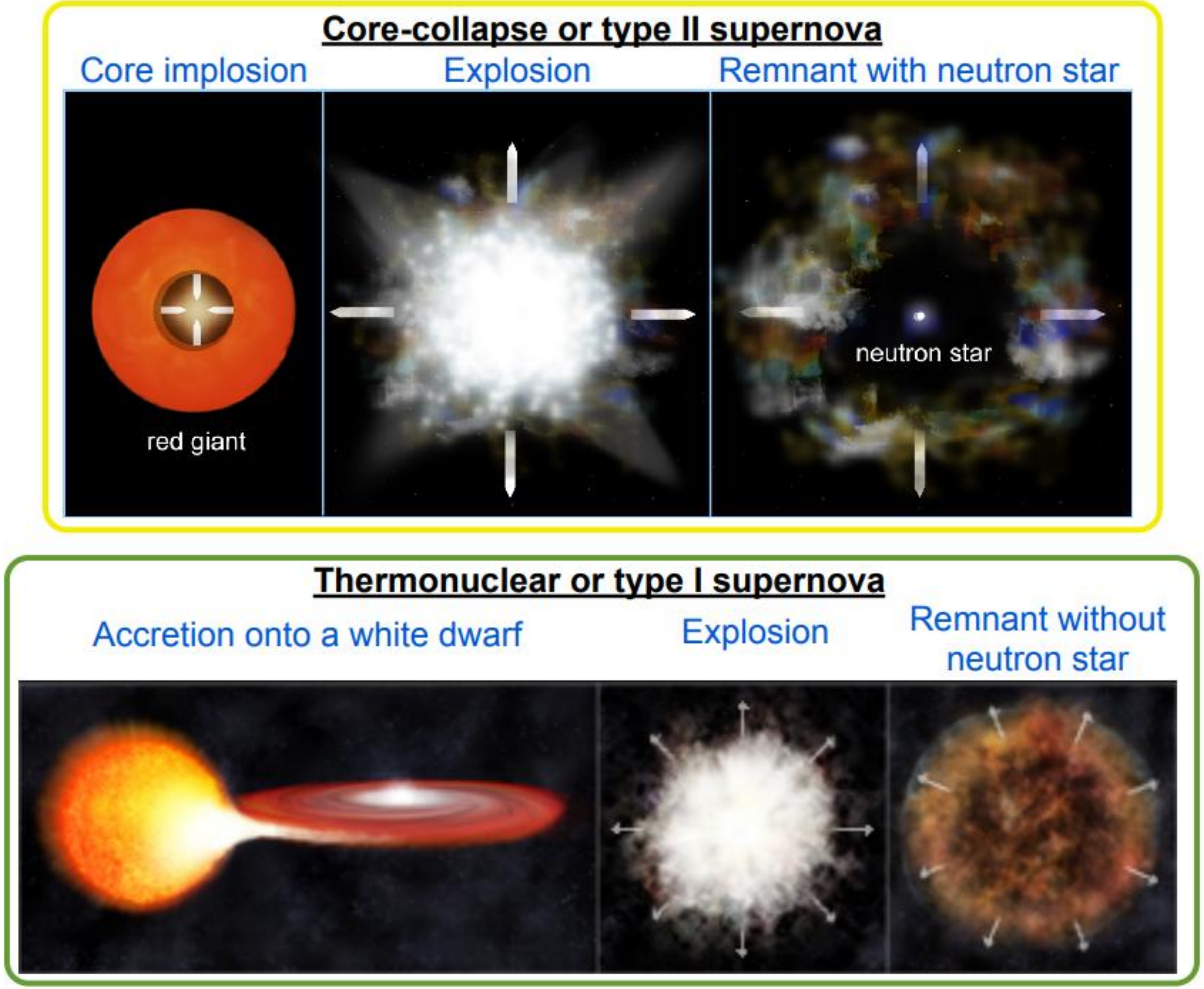
Phase I: Red supergiant phase.
Phase II: Blue supergiant phase. Helium core contracts and ignites helium burning in the core. The envelope becomes hot and appears blue.
Phase III: Red supergiant phase. Carbon-oxygen core forms. Envelope expands and cools, appears red. Carbon-oxygen core contracts heating up. Carbon burning.

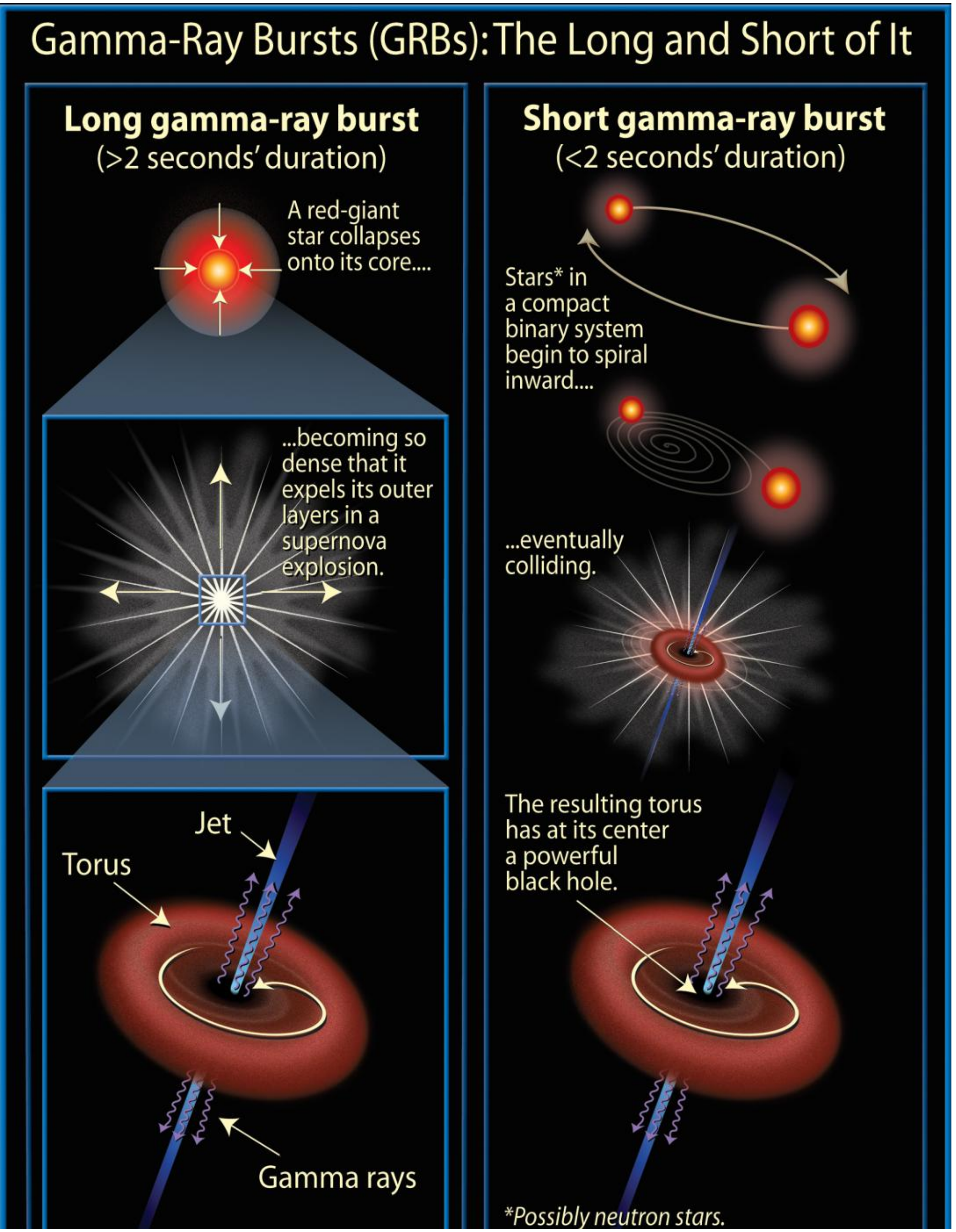
ISAP2021_lecture1_Tamborra.pdf

Alternative to explosion

- Many stars live in binary systems.
- A white dwarf may accumulate material from a companion star (often a red giant). · Thermo-nuclear supernova explosion.

Supernova Types





Extragalactic Sources: Gamma-Ray Bursts

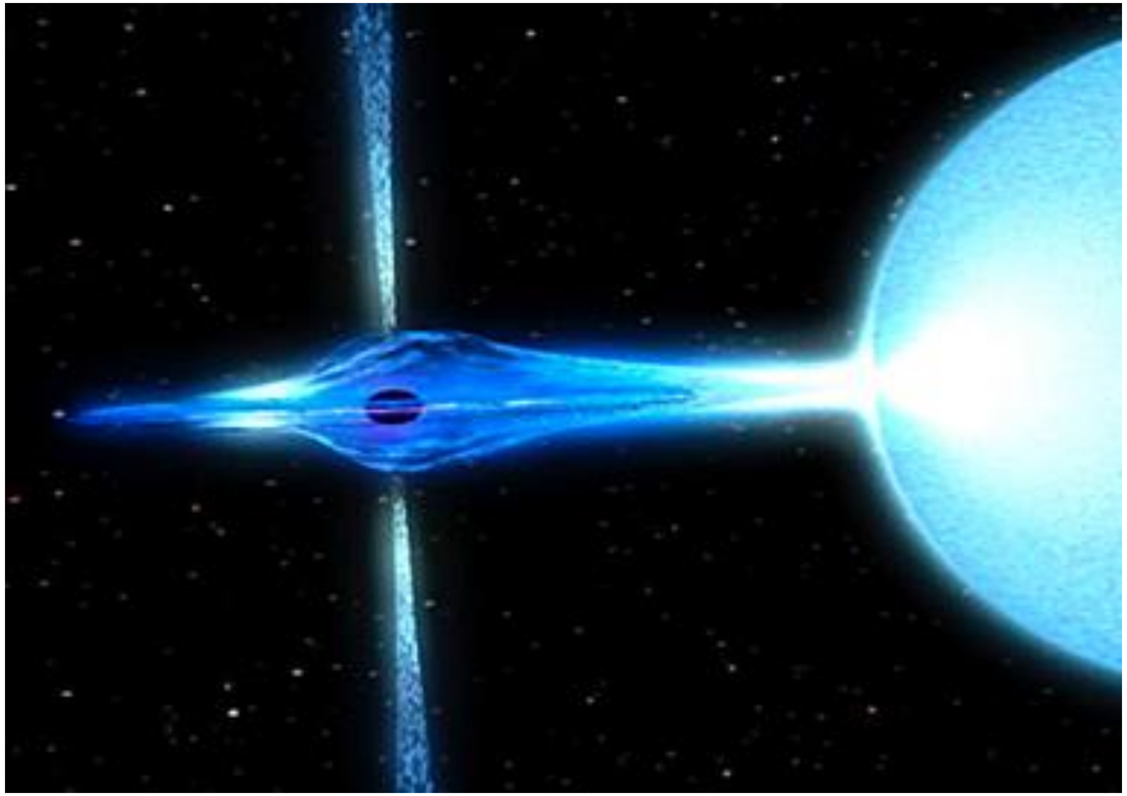
- What are they?
  - Extremely energetic transient explosions
  - Brief flashes of gamma rays (milliseconds to minutes)
  - Occur in distant galaxies
  - Among the most luminous events in the Universe
- They contain:
  - Strong shocks
  - Extremely high photon densities
  - If protons are accelerated in the jet:

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

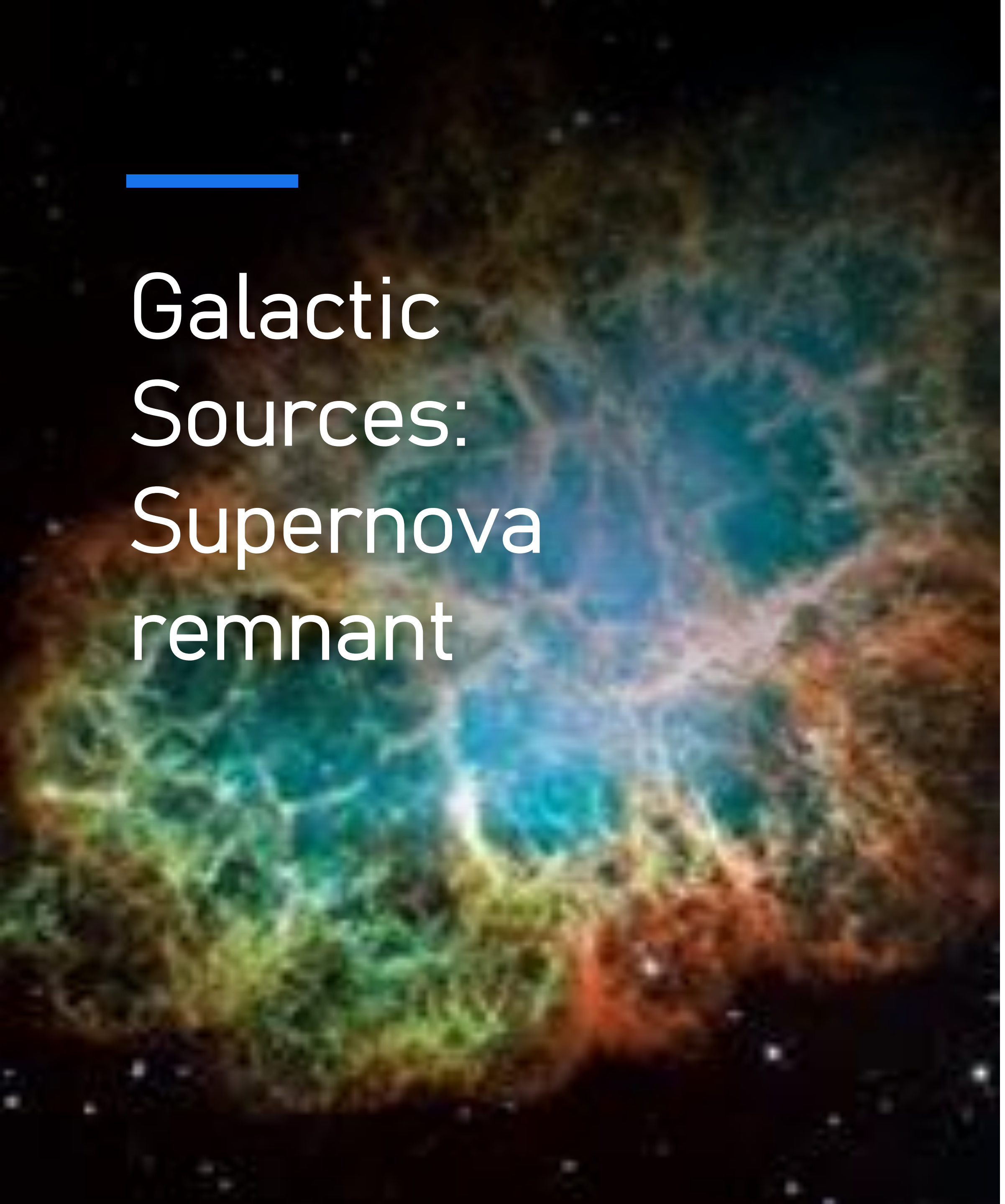
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Galactic Sources: Cygnus X-1



- **High-mass X-ray binary**
  - **Stellar-mass black hole (~20–30 M⊙)**
  - **Companion: massive O-type star**
- **Located in the Milky Way (~2 kpc away)**
- **Matter from the star: Is pulled toward the black hole**
- **Forms an accretion disk and produces strong X-ray emission**
- **Cygnus X-1 is a candidate for p–p neutrino production**

Galactic Sources: Supernova remnant



A **supernova remnant (SNR)** is an expanding shell of gas left behind after a massive star explodes.

The explosion releases:

- $\sim 10^{51}$ erg (or 10^{44} Joules) of energy
- A powerful shock wave
- Expanding plasma moving at thousands of km/s

The shock fronts that can accelerate protons to very high energies. When these protons interact with surrounding gas, they produce pions that decay into neutrinos.

Galactic Sources: Pulsar Wind

Pulsar wind nebula is:

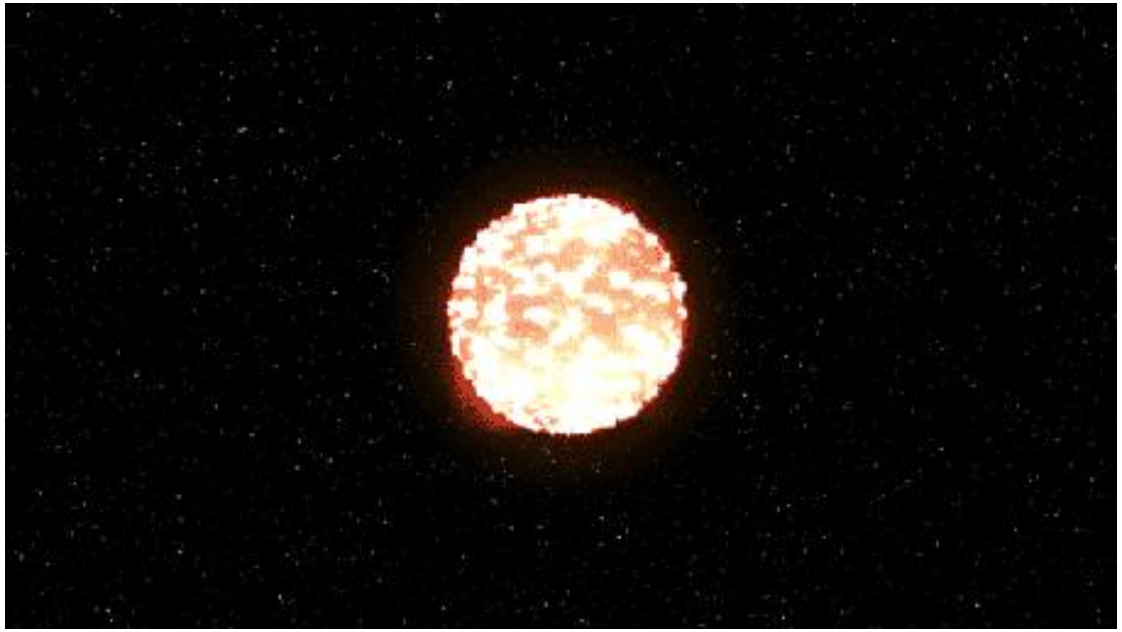
A rapidly rotating neutron star formed after a supernova explosion	Extremely strong magnetic field (~10^{12} G)	Emits beams of radiation	A highly relativistic outflow of particles (mainly electrons and positrons)

PWN are interesting because:

Particles are accelerated at the termination shock where the wind slows down.	The pulsar wind is mainly:	Electrons and positrons (leptonic)	$p + p \rightarrow \pi^{\pm} \rightarrow \mu^{\pm} \rightarrow \nu$

- Leptonic sources → gamma rays only
- Hadronic sources → gamma rays + neutrinos

Neutrinos help distinguish the two.

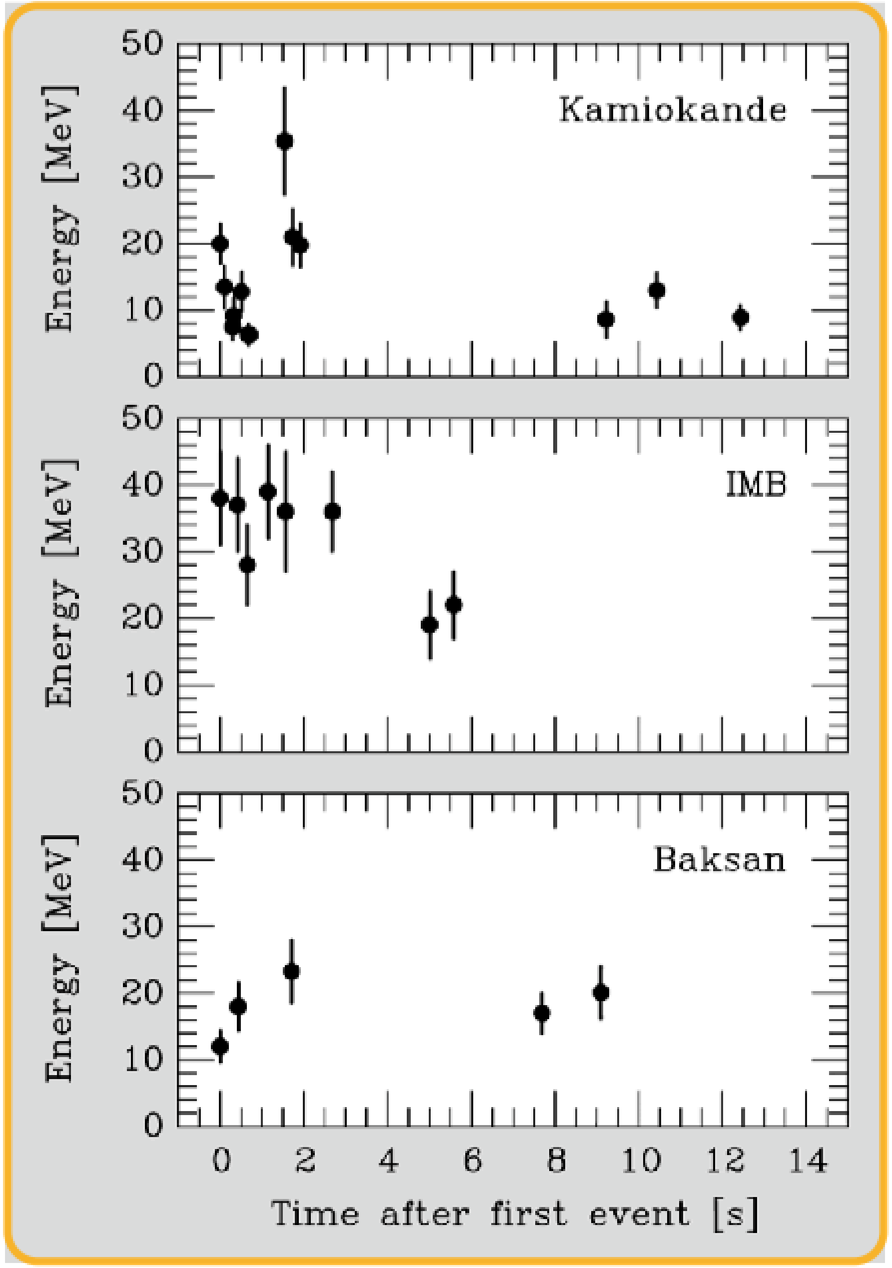


Transient Events: Core-collapse supernovae

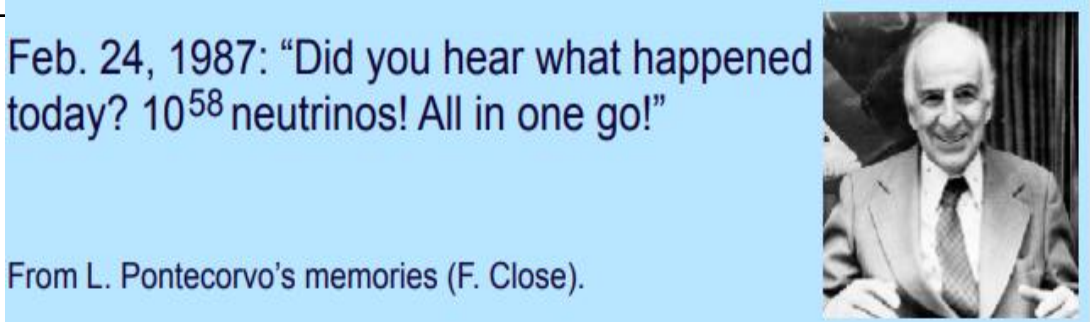
- A massive star ($\gtrsim$ 8 solar masses), collapses under gravity
- The collapse results in:
  - A neutron star or black hole
  - A powerful explosion
  - Enormous neutrino emission (~10^{53} erg released in neutrinos)
  - Neutronization: $p + e^{-} \rightarrow n + \nu_e$
  - First detection: SN 1987A

The brightest supernova since 1604 visible to the naked eye

Supernova 1987A



- Ten neutrino events were detected in a deep mine neutrino detection facility in Japan which coincided with the observation of Supernova 1987A.
- They were detected within a time interval of about 15 seconds.
- A similar facility, IMB in Ohio detected 8 neutrino events in 6 seconds.



Supernova 1987A: Lets talk in Numbers

- Distance: $d = 50$ ϴ̀иЙ̦
- Neutrino energy:

$$E_\nu \sim 10 - 30$$ ЍХŮ

- Total emitted neutrino energy:

$$E_\nu^{tot} \approx 3 \times 10^{53}$$ ХҞ¥

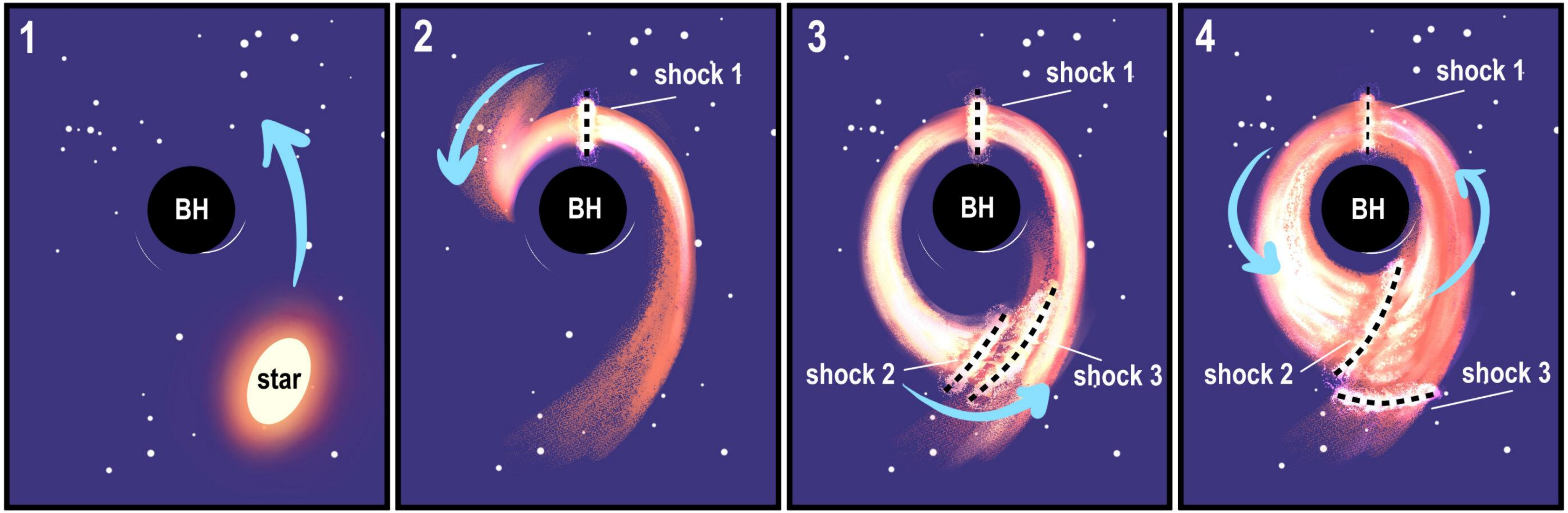
- 99% of supernova energy released as neutrinos.

Transient Events: Tidal Disruptive Events

https://science.nasa.gov/asset/hubble/black-hole-tidal-disruption-event/

This is a video animation of a tidal disruption event (TDE), an intense flash of radiation caused by a supermassive black hole eating a star.

Transient Events: Tidal Disruptive Events

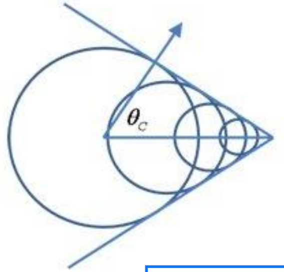


- After the star is disrupted, ~1/2 of the debris is ejected from the system,
- and some fraction remains bound to the BH and is accreted.
- The fallback of debris onto the BH produces a luminous electromagnetic flare that peaks in the UV/X-rays

How the Invisible Becomes Detectable

DETECTION PRINCIPLE OF HIGH-ENERGY NEUTRINOS

How Do We Detect High-Energy Neutrinos?



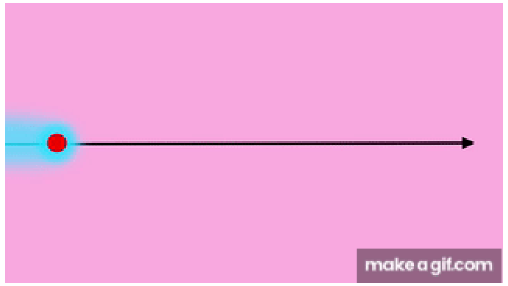
$$\theta_C = \cos^{-1}\left(\frac{1}{\beta n}\right)$$

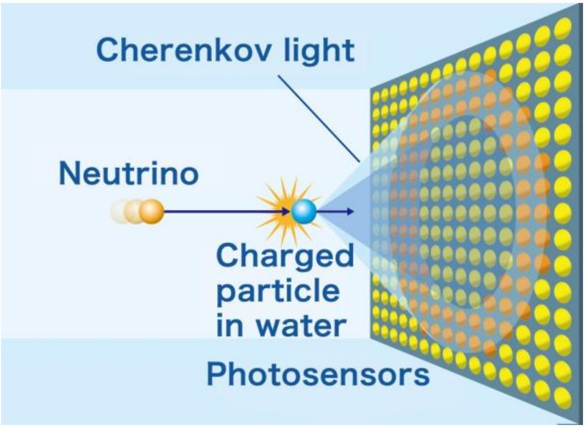
$$\cos\theta = \frac{c}{vn}$$

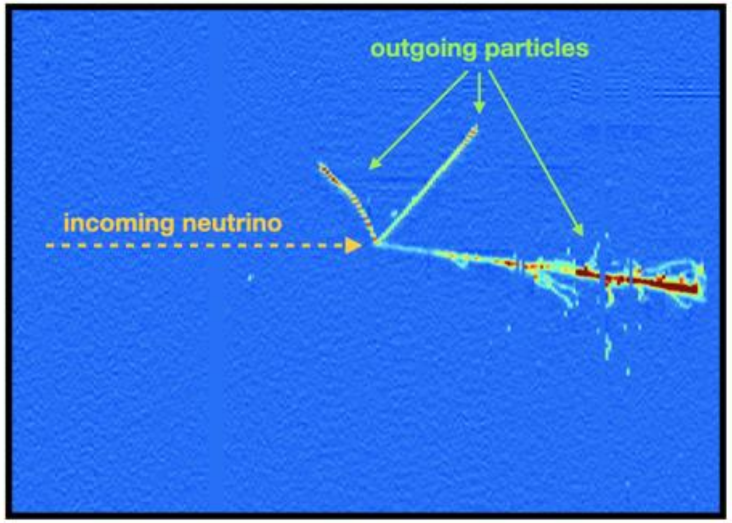
v = particle velocity
n = index of refraction of the medium

For seawater: $n \approx 1.33$
Cherenkov angle: $\theta_c \approx 42°$

- High-energy neutrino enters a large transparent medium (water or ice).
- Occasionally:
  - It interacts with electrons or nuclei of water.
  - Produces a charged lepton (μ, e, or τ).
  - Neutrinos must be detected via their products after an interaction.
  - The charged particle moves faster than light **in that medium** (not faster than ***c*** in vacuum).
  - It emits **Cherenkov radiation** — a cone of blue light.
  - The light is what we detect.







Neutrino Interaction Cross-section

The neutrino **turns into its charged lepton**.

- Charged current (CC):

$$\nu_\ell + N \rightarrow \ell + X$$

- Neutral current (NC):

$$\nu_\ell + N \rightarrow \nu_\ell + X$$

The neutrino does not change identity Only the **hadronic shower** is visible.

- Cross section: tells us how likely an interaction is to occur

$\sigma_{\nu N} \sim 10^{-38}$ ĽF^2(1 3XŮ)

$\sigma_{\nu N} \sim 10^{-34}$ ĽF^2(1 ÞXŮ)

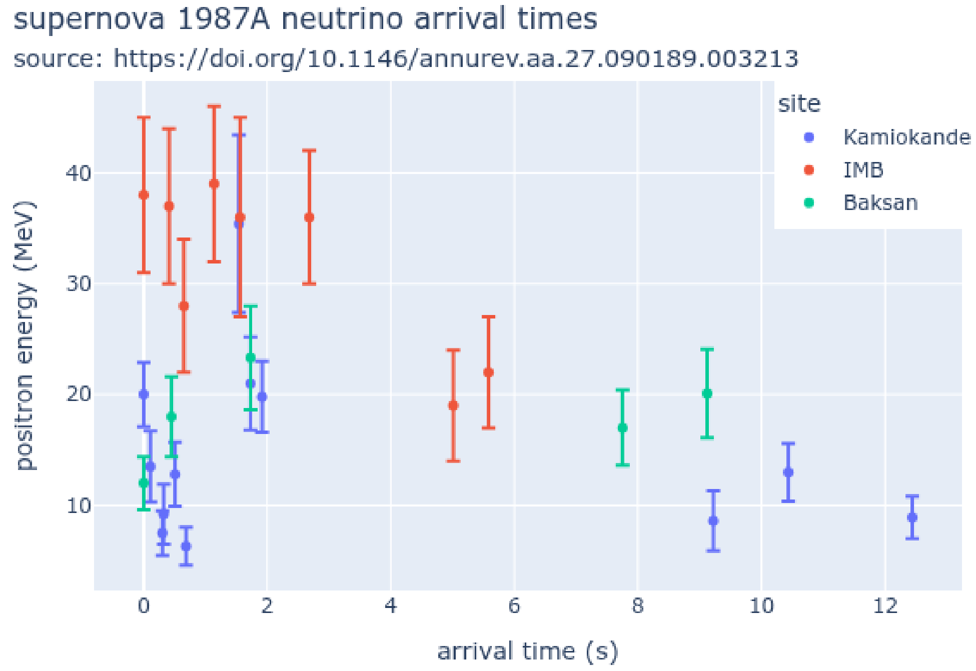
Neutrinos interact via the weak force.
The weak force has **two mediators**:

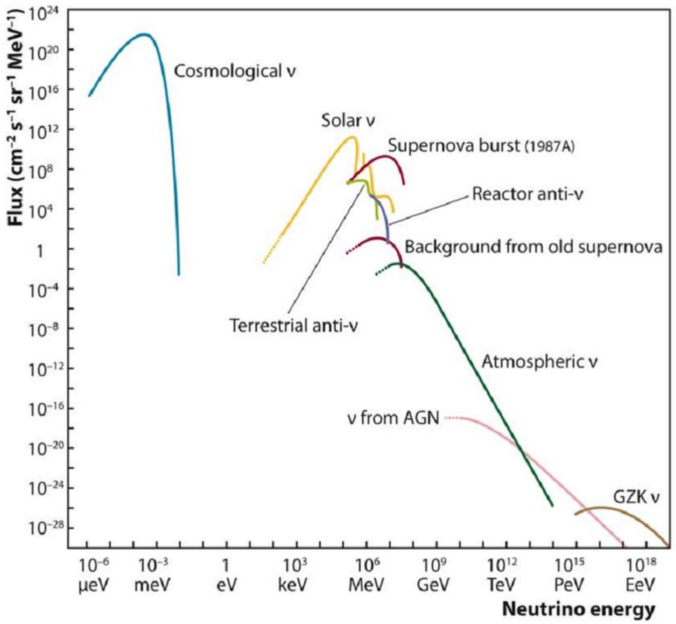
Interaction	Mediator
Charged current	$(W^{\pm})$ boson
Neutral current	(Z^0) boson

This means a neutrino can travel through **light-years of lead without interacting**.
That is why detectors like **km³ water or ice** are needed

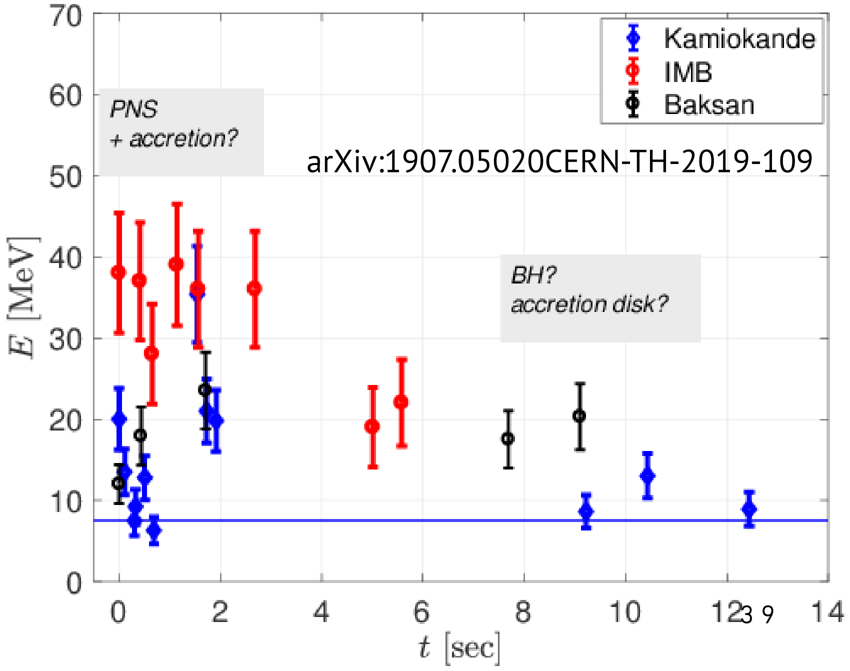
What we measure

- We measure:
  - Arrival time of photons
  - Light intensity
  - Spatial distribution
- From that, we reconstruct:
  - Direction of the neutrino
  - Energy
  - Interaction type





Joutsenvaara, J. (2016). *Deeper understanding at Lab 2: The new experimental hall at Callio Lab underground centre for science and R & D in the Pyhäsalmi Mine, Finland.* PhD dissertation.



Event Topologies

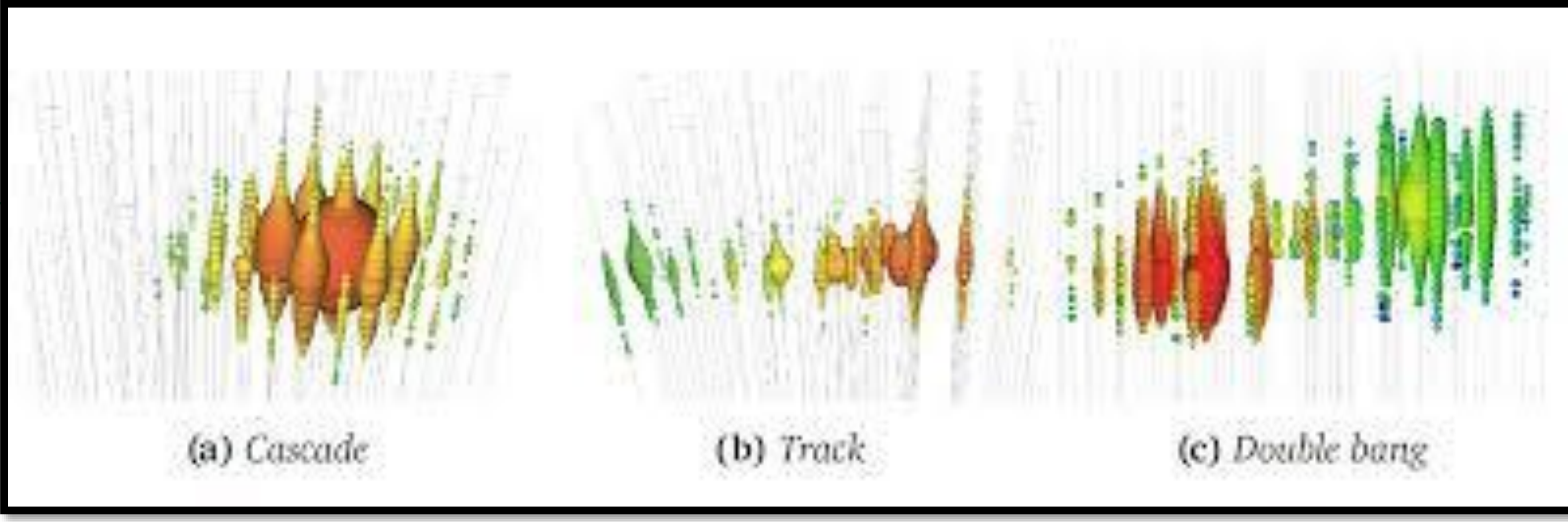
Event topology means **the shape of the light pattern in the detector**.
Different neutrino interactions create **different visible structures**.

Track events
Produced by:

$$\nu_\mu + N \rightarrow \mu$$

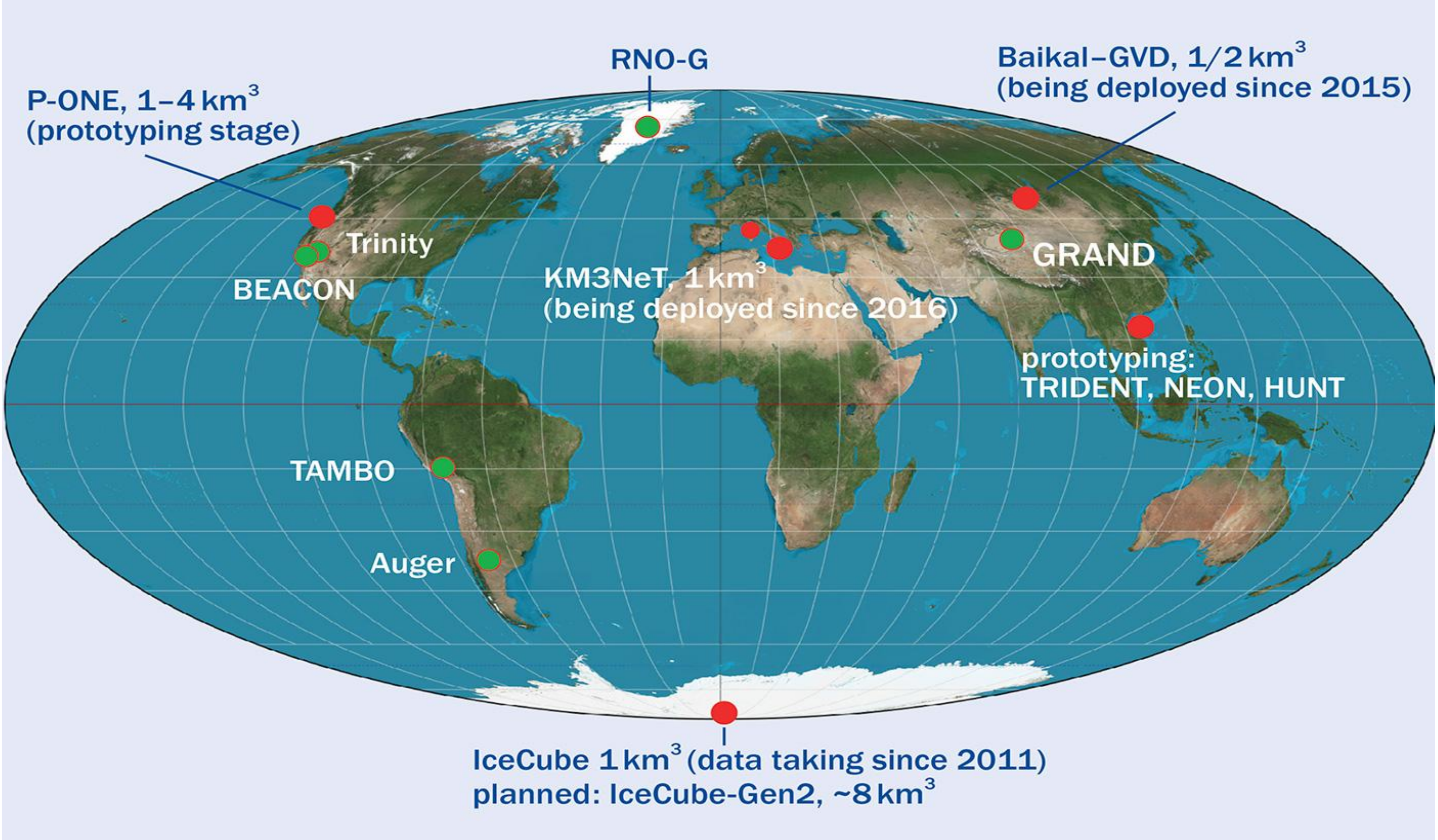
Muon travels **kilometers**.
Detector sees a **long line of light**.

Topology	Interaction
Track	υ_μ
Cascade (spherical light burst)	$\upsilon_e, \upsilon_\tau$
Double bang (Two cascades)	υ_τ



Major High-Energy Neutrino Observatories

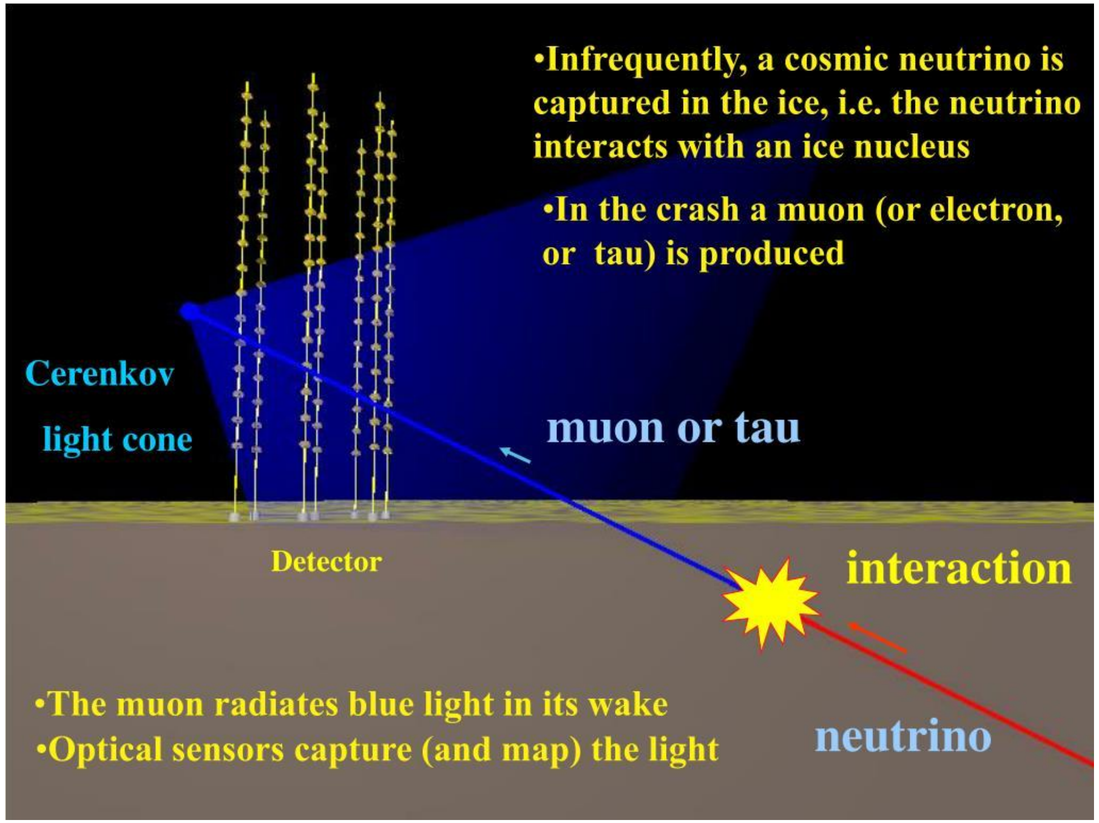
- High-Energy Neutrino Telescopes (TeV–PeV)
  - IceCube- South Pole
  - KM3NeT-Mediterranean Sea
    ANTARES Predecessor of KM3NeT (now decommissioned).
  - Baikal-GVD Lake Baikal, Russia
  - P-ONE Canada
- Long-Baseline & Oscillation Experiments (GeV scale)
  - DUNE (under construction)-South Dakota
  - T2K-Japan
  - NOvAFermilab - Minnesota
- Solar & Low-Energy Neutrinos (MeV scale)
  - Super-Kamiokande- Japan.
  - Sudbury Neutrino Observatory- Canada
  - Borexino-Italy
- Reactor Neutrino Experiments
  - KamLAND- Japan
  - Double Chooz- France
  - Daya Bay Reactor Neutrino Experiment – China
  - JUNO - China



Discovering the neutrino sky

KM3NeT — The Deep-Sea Giant

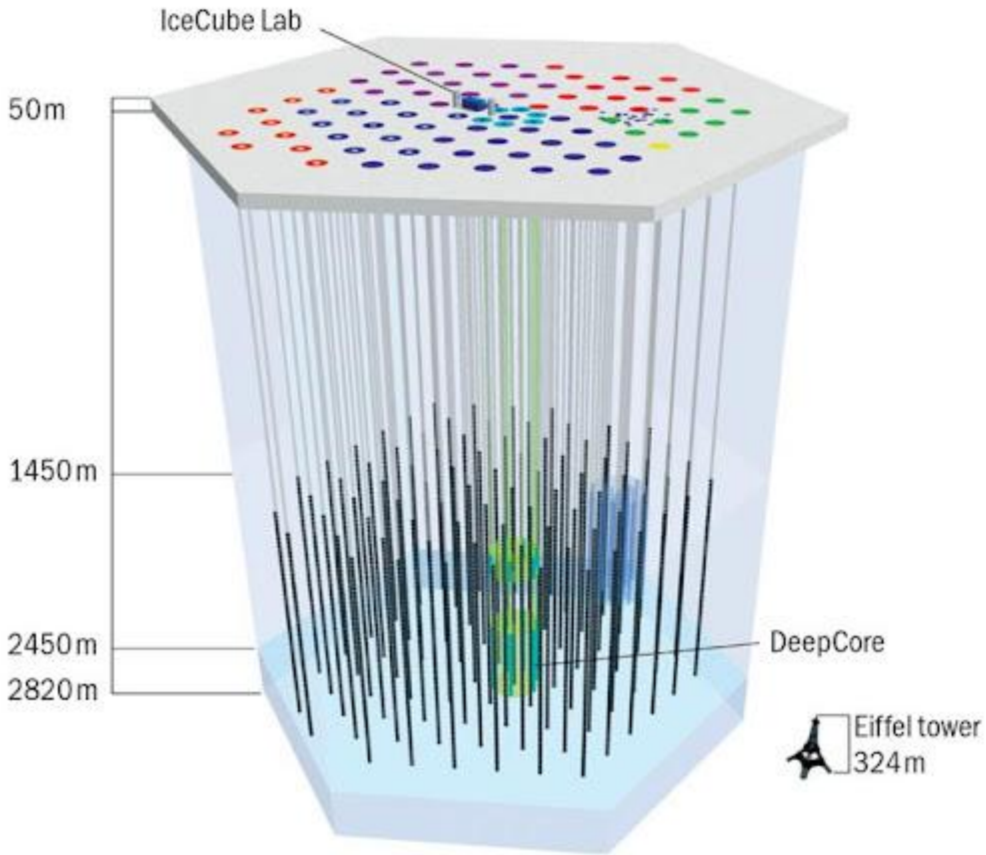
- KM3NeT: **Cubic Kilometer Neutrino Telescope**
- Located in the Mediterranean Sea
- Two main sites:
  - **off the southern tip of Sicily, Italy-** ARCA (Astroparticle Research with Cosmics in the Abyss)
  - **off the coast of Toulon, France-** ORCA (Oscillation Research with Cosmics in the Abyss)
- Uses seawater as a detection medium
- Detects Cherenkov light from charged particles
- 3D array of optical modules
- Kilometer-scale detector



Cities and Sites of KM3NeT

IceCube: The Antarctic Ice Giant

- Located at the **South Pole, Antarctica**
- Embedded deep in the Antarctic ice sheet
- Uses **clear glacial ice** as the detection medium
- Detects **Cherenkov light** produced by charged particles from neutrino interactions
- 3D array of **Digital Optical Modules (DOMs)** deployed in deep ice
- Instrumented volume of about **1 cubic kilometer**



A S

Flux of astrophysical neutrinos

how many particles pass through a surface per unit time

- IceCube flux:

$$E^2\Phi_\nu \approx 6 \times 10^{-8}\ \text{3XŮÅĂF}^{-2}\text{o}^{-1}\text{oK}^{-1}$$

- Energy range:

$$10\ \text{TXŮ} - 10\ \text{ÞXŮ}$$

The E^2 factor is used to make **power-law spectra easier to visualize.**

"Fun Fact"

$$\Phi_{\text{OBVƂK}} \approx 6 \times 10^{10}\ \text{ЍF}^{-2}\text{o}^{-1}$$

So **60 billion neutrinos pass through your fingernail every second.**, But they almost never interact.

Cosmic particle spectra follow power laws

$$\frac{dN}{dE} \propto E^{-2}$$

Therefore:

•many low-energy particles

•few high-energy particles

KM3NeT and IceCube Differences

Parameter	Value
Depth	2500–3500 m
DOM PMTs	31 per module
ARCA volume	~1 km^3
Angular resolution	~0.1° (tracks)
Energy range	100 GeV – PeV

Parameter	Value
Depth	1450–2450 m
DOMs	5160
Strings	86
Volume	~1 km^3

Why in the Deep Sea?

- **Shielded from atmospheric muons**
- **Huge detection volume**
- **Dark environment**
- **Water advantages:**
  - **Better angular resolution due to light scattering properties**
  - **Nature provides this for free.**

Why It Matters: opening a completely new window on the Universe

- Neutrino astronomy helps answer:
  - Where are cosmic rays born?
  - How do black holes accelerate matter?
  - What is the neutrino mass ordering?
  - Is there new physics at extreme energies?

The Human & Technological Side

- Deep-Sea Engineering
  - Deployment at >3 km depth
  - High-pressure optical modules & underwater robotics
- International Collaboration
  - Global scientific teams
  - Shared infrastructure and coordinated observations
- Data Science Challenges
  - Petabytes of data per year
  - Machine learning for reconstruction & background rejection

Future Outlook

Full KM3NeT Completion
- Completion of ARCA and ORCA building blocks
- Increased instrumented volume
- Improved angular resolution and sensitivity
- Stronger constraints on Galactic sources

Next-Generation Detectors
- IceCube-Gen2
- Radio detection arrays (EeV scale)
- Hybrid optical + radio techniques
- Larger instrumented volumes

Joint Analyses with IceCube
- Full-sky coverage (North + South)
- Increased statistics
- Faster transient follow-ups
- Stronger multi-messenger coordination

New Physics Beyond the Standard Model
- Non-standard neutrino interactions
- Sterile neutrinos
- Dark matter signatures

The next decade could transform neutrino astronomy from a discovery phase to a precision science.

“The Universe speaks in neutrinos.
We finally learned how to listen.”

THANK YOU