# *Why does Fundamental Physics need Mega Science Projects*

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Software Tools and Techniques used in EHEP and its Applications.

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# Why does Fundamental Physics need Mega Science Projects?

- A few generalities. What are Mega Science projects?
- Which Mega Science Projects? In which way are they'Mega' projects?
- Which scientific quests drive the projects and why they need to be 'mega'? (Mainly for particle physics.)
- Relevance of the Mega Projects to India and Indian Science.

In general there are two kinds of research:

Basic Research: curiosity driven.

In fact historically development of Science and Technology in our Society has been driven by that. Both experimental and theoretical.

Historically individuals and small groups were involved. Of late, the nature of some of the basic scientific queries have shifted the experiments out of the reach of single group, single University/laboratory or even single country.

Has led to global, large scale projects which require collaborative participation of countries not just financially but technologically! These are 'mega' projects driven by Basic Science!

Applied Research: Applying and broadening available scientific knowledge to specific Technology aims.

Advantages of expenditures for science, society and the state obvious and not questioned.

Examples in the Indian context of such projects are various 'mega' projects by ISRO, DAE and DRDO

ISRO launched satellites, first may be for defence purposes, then used for societal/educational applications.

Now those capabilities are being used for basic science research: Astrosat, Chadrayan and Mangalyan.

DAE has made strides in Nuclear weapons, Nuclear power : eg fast breeder reactor, Nuclear Medicine....

India at present in engaged (or is preparing to engage) in many 'Mega' Basic Science projects:

Subject of particle physics:

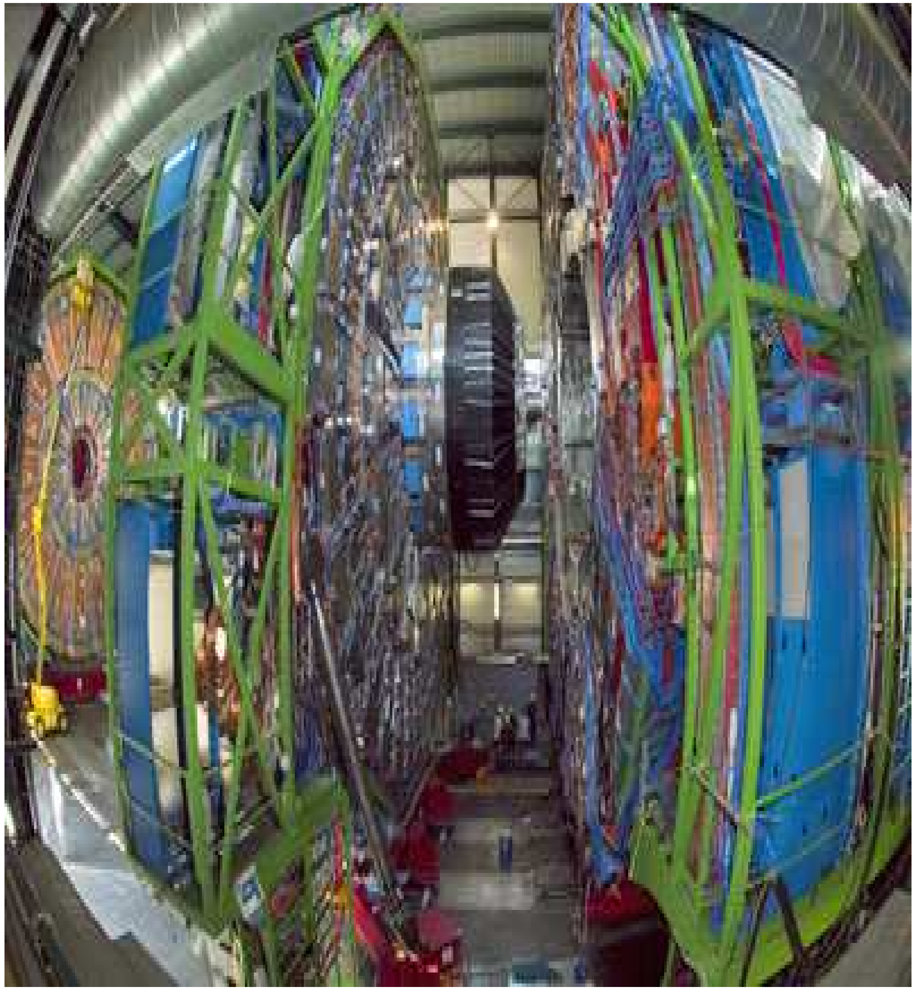
The LHC accelerator, experiments at the Large Hadron Collider(LHC) and in general CERN:

Explorations at the 'Heart of Matter'

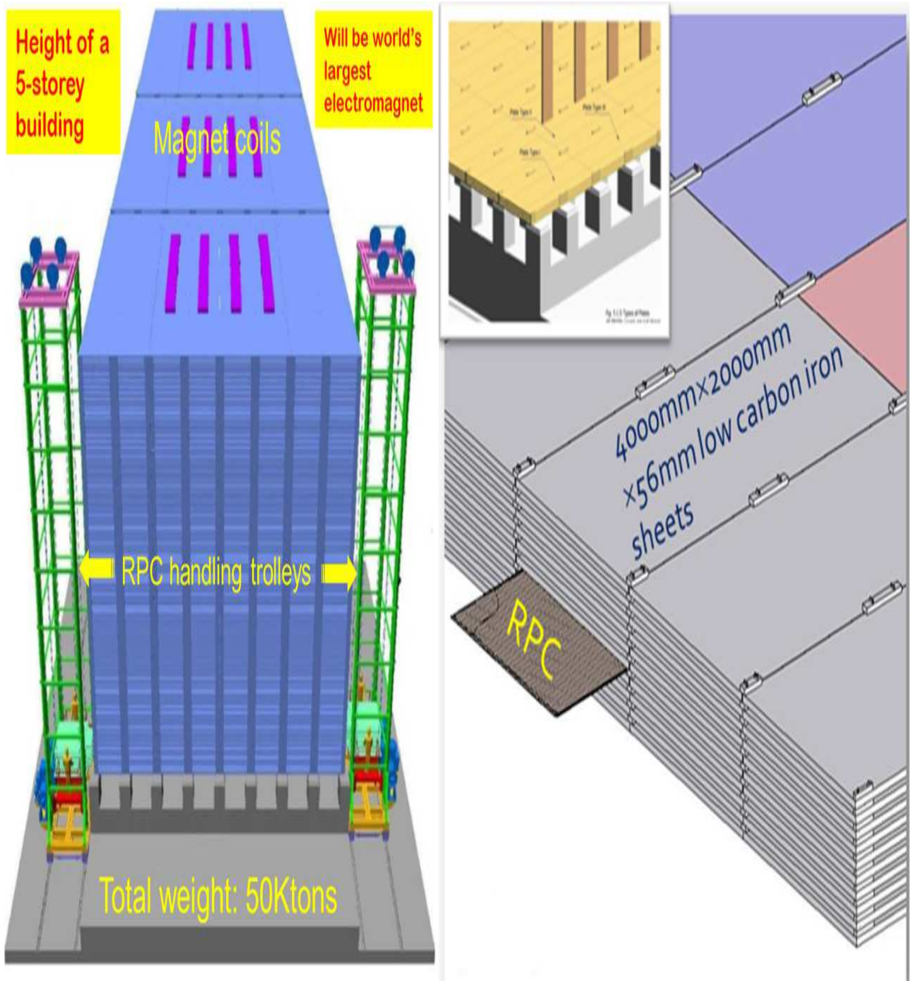
Indian Neutrino Observatory: INO Home based, indigenous

Explorations in neutrino physics and hence existence of possible new interactions and new particles as well as getting a better understanding of objects astrophysical!

LHC (27km long)



CMS detector





Planned INO detector

Planned INO laboratory

Thanks: B. Satyanarayana.

In Astrophysics and Astronomy:

The Laser Interferometry Gravitational Observatory (LIGO) -India

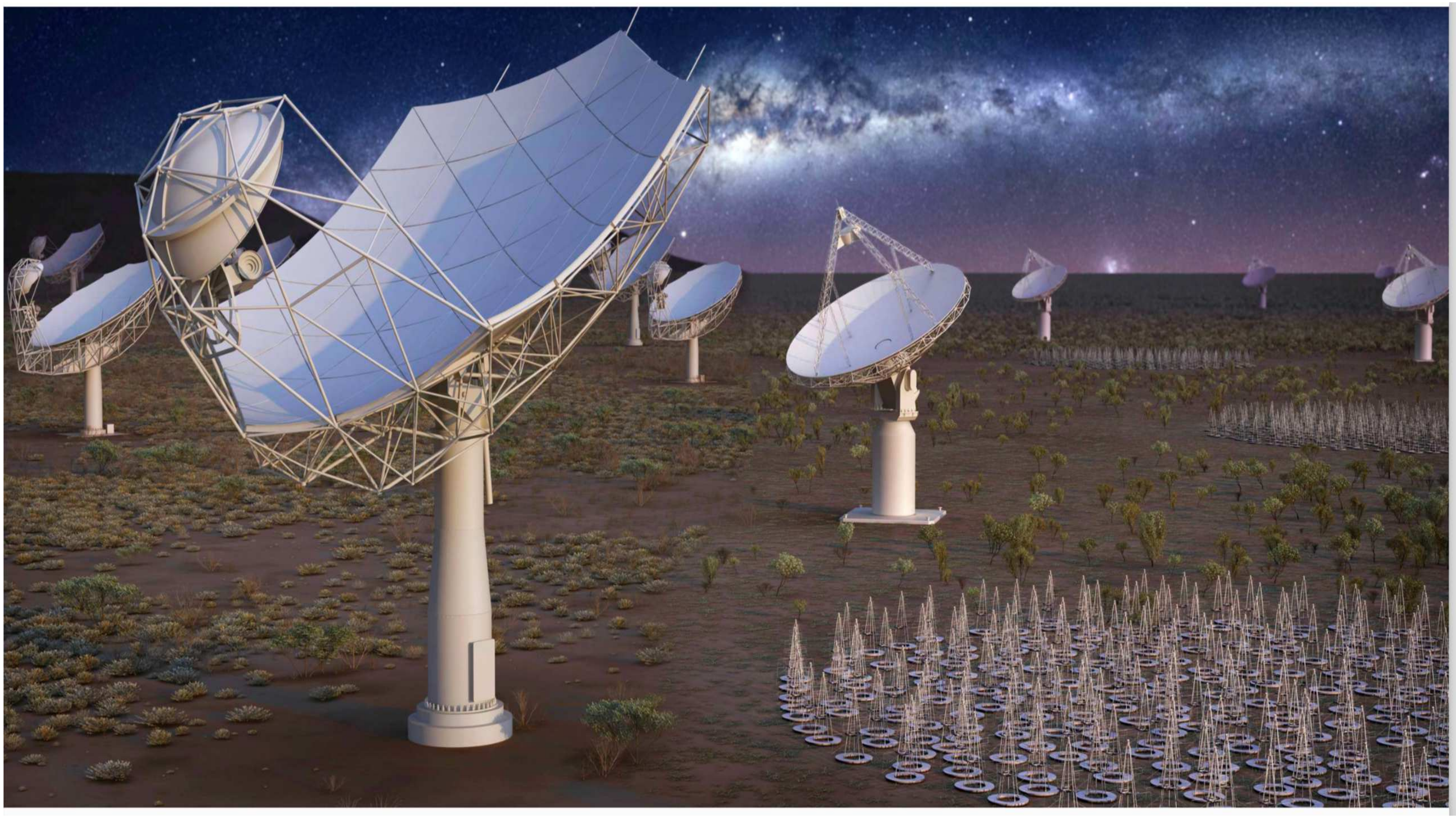
Gravitational Wave observations and study the physics of high gravitational fields including 'black holes'

Square Kilometre Array: SKA (Radio Telescope).

Nest step in Radio Astronomy beyond the 'Giant Meter Wave Radio Telescope' in India which is near Pune!


LIGO arms: 4 km long, need to measure a displacement of $\sim 10^{-18}$ m. Need cutting edge laser technology.

## Thanks : Tarun Souradeep (IISER-Pune)



Thanks: Yashwant Gupta (SKA project leader, NCRA)

# Background about the SKA

- The SKA is one of the next gen global mega-projects – future of radio astronomy
- Full, final version of SKA :
  - 1 square km (1,000,000 sq m) collecting area (~ 30 x GMRT !), with ~ 3000 small sized antennas, with larger field of view
  - High resolution, with antennas spread out over distances up to ~ 1000 km, but connected in real-time (by optical fibre)
  - Wide frequency range: 70 MHz - 10 GHz
- Location : Australia & S. Africa (radio quiet regions, away from human habitat)
- Cutting edge science in all front line areas of astrophysics (including uGMRT)
- Several next generation technologies involved : from electronics to optical fibre data transport, to sophisticated signal processing, high performance computing, big data, AI & ML for data analysis and interpretation etc.

Thanks: Yashwant Gupta (NCRA)

All the projects address fundamental questions about secrets of nature!

All need cutting edge technology and have led to new developments in the same!

All are huge projects.

All need global participation. No one group, no one Institute or one country has the intellectual and monetary resources to do it alone.

In each case, I will tell you a little more about the history of India's participation in the area and the science these are doing

Discuss in detail about the scientific quests that drive these big projects. 'Why does fundamental physics need 'mega' projects?'

## What are the bricks and mortar of edifice of life?

- The question has remained the same through the ages.

- Answers have changed. Our perception of what the parts are has changed as our understanding of how the parts are put together has grown!

**Efforts to answer this question $\Rightarrow$ the development of Science.**

'Elements' $\rightarrow$ Chemical elements $\rightarrow$ molecules $\rightarrow$ atoms $\rightarrow$ nuclei $\rightarrow$ neutrons/prrotons $\rightarrow$ quarks, leptons,..

$$\Downarrow$$

Elementary Particle Physics

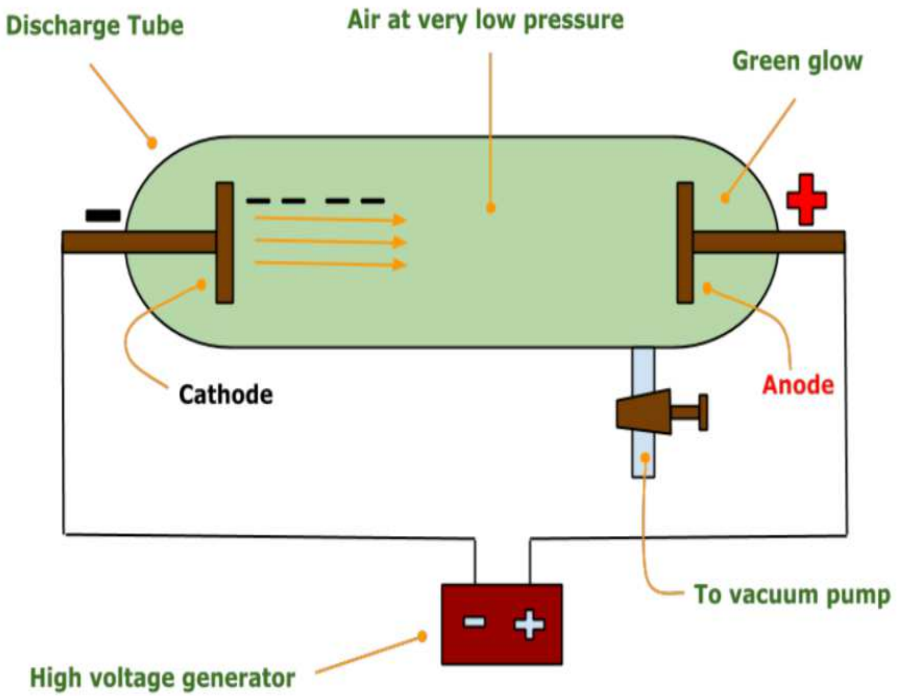
The accepted world view:

Fundamental Particles are 1) the matter fermions : quarks and leptons, 2) the force carriers called bosons: the photon, the W/Z-boson, the gluon

*and*

**Final piece of the puzzle Higgs Boson**.

*In principle* laws of physics which govern the behaviour of these elemental blocks, allows us to predict behaviour of *all matter*.

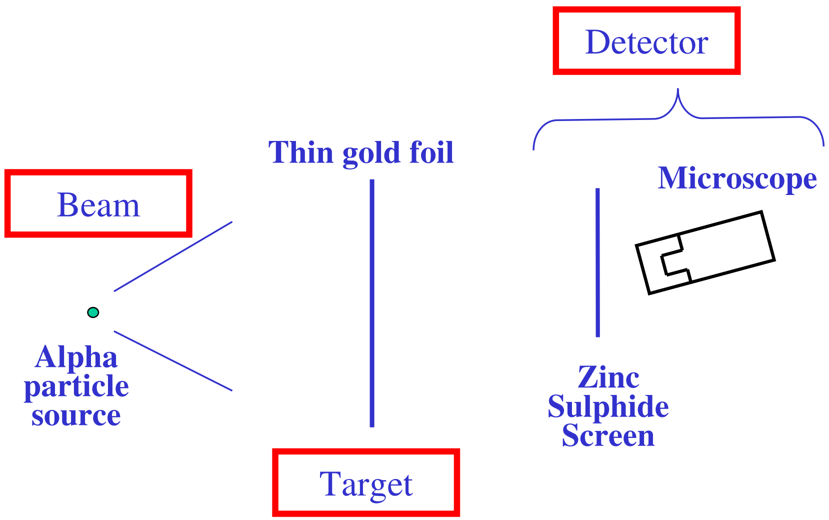



Production of cathode rays

J. J. Thomson

Electron was born in a small, tabletop experiment with a high vacuum cathode ray tube in 1897!

## The Rutherford scattering experiment: shaped the physics of the Century!




# of $\alpha$ particles scattered from the gold foil at different angles were counted.

Most $\alpha$ particles went undeflected.

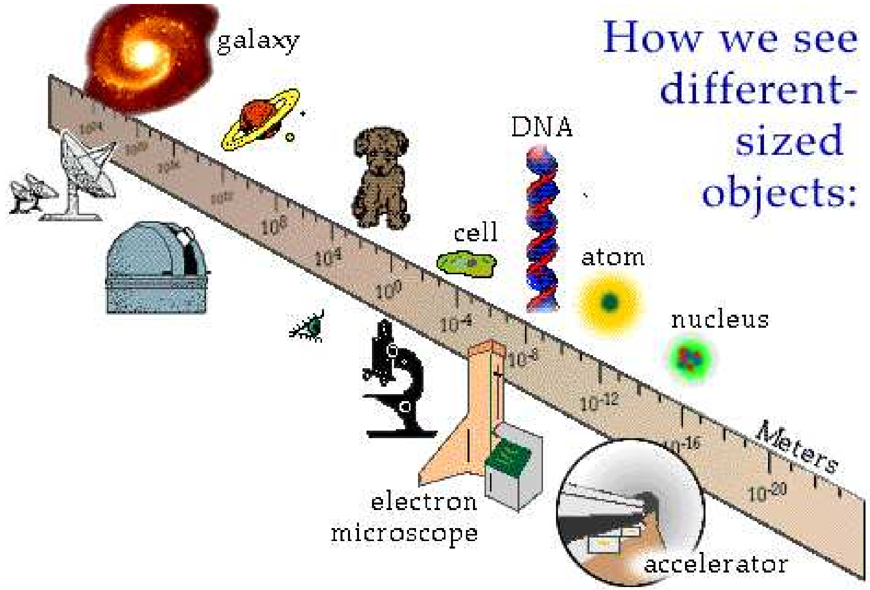
BUT SOME REBOUNDED

Using the knowledge of Classical Mechanics and Electrodynamics Rutherford concluded from this: atom has a point like nucleus.

High energy particle beams $\simeq$ a meter stick
Measure the size by scattering the beam off the object.

Increase resolving power by lowering wavelengths and hence increasing energies.

How do we have high energies?




Higher and higher energies to probe smaller and smaller distances. 'elementary particle physics' is $\sim$ 'high energy physics'. The tools we use to measure sizes of objects changes with the size that they have!

The relationship between our increasing knowledge of how constituents are put together at a given level and finding structures at a shorter distance scale is very interesting.

Some of the constituents came unannounced to the party of course! In turn the experimental results have propelled developments of new theoretical ideas.

We theorists have been able to predict new particles sometimes inclusive of their masses (and/or new interactions), based on the knowledge available on the interactions which hold the constituents together! Experiments have confirmed or disproved this.

Note that the nucleon structure of a nucleus was arrived at by observation of patterns in properties of nuclei.

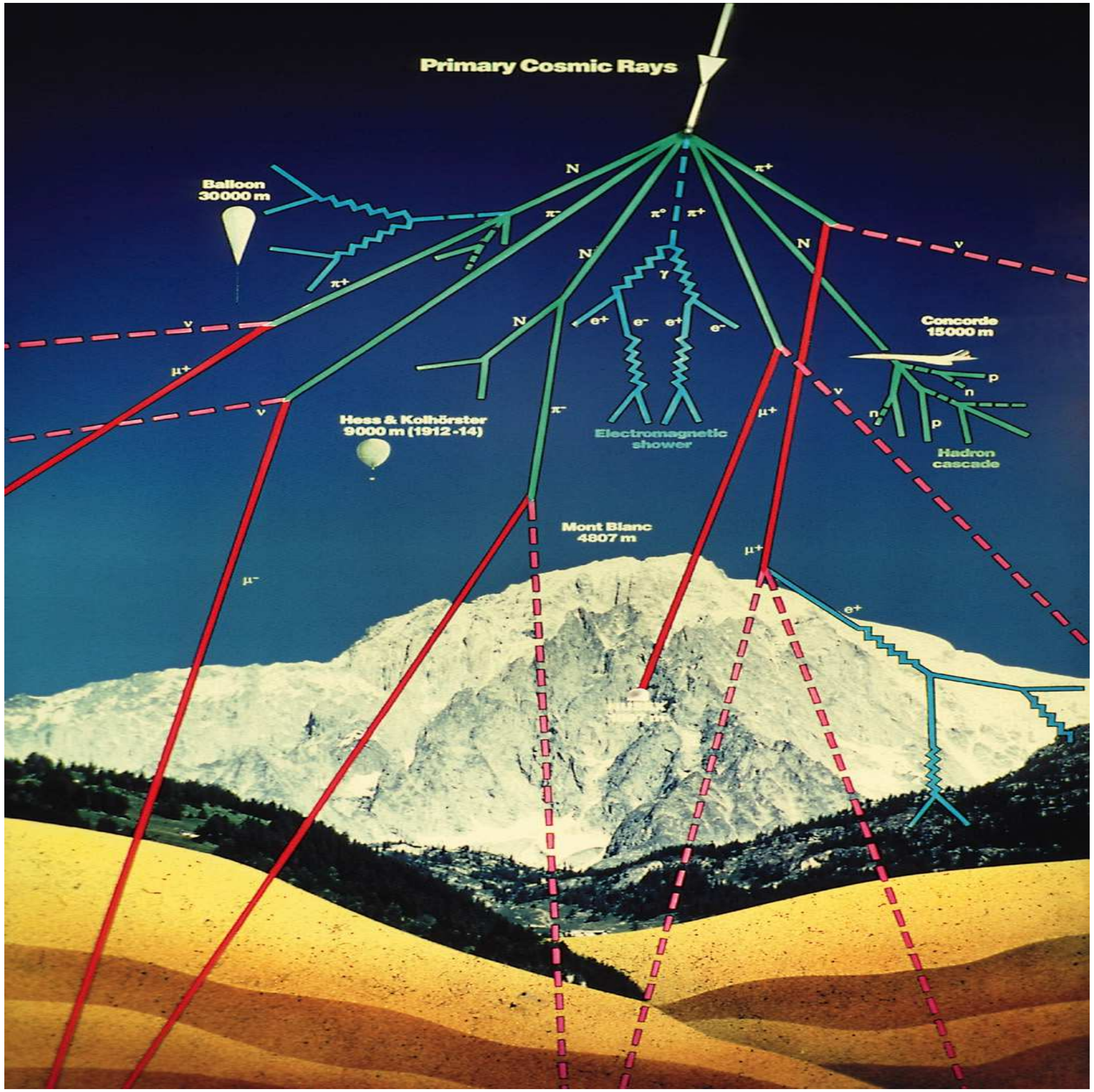
The nucleons *neutrons and protons* were observed outside the nucleus.

Needed more energetic particles to unravel the secrets. Nuclear reactions.

Rutherford: It has long been my ambition to have available a copious supply of atoms and electrons which have energies transcending those of the $\alpha$ , $\beta$ particles from the radioactive bodies.

1)'Natural' Accelerators: Cosmic Rays.

2)Man made accelerators.




A Search for Nuclear Disintegrations Produced by... http

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## A Search for Nuclear Disintegrations Produced by Slow Negative Heavy Mesons

M. W. Friedlander, G. G. Harris and M. G. K. Menon

**Abstract**

This paper describes the preliminary results of a search for evidence of the nuclear interactions of negative heavy mesons. A qualitative analysis is given of the possible characteristics of their interactions and the appearance these might be expected to have in photographic emulsions. 37 ml. of emulsion, in which are recorded 10 000 stars and 1200 slow $\pi $-mesons, have been completely examined. In the conditions of exposure, such a volume should contain six examples, with good geometry, of the decay of heavy mesons. Mass measurements have been carried out, by the range/scattering method, on 417 tracks of $\sigma $-mesons. In addition, 1800 $\sigma $-mesons, observed in 42 ml. of emulsion, have been examined. No disintegrations which can be attributed to heavy mesons have been found. The results suggest that some of the negative heavy mesons, on being brought to rest in photographic emulsions, behave in a manner qualitatively different from that of negative $\pi $-particles. Possible explanations for this result are suggested.

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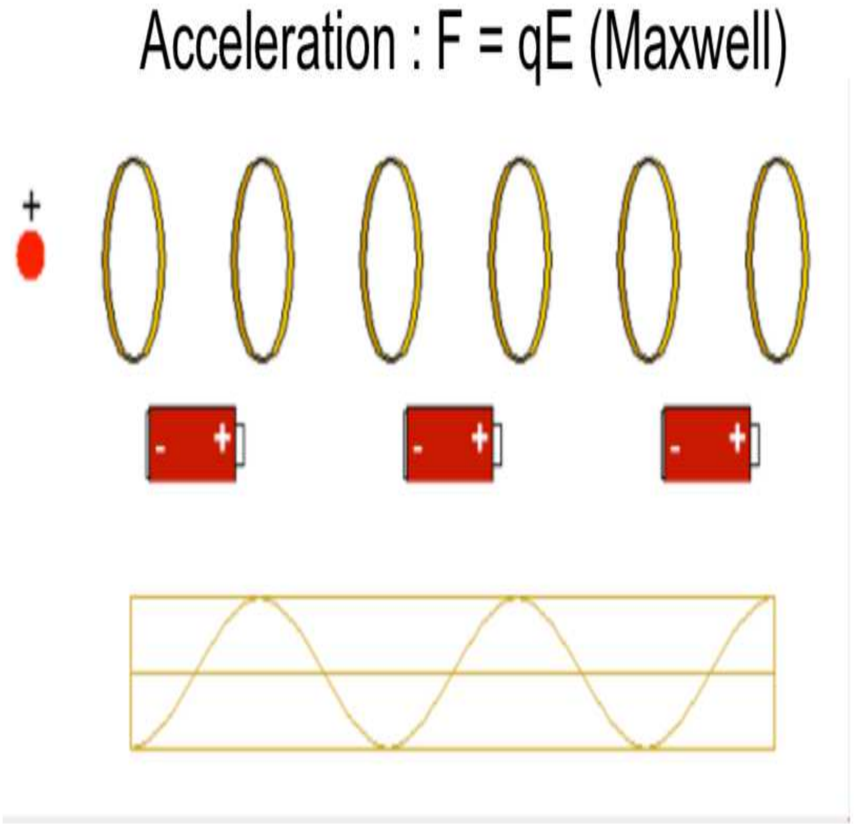
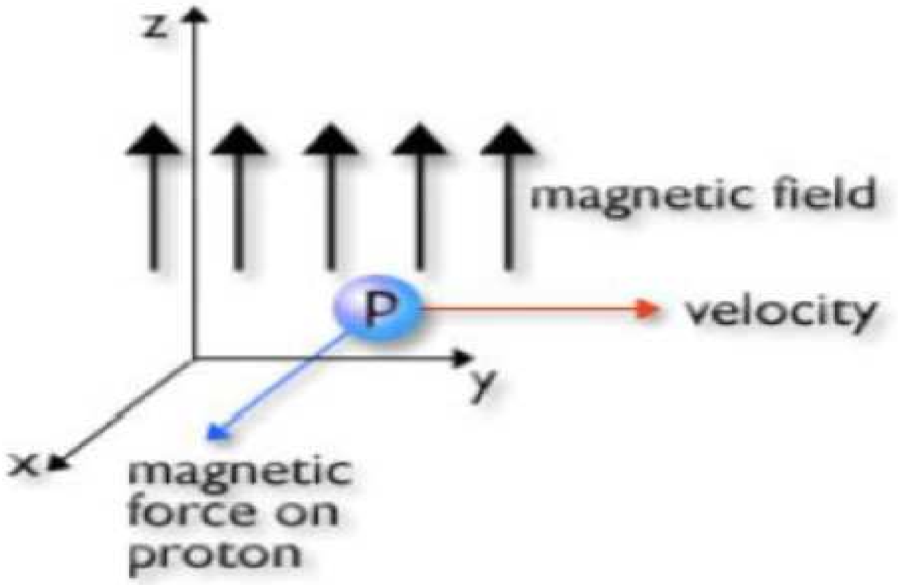
Reference: Proc. R. Soc. Lond. A January 1954, vol. 221 no. 1146 394-405.

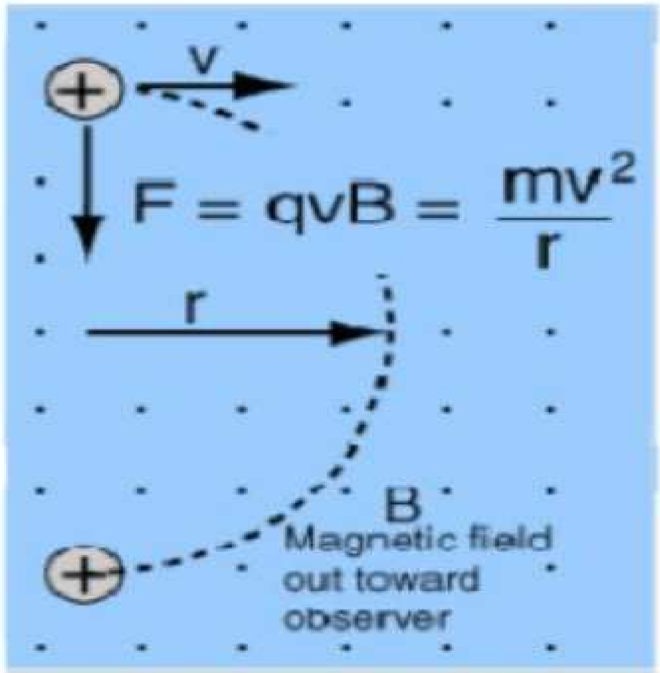




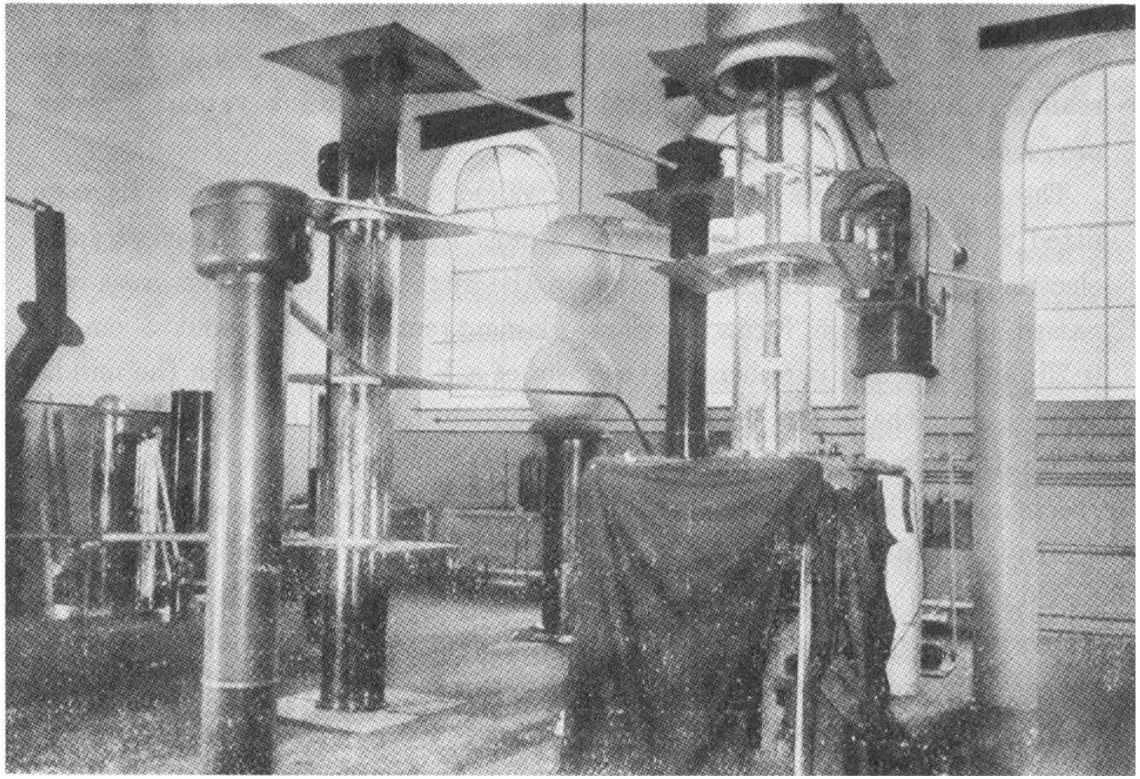
Linacs followed by accleration in Radio Frequency (RF) Cavities.

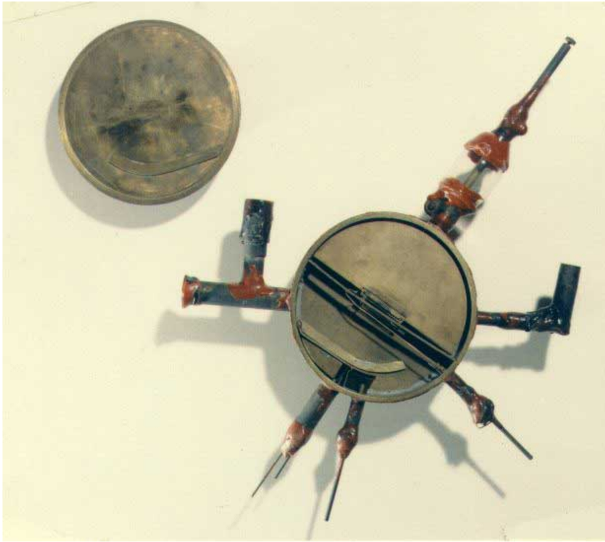
## Use magnetic fields!




Magnetic fields are used to direct/keep the particles in orbits, focus the beams etc.





Cockroft-Walton Accelerator

Fitted inside a room (1931)

First Cyclotron(4.5 inches)

Lawrence-Livingston (1933)

11 inch: accn. to 80 KeV protons.

(from aip/history web site)

Tevatron Van de Graf generator

LHC Tunnel : 27 km

Higher energy Not just to look deeper inside the matter.

As time went along the colliders and fixed target machine results did not find substructure at smaller distances, but higher energies found the newer, heavier particles and newer interactions predicted by the theories, constructed based on the results of the earlier machines.

Higher energies and precision measurements required bigger and more complex detectors!

How do we know what energies we need to go to and what precisions we need to aim for?

Science and Technology together join hands in deciding how we go on!

For Rutherford the energy required was decided by Gamow's theory of $\alpha$ decay which predicted the height of Coulomb Barrier! This was a few Million Electron Volts : MeV.

Many decades later Glashow, Salam and Weinberg's theory set the bar for HEP machines to produce the top $t$ quark, $W, Z$ bosons and the Higgs $h$. This was more than a million times larger.

The hand in hand development of theory and experiments to measure/detect and technology to build!

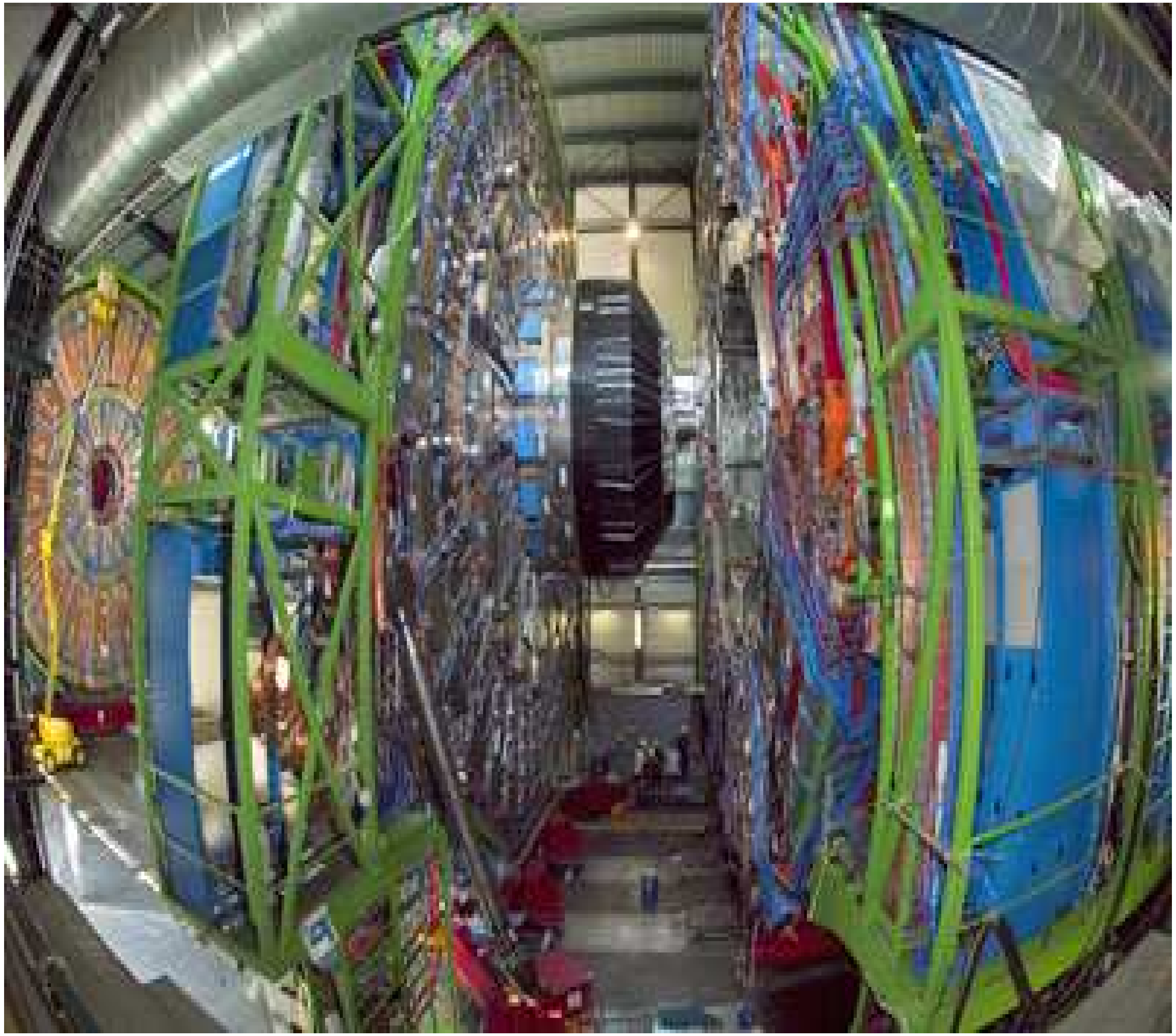
Energies of particles measured by radiation loss: calorimeters

But particles like $\mu$ do not lose energy easily. Energy measured using bending of tracks. But high energy means very little bending.

Recall

$$\frac{v}{r} \propto B$$

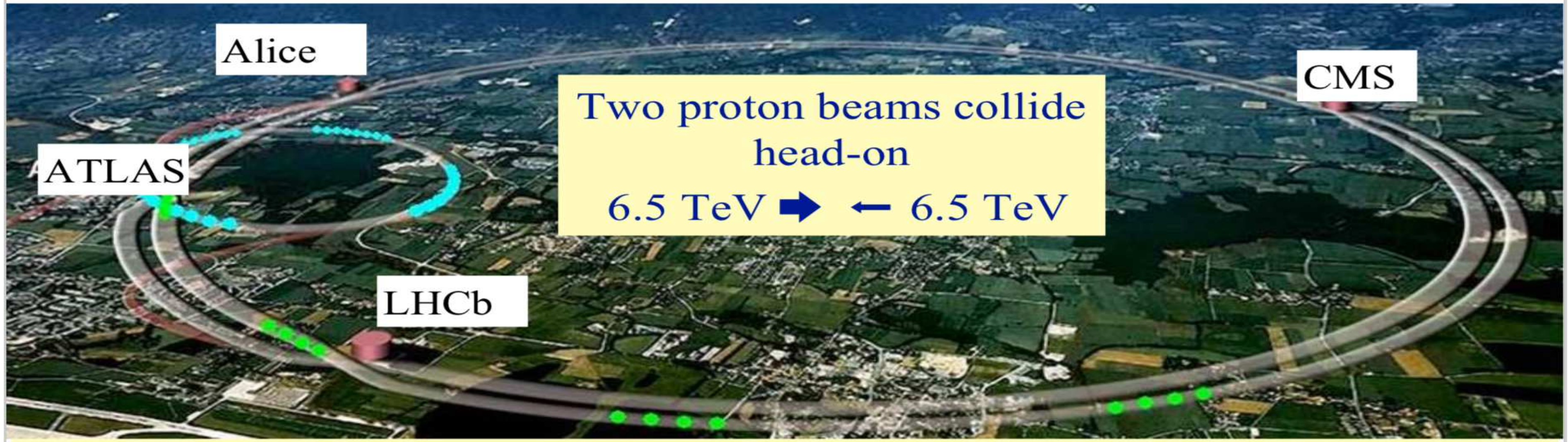
$B$ fixed by technology and cost! Need larger $r$ for faster $\mu$



Shown here is the CMS detector: Indian physicists built parts of it.

Also participation in ALICE to study Heavy Ion Physics.

Indian theorists work on issues related to LHC physics!




*Squeezes energy into a space about a million million times smaller than a mosquito, and temperature billion times higher than that at sun.*

The energy density and temperature that are produced in the collisions at the LHC are similar to those that existed immediatly after the Big Bang.

It found the Higgs in 2012 and the physics Nobel prize in 2013 was awarded for the discovery. Would have been impossible without the LHC and the experiments CMS/ATLAS.

LHC accelerator and LHC experiments were the end station of a journey which began in a small room in 1897 in a small table top experiment.

This experiment allowed us to establish the correctness of the Standard Model(SM) of Particle Physics.

What next?

Is it the end of the journey?

Far from it!

There exist many observational reasons, some in the world of particles and some cosmological which indicate that physics particles and interactions beyond the SM (BSM) exists. Where does cosmology come in to picture?

In principle the basic 'laws' of Physics can 'explain' behaviour of matter of all shapes and sizes.

Do these laws of 'elementary' particles governing the beaviour of objects at the heart of 'nuclei' of 'atoms' have anything to say for 'Cosmic' observations?

*Answer is YES: Not just in 'principle' but in 'practice'.*

Cosmic distances: millions of Parsecs. (1 Parsec: $\sim$ 200 times the earth-sun distance.)

Size of a nucleus: one tenth of a billion billion centimeter
Electron size *less than* billion billion billionth of a meter stick.

Knowledge of the laws of Physics at this distance scale is *necessary* to explain,

1. Why do we exist? Less dramatically why does our Universe contain much more matter than antimatter?

2. Why does most of the matter in the Universe not shine?

3. Why is the Universe accelerating?

Interplay of physics at the 'micro' and 'macro' scale drives the understanding of physics at 'heart of matter' further.

• We have direct evidence for the nonzero $\nu$ masses (Physics Nobel prize 2015) (INO)

• We have found a light Higgs boson at the LHC! (Physics Nobel Prize 2013)(LHC, ILC...)

• We feel the force of gravity but do NOT have a QUANTUM description! (LIGO-India, SKA..)

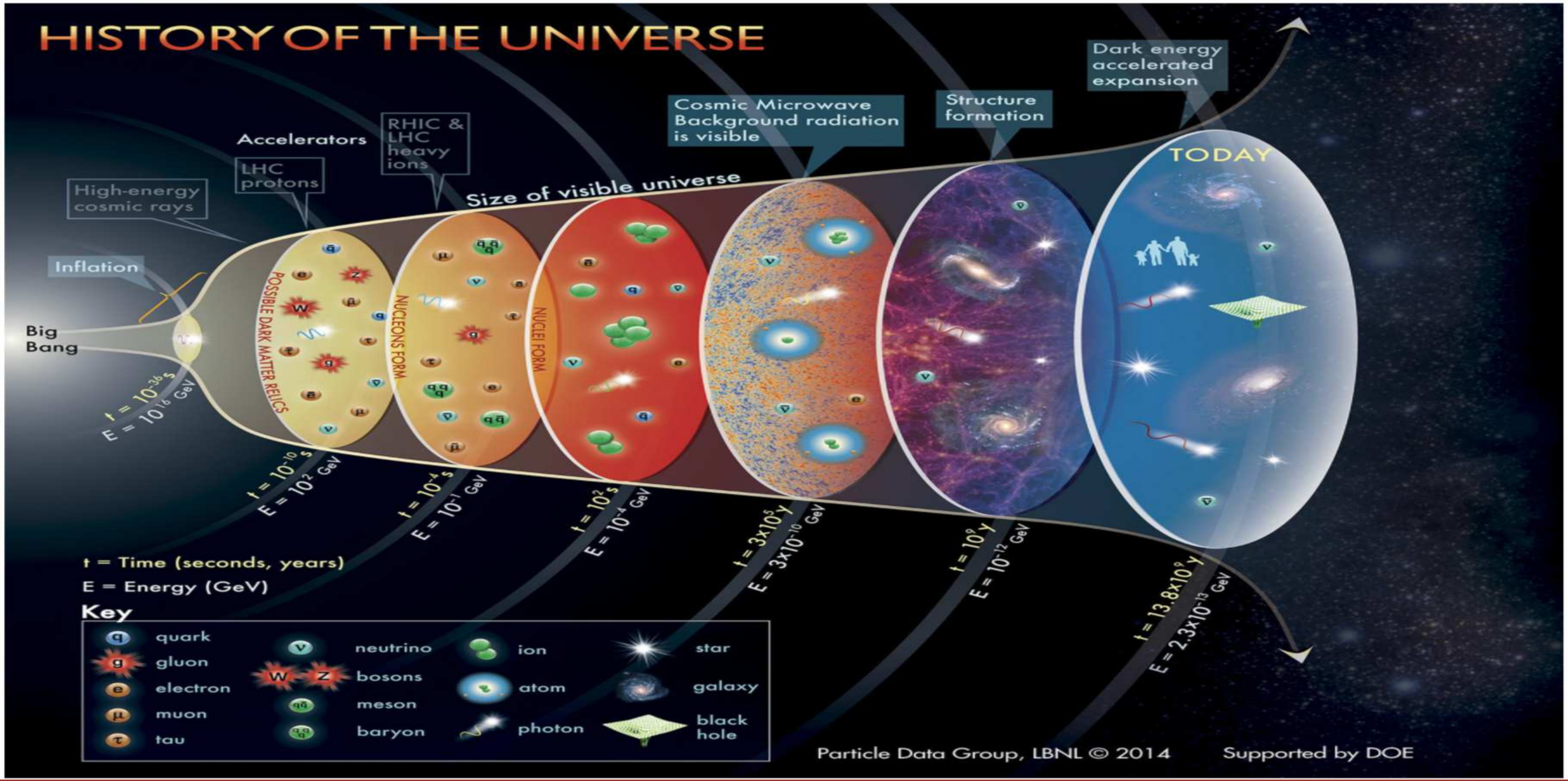
• Dark Matter makes up 27% of the Universe.! (Physics Nobel 2019)(INO?)

• Need to understand why matter dominates completely over anti-matter in our Universe, where at the beginning they are equal! (LHC, INO..)

• Cosmic Acceleration.(Physics Nobel Prize 2011) (LIGO-India? SKA?)

The micro and macro connection indicates that one needs to think of new uses for the old tools and new tools specifically designed for the purpose.

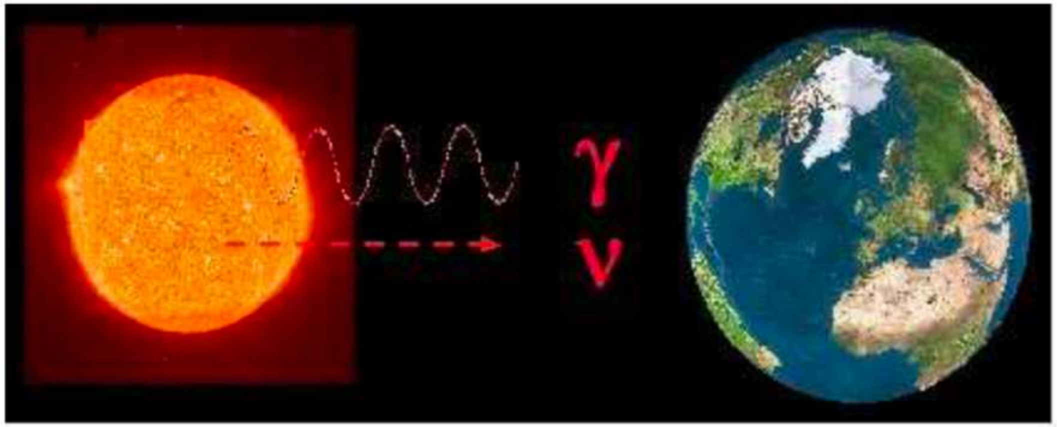
Welcome to the world of astroparticle physics.

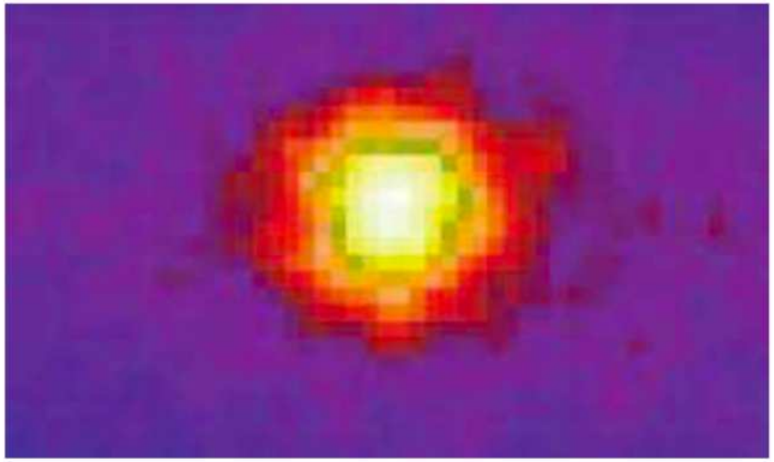



LHC can offer a probe of some of the physics that we think went on *before* $T \sim$ MeV!

We will probe the universe through probes in a range of wavelengths: the optical (Hanley), the radio (GMRT,SKA), Gravitational (LIGO),Neutrinos (Icecube, DUNE,INO) and colliders (LHC,ILC).

Example: Picture of sun through photons and through $\nu$'s:



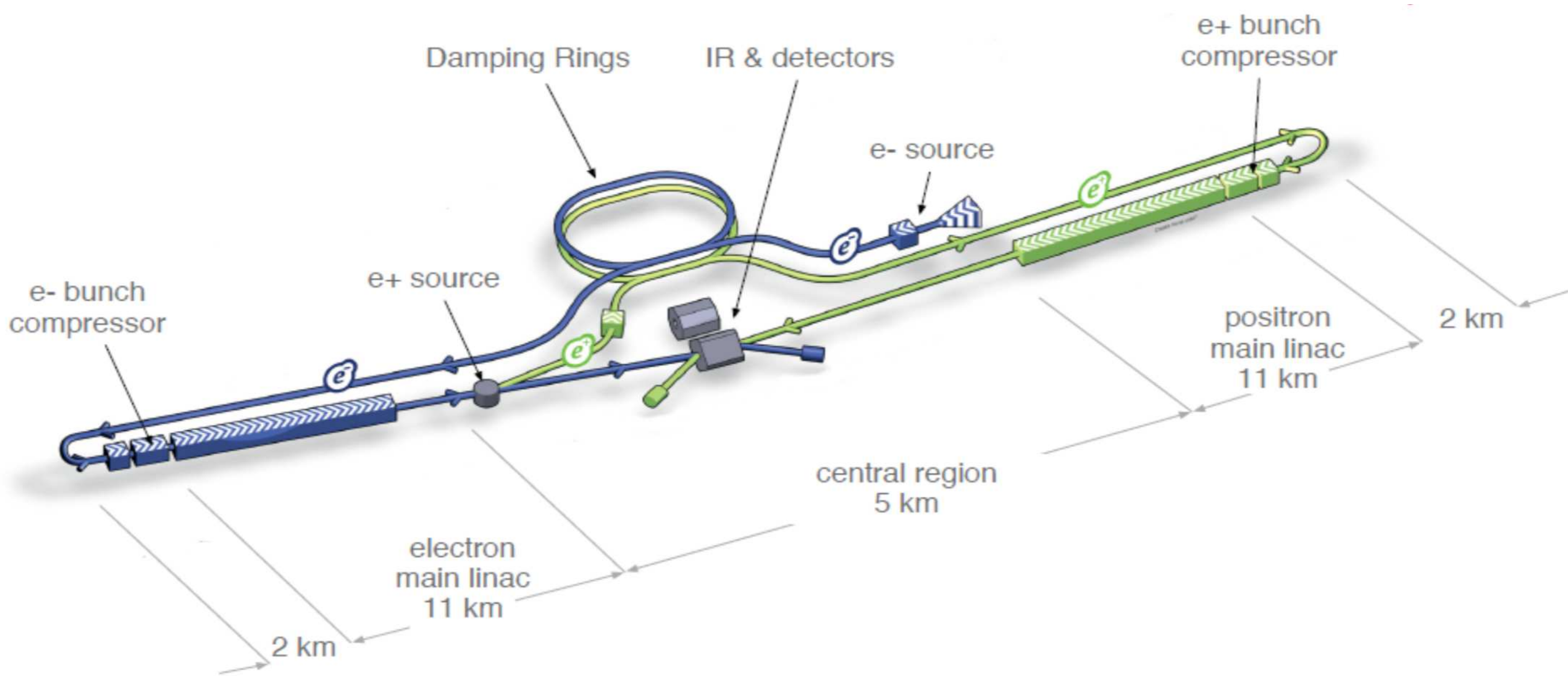



Decade of Multiwavelength, multimessenger Astronomy!

This connection now drives the exploration of the cosmos through the particle physics window and through astronomy/astrophysics experiments.

These questions and much more are the drivers of the LIGO, SKA and INO!

## Plans after the Higgs and the LHC?




Particle Physicists are thinking of, eg., The International Linear Collider!

Mega sizes, mega complexity also mean mega expenses

Also need for million different types of expertise.

No one person, no one laboratory, no one country can do this anymore alone.

**International collaborations are necessary.**

Now let us see how India got involved in these ’mega prrojects.

## Mega-project 1: CERN/LHC and India.

India-CERN collaboration began around 1999. Modest investment of Rs. 25 Crores over five years till 2004.

LHC required precision machining, positioning and measurements.

For example the protons beams have to keep true to their path to much less than a micron in travelling over 27 km at the LHC! The magnetic fields have to be very precise!

India made the 'precision magnet positioning system' (PMPS) for the LHC near Bengaluru Also contributed to the LHC machine magnet testing!

India participated in building the CMS detector and also the ALICE detector and of course in taking data and analysing it.

**In fact India was invited to be an observer on the CERN Council as a result of these important contributions of Indian Engineers and Scientists.**

For the last few years India is an associate member of the CERN and has a representation on the CERN Council.

CERN not only has LHC experiments but also Nuclear Physics experiments some of which India participates in and also on future accelerator development.

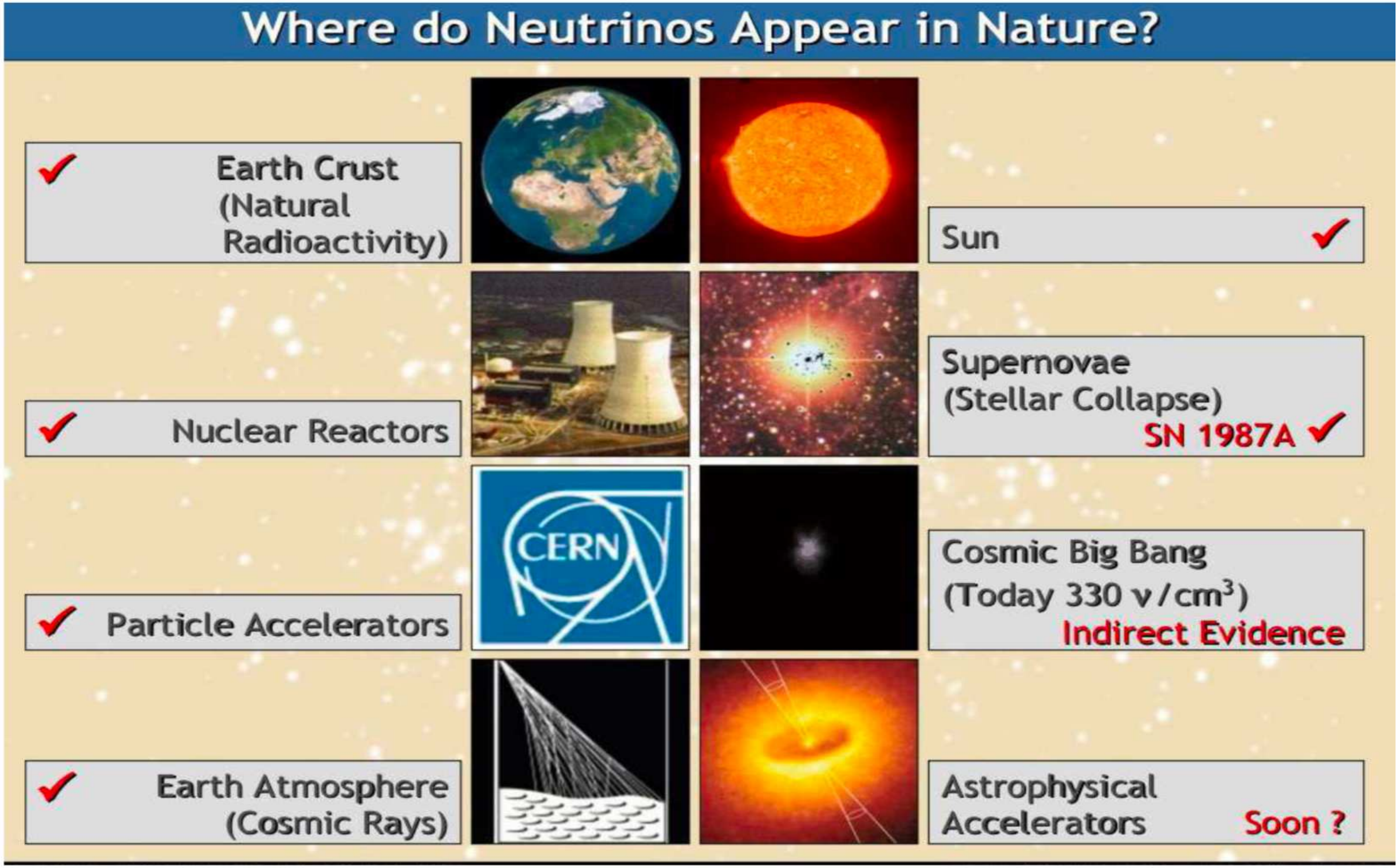
## Mega Project-2 : INO

The 2015 Nobel prize celebrated the fact what the particle physicists already knew for other reasons.

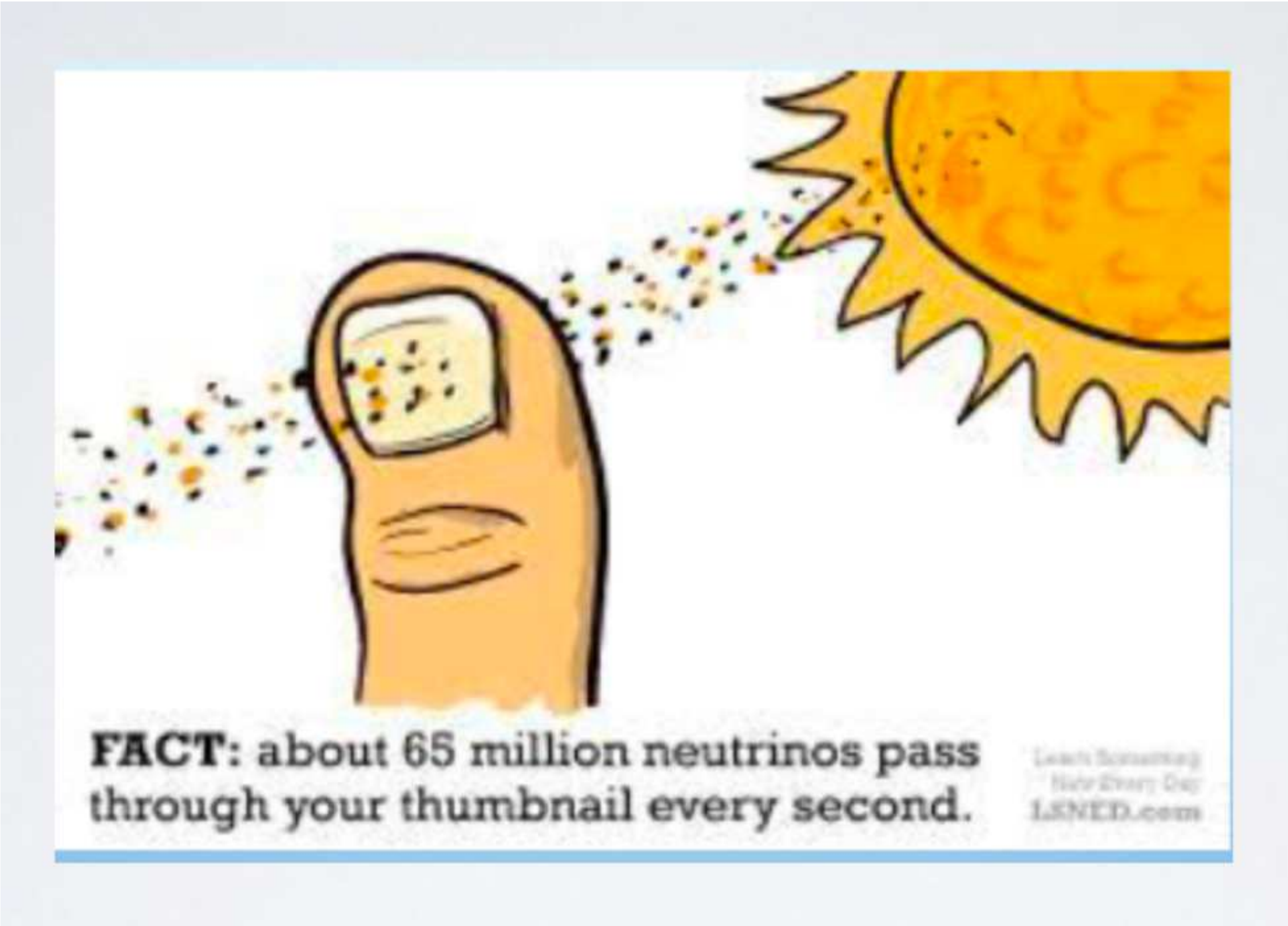
Nonzero masses of $\nu$'s herald new physics, particles and interactions, beyond the standard model of particle physics.

$\nu$ 's: subject of intense experimental and theoretical attention. World wide there exist a number of International collaborative $\nu$ experiments.

$\nu$'s interact very weakly and will pass through the entire earth without interacting, depending on its energy! Hence one requires 'huge' detectors.


Where do Neutrinos Appear in Nature?
✓ Earth Crust (Natural Radioactivity)
✓ Nuclear Reactors
✓ Particle Accelerators
✓ Earth Atmosphere (Cosmic Rays)
CERN
Sun ✓
Supernovae (Stellar Collapse) SN 1987A ✓
Cosmic Big Bang (Today 330 ν/cm³) Indirect Evidence
Astrophysical Accelerators Soon ?

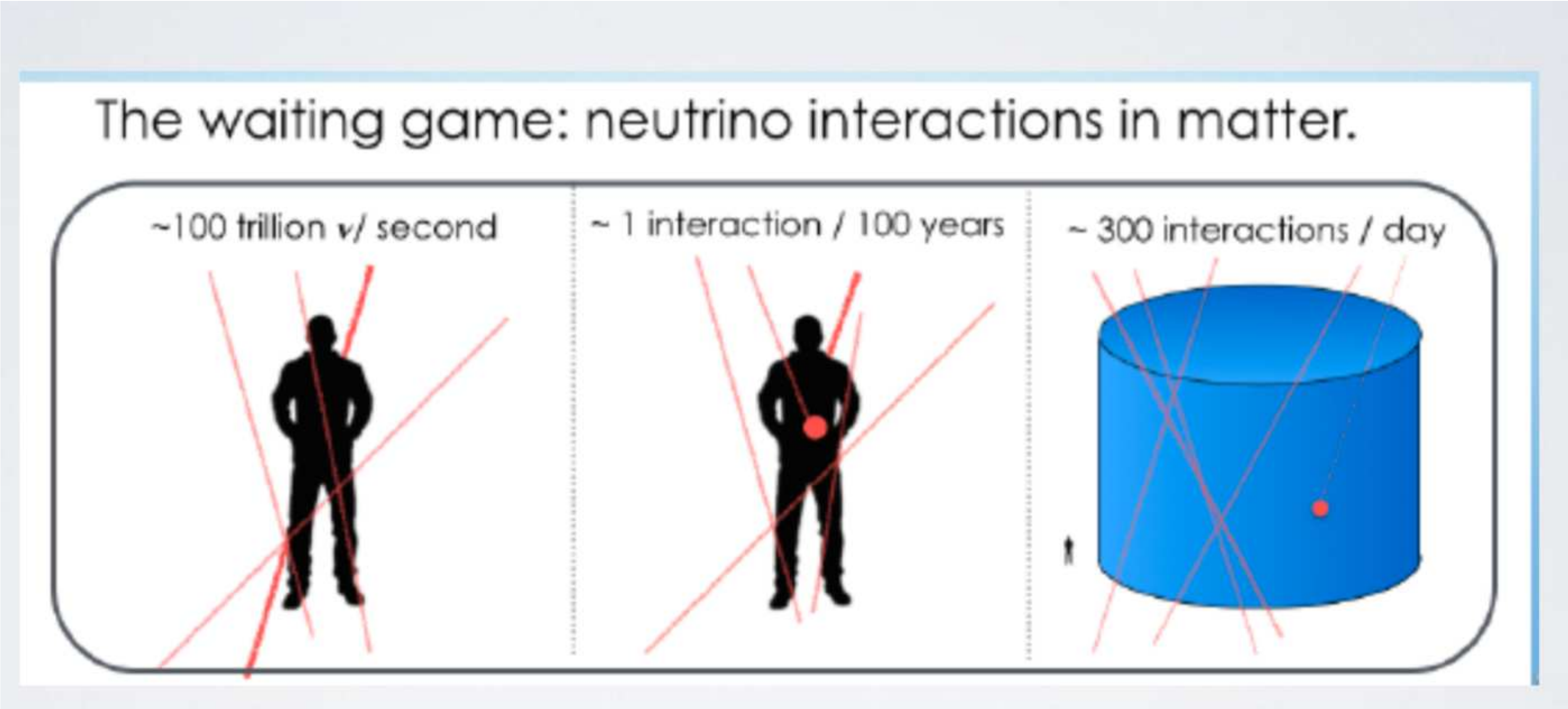
$\nu$ appear in nature, large in numbers!



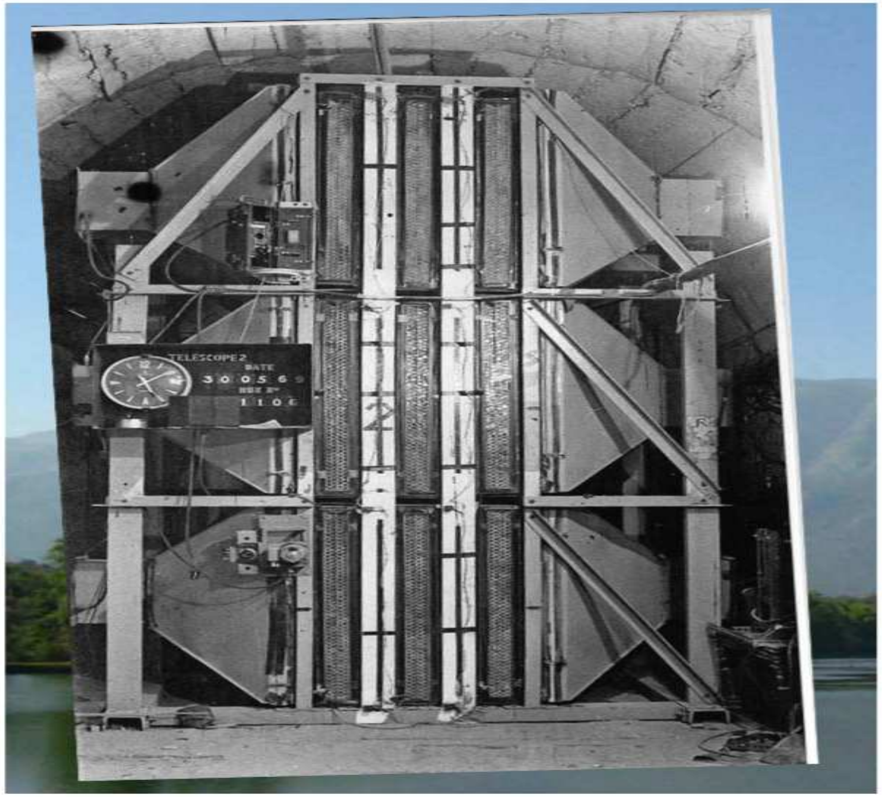
Neutrinos interact weakly

The invisible particle


Detecting them is a waiting game:



India has been part of this waiting game since long ago!
But many other things other than neutrino interactions happen in these detectors and they happen at much bigger rates.
People get rid of many of these by going underground, under the rocks.
Again it means excavations, using mines and so on.

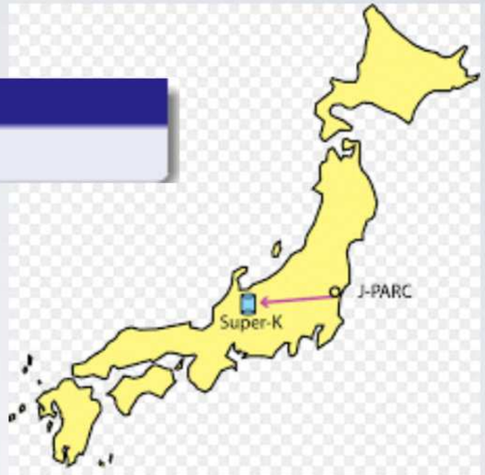


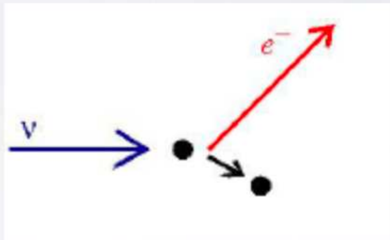

One of the first detections Kolar Gold Mine, India, 1965

# Super-Kamiokande

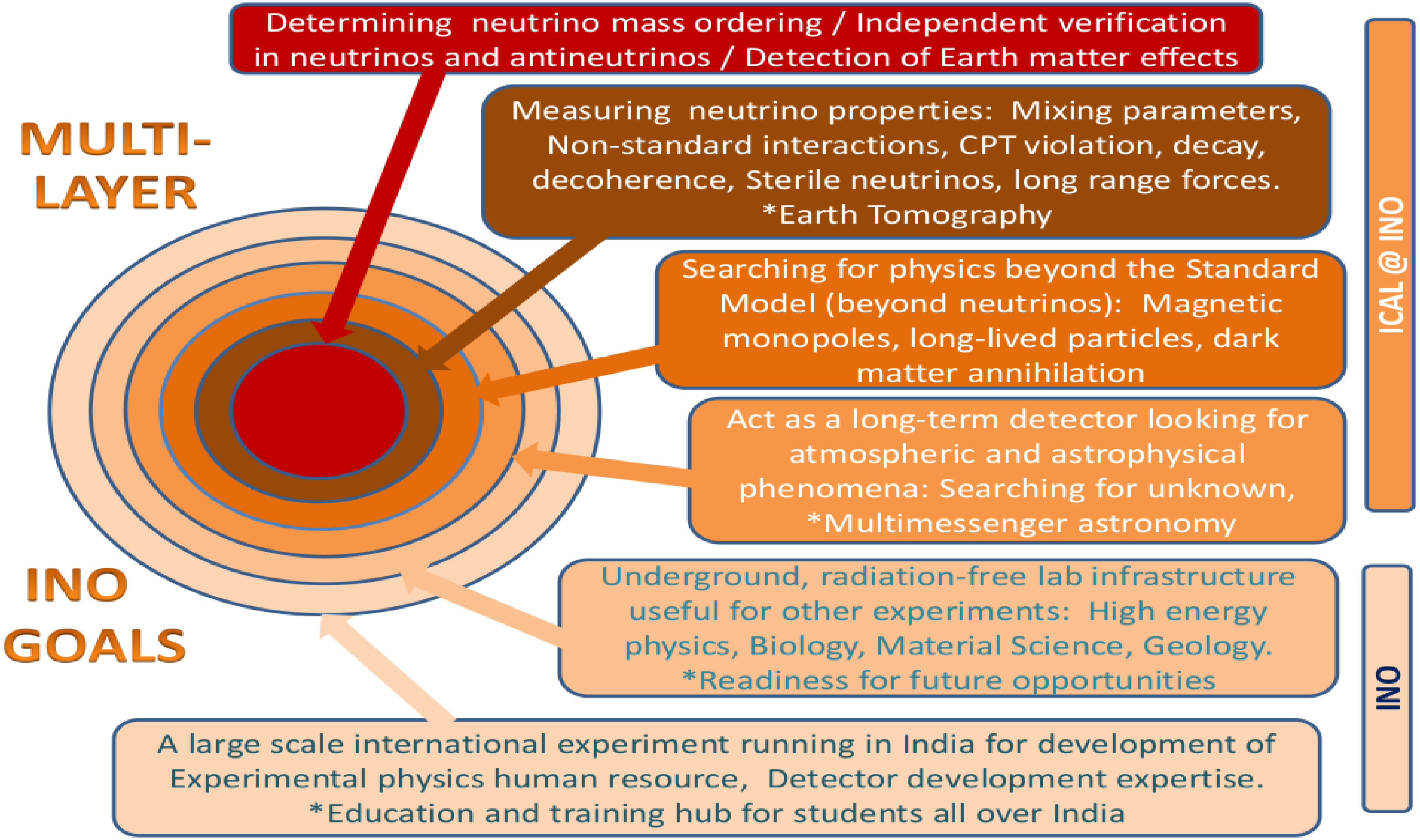
**Superkamiokande: 50 kiloton**

50 kiloton water = 50 000 000 litres




**Observes only 5-10 neutrinos per day**


MULTI-
LAYER
INO
GOALS
Determining neutrino mass ordering / Independent verification in neutrinos and antineutrinos / Detection of Earth matter effects
Measuring neutrino properties: Mixing parameters, Non-standard interactions, CPT violation, decay, decoherence, Sterile neutrinos, long range forces. *Earth Tomography
Searching for physics beyond the Standard Model (beyond neutrinos): Magnetic monopoles, long-lived particles, dark matter annihilation
Act as a long-term detector looking for atmospheric and astrophysical phenomena: Searching for unknown, *Multimessenger astronomy
Underground, radiation-free lab infrastructure useful for other experiments: High energy physics, Biology, Material Science, Geology. *Readiness for future opportunities
A large scale international experiment running in India for development of Experimental physics human resource, Detector development expertise. *Education and training hub for students all over India
ICAL @ INO
INO

Indian Neutrino Observatory is our own Indian, indigenous ’mega’ project.

It uses a technology with magnetic fields not used by other detectors worldwide.

Proposal (sanctioned) is for 1500 crores for a period of 10 years. 100 crores have been used for R & D, building a prototype which is running and taking data.

The physicists have worked very hard and shown they can achieve their goals of determination of mass hierarchy of the three different types of $\nu$’s and also studying CP violation. These are theoretically very interesting quantities and can perhaps hold a solution to the matter-antimatter asymmetry problem.

Very disheartening are the problems they have been having and obstacles in their path.

At present waiting for the last clearance from the SC. The National Green Tribunal has cleared it but that clearance has been appealed against.

The experiment has lost important time and we hope that it can start soon and do interesting physics.

This is where the scientific temper and scientifically mature society is required.

Quote: 'I will not let a single $\nu$ enter Theni! not realising that there is no way one can stop the $\nu' s$ moving around and nor do they do any harm!

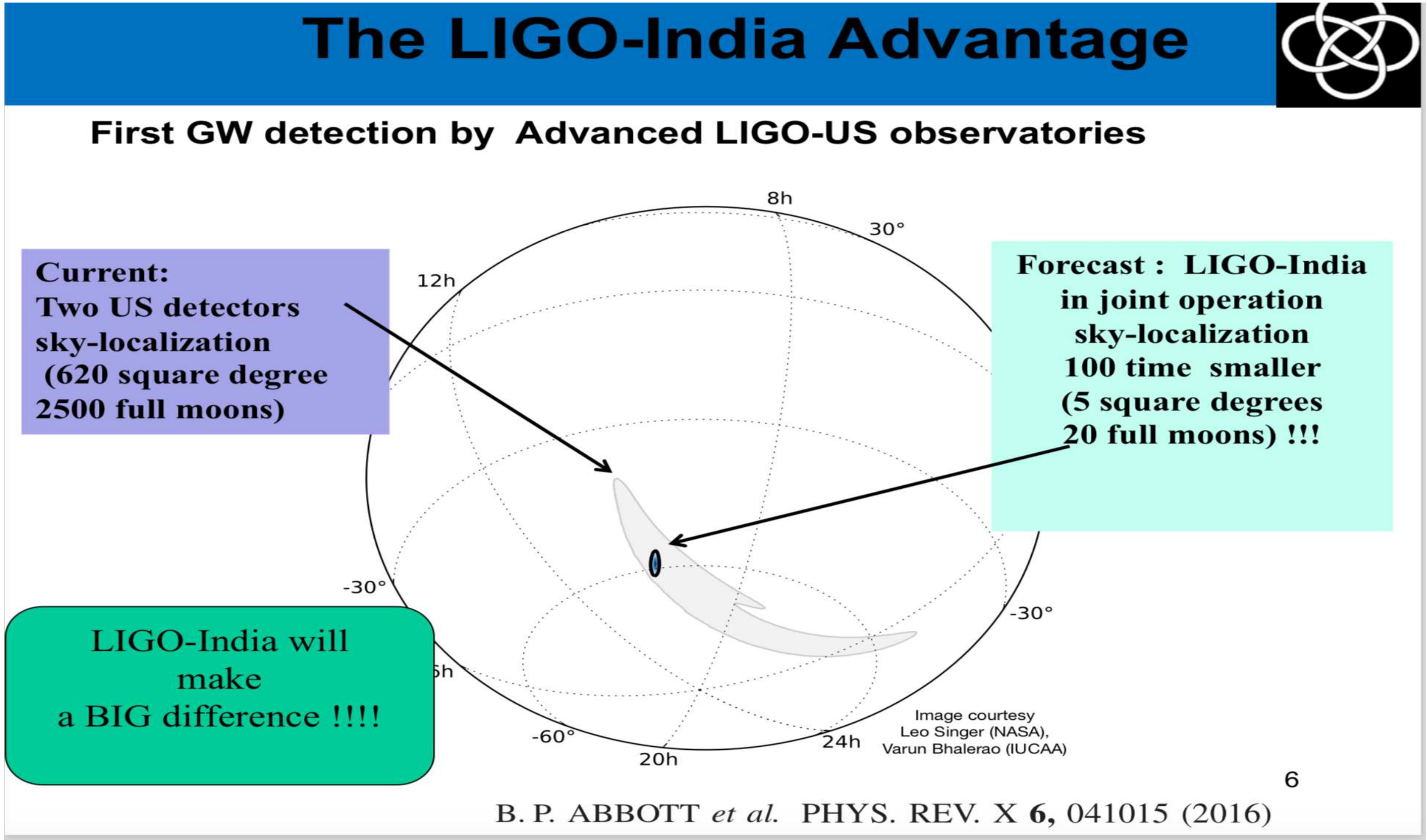
## Mega Projects -3 LIGO-India

History of the theory activity from pioneers like C. V. Vishveshwara, S.V. Dhurandhar and Bala Iyer to name a few.

The first Gravitational wave detection experiment paper had Indian authors because of this theoretical contribution.

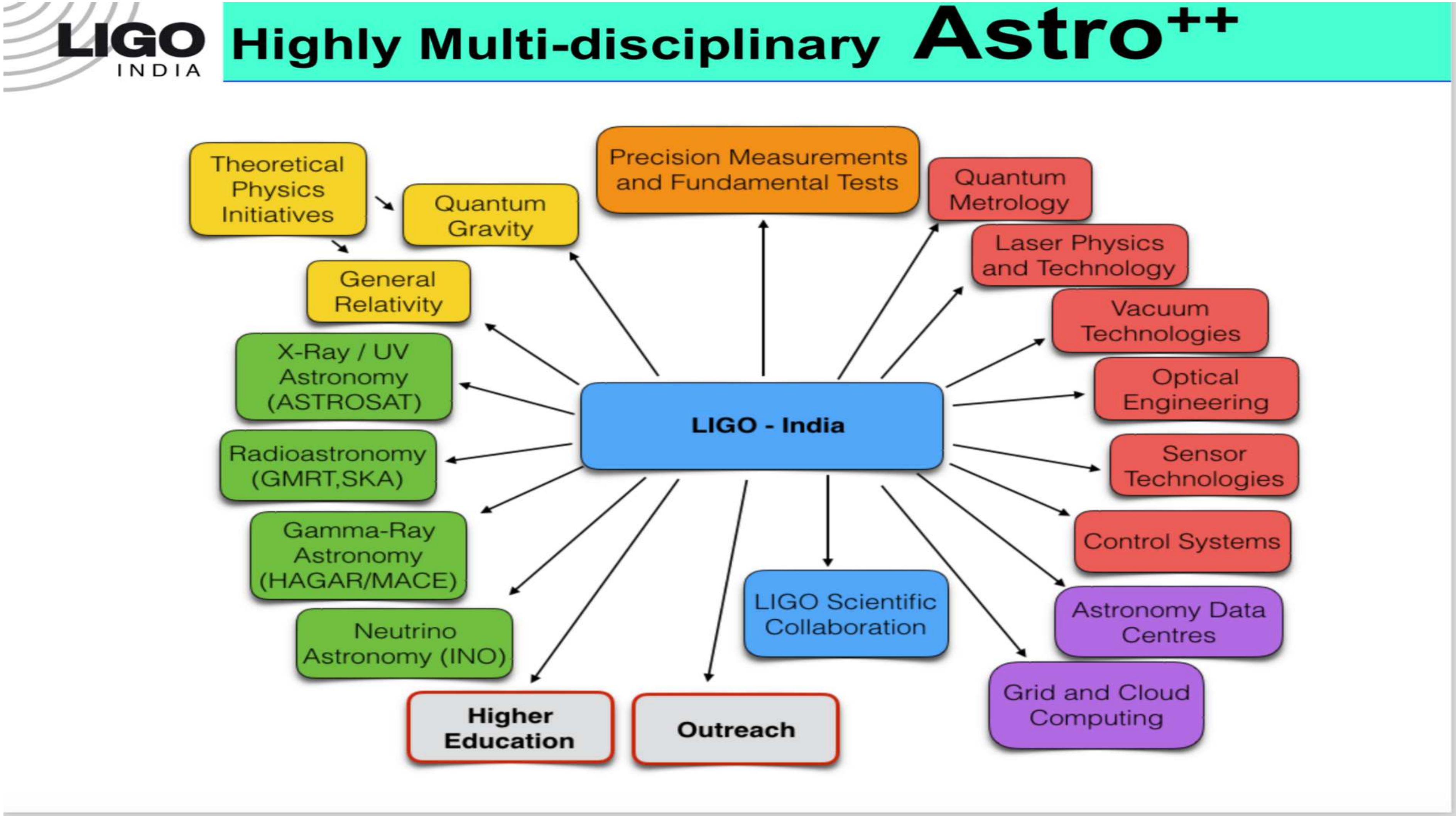
Finally LIGO(India) got a go ahead in 2015.

Discussions of participation in Gravitational Wave detection expts were on for a long time.




India's geographical position makes its contribution unique.

(Thanks: Tarun Souradeep)




Thanks: Tarun Souradeep

Mega Project 4: (SKA)

Radio Astronomy in India : very vibrant.

Giant Meter Wave Radio Telescope (GMRT) built near Pune.

It was built between 1981-1998. Its architect was Dr. Govind Swarup. For about 50 crores over 20 years. **Has delivered exciting, important science. International scientists buy time to do experiments with the facility.**

**Established the credentials of the Indian scientists in the field Internationally.**

uGMRT: upgrade of GMRT about 100 crores.

SKA (India): 70 crores in 7 years for developmental work.

Now await sanction of 1250 crores over a period of 10 years.

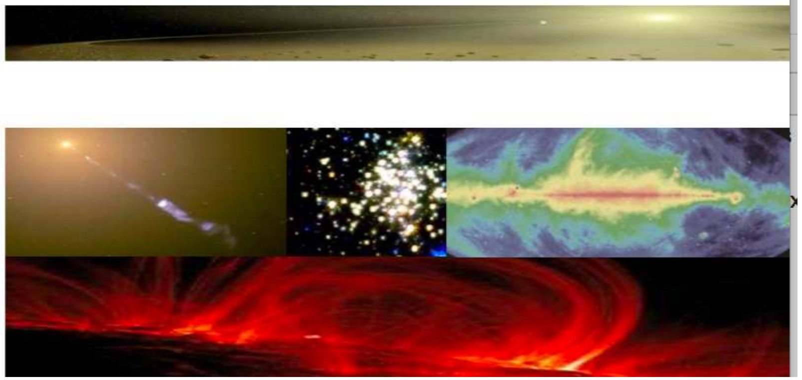
Indian group has developed the 'brain' of this system: The telescope manager system.

When the experiment runs and India would be a member, India will be responsible for the running of the telescope and will play an important role in the data analysis. This will require developmental opportunities to young for AI and ML.

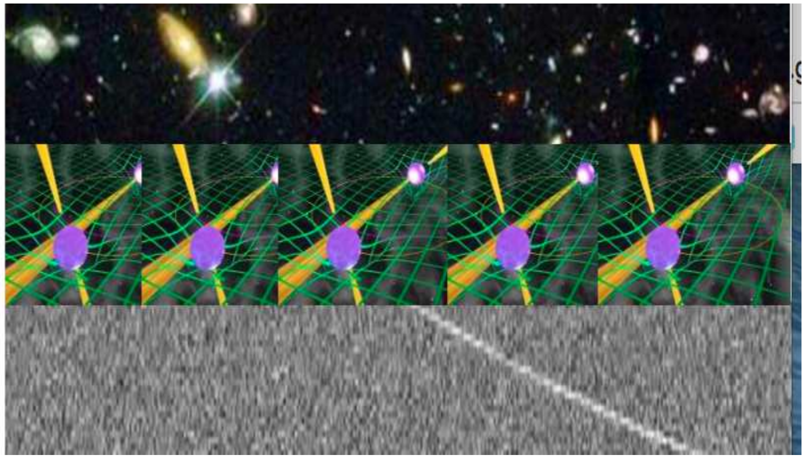
Due to the experience of GMRT and uGMRT the Indian community will be well placed to reap giant physics dividends.

# Science with the SKA

- Cosmic Dawn & EoR : direct imaging of the earliest structures
- Cosmology & Dark Energy : primordial non-Gaussianity, super-horizon scales and the matter dipole
- Galaxy Evolution (via Radio Continuum and Neutral Hydrogen) : star formation rates, resolved gaseous disks and angular momentum growth;



- Strong-field Tests of Gravity with Pulsars & Black Holes : gravity waves & fundamental physics; was Einstein right ?
- The Cradle of Life & Astrobiology : detecting proto-planetary disks, search for complex molecules (building blocks of life), SETI



Thanks Yashwant Gupta(NCRA)

## Relevance of India to Mega Projects:

These Mega projects are endeavours to seek answers to fundamental questions. As one can see the Indian Scientific Community has earned its place in these mega projects. It needs the 'rajashraya', support from the state to take that place.

The community has made important contributions in the area. For example the GMRT has been the pathfinder facility for SKA, theorists had made pioneering and important contributions to the subject of gravitational wave detection and the particle physics community boasts of one of the earliest detection of atmospheric neutrinos at KGF.

Now with an India that is no longer a 'developing' country we have both the intellectual and the technical/financial capital, to take its rightful place on the world scientific scene. One way is by building National Mega projects and participating in these International Mega Projects. International community invites this participation not just for the funds but for the science we can contribute!

The human resource in R&D per million in India is only 200-300 compared to countries like USA and China where it is 4500 and 1500 respectively. (Unesco Statistics Institute)

Development of trained scientific HR is important for country's progress. The Mega projects will provide the focal point for this. Mission oriented projects always do that more easily!

For example:

LIGO uses Laser technology.

Potential technology spin-offs will impact quantum computing and quantum key distribution (QKD) for secure communications. New ground for optics and communication technology in India + Cold atom labs, Precision force measurements,....

High Potential to draw the best Indian UG students, typically interested in theoretical physics, into experimental science !!!

## Technology gain: particle physics

World Wide Web was invented at CERN and changed our lives for ever!

Development of imaging crystals for particle detectors led us to PET scanners.

Development of electronics in high magnetic field to read out these crystals now led to the development of a new scanner which will combine advantages of MRI and PET.

Due to India's participation in experiments at CERN, Indian groups developed indigenously, data acquisition chips which were actually used in these experiments. This knowledge can find other applications!

Technology gains from esoteric basic science :

1)General theory of relativity and GPS.

2) Michael Faraday in answer to William Gladstone's question about 'utility of his new fangled blue sky research on electricity' : Sir, One day you will tax it!

3)Development of semi conductors, lasers, masers all were discovered in curiosity driven research.

4) Formal developments in number theory / quantum mechanics were useful for developments in quantum information, cryptology.

True. Sometimes the time gaps are large. Not every fundamental theoretical development will lead to application for mankind and society.

## Blue Sky vs Applied?

Rolf Heuer, Former CERN DG:

Governments often speak of basic and applied science as if we have a choice. We do not. The two form part of a virtuous circle that we interrupt at our peril. We need both if we're to lay the foundations for future prosperity, and we need to ensure that knowledge is shared between the two.

My own thoughts:

Pure research by our colleagues in Coronaviruses was useful as they were ready now to translate it into vaccine development.

The science discoveries made in these mega projects, the technological developments that happen during their execution will show us the way and India will be an important part of this journey.