Status, Challenges and Opportunities in Physical Sciences

Physics community within India is large compared to other fields of research and active; it has made important contributions. Currently India ranks close to 10^{th} globally in most metrics of different subfields of physics. However, there is an urgent need to develop strategies to plan for the next 10 years so that India can make innovative and impacting contributions to leapfrog. To make a global impact there is a need to prioritize research and choose possibly risky areas that could be enormously important for the country; this may happen at the cost of existing areas.

This report consists of broadly three parts:

These subparts focus on what are new and exciting areas of research that could be prioritized. It also emphasizes possible strategies that various funding agencies could adapt to catalyze research. There is a need for sustained scientific support and funding to few key targeted projects.

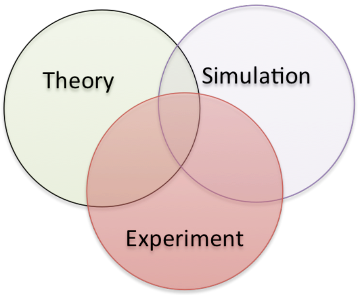
Vibrant physics research is key for the needs as,

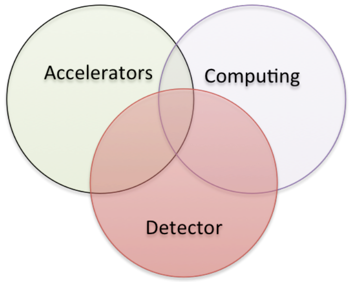
I. It creates an ecosystem of high technology expertise.
II. It can nucleate private industry that is needed to support growth.
III. Trained manpower as today's fundamental science will become technology.

While we discuss field specific strategies in detail. Some key points are:

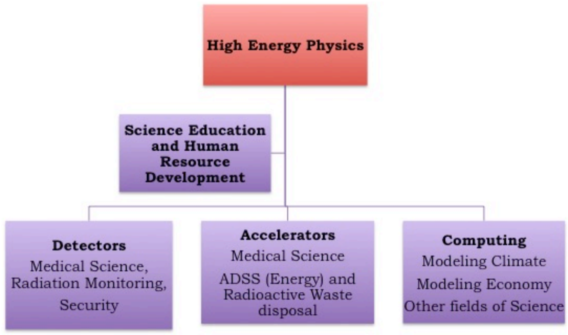
1. Enabling the attracting of talent at several levels as researchers.
2. Sustained support for developmental work in new areas.
3. Augmenting capacity building for development of detectors, high end electronics, cryogenics, advanced materials, ultra high vacuum, high power lasers, precision optics, processing and precision engineering.
4. Development of computing infrastructure.
5. Enhance closer collaboration between theoretical, computational and experimental sciences.
6. Establishment of rigorous international peer review system and advisory boards to leverage international expertise and increase accountability.

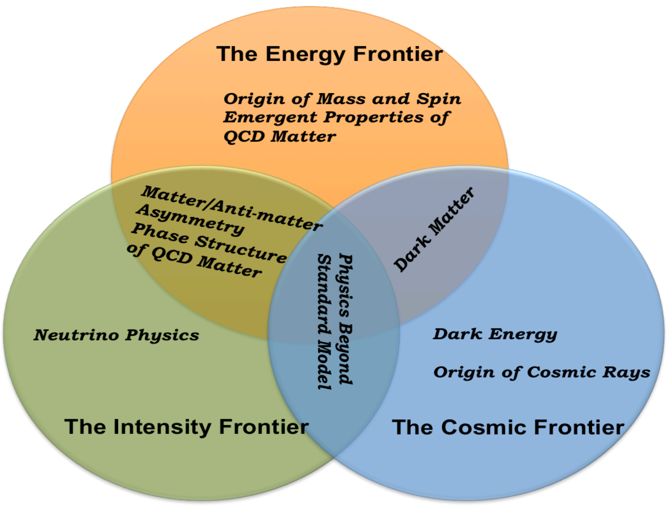
High Energy Physics Program





The program involves an intricate combination of Experiment, Theory and Simulation. For success of the program it needs a combination of all the above three also contributing to develop state-of-the art accelerator facility, detector system and computing infrastructure. Theory is based on – Quantum field theory of relativistic matter and simulation of which requires high computing resources. The R&D in this field has societal impact as depicted in the figure. The next generation of discoveries will take place in the facilities that operate in the frontiers of energy, intensity and cosmic sources.





Some of the fundamental physics questions to be addressed:

(A1) How do the strong interactions amongst quarks and gluons inside the nucleons result in confinement and collectively result in their properties such as mass and spin?

(A2) What are the phase structures of QCD matter ?

(A3) How does a nucleus look in terms of its partonic content? Does the gluon density saturate to gluonic matter of universal properties?

(B1) What are the constituents of dark matter? Is it different than normal matter?

(B2) What is the origin of neutrino masses? Are ν's their own anti-particles?

(B3) What is the source of matter/anti-matter asymmetry in nature?

(B3) Precise knowledge of properties of low mass Higgs boson and its relevance to physics beyond Standard Model ?

(B4) Are there new particles (SUSY ..) & interactions?

(B5)Why is gravity weaker than EM force, do all forces unify at high energies ?

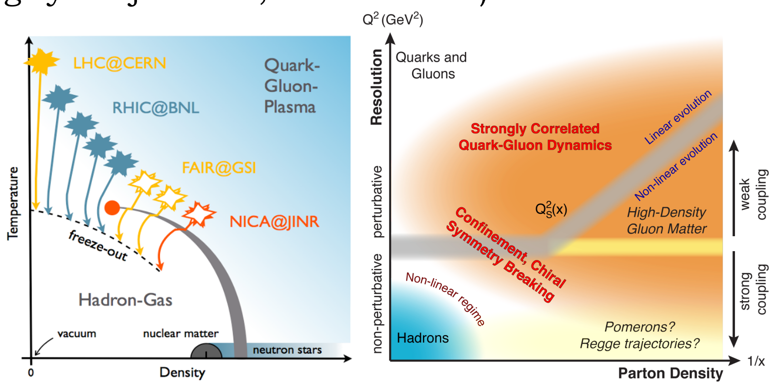
Emergent Properties of QCD matter

The fundamental constituents of visible matter in the Universe are quarks and gluons. The fundamental theory that governs their interaction is Quantum Chromodynamics (QCD).

Nobel Prizes: 2004: "for the discovery of asymptotic freedom in the theory of the strong interaction", **1990**: for Deep Inelastic Scattering

Fundamental question: How the many-body interaction of quark and gluon fields leads to a confined structure and lead to properties of hadrons (spin, mass, etc) and how their interactions decide the phase structure (phases, critical point, order of transition etc) and phase properties (viscosity, opacity, diffusion/drag coefficient etc) in the QCD phase diagram?

Goal: Experimental and theoretical realization of the QCD phase diagram (largely conjectured, shown below) to a reasonable accuracy.



Challenges: It needs large experimental accelerator facility, state-of-the-art detectors and electronics and high performance computing systems. In addition one needs to define proper observables, develop analysis tools and simulate QCD to measure and quantify properties of the phases in the QCD phase diagram. India must participate in all programs listed below as it has a common thread.

Opportunities:

Facility	Science Case	Potential India Contributions
Large Hadron Collider	Emergent properties of QCD matter	Physics, Detector development and Electronics
Relativistic Heavy-Ion Collider	Phase structure of QCD Phase diagram	Physics
Facility for Anti-Proton and Ion Research		Physics, Detector development and Electronics
Electron Ion Collider	Nucleon spin and ultimate picture of nuclei (Emergent properties of QCD)	Physics, Detector development and Electronics
Future Collider	Emergent properties of QCD matter	Physics, Detector development and Electronics
High Performance Computing	Emergent properties of QCD Matter	Needs for better computing facility nationally

Neutrino Physics

Neutrinos are one of the most abundantly found particles, yet one of the most difficult to detect due to their nature of interactions. They have several source of production in nature and bring a rich source of physics questions, some of which has led to profound discoveries as listed below.

Year	Science case meriting Nobel Prize
2015	*For the discovery of neutrino oscillations, which shows that neutrinos have mass.*
2002	*For pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos.*
1995	*For the detection of the neutrino.*
1988	*For the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino.*

Open fundamental questions: What are the absolute masses of neutrinos and how have they shaped the evolution of the Universe? Are neutrinos their own anti-particles? Why is there more matter than anti-matter in the Universe? Can we measure the CMBR equivalent for neutrinos? Precision measurements of all the oscillation parameters.

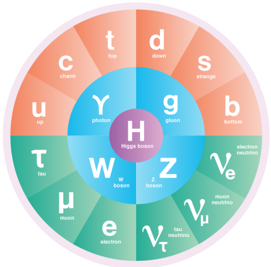
Challenges: State of the art detectors and innovative ideas of addressing the background to various kinds of neutrino measurements. INO program is essential for leadership in this area

Opportunities:

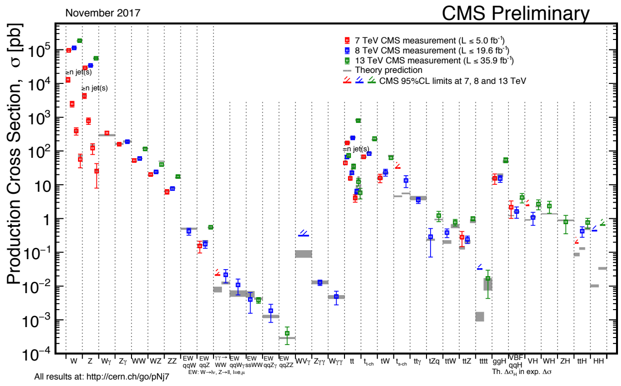
Measurement	Physics Goal	Facility
Rare beta decay process: Neutrinoless double beta decay	Violation of lepton number conservation. νs are their own antiparticles (Majorana particles). Matter-anti-matter asymmetry in Universe	CUORE, EXO-200, MJD, NEXT, PANDAX-III, SNO+, KATRIN, **INO (in India)**
ν oscillation parameters	Physics beyond Standard Model, Mass hierarchy	Chooz, Daya Bay, RENO, LBNE, DUNE, **INO(India)**
Mass of the neutrino - β decay of tritium	Absolute masses of neutrinos	KATRIN, Project 8
Spectrum of cosmological ν (low energy)	Similar information as CMBR photons	Ideas exists, PTOLEMY
Elastic scattering of ν from nuclei	Improved knowledge of nature of neutrino interactions	CENNS, COHERENT, MINER
Astrophysical ν, galactic sources	life time of neutrinos	ICECUBE

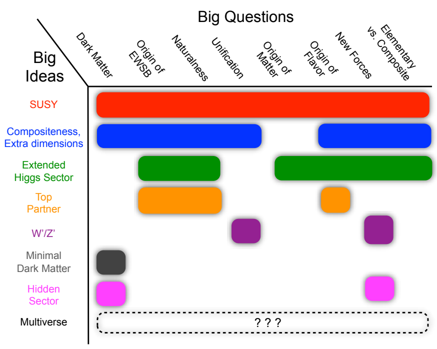
Physics with Colliders and Beyond Standard Model

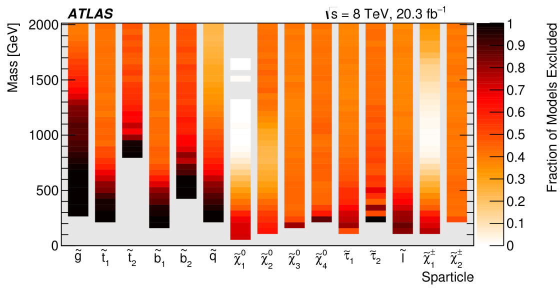
The Standard Model (SM) is a kind of periodic table of particle physics.



It lists the fundamental particles (shown in the left figure) that make up the visible matter along with three fundamental interactions – strong, electromagnetic and weak. The SM is now experimentally verified with discovery of Higgs boson in 2012. Building of the model started with the discovery of electron in 1897. The status on the success of SM is shown in the figure on the right. It compares the cross section of various processes measured in the LHC experiment and to that calculated in the SM theory. **Measuring with high precision properties of Higgs boson and its interaction is one of the current goals of high-energy physics**. However the following features of the known Universe are not part of the SM and hence the need to go Beyond Standard Model (BSM): (a) Gravity, (b) Mass of neutrinos, (c) Dark Matter and (d) Dark Energy. The status and challenges of various theories/ideas that can address the different BSM physics is given in the figure on the left. The most promising of the theories is Supersymmetry (SUSY). In **SUSY new particles (sparticles) are expected to exist and their search is one of main goals and challenges at LHC.** The status of the search of these sparticles is shown in the figure on the right. The complete search space has not been exhausted at LHC and may require a higher energy collider. Discovery of SUSY can be a significant step towards Grand Unification and is likely to provide an answer to the dark matter mystery.



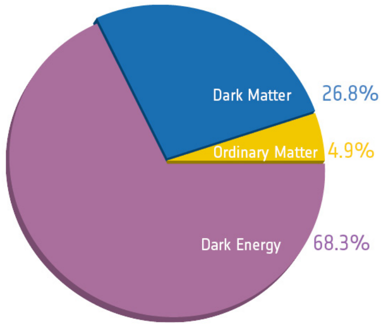




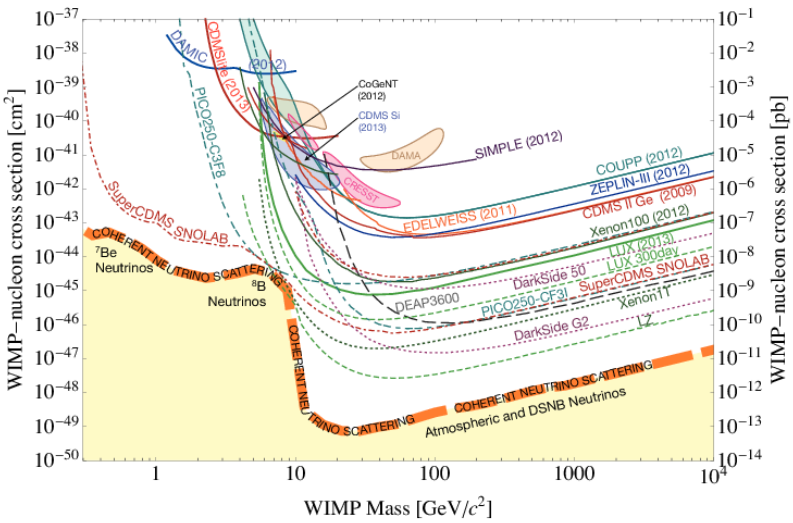
Opportunities:

Facility	Science Case	Indian Contribution
LHC(high luminosity)	Precision Higgs, top, W, Z properties and BSM	Physics, detector, electronics
Future pp Collider	BSM physics	Physics,detector,electronics
New e+e- Collider	Precision measurements of properties of Higgs+ BSM	Physics, detector, electronics

Dark Matter



Status: A variety of astrophysical and cosmological observations give strong indications that there exists a large amount of non-luminous, non-baryonic "Dark Matter" in the Universe that dominates the total amount of gravitating matter in the Universe. Current estimates put the Dark Matter to be constituting about 26.8% of the total mass-energy budget of the Universe. However not much is know about the constituents and properties of Dark Matter. The two potential candidates are (a) Weakly Interacting Massive Particles (WIMPS) and (b) Axion-like Particles (ALPs). They need to be non-baryonic and have very weak interaction with Standard Model particles. Searches for Dark Matter is being carried out in two directions (a) Direct Search (Elastic scattering of DM with detector Nuclei) and (b) Indirect Search (Accelerators, Neutrinos, gamma rays, positron from WMIP annihilations) . The current status on the Dark Matter Search is shown in the exclusion plot of WIMP Mass and interaction cross section shown in the figure in the left. Looking at the exclusion plot the concentration now is to look at low mass WIMPS. Discovery of DM candidates is one of the key open questions in science.



Challenges: State-of-the-art detectors and innovative ways to control and understand the background to DM search. Indian program is essential so as not to miss out this fundamental physics.

Opportunities:

Search	Signal	Facility
Direct DM	Elastic Scattering of DM with detector Nuclei	SuperCDMS, DINO (in India), LUX, XENON1T, PANDAX-II, LZ, DM-2
Indirect Search	Signals from WIMP annihilations	AMS, FERMI-LAT, Super-K, ICECUBE
Accelerators	DM-nucleon scattering, mono-X	LHC

Science Impact on Society and Technology generation

All the programs require advancing of technologies associated with instrumentation, computing and will lead to development of education. All measurements will require a few orders of magnitude of improvement in sensitivity and control on errors on the measurements to high level. While achieving these objectives for science discoveries we will advance the research in instrumentation and education. This will have direct benefit to society. A few possibilities are listed below.

Technology/ R&D	**Need**	**Science Case**	**Challenge**	**Societal Benefits**
Computing hardware, applied mathematics and computer science.	Exascale (1000 PFLOPS/s) computing facility	Analysis of data and storage. Solving Quantum Field Theory or relativistic matter to simulating Stellar explosions.	Overcome limitations of CMOS technology and power requirements – Hetrostructures (GPUs). Software development to optimize code performance in new platforms.	Also needed to solve scientific issues related to Environment, Security, Economy etc
Detector and Electronics Cryogenic system Accelerator systems	High position and timing resolution, efficiency and purity of signal High intensity and high energy beams	Resolving thousands of charged tracks in Colliders Measuring the tiny energy deposited by for example beta decay electron Detecting rare processes	Signal to noise ratio Charge/signal collection efficiency Innovative cryogenic systems Go beyond the LHC accelerator technologies	High resolution (position and time) and high channel counts could lead to miniaturization of PET scanners /medical imaging devices. Needed in security, medical dose verifications etc Nuclear non-proliferation, remote reactor monitoring (Reactor Anti-ν application) Energy needs, waste management
Education	Spread of scientific knowledge	Understanding Nature	Funding and Human resources	Knowledgeable & scientifically literate society

Support from Funding Agency

(A) Such programs need sustained and assured funding for a long term ~ 10-15 years (the questions addressed are gloablly acknowledge to be fundamental to science). Gobal (international scientists, postdocs, students) participation key to success.
(B) Support in a time bound manner for state-of-art R&D in detectors and electronics (identify a few key detector concepts in various sub-programs, fund generously, flexibly and build team of competent people). This is key to success.
(C) Support and facilitate leadership role of Indian scientists in international projects. Identify and facilitate training of Indian scientific personnel in international projects. This will be catalysis to having national level projects.
(D) Identify few key high impact science projects and build teams to address the scientific problem in time bound manner. Statrt-up grants at the level of 5-10 Crs needs to be provided for key high impact projects for a faculty.
(E) Develop good computing facility to simulate physics based on Quantum Field Theory of relativistic matter – the underlying theory for the above projects.

References:

Figure in section related to Emergent properties of QCD – US Long range Plan and https://arxiv.org/abs/1708.01527
Figure in section related to Physics of Colliders and Beyond Standard Model - https://arxiv.org/abs/1311.0299 and CMS and ATLAS results
Sensitivity plot in Dark Matter Section - Snowmass report, 2013

Astrophysics and Cosmology

India is poised to become a global leader in Astrophysics. We are part of nearly all international mega-projects and building our own international-class facilities. However, to make the most of out of this enormous opportunity, urgent funding is required for specific purposes, broadly to

- support the community to get them ready to make optimal use of the facilities being built,
- setup laboratories & develop human resources to contribute to the projects and beyond,
- explore avenues and build up communities to participate in the future missions.

Status, challenges and opportunities specific to different areas of Astronomy are given below.

Gravitational Waves (GW), is undoubtedly the most visible, frontier area of research in Astronomy & Astrophysics right now. The detection of GW has received several accolades, including the Special Breakthrough prize in 2016 (the included 37 Indian researchers from 9 institutions), and was awarded the Nobel Prize in Physics in 2017. This heralds an era of path-breaking science in the coming decades with a global network of ground-based detectors, including LIGO-India, that is being built on Indian soil. LIGO-India project is bringing together expertise from a wide range of basic sciences and technology streams in the country. Critical and timely support is however needed from the government for nurturing of this nascent but rapidly growing community. In particular, **researchers that are moving into this field from allied areas urgently need funding for infrastructure and human resource development to set up LIGO-India related research groups and laboratories at their home institutions and universities**, to grow in expertise to contribute at par with other international groups in this global quest by the time LIGO-India is constructed in the early 2020s. This support also nurtures spin-off technologies and human resources in the field of large volume ultrahigh vacuum design and fabrication, high power laser development, precision optics, secure transportation and management of large volume of data, seismic sensors and sophisticated data analysis. These technologies may help India become a major manufacturer of LIGO like instruments in future, even to meet requirements outside India. In addition, avenues need to be explored to assess the scope for Indian involvement in future ground- and space-based detectors, for which technical activities have started in multiple countries and a global workforce is being created.

Time domain astrophysics is a prime focus area in global astrophysics now. Indian scientists have made a mark in this area, and more so in the recent times with electromagnetic follow-up of GW sources, which is challenging our current understanding of astrophysics. India is also beginning to make headway in the world in terms of observational resources, with various meter-class and a 3.6 m optical telescope constructed recently, upgrades in the GMRT, and the AstroSat. Due to the longitudinal separation from other major observatories, Indian telescopes can observe sources when they are not visible from anywhere else in the world. India's participation in global projects like GROWTH, LIGO, etc., and upcoming mega-projects like TMT, SKA and LSST provides an excellent opportunity to leverage this advantage. Existing "general purpose" facilities are however not well-suited for time-domain work. Focusing on automation facilities for existing telescopes, specialised telescopes, associated instruments, training to develop skilled astronomers and, **very importantly, expedited funding, can propel us into leadership positions in those areas**. Cost-effective special-purpose small space telescopes can address specific scientific problems and obtain paradigm-changing results.

Ground-based Optical Astronomy is currently poised for a giant leap. Astronomy literally grows in leaps and bounds interspersed with periods of slow growth consolidation when new technologies mature. Over the next decade, cutting edge optical astronomy will move from the present 10-m class telescopes to the future Giant Telescopes, signifying the next major leap in optical astronomy. India's participation in the **Thirty Metre Telescope (TMT)** Project, along with Canada, China, Japan and the US, will ensure that we are part of this future. **There is an urgent need to prepare the Indian astronomy community to be globally competitive in the era of large telescopes**. Two initiatives are required for this.

1. Set up a world class instrumentation and technology development centre. India has already demonstrated its indigenous potential in several areas like space technology and nuclear science and is rapidly becoming a global hub for technology driven research.
2. Enable access to Indian astronomers to existing large telescopes of diameter 4m-10m. Competitive science cases for a telescope like TMT can be built up only through dedicated observational programmes on relatively smaller telescopes. There is an acute

shortage of access to such telescopes in India and this gap needs to be bridged.

India also has a few meter-class telescopes and is a partner in the 10m Southern African Large Telescope. Apart from the mainstream Astrophysics, the participation of Indian Astronomers in niche emerging areas of Astrophysics, e.g., **time domain astronomy**, search for **extrasolar planets**, using the current and upcoming telescopes, must be explored.

Radio Astronomy is also taking a giant leap, the net collecting area of all the radio telescopes together in the world is going to increase by a humongous factor of 10 in the next decade. The most significant contribution is going to come from the **Square Kilometer Array (SKA)**, in which **India is a Full Member**. India has a long tradition of building radio telescopes, which includes two of the best international facilities, The Ooty Radio Telescope and the Giant Metrewave Radio Telescope. Indian astronomers have also contributed in building and using many radio telescopes across the world. The radio astronomy community in India is thus well developed to participate in the ongoing ambitious projects, though they will still need support to take leading roles in these activities, for example, in handling the gigantic volume of data to be produced by the SKA. Radio telescopes are opening a new window to observe Gravitational Waves at nano-Hertz frequencies, potentially from Super-Massive Black Hole binaries, through Pulsars Timing Arrays (PTAs), formed via precise observations of stable millisecond pulsars. Sustained support will be desirable for **IndPTA**, a nascent Indian initiative for joining the international PTA efforts. Radio Astronomy also offers independent windows to the early universe, especially to probe the epoch when the universe reionized after passing through a long dark phase. India, with a solid history in radio astronomy and cosmology, may be able to make a substantial contribution in this area. India is also part of an effort to image massive black hole binaries using joint observation with the **Event Horizon Telescope** and radio telescopes.

Space Astronomy: India is deeply involved in multi-wavelength space telescopes, a solar mission is under development and a cosmic microwave background (CMB) mission is under consideration. **Space based gravitational waves detectors** and **interplanetary missions** promise exciting scientific outcome and significant Indian involvement must be considered.

1. **High Energy Astrophysics:** **AstroSat,** India's currently operating high energy mission, is building legacies in several areas which should be followed up to put India firmly in a leadership position. These include **X-ray Polarisation** measurements for which an Indian mission **XPoSAT** (2019) is due to follow AstroSat. **Multi-wavelength rapid variability** is another globally emerging area, championed by AstroSat. Promoting a tight coordination between all Indian observing facilities for these studies will reap rich benefits in the coming decades. This will be a powerful tool to study processes in extreme gravity, including finding counterparts of Gravitational Wave events. For rapid localisation of such fast transients an interplanetary network of open high energy detectors will be useful to develop. A mission on **Ultraviolet Imaging Spectroscopy** will be another potential successor to AstroSat. Expertise on UV astronomy developed in the country can be harnessed for this very impactful niche activity that will deeply enrich our knowledge of the formation and evolution of galaxies and the intergalactic medium.

2. **Solar observations** are necessary to understand space weather, which is especially crucial for a country like India which is fast becoming a space-reliant nation with many sectors such as defense, intelligence, aviation and communications dependent upon accurate understanding and assessment of our space environment. The near-Earth space environment is governed by variations in the Sun's activity – which generates variable doses of high energy radiation and particle fluxes. Occasionally the Sun also produces space storms which hurl vast amounts of magnetized plasma towards interplanetary space whose impacts range from disruption of satellite operations, telecommunications, GPS navigational networks and air-traffic over the polar region. United States and Europe has already made significant investments to understand and assess space weather. India is planning the launch of the **Aditya-L1 mission** to understand how the Sun produces phenomena that impacts space weather. Coordinated efforts are necessary to develop this crucial research area of immediate relevance to our nation's security, society and aid private sectors that rely on space technologies. Only a few talented early-to-mid career scientists exist in India who have the computational modelling and data analysis expertise necessary to tackle this challenge across the Sun-Earth space domain. **The nation should actively invest**

in manpower, ground-based space weather and solar activity monitoring facilities and a dedicated satellite to observe the whole Sun-Earth system – ideally from Lagrange point L5 in outer space. These actions will enable protection of India's space-reliant sectors and technologies and establish our nation as a formidable space-power.

3. **Cosmic Microwave Background (CMB)** observations ushered in the era of precision cosmology, unravelling insights into the very origin and detailed structure of our Universe. CMB research has been recognised through a Nobel prize to lead scientists of COBE in 2006, and the 2017 Breakthrough Prize to the WMAP team. While exciting observational fronts have opened up in many areas of cosmology, what is yet to be uncovered through improved CMB measurements, remains the most viable route to arriving at definitive answers to much of the outstanding cosmological conundrums. Opportunistically, there are no funded next generation CMB mission at NASA or ESA at this time beyond ESA Planck mission, but both are seeking international partners in this quest. This presents an unique opportunity to ISRO to take on a challenging flagship Astronomy mission in 2025+ time frame with extremely high science return. Besides, this would allow the Indian space program to showcase new highs in its technological prowess in launching a heavy satellite to the second Lagrange point (L2) with its more recent launcher, handling a cryogenic payload, and will also stimulate the Indian programme on detector technology in microwave to millimetre wavelength that also has significant strategic applications. **A visionary investment in the next CMB space mission, together with prompt and timely funding to a comprehensive research programme that supports the required scaling up of the modest community and associated technology development to meet the HRD challenges of such a mission promises the most value in terms of returns in the field of cosmology.**

Condensed matter physics and materials science (CMP&MS)

Globally CMP&MS is a very dynamic and impacting area of research that is critical for improving our fundamental understanding of matter and has led to ground breaking applications in the last 5 decades. The number of researchers working in this field is very large both globally and in India.

Present status of research in this broad area:
The status of research contributions in this area from India is modest. There are certainly areas of excellence within CMP&MS where Indian researchers have made global impact. However, the impact is not as

	Country	↓ Documents	Citable documents	Citations	Self-Citations	Citations per Document	H index
1	United States	467508	461934	8316082	3162090	17.79	598
2	China	383846	381273	3063634	1731979	7.98	292
3	Japan	224454	222580	2528029	845540	11.26	310
4	Germany	191562	189725	2953466	866385	15.42	354
5	France	134236	133159	2011601	538964	14.99	285
6	Russian Federation	119343	118272	841952	309742	7.05	190
7	United Kingdom	112146	110589	1938688	424908	17.29	324
8	South Korea	91031	90032	1002619	237707	11.01	216
9	India	89979	89010	952526	347890	10.59	187
10	Italy	75093	74277	1025379	275778	13.65	227

Table 1: Country rankings in Condensed Matter Physics on the basis of citations tracking across publications in the field. While citations are a flawed metric they do provide a guidance for tracking trends and broad impact of the country.
Source http://www.scimagojr.com/countryrank.php?area=3100&category=3104

broad as it could and should be. Table 1 provides a perspective of impact using one metric.
It is important to understand the reason for the status of CMP&MS within India. Like many fields of research, as practised globally, experimental research needs research infrastructure. Sustained increase in funding within the country has taken place within the last 15 years. Prior to this the funding available was modest and Indian researchers, who are versatile and adapt to ground realities rapidly, focused on areas of research that are not resource intensive. For subfields which require relatively smaller funds such as experimental soft-condensed matter physics, and theoretical condensed matter physics, several Indian researchers from different institutions have been able to make notable globally recognized contributions.

In the last 15 years there has been a rapid and diverse growth in areas like nanoscale physics, optics, plasmonics, low temperature physics, spectroscopy of materials and quantum information. There has been welcome growth in many emerging and impacting areas. Reasonable progress has been made in experimental research which requires medium scale funding such as low temperature mesoscopic physics, growth and characterization of various novel materials, and nanoscale devices. This needs to be sustained over the next 10 years.

However, not much activity exists in the areas requiring, potentially risky , large scale funding, such as quantum computation, quantum information, cold atoms, growth of semiconductor-heterostructures, development of high-purity semiconductors, and topological insulators. There is a need for significant effort in new areas.

Some of the funding in these areas is risky; however, the country needs to invest in new emerging areas as trying to be conservative may deprive the country of first mover's advantage and this could be strategically detrimentally for the country. A cautionary tale in this respect is the case of semiconductors within the Indian context. Our country has not been a major player within the semiconductor revolution and we have been unable to "catch up" – this has had detrimental effect on the development of technology and manufacturing. It is also important for manpower training so that new areas be research focus as some of these fields will result in mature technologies and we need trained manpower as well when this happens in a few decades.

India has large pool of young manpower and we can make significant impact. There is a very positive outlook and needs a systematic approach.

Future emerging areas that should pursued in CMP&MS:

1. Quantum computation and information
    a. Superconducting qubits
    b. Topological quantum computing strategies
    c. Cold atoms and ion trap research for simulation and computing
    d. Encryption and cryptography
2. Topological materials and quantum matter
    a. Topological insulators
    b. Weyl and Dirac materials
    c. 2D materials
    d. High quality materials growth – bulk crystals and molecular beam epitaxy
3. Renewable energy materials
    a. Electrode materials for next generation battery design
    b. Perovskite materials for photo voltaic applications
    c. Piezo generators thermoelectric generators for powering internet of things

4. Computational materials discovery
    a. Rational and ab-initio materials discovery
5. Soft matter research and bio-physics
    a. Brain research
    b. Complexity and self-assembly studies

Suggestions for catalyzing growth in emerging areas:

a. Selectivity of areas: A few focus areas need to be chosen and special cells within the agencies need to developed to monitor progress.

b. Time scale of funding: Emerging fields needs a sustained funding for a larger time window for making a global impact. A times scale of 5 years to 10 years is needed with ambitious goals and closer progress monitoring.

c. International peer review and advisory board for targeted programs: As some of the new areas suggested are emerging and the funding investment is potentially risky there is a need to get input from expertise that exists internationally. This can also provide feedback to modify goals appropriately.

d. Infrastructure and capacity building: CMP&MS research globally relies heavily on infrastructure and facilities like synchrotrons, spectroscopy tools, high magnetic field laboratory, high pressure laboratory, and low temperature research facility; at present India does not have many of these facilities.

There is also a pressing need for materials growth facility like single crystals and MBE enabled growth of quantum materials. It is certainly challenging how these growth facilities can be implemented; however, there are different models used internationally for implementation.

Dedicated nanofabrication facilities for quantum technologies. A large number of nanofabrication facilities exist within the country that are funded by other governmental agencies. The needs of quantum technologies and conventional nanofabrication are often orthogonal and specialized infrastructure needs to be setup.

e. Attracting talent:

1. A significant effort should be made to attract new talent. There are just not enough people in the country working in these emerging areas. A special fellowship with start-up grants in the tune of Rs 5 - 7 crores can be used to attract new talent.

2. There is a need to also make India an attractive destination for international visitors like students and postdocs. A mechanism to support these visits is essential.

f. **Travel support for students and postdocs for international travel:**
Funding support for infrastructure and capacity building is essential and has been supported in the recent times. However, there is an urgent need to find mechanisms for support for students and postdocs for attending international conferences, and collaboration visits. Infrastructure and equipment will need know-how to be utilized fully. Techniques for utilization for resources can be rapidly learnt in personal interactions at conferences. In addition, the feedback at the international conferences is key to translating exciting research to impacting publications.

g. **Prize challenges:**
In certain areas prize challenges can be explored to drive research rapidly. Prize challenges have been extensively used by US agencies like DARPA have led to out of the box thinking. These prizes also open up the problem to a broader base and in certain cases may lead to collaboration with industry.