Gravitational waves: the new quest

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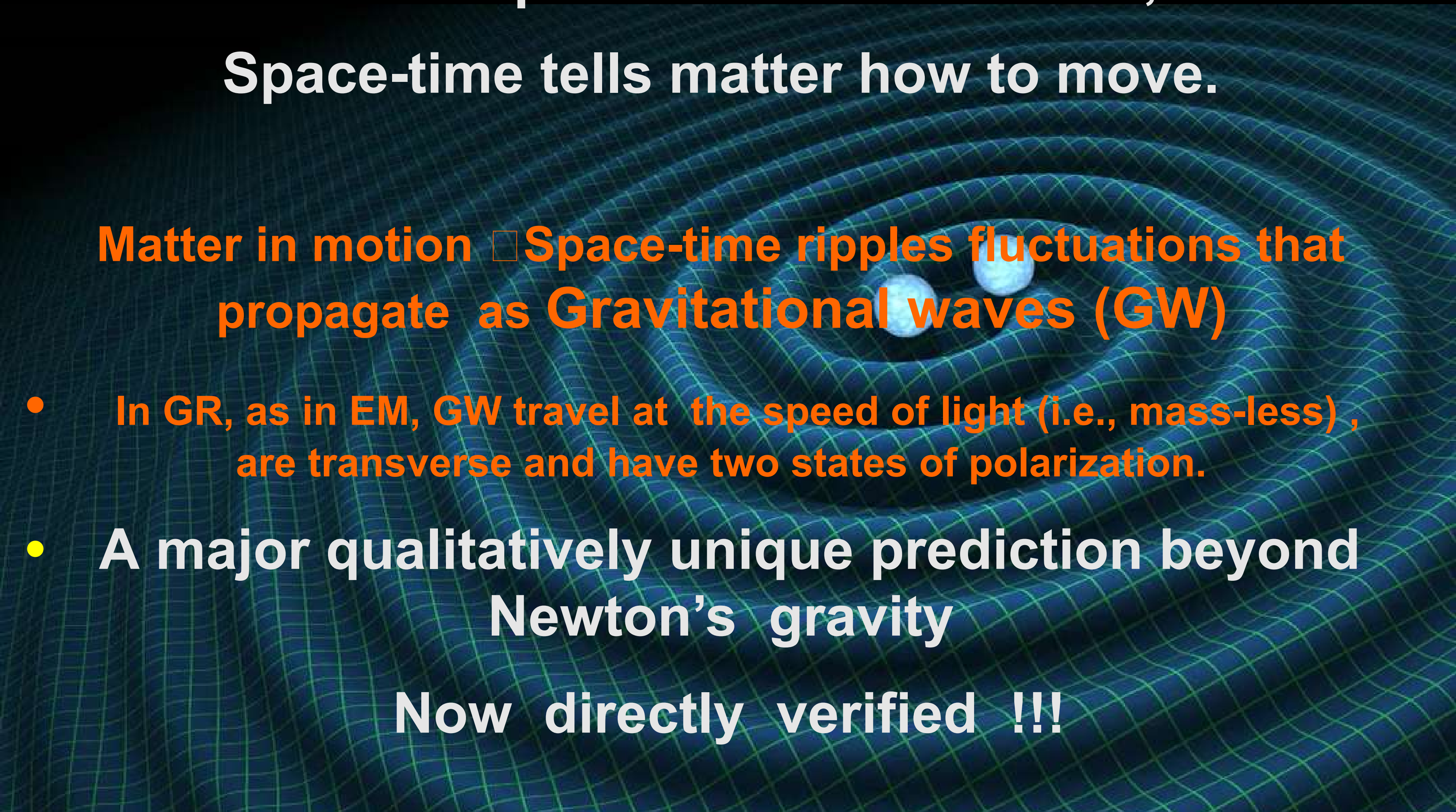
July 16, 2021

Einstein's Gravitation

Matter tells space-time how to curve, and

Space-time tells matter how to move.



Matter in motion → Space-time ripples fluctuations that propagate as Gravitational waves (GW)

- **In GR, as in EM, GW travel at the speed of light (i.e., mass-less), are transverse and have two states of polarization.**
- **A major qualitatively unique prediction beyond Newton's gravity**

Now directly verified !!!

Discovery of the century

Messengers at light-speed brought this news to Earth
on September 14, 2015

LIGO, NSF, Illustration: A. Simonnet (SSU)

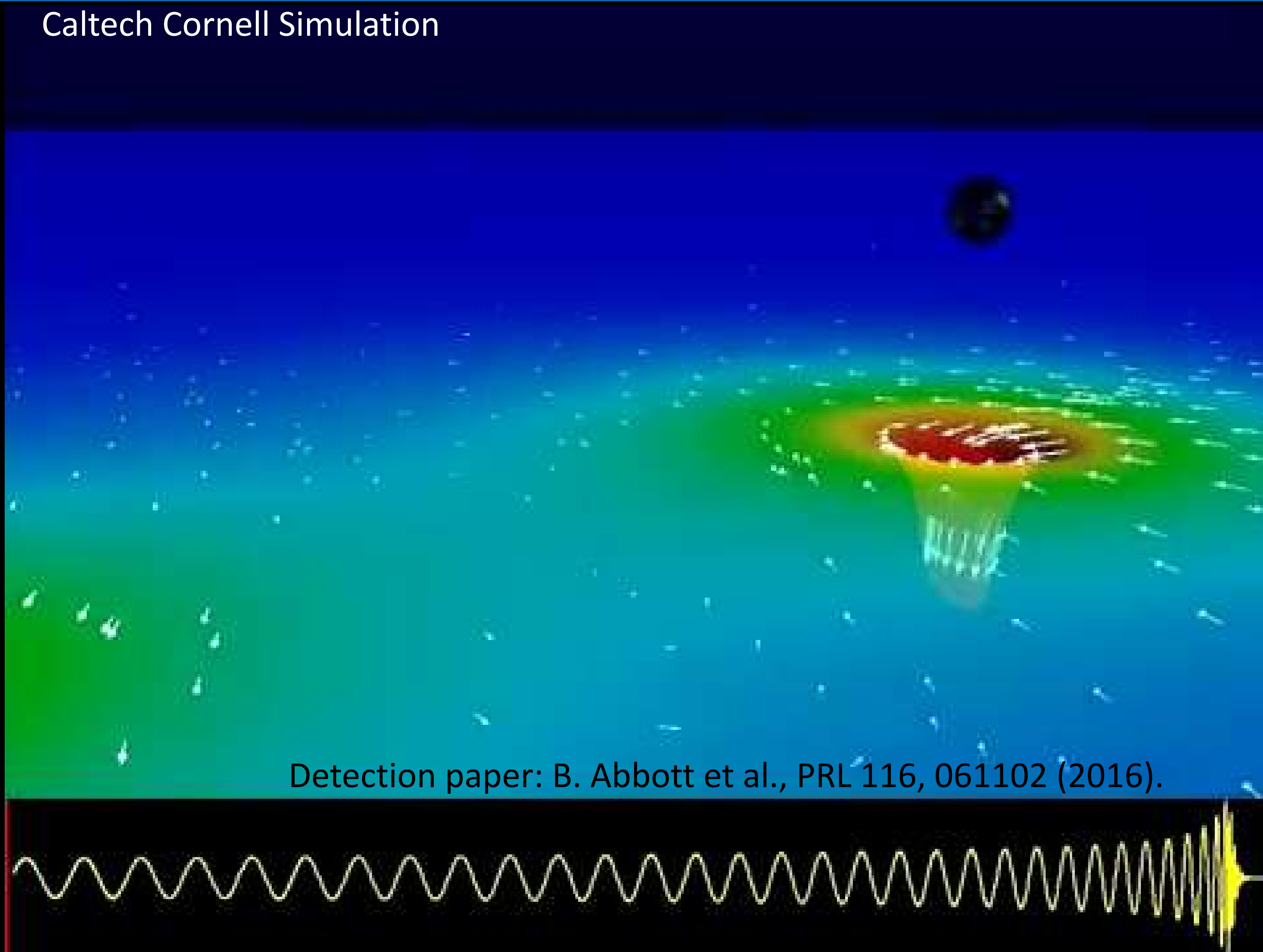
Discovery of the century

Hat trick

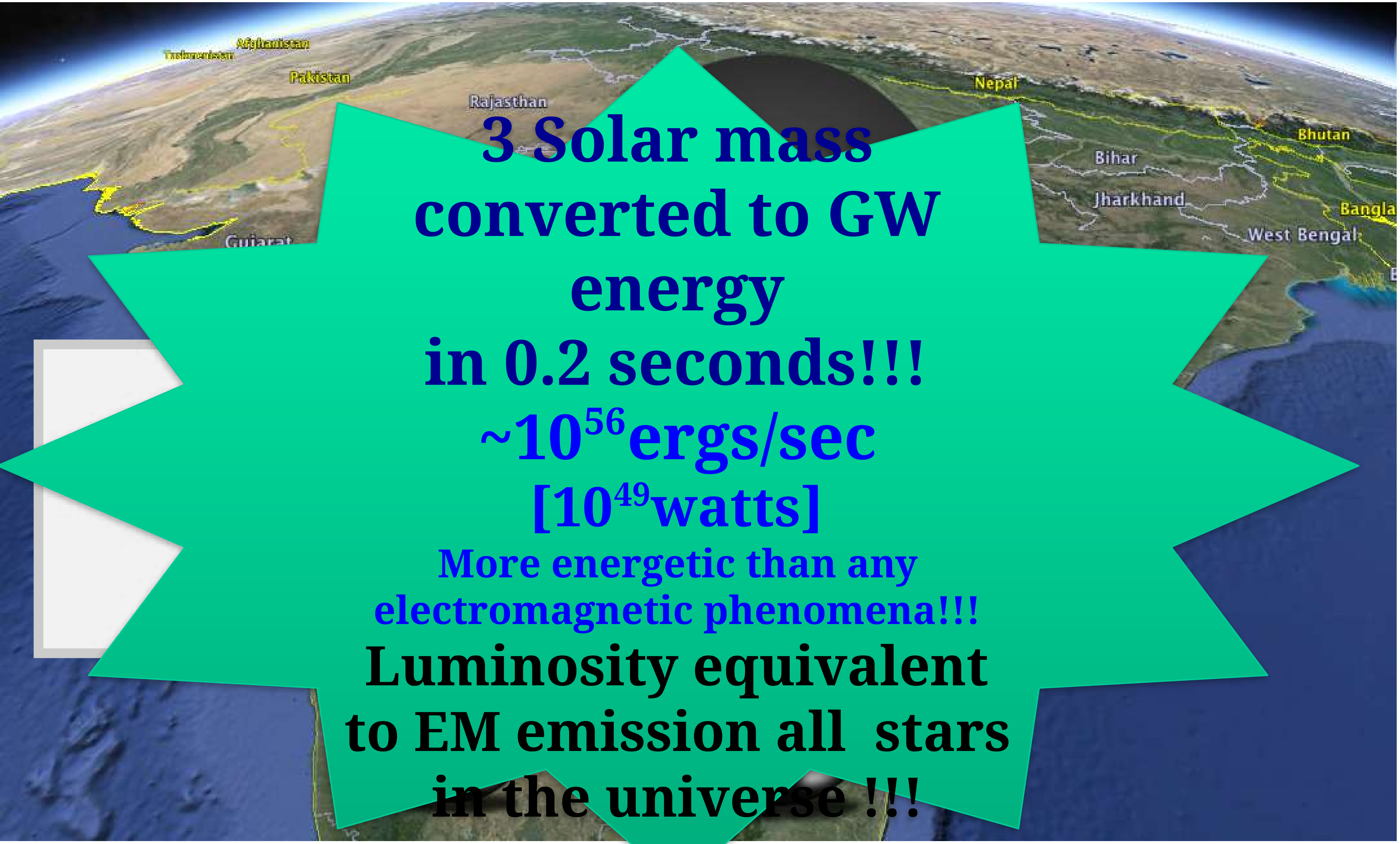
- **Direct Detection of Gravitational Waves**
- **Direct Detection of Blackhole**
- **First Detection of a Blackhole Binary System**

- Black hole ‘ring-down’. C. V. Vishveshwara Nature (1971).
- S. Dhurandhar and B. Sathyaprakash laid the foundation for data analysis(1991).
- Blanchet et al. + Bala Iyer laid the foundations of source modeling (1995).

Black Coalescence revealed



Physics at the Extreme



3 Solar mass converted to GW energy in 0.2 seconds!!!

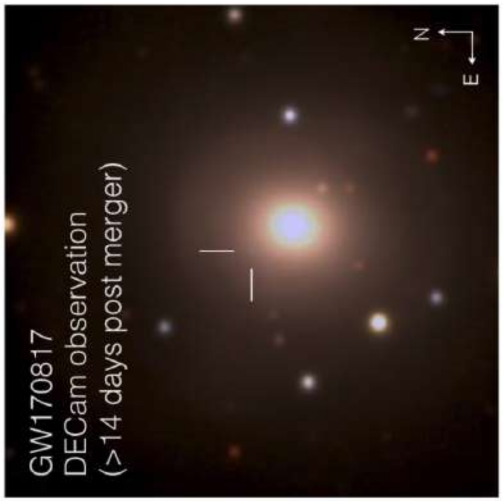
~10^{56}ergs/sec [10^{49}watts]

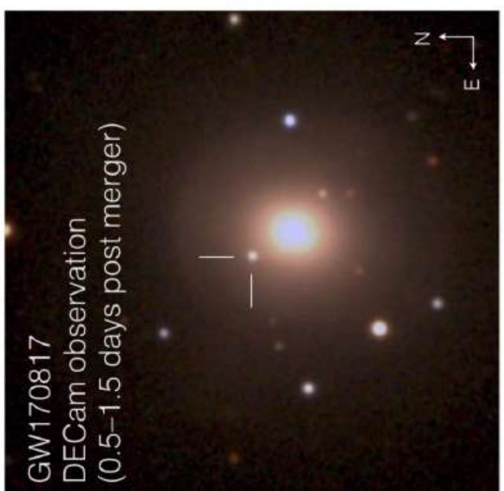
More energetic than any electromagnetic phenomena!!!

Luminosity equivalent to EM emission all stars in the universe !!!

GW Multi-messenger Astronomy

First detection of gravitational waves from colliding **neutron stars**

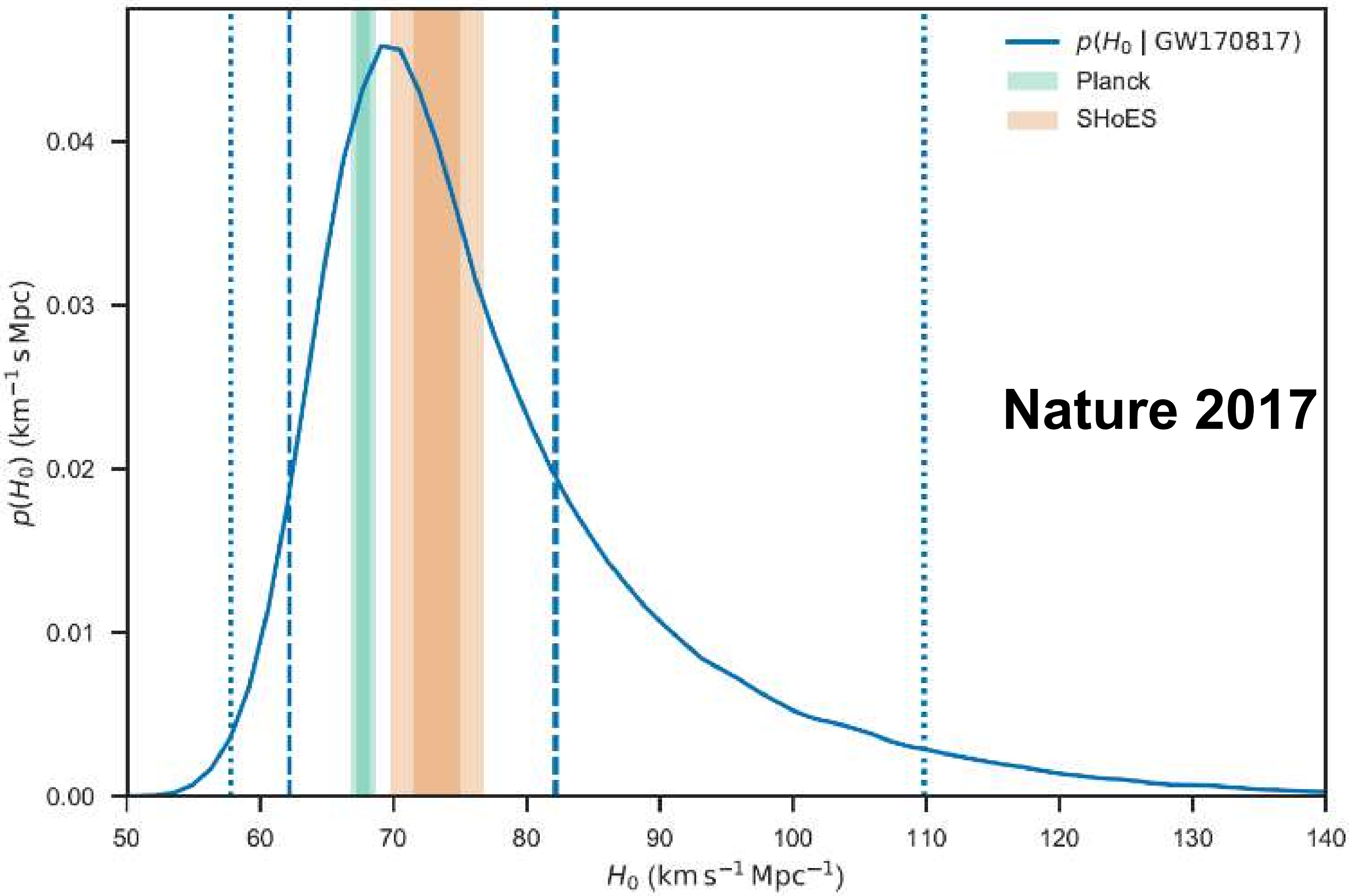




…on Aug 17,2017

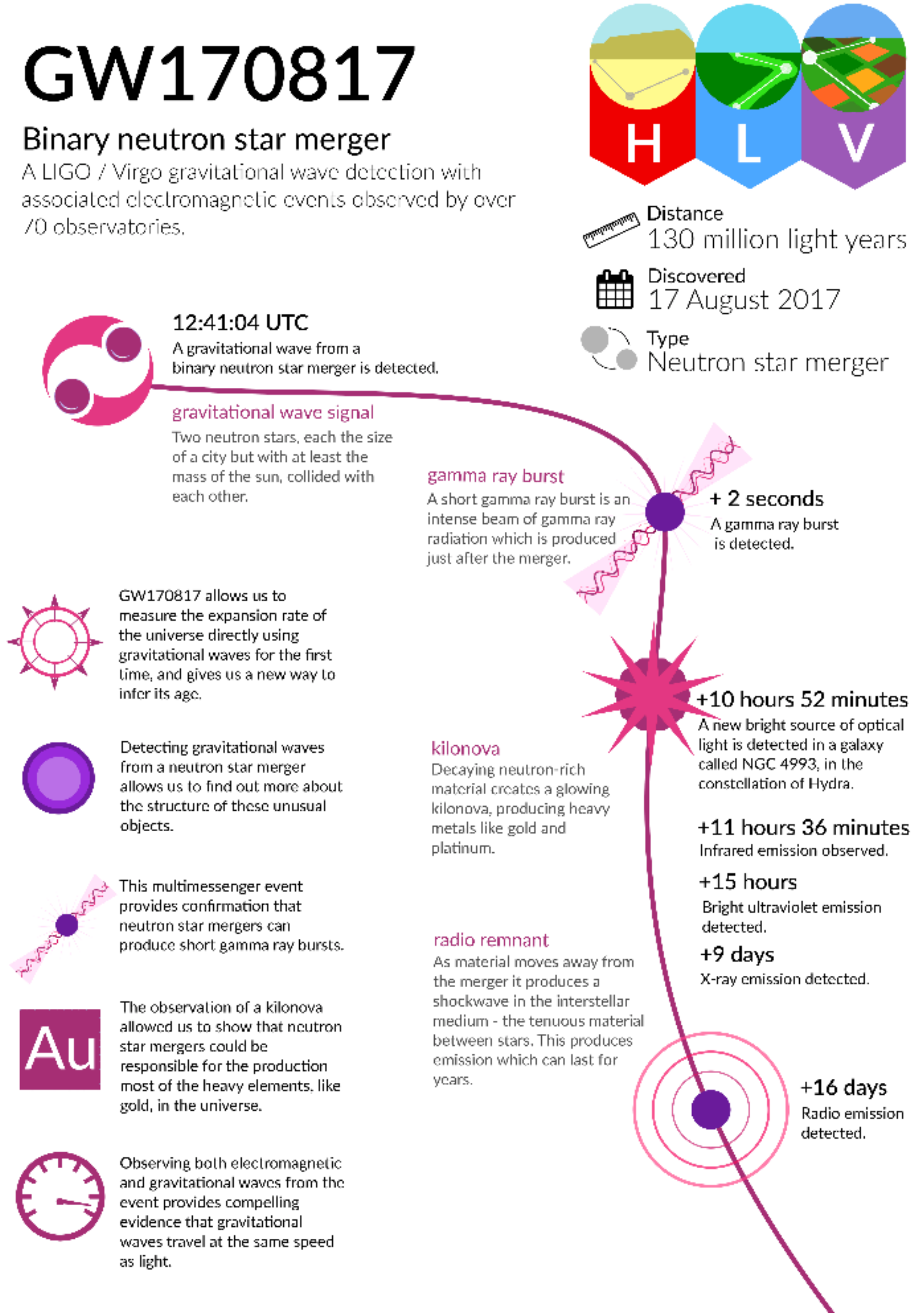
… and GW Cosmology

First measurement of Hubble's constant GW observations



Nature 2017

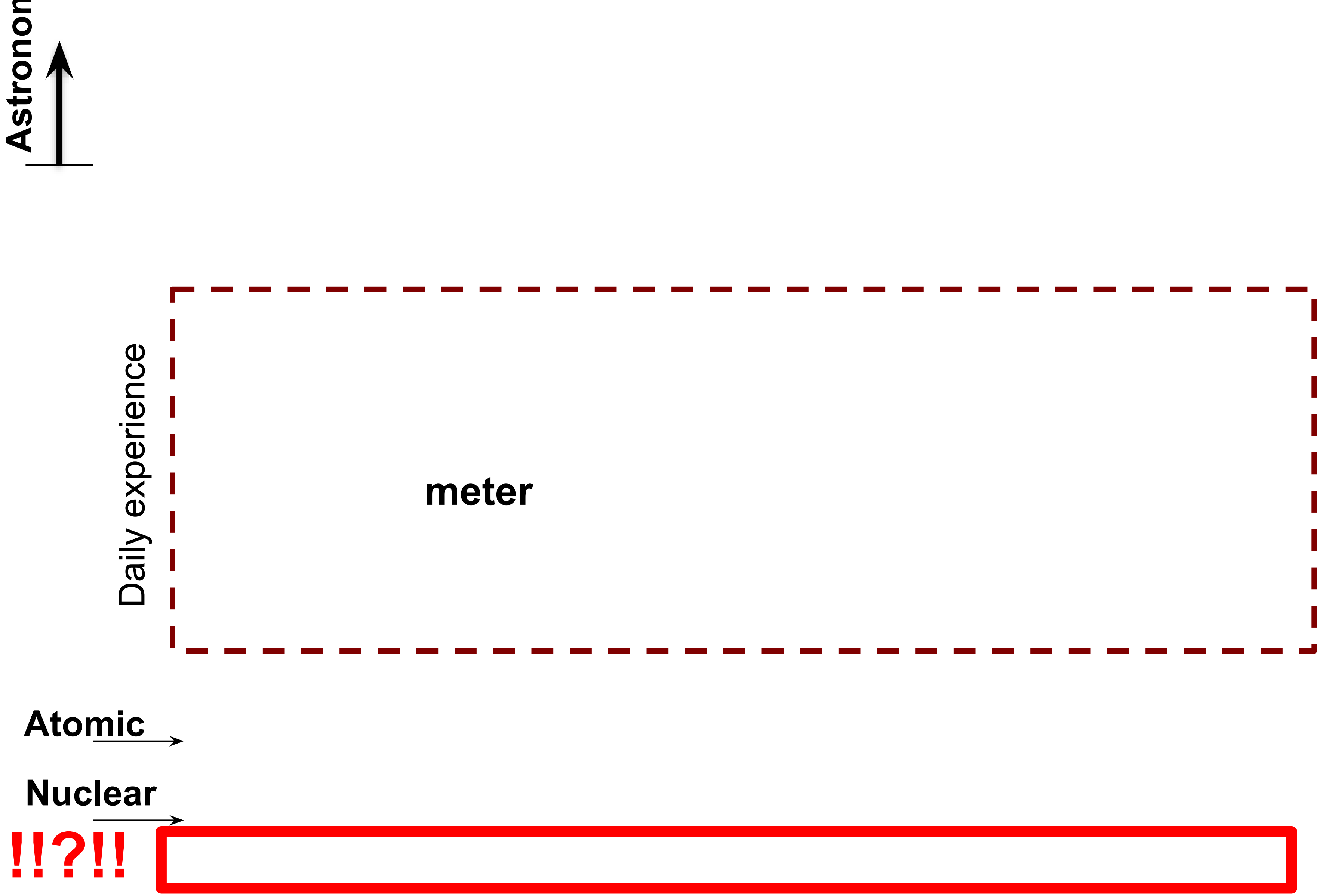
… and providing a Cosmic answer to the Alchemist's quest for gold

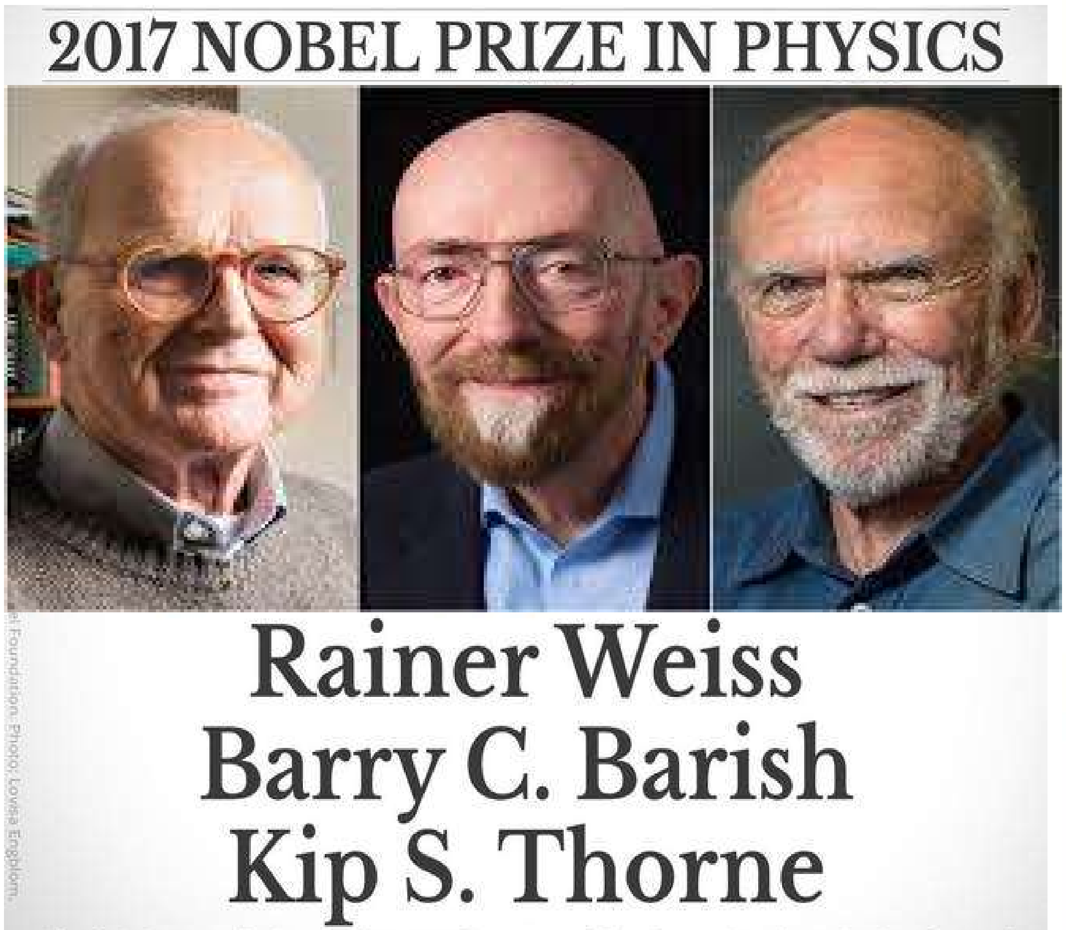


Space-time is stiff !!!!

Peak strain $\Delta L/L$:	10^{-21}	
Maximum displacement ΔL :	2×10^{-18}	m
Size of Hydrogen Atom:	5.3×10^{-11}	m
Size of Hydrogen Nucleus:	8×10^{-16}	m

Boundaries of measurements: Length

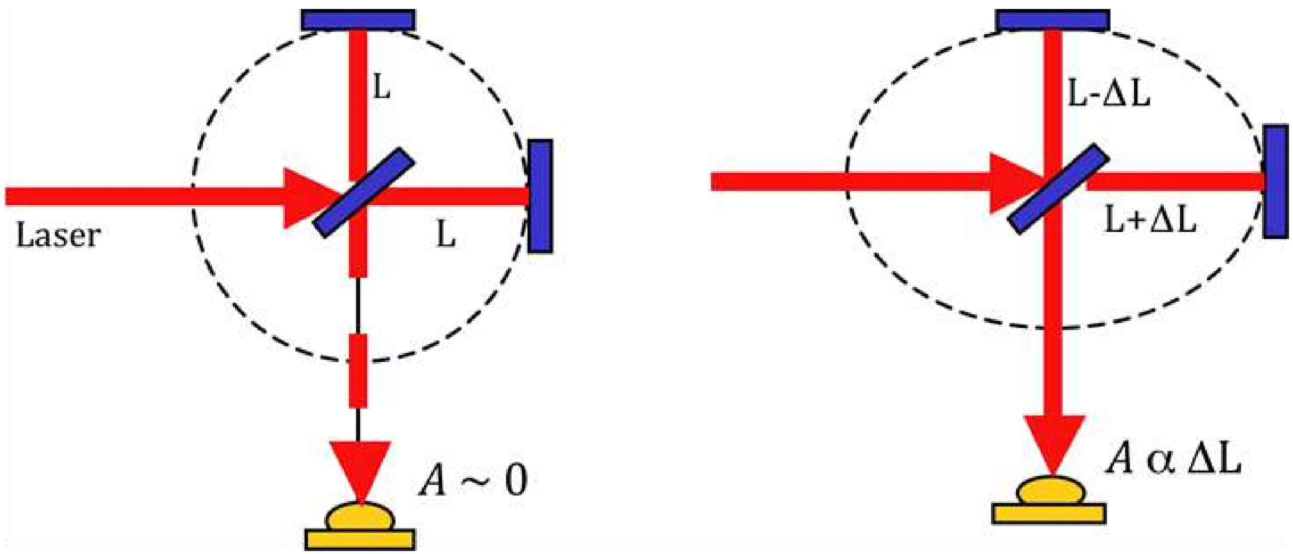




- LIGO discovery paper has 37 authors from 9 Indian institutions,
- About 100 Indian researchers in the Intl. LIGO Science Collab.

Direct Detection of Gravitational Waves

$$\Delta L \sim 10^{-20}\, m/\sqrt{Hz}$$



LIGO

Laser Interferometer Gravitational-Wave Observatory

Large scale ultra-high Vacuum enclosure

Ultra-sensitive Laser interferometer: Optics

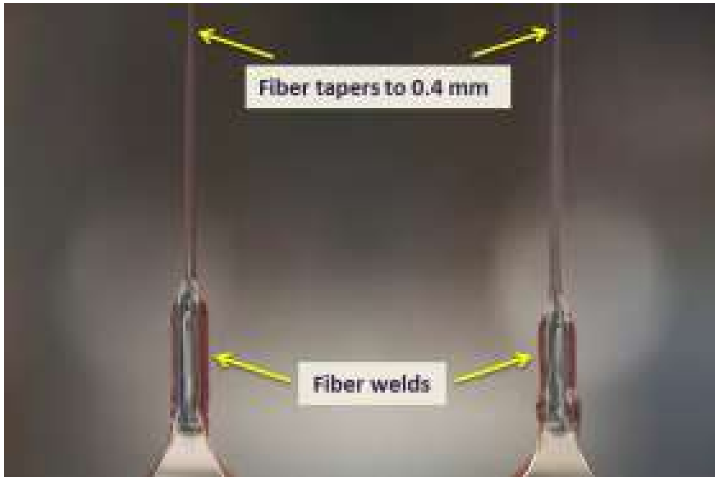
- **Large size**
  - 40 kg, 34 cm
- **Small figure error**
  - 0.15 nm
- **Low absorption**
  - 0.5 ppm
- Lower coating thermal noise

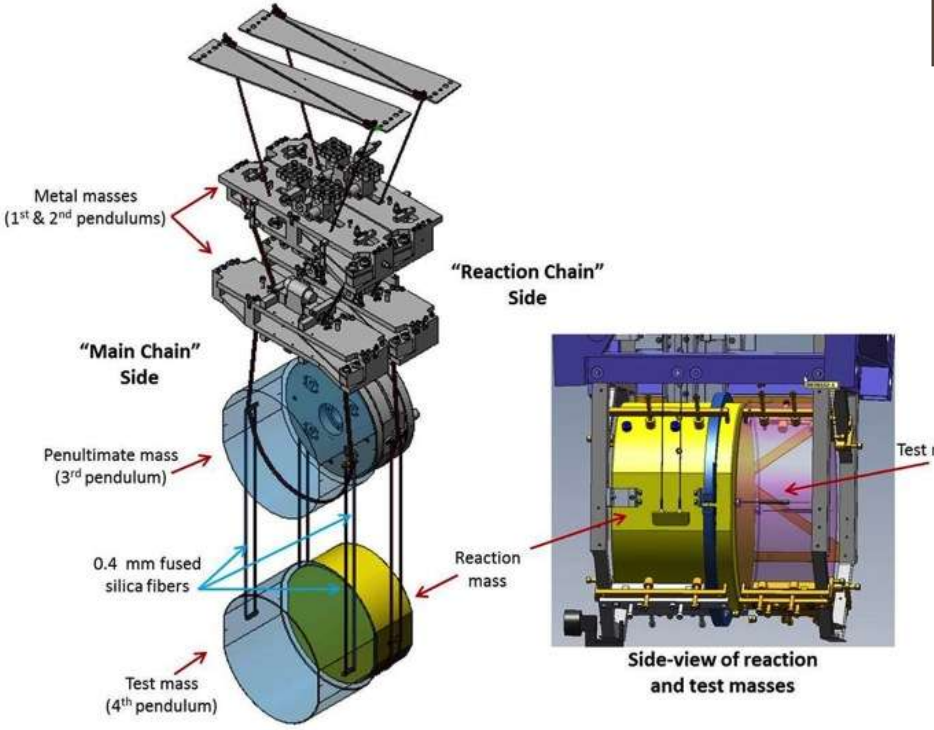
- **Surface specs (λ/3000) : 100 x best telescope optics**
- **Indian laboratories industry is now be challenged to achieve on small scale, e.g., RRCAT 10m prototypes**
- **Technology for such mirror useful for high optical metrology and other specialized applications**

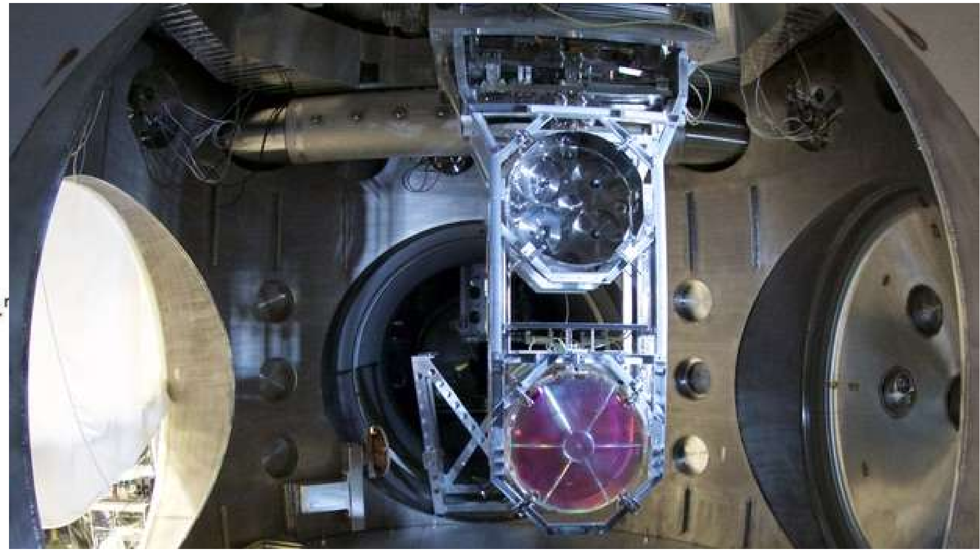
Ultra-sensitive Laser interferometer: Suspension

Mechanical Q~10^8

Seismic isolation ~10^{12}







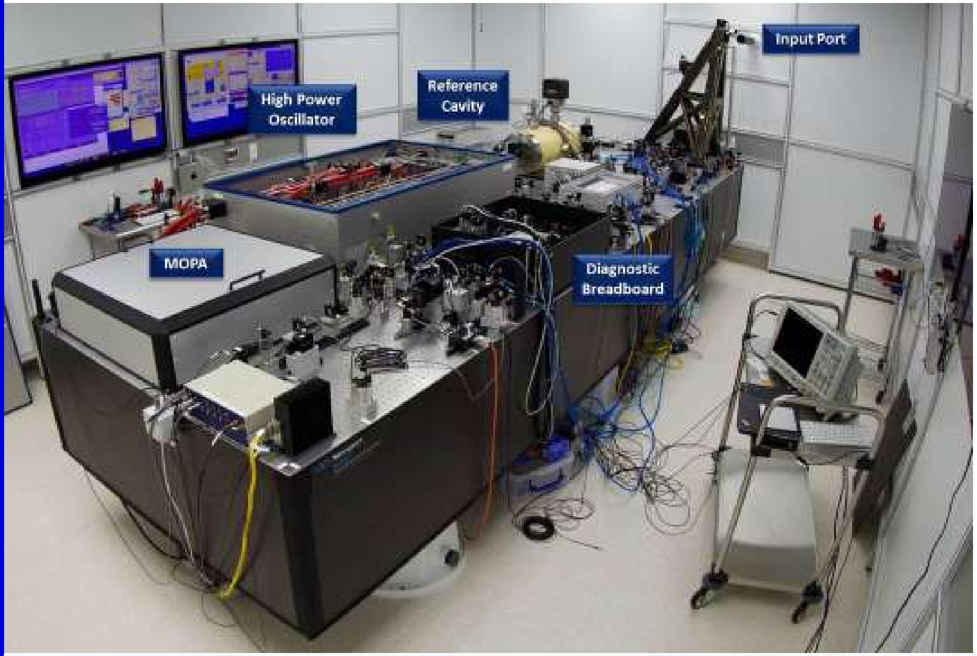
Ultra-Stable narrow line-width Laser

- **Designed and contributed** by Albert Einstein Institute, Germany
- higher power continuous (to beat down photon shot noise)
  - **180W (narrow sub kHz line width)**
- High stability
  - **intensity (parts per billion)** and **frequency stability (mHz)**

Unique globally.

Advanced LIGO laser has spurred RRCAT, IITs and IISER groups to plan development of similar laser capability

Multiple applications of narrow line width laser : Freq time stand, precision metrology, Quantum key distribution, high sensitivity seismic sensors (geo sc.), coherence LIDAR (atm sc.), ….

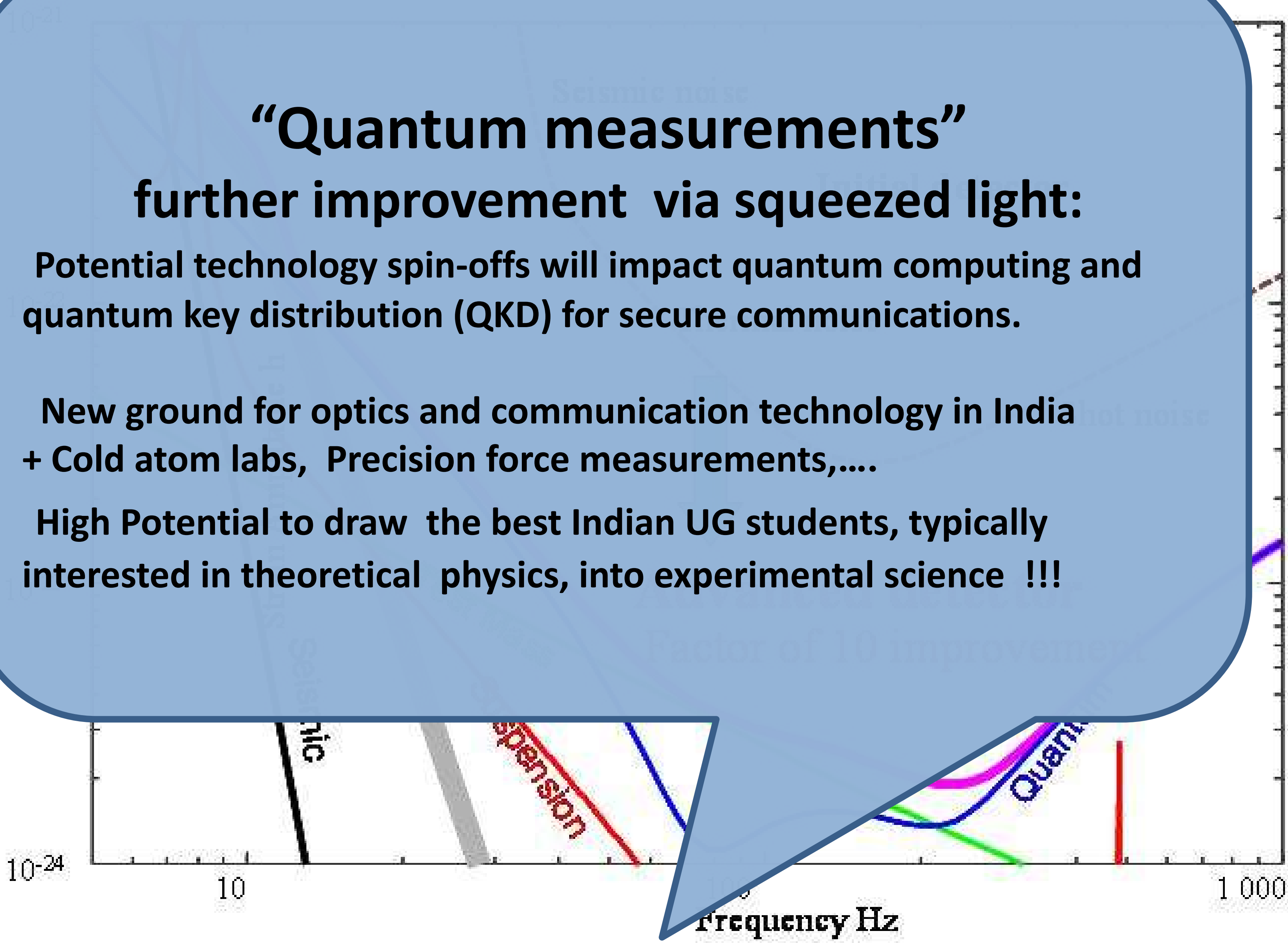


“Quantum measurements”
further improvement via squeezed light:

- 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 !!!



LIGO INDIA

Approved by Union Cabinet on Feb 17, 2016
Now, Site acquired & in construction phase

LIGO-India : Indian quest underway

The LIGO-India Advantage

First GW detection by Advanced LIGO-US observatories

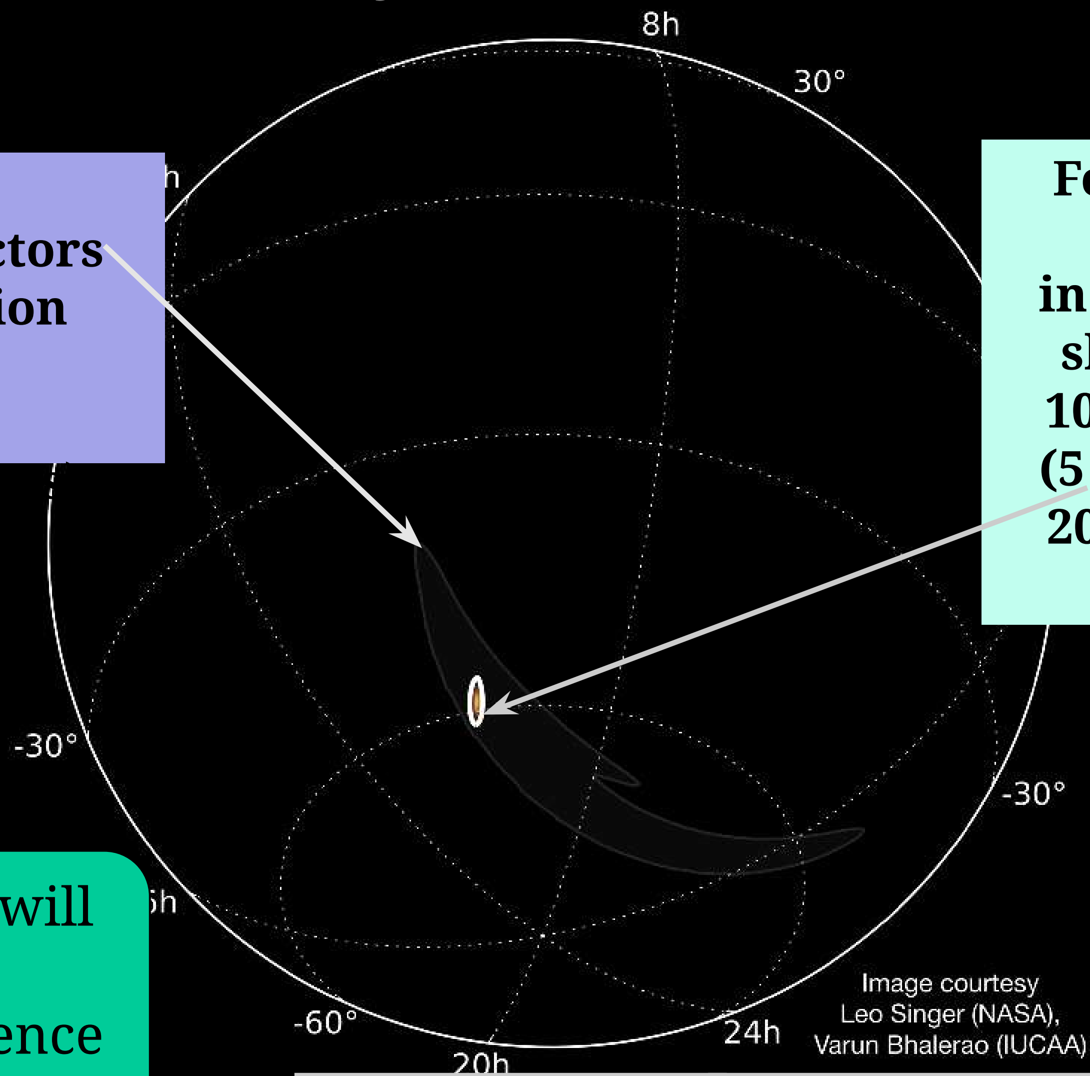


Image courtesy
Leo Singer (NASA),
Varun Bhalerao (IUCAA)

Current:
Two US detectors sky-localization
(620 square degree

Forecast : LIGO-India
in joint operation sky-localization 100 time smaller
(5 square degrees 20 full moons) !!!

LIGO-India will make
a BIG difference !!!!

LIGO-India Project
An Indo-US Collaboration

Funding agencies: NSF (USA) and jointly **DAE**(India) & **DST**(India)

Institutions: LIGO Laboratories, **Caltech** & **MIT** (USA),
LIGO-India: IPR, **IUCAA, RRCAT, DCSEM** (India)

Proposed Indian commitment

- **Construction and Operation of an Advanced LIGO Gravitiational-wave observatory on Indian soil in collaboration with the LIGO Laboratory**
- Infrastructure including 8 km of UHV system (10 million litres) with controls, installation of detector, as well as, the build up the team to build and operate the observatory.

Proposed US commitment

- **The key hardware components of an advanced LIGO detector** (80M USD) + facility design, open technology provided by LIGO-USA.
- Close technology collaboration.

LIGO-India: unique opportunity

Setup, commission & operate by India

By lead institutes: IUCAA (UGC), IPR (DAE), RRCAT(DAE)

IUCAA is the key science stakeholder

- **LIGO-India: Allow full exploitation of *Gravitational-wave observations***

  as integral part of Multi-messenger astronomy

- **High end frontier Technology**

  Transformational for Indian hi-tech capabilities

  in photonics, lasers, controls systems & vacuum

- Strategic Indian Geographical & Demographic advantage

  Implies Global cooperation, not competition

- Research opportunity at home for UG & PG students of S&T

  Implies possibility for extensive HRD and training in frontier areas

LIGO-India 'in principle' Approval
By Indian Union cabinet on Feb 17, 2016

… on a positive note with a BIG BANG !!!!

LIGO-India: Indo-US MoU signed

Indo-US MOU between
Department of Atomic Energy &
Department of Science &Tech., India
and
National Science Foundation, USA
signed on March 31, 2016
at Washington DC
in the personal presence of
Hon. Prime Minister of India

LIGO-India

Continued attention at top-level and recognized nationwide

PM applauds GW community

Narendra Modi @narendramodi · 23h
These scientists have been awarded for detection of gravitational waves, an exceptional scientific accomplishment.
1.7K 4.5K

Narendra Modi @narendramodi · 23h
Congratulations to the Indian scientists who are among the recipients of the Special Breakthrough Prize in Fundamental Physics.
2.4K 5.7K

Mar. 16, 2018: PM at Indian Science Congress

PMO India @PMOIndia · 4h
Our Government has already given the go-ahead to establish 3rd LIGO detector in the country. It will expand our knowledge in basic sciences in the areas of lasers, light waves & computing. I am told that our scientists are tirelessly working towards making this a reality: PM

57 247 821

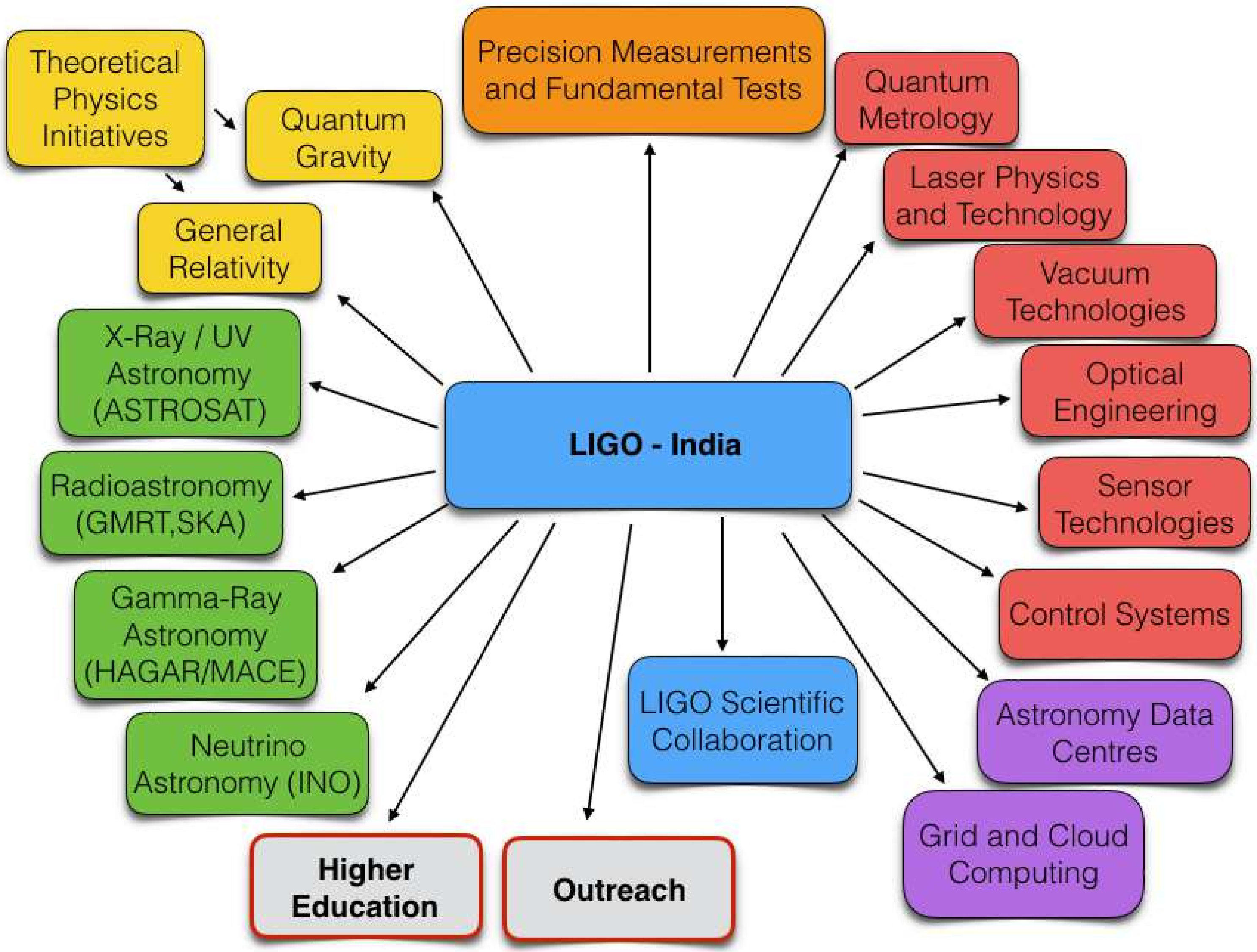
LIGO-India

Engineering concept design of LIGO-India at the site.

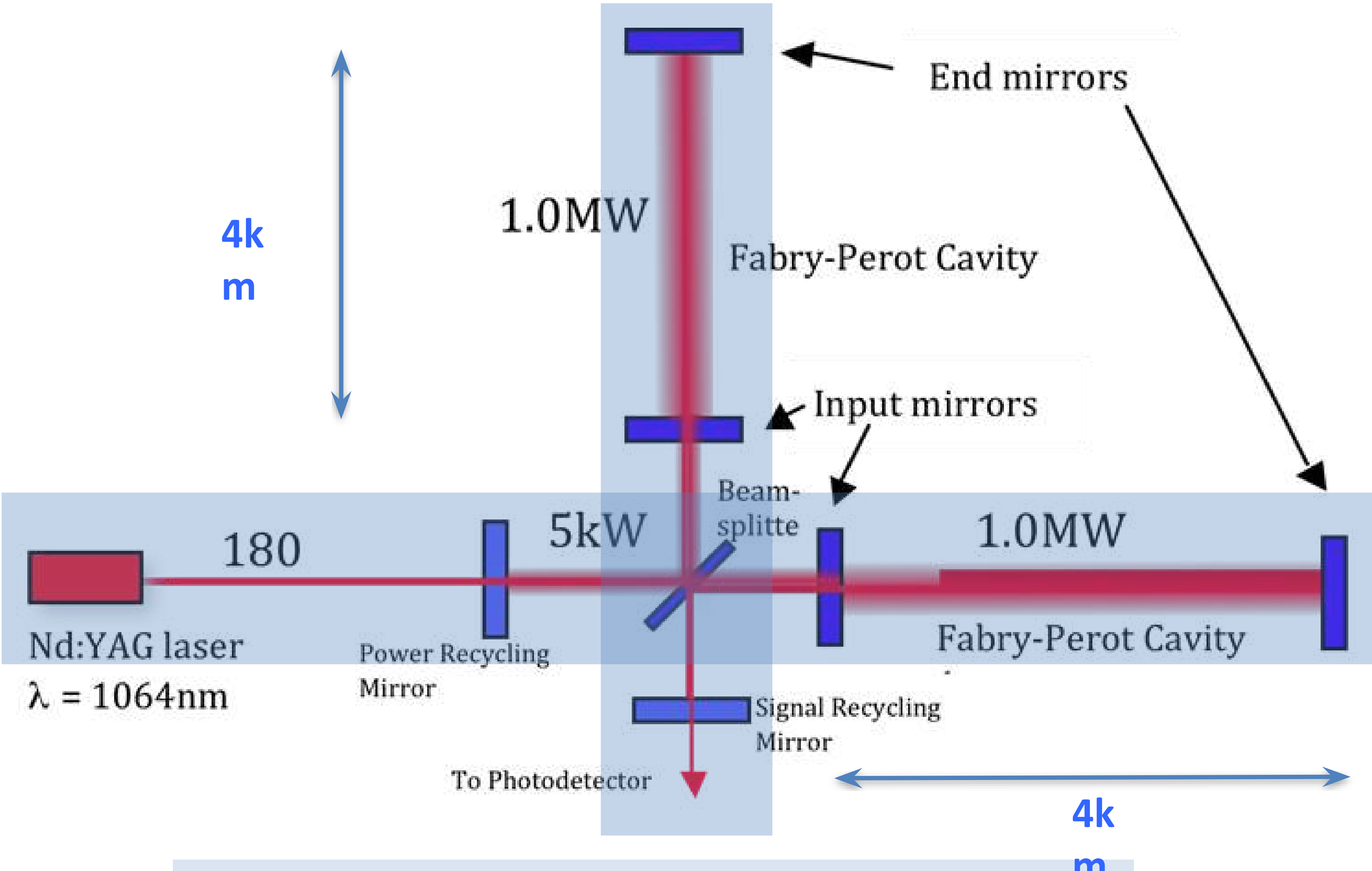
[Courtesy : Tata Consulting Engineers, India]

Terrain data obtained from from SAC, ISRO

Highly Multi-disciplinary Astro^{++}



Schematic of Advanced LIGO detectors



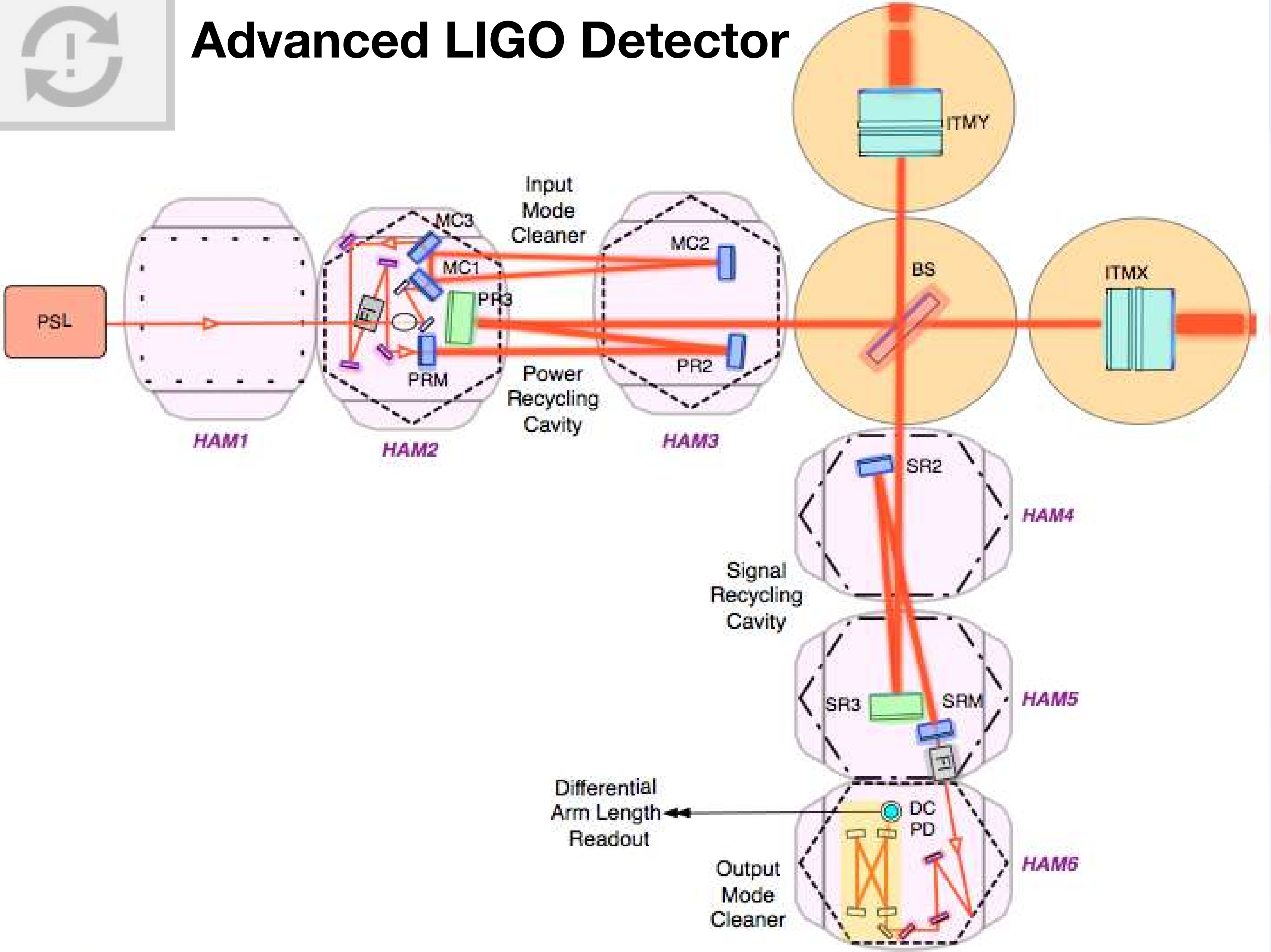
Large scale Ultra high Vacuum to be fabricated in India

10 mega -litres at nano-torr!!!

Large scale ultra-high Vacuum enclosure

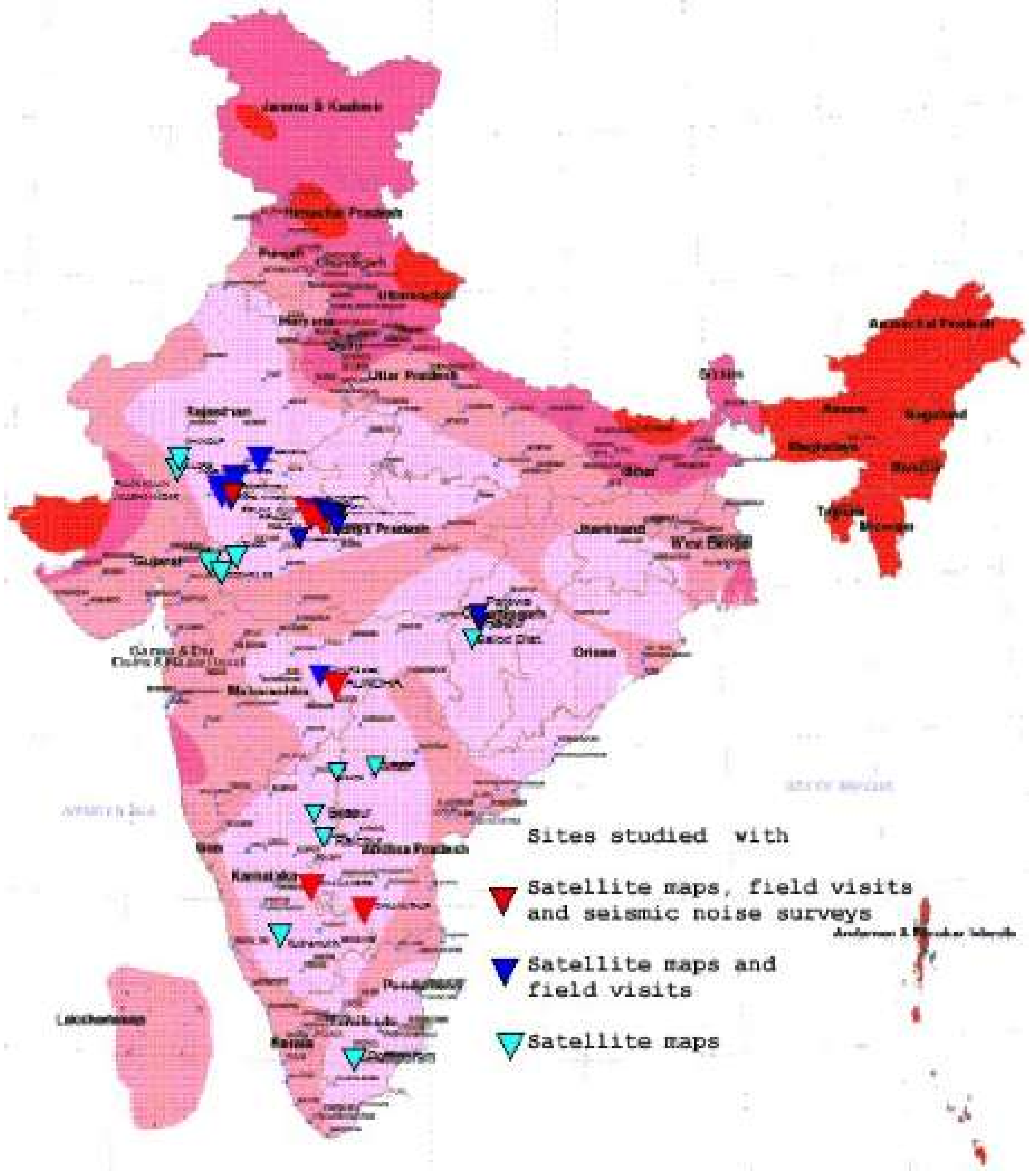
To be fabricated by Industry with designs from LIGO. A pumped volume of 10000m^3 (10Mega-litres), evacuated to an ultra high vacuum of nano-torr (10^{-9} torr).

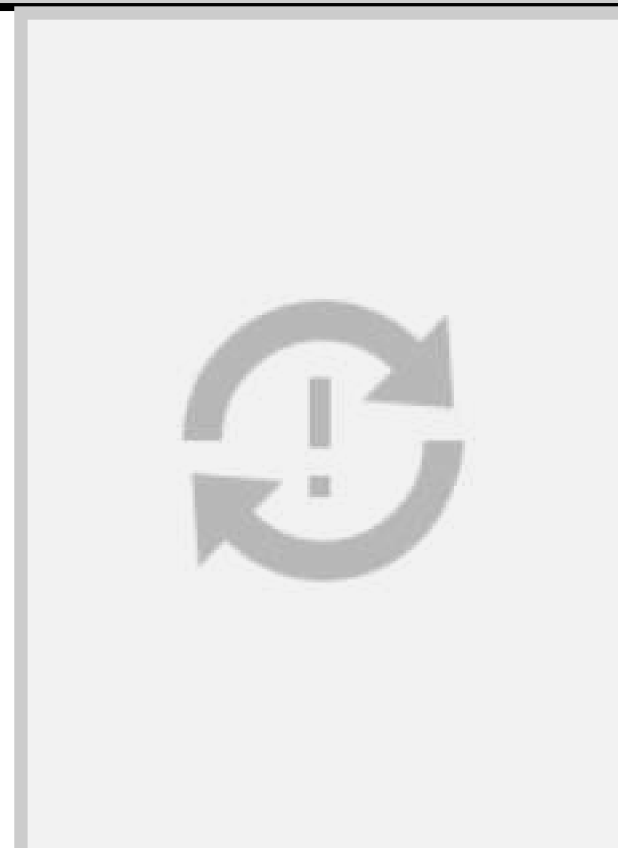
Advanced LIGO Detector



LIGO-India Site search

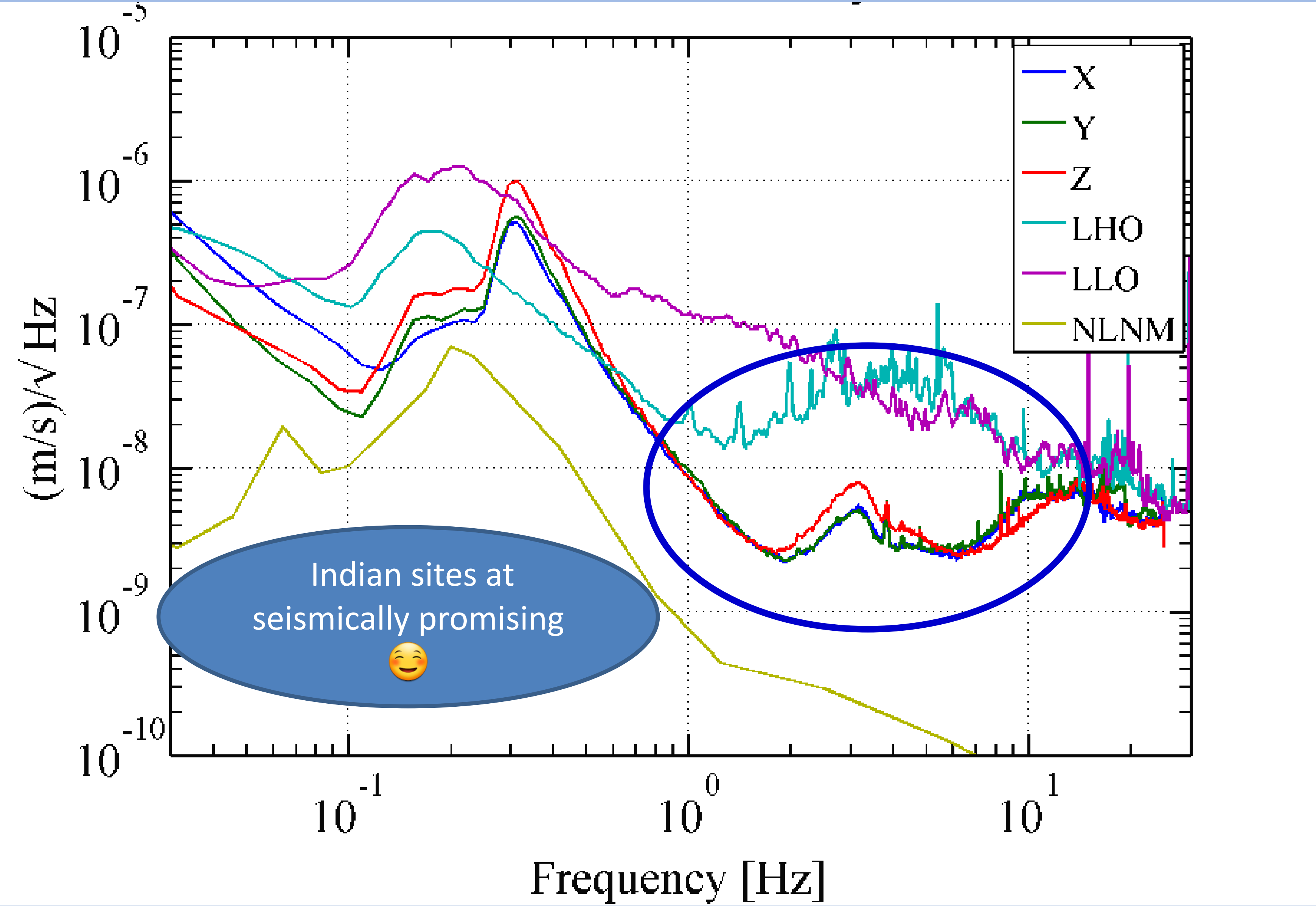
LIGO-India selection
39 site leads followed up
(since Sept 2011)
Recommendation for primary and backup site Jul 2016





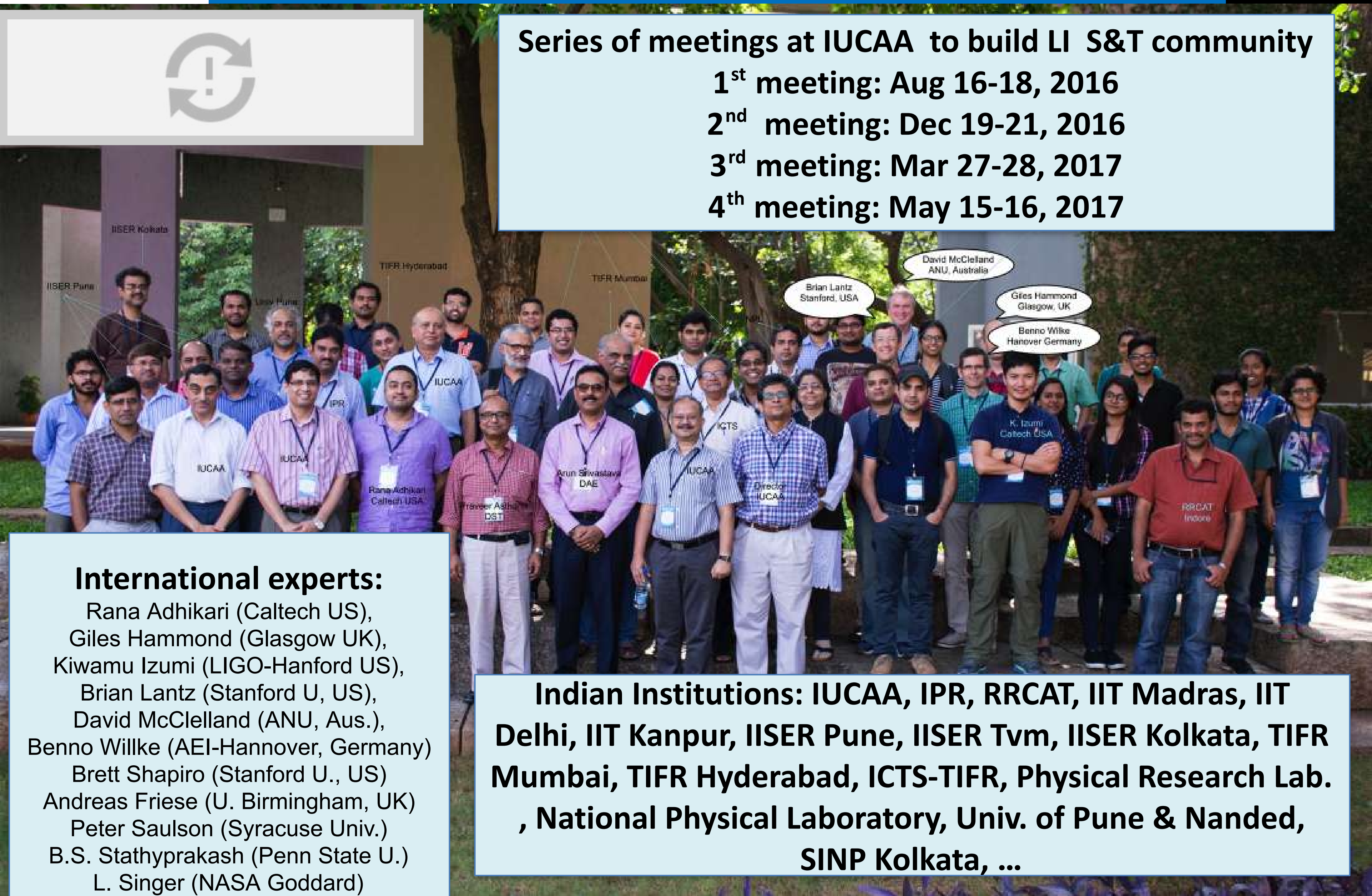
LIGO-India Site Selection

Preliminary Seismic Survey



LIGO-India site

LIGO-India Science buildup



Series of meetings at IUCAA to build LI S&T community

1st meeting: Aug 16-18, 2016

2nd meeting: Dec 19-21, 2016

3rd meeting: Mar 27-28, 2017

4th meeting: May 15-16, 2017

International experts:

Rana Adhikari (Caltech US),
Giles Hammond (Glasgow UK),
Kiwamu Izumi (LIGO-Hanford US),
Brian Lantz (Stanford U, US),
David McClelland (ANU, Aus.),
Benno Willke (AEI-Hannover, Germany)
Brett Shapiro (Stanford U., US)
Andreas Friese (U. Birmingham, UK)
Peter Saulson (Syracuse Univ.)
B.S. Stathyprakash (Penn State U.)
L. Singer (NASA Goddard)

Indian Institutions: IUCAA, IPR, RRCAT, IIT Madras, IIT Delhi, IIT Kanpur, IISER Pune, IISER Tvm, IISER Kolkata, TIFR Mumbai, TIFR Hyderabad, ICTS-TIFR, Physical Research Lab. , National Physical Laboratory, Univ. of Pune & Nanded, SINP Kolkata, …

Emerging Research themes

- **Squeezed light technology:** US LIGO observatories will soon introduce squeezed light in the vacuum port to improve SNR. LI needs concrete plans for early implementation. [Expected partners: RRCAT, IIT Delhi, IISER Pune, ...]

- **Improved Mirror coating :** Thermal noise of the mirror coatings are expected to become the limiting source of noise in the mid frequency band. LI must participate in this global challenge with LSC [Expected partners: SINP, TIFR Hyderabad, ...]

- **Advanced Optics & Laser technology:** Fiber based approach to High power stabilised laser solutions, future cryogenic silicon optics, scatter losses in mirrors in squeezed light cavities, etc. [RRCAT, IIT Madras, IIT Kanpur, IIT Delhi, IISER Kolkata ...].

- **Mitigation Newtonian Gravity noise:** Direct gravitational coupling between moving ground mass and the test masses, a.k.a., Newtonian Noise (NN). Precise measurements of seismic waves, modeling to employ online/offline adaptive noise cancellation techniques [IUCAA, IIT Hyderabad,..]

- **Wind loading noise on LIGO-India building structure:** Variable tilt introduces on the building foundation to strong gusts of wind [DCSEM, IUCAA, BITS Hyderabad, IPR, ...].

- **Data Analysis, Source & detector modeling & GW Astronomy:** Science extraction, Detector characterization, end to end modeling of interferometer and subsystems, EM followup and multi-messenger A&A

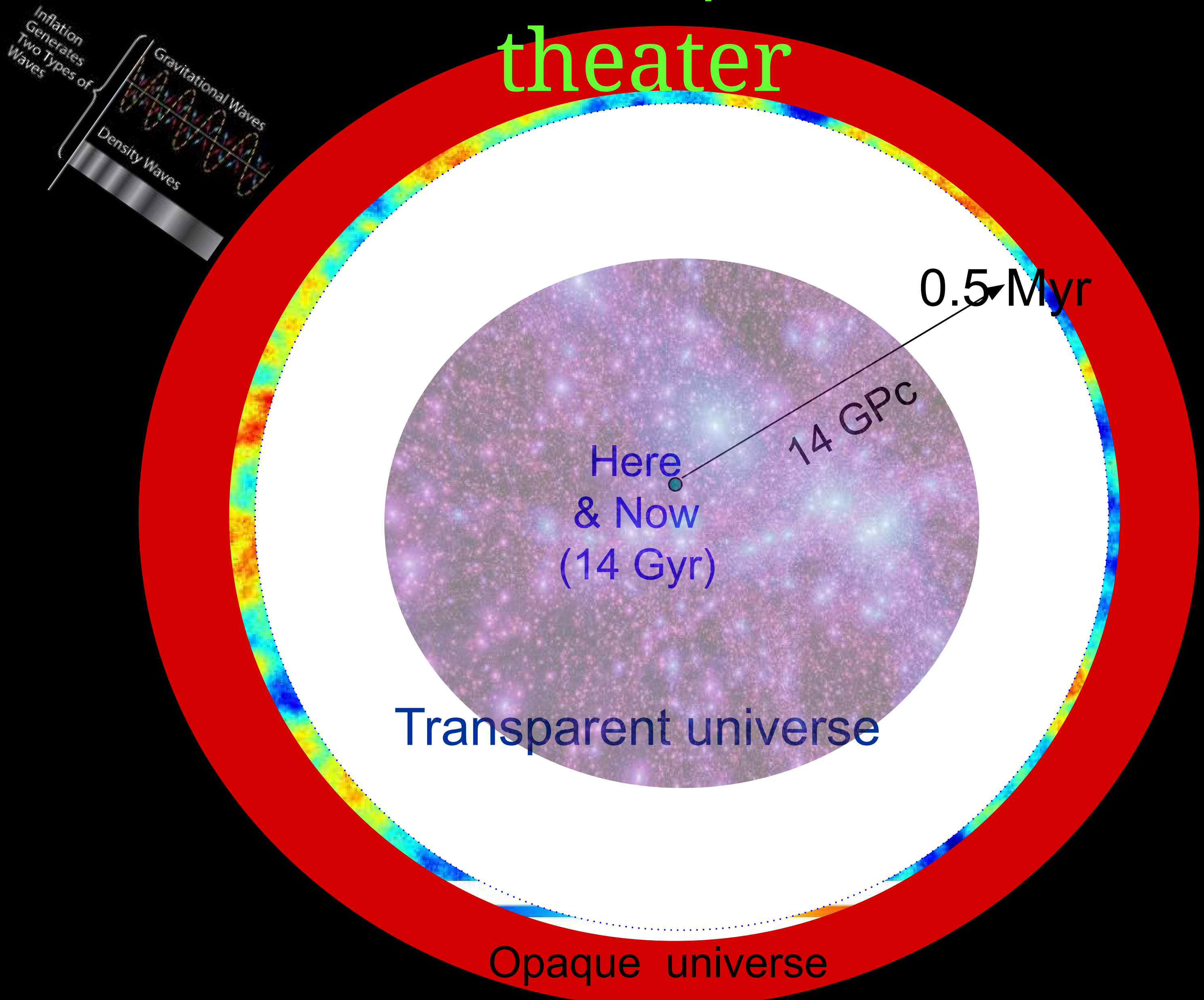
Four windows of GW Astronomy in the next 15 years

Opened 2016

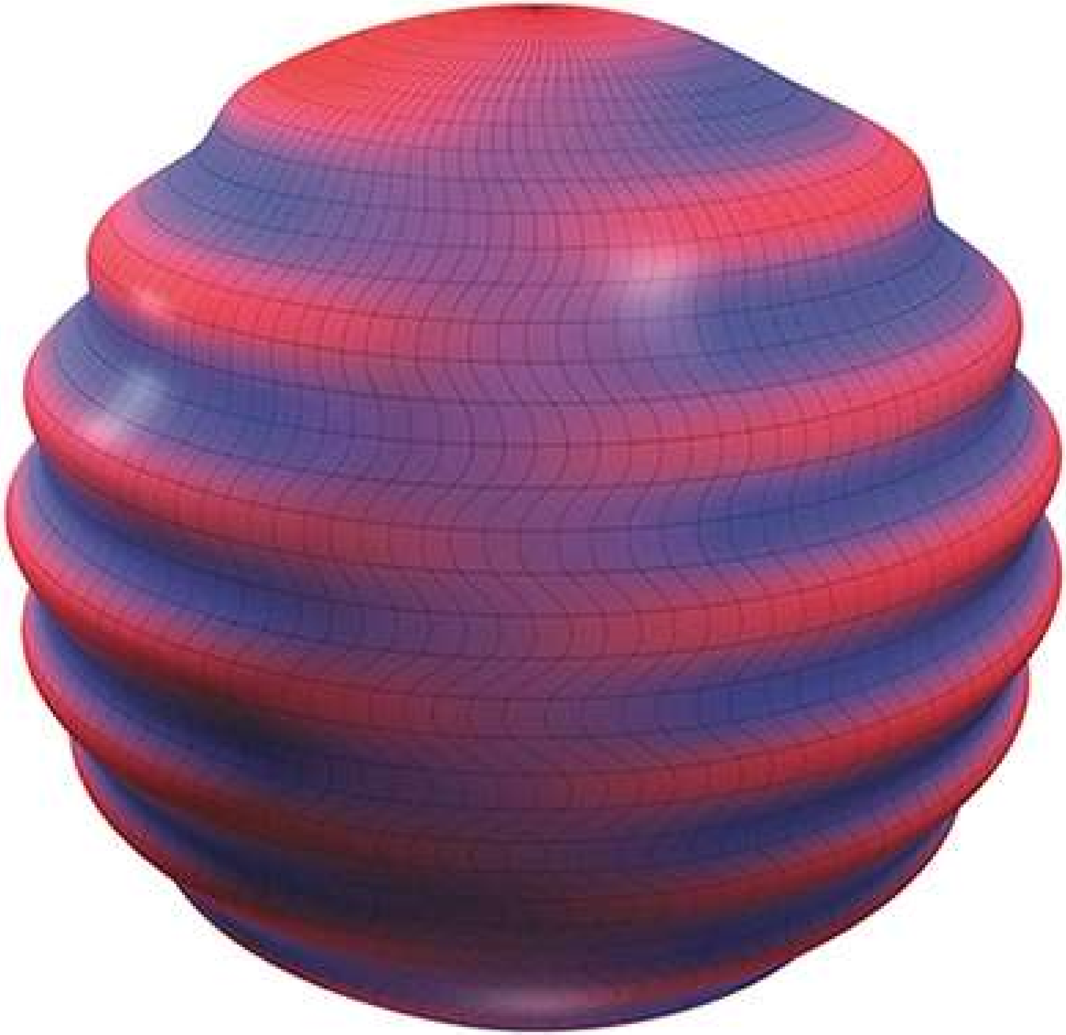
?????

Courtesy: Kip Thorne

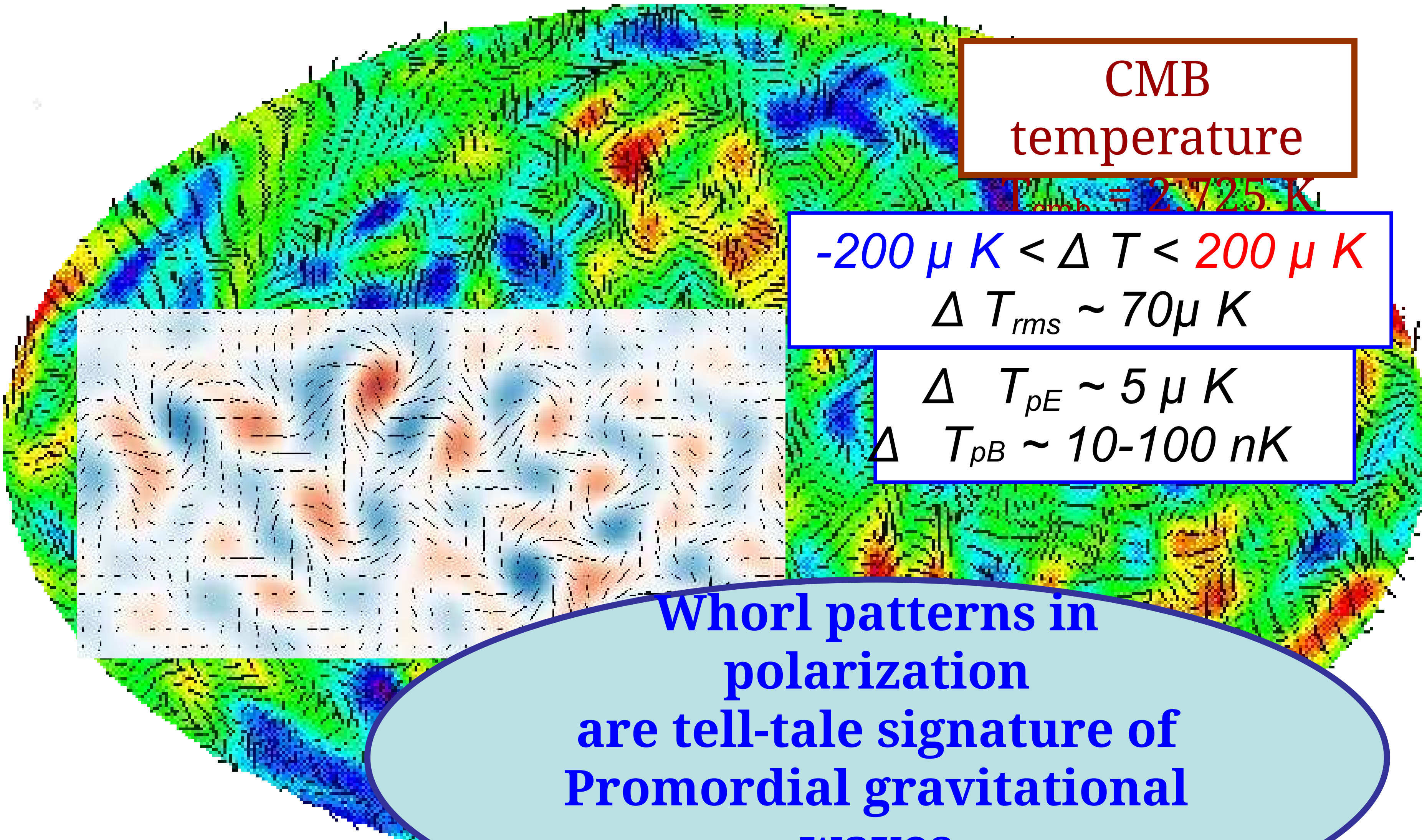
Cosmic "Super–IMAX" theater



Cosmic GW

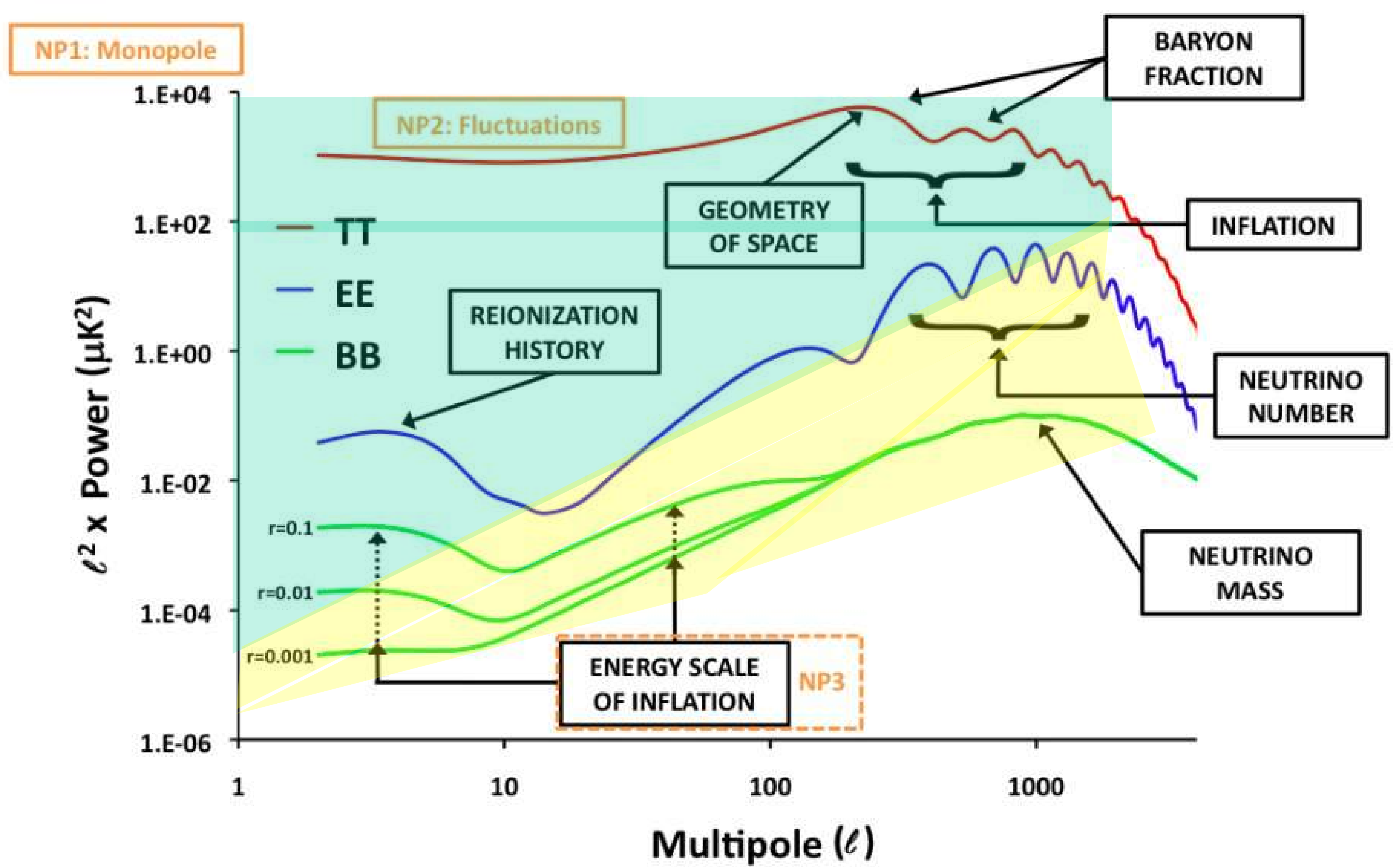


CMB Anisotropy & Polarization



Whorl patterns in polarization are tell-tale signature of Promordial gravitational waves

Cosmic Information in CMB



Quest for Primordial Gravitational waves

- ***A "near-ultimate" CMB polarisation survey***
  (2μK.arcmin sensitivity, 22 bands in 60-900 GHz)
- ***Enhanced spectral characterisation***
  (FT Spectrometer: 36-3000 GHz, sensitivity 100x FIRAS)
- ***Observatory mode (2 years) after survey (4 years)***

Scientific promise

- **Reveal signature of quantum gravity and ultra-HEP in the very early universe**
- **Improve probe of cosmological model by a factor of > 10 million**
- **Map all dark matter and most baryons in the observable universe**
- **Neutrino physics: number of species, total mass and hierarchy.**
- **Unique probe of 'entire'($z<2 \times 10^6$) thermal history of the universe**

CMB-Bharat: a new Indian quest

A Proposal to ISRO on April 16, 2018.

CMB BHĀRAT: AN INDIAN COSMOLOGY CONSORTIUM

CMB-Bharat: a new quest

- **CMB-Bharat:** Cross-institutional Indian cosmology consortium
  Set up formally on Jan 9th at ISRO HQ meet
  ~ 90 members from ~15 institutions/laboratories & growing

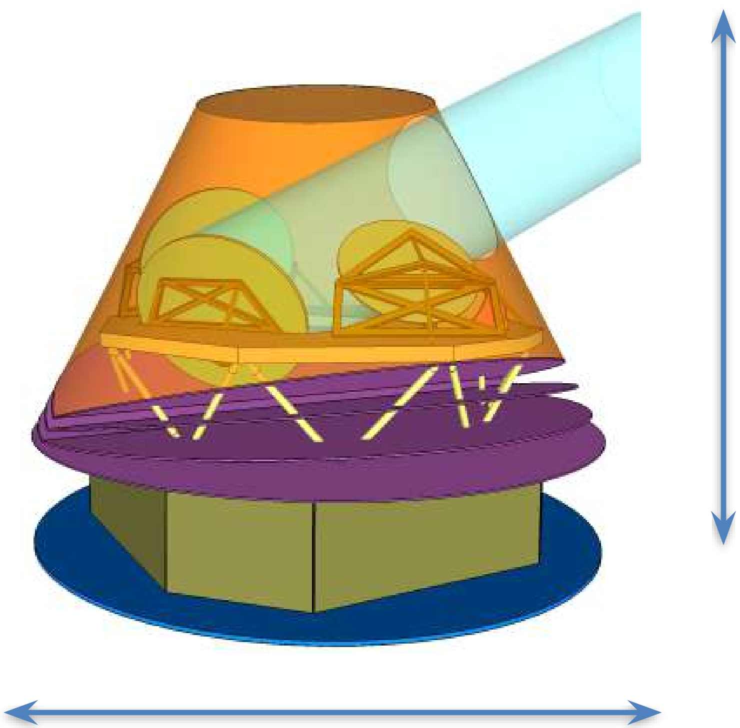
- Meeting organized at ISRO-HQ on Jan 8-9, 2018 to demonstrate an Indian community capable of taking on the science.

- Meeting of ESA-CORE proposal PI & co-PI with Director, SSPO, ISRO in Oct 2018 to explore joint collaboration.

- **ISRO announcement of opportunity (AO) for Astronomy missions & payloads**

- **Proposal by CMB-Bharat to ISRO on Apr 16, 2018.**

CMB-Bharat S/c Specs.



- Total wet mass ≈ 2.0 tons
- Diameter ≈ 4.4 meter
- Height ≈ 4.0 meter
- Power ≈ 2 KW

Adjustments are possible.

Well suited for a GSLV Mk-III launch towards a Sun-Earth L2 orbit

CMB-Bharat Payload schematic

A multifaceted frontier science and astronomy mission

- map sky temperature, linear polarization (~60-1000 GHz),
- spectrum (~30-3000 GHz)
- unprecedented sensitivity, accuracy and angular resolution.

CMB-Bharat: Orbit and scanning

Challenges : - orbitography
- pointing accuracy ≈ 10'
- pointing reconstruction ≈ 10"
- Data flow : ≈ 1 to 8 Mb/s (100 Gb/day)

Boundaries of measurements: Power

Astronomical: Solar
10^{26}watts

Daily experience

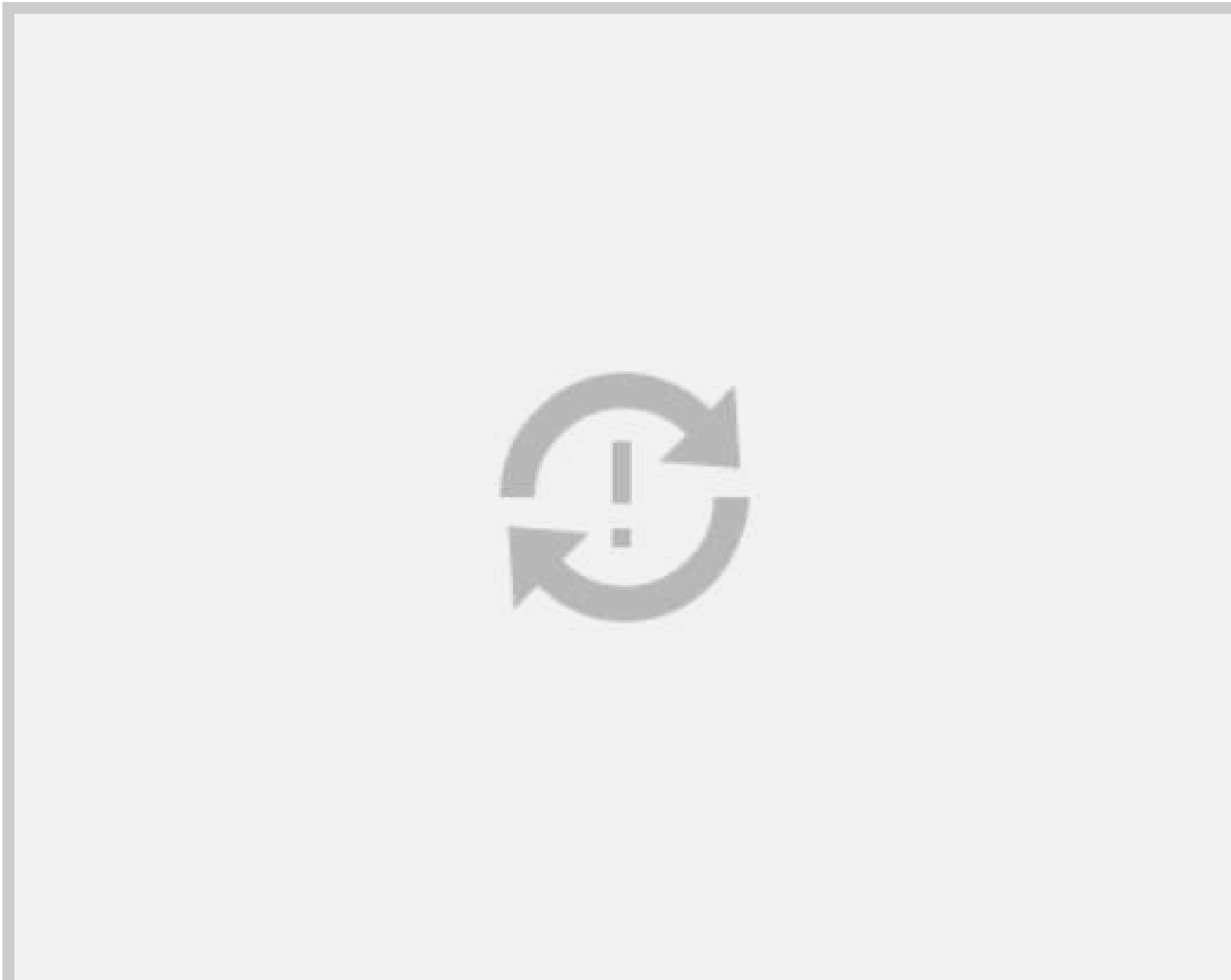
wat
t

FM reception

Cell phone

!!?!!

CMB-Bharat Focal Plane



7800 Polarized Detector channels

3rd generation
CMB space mission
Planck launched 2009

4th generation
CMB space mission

CMB-Bharat ?

Thank you !!!