Subir and the amazing boom in Astroparticle Physics

SubirFest2023
Oxford, 11-13 Sep 2023

Johannes Knapp, DESY

Subir's CV

Subir Sarkar

Rudolf Peierls Centre for Theoretical Physics, University of Oxford,
Clarendon Laboratory, Parks Road, Oxford OX1 3PU, United Kingdom
Tel: +44 (0)1865 273962, Email: subir.sarkar@physics.ox.ac.uk
URL: https://www.physics.ox.ac.uk/our-people/sarkar

Education:

Tata Institute of Fundamental Research, Bombay	PhD	1982
Indian Institute of Technology, Kharagpur	BSc, MSc	1972, 1974

Employment:

2006 – 2021	Professor, University of Oxford (Head of Particle Theory Group, 2011–19)
1998 – 2006	University Lecturer in Physics & Fellow of Linacre College, Oxford
1992 – 1997	PPARC Advanced Fellow & Research Fellow, Wolfson College, Oxford
1990 – 1992	Glasstone Research Fellow, Theoretical Physics, University of Oxford
1987 – 1988	Research Associate, Rutherford Appleton Laboratory, Chilton
1985 – 1986	Visiting Fellow, Department of Astrophysics, University of Oxford
1984 – 1985	Research Associate, European Organisation for Nuclear Research, Geneva
1983 – 1984	Visiting Fellow, Scuola Internazionale Superiore di Studi Avanzati, Trieste
1979 – 1984	Research Associate, Tata Institute of Fundamental Research, Bombay

Research interests:
Theory: Astroparticle physics; Cosmology; High energy astrophysics; Particle phenomenology
Experiments: CERN WA-66 (1985), Auger (2003–12), IceCube (2004–), CTA (2010–), QSHS (2019–), Rubin-LSST (2021-)

Publications: ADS, arXiv, Google Scholar, INSPIRE, ORCID, Web of Science (448 papers, 81,237 citations, h-index=97)

Awards:

- Bruno Rossi Prize of the American Astronomical Society to the IceCube Collaboration, 2021 [shared]
- IUPAP-TIFR Homi Bhabha Medal & Prize, 2017
- Niels Bohr Professorship, University of Copenhagen, 2013–18
- Senior Fellowship, UK Science & Technology Facilities Council, 2006–09
- Advanced Fellowship, UK Particle Physics & Astronomy Research Council, 1992-97
- Indian National Science Talent Scholarship, 1969–78

Visiting Positions:

- Adjunct Professor, Raman Research Institute, 2019–22
- Associate, Discovery Center, Niels Bohr Institute, Copenhagen, 2010–20
- Associate, Institute of Particle Physics Phenomenology, Durham, 2011–12
- Adjunct Professor, Saha Institute of Nuclear Physics, Kolkata, 2008–13
- Adjunct Professor, Tata Institute of Fundamental Research, Mumbai, 2006–09

Academic Service:

⋆ Member, Particle Data Group (2001–)
⋆ Advisory Board: Sant Cugat Forum on Astrophysics (2012–); Helmholtz Alliance on Astroparticle Physics (2012–17); Gruber Cosmology Prize (2014–20); Institute of Physics, Universiteit van Amsterdam (2016-21)
⋆ Editorial Board: SciPost (2016–), Pramana (2013–20), European Physical Journal C (2012–15)
⋆ Scientific Council, International Center for Theoretical Physics Asia-Pacific, Beijing (2018–)
⋆ Steering Committee, European Centre for Astroparticle Theory (2019–20)
⋆ Member, Scientific & Technology Advisory Committee, KM3NeT (2013–20); Requirements Review Panel, CTA (2012)
⋆ Member, IUPAP Commission C4: Astroparticle Physics (2022–25); Programme Review Committee, ApPEC (2005–14); Science Advisory Committee, ASPERA (2007–12); Science Vision Working Group, ASTRONET (2006–08)
⋆ Steering Committee, Astroparticle Physics Group, UK Institute of Physics (2006-08)
⋆ Coordinator, EU Marie Curie Research & Training Networks: UniverseNet (2006–10), Supersymmetry & the Early Universe (2000–04); Member, EU Marie Curie Initial Training Network: UniLHC (2009–13)
⋆ Chair, Consultation Panel on Astroparticle Physics, STFC Programmatic Review (2008)
⋆ Co-ordinator, Oxford-India Network on Theoretical Physical Sciences (2006–21)
⋆ Referee: EC, ERC, ESA; FNU, Denmark; AERES, France; Humboldt Stiftung, DFG & Helmholtz Gemeinschaft, Germany; Ministry of Education, Greece; DAE & DST, India; ANVUR & INFN, Italy; NWO, Netherlands; Royal Society of New Zealand; NRF, South Africa; SNSF, Switzerland; Leverhulme Trust, Royal Society, EPSRC & STFC, UK; DoE & NSF, USA

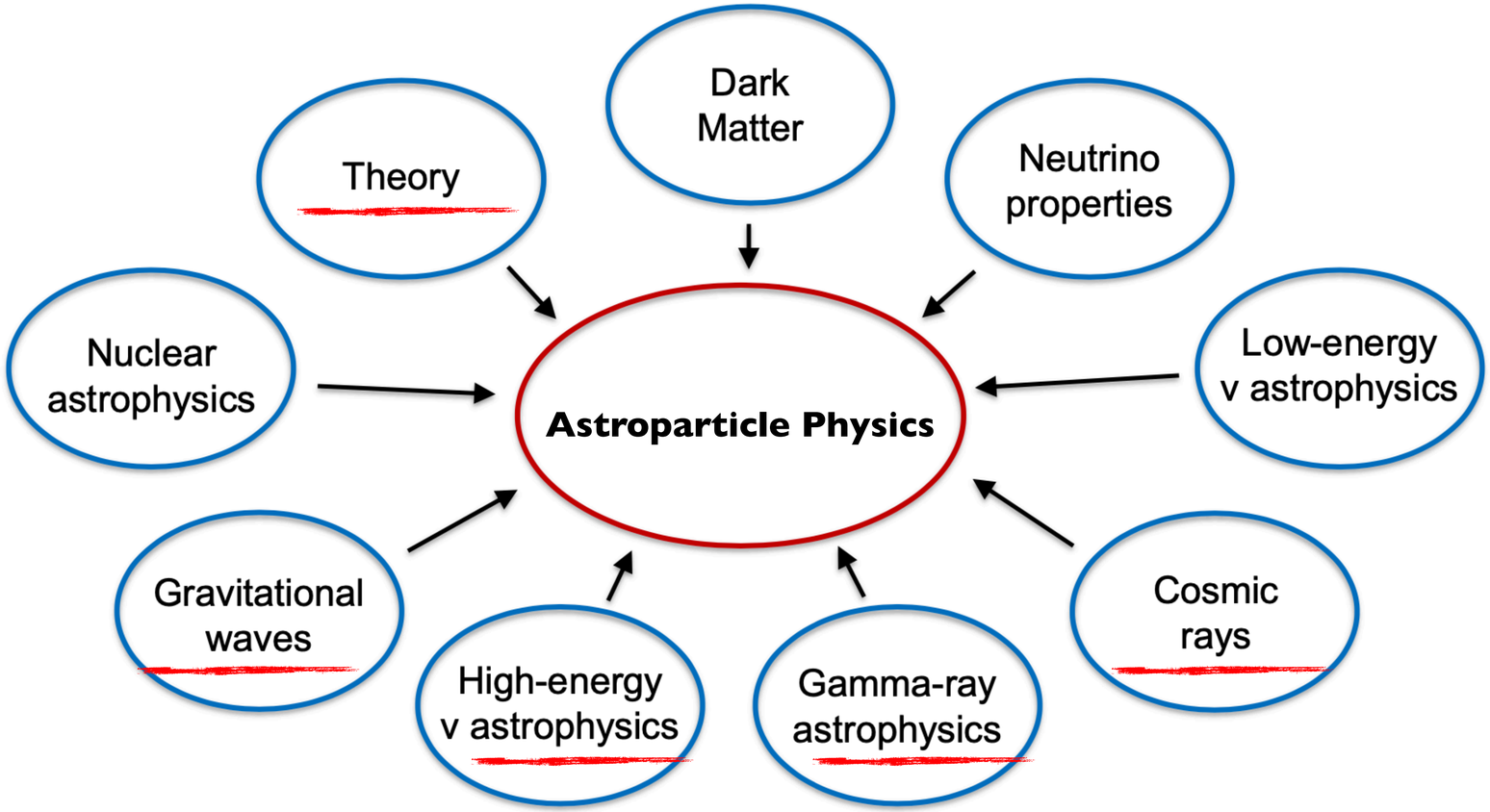
1982	PhD TIFR, Bombay
1984	Postdocs at TIFR Trieste, CERN, RAL
1990	Staff at U Oxford
2019	formally retired

Theory,
Astroparticle Physics, Cosmology,
High-Energy Astrophysics, Early Universe,
Particle Phenomenology

but always close to Experiments:
CERN WA-66 (1985), Auger (2003-12),
IceCube (2004-), CTA (2010-),
QSHS (2019-), Rubin-LSST (2021-)
The physics behind, Methodology, Statistical data analysis

Many achievements, services, honours

Astroparticle Physics



Relation to Particle Physics:

- Nature of DM
- Neutrino Physics
- Hadronic Interactions
- Beyond SM

New windows to Astrophysics & Cosmology:

- UHE particles (CRs, gamma rays, neutrinos)
- Gravitational waves
- DM

Subir's career coincides with the **boom in Astroparticle Physics**.

1982 Subir's PhD
1984 Subir at CERN

1990 arrival in Oxford

1998 involvement in the Pierre Auger Experiment

2006 involvement with AMANDA / IceCube

2009 involvement in CTA

2013 Niels Bohr Professorship, Kobenhagen

2017 Bhabha Medal

today: a highly successful scientist with outstanding worldwide reputation.

1987:	SNR 1987a
1989:	first TeV gamma ray source: Crab nebula
1998:	accelerated expansion of the universe
2004:	HESS detects 16 new sources (in its first year of operation)
	AUGER starts operation
2013	first astrophysical neutrinos seen with IceCube
2015:	grav. waves detected from BH-BH mergers
2018	First neutrino source identified TXS 0506+056
today:	**APP has become a mature research area with great results in the past decades and lasting fascination and potential.**

Subir's beginnings

1976-78: CR composition measurements on SKYLAB

1979: Are Gamma Ray Sources also Cosmic Ray Sources?

1980: A lower limit to the magnetic field in Cassiopeia-A

1980: Gamma ray emission from supernova remnants

1982: PhD Thesis University of Bombay
High Energy Astrophysics of Supernova Remnants

1982: Does the galactic synchrotron radio background originate in old supernova remnants?
The evolution of the radio spectra of supernova remnants.

1983: Acceleration of Electrons in Supernova Remnants — 18th ICRC 1983 Bangalore, India
Supernova Remnants and their X-Ray Emission

Subir at CERN:

1984: Astrophysical consequences of n–$\bar{n}$ oscillations — first Nature paper
The evolution of supernova remnants as radio sources

Cosmological and experimental constraints on the tau neutrino — S Sarkar, AM Cooper
Early Nucleosynthesis — S Sarkar, AM Cooper

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Supernova Remnants and their X-Ray Emission

Subir at CERN:

1984: Astrophysical consequences of n–$\bar{n}$ oscillations — first Nature paper
The evolution of supernova remnants as radio sources

2 citations, but one is from another paper of Subir

Cosmological and experimental constraints on the tau neutrino — S Sarkar, AM Cooper
Early Nucleosynthesis — S Sarkar, AM Cooper

1985: The cosmology of decaying gravitinos

J Ellis, DV Nanopoulos, S Sarkar

Bounds on light gluinos from the BEBC beam dump experiment

AM Cooper-Sarkar, S Sarkar, ……

Search for heavy neutrino decays in the BEBC beam dump experiment

AM Cooper-Sarkar, S Sarkar, ……

1986: Primordial nucleosynthesis, additional neutrinos and neutral currents from the superstring

Cosmological and astrophysical constraints on particle physics

Particle physics and the standard cosmology

1988: Low-Mass Photinos and Supernova 1987a

J Ellis, KA Olive, S Sarkar, DW Sciama

… in general with few, but well-known co-authors

1990: Arrival at Oxford …

By then, a very broad basis has been laid for Subir's future work …

Confront theory with experiments to test the standard models

(of particle physics, and of cosmology)

and any other models / theories

- **with all available data,**
- **be critical and rigorous,**
- **use the best proven methods,**
- **work with the best available people.**

1998: New results from SNR observations:
The Universe shows an accelerated expansion.
"Dark Energy"

Subir's motto:
(not afraid of controversies)

"Extraordinary claims require extraordinary evidence"

- control of the experiment
- transparency on calibration & analysis.
- detailed documentation of every step of analysis

1998: New results from SNR observations: The Universe shows an accelerated expansion. "Dark Energy"

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(not afraid of controversies)

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- control of the experiment
- transparency on calibration & analysis.
- detailed documentation of every step of analysis

Evidence for anisotropy of cosmic acceleration

J Colin, R Mohayaee, M Rameez, S Sarkar

Astronomy & Astrophysics 631, 2019, L13

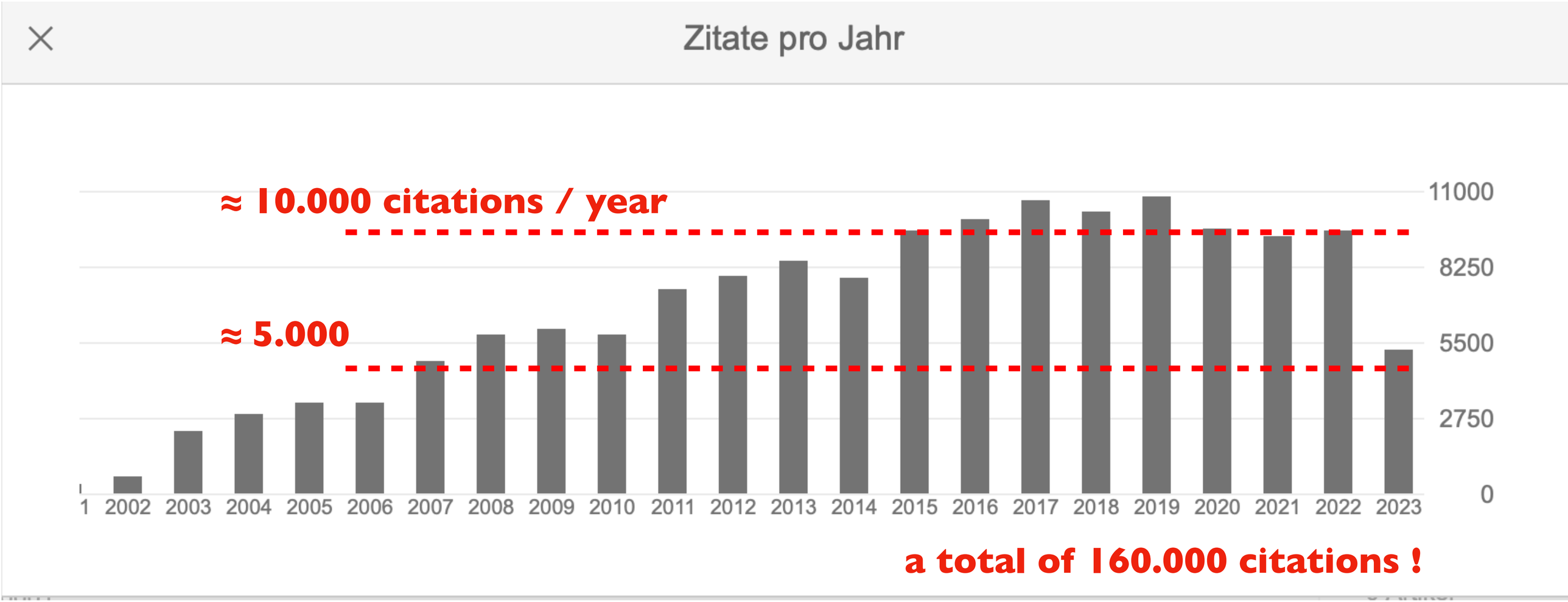
" … Thus the cosmic acceleration deduced from supernovae may be an artefact … rather than evidence for a dominant component of "dark energy" in the Universe."

Heart of darkness

S Sarkar

Inference: International Review of Science 6 (4) 2022

Subir's papers are relevant and very well cited:



Subir's most cited papers:

Review of Particle Physics
2002, 2004, 2006, 2008, 2010, 2012, 2014, 2016, 2018, 2020

≈ 5.000 - 14.000 citations each !!!

Review Articles "Big Bang Nucleosynthesis"
S Sarkar with 1 or 2 co-authors.

based on the article:
Big Bang Nucleosynthesis and physics beyond the Standard Model
Subir Sarkar, Reports on Prog. in Phys. 59, 1493 (1996). 680 citations.

more well-cited papers:

The cosmology of decaying gravitinos
J Ellis, DV Nanopoulos, S Sarkar Nuclear Physics B 259 (1985), 175-188 — 522 citations

Astrophysical constraints on massive unstable neutral relic particles
J Ellis, GB Gelmini, JL Lopez, DV Nanopoulos, S Sarkar
Nuclear Physics B 373 (1992), 399-437 — 527 citations

Tests of quantum gravity from observations of γ-ray bursts
G Amelino-Camelia, J Ellis, NE Mavromatos, DV Nanopoulos,
S Sarkar Nature 393 (1998), 763 — 1791 citations

Extremely high energy cosmic rays from relic particle decays
M Birkel, S Sarkar
Astroparticle Physics 9 (1998), 297-309 — 351 citations

The high energy neutrino cross-section in the Standard Model and
its uncertainty, A Cooper-Sarkar, P Mertsch, S Sarkar
Journal of High Energy Physics (2011) (8), 42 — 279 citations

A travel guide to the dark matter annihilation signal
NW Evans, F Ferrer, S Sarkar Physical Review D 69 (2004), 123501 — 277 citations

Evidence for "new physics" in astroparticle phys. or cosmology observations ?

Subir joins experimental projects:

Some well cited papers of big collaborations: Auger, IceCube, CTA …

Auger

Correlation of the highest-energy cosmic rays with nearby extragalactic objects
Pierre Auger Collaboration, Science 318 (5852), 2007, 938-943 **1291 citations**

Observation of the Suppression of the Flux of Cosmic Rays above 4 x 10^{19} eV
J Abraham et al., Physical Review Letters 101, 2008, 061101 **1132**

IceCube

First observation of PeV-energy neutrinos with IceCube
MG Aartsen et al., Physical review letters 111 (2), 2013, 021103 **1028**

Observation of high-energy astrophysical neutrinos in three years of IceCube data
MG Aartsen et al., Physical Review Letters 113 (10), 2014, 101101 **1791**

Neutrino emission from the direction of the blazar TXS 0506+ 056
prior to the IceCube-170922A alert
M Aartsen et al,, Science 361 (6398), 2018, 147-151 **1114**

CTA

Design concepts for the Cherenkov Telescope Array CTA **936**
CTA Consortium, Experimental Astronomy 32 (3), 2011, 193-316

Science with the Cherenkov Telescope Array
CTA Consortium, 2017 **511**

Subir's role experimental projects:

good feel for the science case from the beginning;
making the case for successful funding applications;

identify worthwhile analyses,
the experimenters alone might overlook

scrutinise the papers written, especially the
introduction (science case) and
conclusions (interpretation / implications);

...

and, of course, help with the hardware.

Subir doing hardware
at Auger in Malargue

Subir: “Auger was very worthwhile doing”

PPARC was first agency to commit
construction money for Auger.

5 h car drives between Mendoza - Malargüe:
great to have Subir as co-driver:
good discussions on physics and life.

Some topics of research of Subir and colleagues relating to Auger:

Exotic neutrino interactions with the Pierre Auger Observatory 2005

S.S. + L Anchordoqui, D Hooper, …

A blind search for correlations of Auger events with BL Lacs 2006

S.S. + F Ferrer

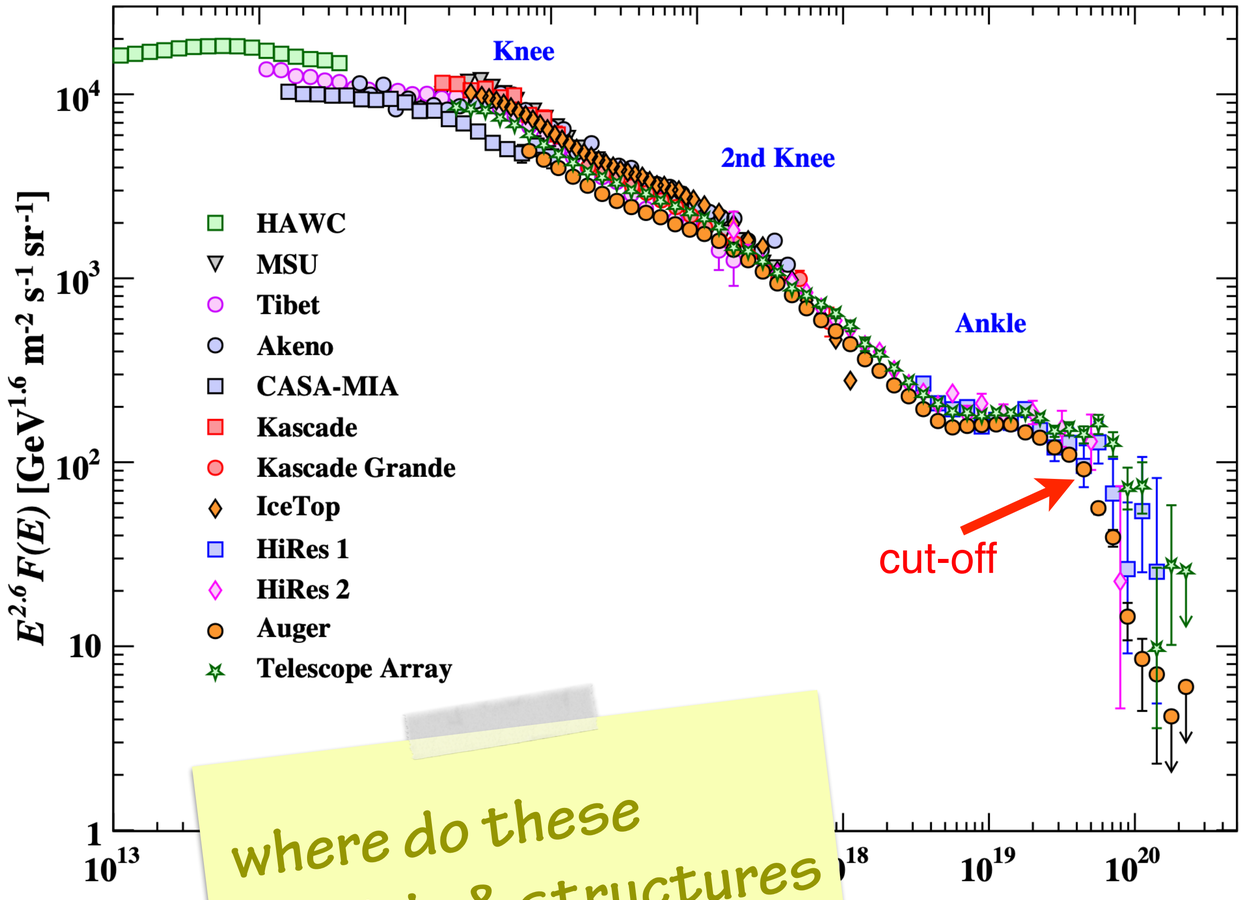
The intergalactic propagation of ultra-high energy cosmic ray nuclei 2007

S.S. + D Hooper, AM Taylor

Precision Auger data and the "GZK cutoff" 2010

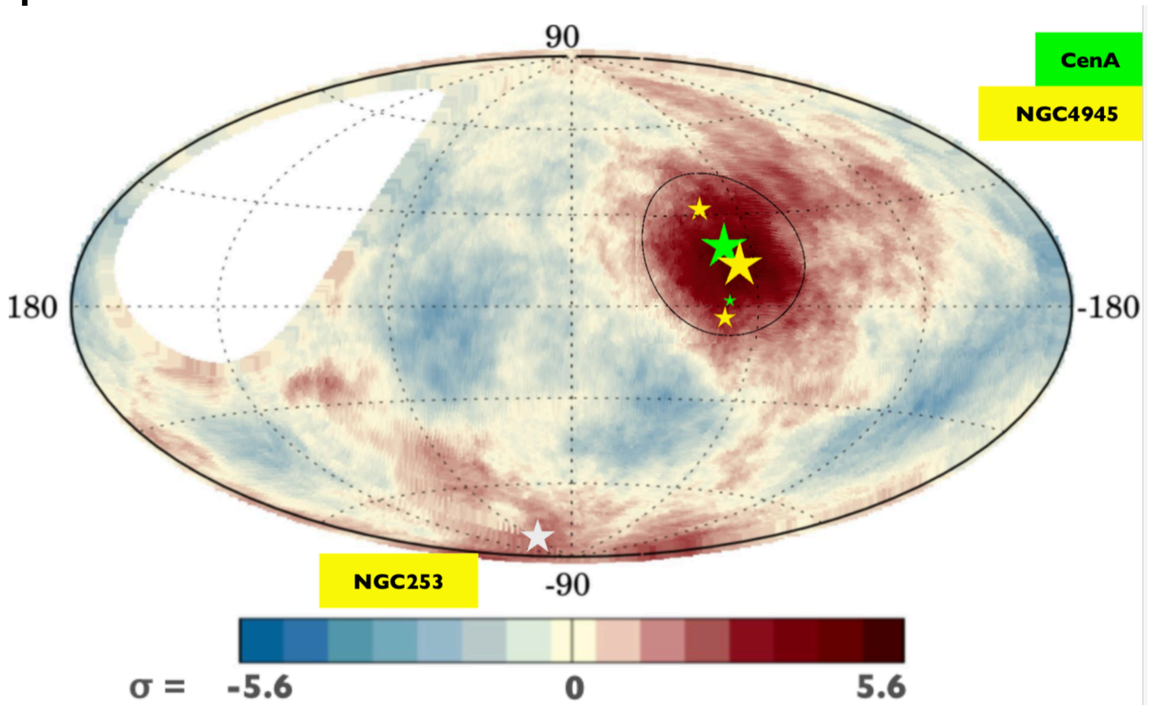
S.S. + L Anchordoqui, …

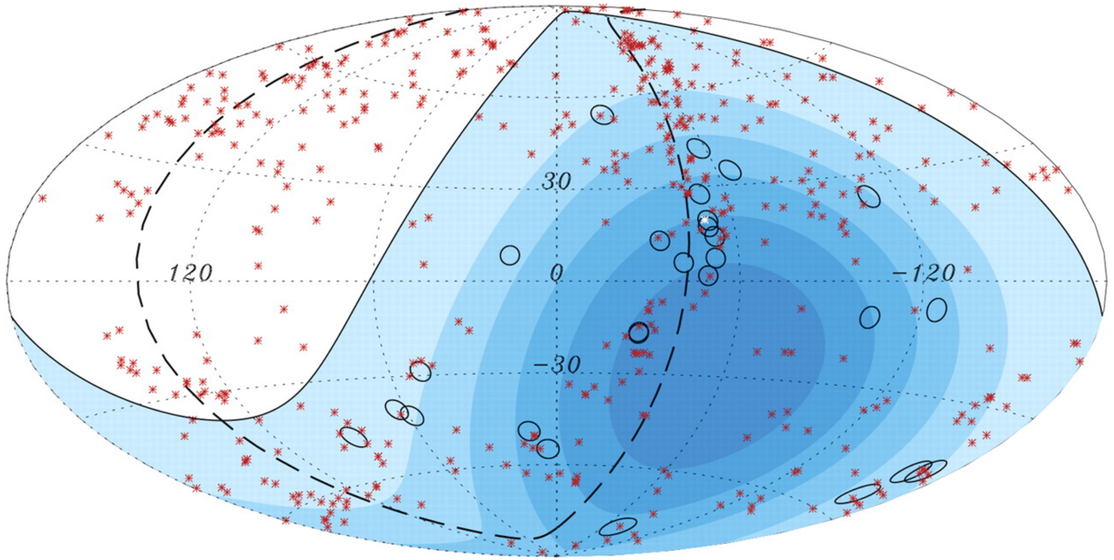
The spectrum: clear structures



where do these particle & structures come from ?

Anisotropies & Correlations



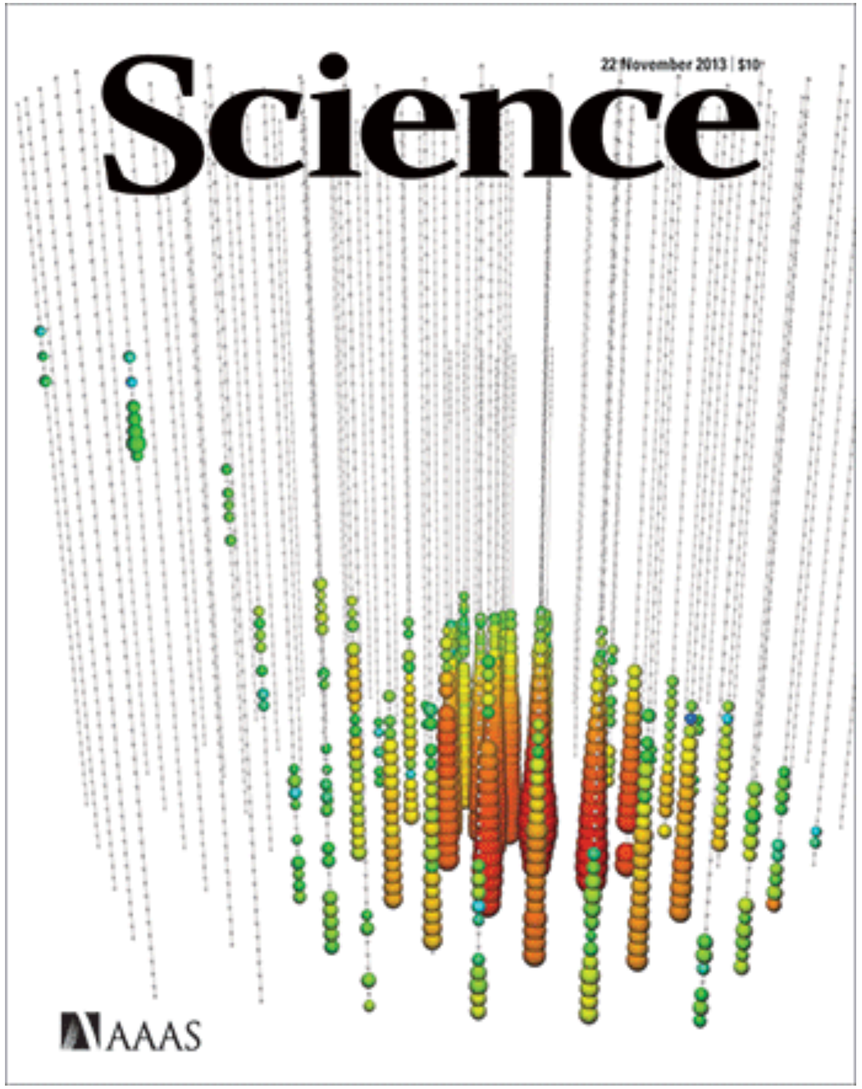


2013: The "birth" of (high-energy) Neutrino Astronomy

28 high-energy νs

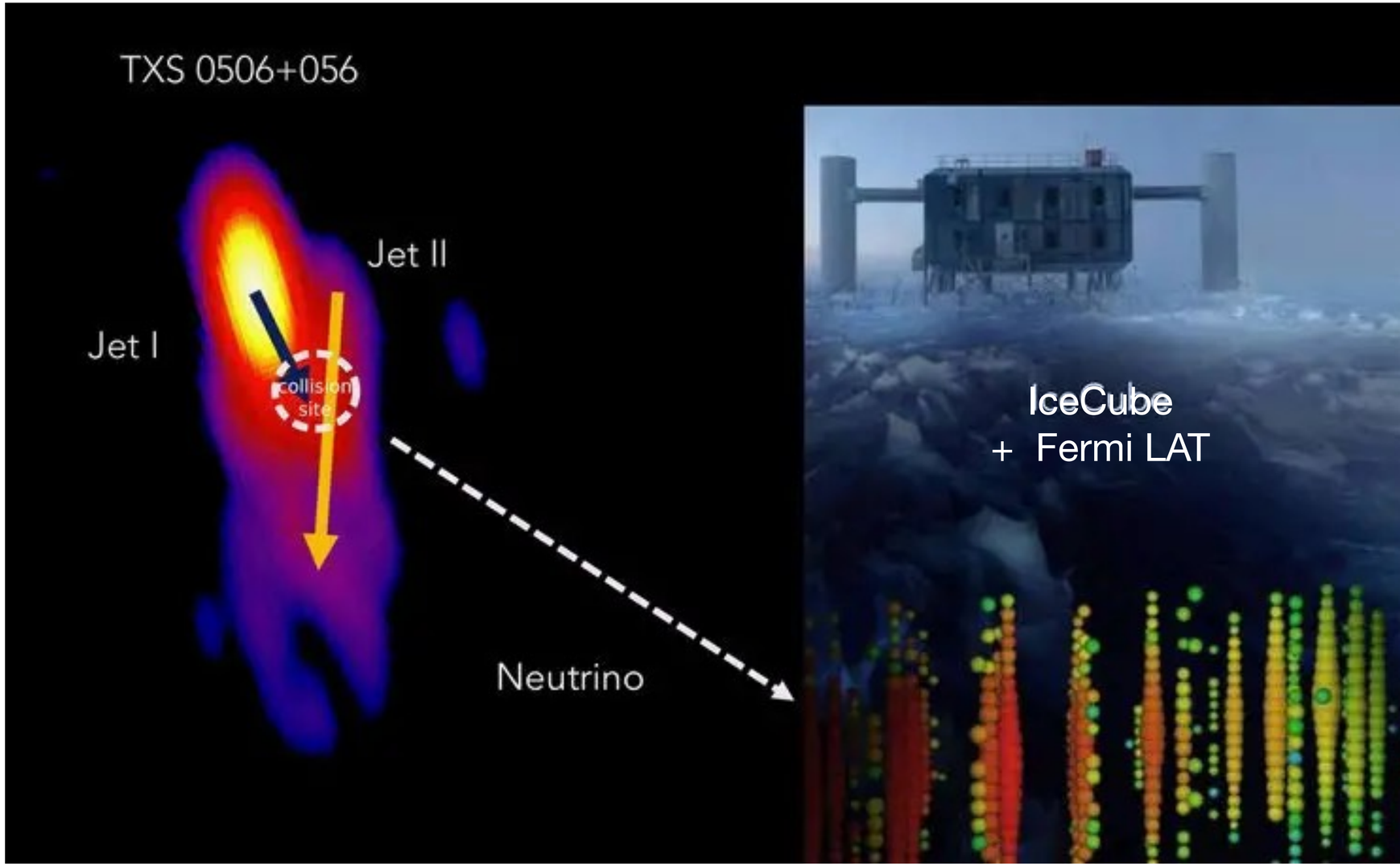
Clear evidence for astrophysical origin

(>5σ)



2018: first neutrino source TXS 0506+056

seen in coincidence (space and time) **with a flare in photons …**



Multi-messenger observations of a binary neutron star merger

BP Abbott et al. The Astrophysical Journal Letters 848, **2017**, L12 1-59 **>3200 citations**

3677 authors from 60 collaborations

LIGO Scientific Collaboration
Virgo Collaboration,
Fermi GBM,
INTEGRAL,
IceCube Collaboration,
AstroSat Cadmium Zinc Telluride Imager Team,
IPN Collaboration,
The Insight-HXMT Collaboration,
ANTARES Collaboration,
The Swift Collaboration,
AGILE Team,
The 1M2H Team,
The Dark Energy Camera GW-EM Collaboration
The DES Collaboration,
The DLT40 Collaboration,
GRAWITA
The Fermi Large Area Telescope Collaboration,
ATCA: Australia Telescope Compact Array,
ASKAP: Australian SKA Pathfinder,
Las Cumbres Observatory Group,
OzGrav,
DWF (Deeper, Wider, Faster Program),
AST3
CAASTRO Collaborations,
The VINROUGE Collaboration,
MASTER Collaboration,
J-GEM,
GROWTH,
JAGWAR,
Caltech-NRAO,
TTU-NRAO,
NuSTAR Collaborations,
Pan-STARRS,
The MAXI Team,
TZAC Consortium,
KU Collaboration,
Nordic Optical Telescope, ePESSTO,
GROND,
Texas Tech University,
SALT Group,
TOROS: Transient Robotic Observatory of the South,
The BOOTES Collaboration,
MWA: Murchison Widefield Array,
The CALET Collaboration,
IKI-GW Follow-up Collaboration,
H.E.S.S. Collaboration,
LOFAR Collaboration,
LWA: Long Wavelength Array,
HAWC Collaboration,
The Pierre Auger Collaboration,
ALMA Collaboration,
Euro VLBI Team,
Pi of the Sky Collaboration,
The Chandra Team at McGill University,
DFN: Desert Fireball Network,
ATLAS,
High Time Resolution Universe Survey,
RIMAS,
RATIR,
SKA South Africa/MeerKAT

Great Science result !!

but also shows how large the
Astroparticle Physics Community has grown
and the power of combined analyses.

Cherenkov Telescope Array

The UK had a keen interest in CTA from the outset.
(involvement in HESS, VERITAS, X-ray Astronomy, …)

CTA was promising large improvement in
sensitivity (i.e number of sources,
energy range (10 GeV …TeV …PeV)
capability for transients
sky surveys

Important papers to make the case to funding agencies around the world..

Design concepts for the Cherenkov Telescope Array CTA
CTA Consortium, Exp. Astronomy 32 (3), 2011, 193-316

Science with the Cherenkov Telescope Array
CTA Consortium, 2017

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Science with the Cherenkov Telescope Array
CTA Consortium, 2017

1. Introduction to CTA Science
2. Synergies
3. Core Programme Overview
4. Dark Matter Programme
5. KSP: Galactic Centre
6. KSP: Galactic Plane Survey
7. KSP: LMC Survey
8. KSP: Extragalactic Survey
9. KSP: Transients
10. KSP: Cosmic Ray PeVatrons
11. KSP: Star Forming Systems
12. KSP: Active Galactic Nuclei
13. KSP: Clusters of Galaxies
14. Capabilities beyond Gamma Rays
15. Appendix: Simulating CTA

The UK had a keen interest in CTA from the outset.

(involvement in HESS, VERITAS, X-ray Astronomy, …)

Durham	P Chadwick, et al,
Leeds	J Knapp (chair of CB) et al.
Leicester	J Hinton (project scientist) et al.
Liverpool	T Greenshaw (SST coordinator)
Oxford	G Cotter, S Sarkar
RAL	N McCubbin

We offered to host the Consortium Meeting, typical 200 participants (of about 1000 members) in Nov. 2010 in the UK.

N McCubbin, S Sarkar organised it in Oxford.

The highlight of the meeting was the **Conference dinner**
in the newly renovated Ashmolean Museum.

We visited the Museum, saw some exhibits,
got a nice intro from the director,
had plenty of drinks and some nibbles,
and enjoyed talking to colleagues.

very nice,
very posh,
rather expensive

But the **nibbles actually were** the dinner !
All were still hungry, nerves were on edge.

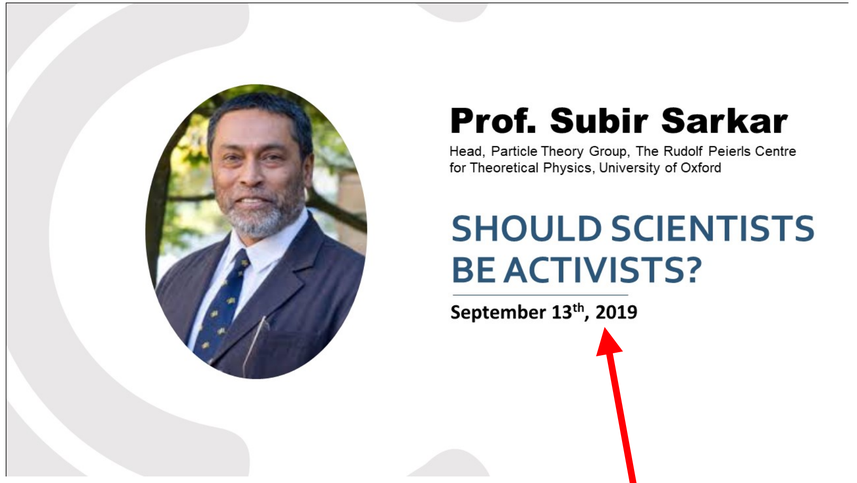
That night, the kebab van
in front of the museum,
made the business of a lifetime.

Subir & Norman apologised
profusely to the meeting
the other morning.

An unforgettable meeting
for all involved.

Subir, a great educator / communicator

countless lectures for students
research talks for physics colleagues
talks to the wider public on science and
the role of Science in Society



Yes !

Subir picked good students and trained them exceptionally well (by example).

He had (and still has) many engagements at Indian universities and research labs,
e.g. the bi-annual Winter School on Astroparticle Physics (TIFR, Bose Institute)
several adjunct professorships at Indian universities

1988-89 work for an Indian NGO (Eklavya, Bhopal) on science education and popularisation after the Bhopal chemical disaster in 1984.

Together with his wife Mandy.

Since 2007, Subir has been a trustee of the BMA (Bhopal Medical Appeal) still seeking justice for survivors of the accident.

Academic Service:

- Member, Particle Data Group (2001–)

- **Advisory Board**: Sant Cugat Forum on Astrophysics (2012–);
  Helmholtz Alliance on Astroparticle Physics (2012–17);
  Gruber Cosmology Prize (2014–20);
  Institute of Physics, Universiteit van Amsterdam (2016-21)

- **Editorial Board:** SciPost (2016–),
  Pramana (2013–20),
  European Physical Journal C (2012–15)

Subir,
When are you sleeping ???

- Scientific Council, International Center for Theoretical Physics Asia-Pacific, Beijing (2018–)
- Steering Committee, European Centre for Astroparticle Theory (2019–20)
- Member, Scientific & Technology Advisory Committee, KM3NeT (2013–20); Requirements Review Panel, CTA (2012)

- Member, IUPAP Commission C4: Astroparticle Physics (2022–25);
  Programme Review Committee, ApPEC (2005–14);
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- Coordinator, EU Marie Curie Research & Training Networks: UniverseNet (2006–10), Supersymmetry & the Early Universe (2000–04); Member, EU Marie Curie Initial Training Network: UniLHC (2009–13)

- Chair, Consultation Panel on Astroparticle Physics, STFC Programmatic Review (2008)

- Co-ordinator, Oxford-India Network on Theoretical Physical Sciences (2006–21)

- **Referee:** EC, ERC, ESA; FNU, Denmark; AERES, France; Humboldt Stiftung, DFG & Helmholtz Gemeinschaft, Germany; Ministry of Education, Greece; DAE & DST, India; ANVUR & INFN, Italy; NWO, Netherlands; Royal Society of New Zealand; NRF, South Africa; SNSF, Switzerland; Leverhulme Trust, Royal Society, EPSRC & STFC, UK; DoE & NSF, USA

Subir and the International Cosmic Ray Conferences

International Union for
Pure and Applied Physics

Chair of the intl. program committee (section NU)
ICRC 2019 (Madison) &
ICRC 2021 (Berlin)

… a formidable task to assess and sort ≈250 contributions,
which he performed brilliantly (chair of the team)

since 2021: member of the IUPAP commission
C4: Astroparticle Physics for the UK

since 1947
bi-annual conferences
of the C4: Cosmic Rays

since 2013
C4: Astroparticle Physics

ONLINE

ICRC 2021

THE ASTROPARTICLE PHYSICS CONFERENCE

Berlin | Germany

37th International
Cosmic Ray Conference
12–23 July 2021

Subir's Awards:

Indian National Science Talent Scholarship, 1969–78
Advanced Fellowship, UK Particle Physics & Astronomy Research Council, 1992-97
Senior Fellowship, UK Science & Technology Facilities Council, 2006–09

Niels Bohr Professorship, University of Copenhagen, 2013–18
Bhabha Medal & Prize by TIFR and IUPAP, 2017

Awards with the IceCube Collaboration

Various visiting professorships:

Adjunct Professor,	Raman Research Institute, 2019–22
Associate,	Discovery Center, Niels Bohr Institute, Copenhagen, 2010–20
Associate,	Institute of Particle Physics Phenomenology, Durham, 2011–12
Adjunct Professor,	Saha Institute of Nuclear Physics, Kolkata, 2008–13
Adjunct Professor,	Tata Institute of Fundamental Research, Mumbai, 2006–09

Homi Bhabha Medal & Prize

Subir was honoured with the 2017 Homi Bhabha Medal & Prize by TIFR & IUPAP

for his

"Distinguished contributions in the field of high-energy cosmic ray physics and astroparticle physics over an extended academic career."

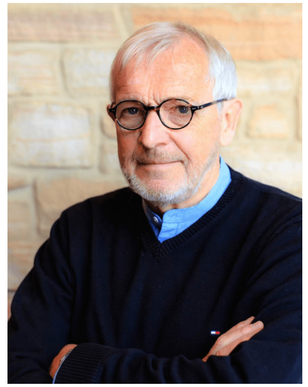
A worthy winner ...
in very good company


A Wolfendale,


H Völk,


T Gaisser,


T Kajita,


F Halzen

Subir has done very well …

Scientific output:	**+++**
Teaching & outreach:	**+++**
Academic Service:	**+++**
Awards:	**+++**

The Boom in Astroparticle Physics

Cosmic rays, gamma rays, neutrinos, grav. waves

… the situation in 1990

(i.e. 33 years ago)

world community ≈ 200 persons (?)

Cosmic Rays 1990

CR Spectrum measured with ground arrays
(scintillators, water tanks, air fluorescence)

Steep spectrum, difficult to measure.
Poor quality, mostly too small detectors, low statistics

unknown: mass composition, sources, systematics

Linsley 1963: 1 event at $\approx 10^{20}$ eV
Fly's Eye 1991: 1 event at 3×10^{20} eV

Interactions with CMB: GZK Cutoff in the UHE CR spectrum,? local sources?

Experiments disagreed on spectrum near GZK energy:
cutoff or not ??? top-down production of $>10^{20}$ eV ? top. defects ?
at UHE: no ankle, no GZK cut-off

SNR, Fermi acceleration at strong shocks,
Radio (synchrotron),
X-rays to study acceleration in SNRs

SNR for higher energies?

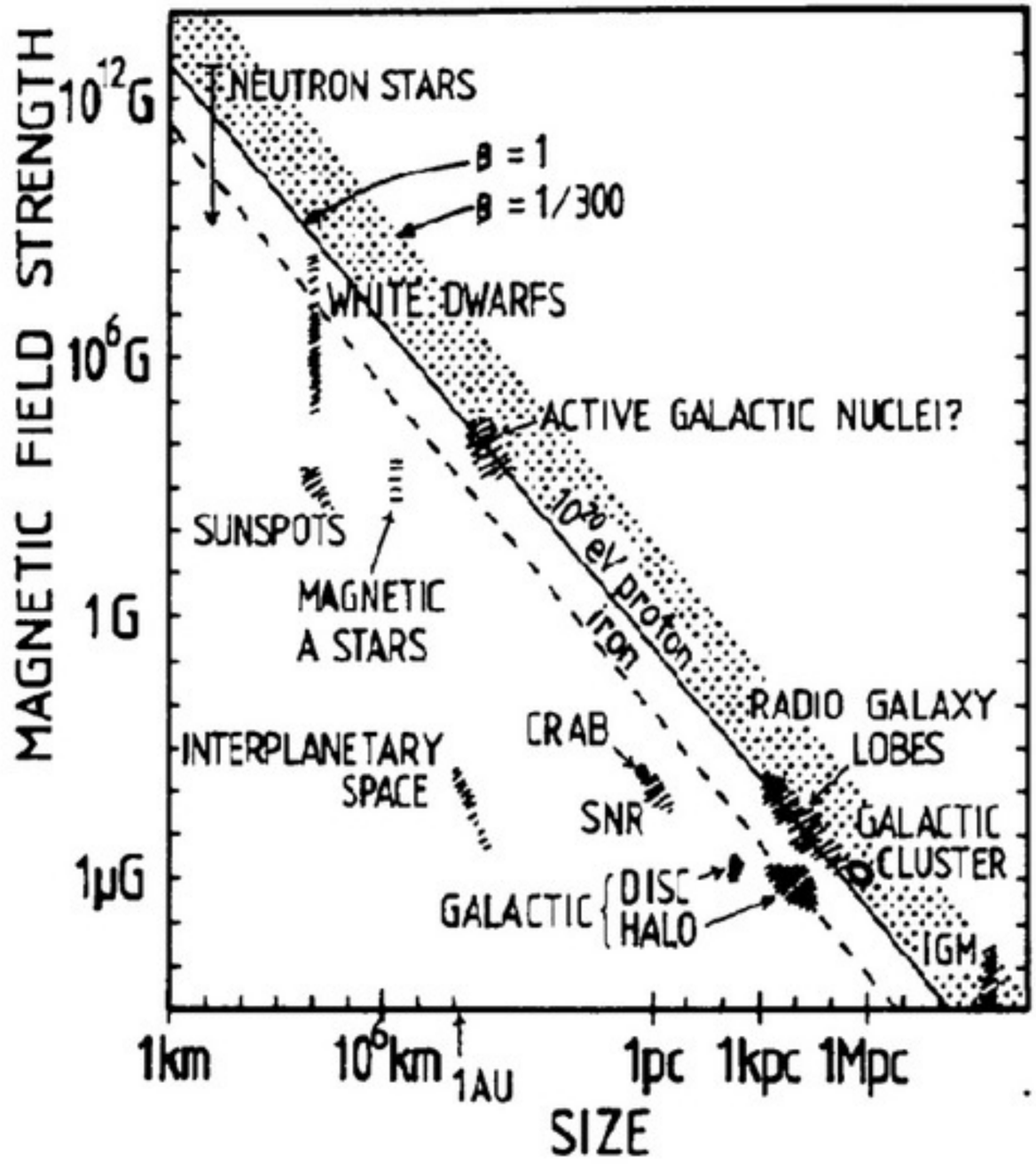
UHECR ???

1984: Hillas Plot

Spectrum ??

Composition ???

B L > const. E / Z



Cosmic Rays today

balloon expts: HEAT, Cresst, Tracer, Cream, … LD balloon flights
Space expts. … **CGRO**, **Fermi**, Pamela, **AMS …**

particle identification,
years of operation.

EAS top, EAS100, …, **Kascade, Kascade Grande**, IceTop, …

e, γ, μ, h

CORSIKA + QGSjet, EPOS, GEANT
numerical simulations of high-energy atmospheric cascades

Akeno vs Flys Eye, AGASA vs Hires,
particle arrays vs Fluorescence detectors

Auger vs TA, …

e, γ, μ

water Cherenkov + Fluorescence,
atmospheric monitoring
charged particle astronomy at UHEs?

Hybrid expts. (array + fluorescence)
Radio detection of air showers
FD from space ???

Mag. field amplification, particle acceleration in sources,
propagation in gal and extragal fields: Galprop, CRPropa,
simulations of acceleration processes in sources

Multi parameters, messenger approach

multivariate analyses, …
massive computing power,

Gamma Rays 1990

suggested since the 1950s: e.g. Crab nebula, TeV energies
to be measured via air showers and Cherenkov light.

enhanced fluxes from certain spots? no success
Kiel array Cyg-X3: CASA-MIA, Hegra ,
Many false alarms.

1989: Whipple 10 m Cherenkov telescope (built in 1968)
+ pixelated camera for imaging,
+ clever image analysis (Hillas parameters)

Crab Nebula, **9σ significance** after 50 h our observation

Historic Timeline

Ingredients ready		1948	
Whipple 10-m telescope built		1968	
			first detection
Crab Nebula	PWN	1989	Whipple
Markarian 421	HBL	1992	Whipple
Markarian 501	HBL	1996	Whipple
3C66A	IBL	1998	Crimea
1ES 2344+514	HBL	1998	Whipple
PKS 2155-304	HBL	1999	Durham Mark 6
1ES 1959+650	HBL	1999	Telescope Array
RX J1713.7-3946	Shell	2000	Cangaroo
Cas A	Shell	2001	HEGRA <=== stereo
Bl Lac	IBL	2001	Crimea
H 1426+428	HBL	2002	Whipple
TeV J2032+4130	UNID	2002	HEGRA
M87	FR1	2003	HEGRA
Galactic Centre	UNID	2004	Cangaroo
			HESS started observations
... 16 new sources		2005	
... 17 new sources		2006	

~40 years

~10 years

~5 years

+ MAGIC, VERITAS

272 sources **2023:** **from many source types.**

TeV astronomy highlights

from **HESS, MAGIC** and **VERITAS**
Descartes & Rossi Prize for HESS

Supernova remnants:	Nature	432 (2004) 75		
Microquasars:	Science	309 (2005) 746	Science	312 (2006) 1771
Pulsars:	Science	322 (2008) 1221	Science	334 (2011) 69
Galactic Centre:	Nature	439 (2006) 695	Nature	531 (2016) 476
Galactic Survey:	Science	307 (2005) 1839		
LMC:	Science	347 (2015) 406		
Black Holes:	Science	346 (2014) 1080		
Starbursts:	Nature	462 (2009) 770	Science	326 (2009) 1080
Active Galactic Nuclei:	Science	314 (2006) 1424	Science	325 (2009) 444
EBL:	Nature	440 (2006) 1018	Science	320 (2008) 752
Dark Matter:	PRL	96 (2006) 221102	PRL	106 (2011) 161301
	PRL	114 (2015) 081301	PRL	110 (2013) 41301
Lorentz Invariance:	PRL	101 (2008) 170402		
Cosmic Ray Electrons:	PRL	101 (2008) 261104		

…. plus many more

+ many papers in other journals
… a booming field.

Currently 272 sources
many different source types:

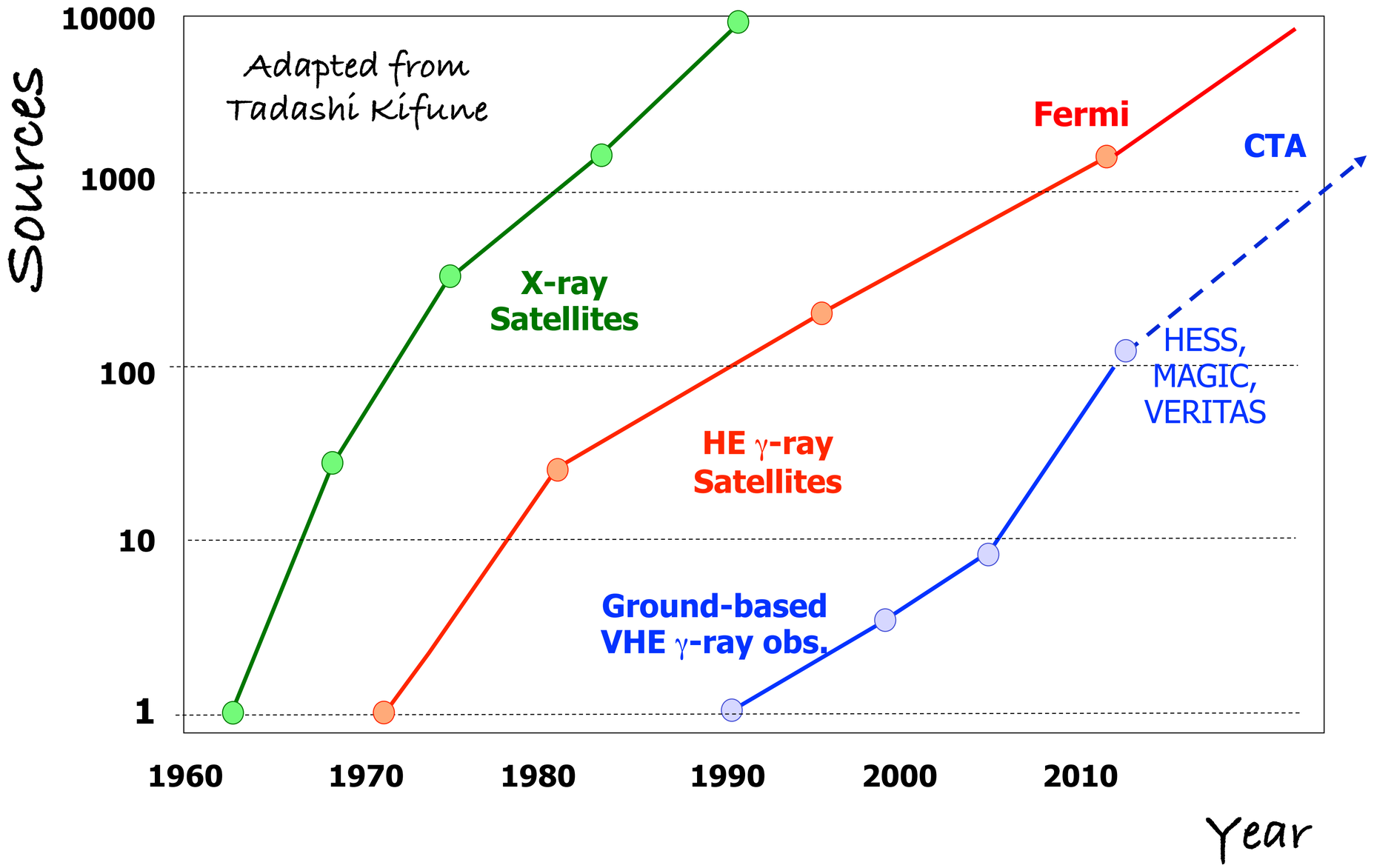
SNRs
Novae
Bombarded molecular clouds
Colliding wind binaries
Massive stellar clusters
Pulsars & PWNs
Microquasar jets
Supermassive black hole Str A*

gamma ray are
almost everywhere

Starburst galaxies
Milky Way satellites
Radio galaxies
flat-spectrum radio quasars
BL Lacs
Gamma ray bursts

Source Number

Gamma-Ray Astronomy goes "mainstream"



Gamma Rays today

high sensitivity, transients

Cherenkov telescopes: Whipple, **HESS, MAGIC, VERITAS**, **CTA**
LHAASO, HAWC, SWGO

full sky coverage, PeV sources

Satellite instruments: CGRO, **Fermi,** ….

large progress in technology, methods, calibration, analysis, …

Multi wavelengths: el.mag. radiation, cross alerting with satellites, transients, neutrino and grav.wave events

Neutrinos 1990

old idea (1970s) to use neutrinos for astronomy.
travel straight, are not absorbed

1990: SN 1987a: neutrinos seen !!

Indications of deficit in muon neutrinos: oscillations ?

DUMAND: underwater telescope in ocean: plans and tests, but termination in 1995

Baikal: 1. string deployed.
saw later also the first neutrino track

Neutrinos today

from 1994 planning for neutrino detection in Antarctic ice.
Operation: 1996–2009 AMANDA
2010– **IceCube** (≈1 km3)

KM3NeT construction since 2015, partly operational.

2013: breakthrough of the year 2013: IceCube
2018: first neutrino source TXS 0506+056 IceCube and Fermi-LAT

many exciting results…. astrophysical neutrinos,
flavour ratios, oscillations
correlation with el.mag. outbursts

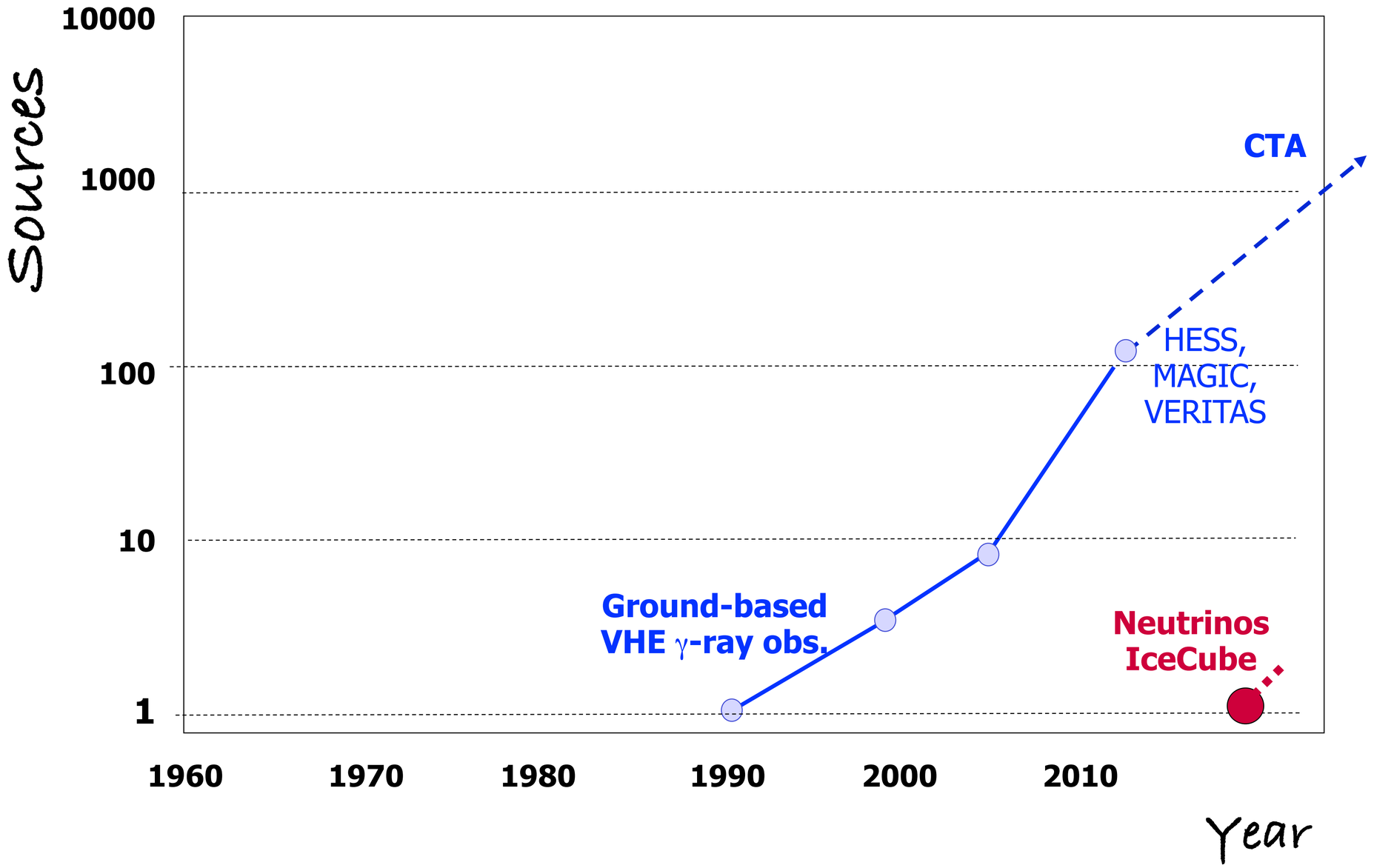
Plans for IceCube Gen-2, ≈10 km^3 , a denser center, a larger top array

large progress in technology, methods, calibration, analysis, …
develop radio detection …

Multi messenger: cross alerting with el.mag. radiation,
from satellites, transients and grav.wave events

Source Number

Identified Neutrino sources



Grav. waves 1990:

old prediction (1916), but very difficult to detect.

1980s: Hulse &Taylor
indirect evidence: period change of a double pulsar system
confirmed predictions of GRT.

several experimental activities (for direct detection) with
Webber bars, early interferometers,…
hopelessly lacking sensitivity for a detection.
It seemed too ambitious…

Thus, in 1990 for most Astrophysicists this was just not on the radar yet.

Grav. waves today:

1994–2002 construction of LIGO interferometer
2008–2015 upgrade to **Advanced LIGO**
… battling down the background noise

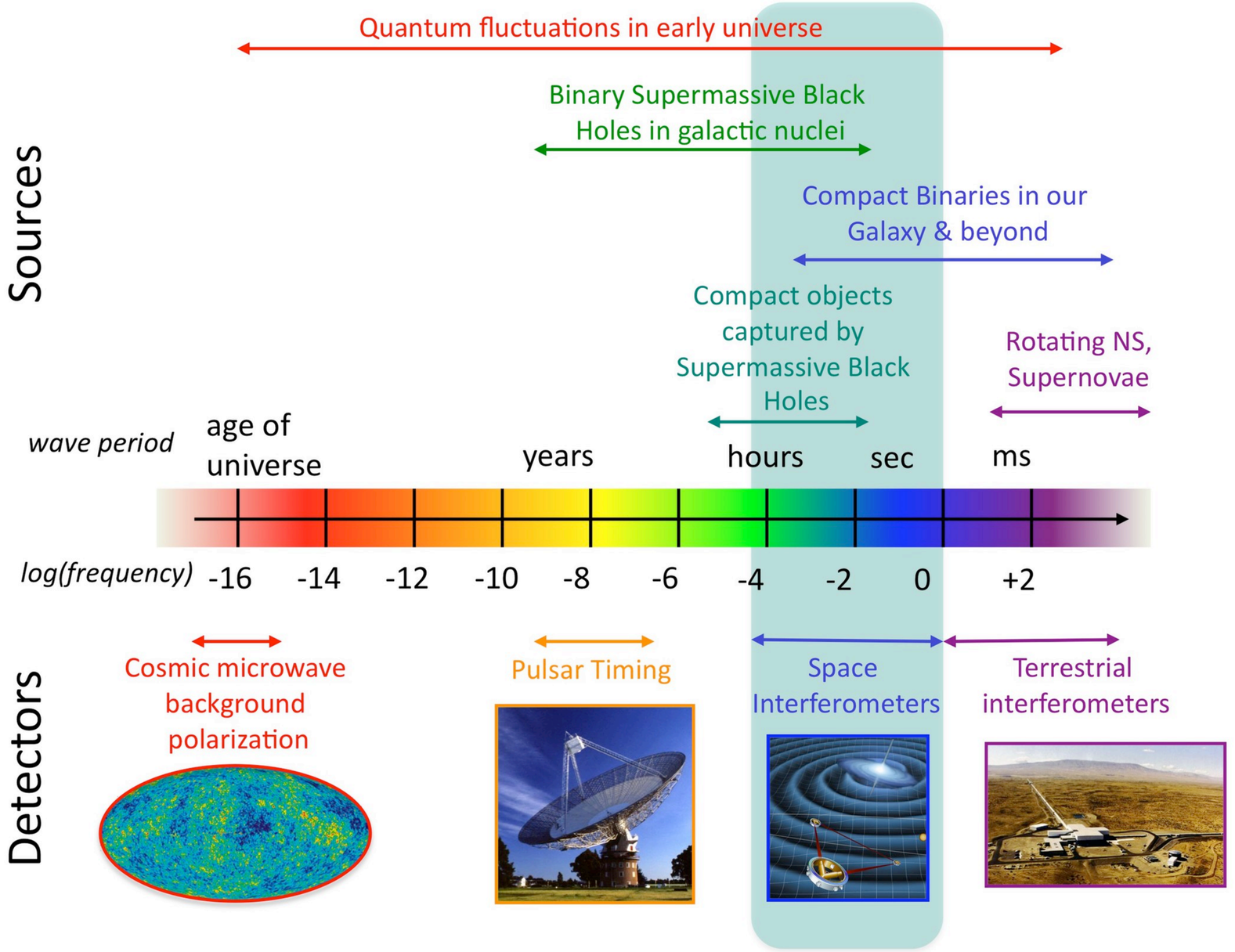
2015 first BH-BH merger detected.
until now many (hundreds) events were recorded,
partly also seen in el.mag. radiation
next round of improvements underway.

"A revolutionary new view on the universe"

… with stunning results and great new potential

Gravitational waves efforts:
LIGO, Geo600, Virgo, **adv. LIGO+GEO, VIRGO, KAGRA, …**
ET, Cosmic Explorer …
LISA, PTAs, CMB

The Gravitational Wave Spectrum



10 Nobel Prizes in Physics for work relevant to Astroparticle Physics

The Nobel Prize in Physics 2020
Roger Penrose "black hole formation is a robust prediction of the GRT"
Reinhard Genzel and Andrea Ghez "supermassive compact object at the centre of our galaxy"

The Nobel Prize in Physics 2019
James Peebles "theoretical discoveries in physical cosmology"

The Nobel Prize in Physics 2017
Rainer Weiss, Barry C. Barish and Kip S. Thorne "observation of gravitational waves"

The Nobel Prize in Physics 2015
Takaaki Kajita and Arthur B. McDonald "neutrino oscillations, which shows that neutrinos have mass"

The Nobel Prize in Physics 2011
Saul Perlmutter, Brian P. Schmidt and Adam G. Riess "accelerating expansion of the Universe"

The Nobel Prize in Physics 2006
John C. Mather and George F. Smoot "blackbody form and anisotropy of the CMBR"

The Nobel Prize in Physics 2002
Raymond Davis Jr. and Masatoshi Koshiba "detection of cosmic neutrinos"

The Nobel Prize in Physics 1995
Frederick Reines "detection of the neutrino"

The Nobel Prize in Physics 1993
Russell A. Hulse and Joseph H. Taylor Jr. "pulsars as possibility to study gravitation"

The Nobel Prize in Physics 1983
Subramanyan Chandrasekhar "physical processes on structure and evolution of the stars"
William Alfred Fowler "nuclear reactions for the formation of the chemical elements in the universe"

HUGE scientific progress in APP since 1990!

new communities have formed (national and international)

world community now **> 10000**

substantial **funding** was obtained

new **Journals** for APP, lots of papers …

new institutes & **positions** at universities and research labs.

IUPAP: **Astroparticle Physics Commission** (C4, renamed from cosmic rays)

….

The last 40 years in Astroparticle Physics
very exciting times !!! truly a **boom period.**

Everyone of us has contributed an ε to this success.

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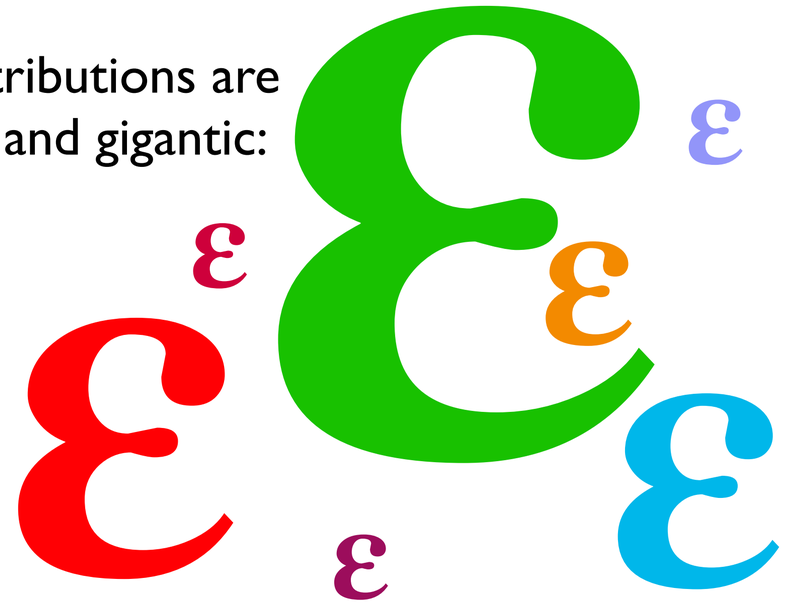
Everyone of us has contributed an ε to this success.

But **Subir's** contributions are very wide-spread and gigantic:



We admire very much Subir's
professional qualities,
his **courage** to think
"outside the box"
and his **humane character .**

and …

Subir is an
independent mind &
deep thinker.

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… may be helped by living partly
on the remote Greek island Hydra,
with a good mix of Sun, sea, meditation,
good food, yoga and physics ?

Now at 70:

Will he **“retire”** to his retreat and become a gardener?

Probably not …

he is still active and going strong …

Another Oxford Professor may serve as a good example:

D.H. Perkins has written his most-cited few-author paper
at the age of **77**, it became the second-most-cited work
in his long and distinguished career.

Tri-bimaximal mixing and the neutrino oscillation data
P.F. Harrison, D.H. Perkins, W.G. Scott,
Phys.Lett. B 530 (2002) 167

> 1600 citations

and still counting

… and Don Perkins was **very proud** of this.

So, go Subir, go …

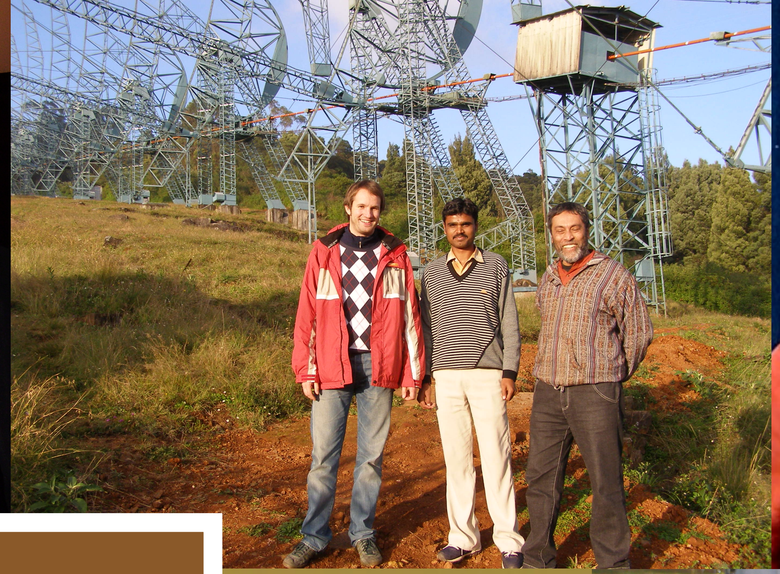
Subir ... my role model

Subir ... my role model (at least in some activities)

Happy Birthday, Subir!

**Thanks for all your work,
all the best for many
good years to come,
& thanks for your friendship.**





Some photos ...