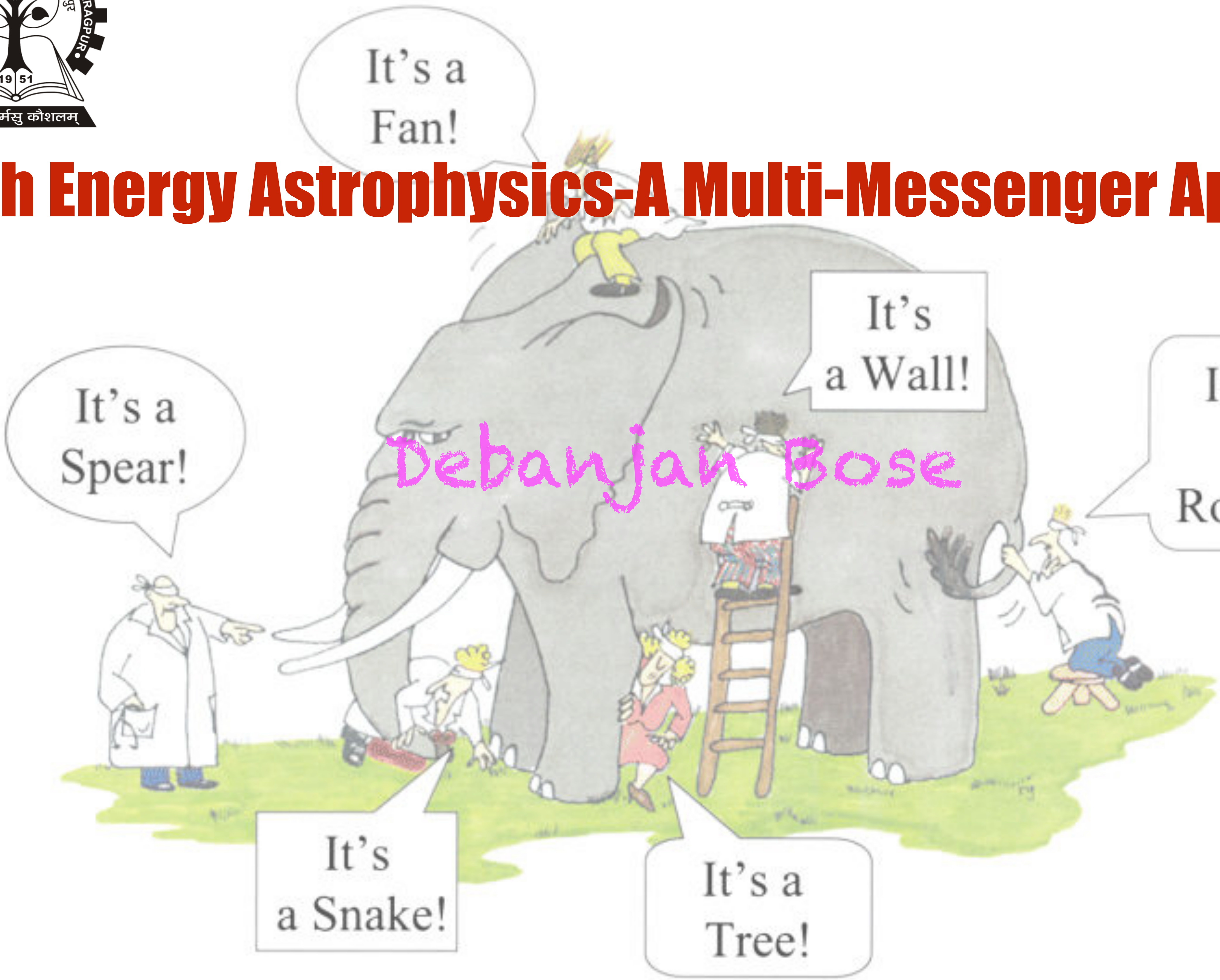
High Energy Astrophysics-A Multi-Messenger Approach



Debanjan Bose

WHEPP XV @ IISER, Bhopal, 2017

Plan of Talk

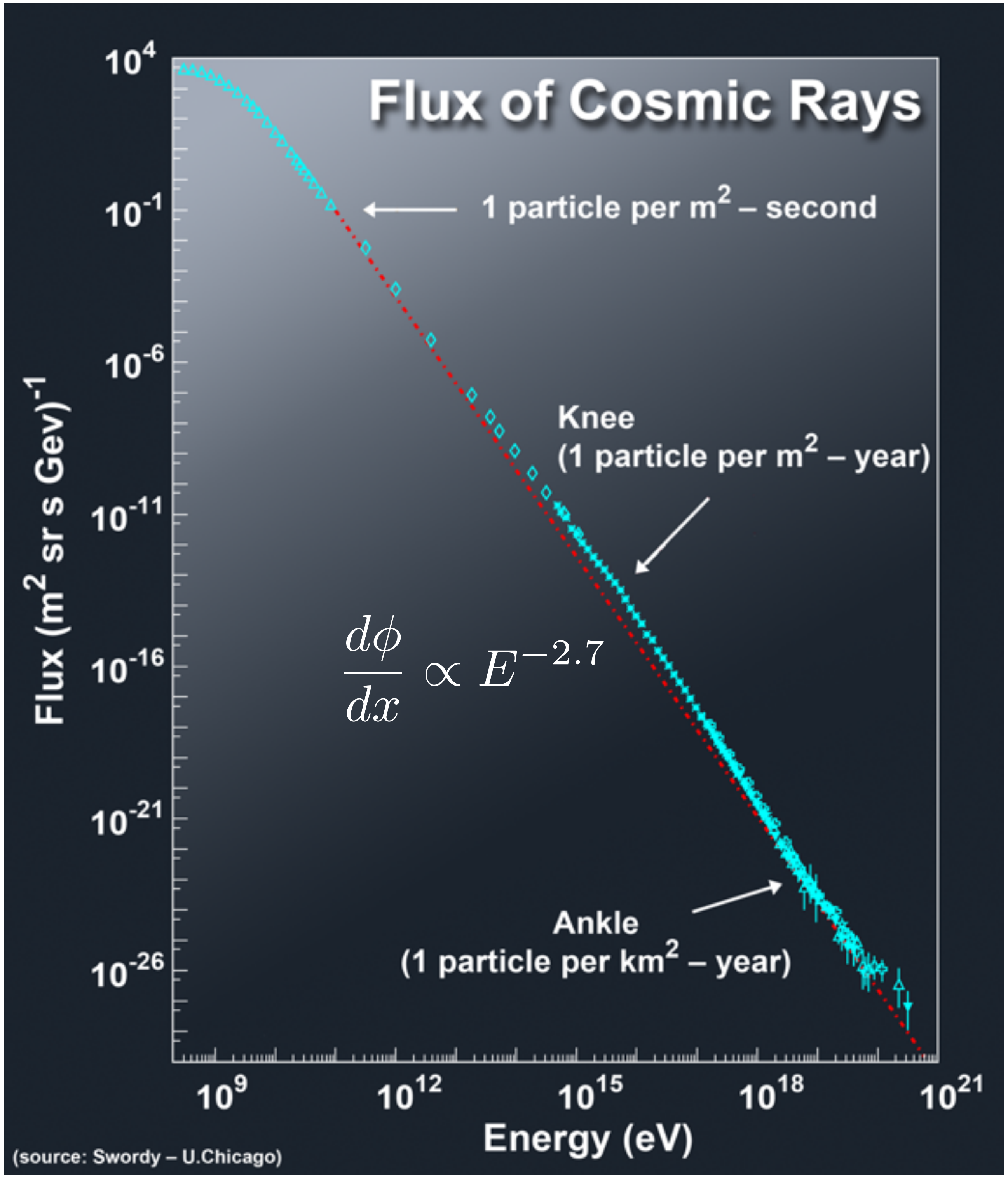
- Why do we need to study high energy Universe?
- Importance of Multi-Messenger Astronomy
- Messengers at high energy regime and detection methods
- Current Status & Future Prospects of Ground Based Telescopes - Gamma-ray & Neutrino
- Connection with Gravitational Waves

Science @ Very High Energies

Study of Non-Thermal Universe

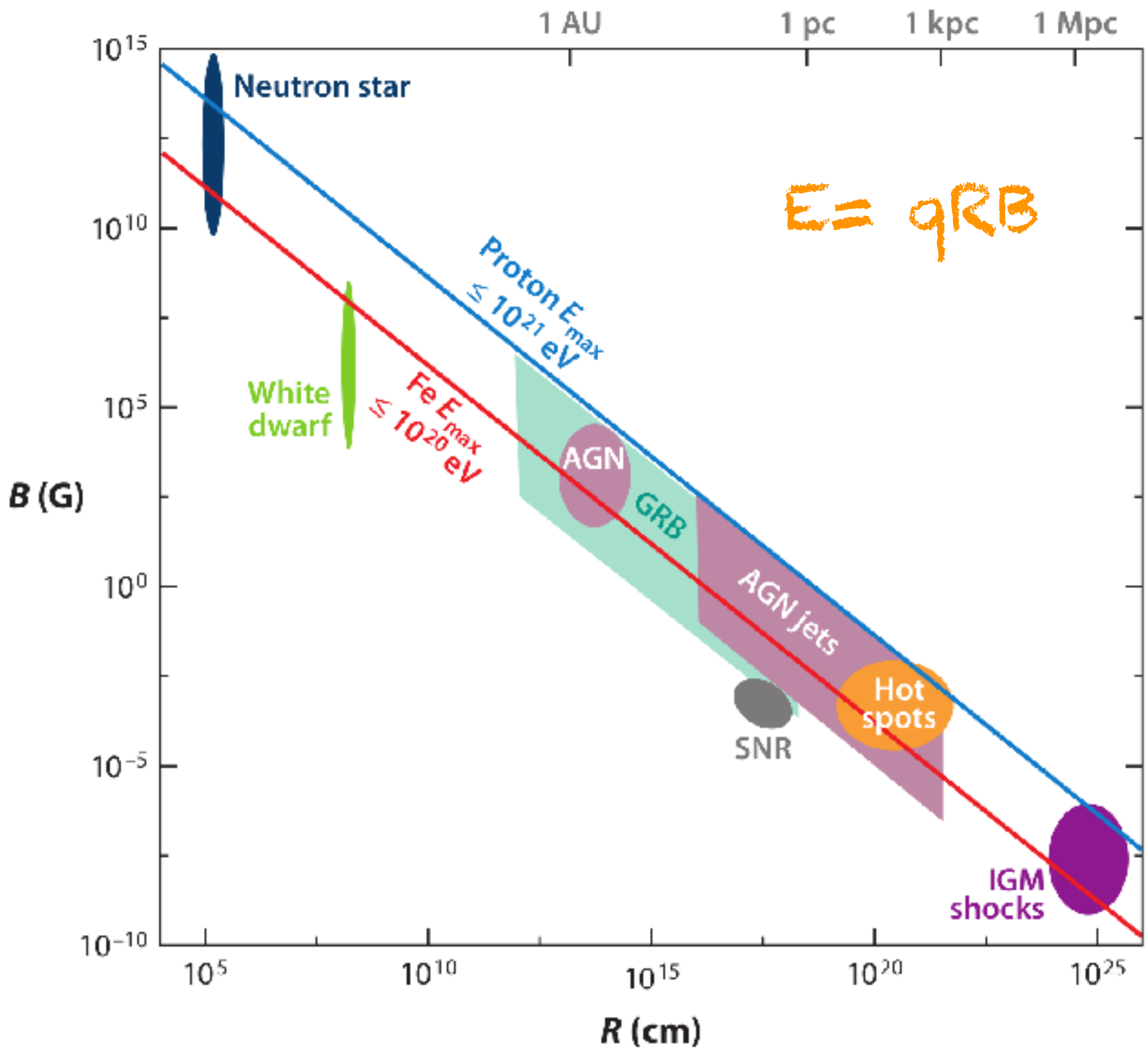
- **Understanding the Origin and Role of Relativistic Cosmic Particles**
  - Where they are produced, How they are produced, What role they play
- **Probing Extreme Environments**
  - What happens close to NS/BH, Understanding relativistic jets
- **Exploring Unknown Universe**
  - Dark matter, Quantum Gravitational Effects etc

Main Motivation @ High Energies
Solve Cosmic-ray Puzzle



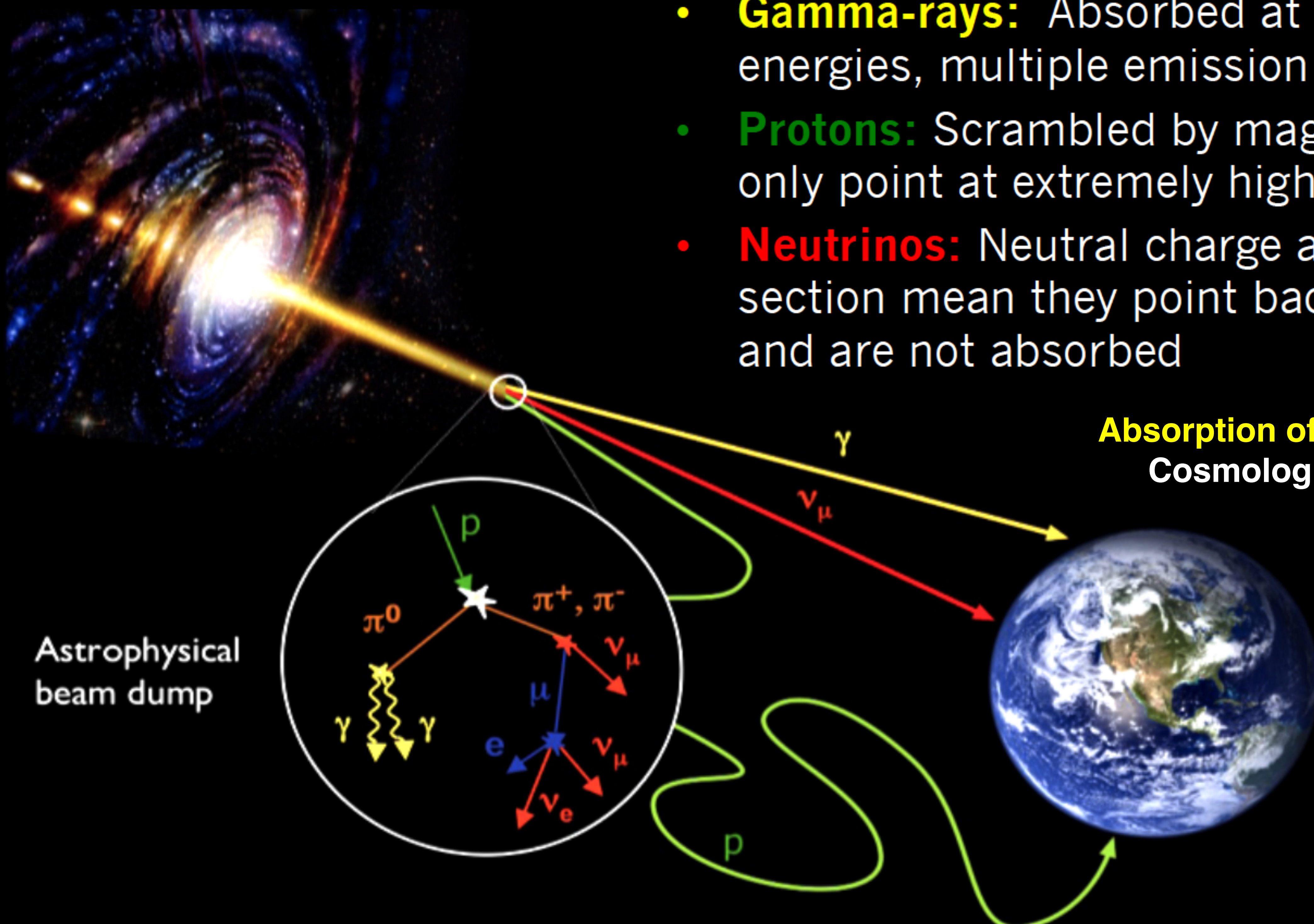
- Mostly composed of proton (90%)
- Source of Origin not known
- Upto around knee probably produced in the galaxy by Supernova
- Higher energy component has extra-galactic origin, sources could be AGN, GRBs

Cosmic-Ray Sources & Acceleration Mechanism (Hillas Plot)



Cosmic Messengers @ High Energies

- **Gamma-rays:** Absorbed at highest energies, multiple emission mechanisms
- **Protons:** Scrambled by magnetic fields, only point at extremely high energies
- **Neutrinos:** Neutral charge and low cross-section mean they point back to source and are not absorbed



Absorption of Gamma-rays :
Cosmological Studies

Active Galactic Nuclei (AGN)

Normal Galaxies (e.g. Milky Way) : Characterised by **Thermal Emission**

Active Galaxies : Characterised by **Non-Thermal Emission**

They are very bright objects brightness >> luminosity of normal galaxy

They are detected across the entire electromagnetic spectrum : radio-IR-Optical-UV-X-γ

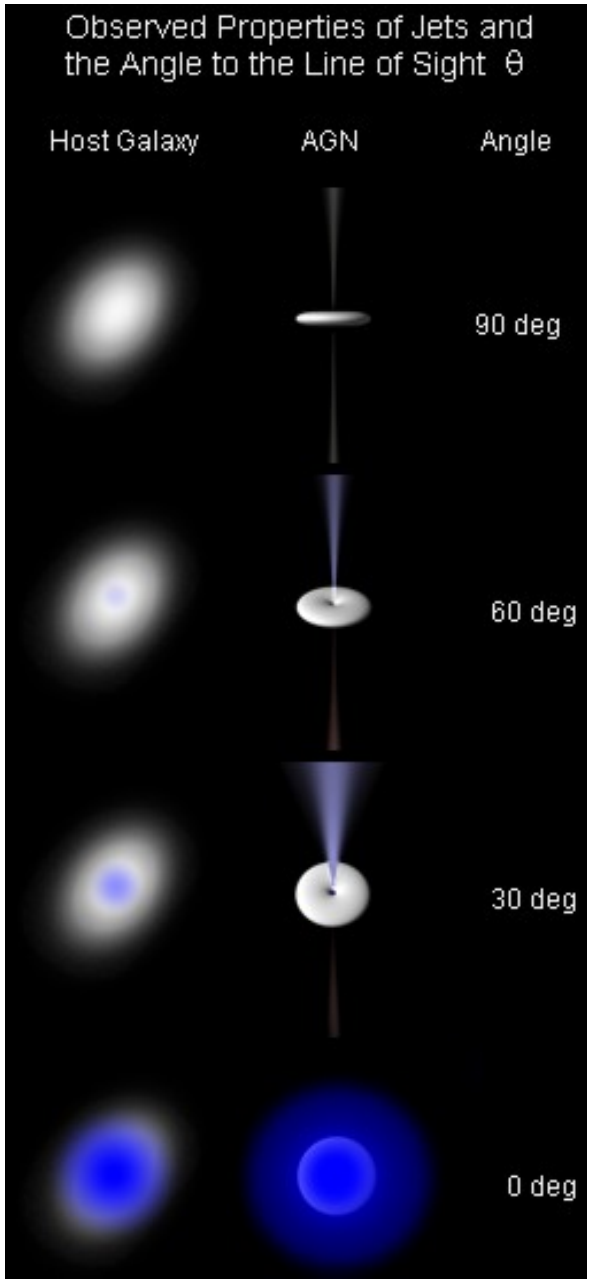
They are believed to be powered by accretion of mass onto a Super Massive **(10^6–10^9 M_{SUN})** **Black Hole** at the centre

Radius of SMBH ~ 10^{13} cm

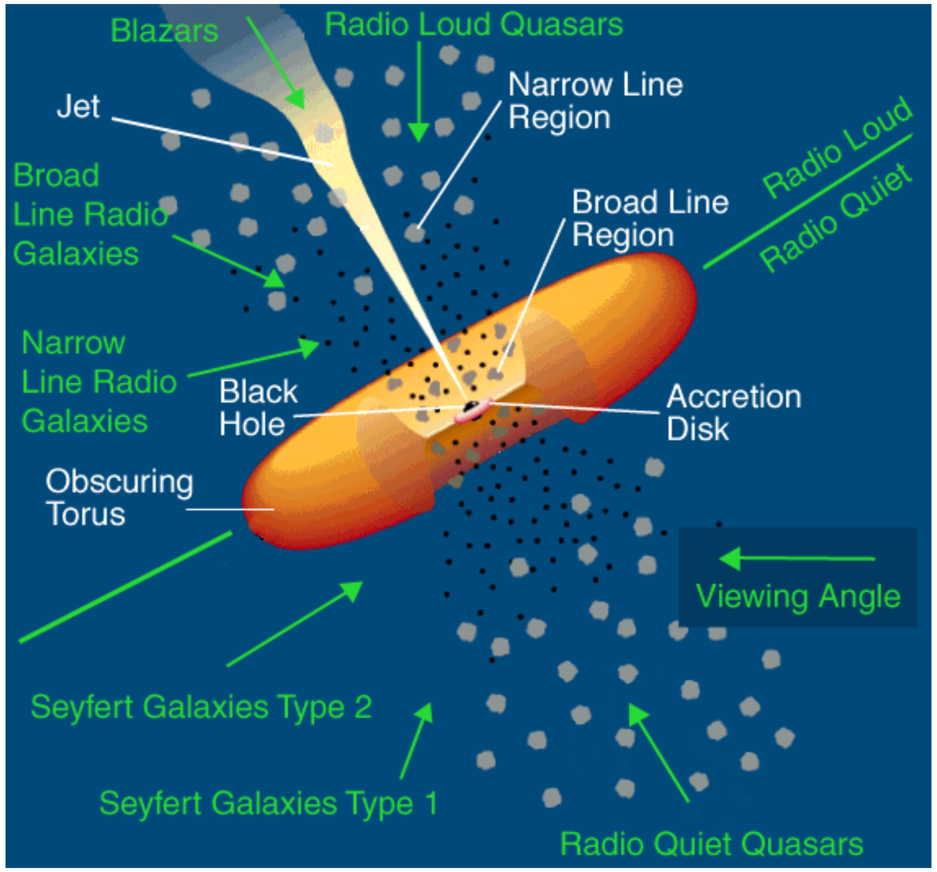
Radius of accretion disk ~ 10^{14} cm

Inner radius of dusty torus ~ 10^{17} cm

Extension of radio jets upto 10^{24} cm



Blazars : A Class of AGN



Majority of the Sources ~ 50%
@ Energies > GeV are Blazars

Blazar - jets are closely aligned with line of sight

Two Classes :: BL Lac & FSRQ

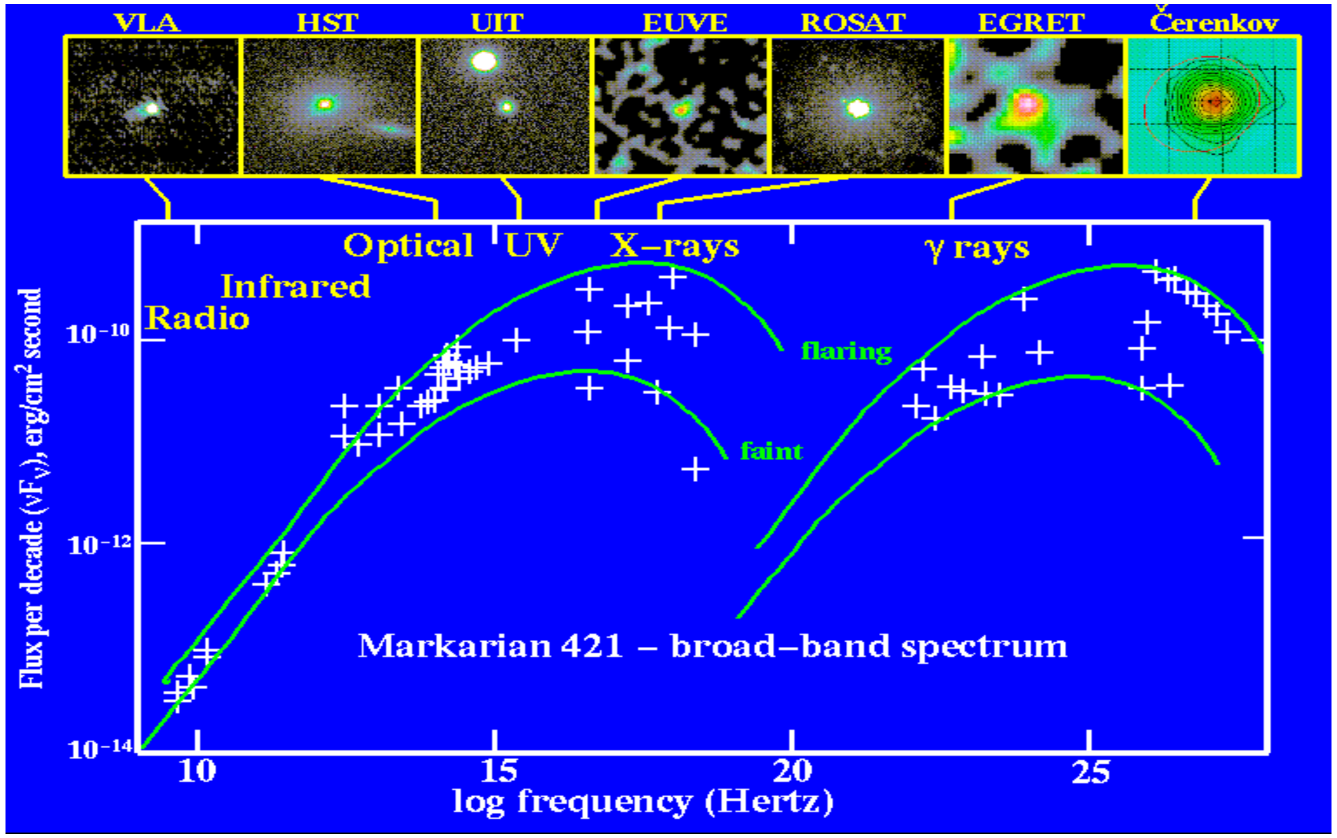
Unique tool to probe physics
of extreme environments

Jets are extended upto kpc or even Mpc

Doppler Boosting

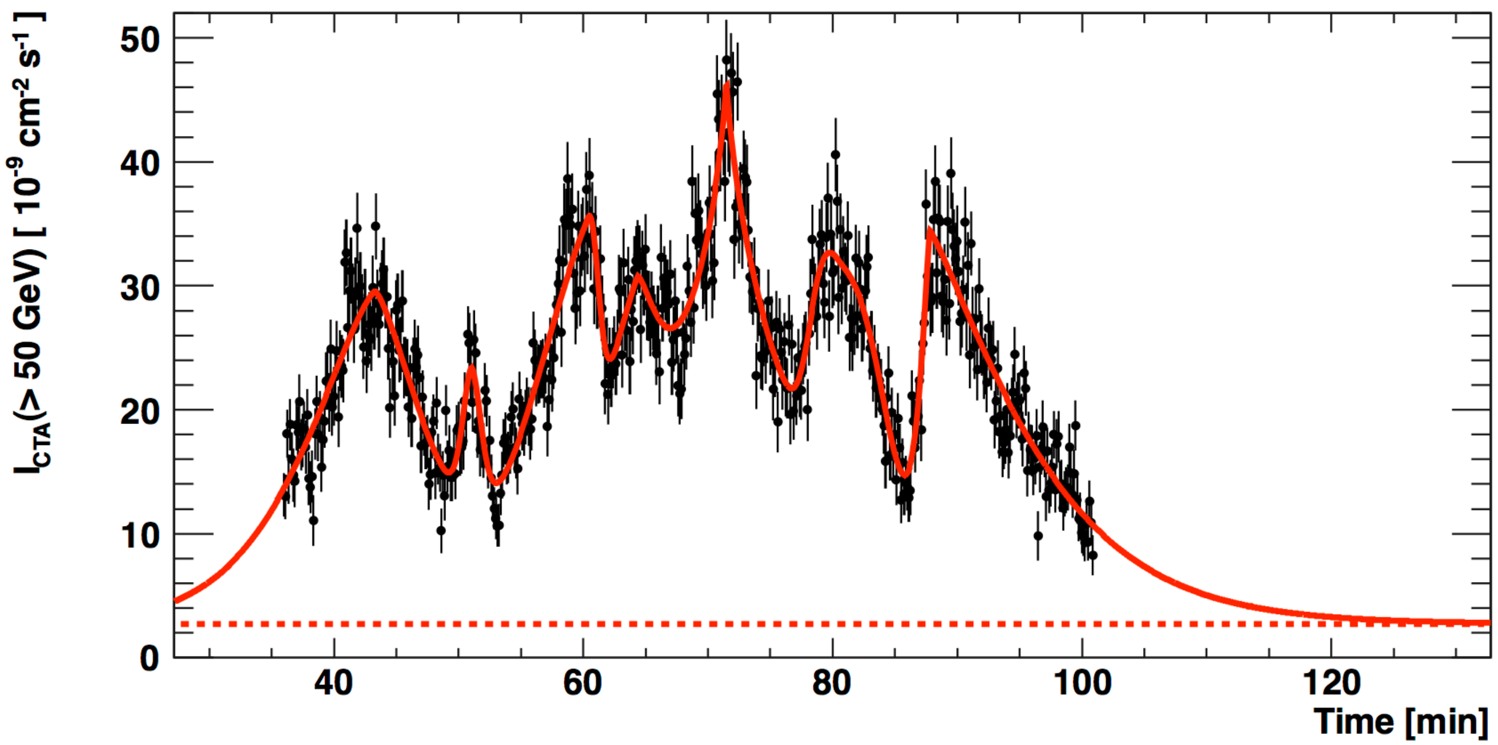
- If a relativistic jet is viewed at small angle to its axis, the observed emission is amplified because of relativistic beaming
- Given the compactness of Blazars - as suggested by their observed short variability timescales - all GeV/TeV photons would absorbed through pair-production with target X-ray/IR photons
- Beaming ensures that γ-photon encounters less opacity and therefore manages to escape the source

Multi-wavelength Detection of Blazars



Many Blazars Dectected across EM spectrum

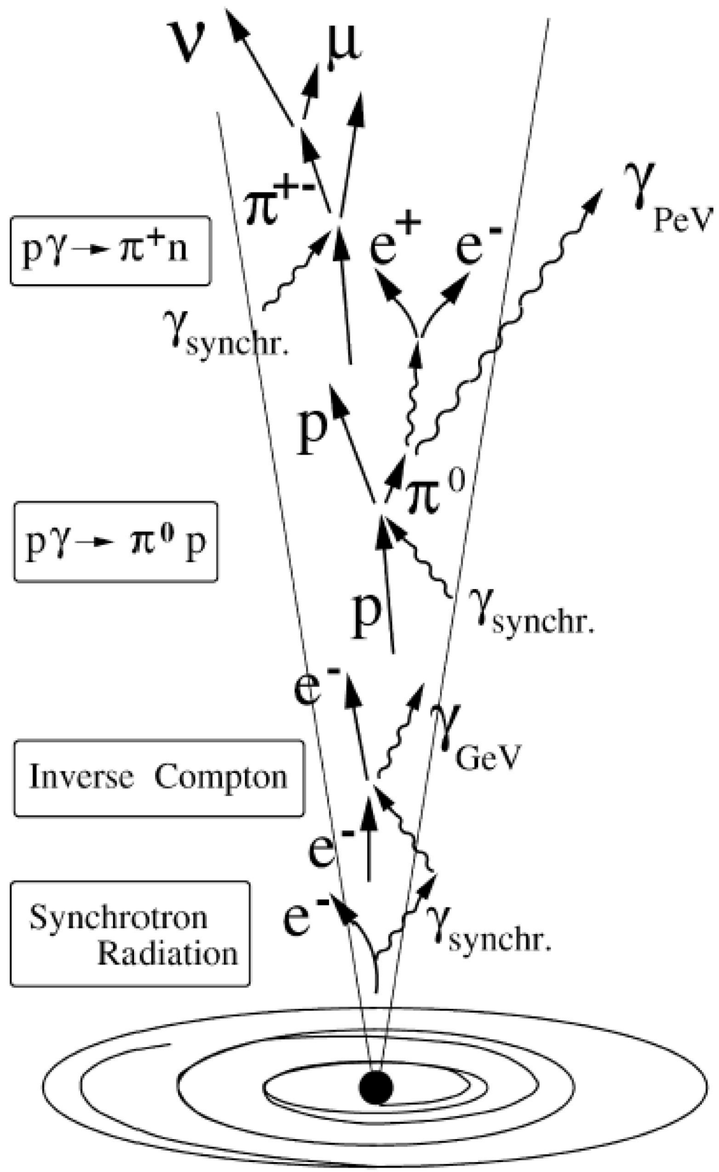
Characterised by Double Hump Structure

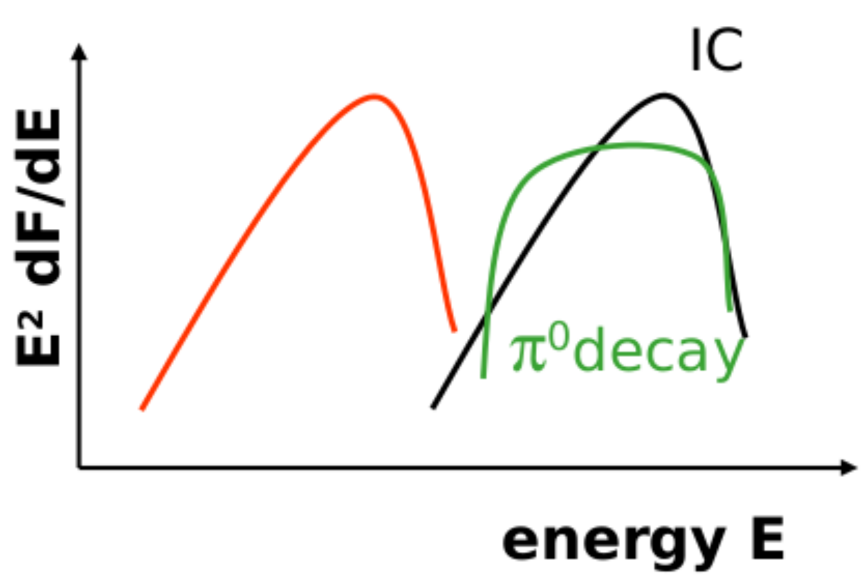


Highly Variable : Minutes to Years

Rapid variability puts Limit to Size of emission region due to light crossing time arguments

Emission Mechanisms @ Very High Energies





Leptonic Models

Synchrotron-Self Compton

External Compton

VHE γ-rays from Blazars

Space-borne and ground based telescopes has detected VHE γ-rays : can be explained by leptonic models

If they are source of cosmic rays then protons are also accelerated

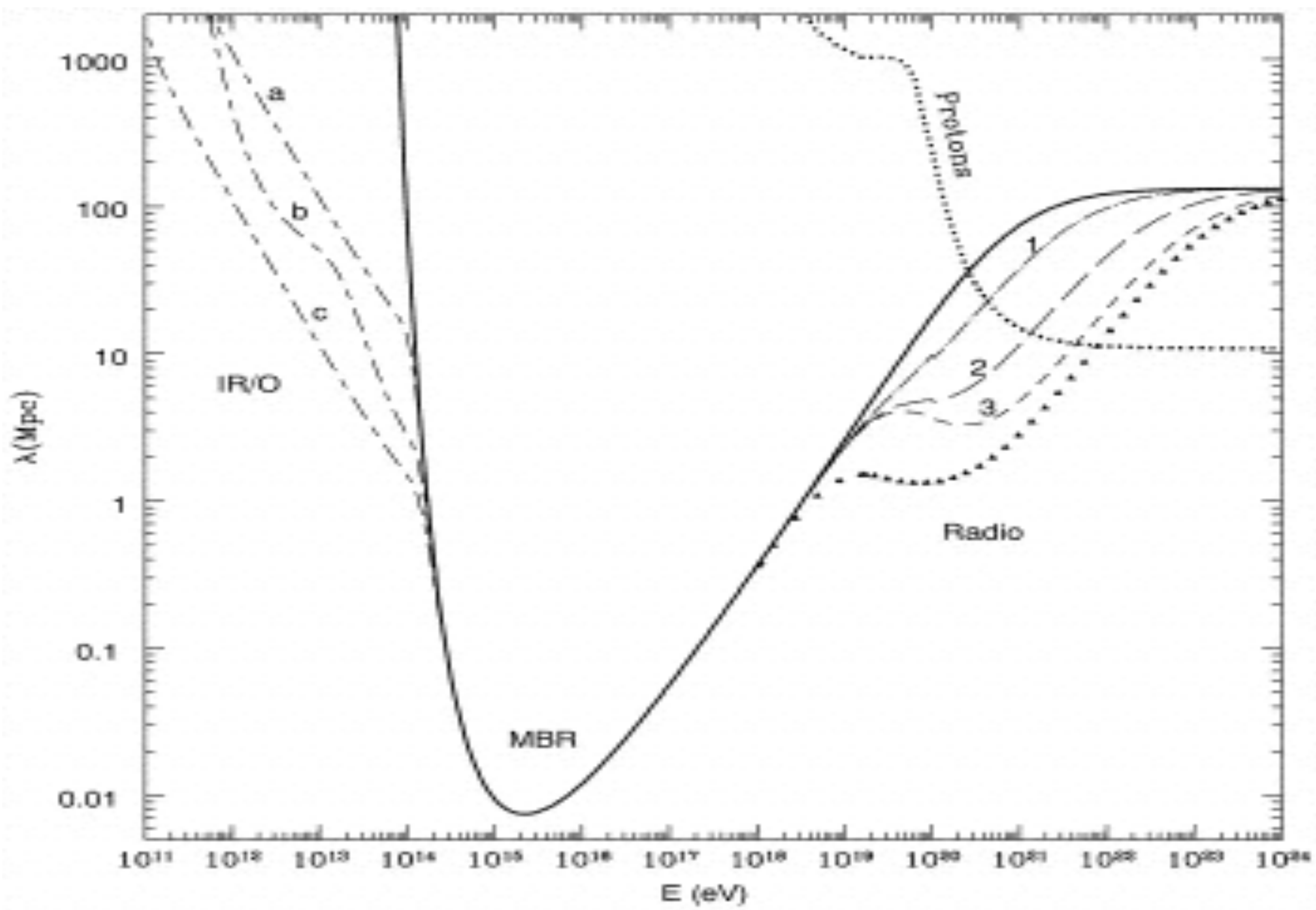
Hadronic Models

Proton-Proton Collisions

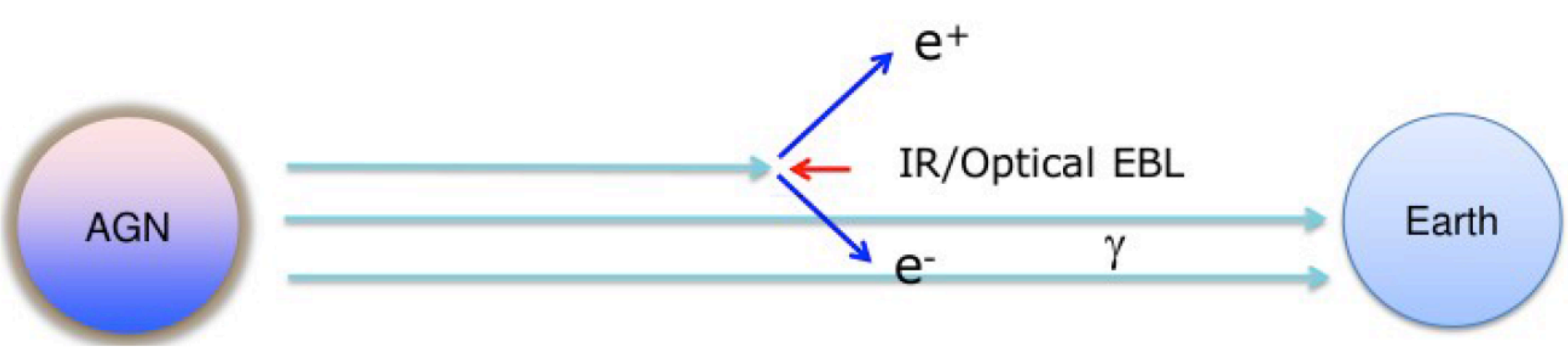
Proton-Photon Collisons

By Product **Neutrinos**

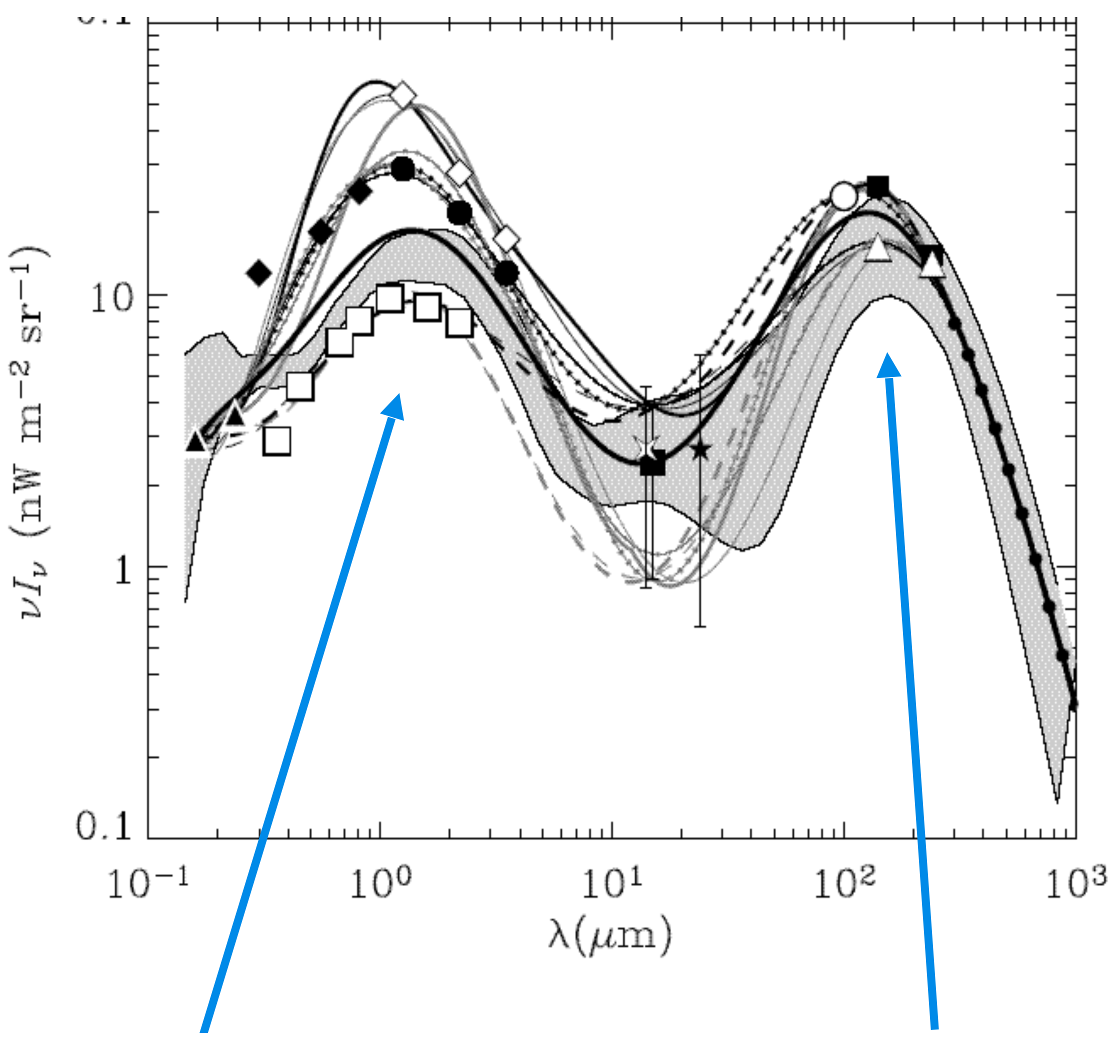
Gamma-ray Universe is Limited



A Blessing in Disguise



Extra-galactic Background Light (EBL)



Extra-Galactic Background Light is consists of Stellar light emitted and partially reprocessed by dust throughout the entire history of cosmic evolution. This also includes light emitted from hypothetical stars before galaxies were formed

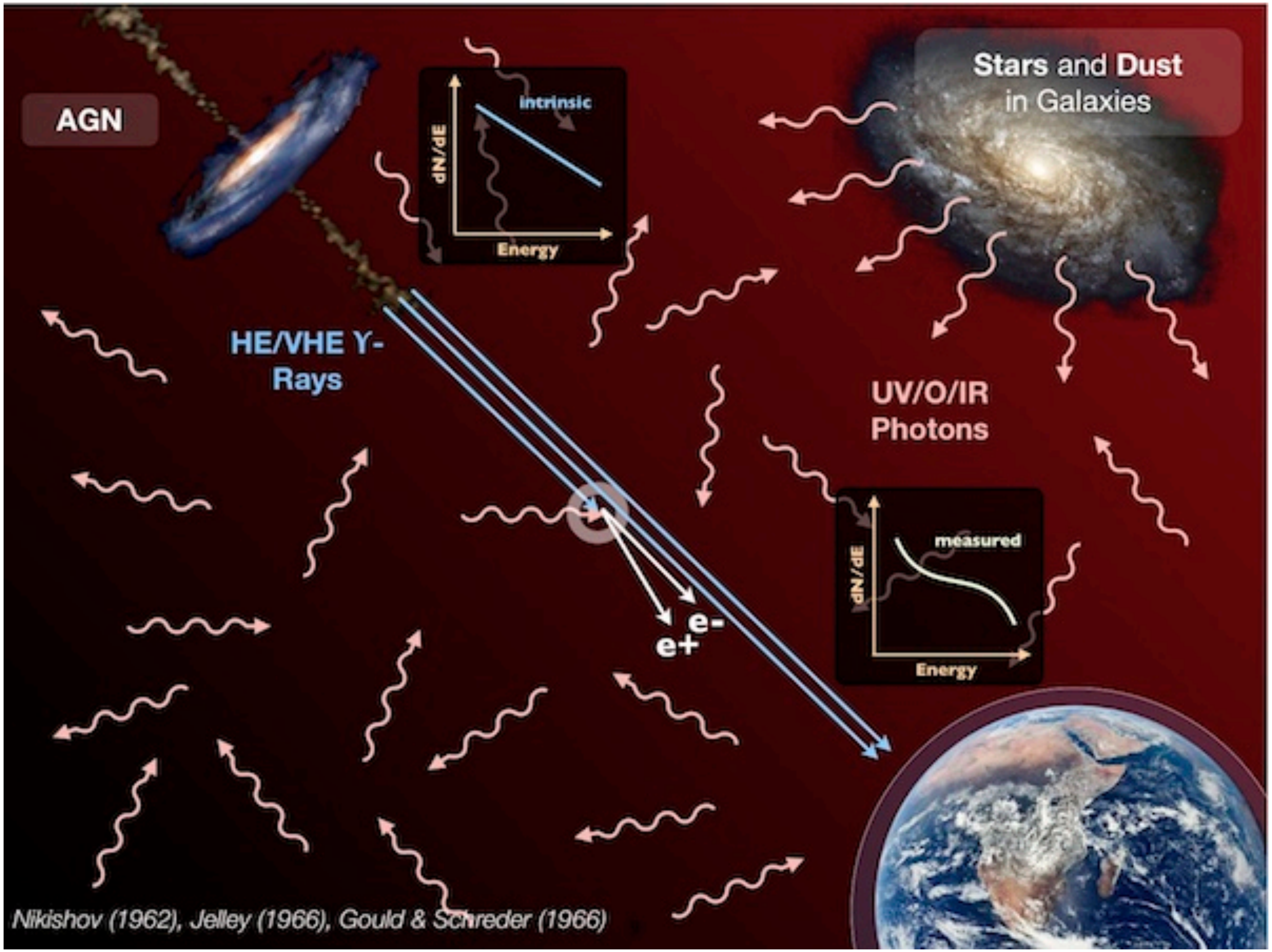
Study of EBL is important from Cosmological point of view - It contains informations about evolution of the Universe.

Direct measurements of EBL very difficult due to foreground emission from our solar system & galaxy

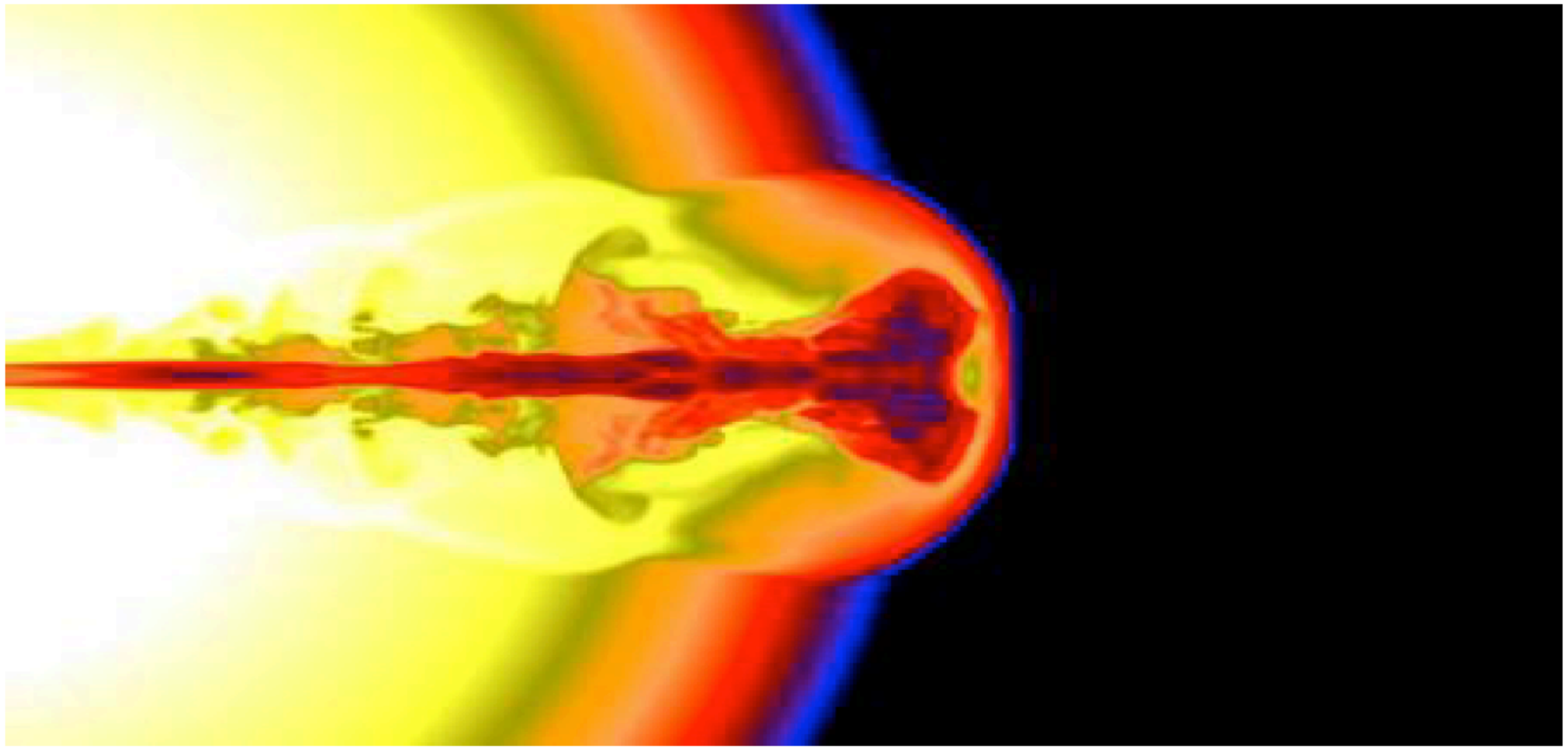
Redshifted stellar light   Redshifted dust light

Study EBL Using AGN

Study Several Sources at Different Distances Helps us to Measure EBL



Gamma Ray Bursts (GRBs)



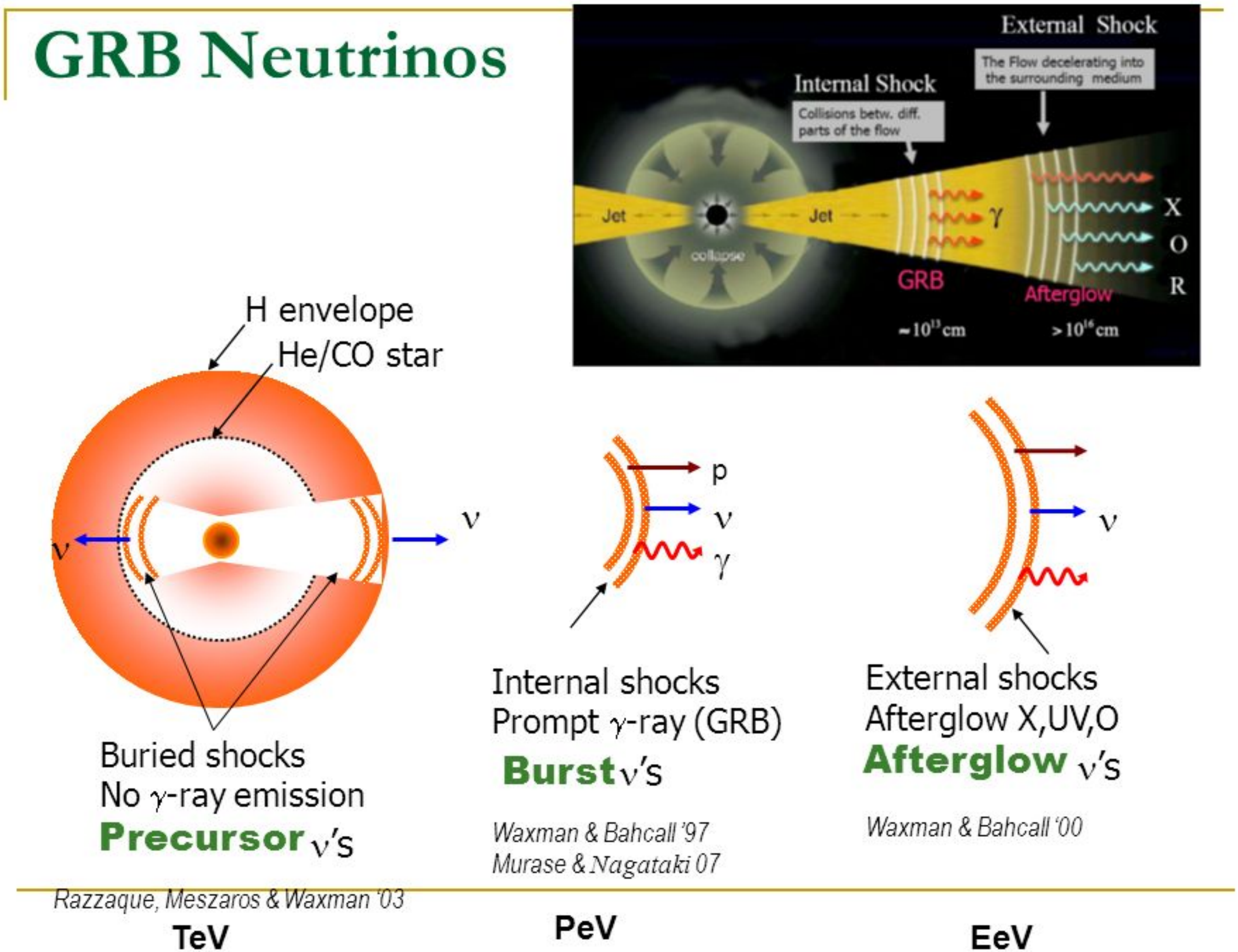
Solar rest mass worth of gravitational energy released in few Seconds

Most Violent Events of the Universe

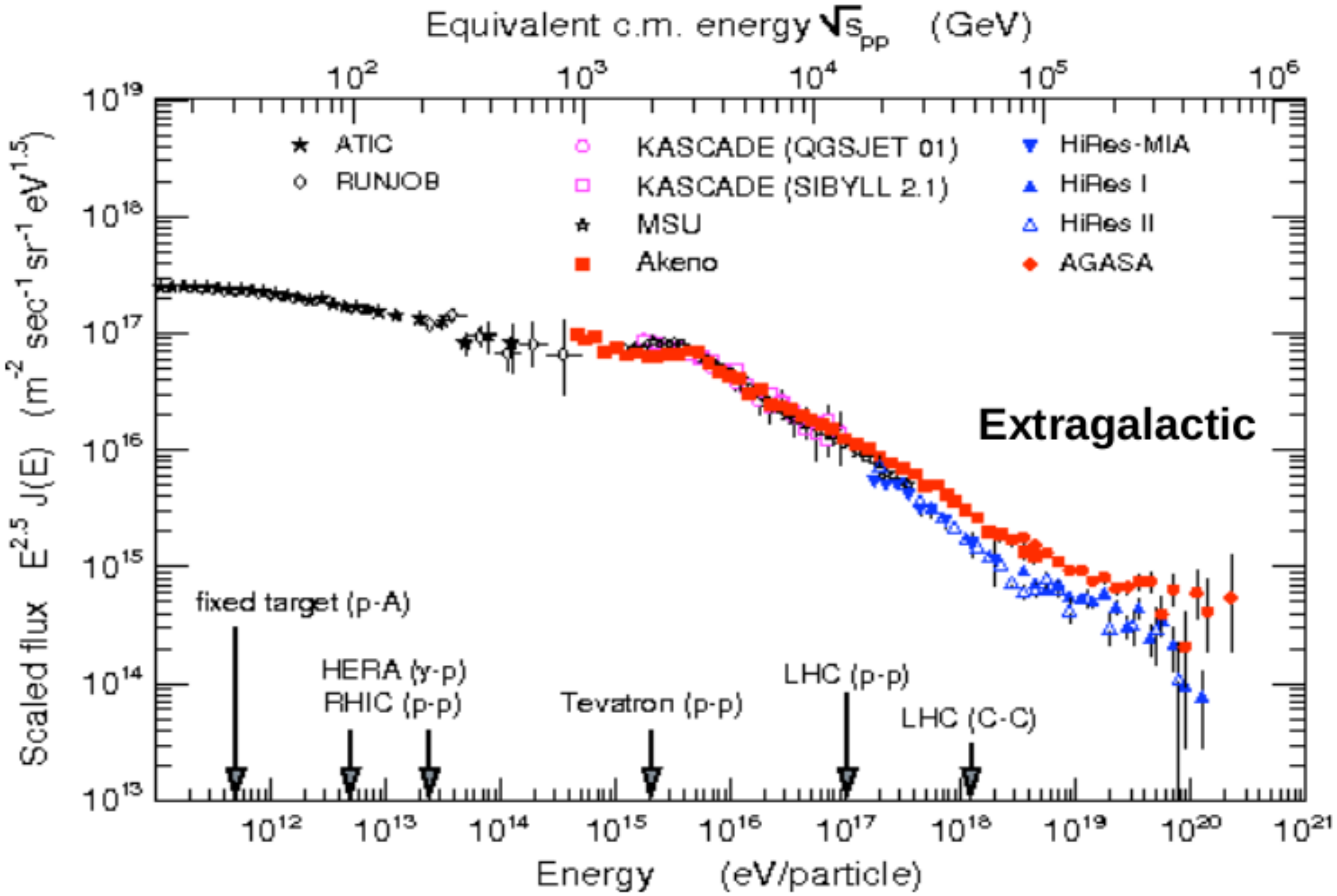
- Releases 10^{53}-10^{54} ergs/sec in few seconds
- Long GRBs (> 2s) - Collapse of massive star into a black hole
- Short GRBs (< 2s) - Merger of two compact objects (NS-NS or NS-BH) into a black hole

EM energy released by GRBs in few seconds = Energy released by Sun during entire lifetime (10^{10} years)

Gamma Ray Bursts



Cosmic ray - Neutrino Connection : GRBs



Energy Density of EG CR

$\rho_{CR} \sim 10^{45}\ ergs/yr/Mpc^3$

Gamma-ray Bursts

$\rho_{GRBs} \sim 10^{45}\ ergs/yr/Mpc^3$

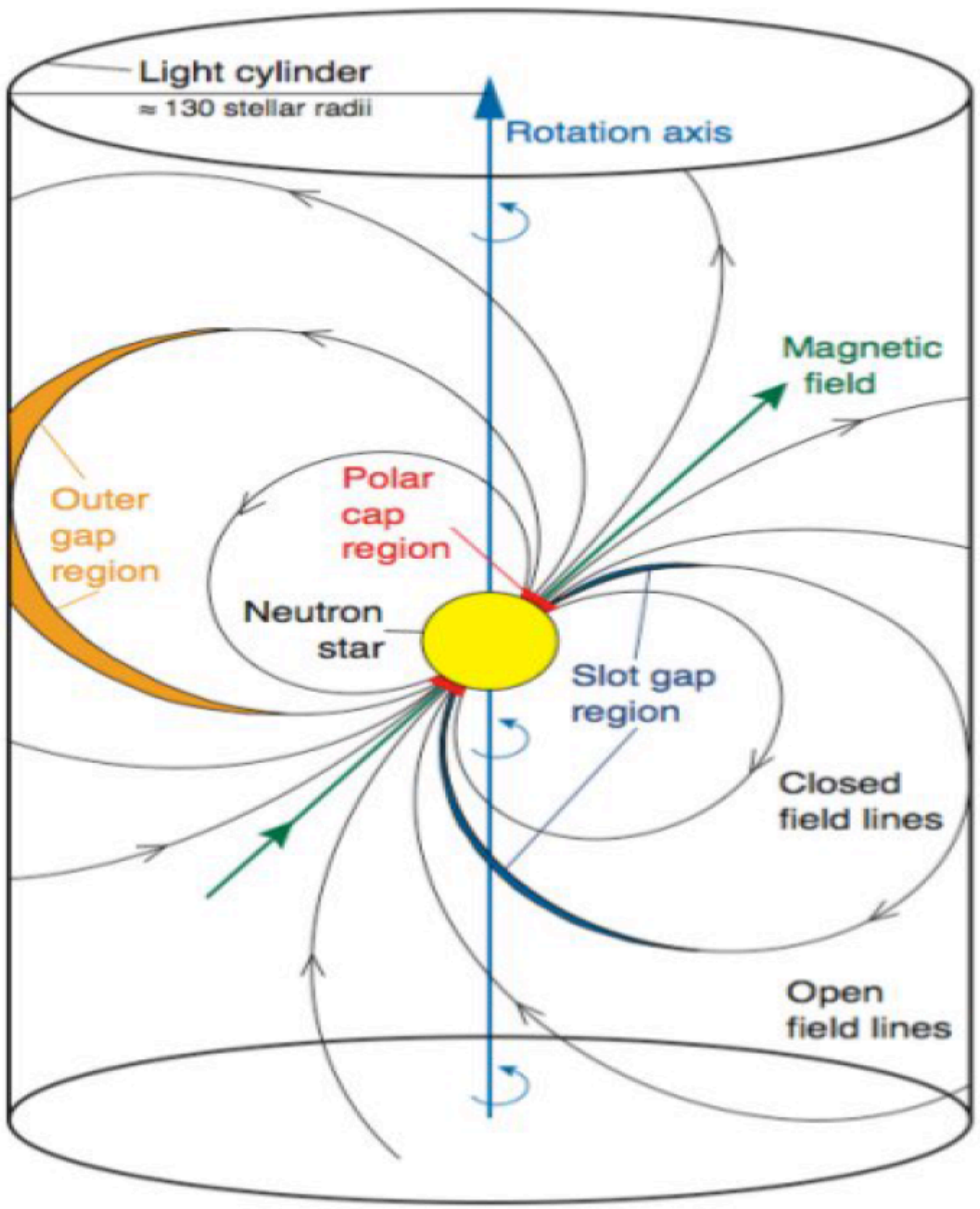
From :

(2-3)$10^{51} ergs \times 300/yr/Gpc^3$

Waxman (1995)

GRBs could provide environment and energy to explain the highest energy cosmic rays!

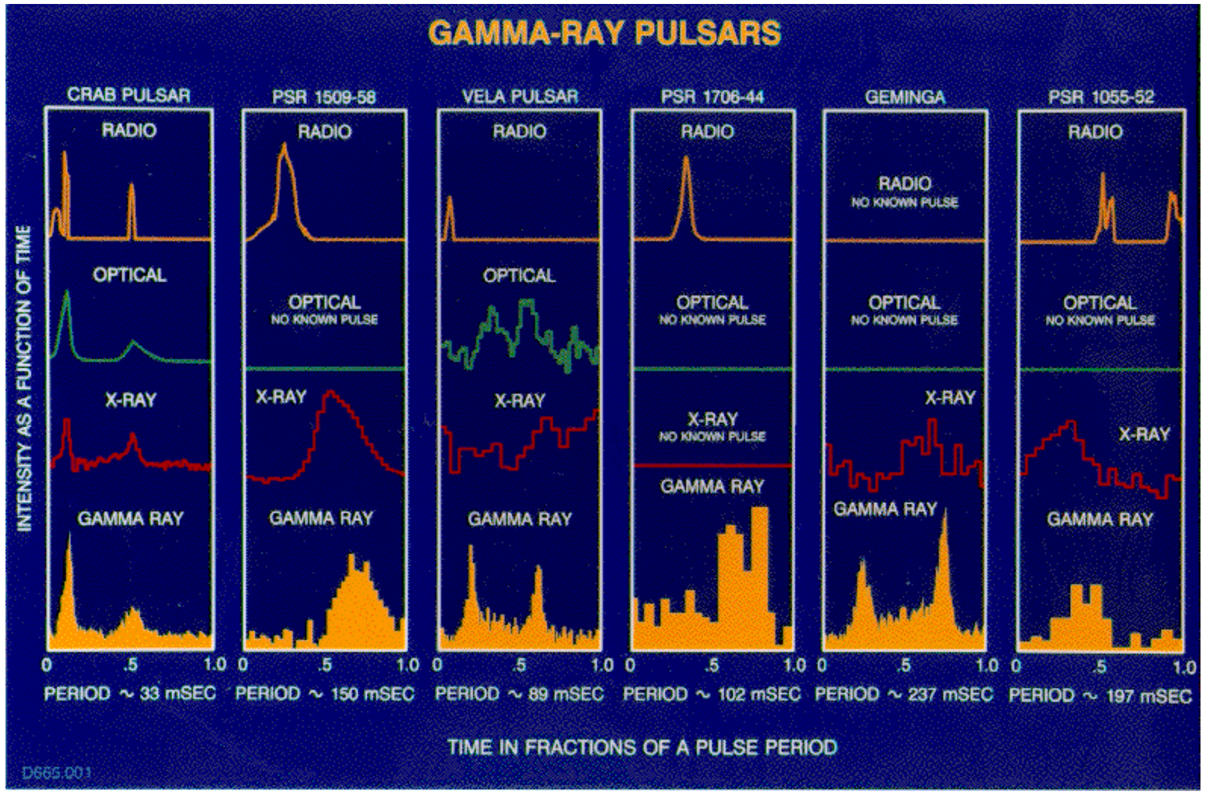
Galactic Source : Crab Pulsar

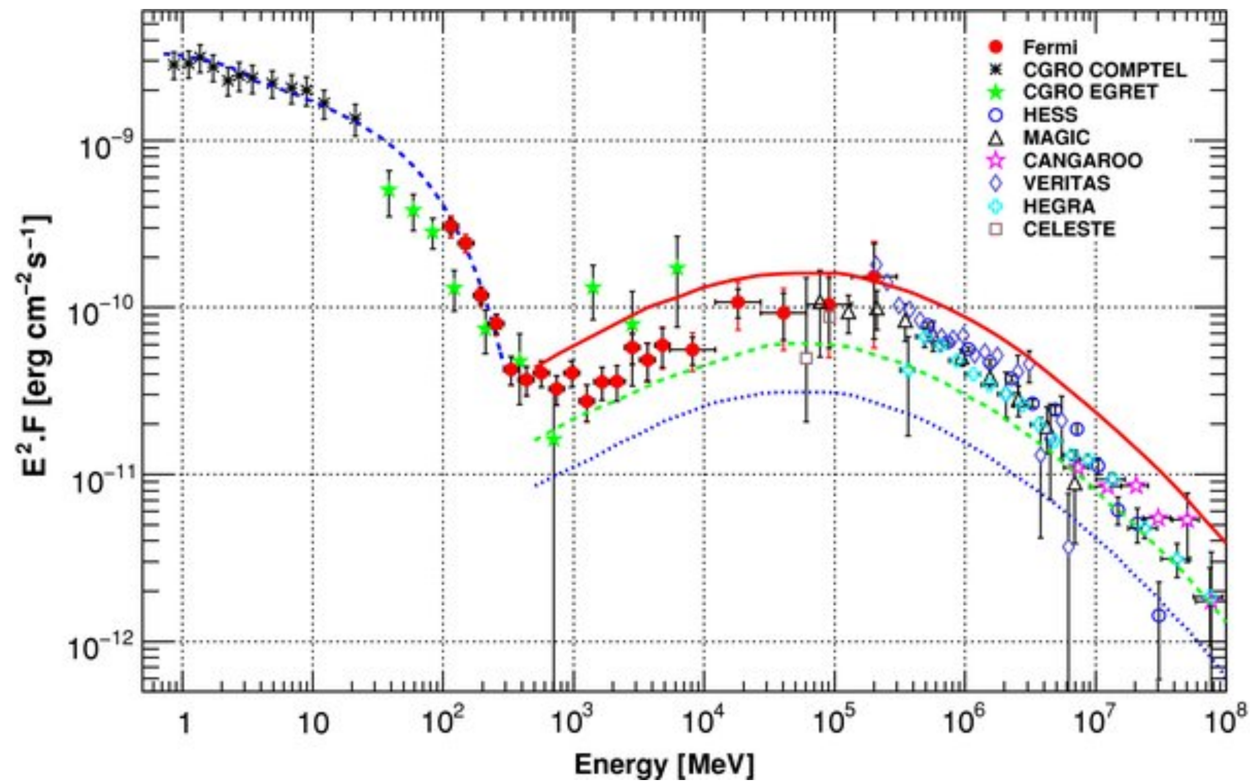


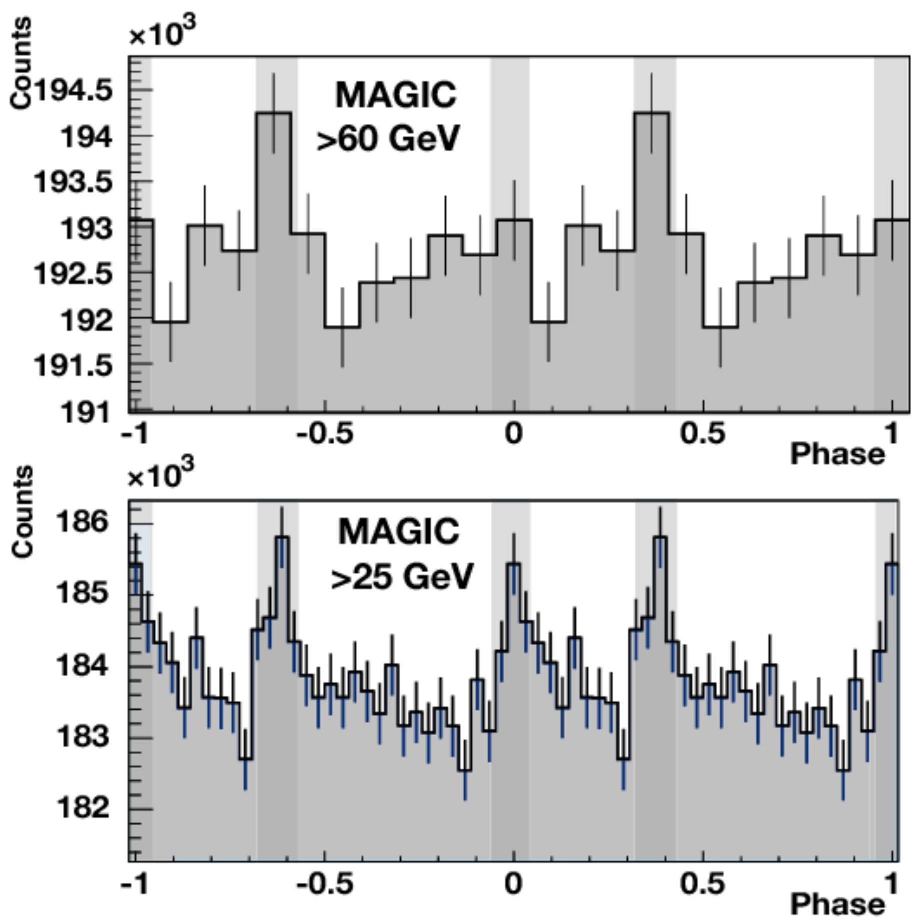
Crab Pulsar

- Rotating neutron stars
- Detected across electromagnetic spectrum from radio to gamma-rays
- Cherenkov telescopes have detected both continuous and pulsed emission from Crab
- According to some models protons or ions are also present along with $e^{\pm}$ in the magnetized wind of relativistic plasma, p-p and p-γ processes produce γ's & ν's through meson decays

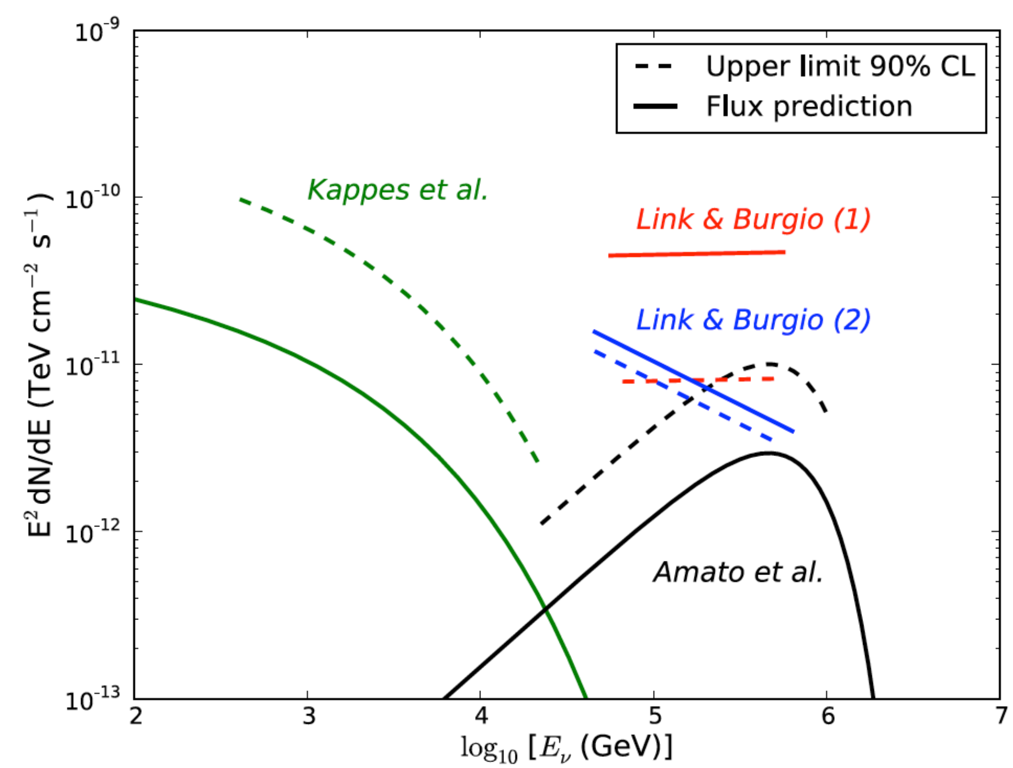
HE Emission from Crab Pulsar



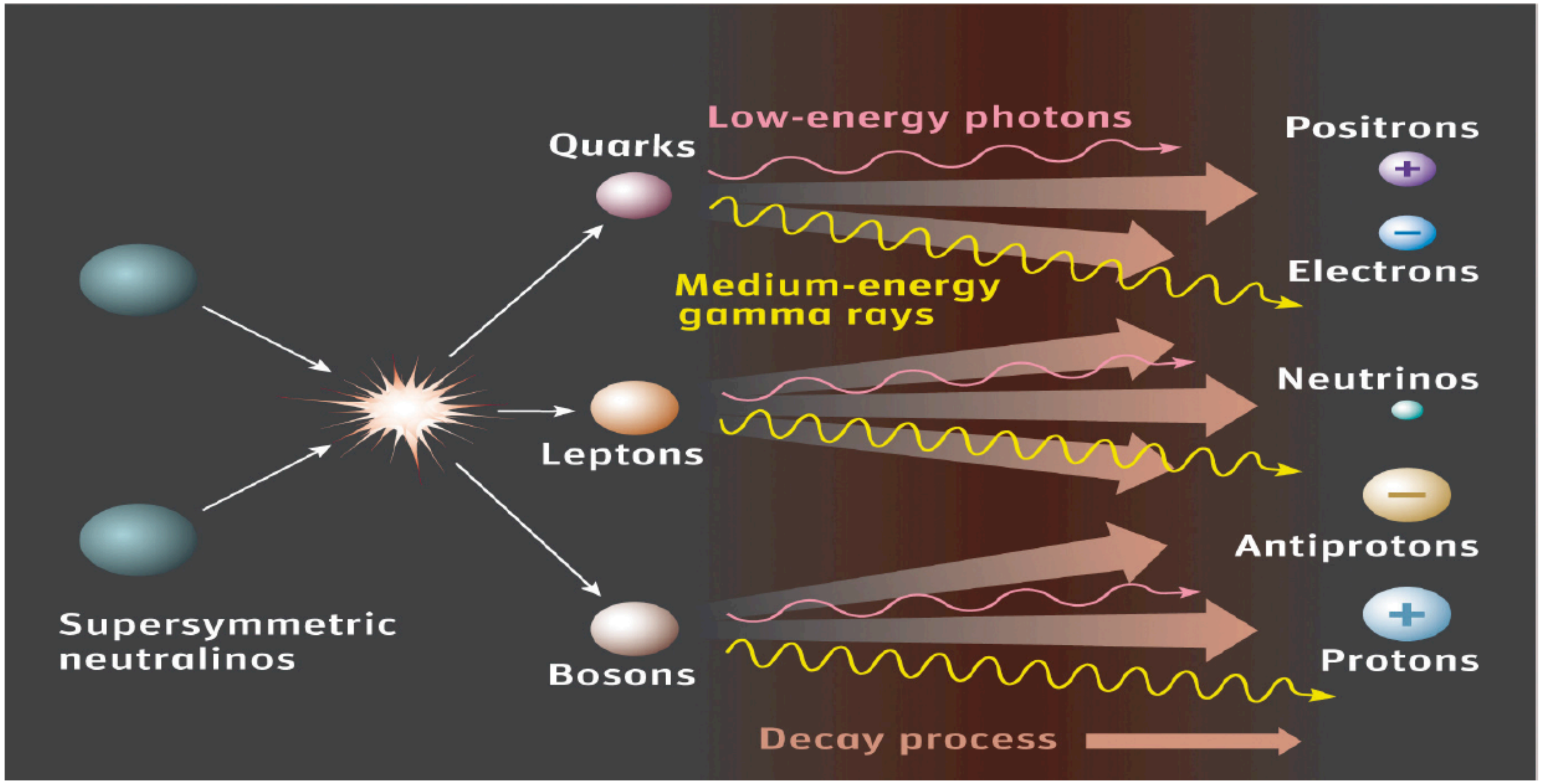




September, 2010 Crab went into a flare state (Unusual)



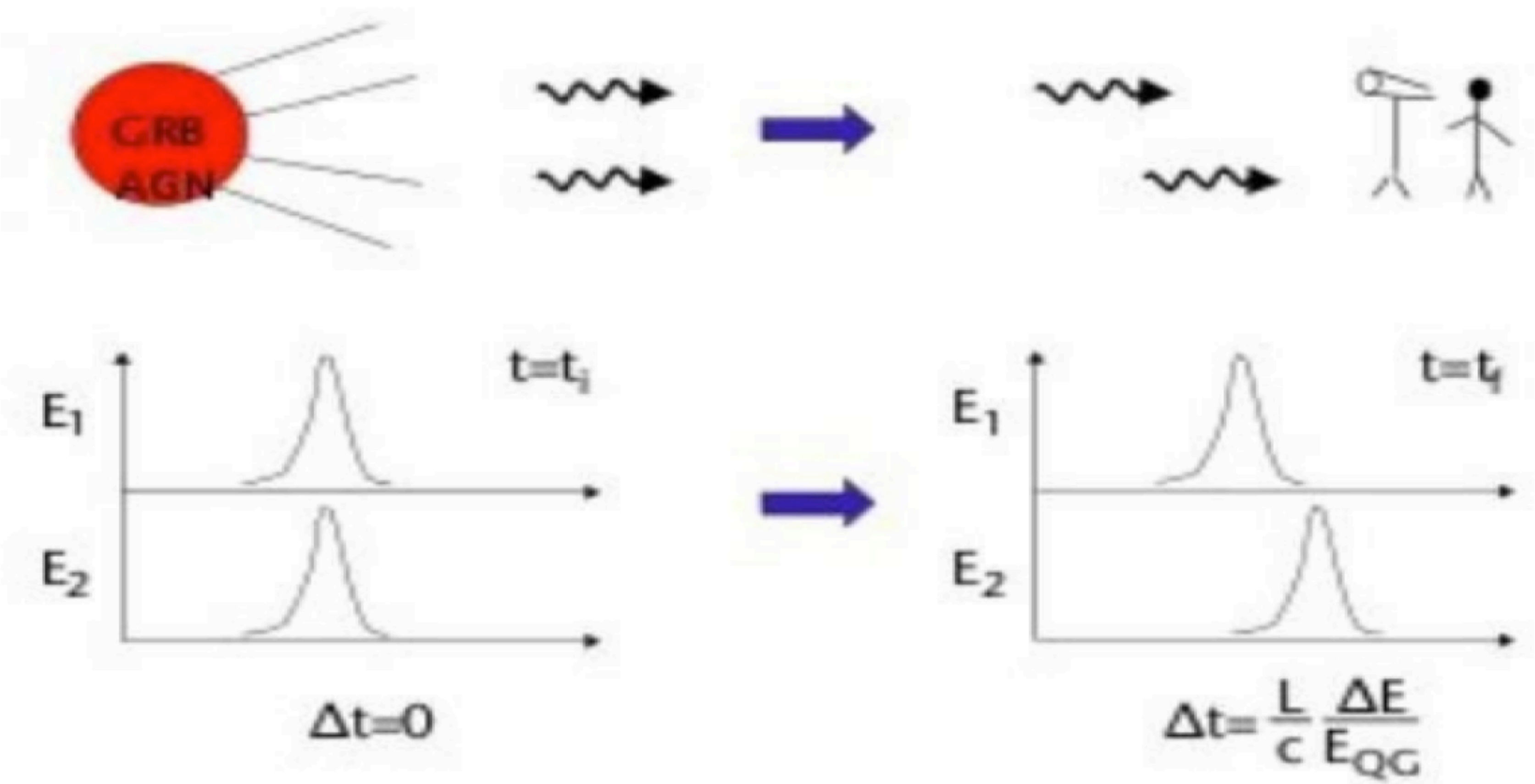
Indirect Search for Dark Matter



WIMP Searches

- Look for objects where dark matter might have accumulated over the evolution of the Universe
- Search for γ's & ν's from WIMP annihilation
- Probable sources : Sun, Earth, Galactic Center, Dwarf Spheroids

Search for Lorentz Invariance Violation

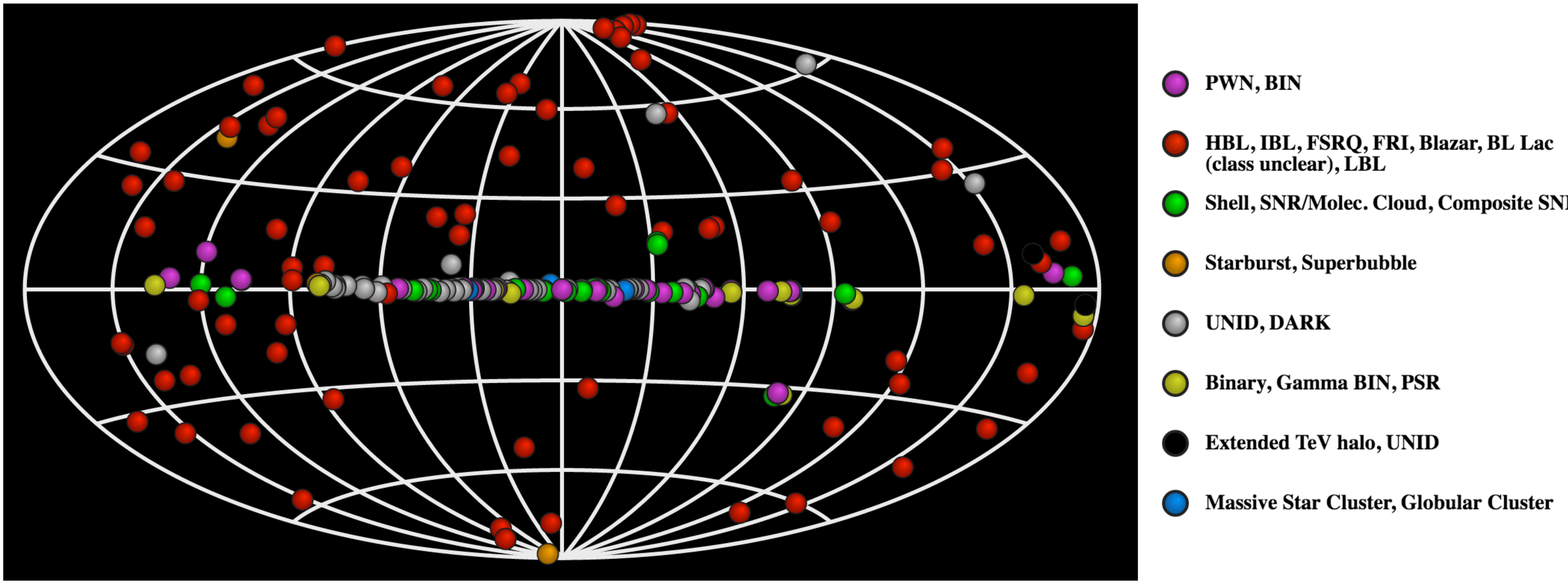


Lorentz Invariance

- Some theories of QG suggests that Lorentz invariance may breakdown near Planck length (1.62×10^{-33}cm)
- Causing γ's & ν's of different energies travelling at different speed
- Transient sources (AGN/GRBs) needed to measure such delays

Sky @ Very High Energies

VHE Gamma-ray Sources as Seen by Ground Based Gamma-ray Telescopes



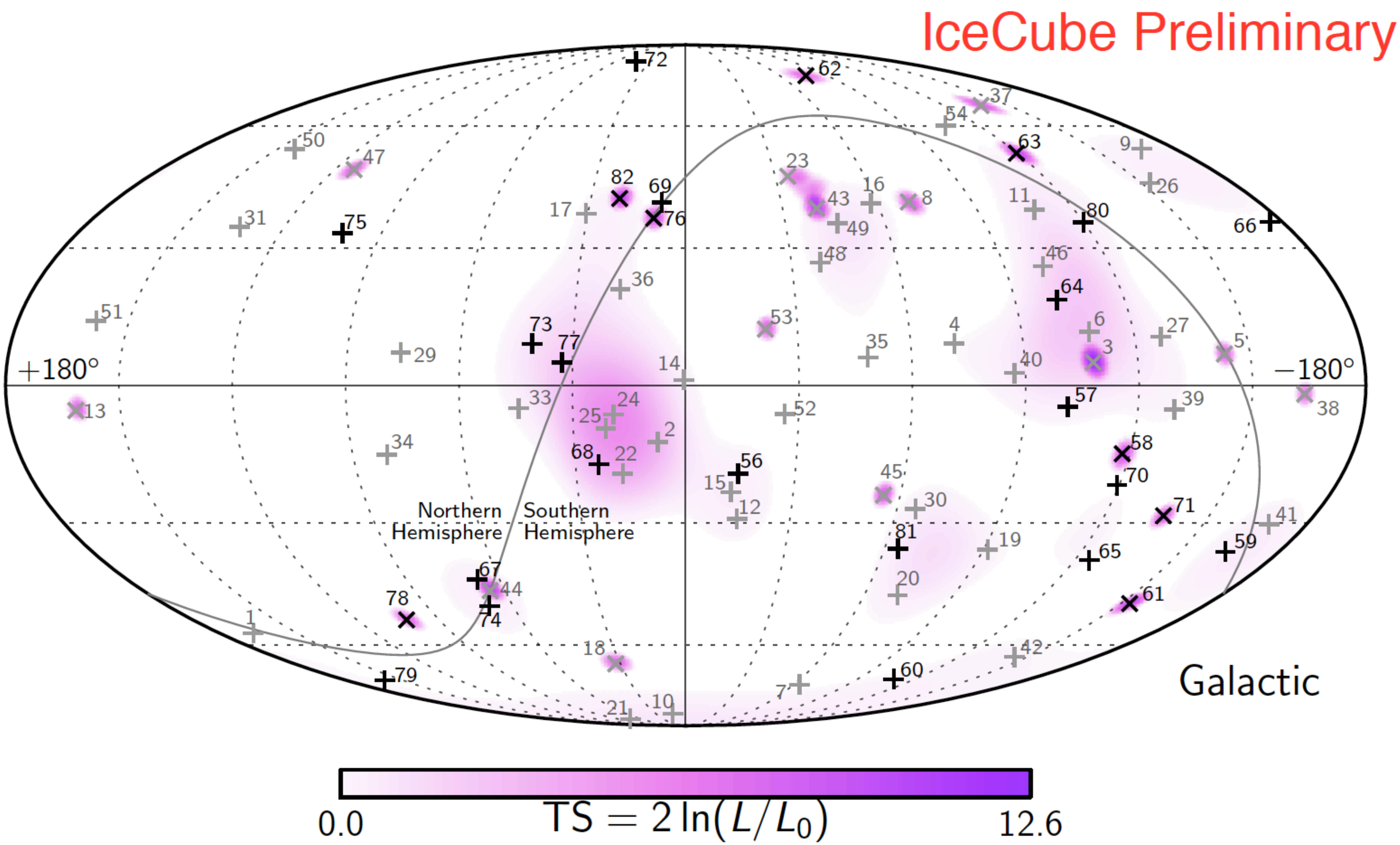
Majority of the Sources are Blazars

So far no GRBs are detected by Ground Based Gamma-ray telescopes

Only few detected in GeV energies

Also there are technical issues, such as limited duty cycle, small field of view

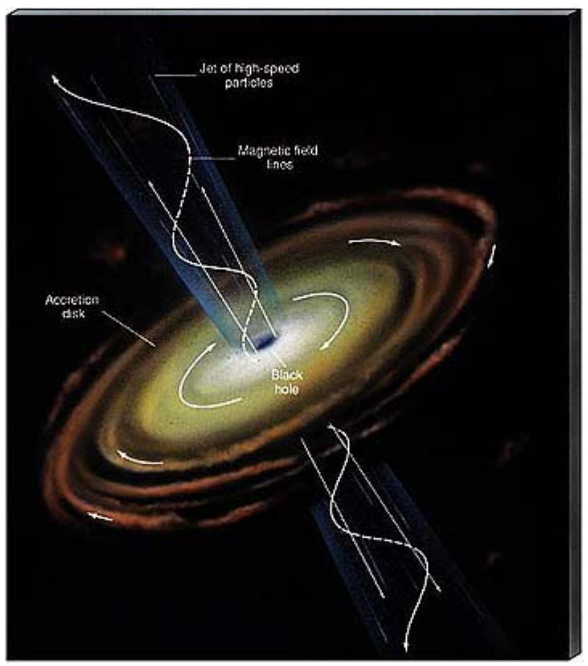
Skymap - High Energy Neutrino Events



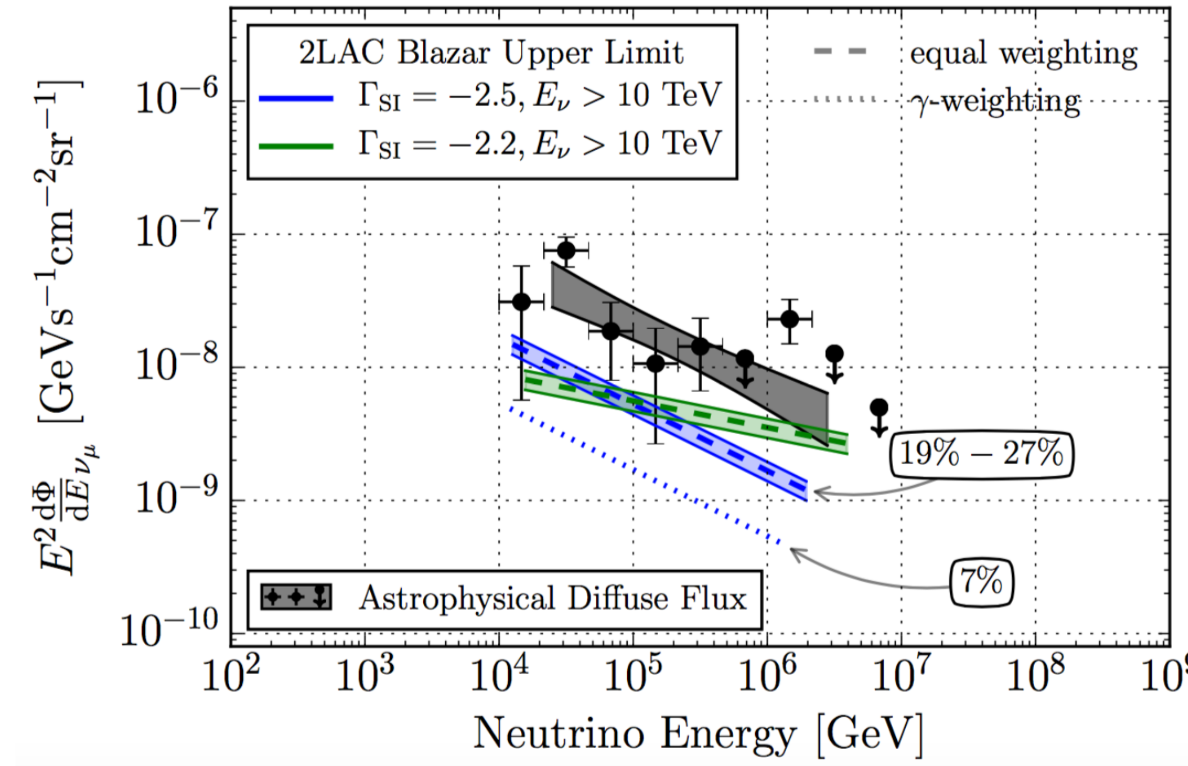
No Significant Clustering Found Including Around Galactic Plane

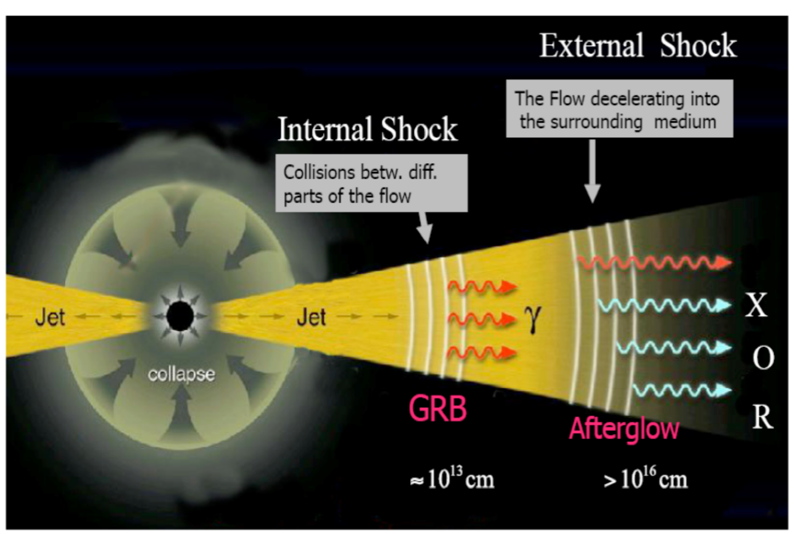
PoS (ICRC2017) 981

Where Are They Coming From ?

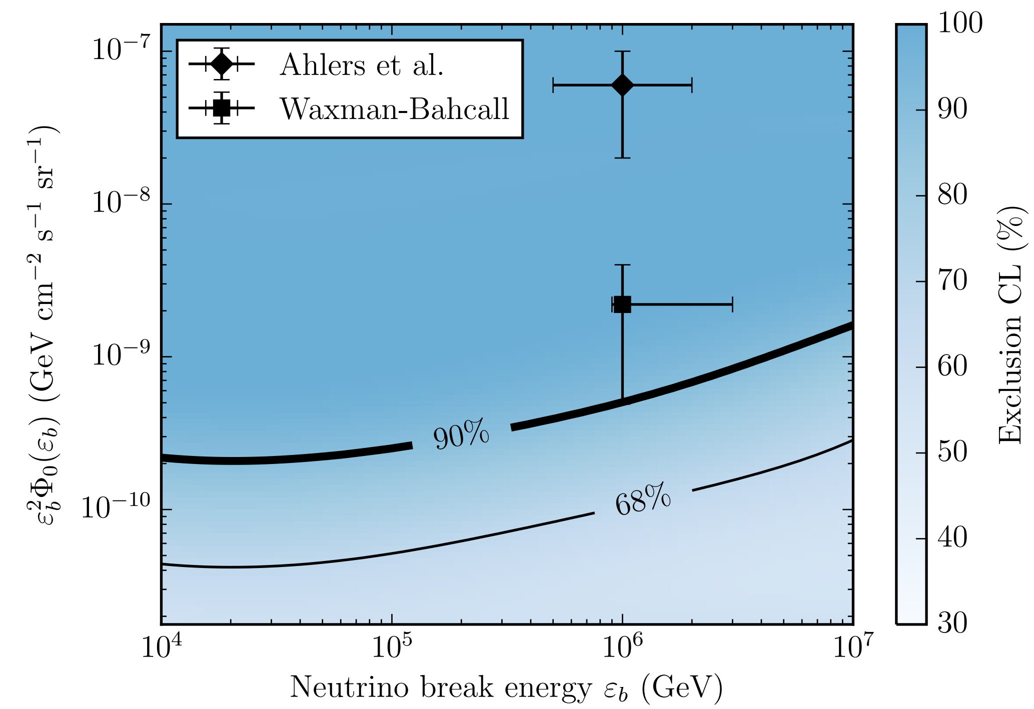


AGN < 30%





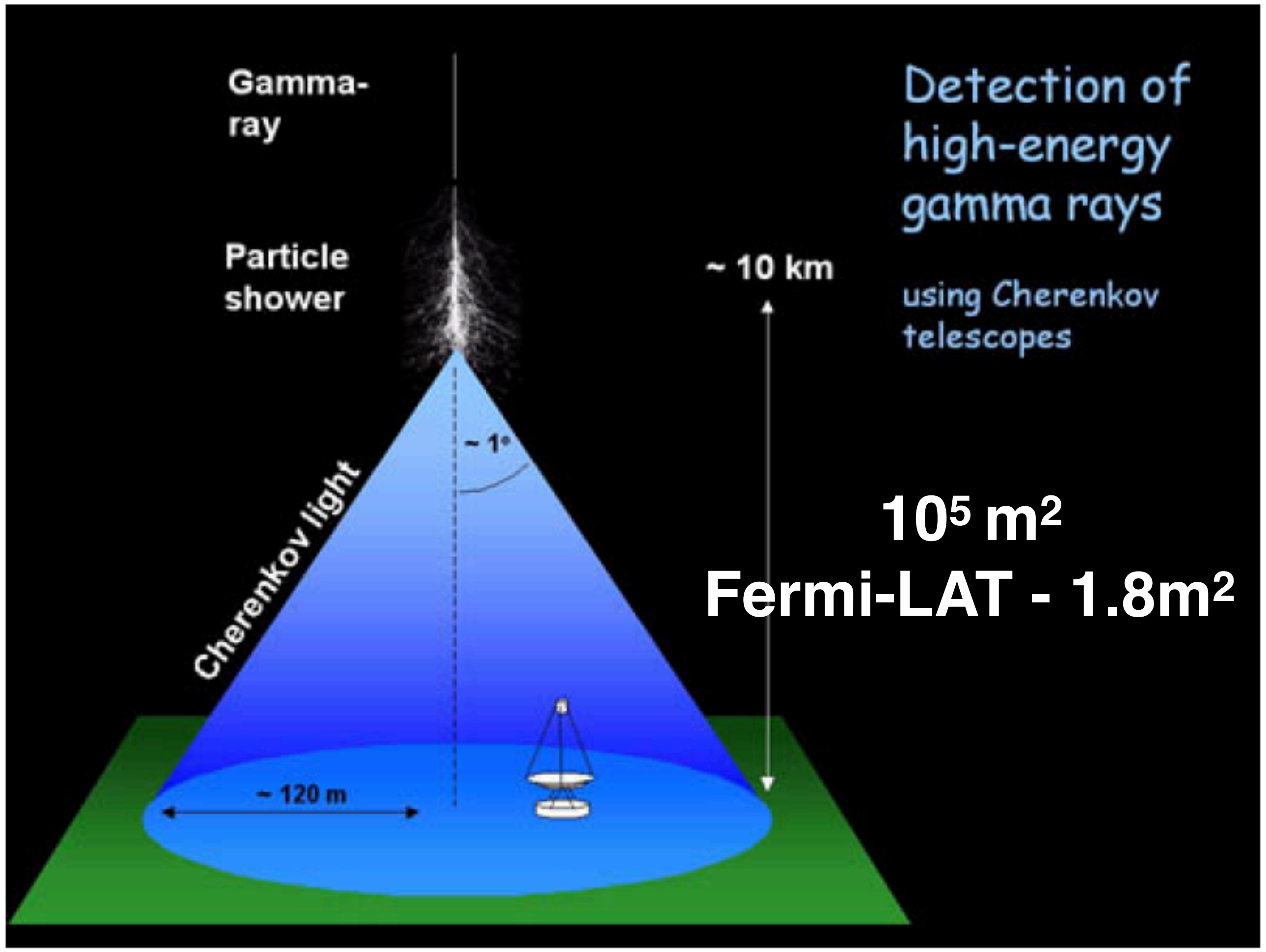
GRBs < 1%

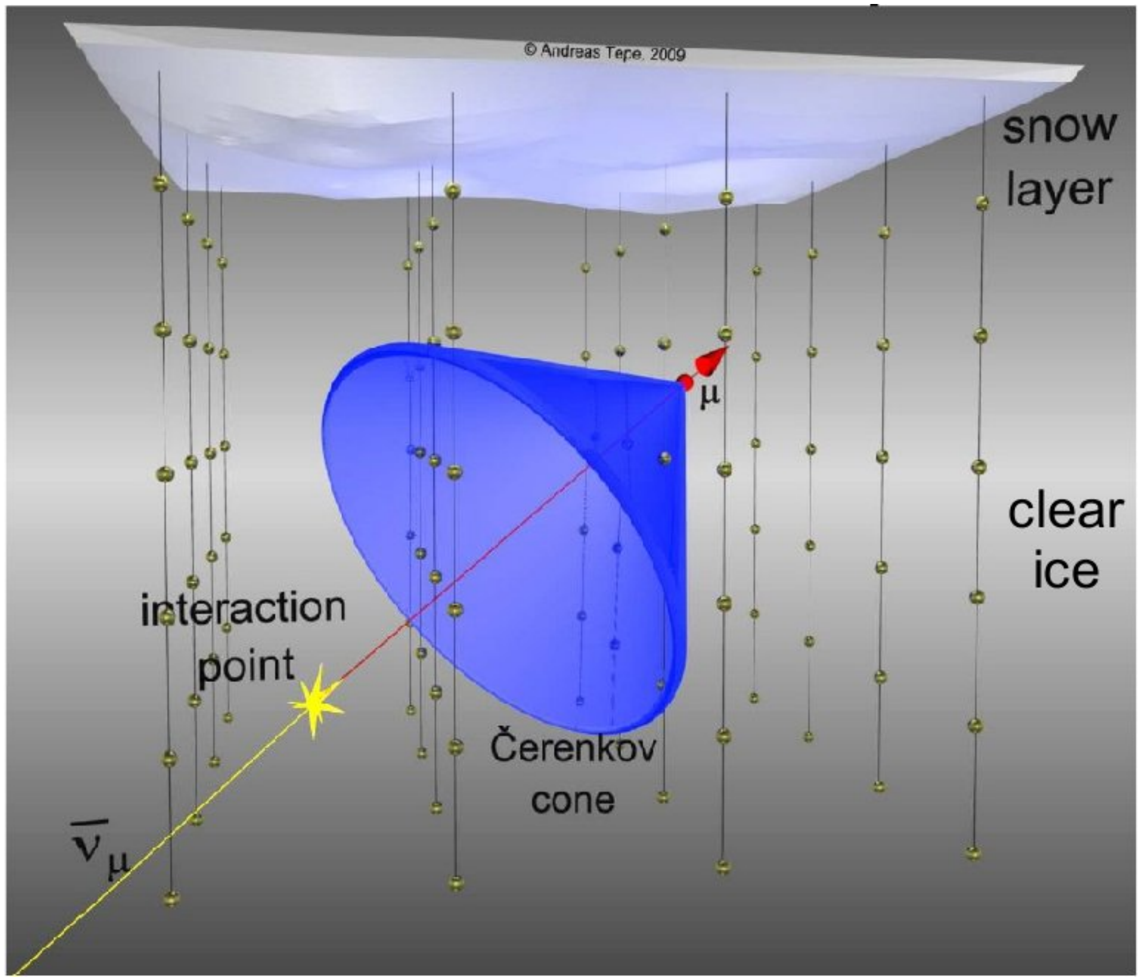


Astrophysical Flux is Compatible with Diffuse Flux

Detection Techniques @ Very High Energies
Current Gamma-ray & Neutrino Telescopes

Gamma-ray & Neutrino Detection Technique @ HE in Ground

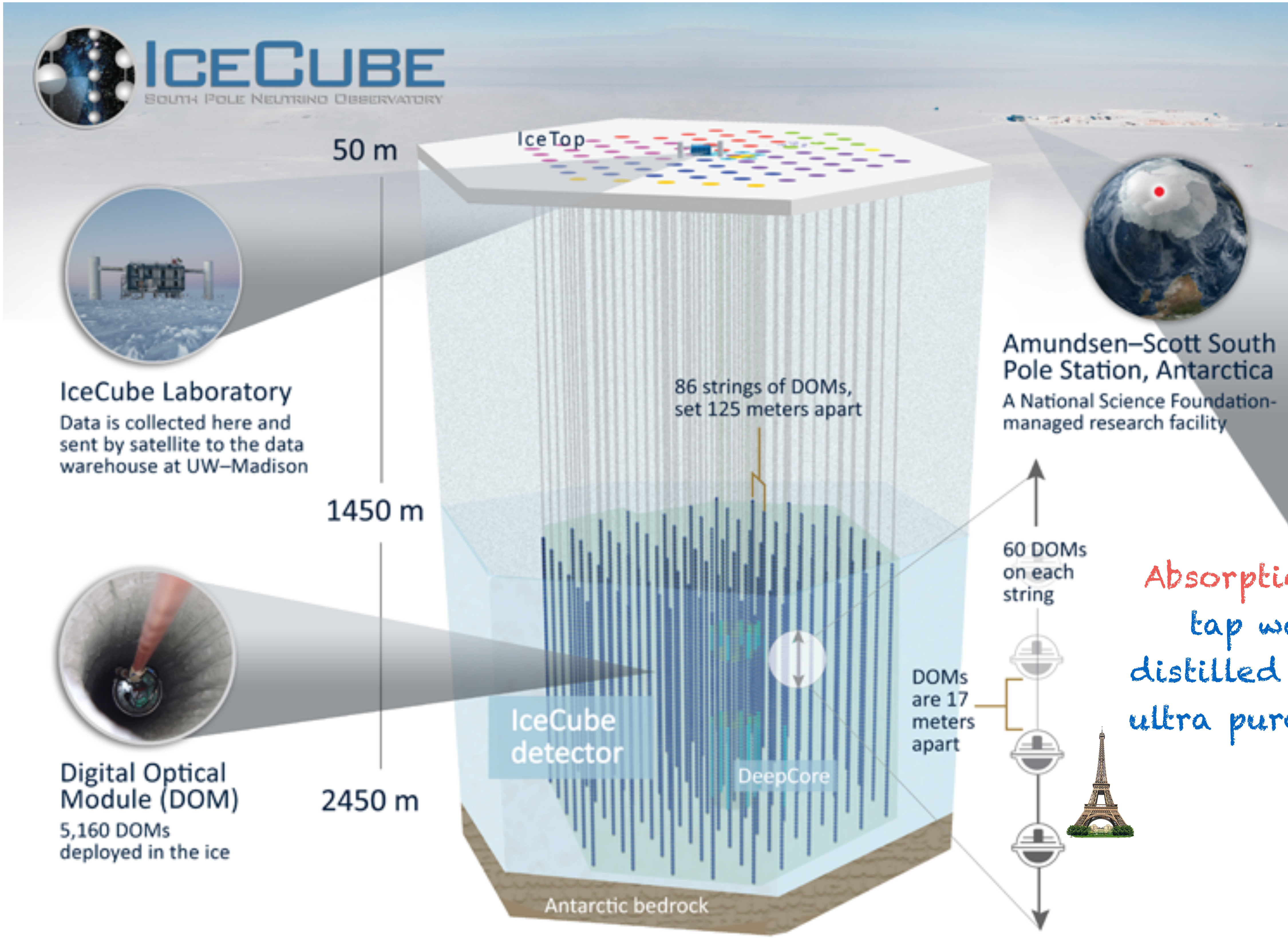




As the energy increases Flux of Gamma-rays & Neutrinos Decreases
So we Need Big Detectors !!
Fortunately Secondary Particles Produced by Their Interaction
Emit Cherenkov Light in Optical-UV Range
Therefore We Need Natural Transparent Medium
For Gamma-rays : Atmosphere
For Neutrinos : Ice / Water

Ground Based Gamma-ray Telescopes

IceCube Neutrino Telescope



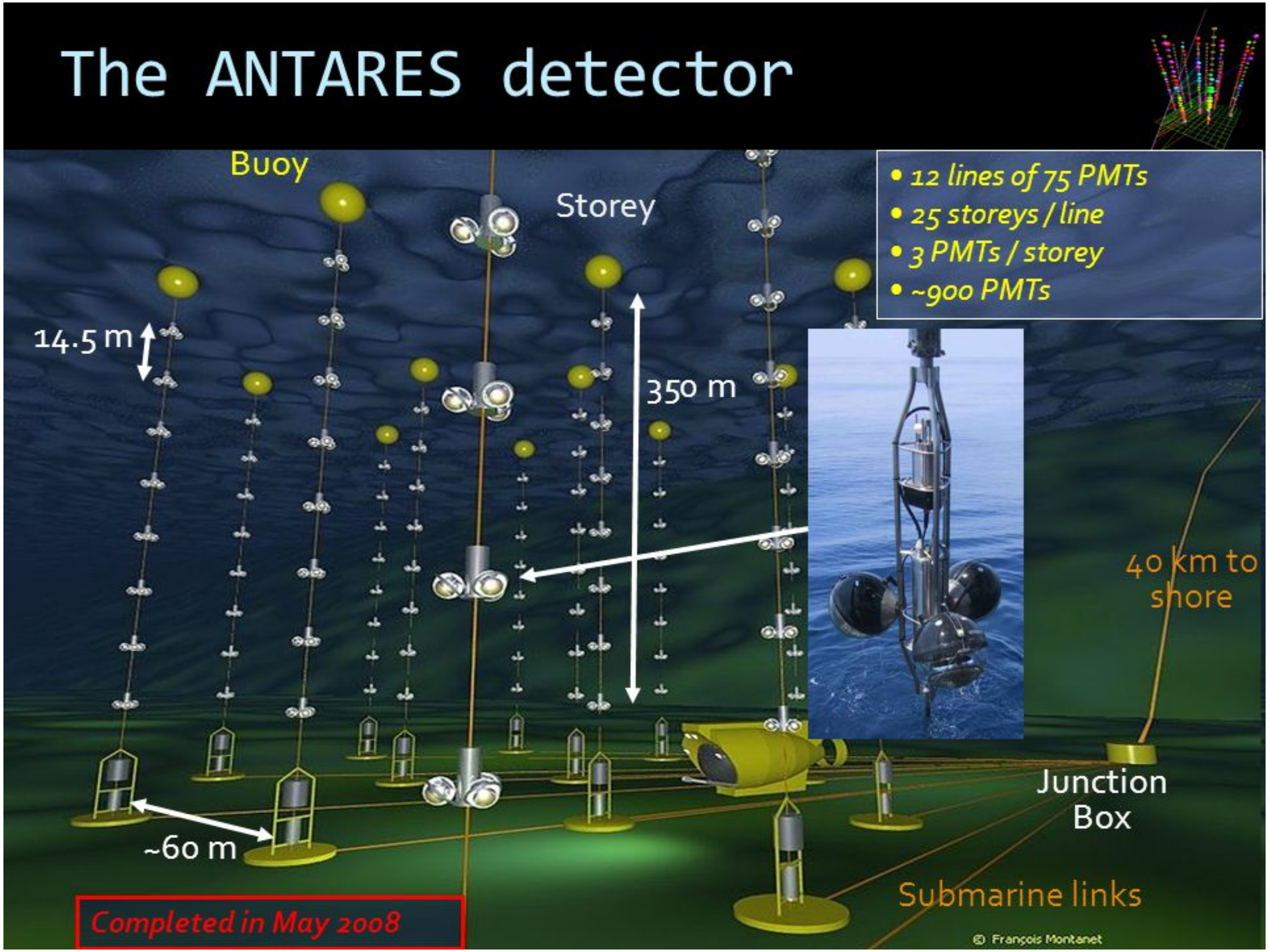
Absorption Length

tap water 2m

distilled water 10m

ultra pure ice 200m

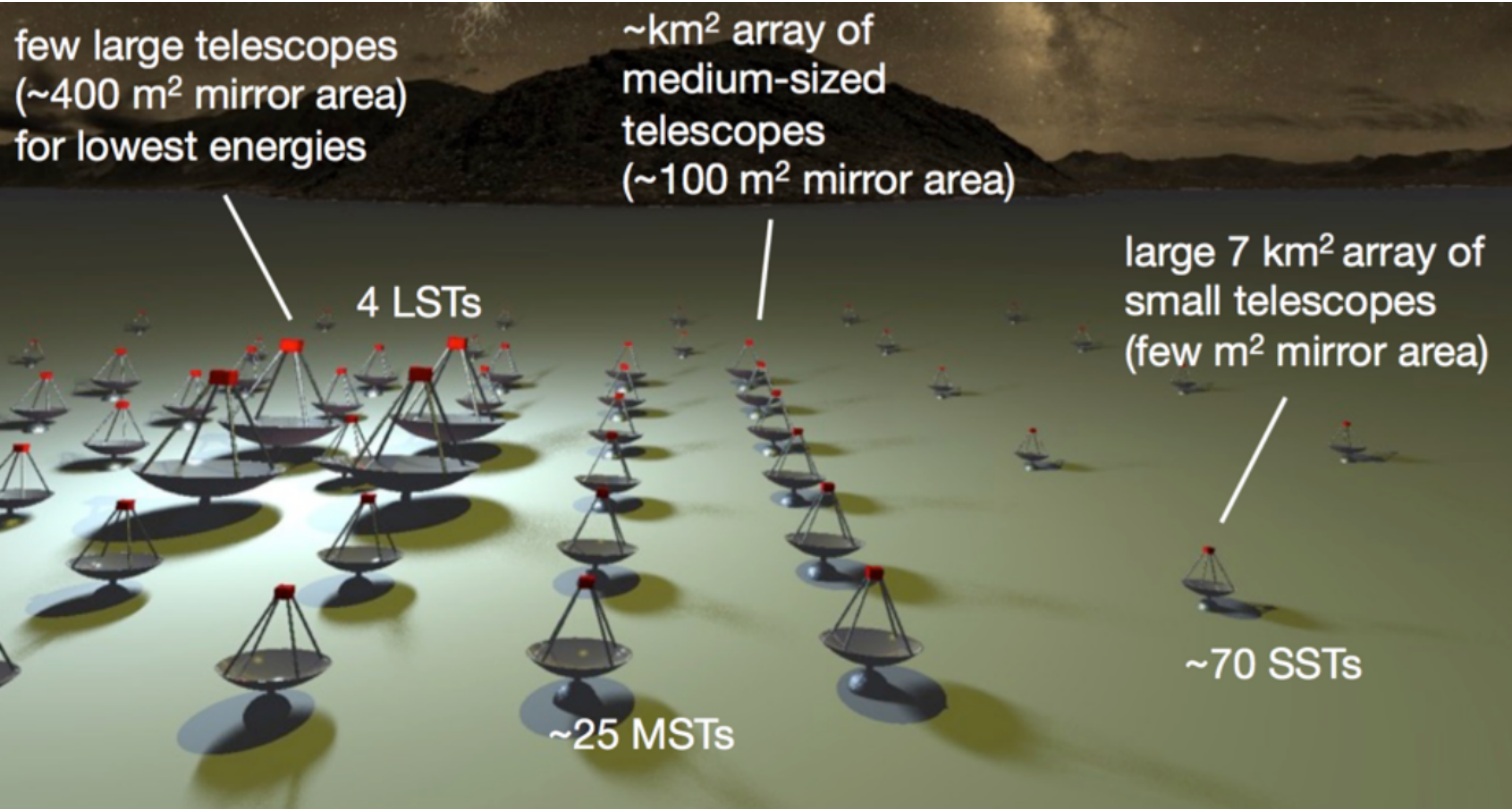
Neutrino Telescopes



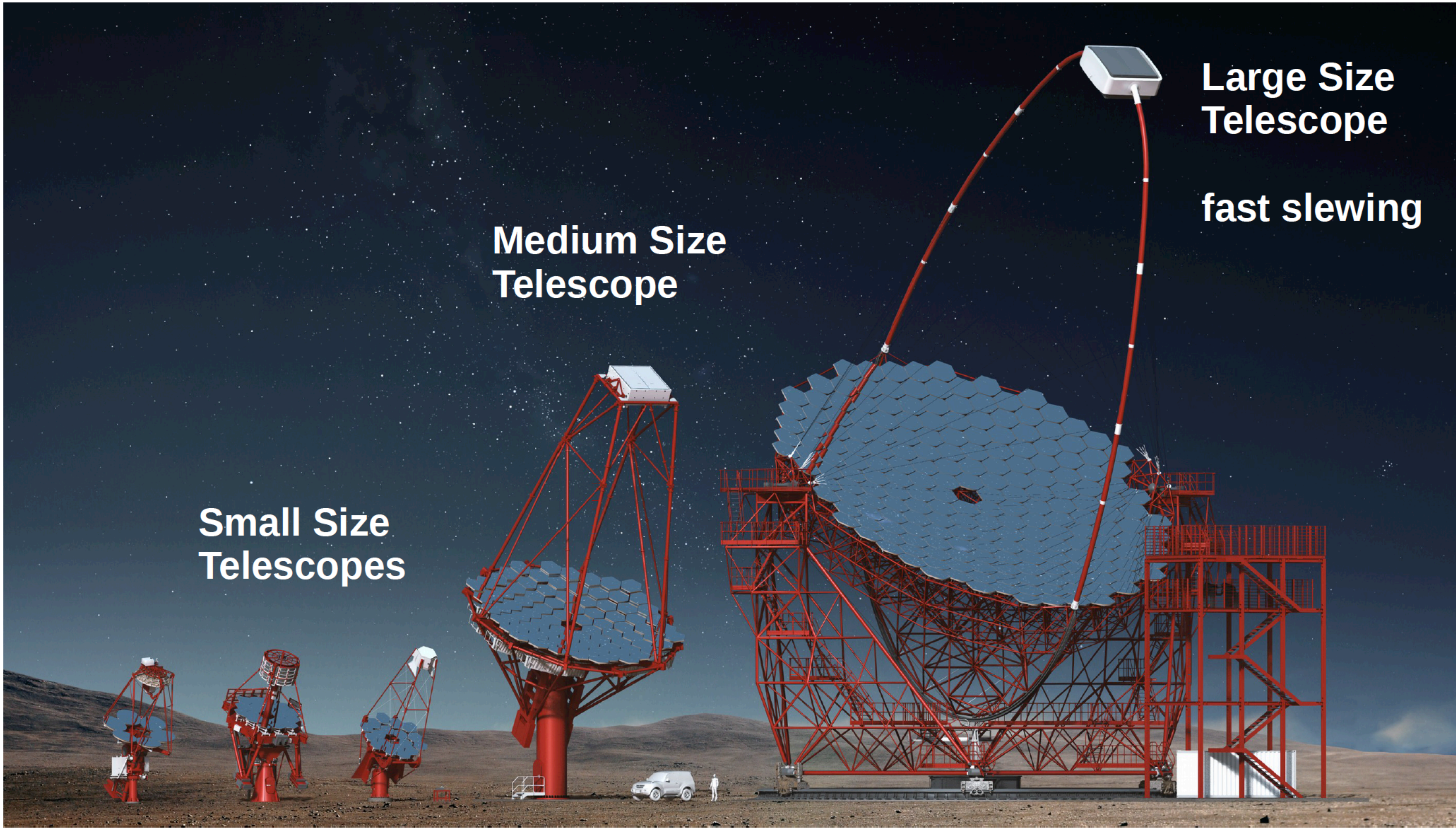
Located at the Mediterranean

Future @ Very High Energies

Cherenkov Telescopes Array

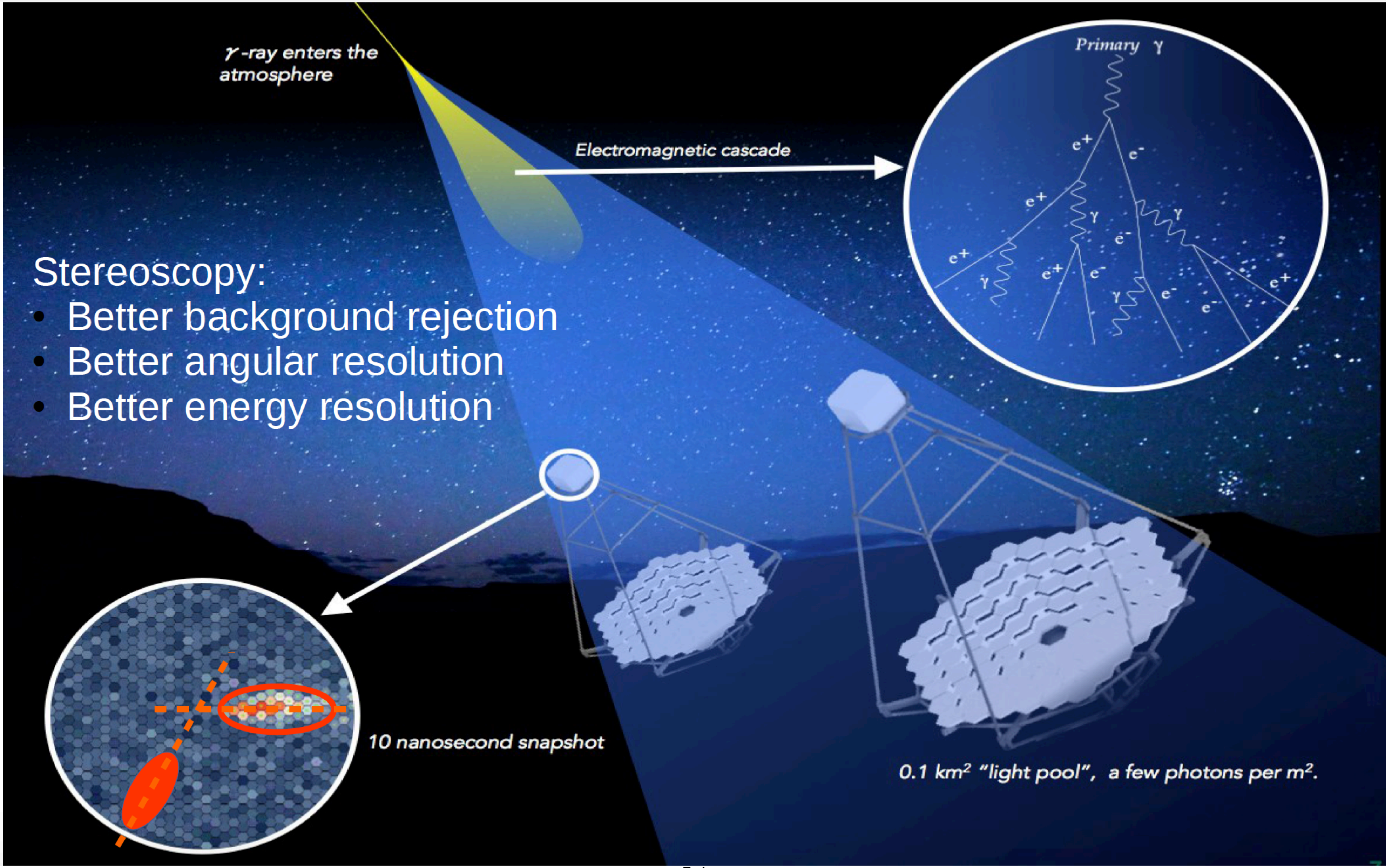


Cherenkov Telescopes Array

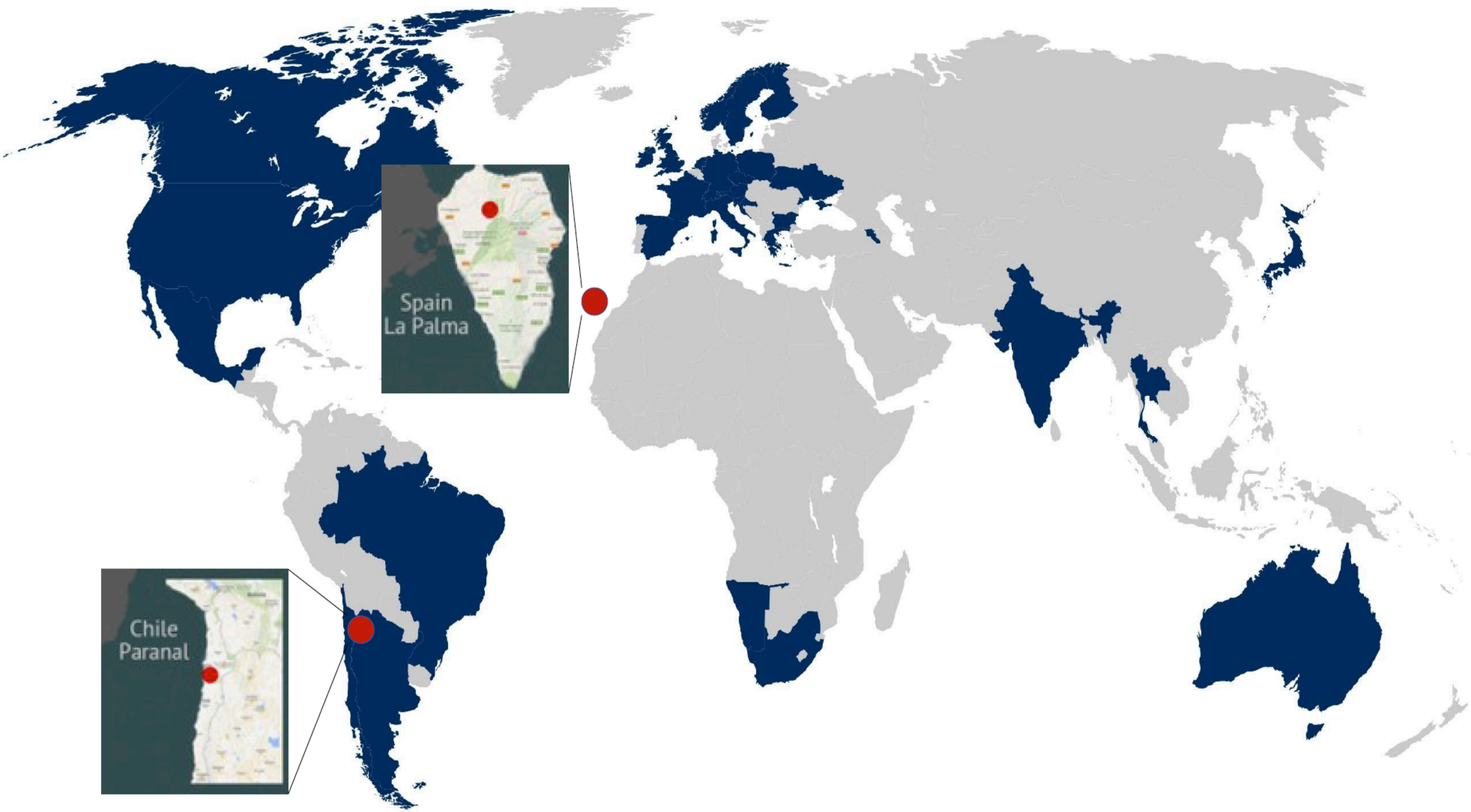


Cherenkov Telescopes Array

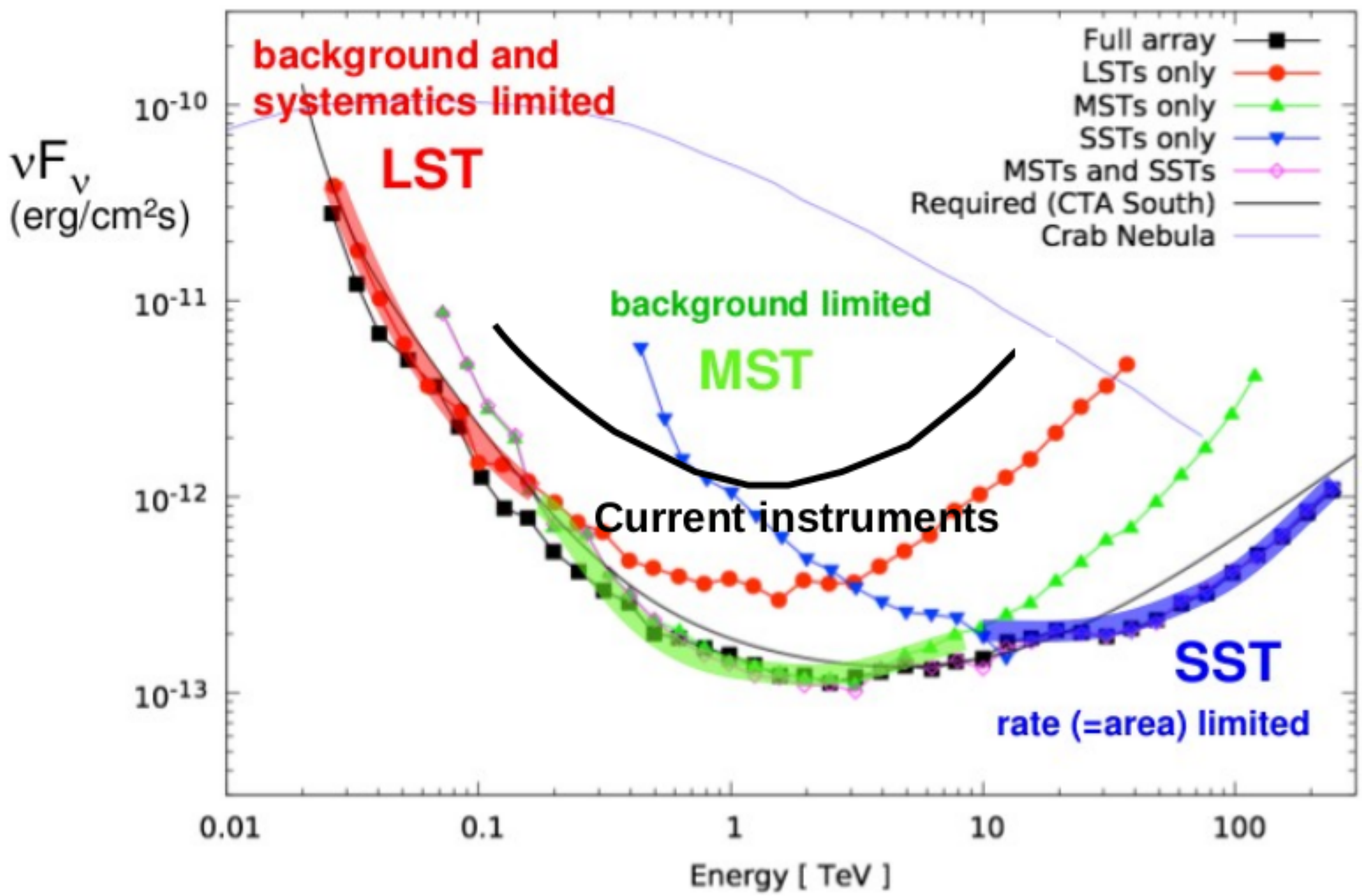
Stereoscopy:
- Better background rejection
- Better angular resolution
- Better energy resolution



Cherenkov Telescopes Array

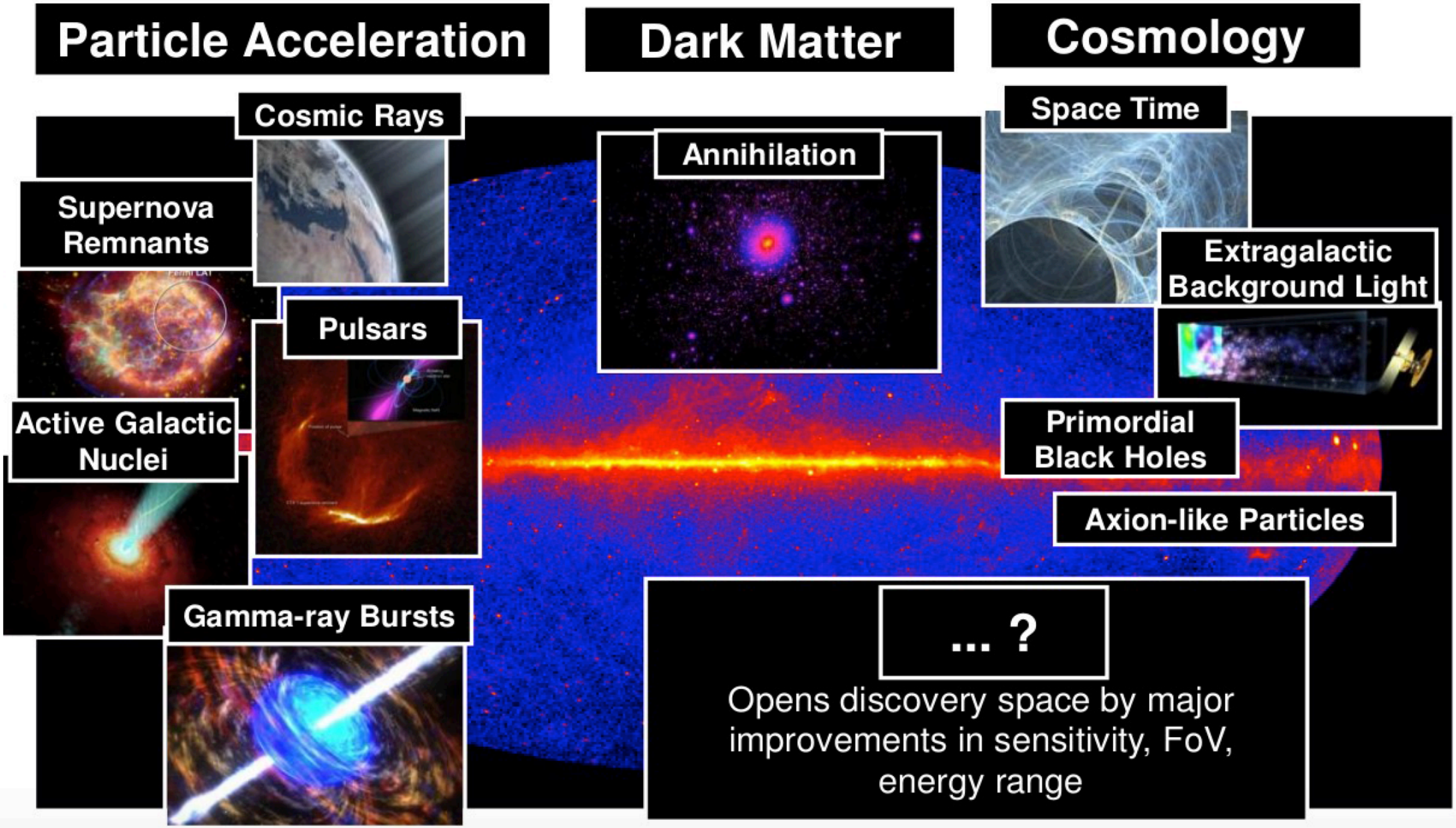


Cherenkov Telescopes Array



- Improve sensitivity by an order of magnitude
- Extend energy range 20 GeV to 300 TeV
- Improve energy and angular resolution (factor 2-3)
- Widen telescope field of view
- Survey full sky
- Observe fast transient phenomena

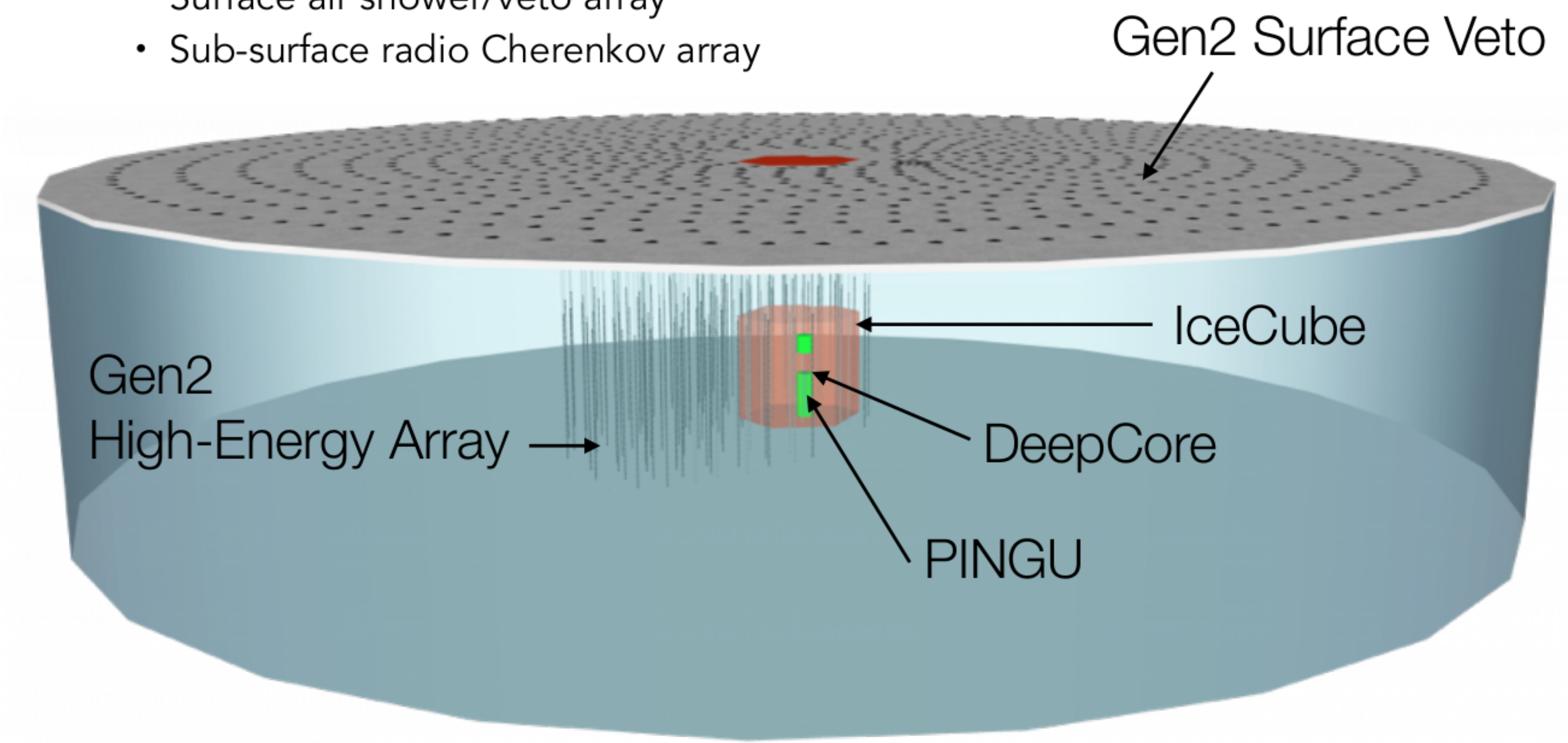
Cherenkov Telescopes Array



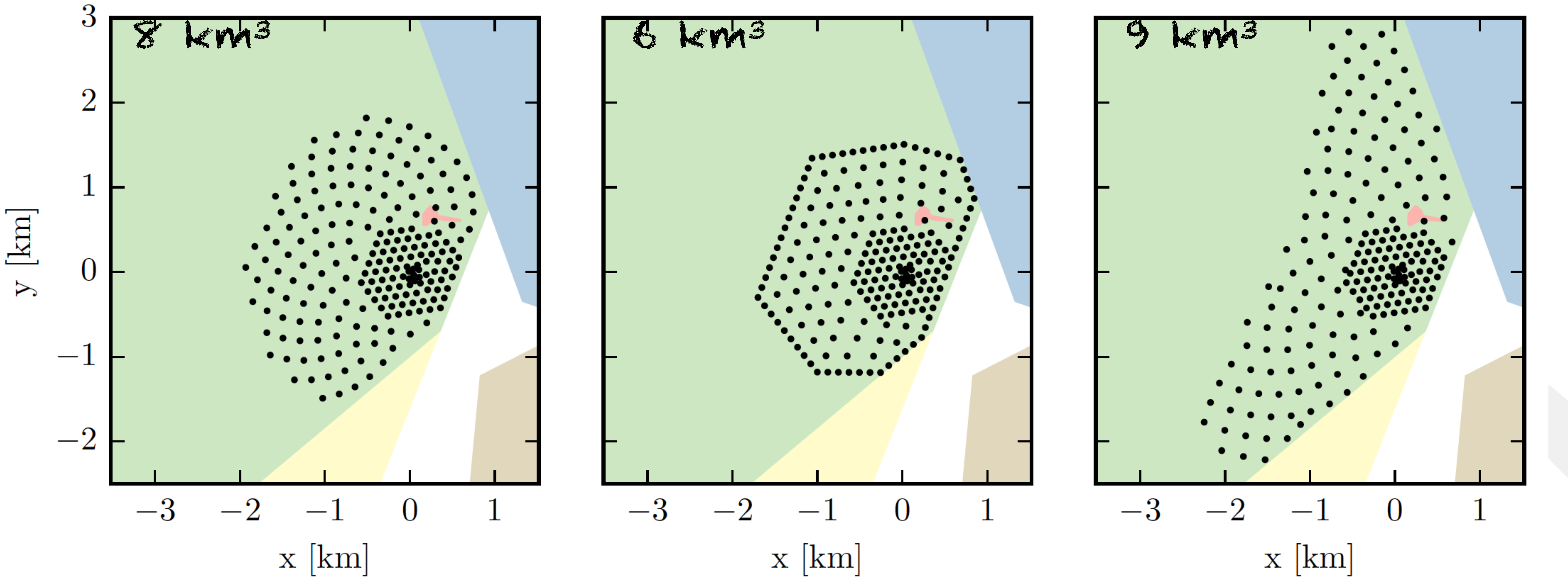
ICECUBE GEN2

- Gen2 high energy array
- PINGU low energy extension
- Surface air shower/veto array
- Sub-surface radio Cherenkov array

Gentoo penguin



High Energy Extension

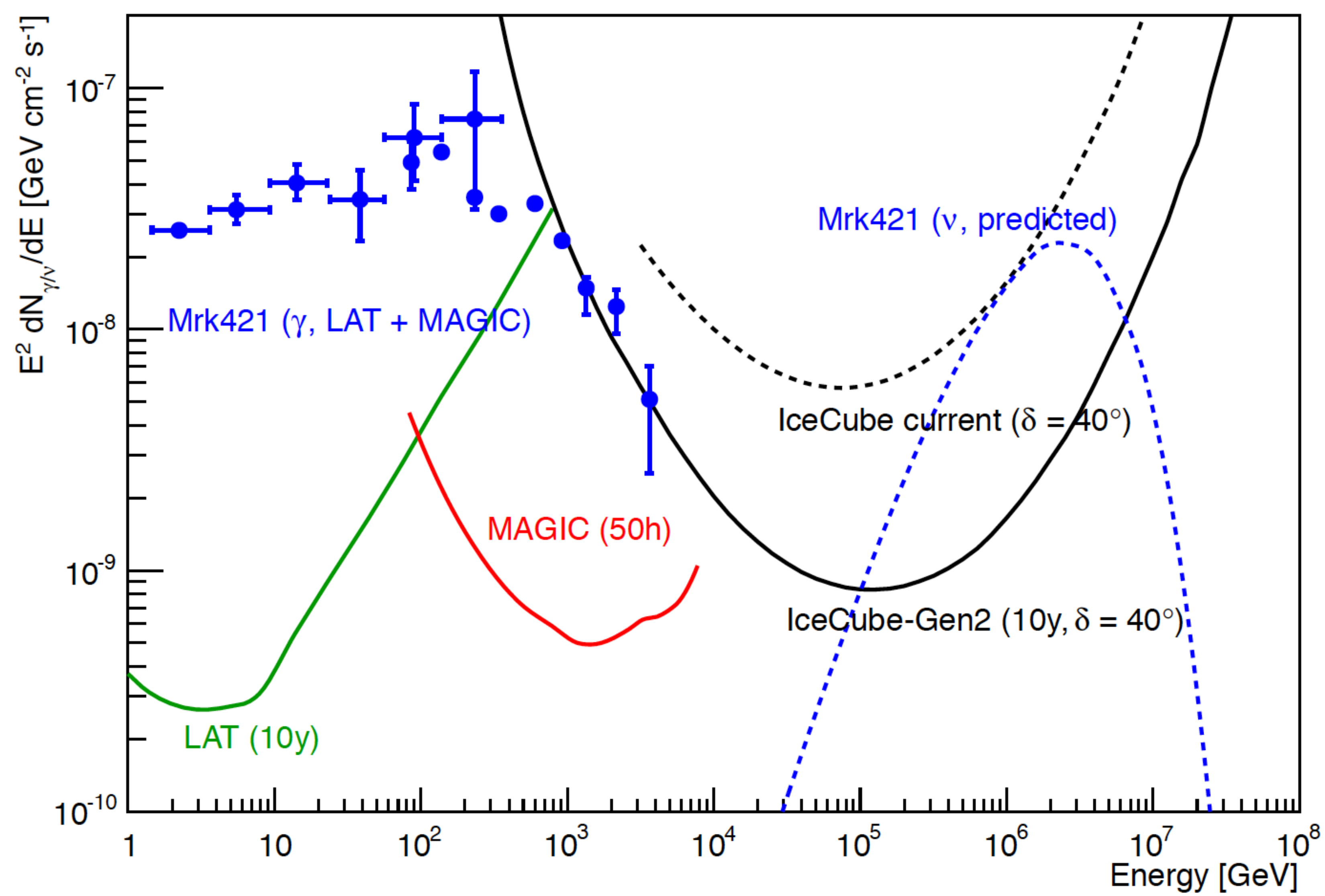


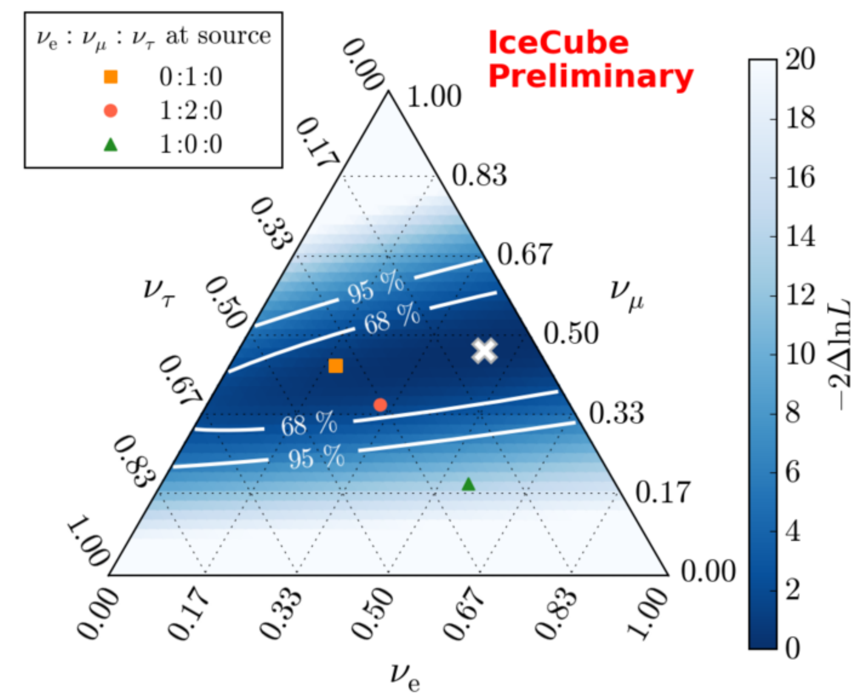
- Resolving the sources of astrophysical neutrinos
- Neutrinos from highest energy cosmic rays
- Are there signature of new physics at >= PeV energies ?
- Number of observed cosmic neutrinos will be ten times

white paper (arXiv : 1412.5106)

next version coming soon

High Energy Neutrinos from Blazars

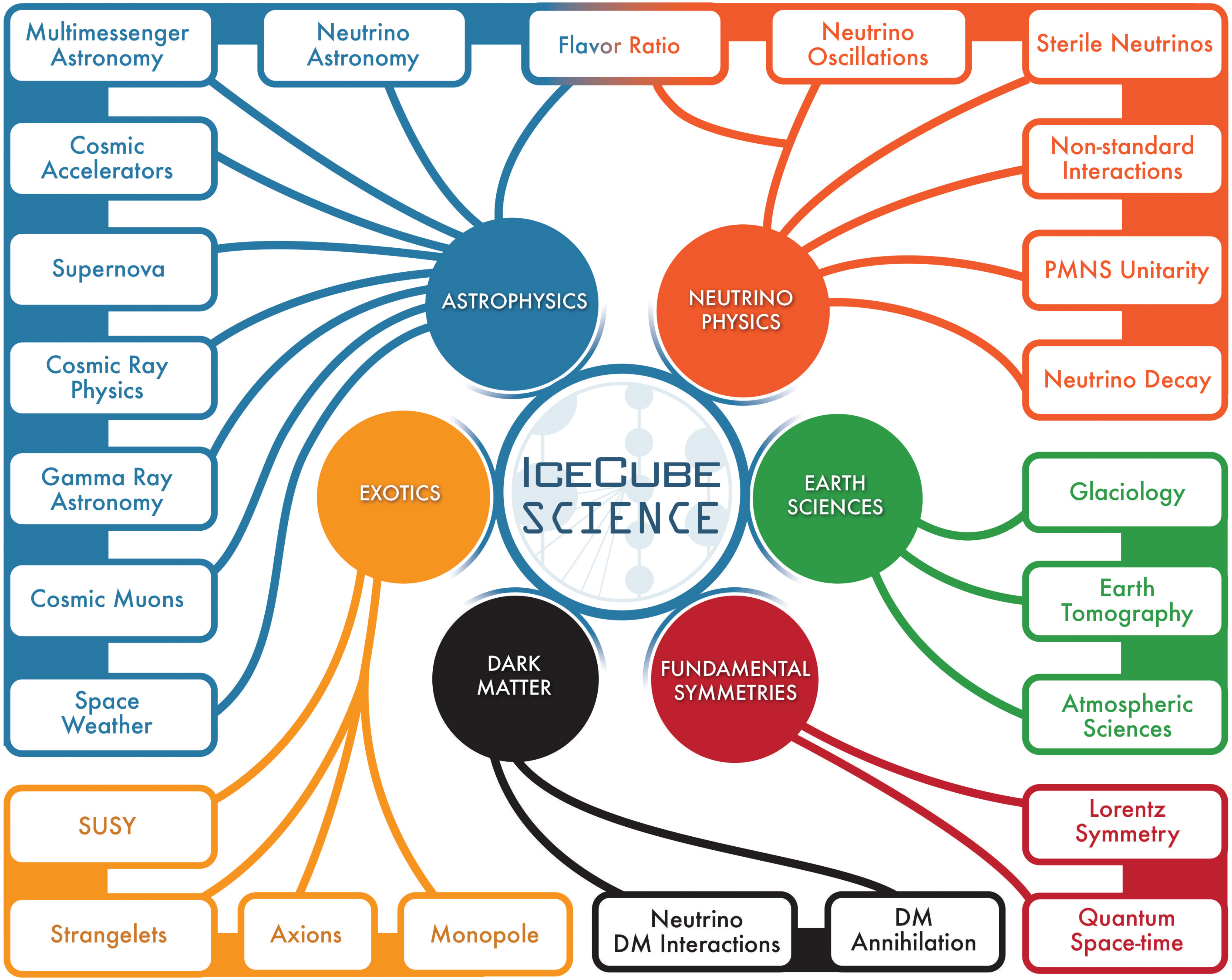




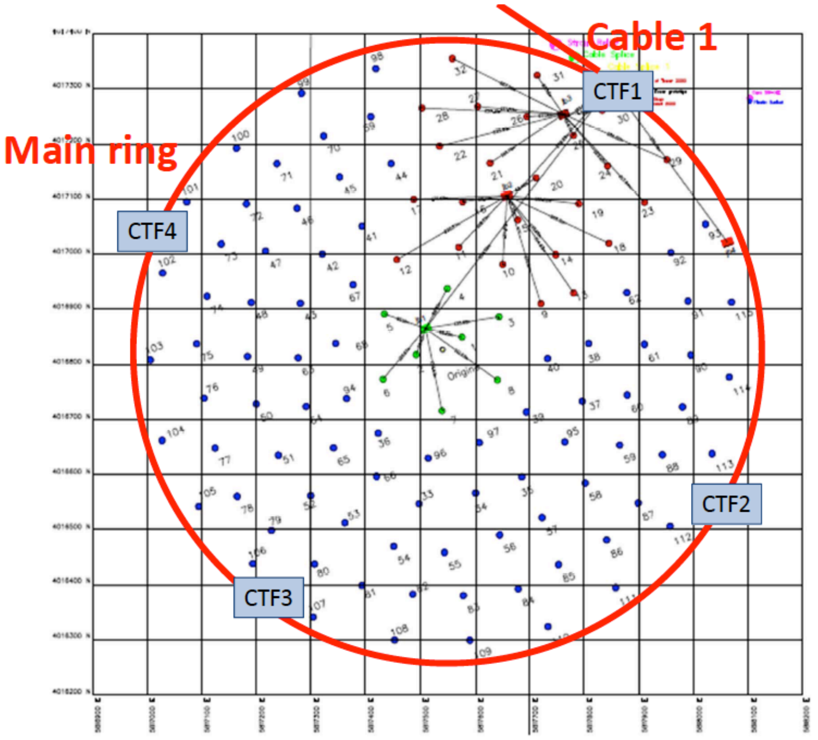
Detection of neutrinos from AGN also give important clue about the surroundings e.g. radiation density, magnetic field

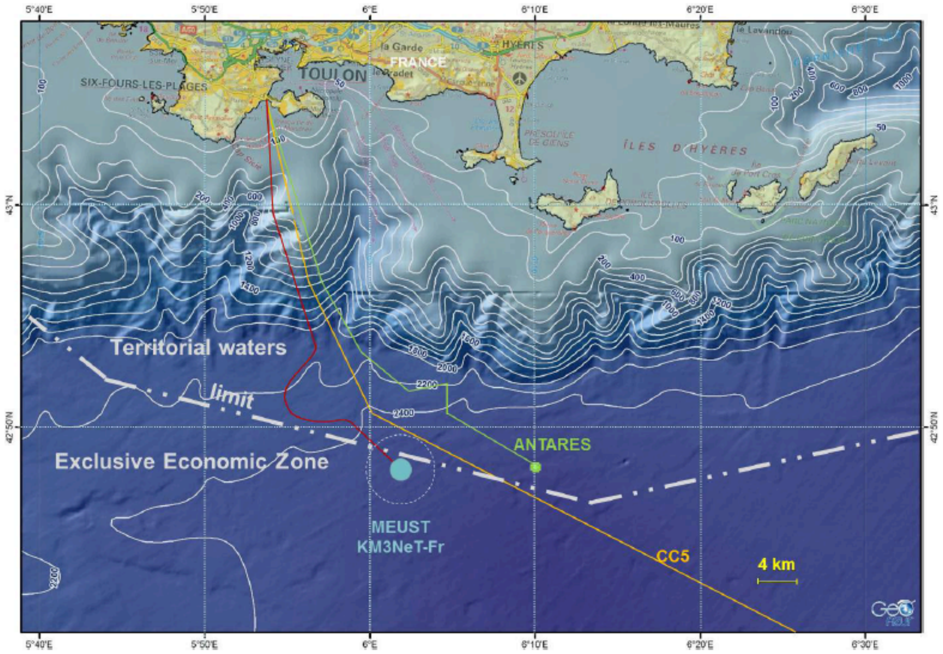
Highest Energy Neutrinos : observed sub-PeV neutrinos, AGN cores would be very viable source candidates strong thermal radiation fields present there turn the cores opaque to GeV gamma-rays

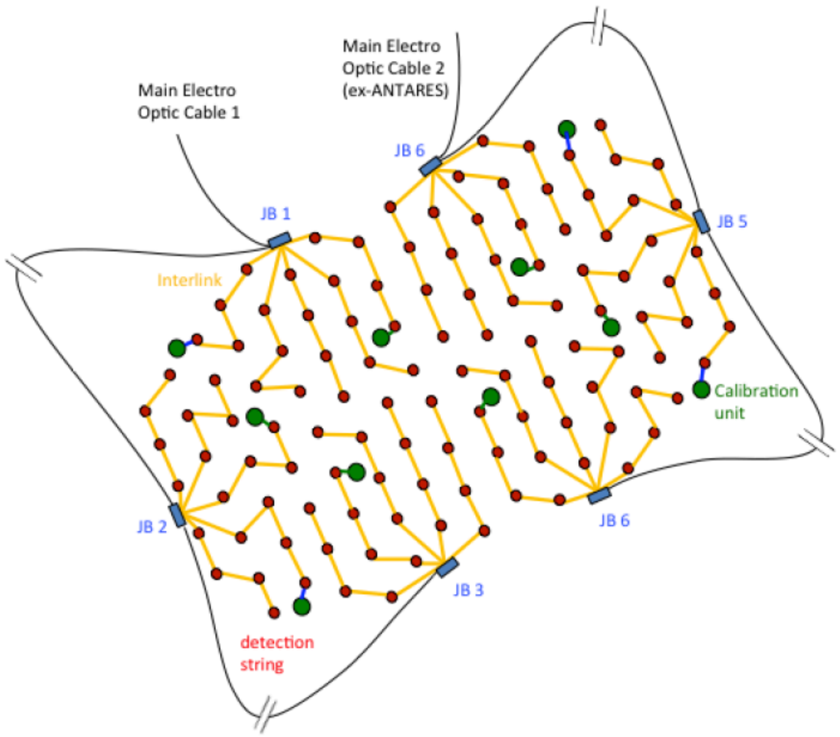
Science with IceCube



ARCA & ORCA @ Mediterranean

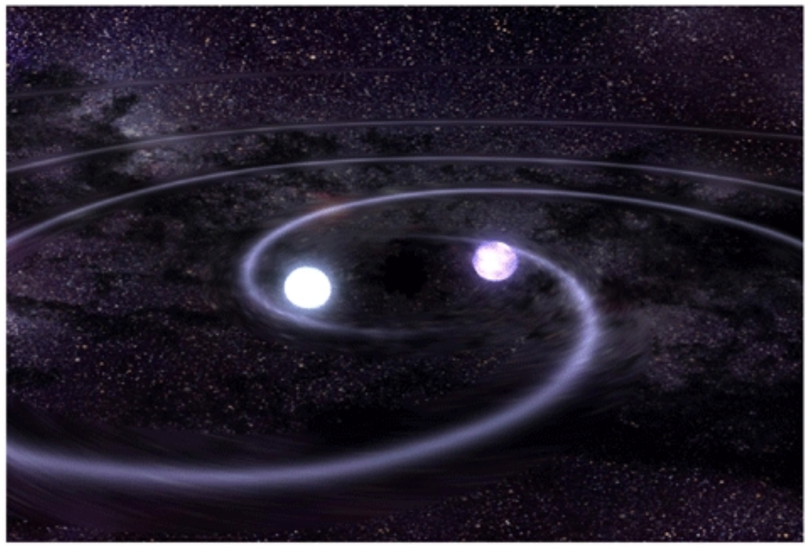
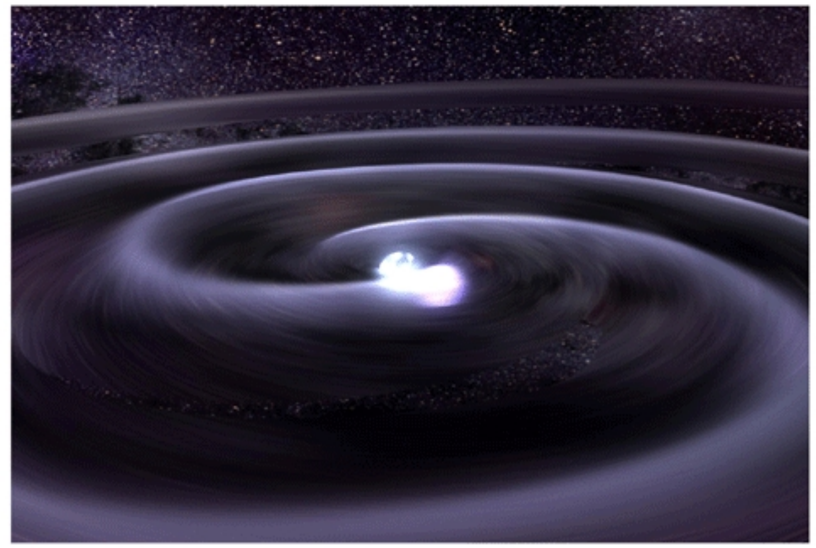
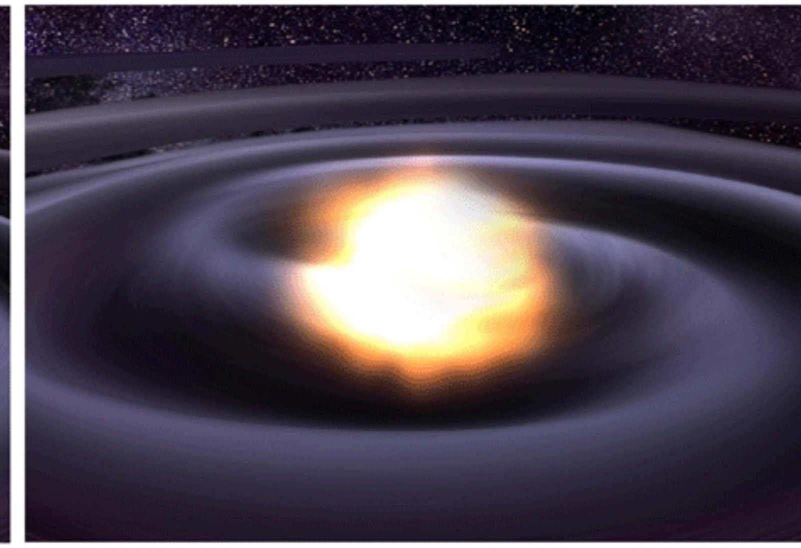






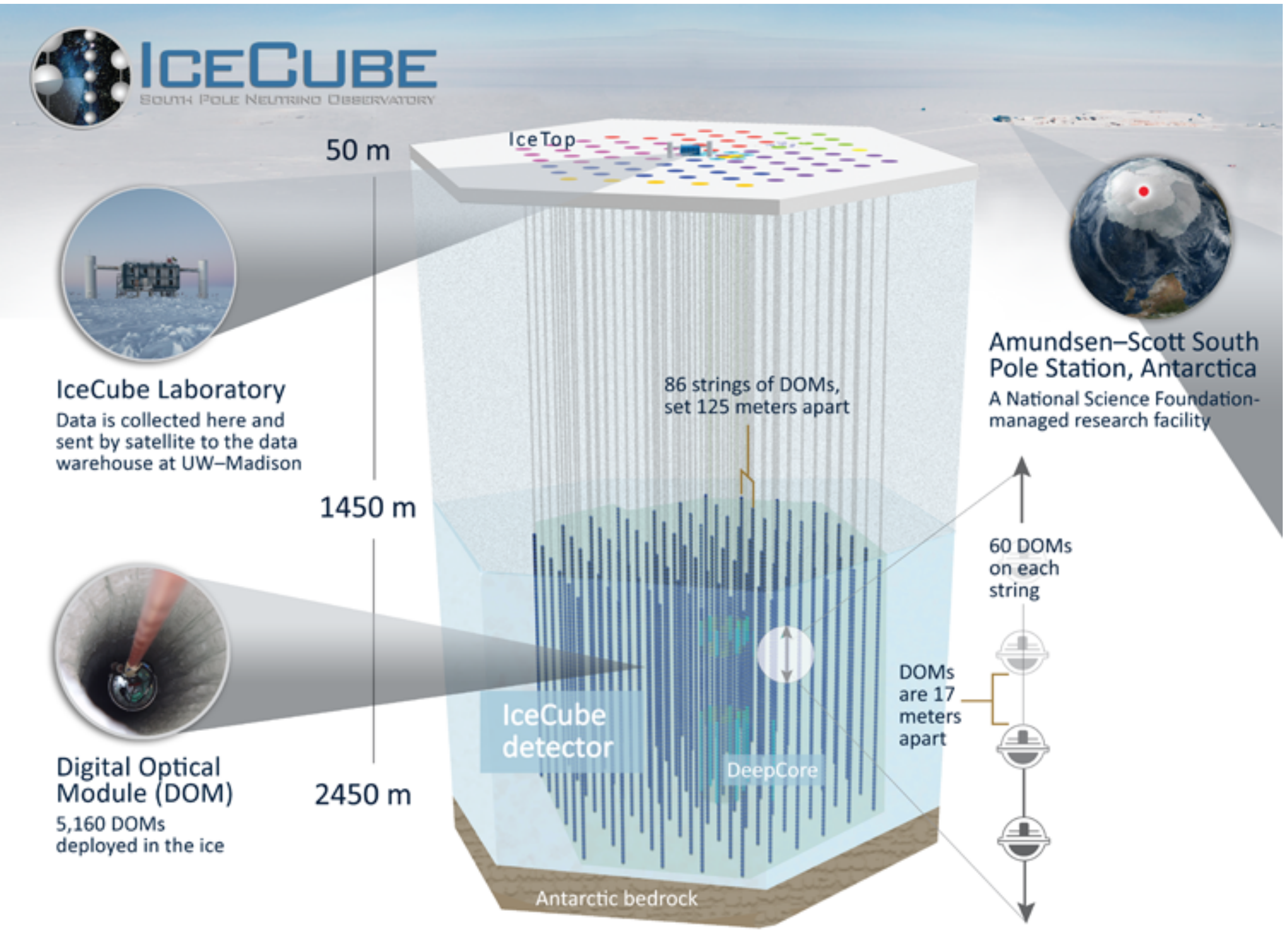
& Gravitational Waves

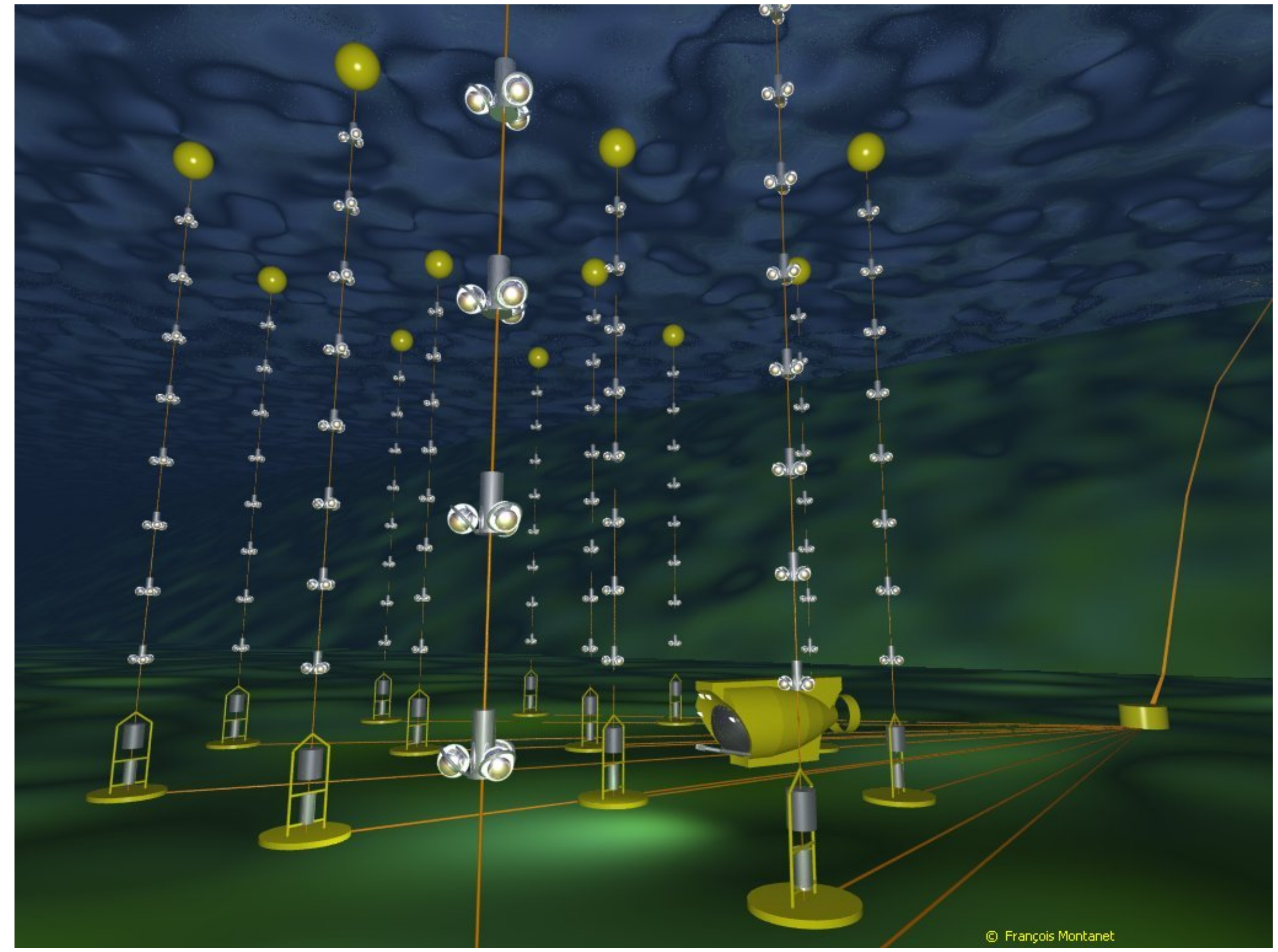
Gravitational Wave on 17.08.2017

- Gravitational Waves expected to accompany by thermal, non-thermal radiations also with neutrinos
- Due to strong absorption at early times and beaming effect EM radiation is shrouded not neutrinos
- GWs can provide new info about progenitor system

IceCube & ANTARES Followed GW170817



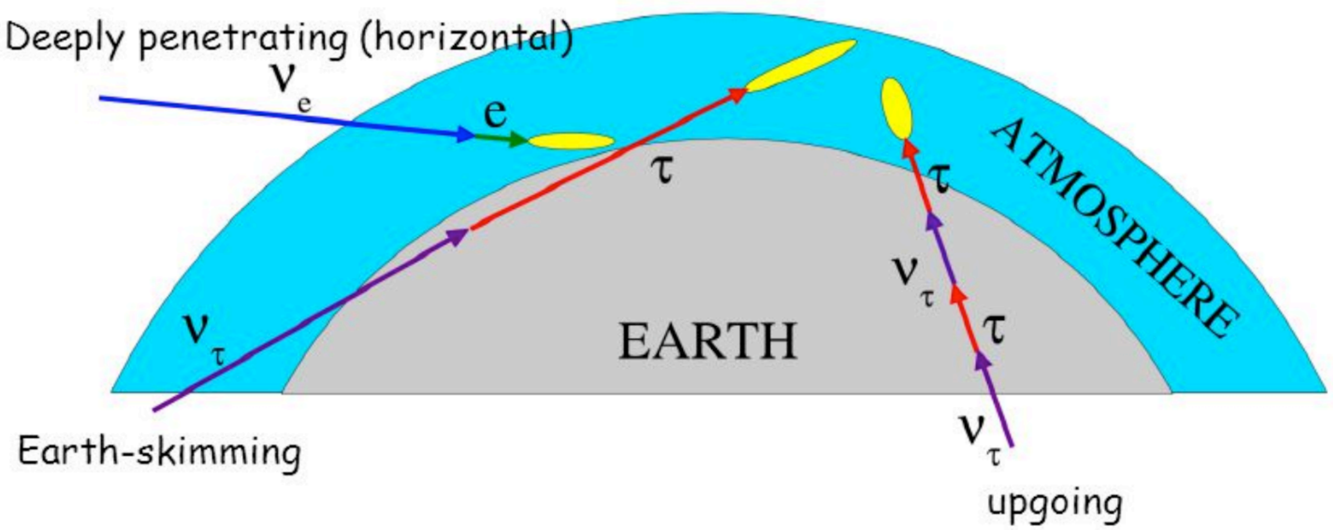


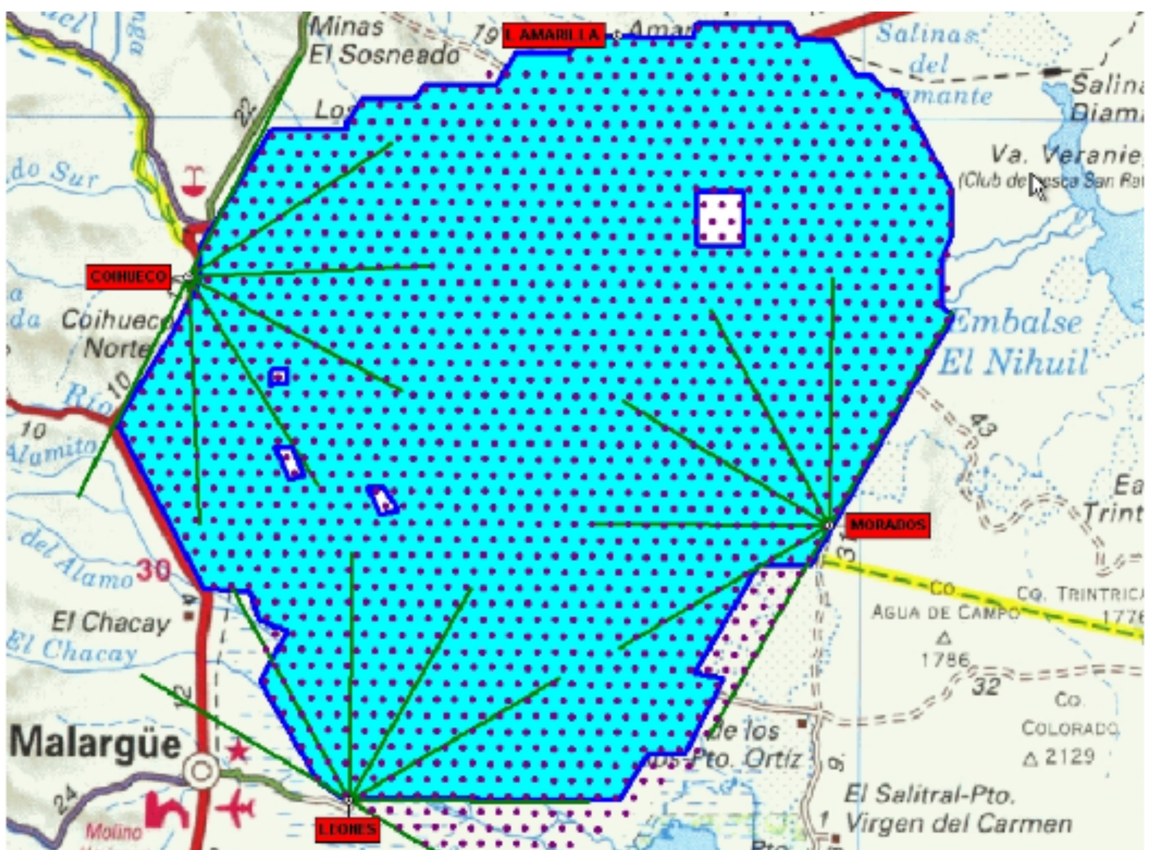
Searched for neutrinos
in coincidenze with
GW170817
in energy range
1TeV - 1EeV

In water scattering
angle is less
thus angular resolution
better
0.4° for tracks
3° for showers

Searched for neutrinos
in coincidenze with
GW170817
in energy range
20 TeV - 20 PeV

UHE Neutrinos - Pierre Auger Observatory





Auger EAS expt. 3000 sq. km

1660 water - Cherenkov stations

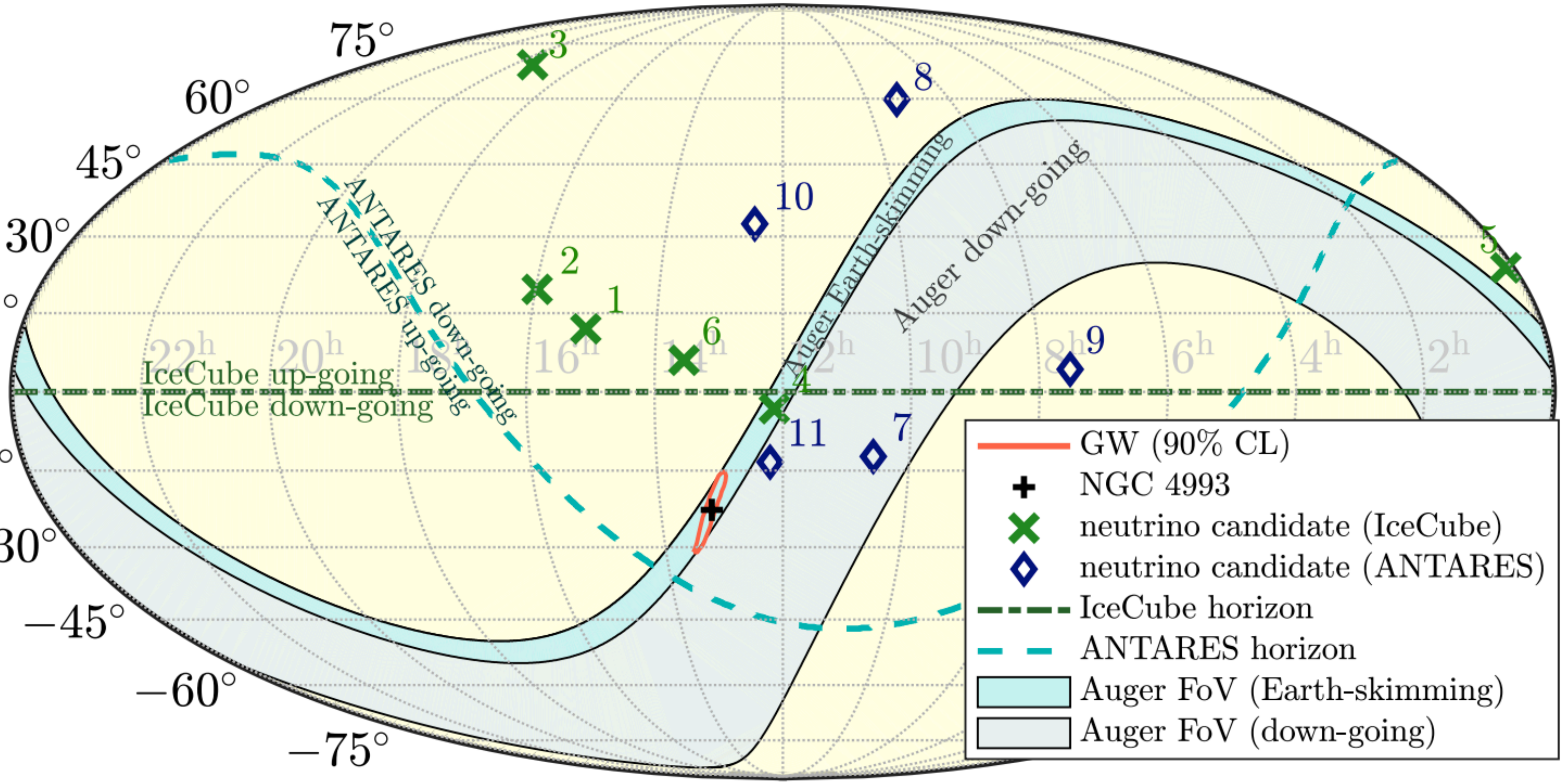
Surface Detectors

neutrinos above 10^{17} eV

$\nu_{e,\mu,\tau}$ *at large zenith angles* $60^\circ < \theta < 90^\circ$

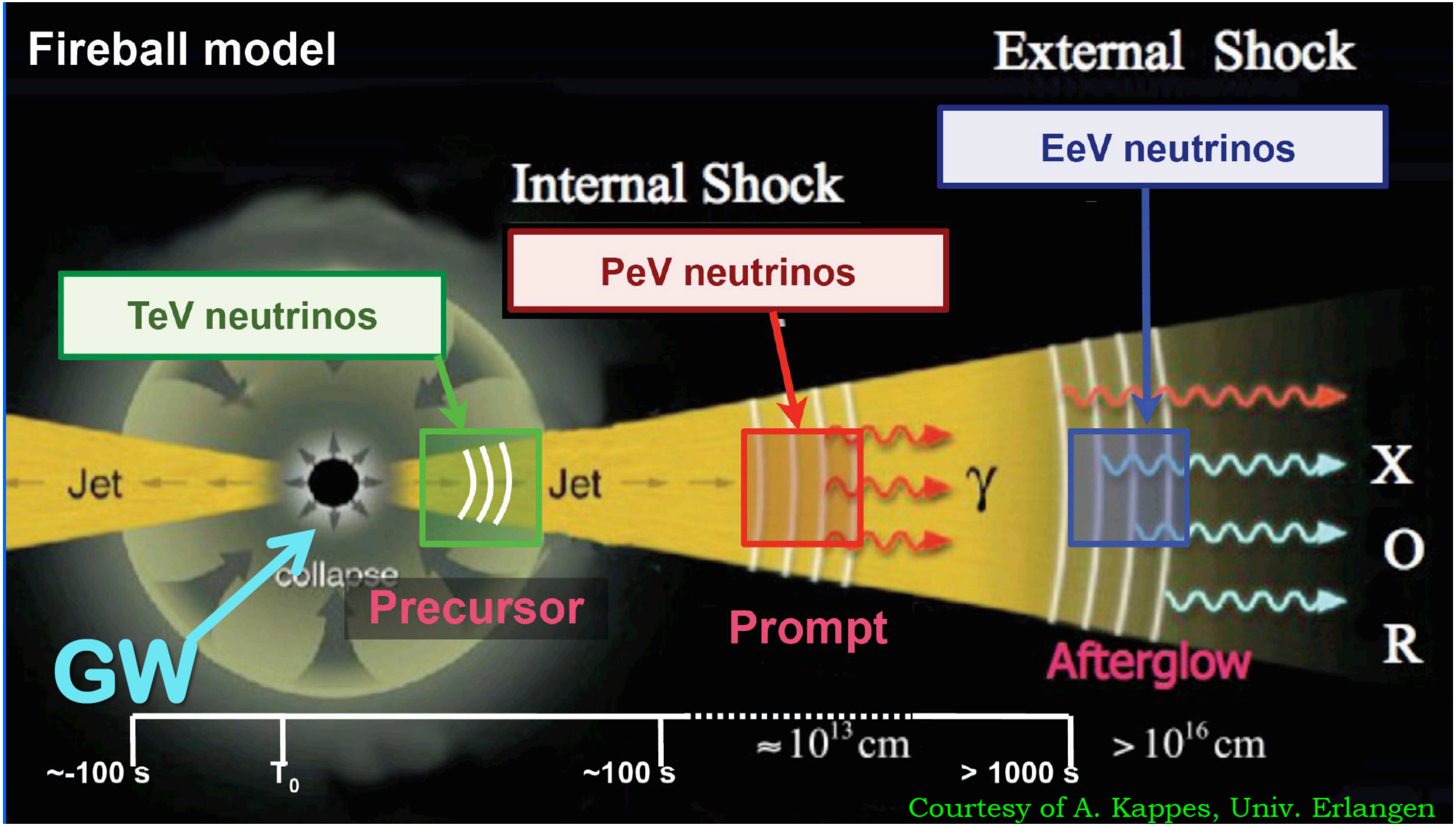
Earth Skimming ν_τ : $90^\circ < \theta < 95^\circ$

Localizations and sensitive sky areas at the time of the GW170817

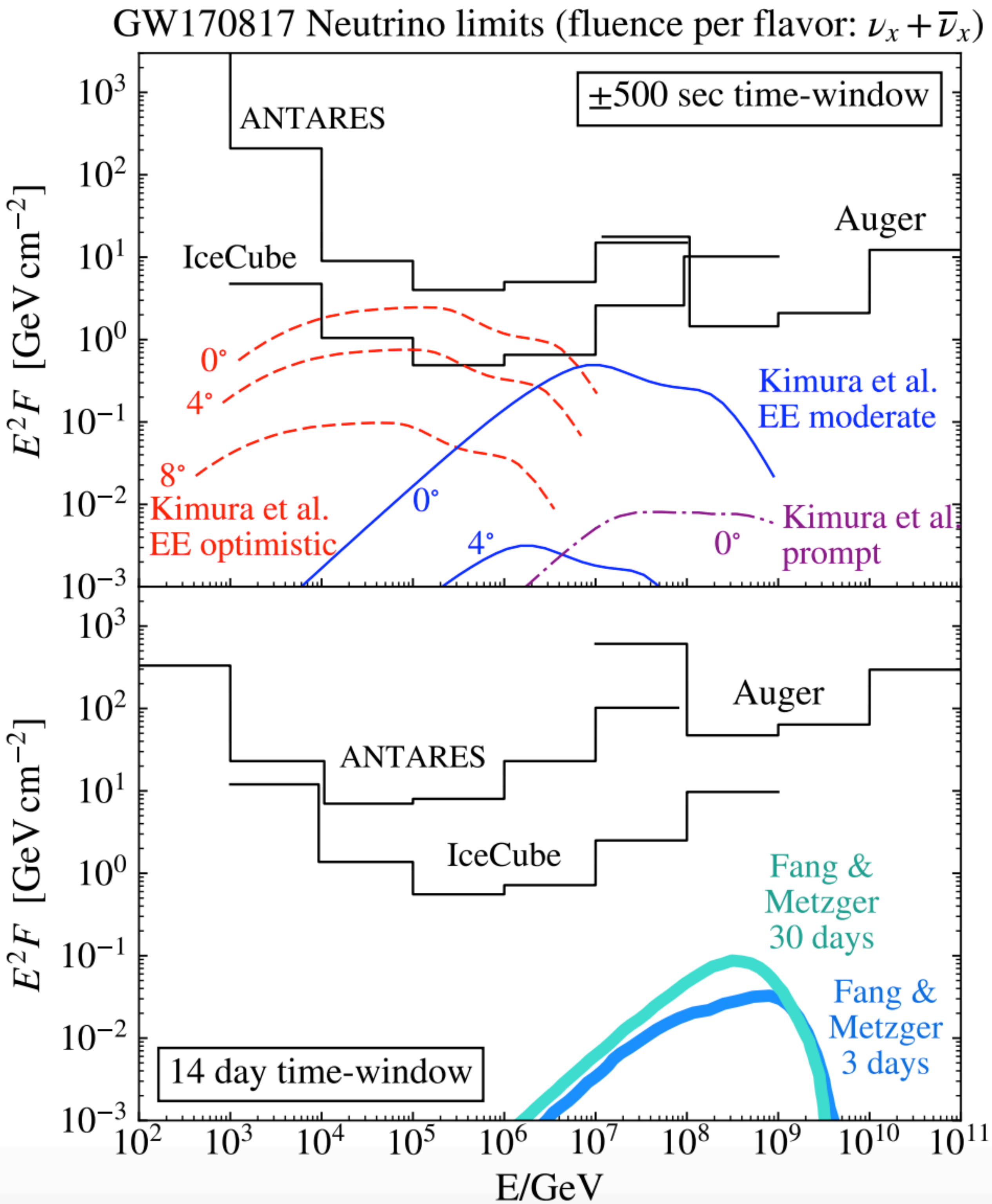


arXiv : 1710.05839

Possible GW & HEN Connection



No Neutrinos found correlated in space/ time with GW170817



IF rapidly rotating NS formed & doesn't collapse into BH immediately, can power relativistic wind - EE, gamma-ray attenuate due optical depth, HE neutrinos can escape (± 500 s)

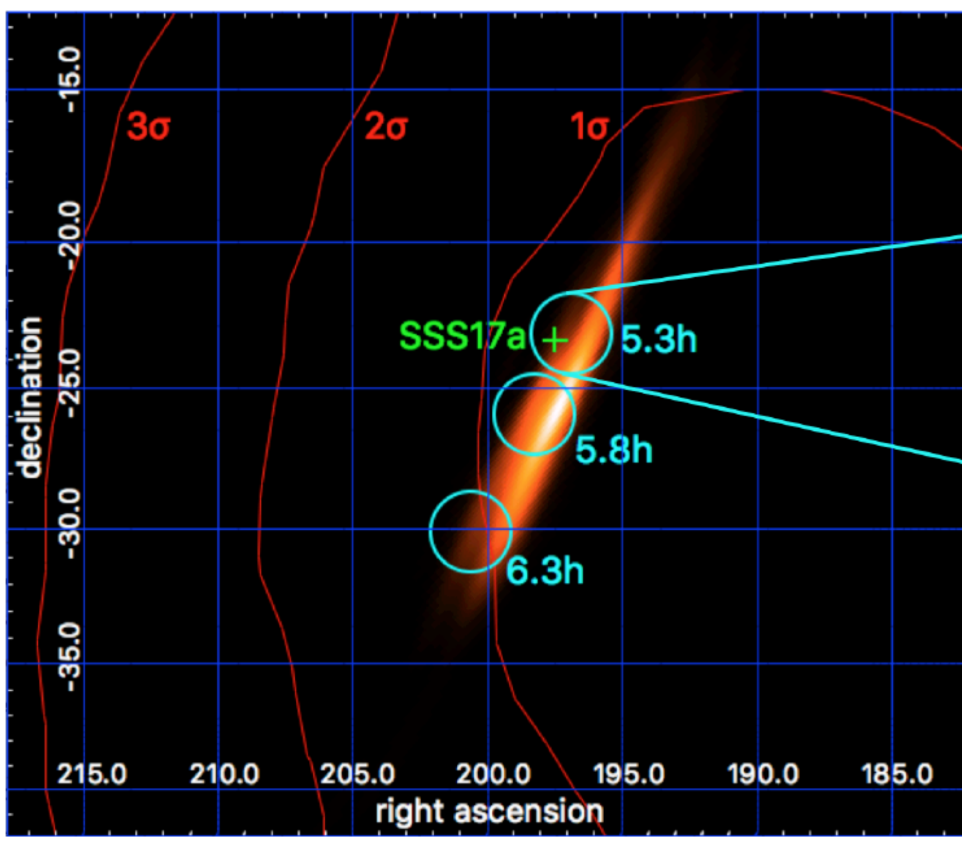
Also it may trap wind energy until it expands and becomes transparent. This process can convert some of the wind energy to HE particles, producing a long term neutrino radiation, which can last for several days (14 days)

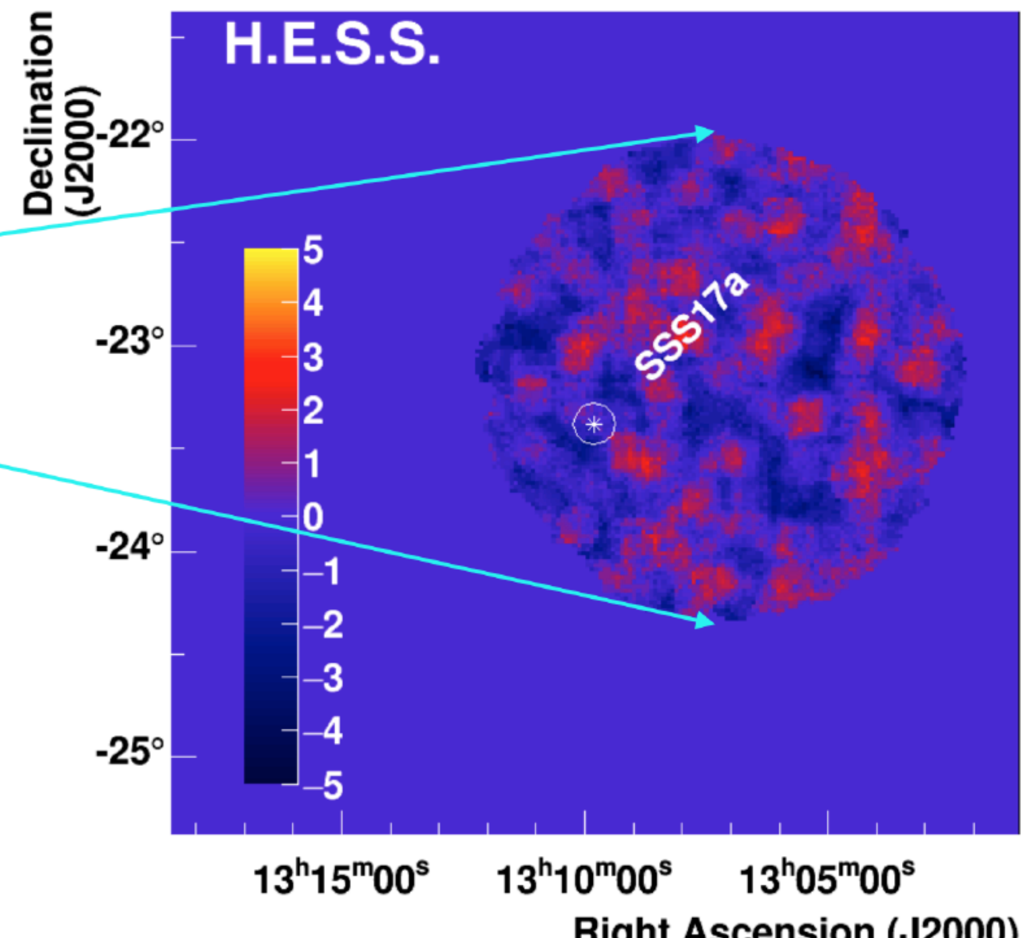
IceCube detector is also sensitive to outbursts of MeV neutrinos via a simultaneous increase in all PMTs for Galactic core-collapse SNs

But this event was located too far

HESS Telescope Followed GW170817

HESS followup strategy planned carefully due to its small field of view and limited duty cycle





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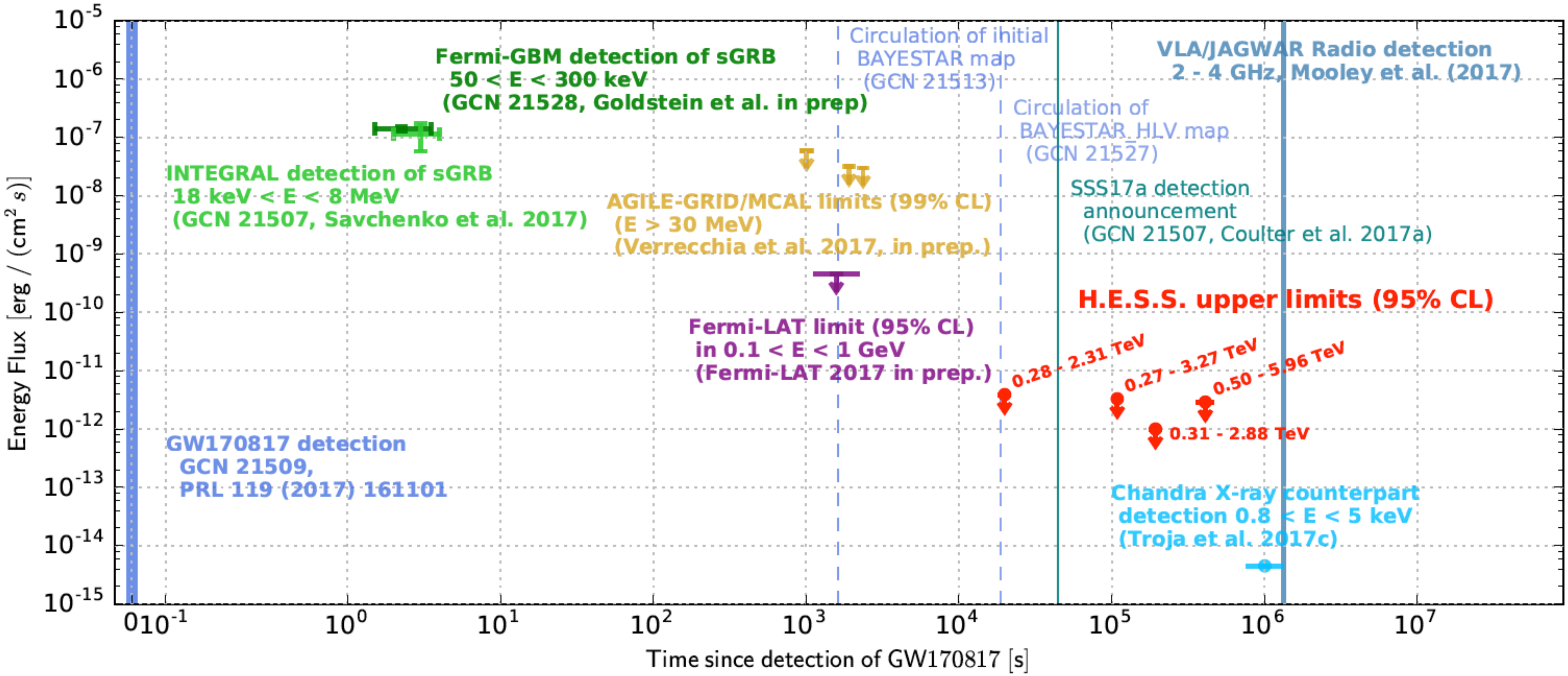
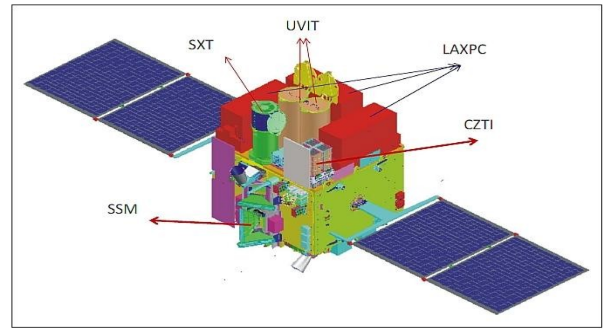
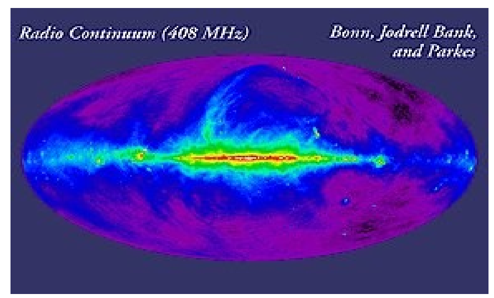
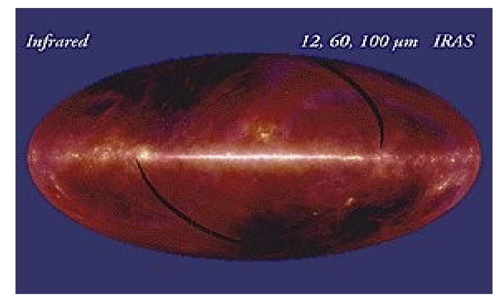


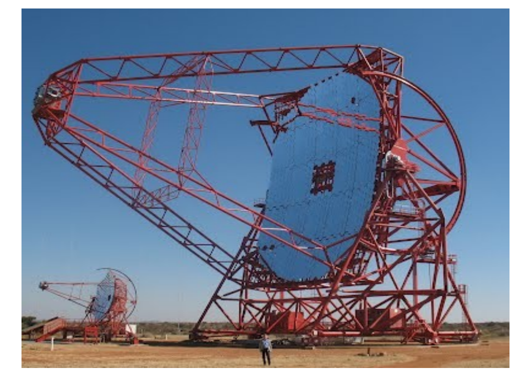
arXiv : 1710.05862

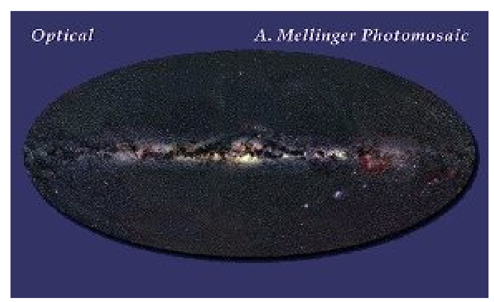
GWs & Neutrinos add new dimensions to Multi-Messenger Astronomy

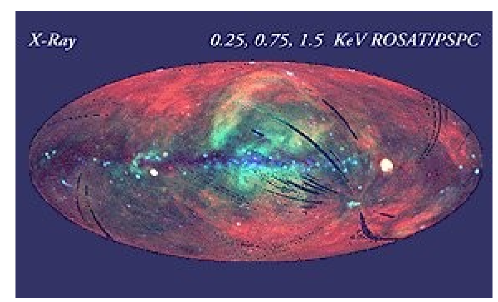


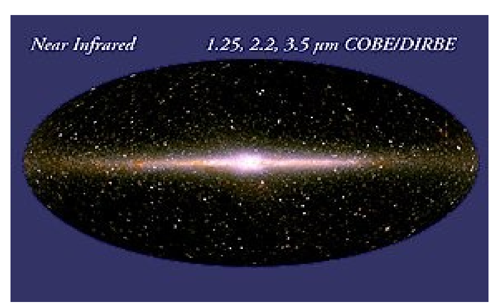


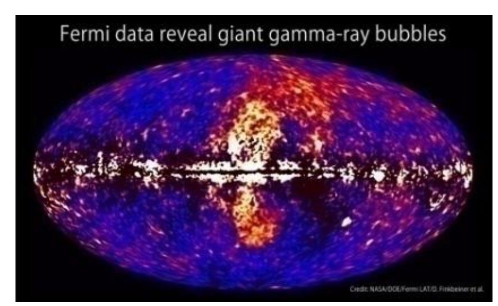


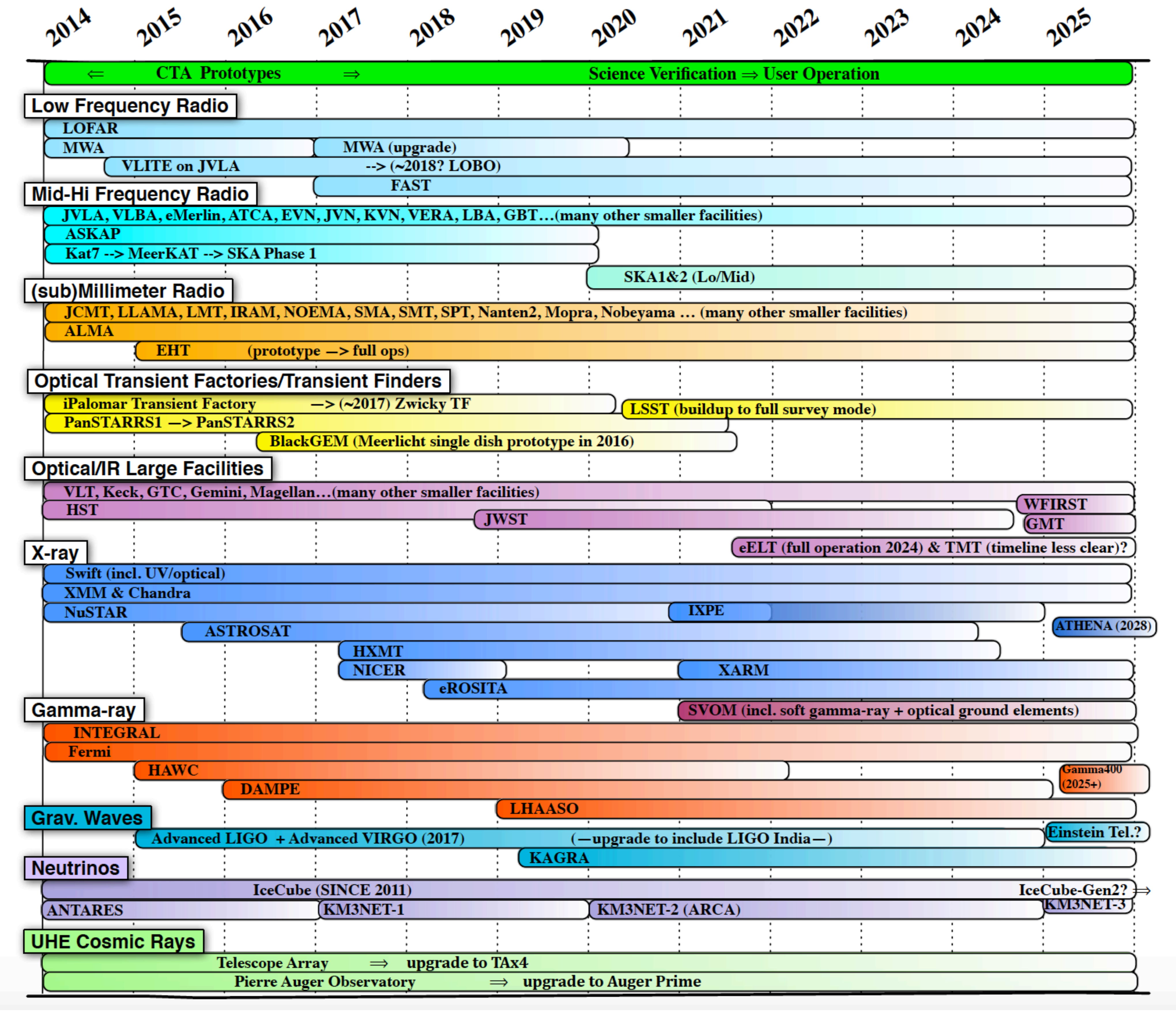











2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
⇐ CTA Prototypes ⇒
Science Verification ⇒ User Operation
Low Frequency Radio
LOFAR
MWA
MWA (upgrade)
VLITE on JVLA
--> (~2018? LOBO)
FAST
Mid-Hi Frequency Radio
JVLA, VLBA, eMerlin, ATCA, EVN, JVN, KVN, VERA, LBA, GBT…(many other smaller facilities)
ASKAP
Kat7 --> MeerKAT --> SKA Phase 1
SKA1&2 (Lo/Mid)
(sub)Millimeter Radio
JCMT, LLAMA, LMT, IRAM, NOEMA, SMA, SMT, SPT, Nanten2, Mopra, Nobeyama … (many other smaller facilities)
ALMA
EHT
(prototype —> full ops)
Optical Transient Factories/Transient Finders
iPalomar Transient Factory
—> (~2017) Zwicky TF
LSST (buildup to full survey mode)
PanSTARRS1 —> PanSTARRS2
BlackGEM (Meerlicht single dish prototype in 2016)
Optical/IR Large Facilities
VLT, Keck, GTC, Gemini, Magellan…(many other smaller facilities)
HST
WFIRST
JWST
GMT
eELT (full operation 2024) & TMT (timeline less clear)?
X-ray
Swift (incl. UV/optical)
XMM & Chandra
NuSTAR
IXPE
ATHENA (2028)
ASTROSAT
HXMT
NICER
XARM
eROSITA
Gamma-ray
SVOM (incl. soft gamma-ray + optical ground elements)
INTEGRAL
Fermi
HAWC
Gamma400 (2025+)
DAMPE
LHAASO
Grav. Waves
Einstein Tel.?
Advanced LIGO + Advanced VIRGO (2017)
(—upgrade to include LIGO India—)
KAGRA
Neutrinos
IceCube (SINCE 2011)
IceCube-Gen2? ⇒
ANTARES
KM3NET-1
KM3NET-2 (ARCA)
KM3NET-3
UHE Cosmic Rays
Telescope Array ⇒ upgrade to TAx4
Pierre Auger Observatory ⇒ upgrade to Auger Prime

Thanks !