"Exploring the Universe with Multi-Messengers"
UTokyo-NY Event
Feb. 12, 2022

Multi-Messenger Astronomy and Institute for Cosmic Ray Research (ICRR)

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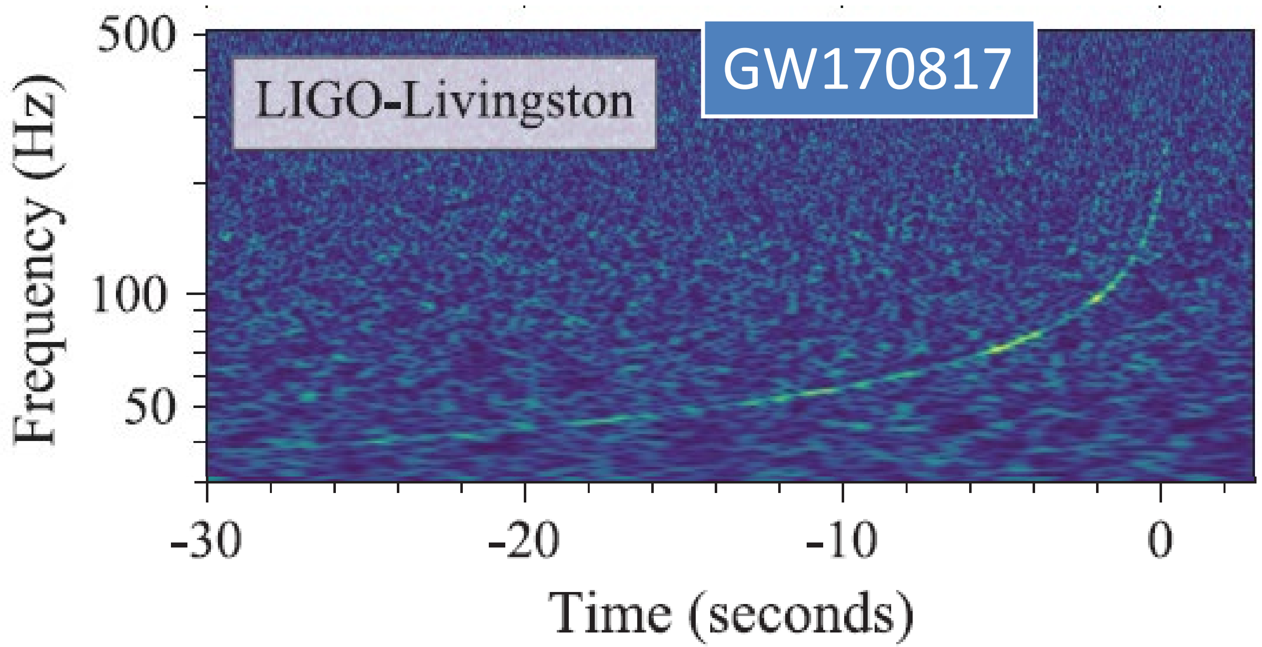
Outline

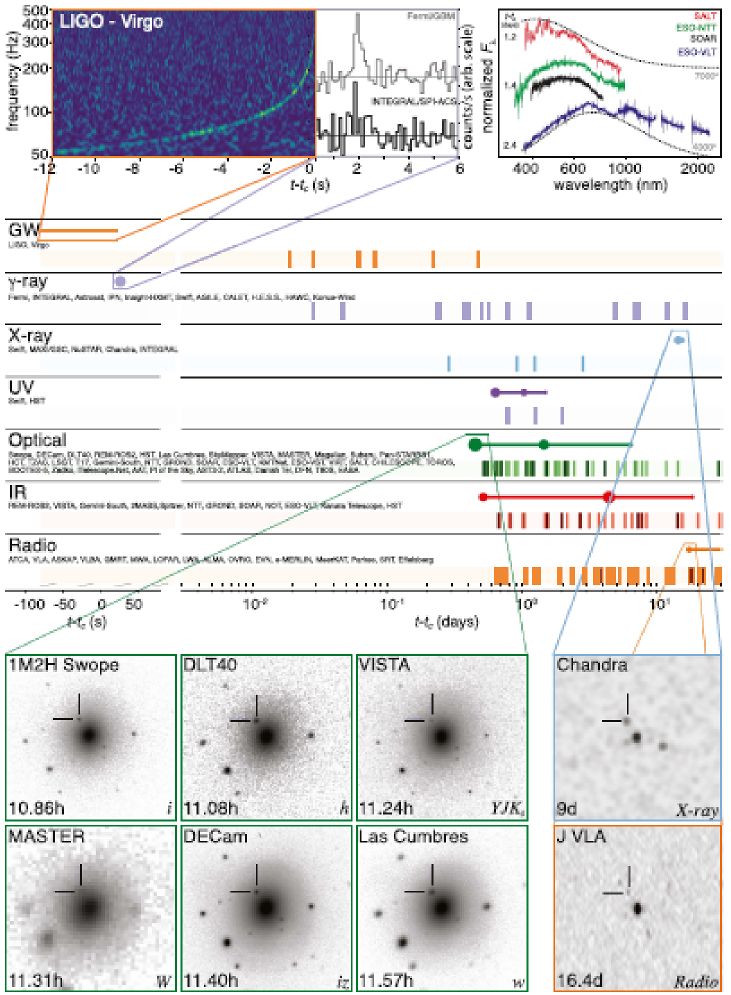
- *Introduction*
- *Gravitational waves: KAGRA*
- *Gamma rays: CTA*
- *Highest energy cosmic rays: Telescope Array (TA)*
- *Cosmic rays and gamma rays: Tibet ASγ and ALPACA*
- *Neutrinos: Super-Kamiokande and Hyper-Kamiokande*
- *Summary*

Introduction

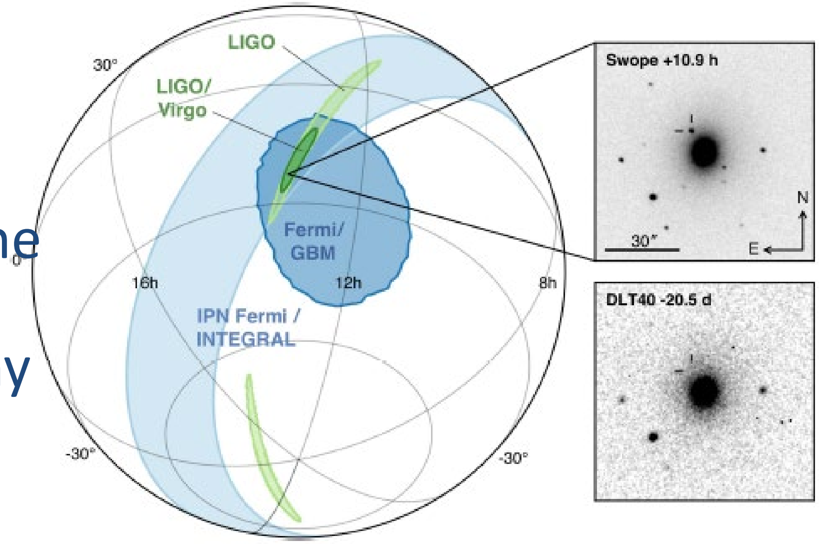
Introduction: Era of multi-messenger astronomy (1)



LIGO Scientific Collaboration and Virgo Collaboration, , PRL 119, 161101 (2017), PRL 119, 141101 (2017), ApJL, 848 L12 (2017), …. arXiv: 1811.1290, https://www.ligo.caltech.edu/gallery



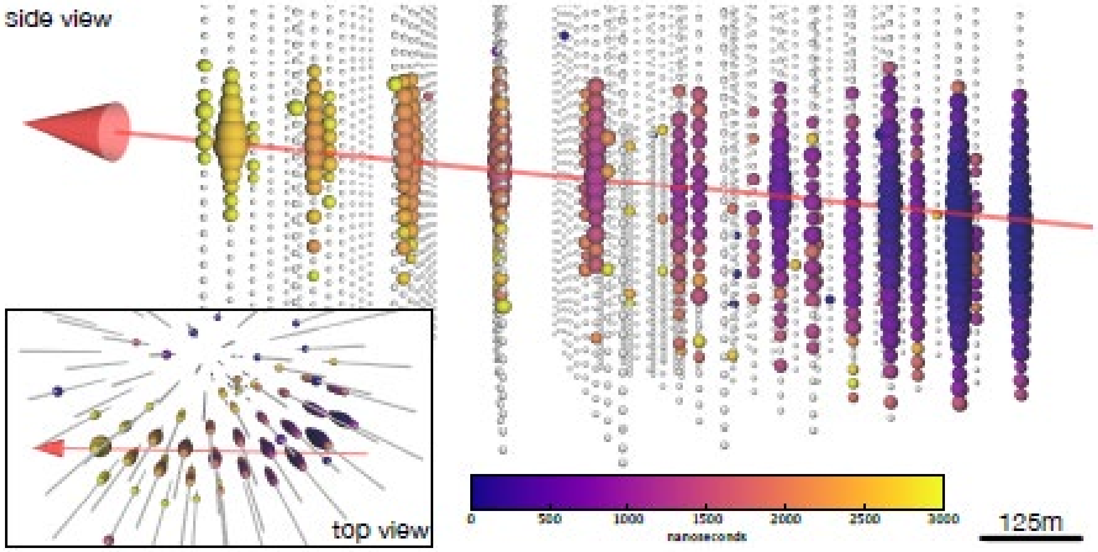
Detection of a merger of binary neutron stars by LIGO and Virgo together with multi wave-length electromagnetic observations was one of the highlight in recent science! These observations have told us many interesting results such as the generation of heavy elements.



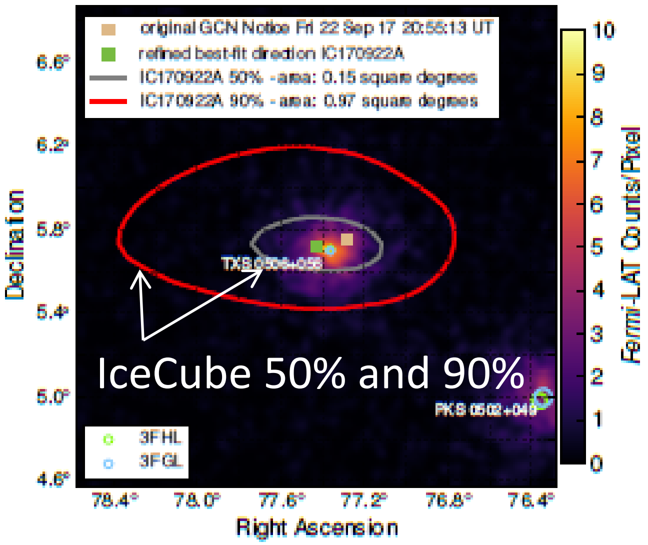
Introduction: Era of multi-messenger astronomy (2)

IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift=NuSTAR, VERITAS, and VLA/17B-403 teams, Science 361 (2018) 6398, eaat1378

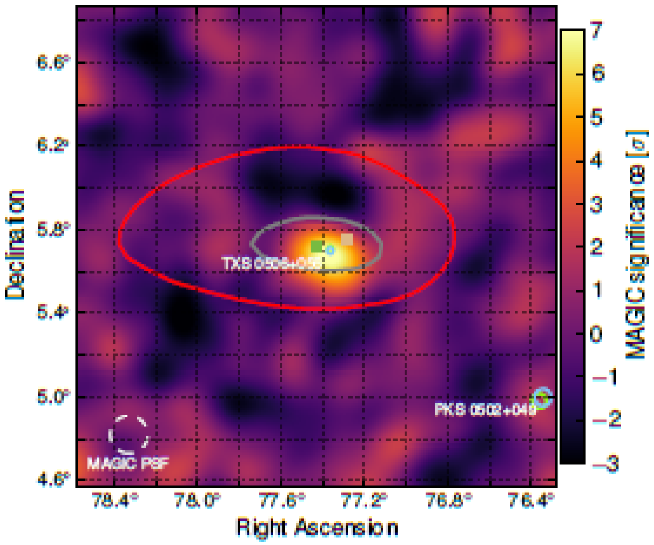
IceCube-170922A



(A) Fermi-LAT



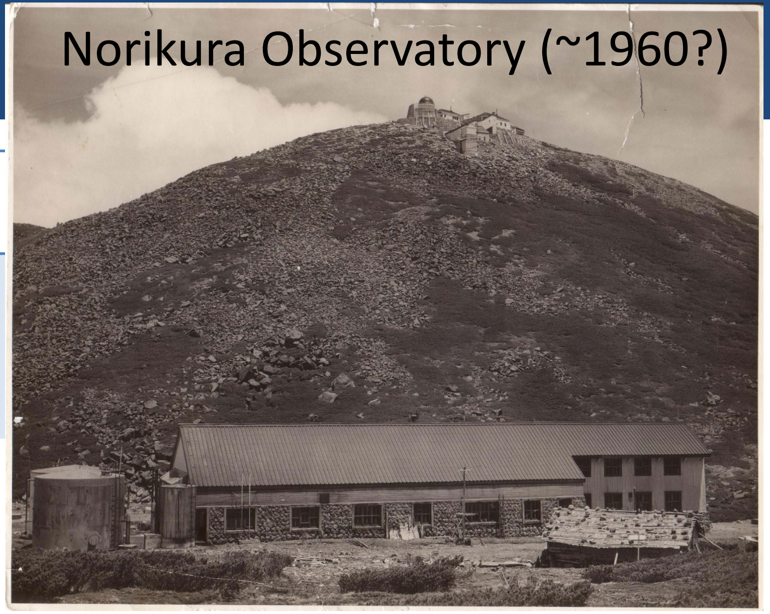
(B) MAGIC



Detection of very high-energy neutrinos by IceCube together with multi wave-length electromagnetic observations, and the identification of the source object (blazar) was another milestone event!

These examples indicate that we are entering the new era of multi-messenger astronomy.
We expect that many exciting discoveries are ahead of us!
➔ ICRR would like to contribute to the advancement of multi-messenger astronomy.

Introduction: History of ICRR



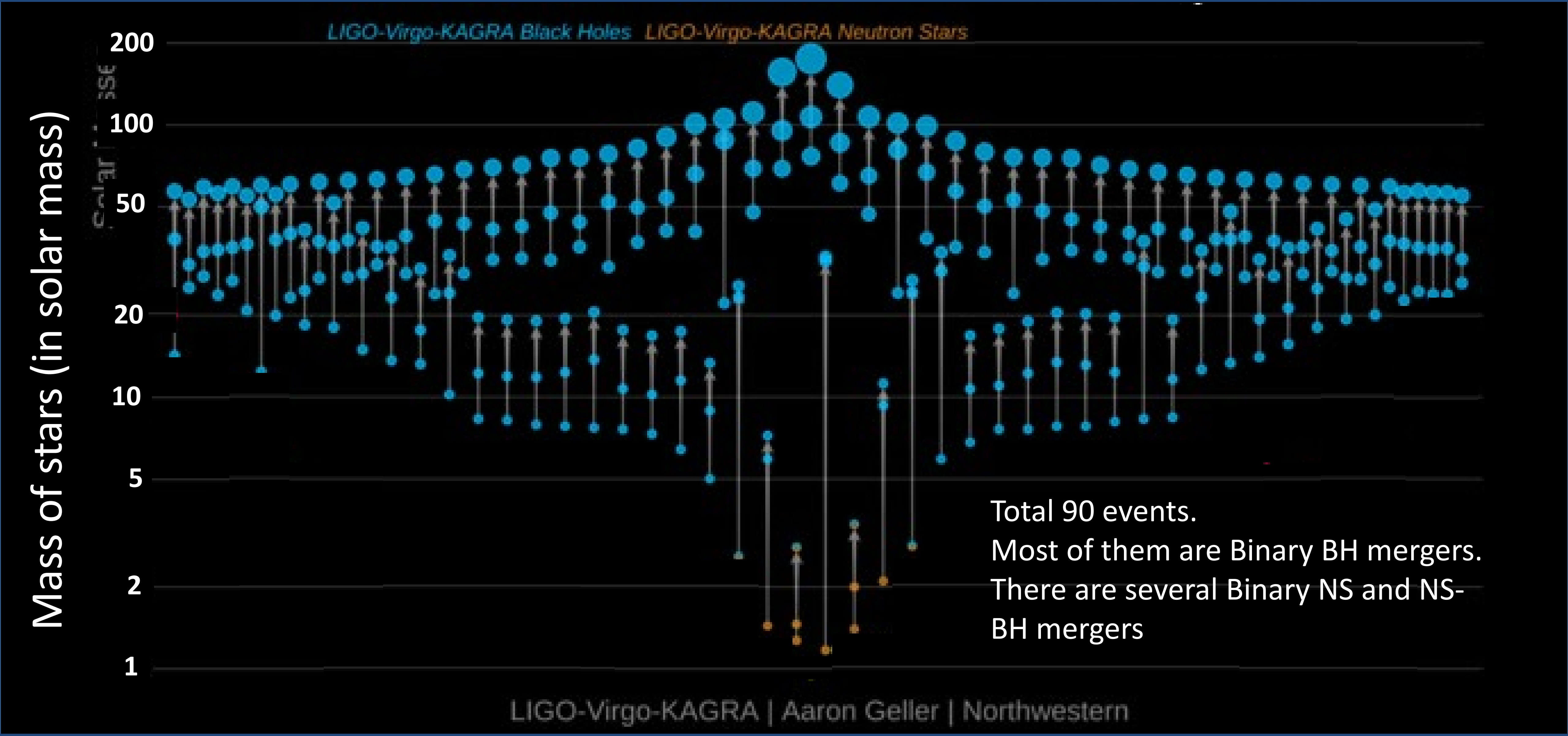
1953	Cosmic Ray Observatory, Univ. of Tokyo was established.
1976	Institute for Cosmic Ray Research (ICRR), Univ. of Tokyo was established (reorganized from the observatory).
….	…
1991	Construction of **Super-K** started. (The experiment started in 1996.)
1993	Construction of the **Tibet Asγ** experiment started.
2003	The construction of **Telescope Array** (for the highest energy cosmic ray studies) started in Utah. (The experiment started in 2008.)
2010	The construction of **KAGRA** (gravitational wave project) started.
2018	The first **CTA-LST** was constructed at La Palma.
2020	The construction of **Hyper-Kamiokande** started.

ICRR related facilities

Gravitational waves: KAGRA

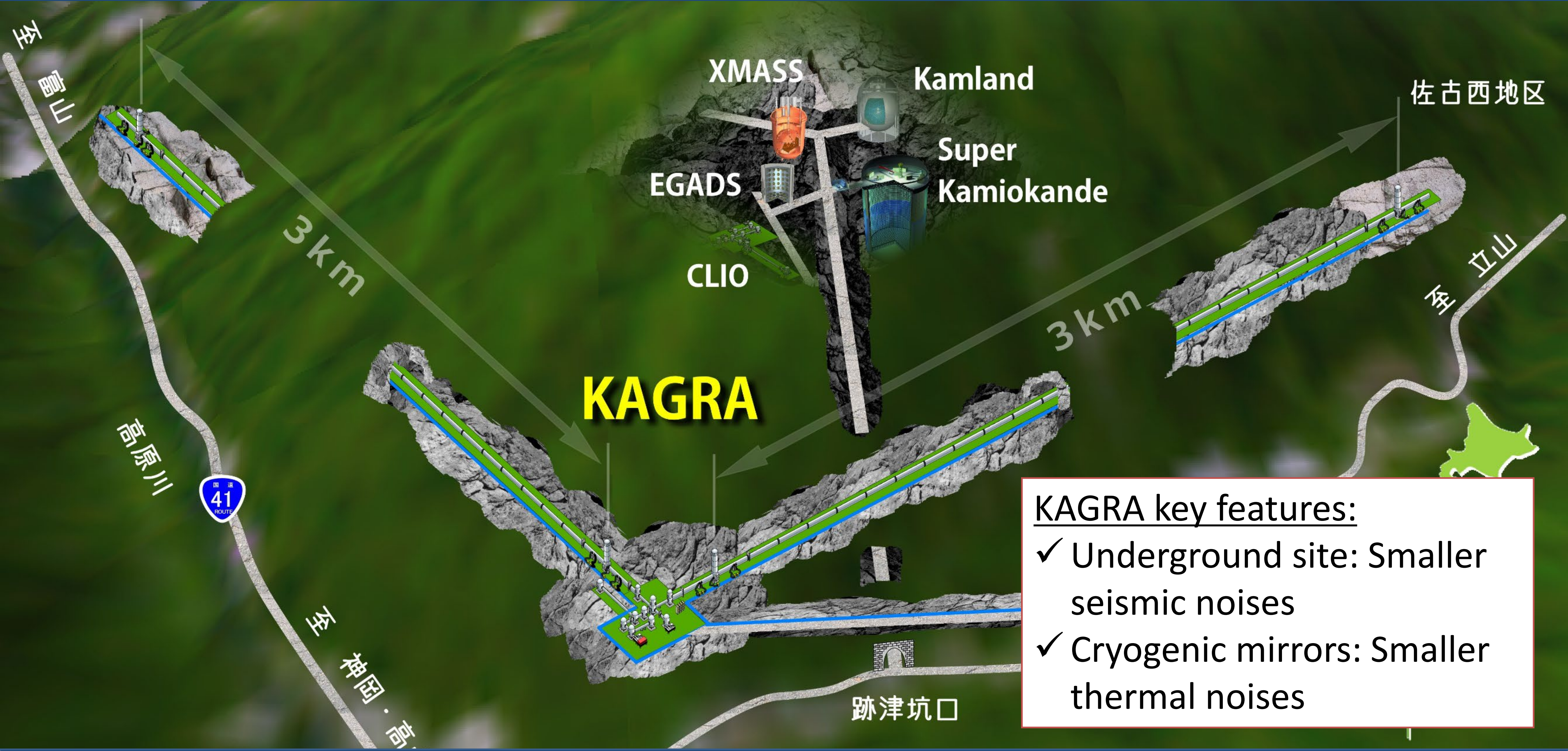
Summary of LIGO-Virgo observations

Credit: LIGO-Virgo



Total 90 events.
Most of them are Binary BH mergers.
There are several Binary NS and NS-BH mergers

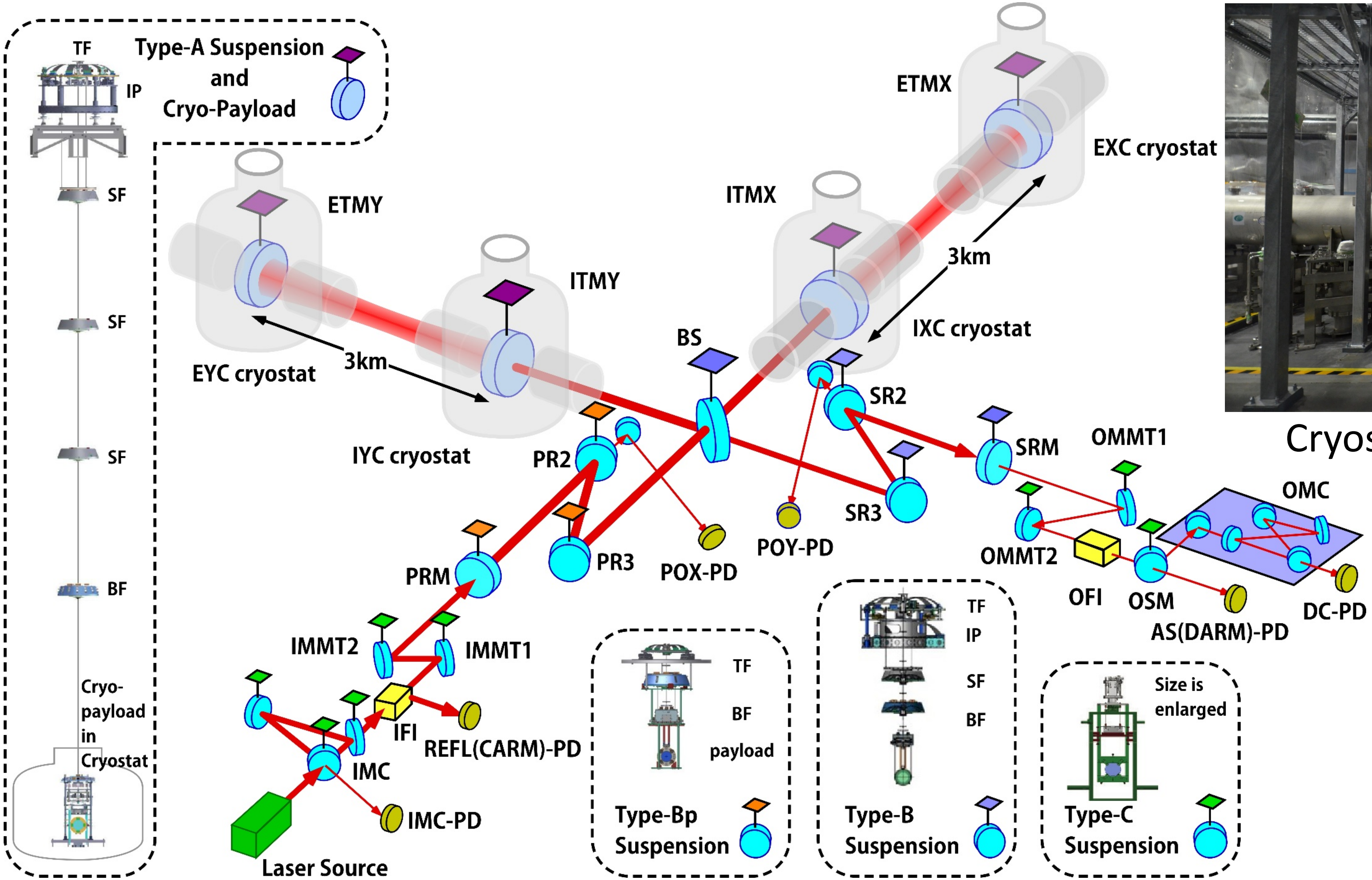
KAGRA



KAGRA key features:

- ✓ Underground site: Smaller seismic noises
- ✓ Cryogenic mirrors: Smaller thermal noises

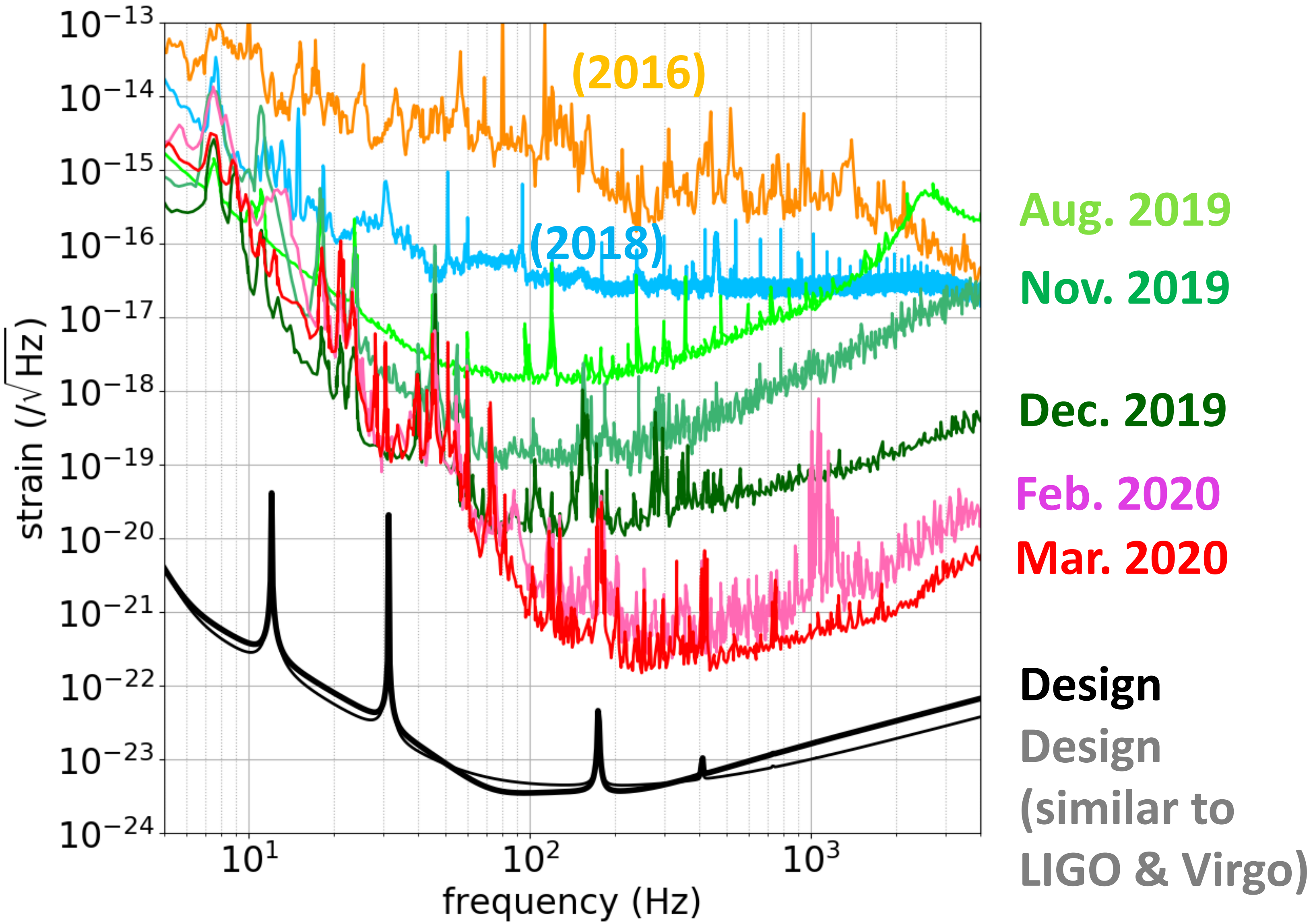
KAGRA configuration



Cryostat for a test mass mirror

Overall, the KAGRA optical configuration is very similar to LIGO and Virgo except for cryogenic mirrors.

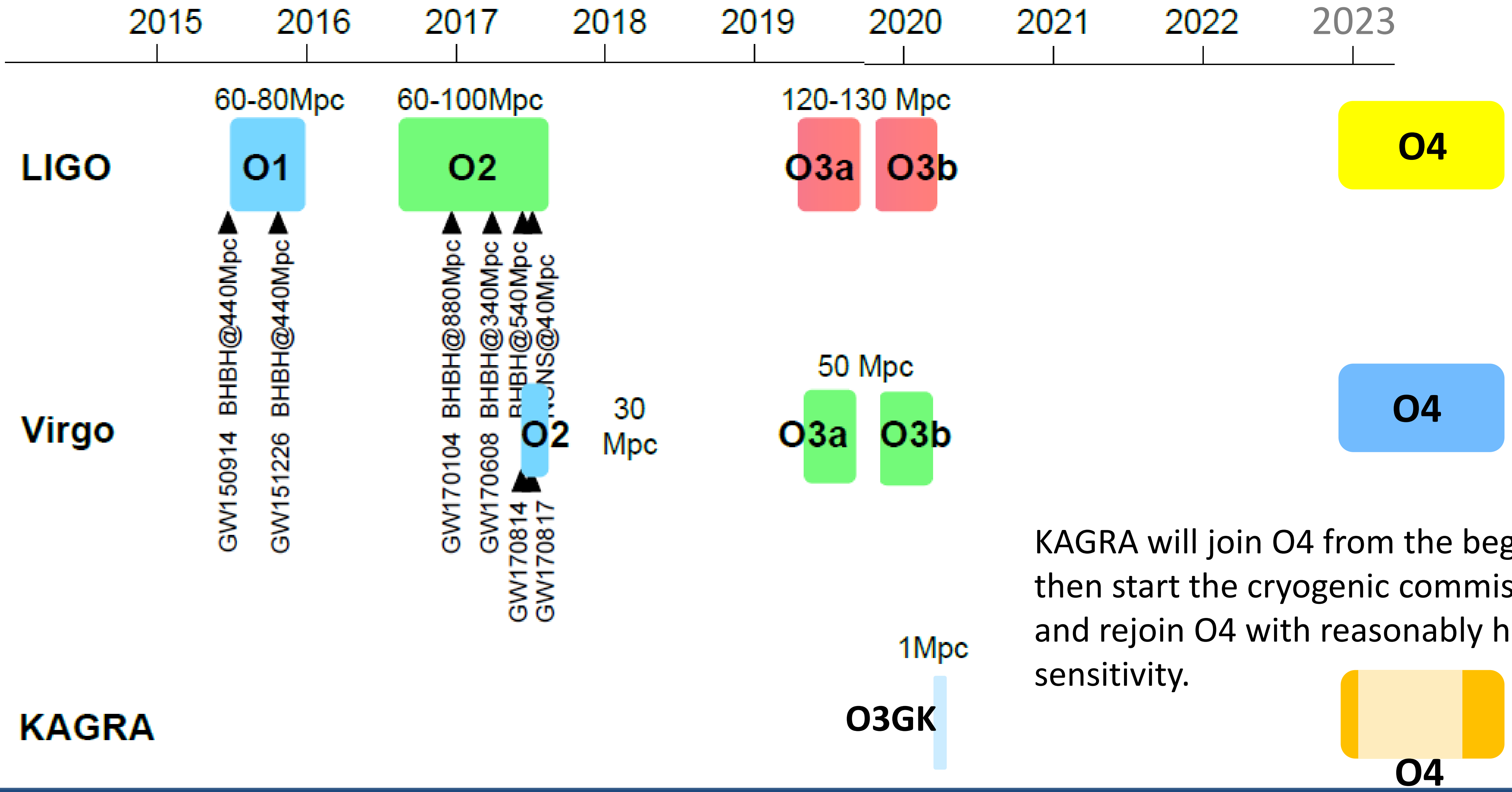
KAGRA sensitivity history



- ✓ KAGRA has finished the installation in the spring of 2019.
- ✓ After a very intense commissioning period, KAGRA started the observation in April 2020.
- ✓ Unfortunately, due to COVID-19, we stopped the operation in 2 weeks.

Observation history and plan

Original by H. Shinkai, slightly modified

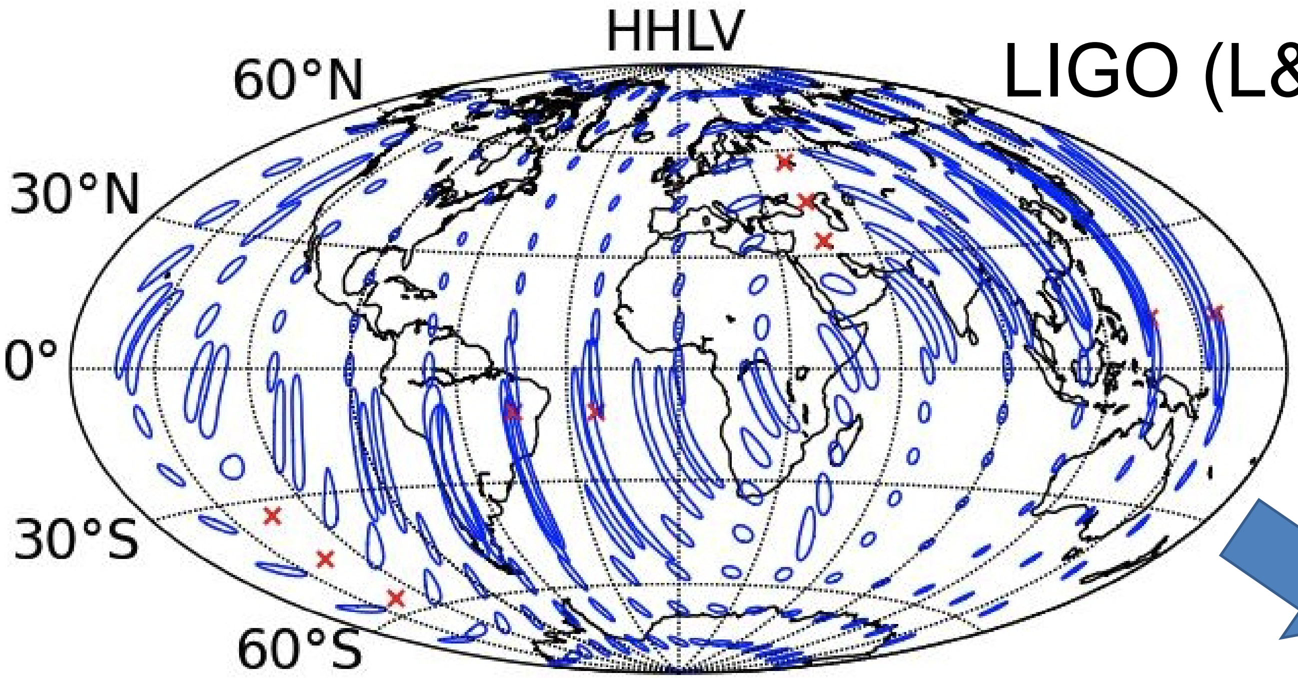


KAGRA will join O4 from the beginning, then start the cryogenic commissioning, and rejoin O4 with reasonably high sensitivity.

Sky localization

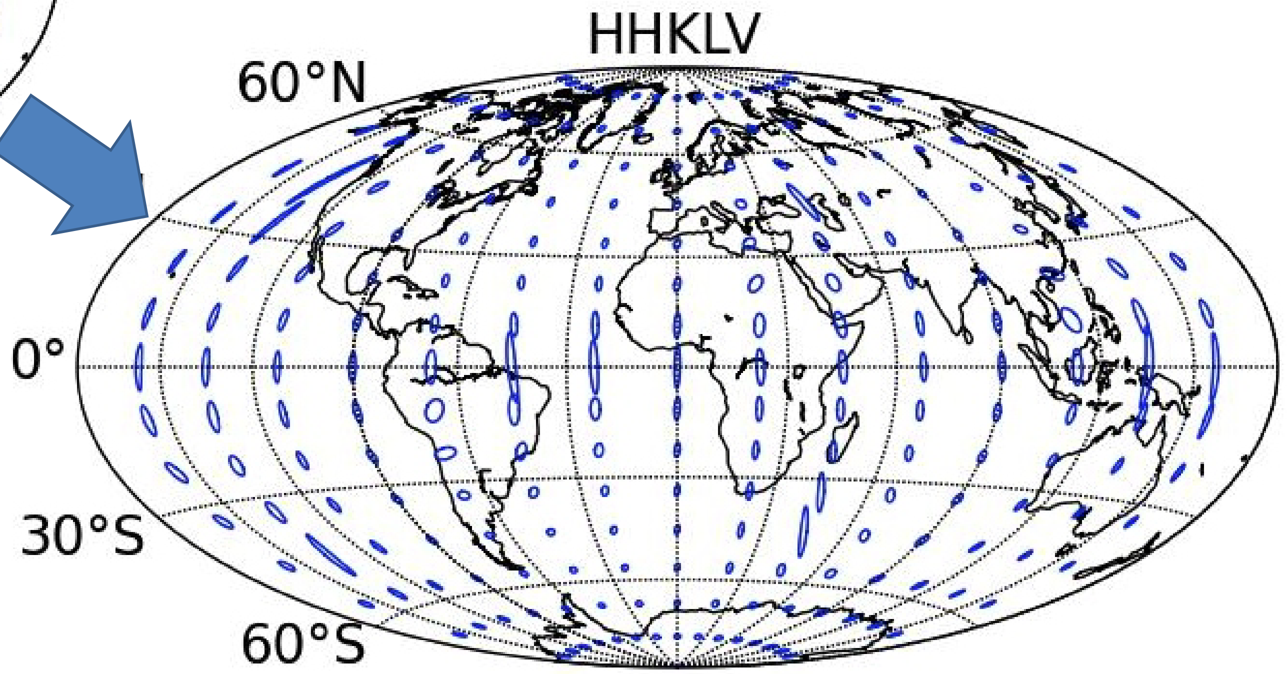
S. Fairhurst, "*Improved source localization with LIGO India*", J. Phys.: Conf. Ser. 484 012007

LIGO (L&H) + Virgo



x Observation not possible

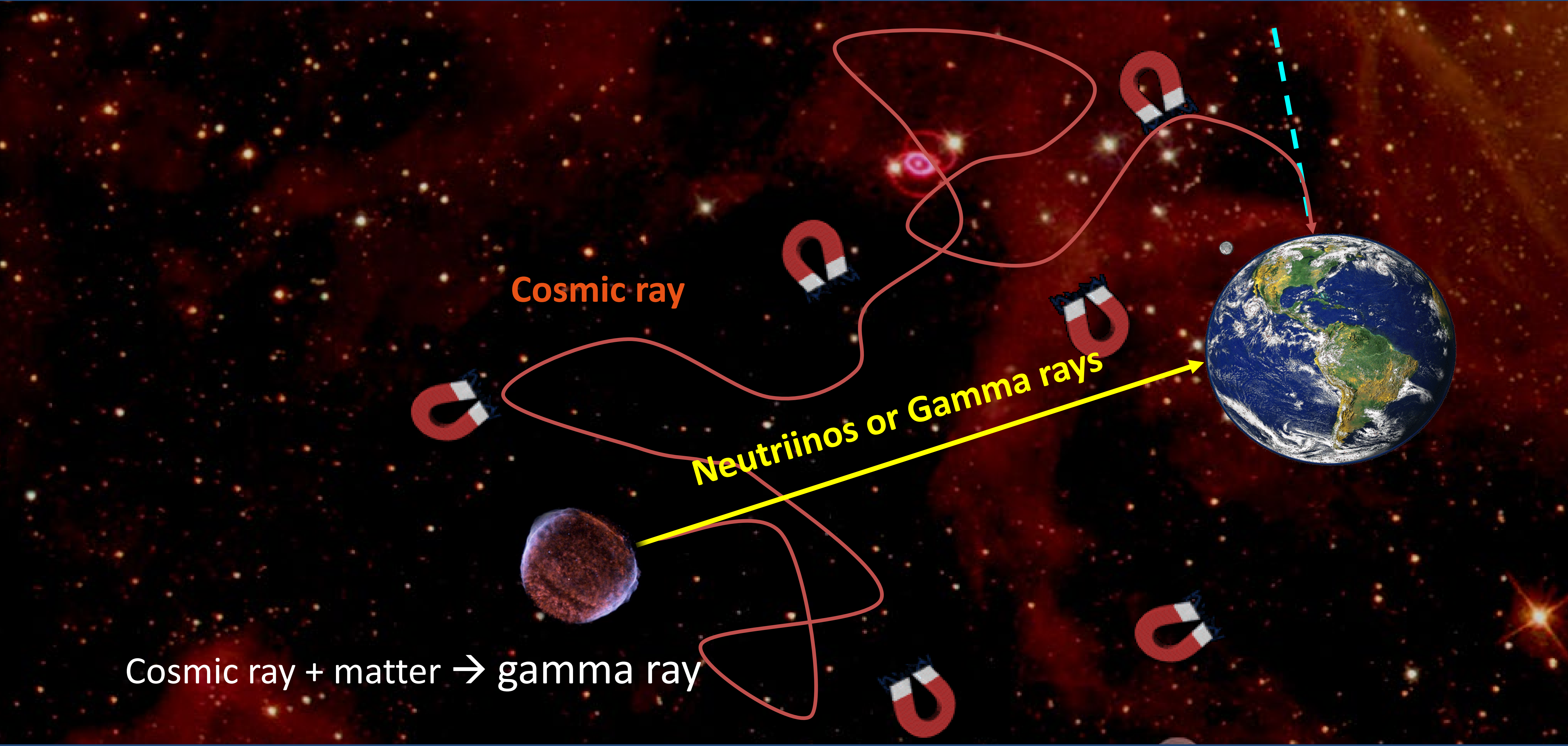
LIGO (L&H) + Virgo + KAGRA



KAGRA would like to contribute to the GW and multi-messenger astronomy!

Gamma rays: CTA

How can we know the source of cosmic rays



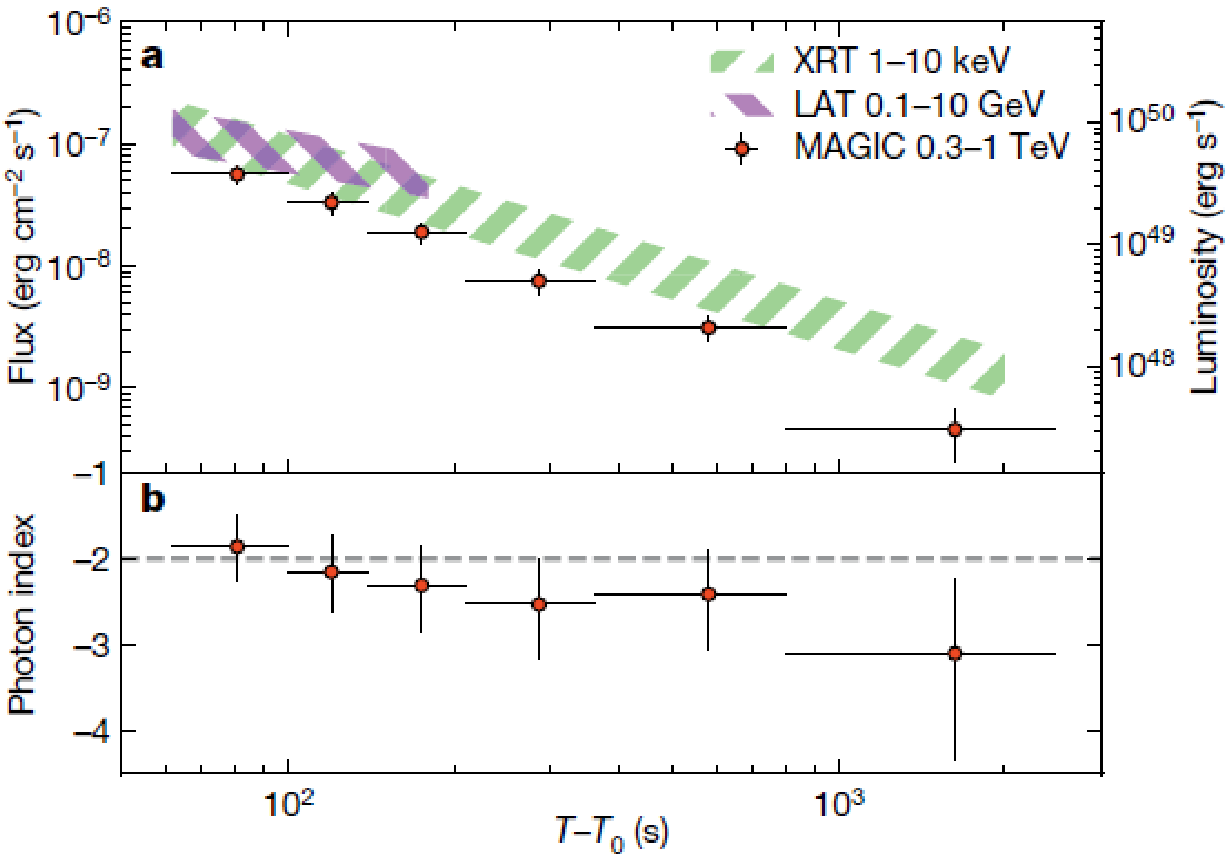
Joining MAGIC collaboration

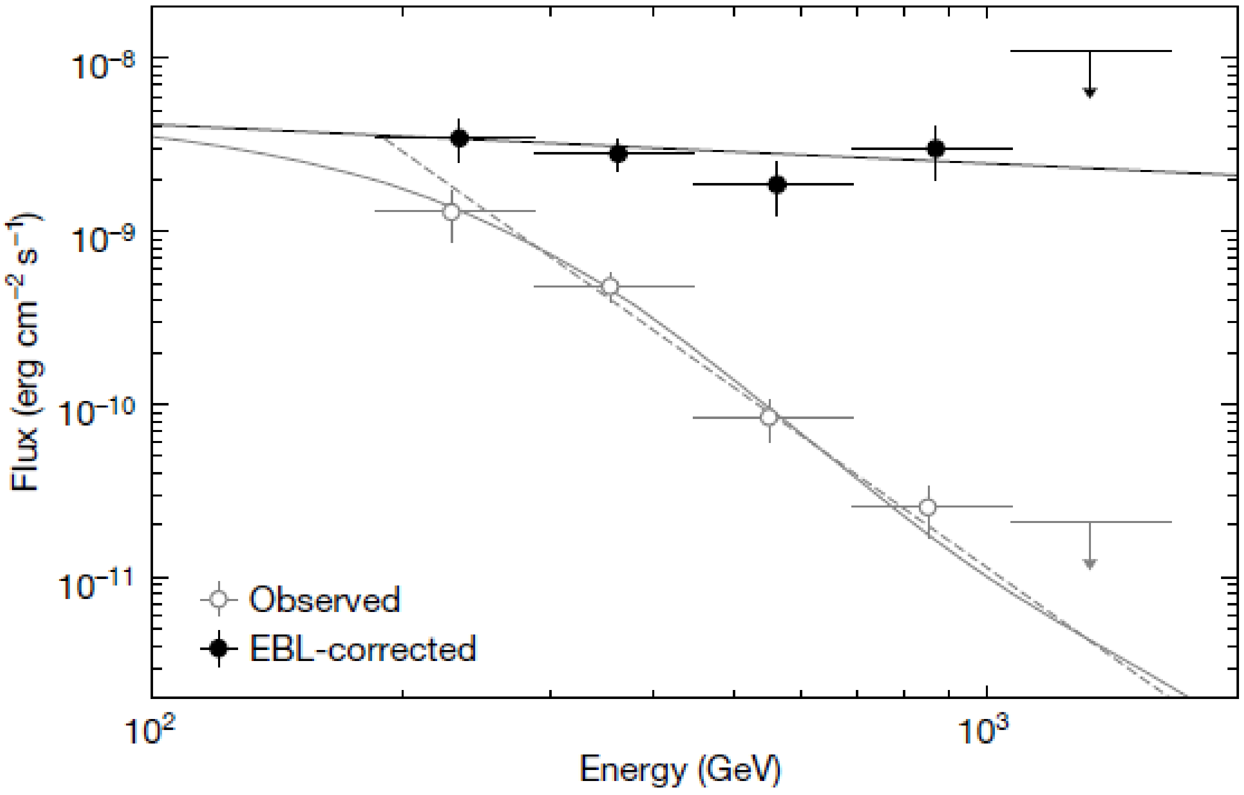
（La Palma, Spain）

Credit：MAGIC collaboration

Recent highlight: TeV emission from the γ-ray burst GRB 190114C

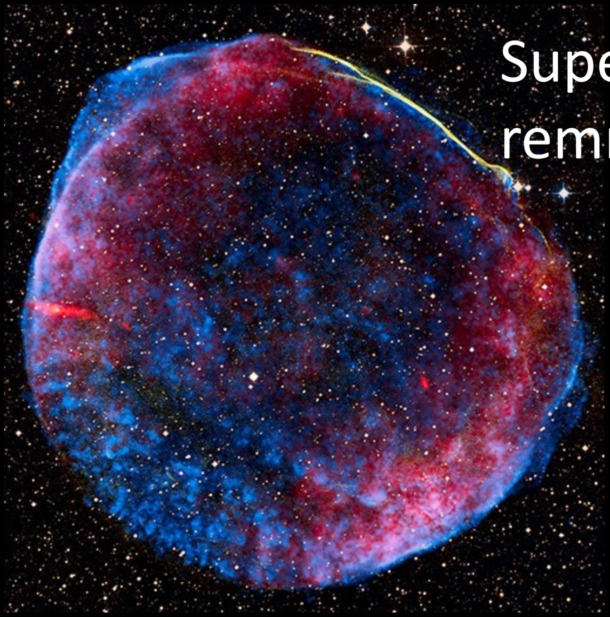
MAGIC collaboration, Nature 575 (2019) 455



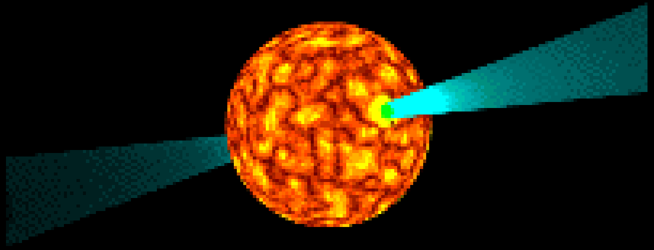


The first unambiguous detection of TeV gamma rays from GRB!

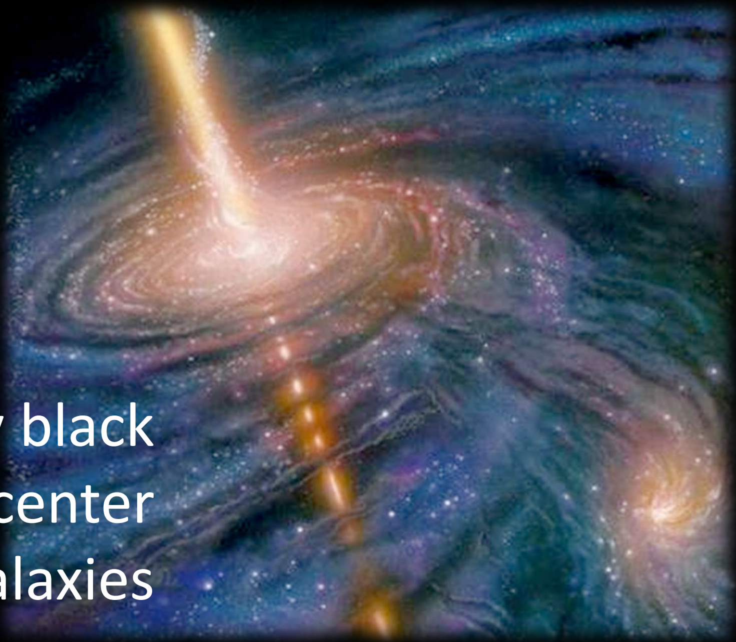
Astronomical objects to be studied with gamma rays



Supernova remnants

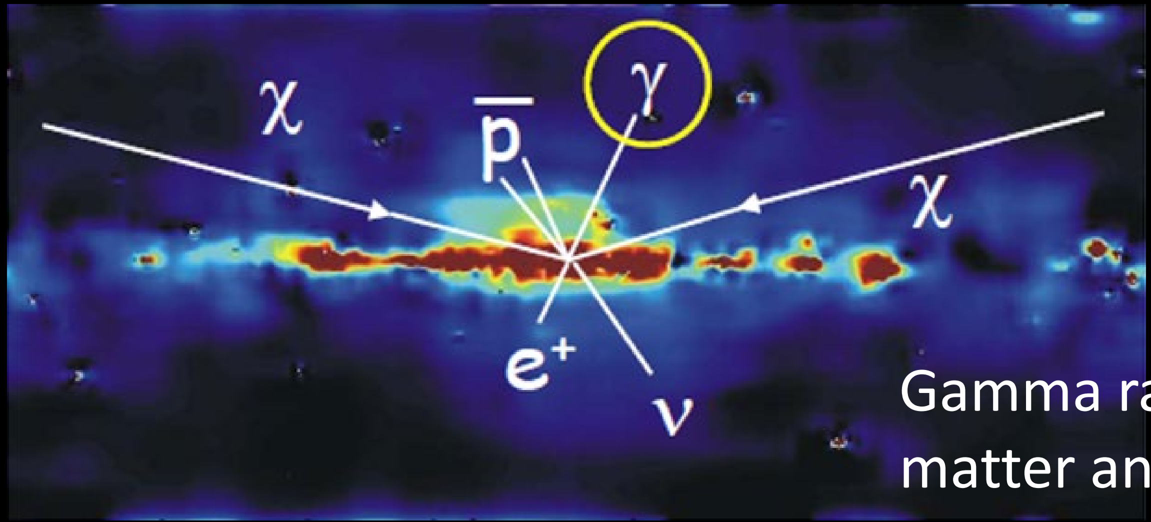


pulsars



Super heavy black holes at the center of galaxies

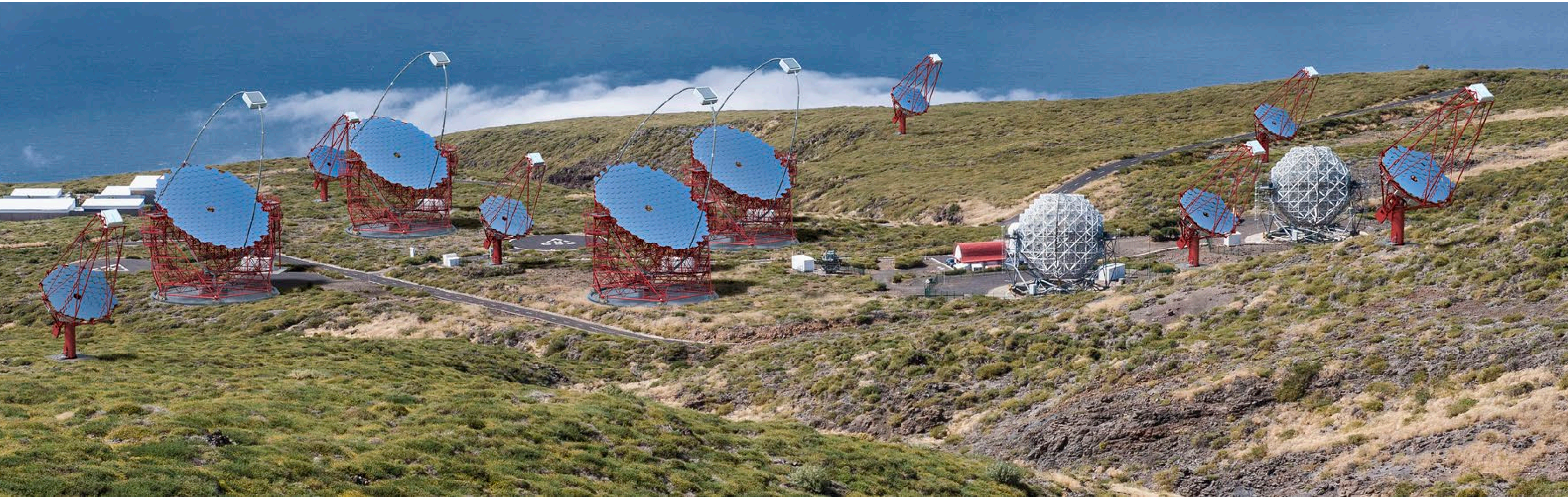
Gamma ray bursts



Gamma rays from dark matter annihilation

Next generation gamma ray telescope (CTA)

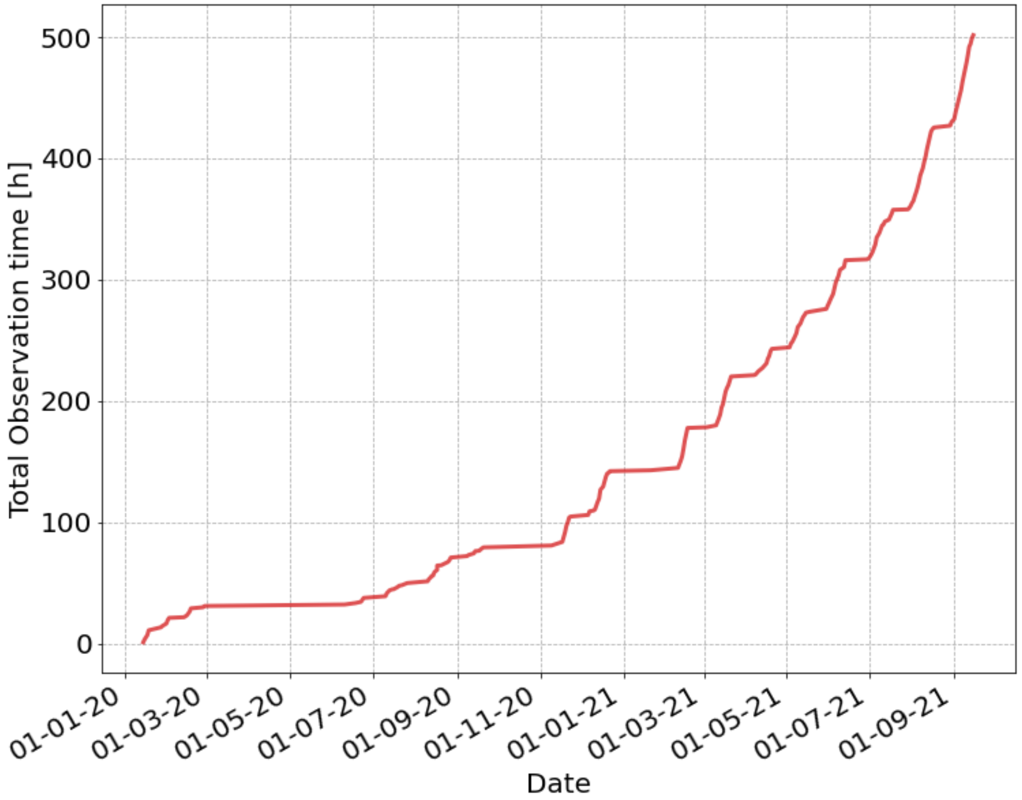
Credit: CTA Consortium



ICRR is joining CTA, in particular in the LST project in the north site.
(The image is for the north at La Palma, Spain.)

The first CTA-LST

Inauguration ceremony on Oct. 10, 2018



500 hours of scientific observation already!

Timeline

Slide from Masahiro Teshima

<table>
<tr><th></th><th>2020</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th><th>2029</th><th>2030</th></tr>
<tr><td rowspan="2">Organization</td><td colspan="3">CTAO gGmbH (Heidelberg)</td><td colspan="8"></td></tr>
<tr><td colspan="2"></td><td colspan="9">CTAO ERIC (European Research Infrastructure Consortium)</td></tr>
</table>

<table>
<tr><th>Alpha Config</th><th>2020</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th><th>2029</th><th>2030</th></tr>
<tr><td rowspan="2">LST North</td><td colspan="5">Comissioning and Operation of LST1</td><td colspan="4" rowspan="2">Operation as 4 LST Array</td><td colspan="2" rowspan="5">Observatory Operation</td></tr>
<tr><td colspan="2">CDR</td><td colspan="3">Deployment of LST2-4</td></tr>
<tr><td>MST North</td><td colspan="2">Design and Finance</td><td>INFRA</td><td colspan="6">Construction of 9MSTs</td></tr>
<tr><td rowspan="2">CTA South</td><td colspan="2" rowspan="2">Array config, Finance and CDR</td><td colspan="2" rowspan="2">INFRA</td><td colspan="5">Construction and Deplyment of 14 MSTs</td></tr>
<tr><td colspan="5">Construction and Deployment of 37 SSTs</td></tr>
</table>

<table>
<tr><th>Extension</th><th>2020</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th><th>2029</th><th>2030</th></tr>
<tr><td>LST South</td><td></td><td colspan="2">Finance / CDR</td><td colspan="3">Construction of 4 LSTs ???</td><td colspan="5">Operation ???</td></tr>
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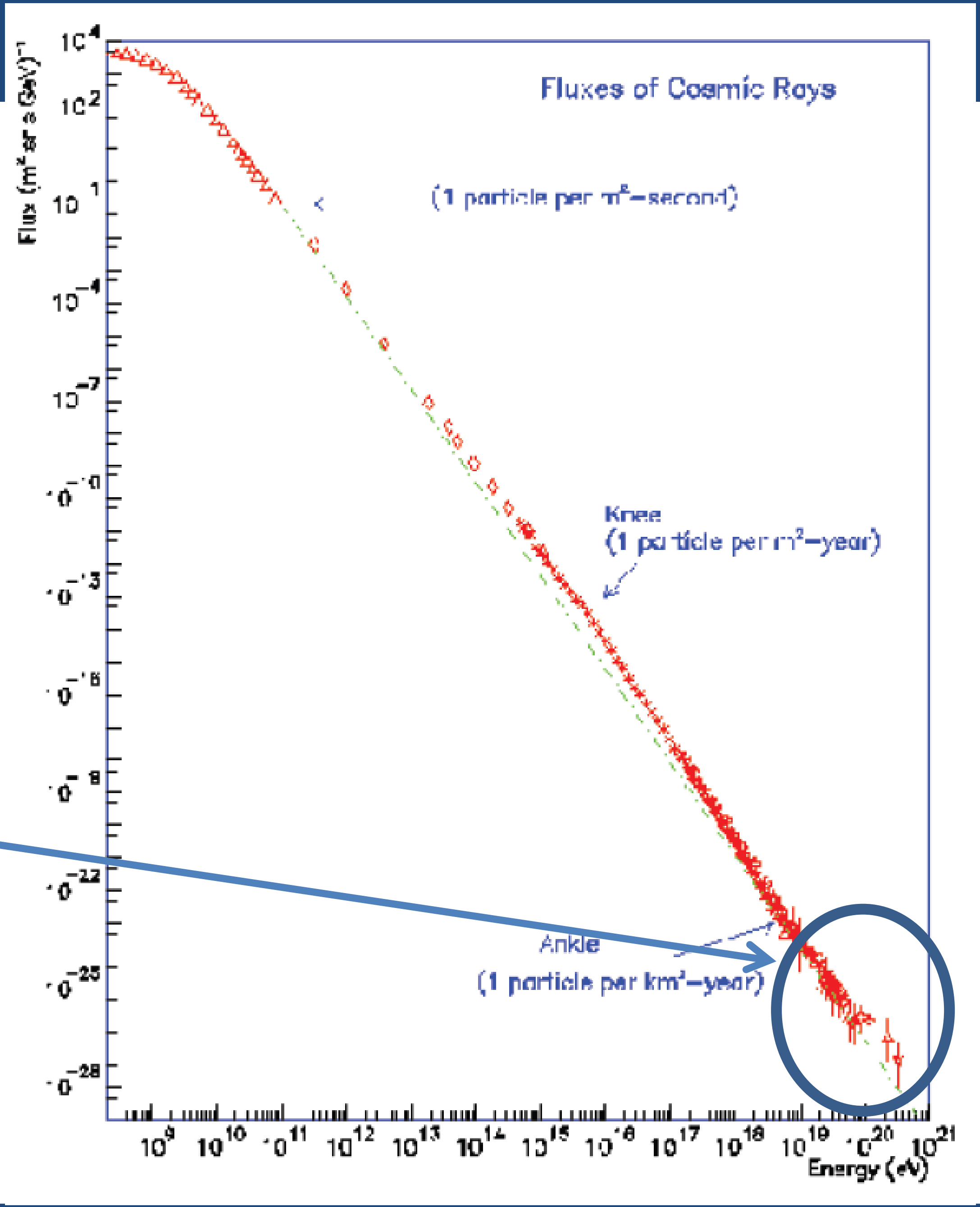
Most exciting time!
Expecting many exciting results from CTA!

Highest energy cosmic rays: Telescope Array (TA)

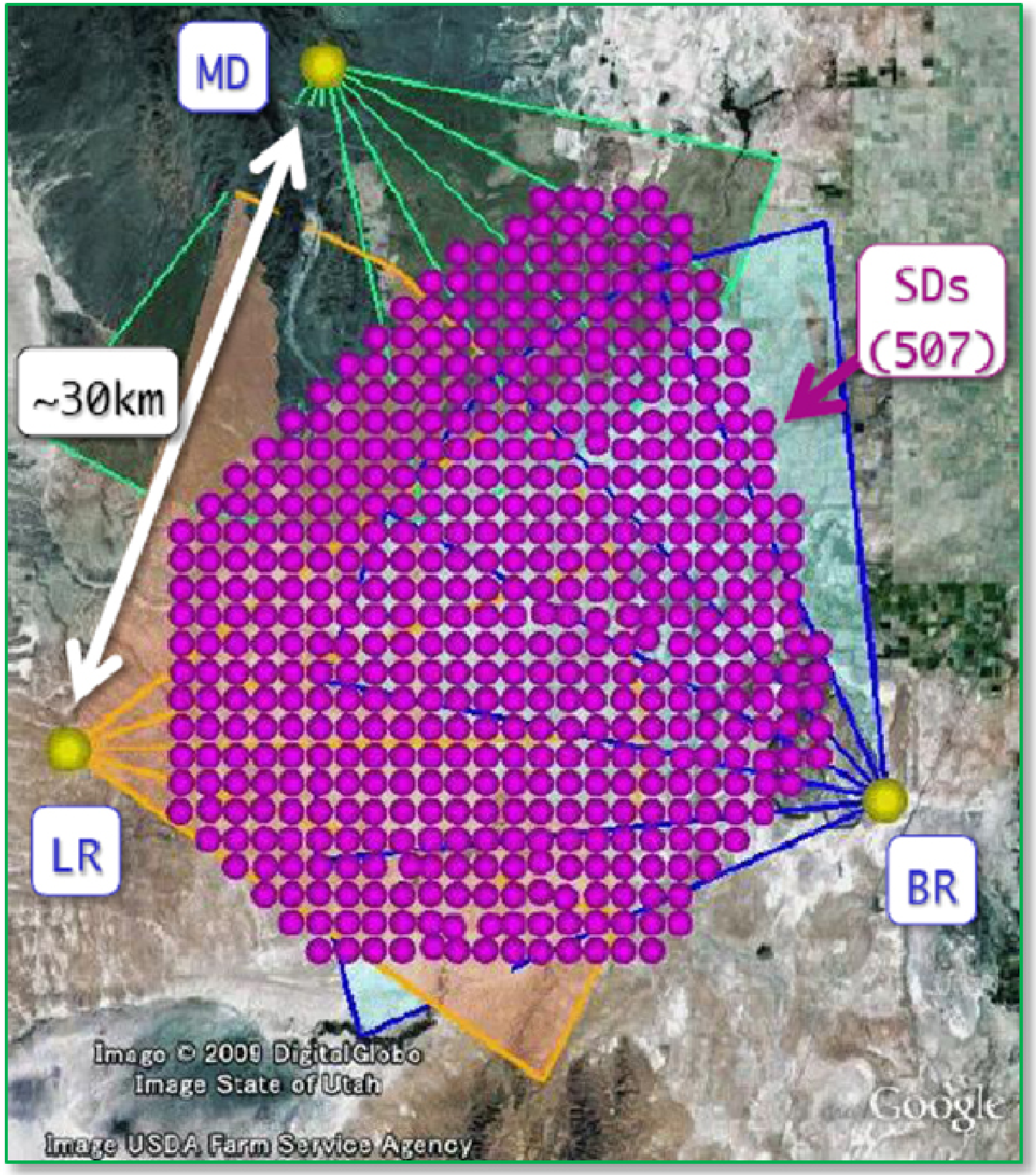
Cosmic ray energy spectrum



✓End of cosmic ray spectrum?

✓How and where these cosmic rays are accelerated?

Telescope Array (TA, @Utah, USA)



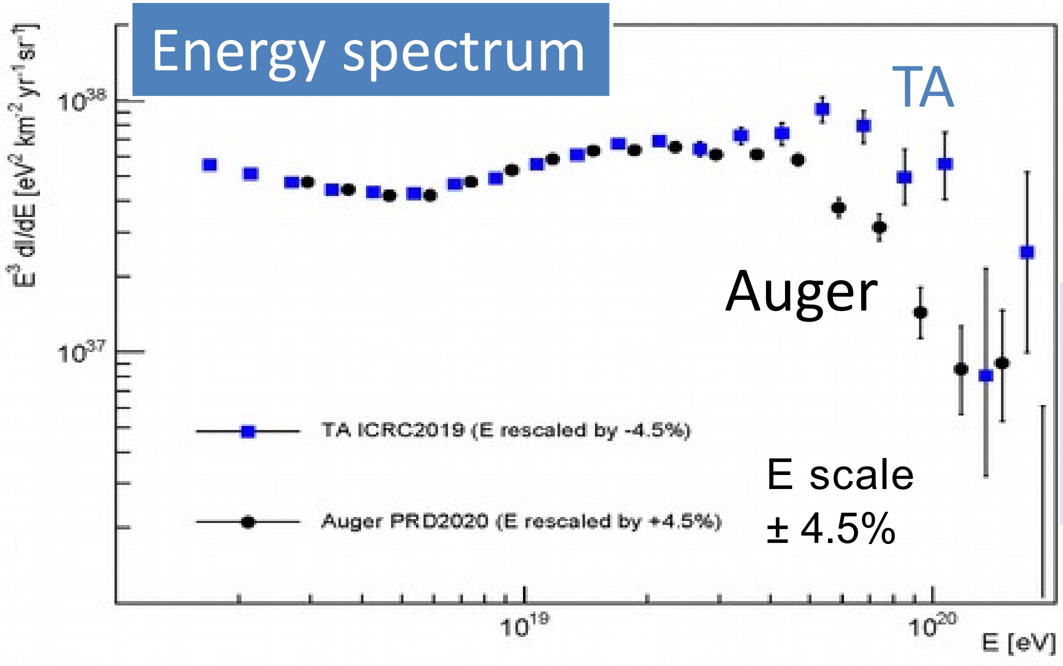
Fluorescence Detectors(FDs)
- 3 stations

Surface detectors(SDs)
- 507 scintillation detectors ($3m^2$)
- 1.2km spacing
- total coverage ~$700km^2$

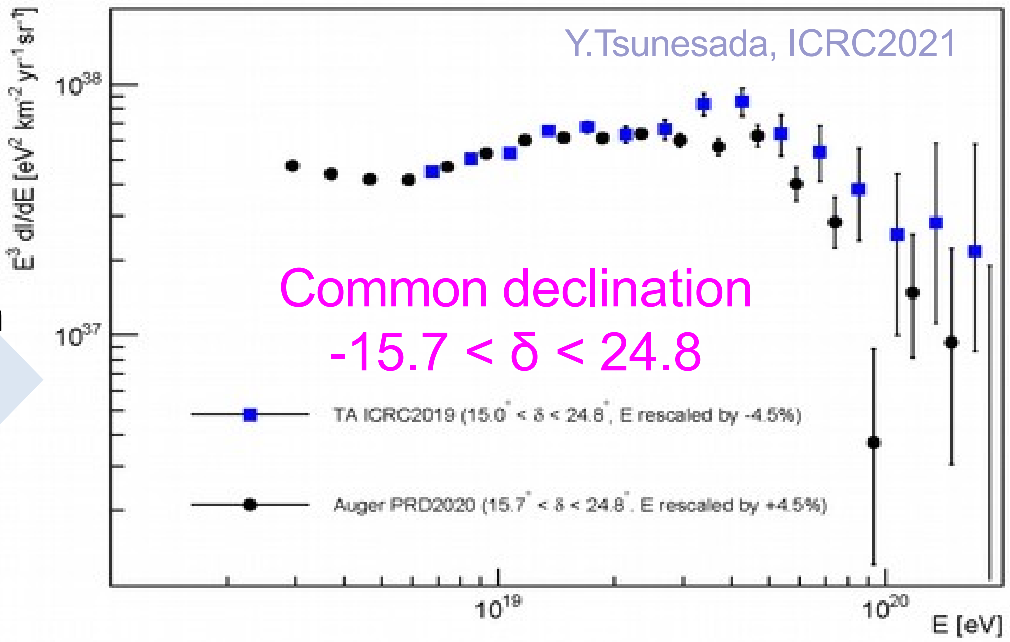
TALE (TA Low Energy Ext.)

TA highlights

Energy spectrum

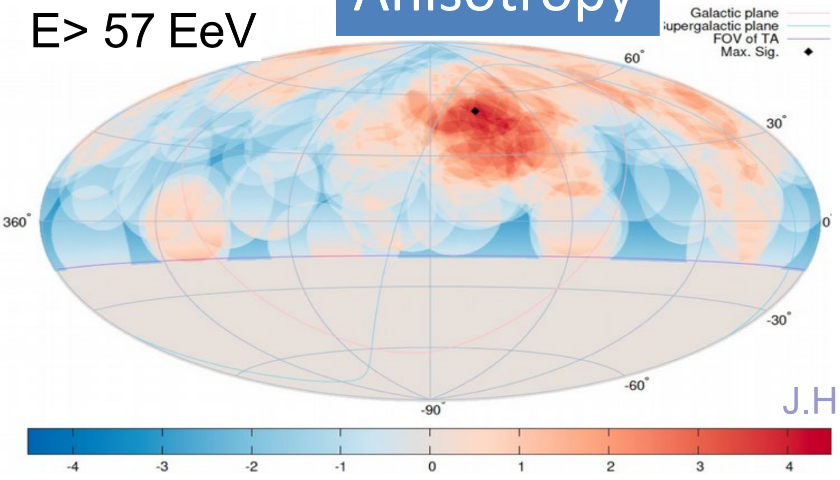


Taking the common declination (Auger + TA WG)

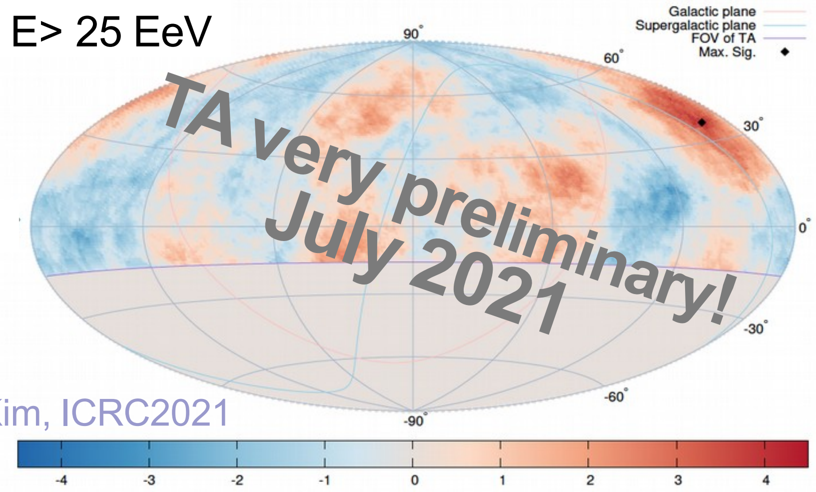


Anisotropy

E> 57 EeV



E> 25 EeV



J.H. Kim, ICRC2021

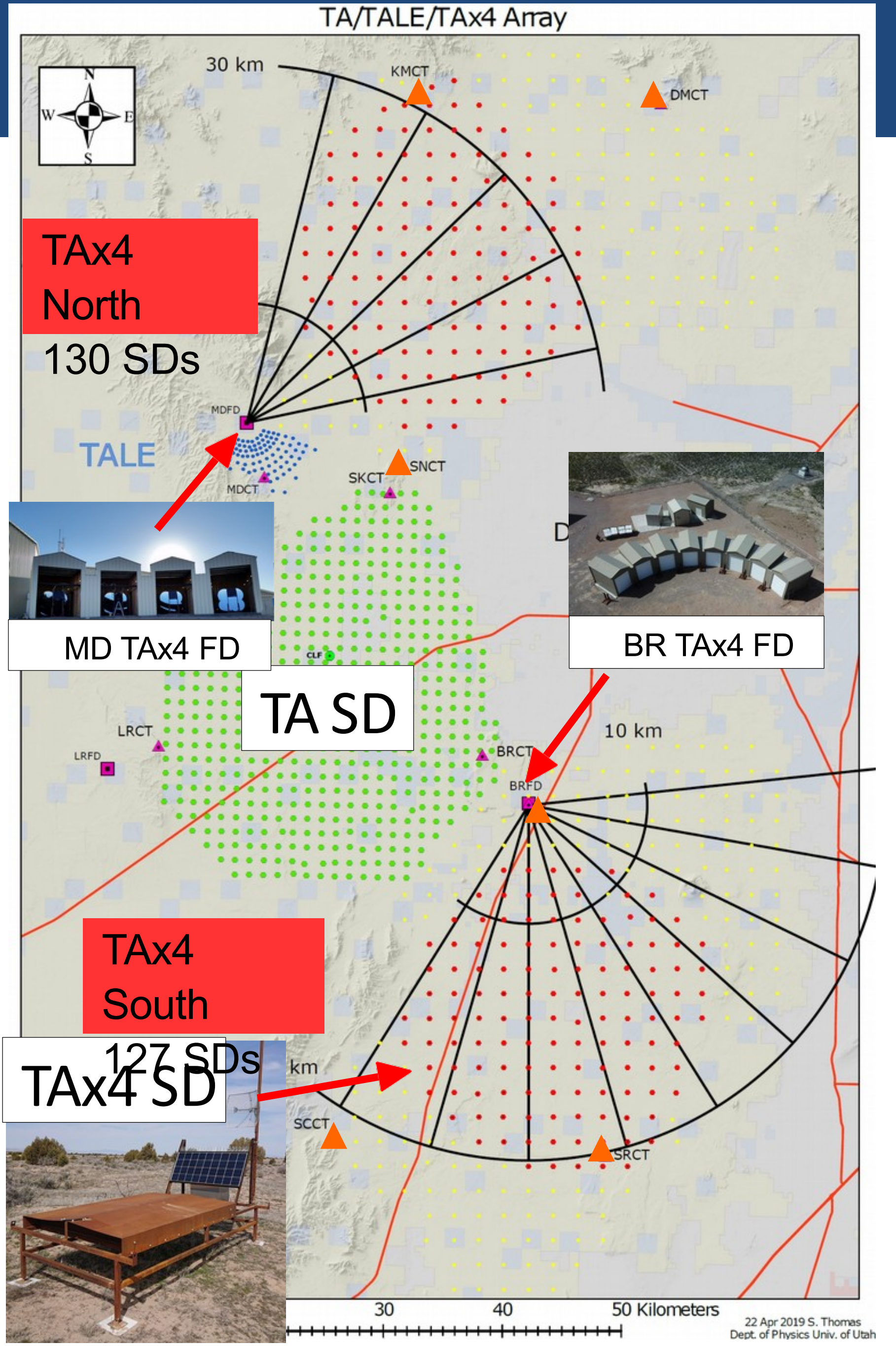
- ✓ The data are very interesting.
- ✓ With time, we better understand the data.

➔ We expect exciting new results in the near future!

TAx4

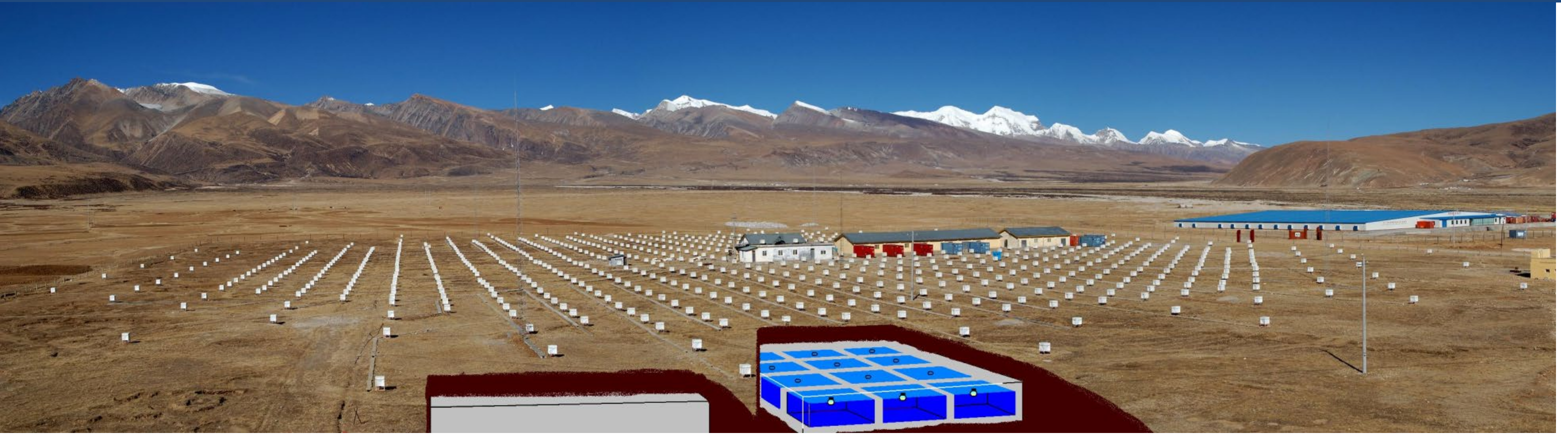
Because the hos-spot data gave some indication for the source location of the highest energy cosmic rays, TAx4 (extension of the surface coverage by x4, 3000 km^2) was proposed.

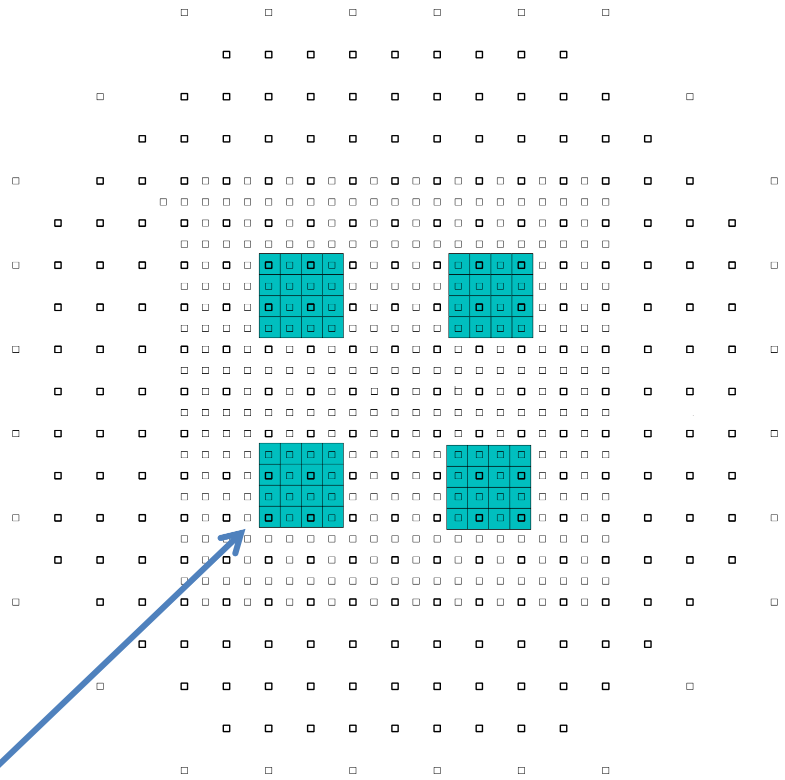
So far:
257 SDs (out of 500 SDs) were installed in the site.
+ 2 new FD stations.



Cosmic rays and gamma rays: Tibet ASγ and ALPACA

Tibet ASγ experiment





- Site: Tibet (90.522°E, 30.102°N) 4,300 m a.s.l.

<u>Present Performance</u>

- ✓ Effective area ~65,700 m^2
- ✓ Angular resolution ~0.5° @10TeV, ~0.2° @100TeV
- ✓ Energy resolution ~40%@10TeVγ, ~20%@100TeVγ

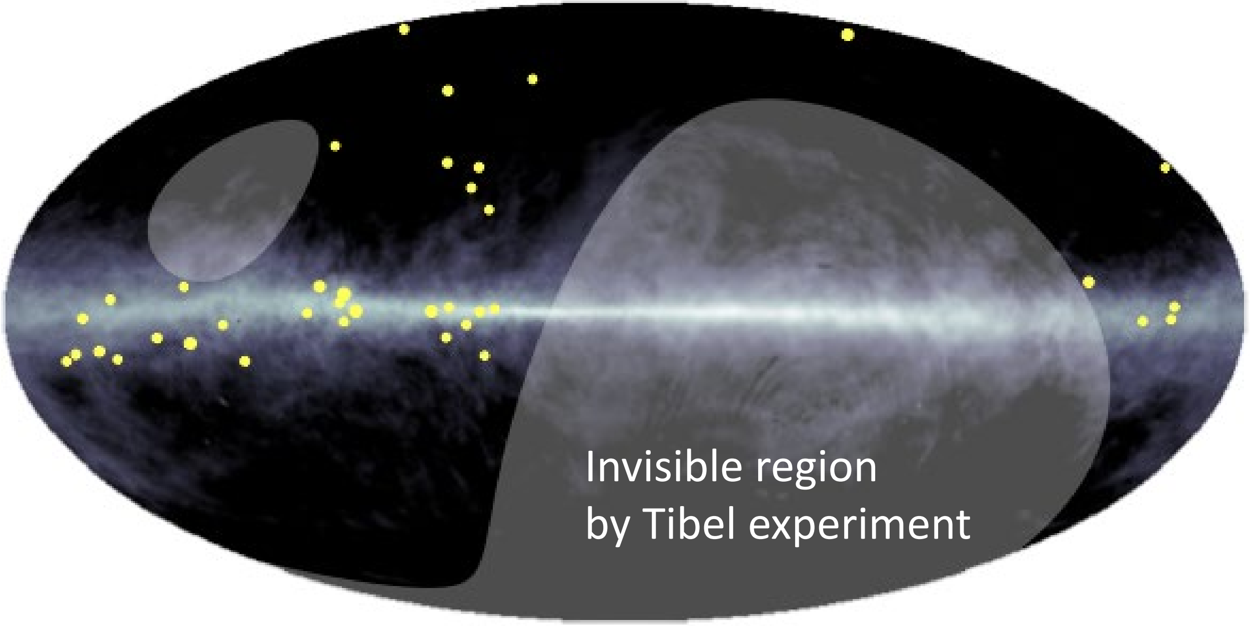
<u>Underground water Ch. Muon detector</u>

- ✓ (2.4 m underground, total 3400 m^2)
- ✓ ~99.9% CR rejection & ~90% γ efficiency @100 TeV (depending on the cut)

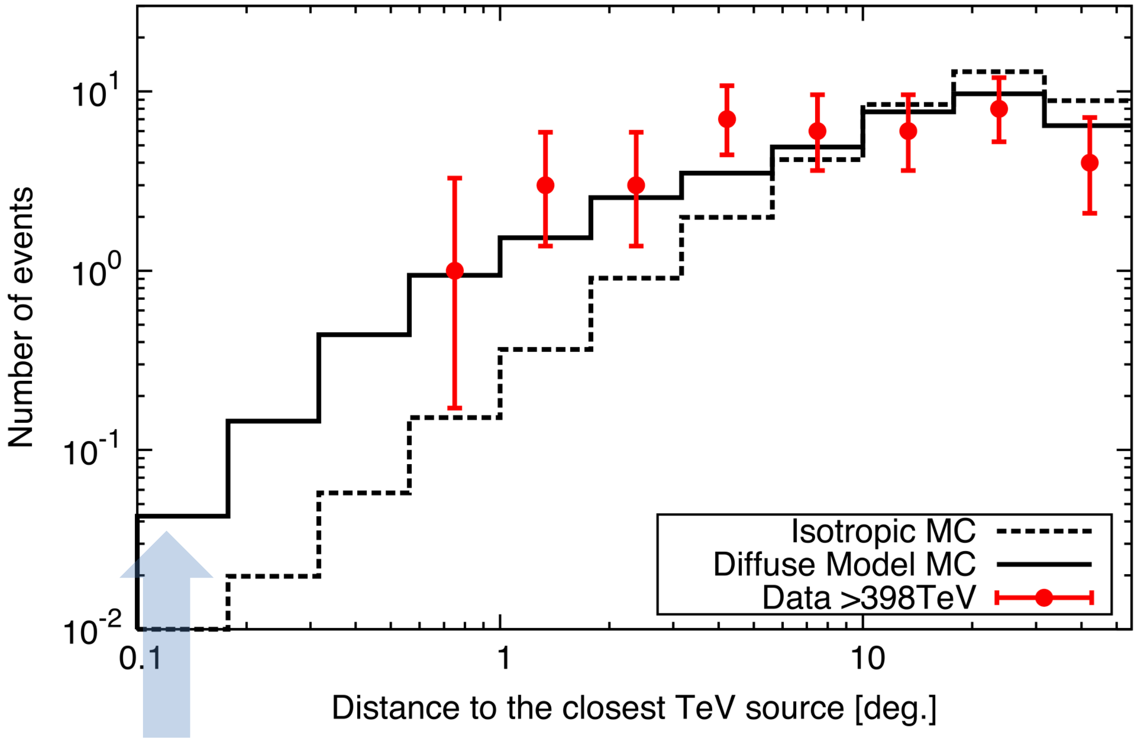
Tibet ASγ highlight

M. Amenomori et al., PRL, 126, 141101 (2021)

Distribution of gamma ray candidates after very tight muon-cut:



398 – 1000 TeV



No event around 0 → No correlation with known TeV sources

Evidence for galactic cosmic rays beyond PeV energies.

Together with the other results → Sub-PeV gamma ray astronomy

ALPACA

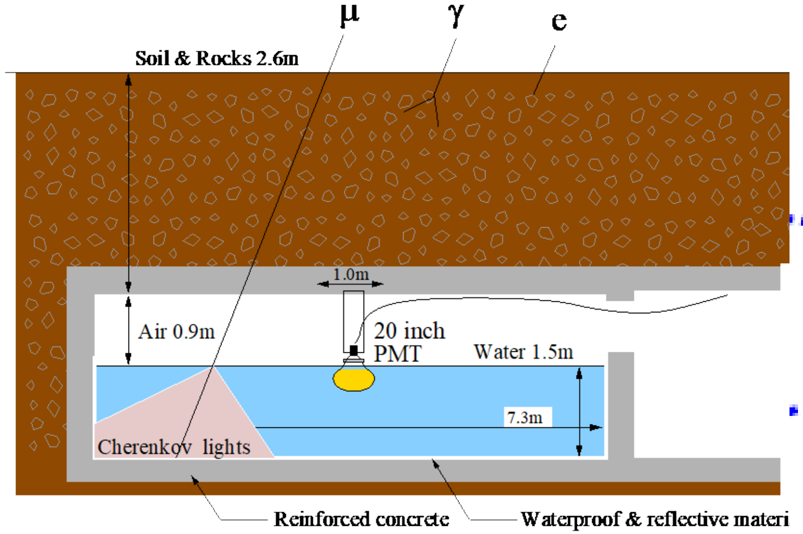
M. Shiomi, ICRR Jan. 2022

Motivation:

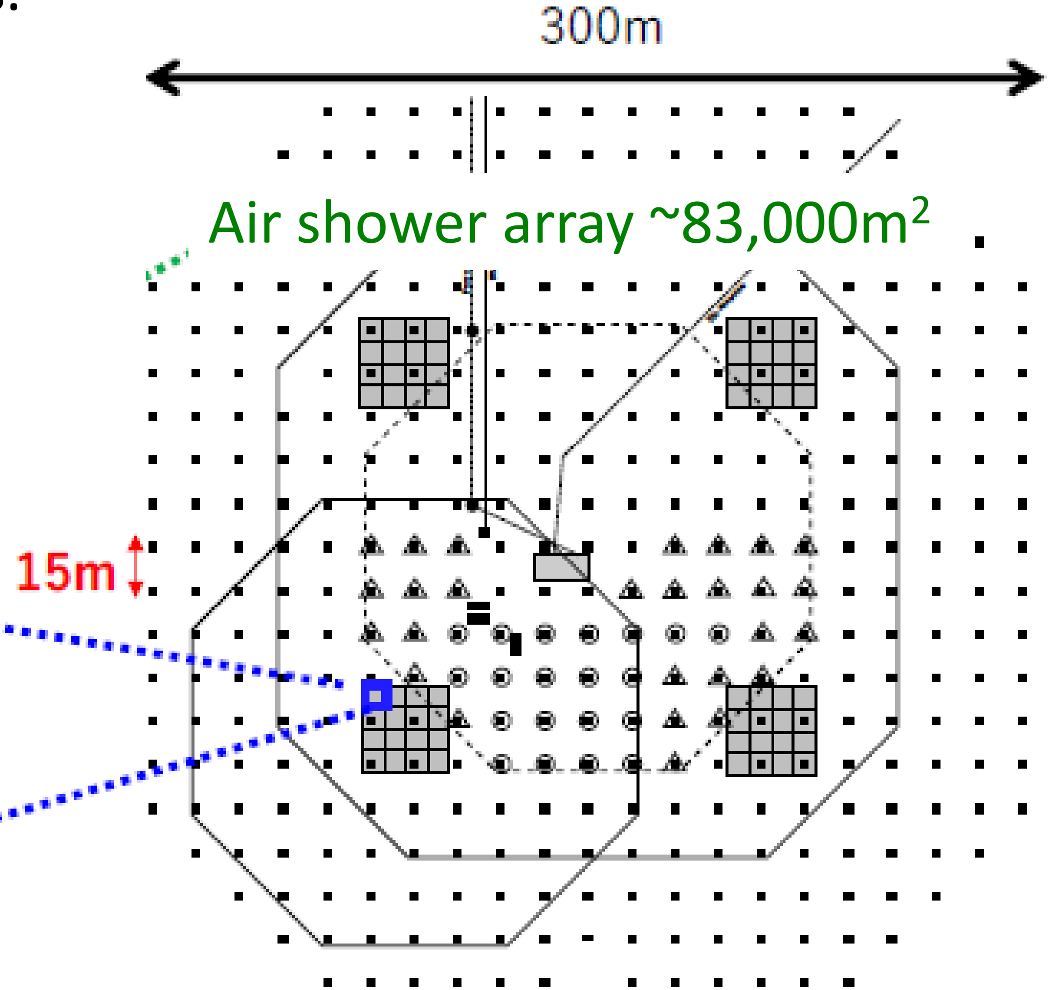
- ✓ Southern sky should be richer in 100 TeV gamma rays.
- ✓ Cosmic ray physics.

Timeline:

- ✓ ALPAQUITA (~25% ALPACA) in 2022.
- ✓ ALPACA (half) (half density) in 2022-2023.
- ✓ …

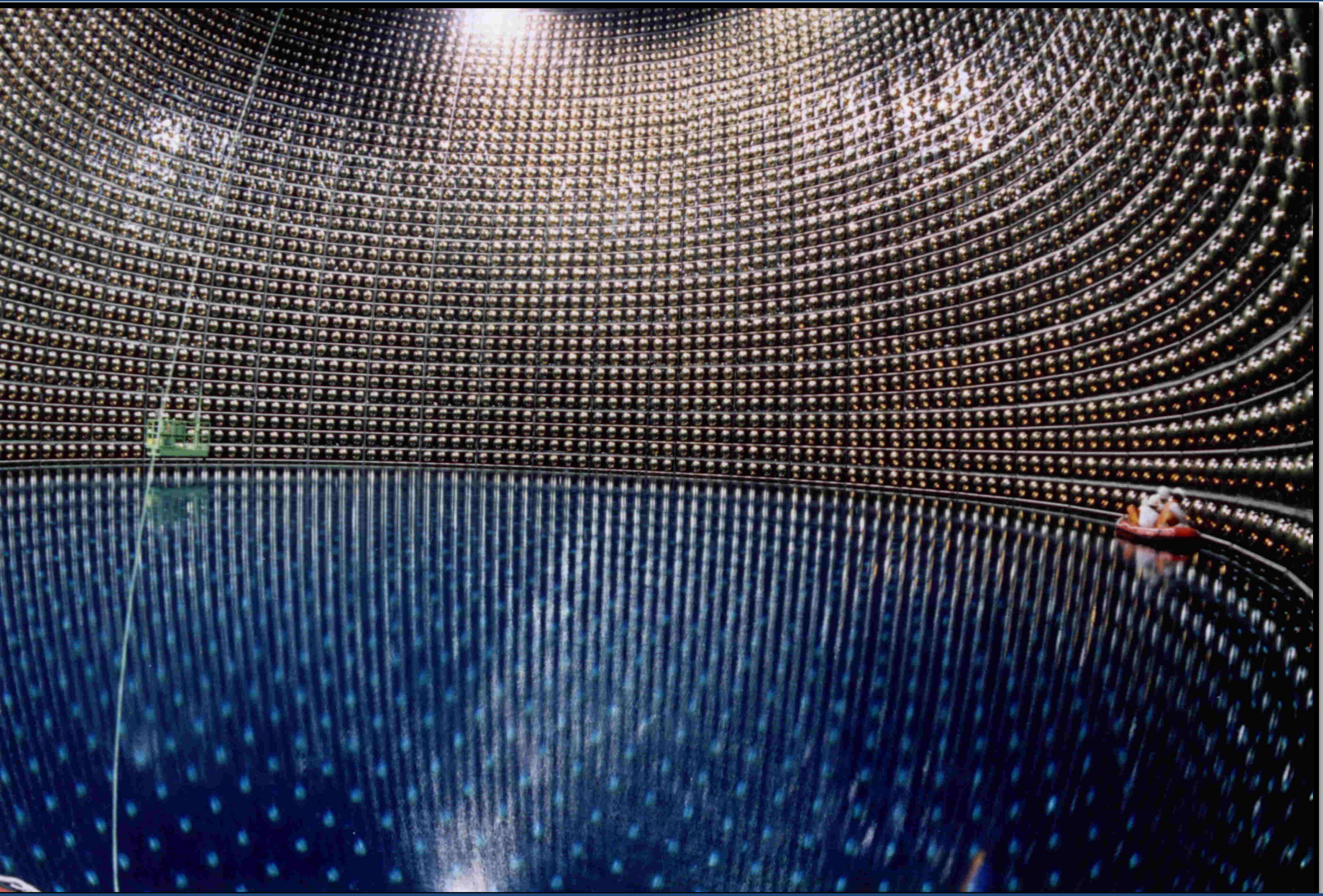


Underground Water-Chere
muon detectors ~3600m2



Neutrinos:
Super-Kamiokande and Hyper-Kamiokande

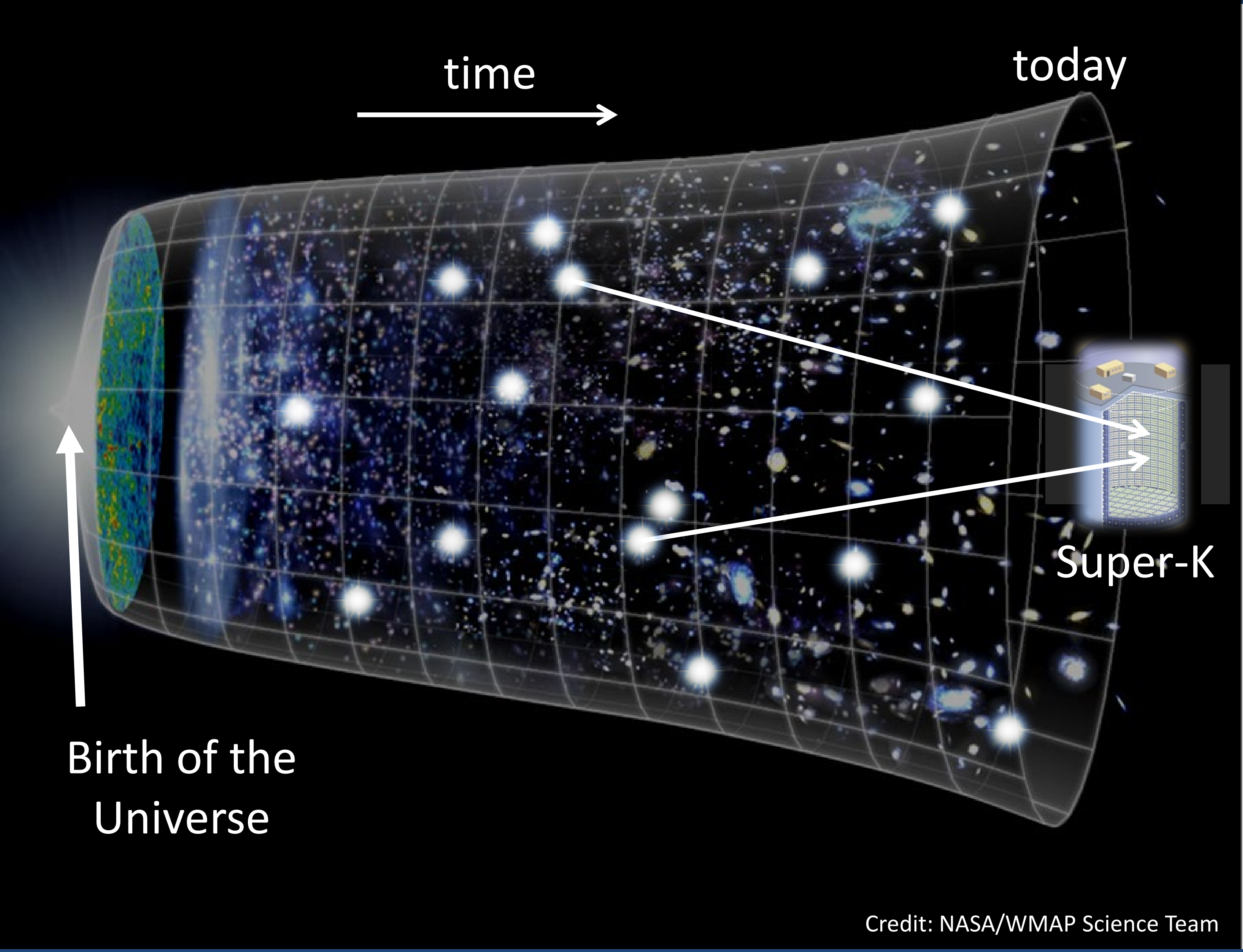
Super-Kamiokande (1996~)



<u>Super-K has contributed substantially to:</u>

- ✓ The discovery of neutrino oscillation (atmospheric neutrinos),
- ✓ Solar neutrino oscillation,
- ✓ K2K LBL experiment, and
- ✓ T2K LBL experiment.

Detecting Supernova relic neutrinos

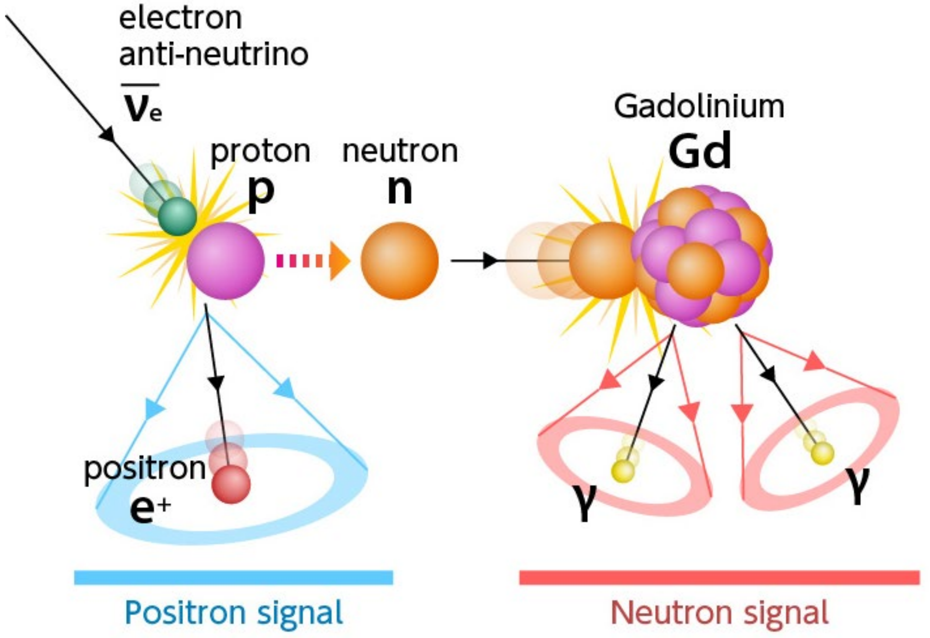


Super-Kamiokande wants to observe neutrinos produced by the Supernova explosion in the past Universe!

$\bar{\nu}_e + p \rightarrow e^+ + n$,

$n + Gd \rightarrow Gd + \gamma$'s

(total E of γ's ~8MeV)



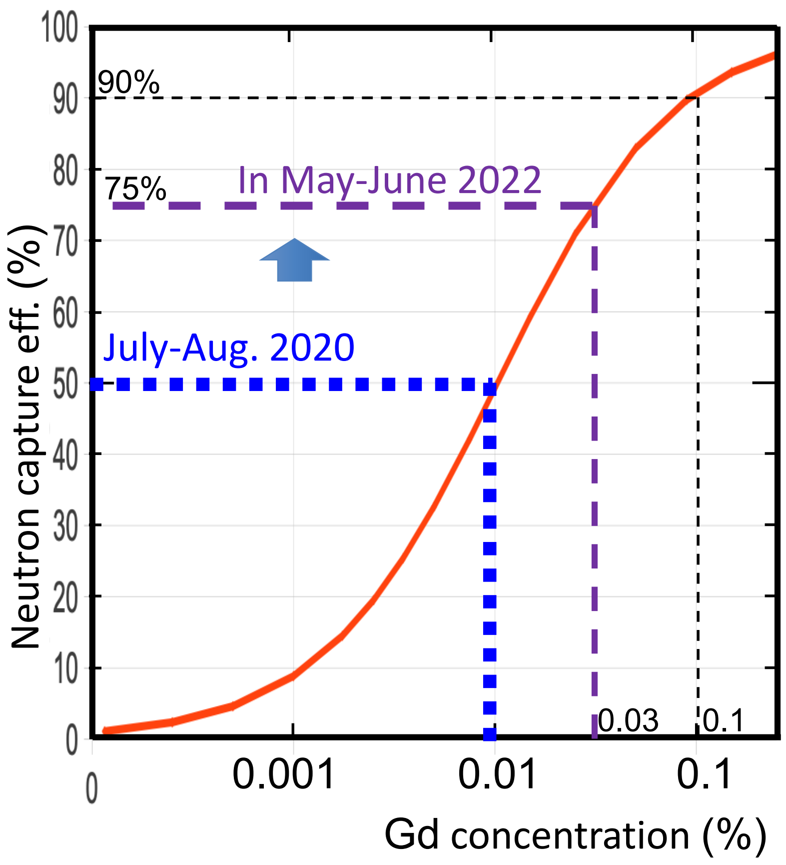
Status and plans

- <u>0.01%Gd concentration（2020)</u>
  13 tons of ultra-pure $Gd_2(SO_4)_3{\cdot}8H_2O$ was loaded.
  Neutron capture efficiency（ε): ~50%

- <u>Data taking (Sep. 2020 – May 2022)</u>
  Data taking with ε=50%. Checking water transparency, neutron capture efficiency. OK!

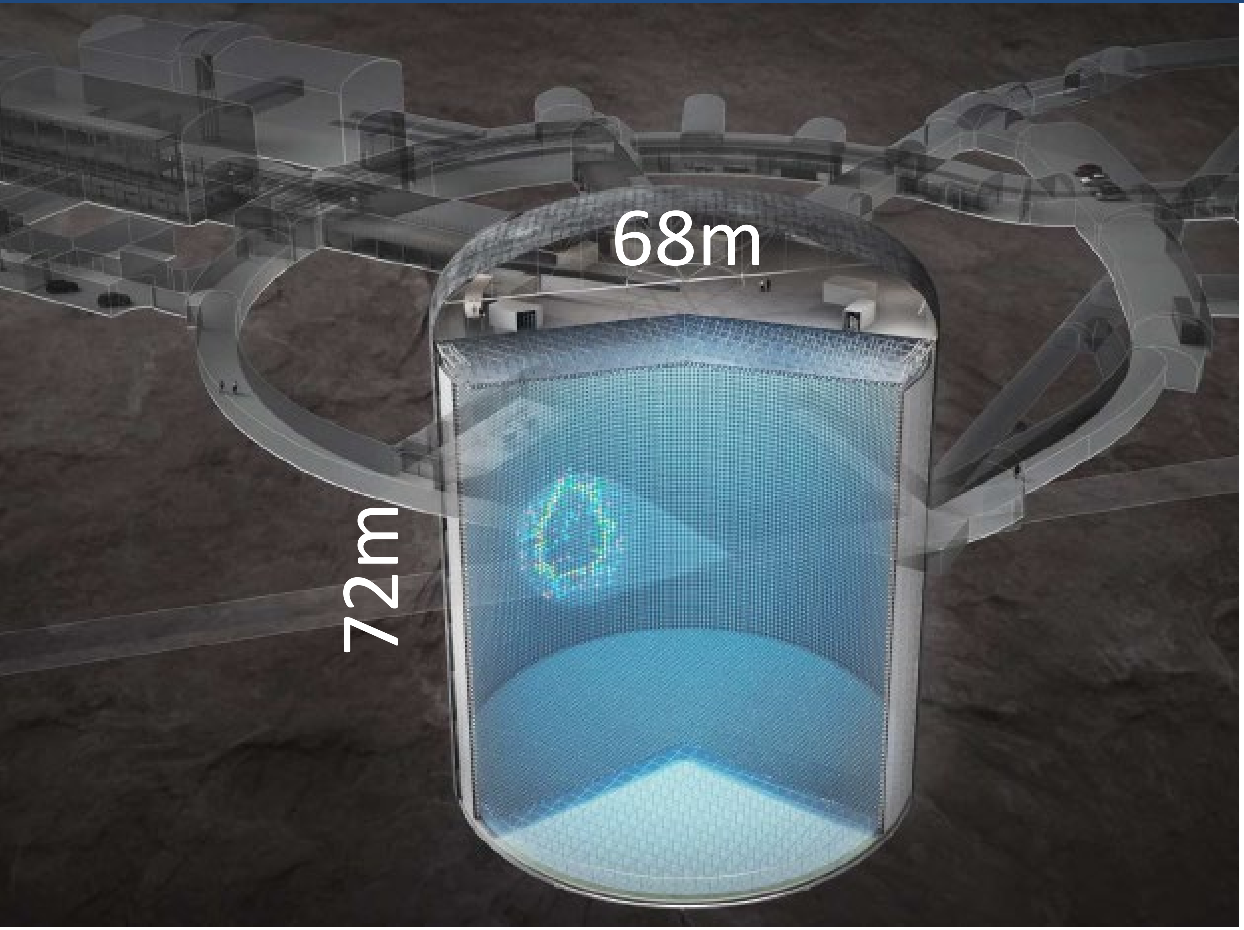
- <u>Increase Gd concentration to 0.03%</u> in May-June 2022.
  ε will increase to 75%. 26 tons of ultra-pure $Gd_2(SO_4)_3{\cdot}8H_2O$ are being produced.

- <u>Long term observation（2022-2027)</u>
  Expected number of SRN events is 5~13 in 5 years.（with ε=75%)



New water system to purify the Gd loaded water

Hyper-Kamiokande



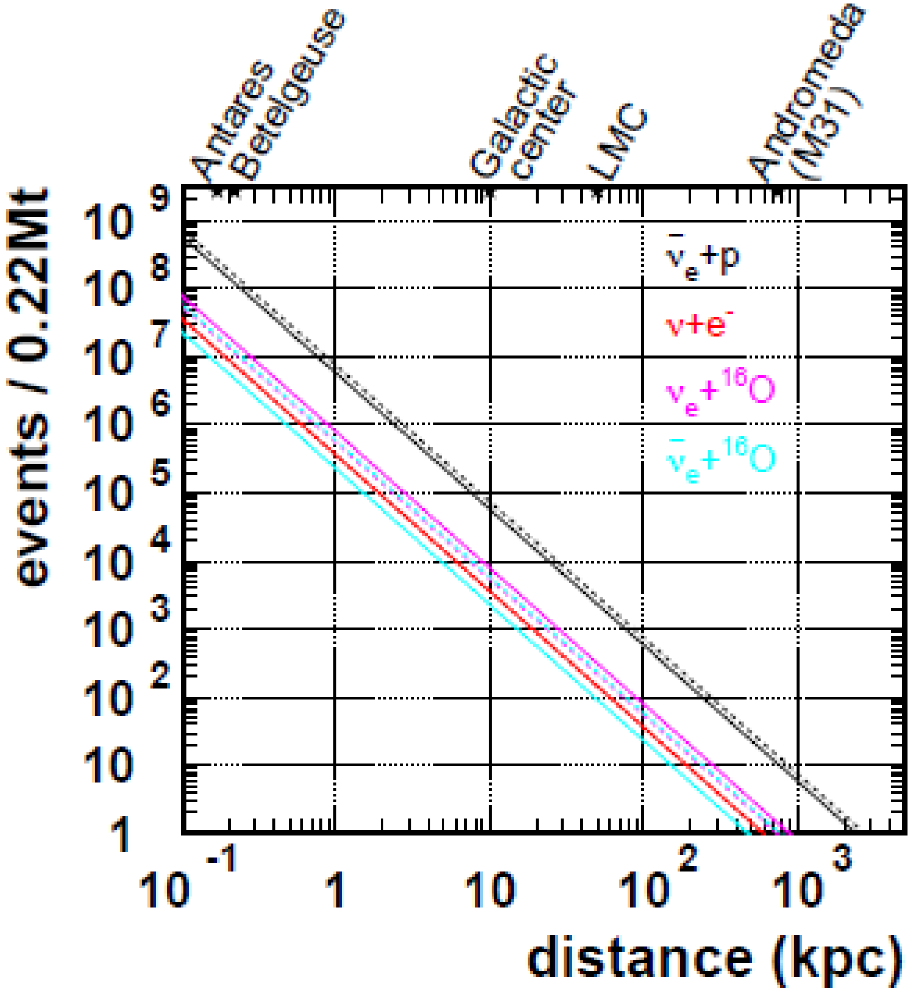
Excavation of the access tunnel to Hyper-K

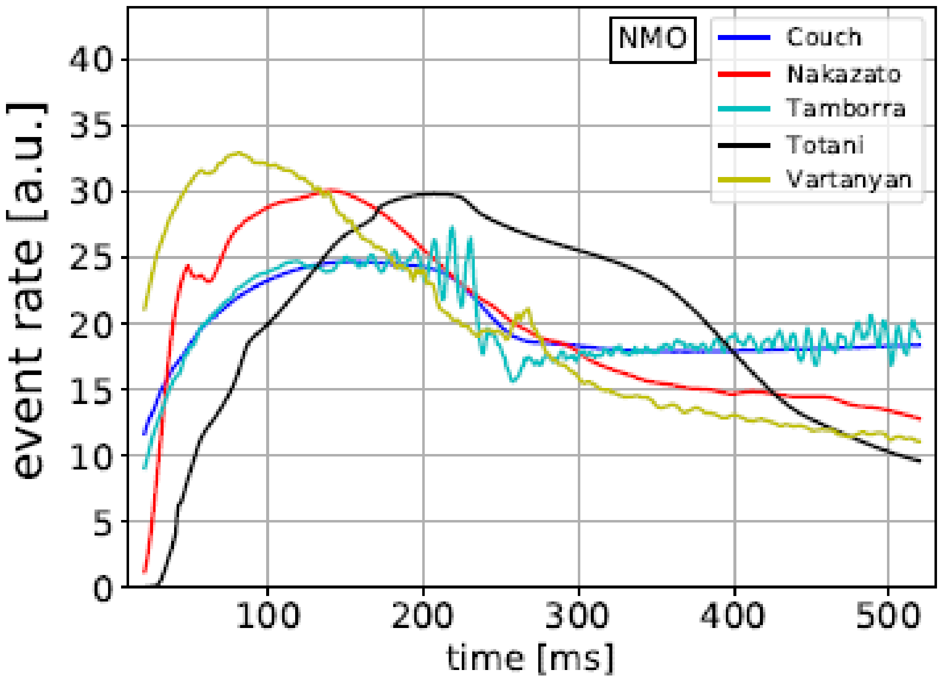
Hyper-Kamiokande collaboration
~500 members from 20 countries

- About 8 times larger (in the fiducial mass) than Super-K. (1.3 MW J-PARC neutrino beam.)
- Many important research topics in neutrino physics and astrophysics.
- The construction started in 2020. The experiment will start in ~2027!

Hyper-K and neutrino astrophysics

Hyper-K collab. Astrophys. J. 916 (2021) 1, 15





Hyper-K can distinguish between different explosion models.

Thanks to its very large mass, Hyper-K will observe many neutrinos events. (If a supernova explodes at the Galactic center, $O(10^5)$ events will be observed.)

Also multi-messenger observation with GW and electromagnetic telescopes should be very .important to really understand the supernova explosion mechanism.

Summary:
Very exciting multi-messenger astronomy is starting.
ICRR would like to contribute to the multi-messenger astronomy.