

Hyper-Kamiokande experiment

ILANCE, LLR, LPNHE, OMEGA

IN2P3 physicists and engineers

ILANCE: M. Gonin, G. Pronost (postdoc)

LLR: A. Afiri, M. Buizza-Avanzini, O. Drapier, F. Gastaldi, M. Louzir, T. Mueller, J. Nanni, P. Paganini, B. Quilain, A. Beauchene (PhD student)

LPNHE: A. Blondel, J. Dumarchez, C. Giganti, M. Guigue, M. Martini, B. Popov, S. Russo, V. Voisin, M. Zito, W. Saenz (postdoc ANR), L. Mellet (PhD student), C. Dalmazzone (PhD student) + one more ANR postdoc starting from 2023

OMEGA: S. Callier, P. Dinaucourt, S. Conforti, F. Dulucq, L. Raux, C. de la Taille

APC: C. Volpe (theoretician)

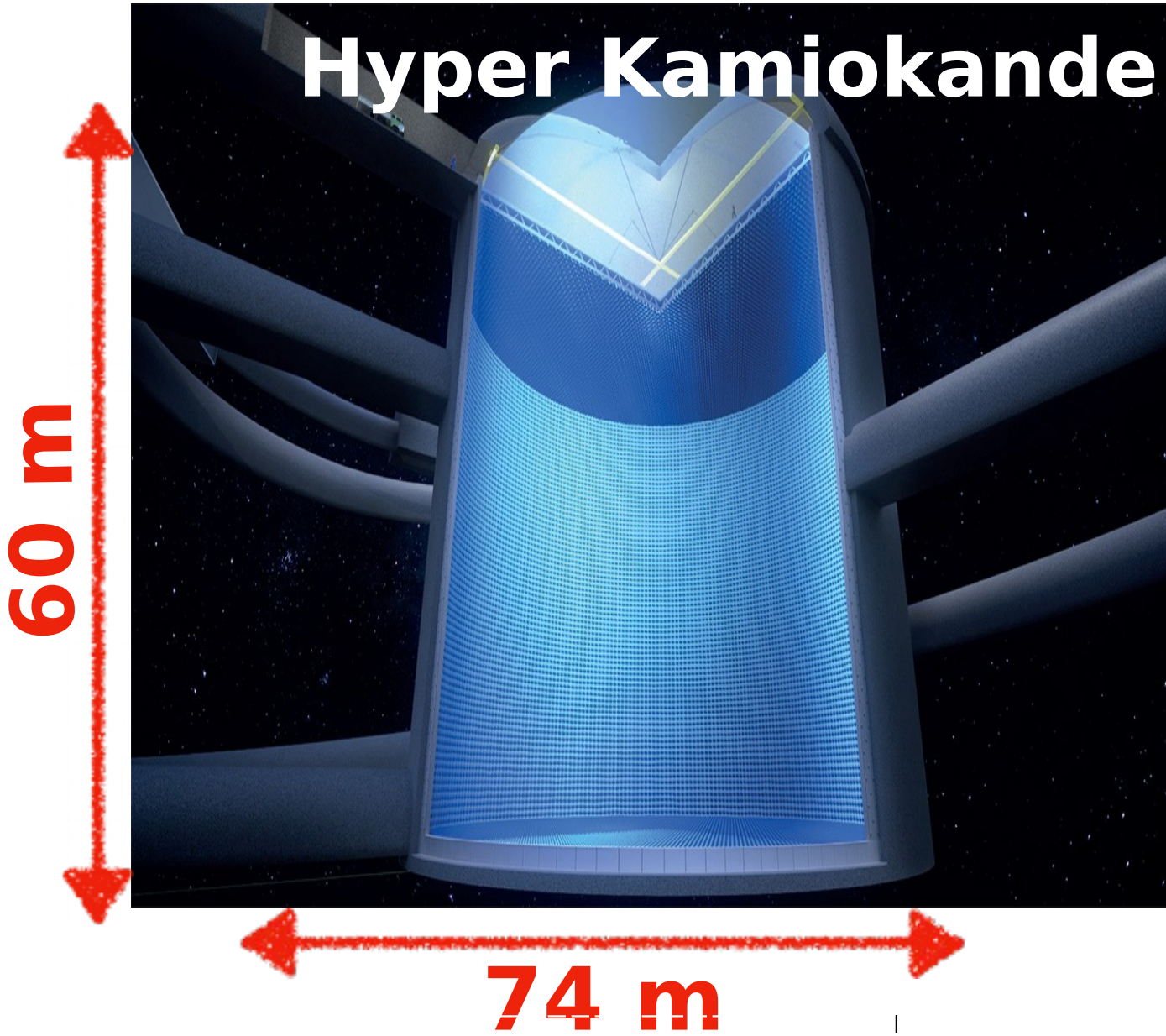
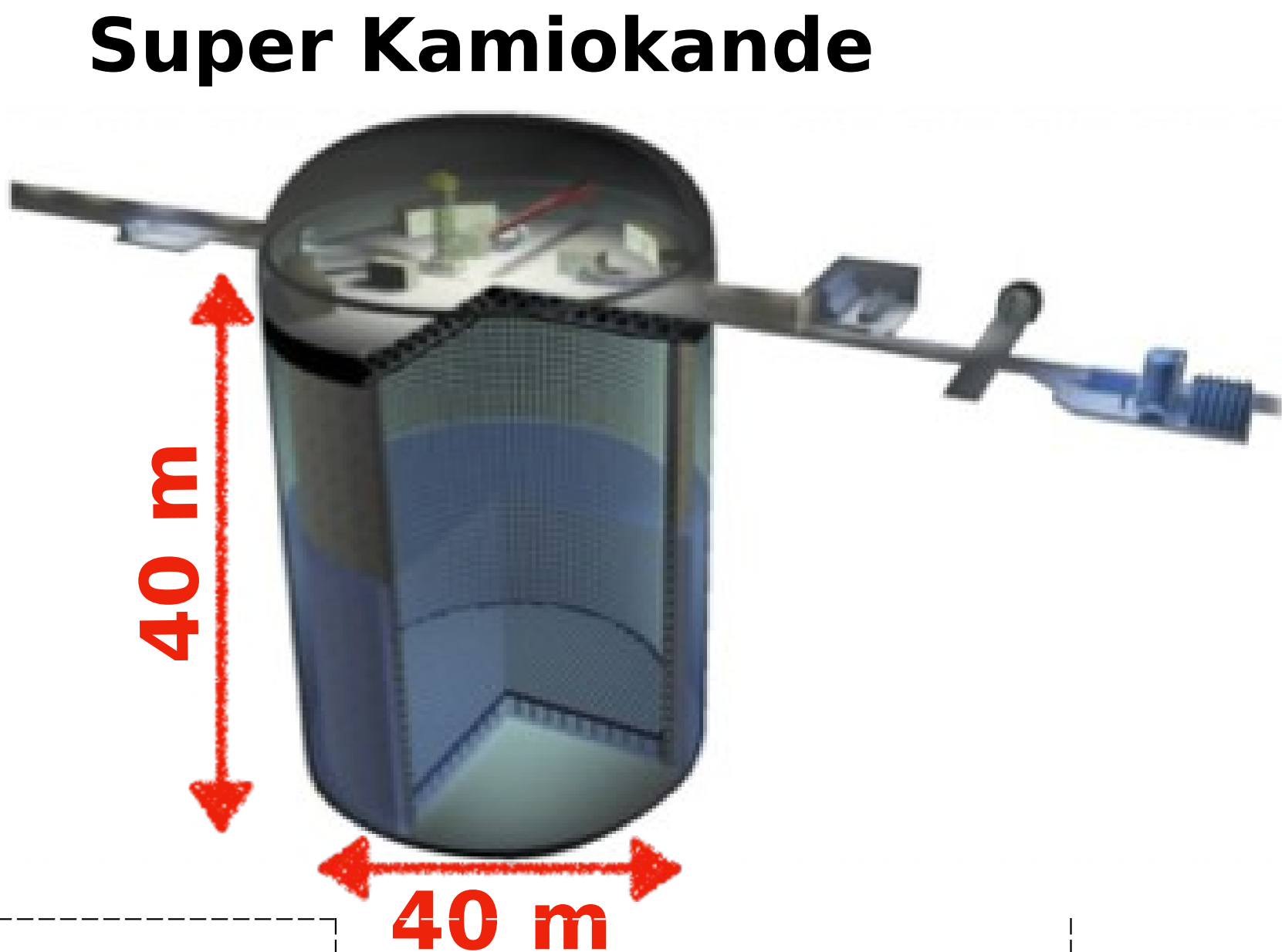
Natural continuation of our participation in the Japanese neutrino program (T2K and SK)
In close collaboration with CEA-IRFU colleagues

Hyper-Kamiokande in Japan



- Third generation Water Cherenkov detector in Japan
- Based on the experience from T2K and Super-Kamiokande
- 295 km and 2.5° off-axis w.r.t. existing neutrino beam from J-PARC
- Existing near detector ND280 currently being upgraded for T2K-II
- Vast non-accelerator scientific program

Hyper-Kamiokande vs Super-Kamiokande



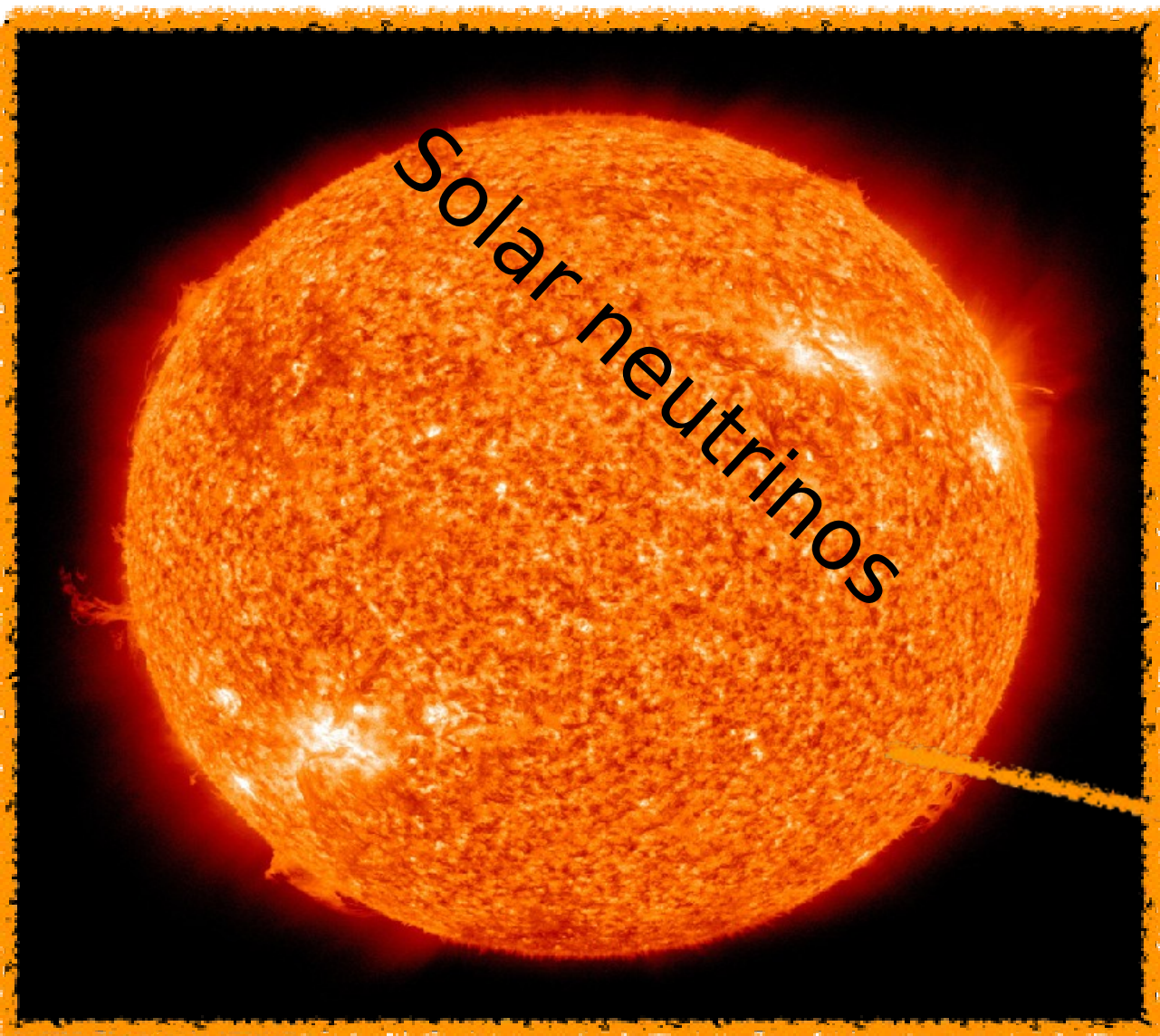
	Super Kamiokande	Hyper Kamiokande
Site	Mozumi-yama	Tochibora-yama
Number of ID 20'' PMTs	11 129	>20,000
Photo-coverage	40 %	>20%
Single-photon efficiency/PMT	~12%	~24%
Dark rate/PMT	~4 kHz	~4kHz
Time resolution of 1 photon	~3 ns	~1.1 ns
Total/fiducial mass (kton)	50 / 22.5	260 / 187

Fiducial volume x8:
→ **non-beam ν physics**

Beam neutrino event rate x 20:
→ **beam ν physics**

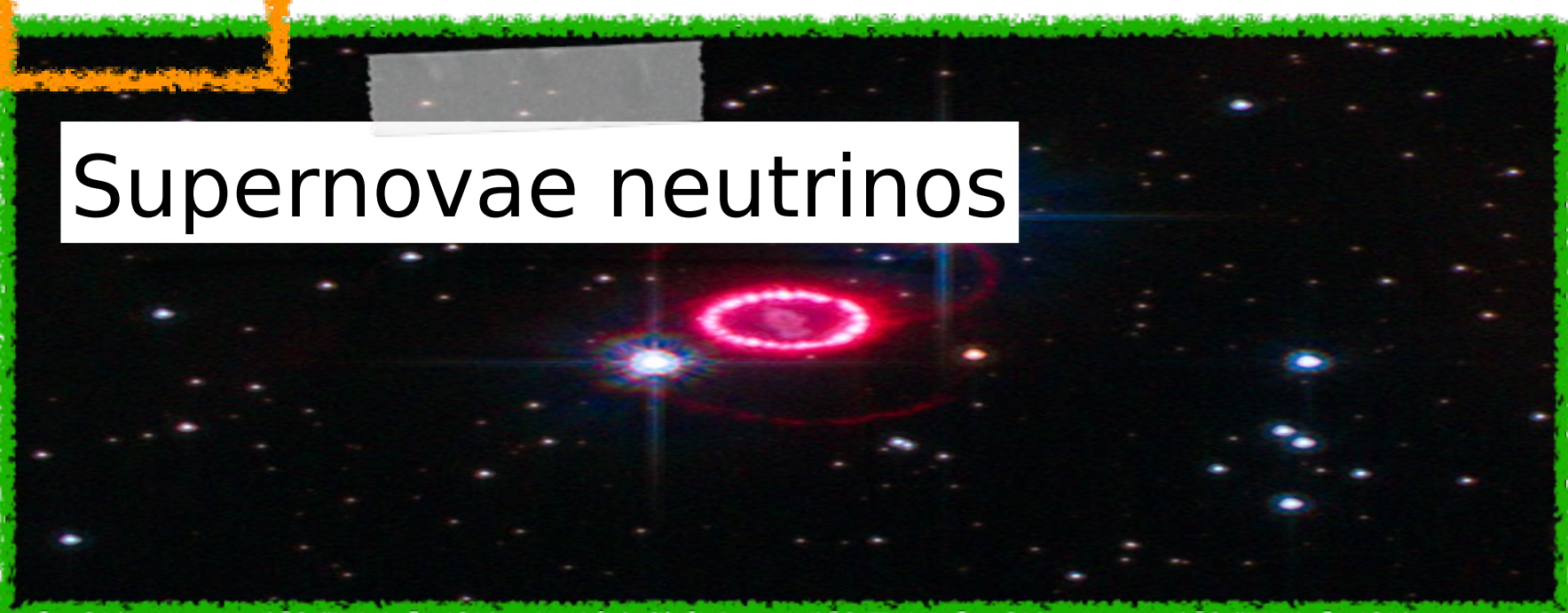
Start operations in 2027 with 240 kt.MW and an assumed runtime 10^7 s per year

Hyper-Kamiokande physics program

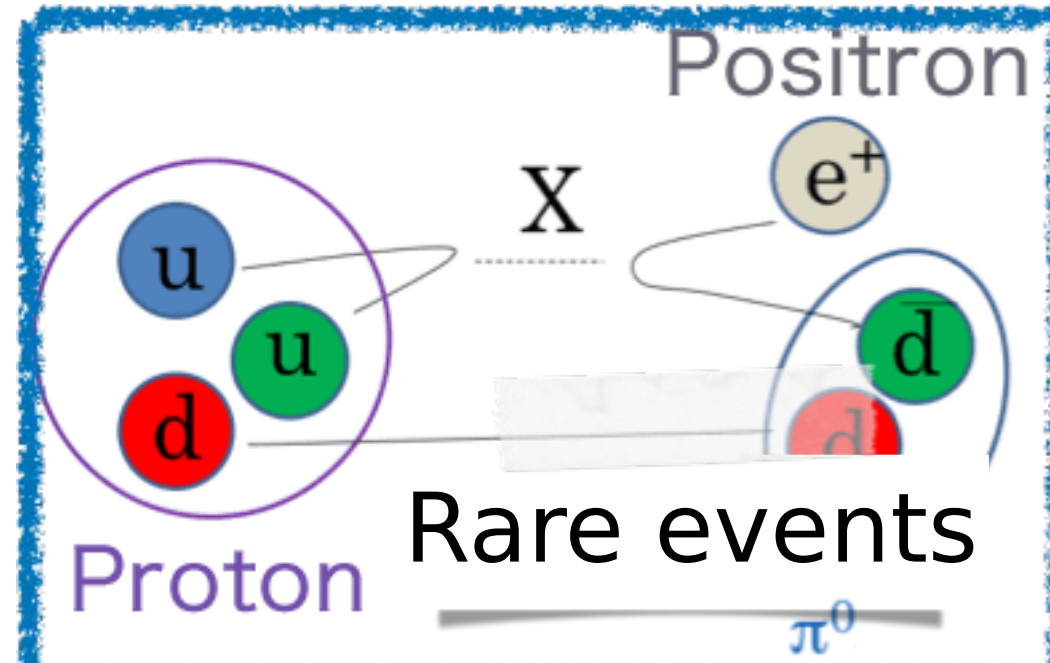


ν_e

MSW effect
Non-standard interactions

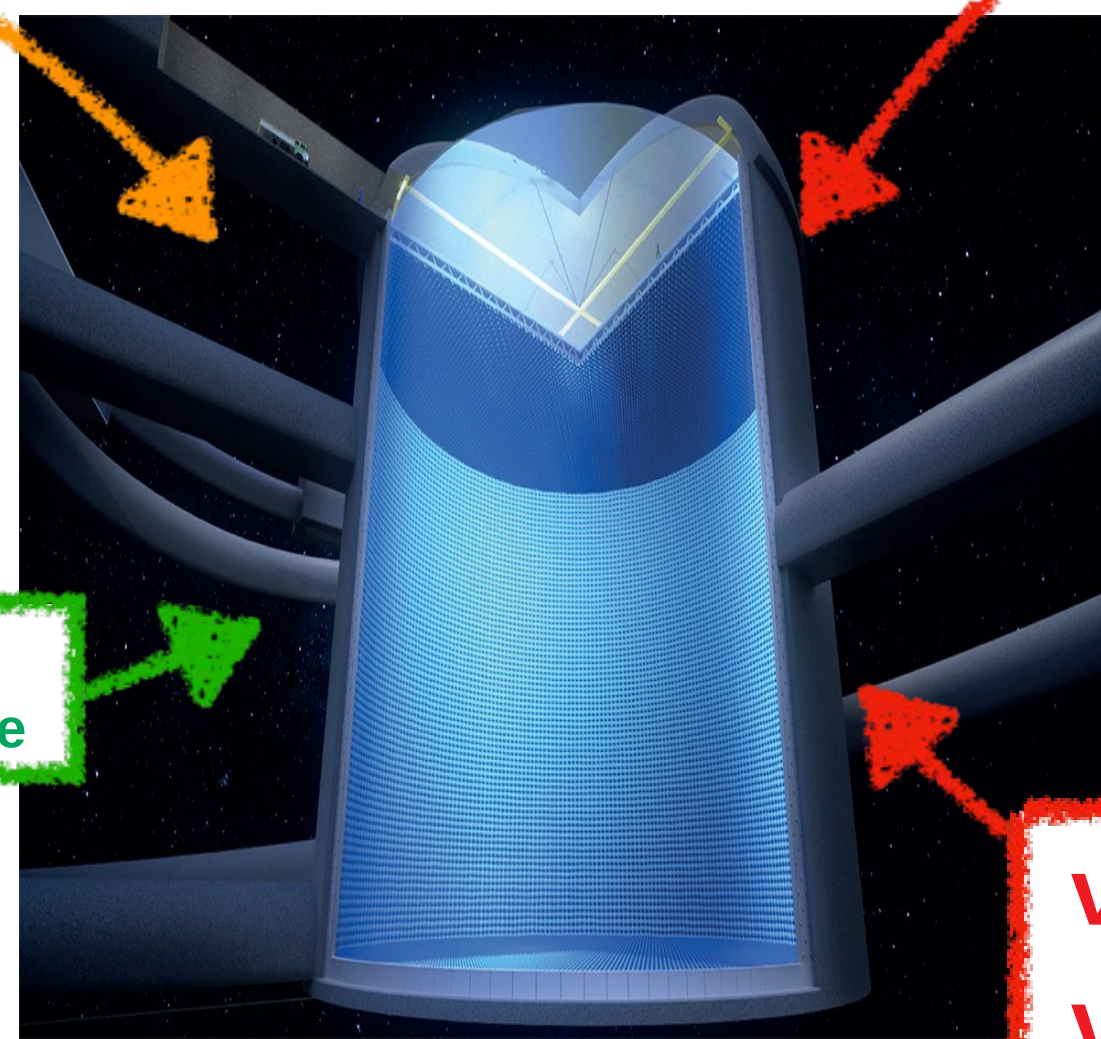


- Transient SNv : constrain SN profile models
- Relic SNv : constrain cosmic star formation



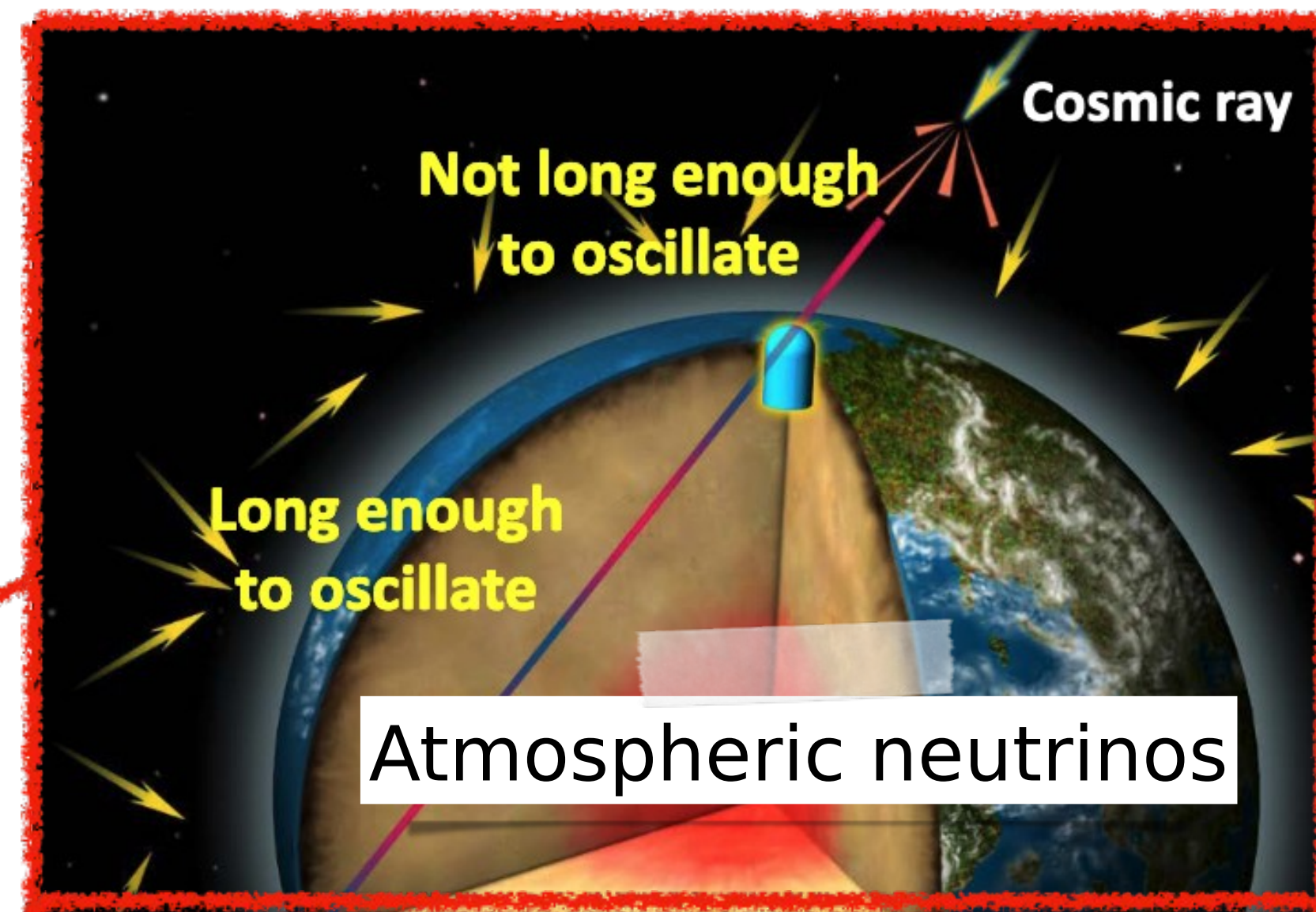
- **Probe Grand Unified Theories via p-decay or n- \bar{n} oscillation**

$\nu_e \bar{\nu}_e$
 $\nu_\mu \bar{\nu}_\mu$



$\bar{\nu}_e$

$\nu_e \bar{\nu}_e$
 $\nu_\mu \bar{\nu}_\mu$



Atmospheric neutrinos

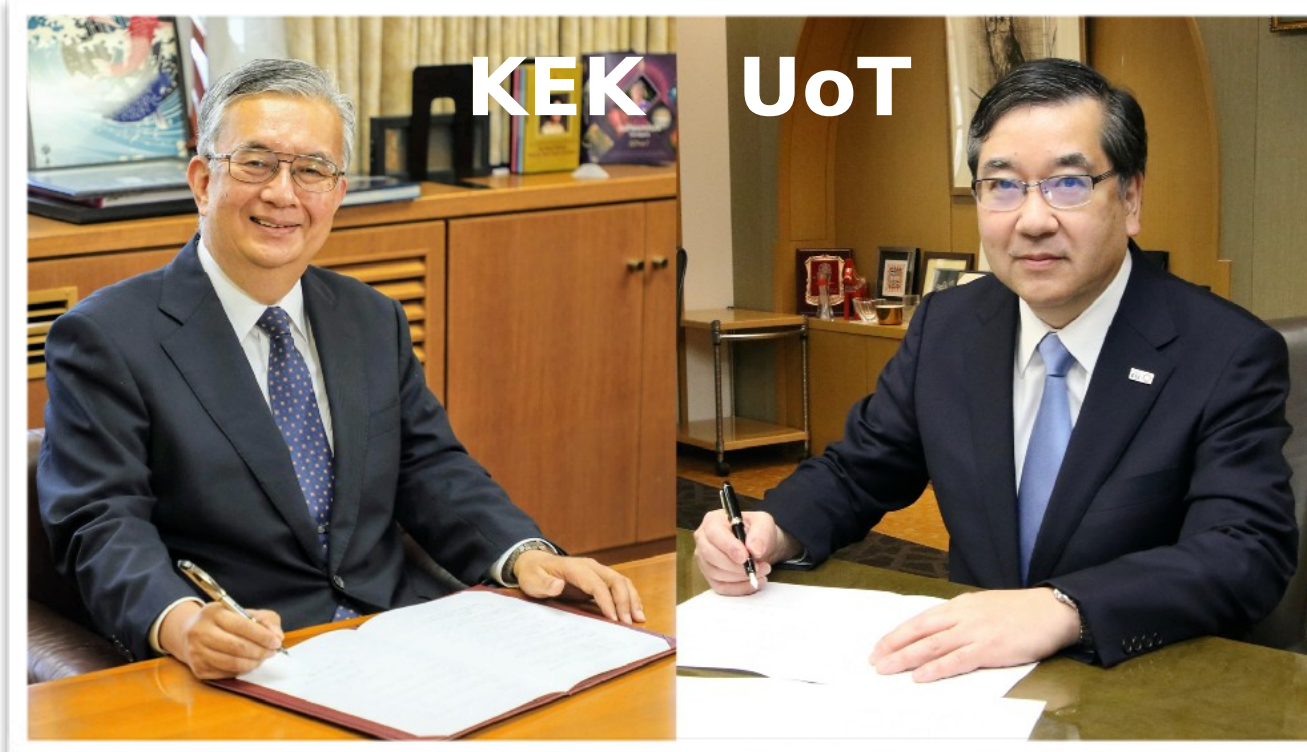
- **Observe CP violation for leptons at 5σ**
- **Precise measurement of δ_{CP}**
- **High sensitivity to ν mass ordering**



J-PARC accelerator neutrinos

Experiment approval: key dates

Conclusions of 2018 SC : “Le projet n’est pas actuellement approuvé au Japon et il n’y a pas suffisamment d’informations quant à l’organisation du projet pour envisager et discuter des participations directes à HK.”

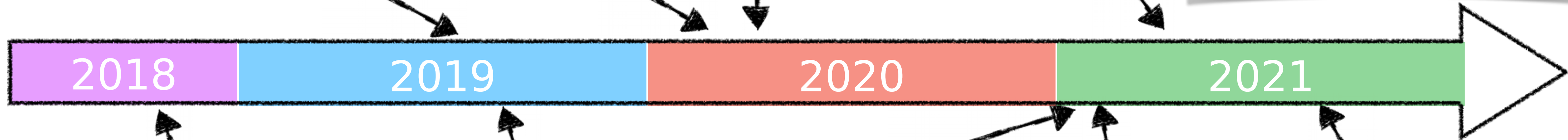
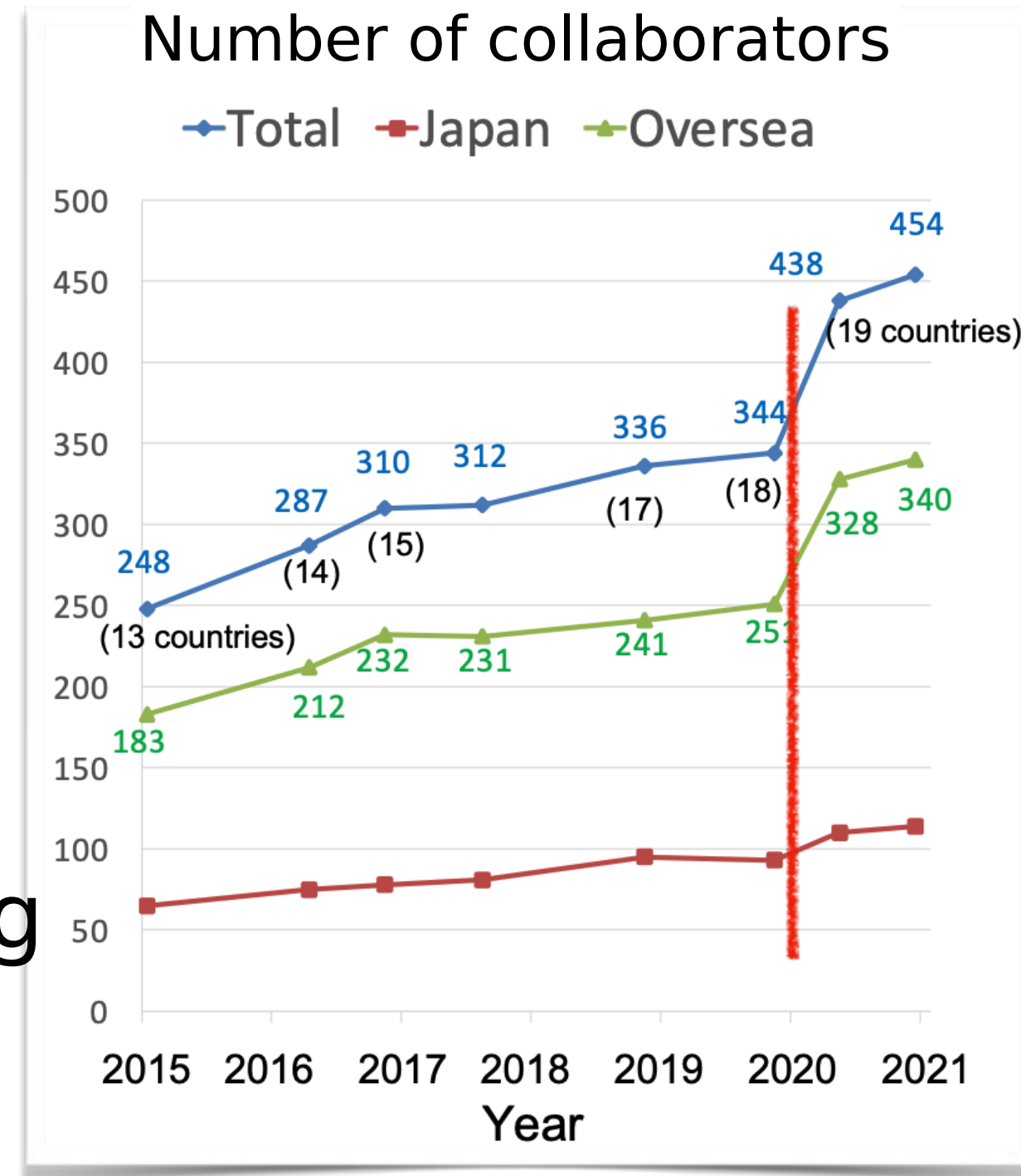


May 2020:

Aug. 2019: MEXT approval of HK project

Feb. 2020: HK budget approved

May 2021: Groundbreaking ceremony



Oct. 2018: IN2P3 CS discussing HK

Oct. 2019: LPNHE CS approved HK

Jan. 2021: CEA CS approved HK

March 2021: LLR CS approved HK

Oct. 2021: IN2P3 CS discussing HK

Conclusions of the 2021 SC

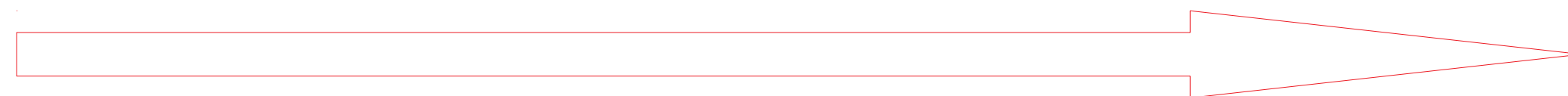
6.3. Avis du Conseil

La dernière présentation de la contribution de l'IN2P3 à HK en session du Conseil Scientifique de l'IN2P3 est assez récente (octobre 2018). En octobre 2021, le Conseil constate une évolution positive remarquable au cours des deux dernières années :

- Le projet HK est approuvé par le gouvernement japonais en août 2019, le budget (500 M\$) est voté en février 2020, et le début de la prise de données est confirmé pour 2027 ;
- Deux laboratoires de l'IN2P3 (LPNHE, LLR) et le CEA, soutenus par leurs conseils scientifiques respectifs, rejoignent le projet HK, en octobre 2019 pour le LPNHE, en janvier 2021 pour le CEA, et en mars 2021 pour le LLR.

...

Le Conseil souligne cependant qu'un engagement technique direct sur le détecteur lointain de HK est requis pour confirmer et valider le ticket d'entrée de l'IN2P3 dans HK⁴, et considère que la participation centrale proposée par le LPNHE et le LLR en collaboration avec OMEGA sur le digitaliseur HKROC et sur le système de distribution d'horloge répond à cette condition dans une enveloppe budgétaire raisonnable. Le Conseil note également que les équipes de l'IN2P3 proposent une réflexion pour contribuer aux coûts d'opération à travers la participation du CC-IN2P3.



**RD4HK initiated in 2022
(Benjamin's talk)**

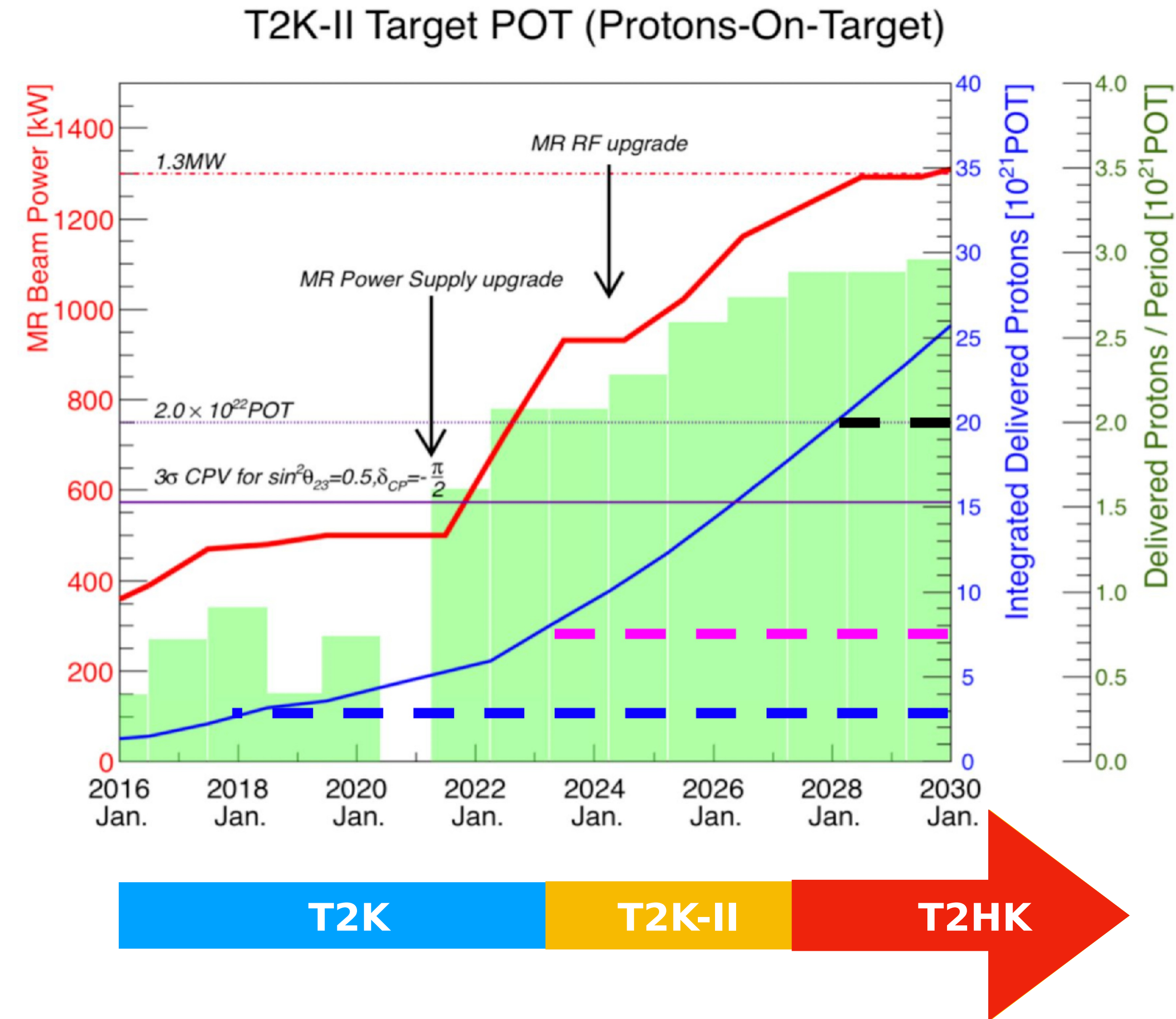
Tokai to HK: heritage from T2K

Accelerator upgrade

Power increase (500kW --> 1.3 MW)

x2.7 more stats per s (wrt T2K-I)

$\nu / \bar{\nu}$ flux uncertainty < 5% thanks to
NA61/SHINE hadroproduction measurements



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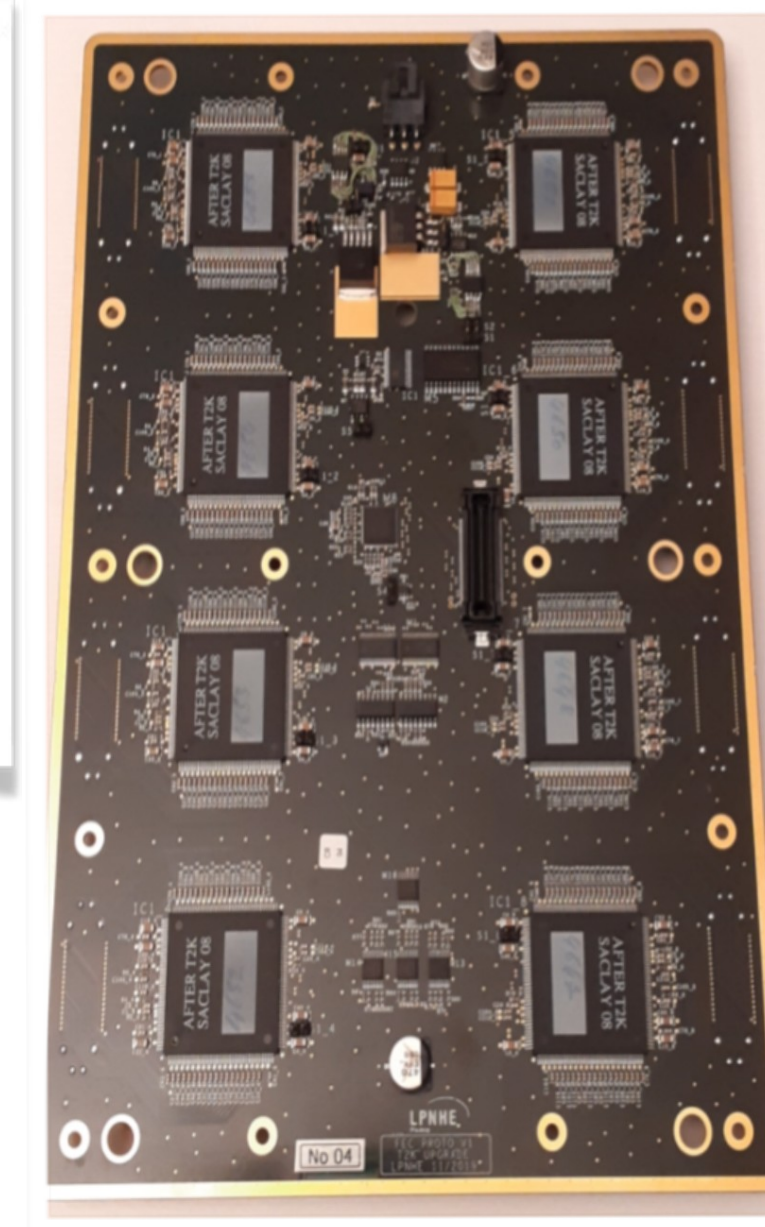
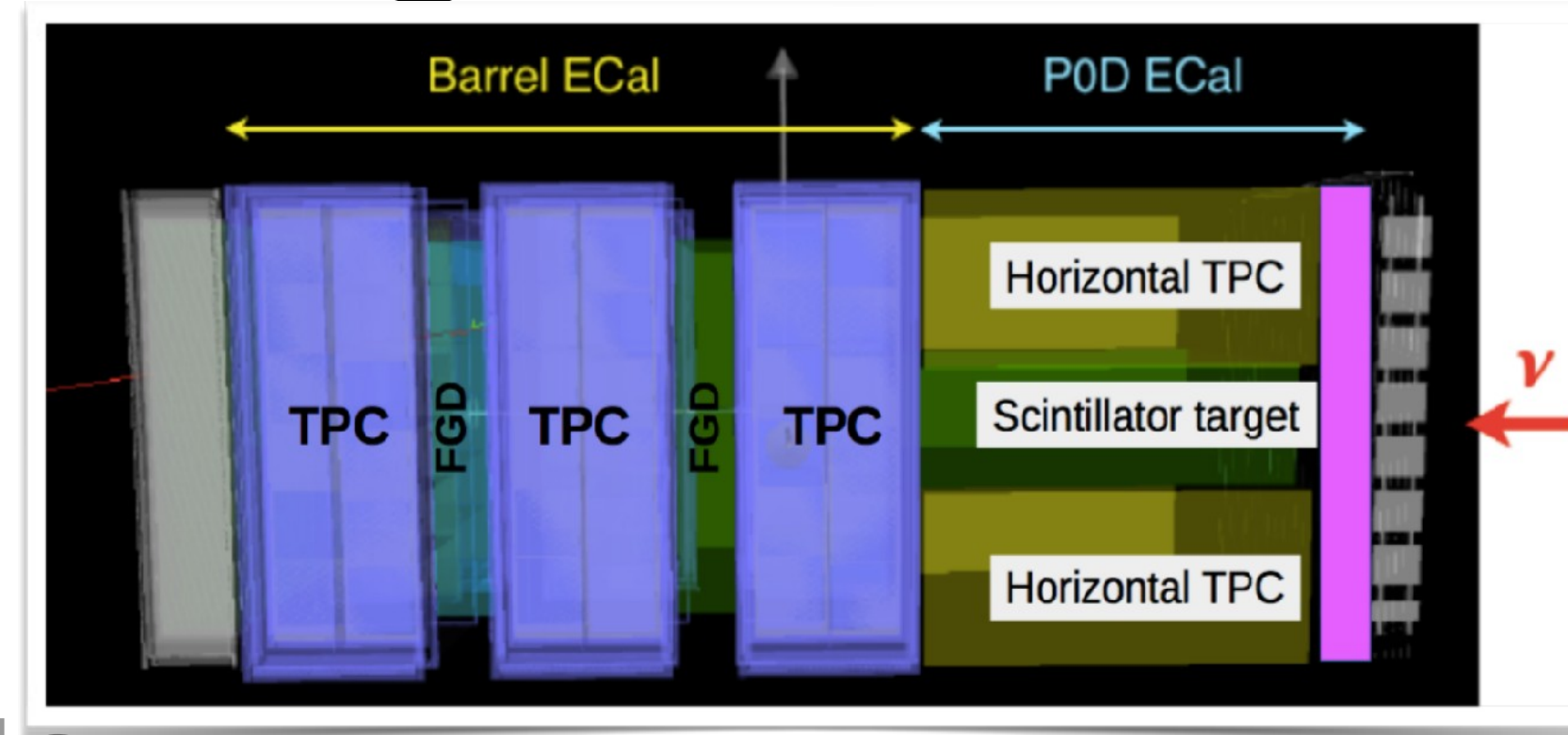
Magnetized near detector @280 m (ND280)

Used for T2K Oscillation Analysis for >10 years

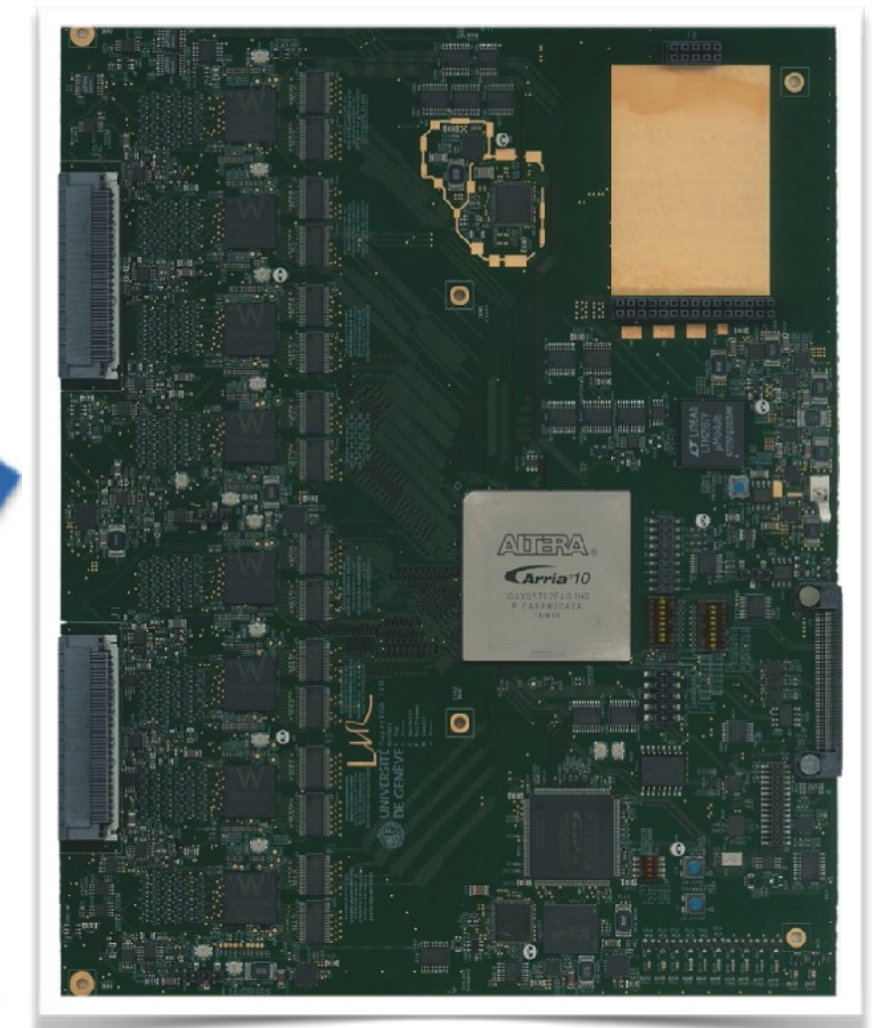
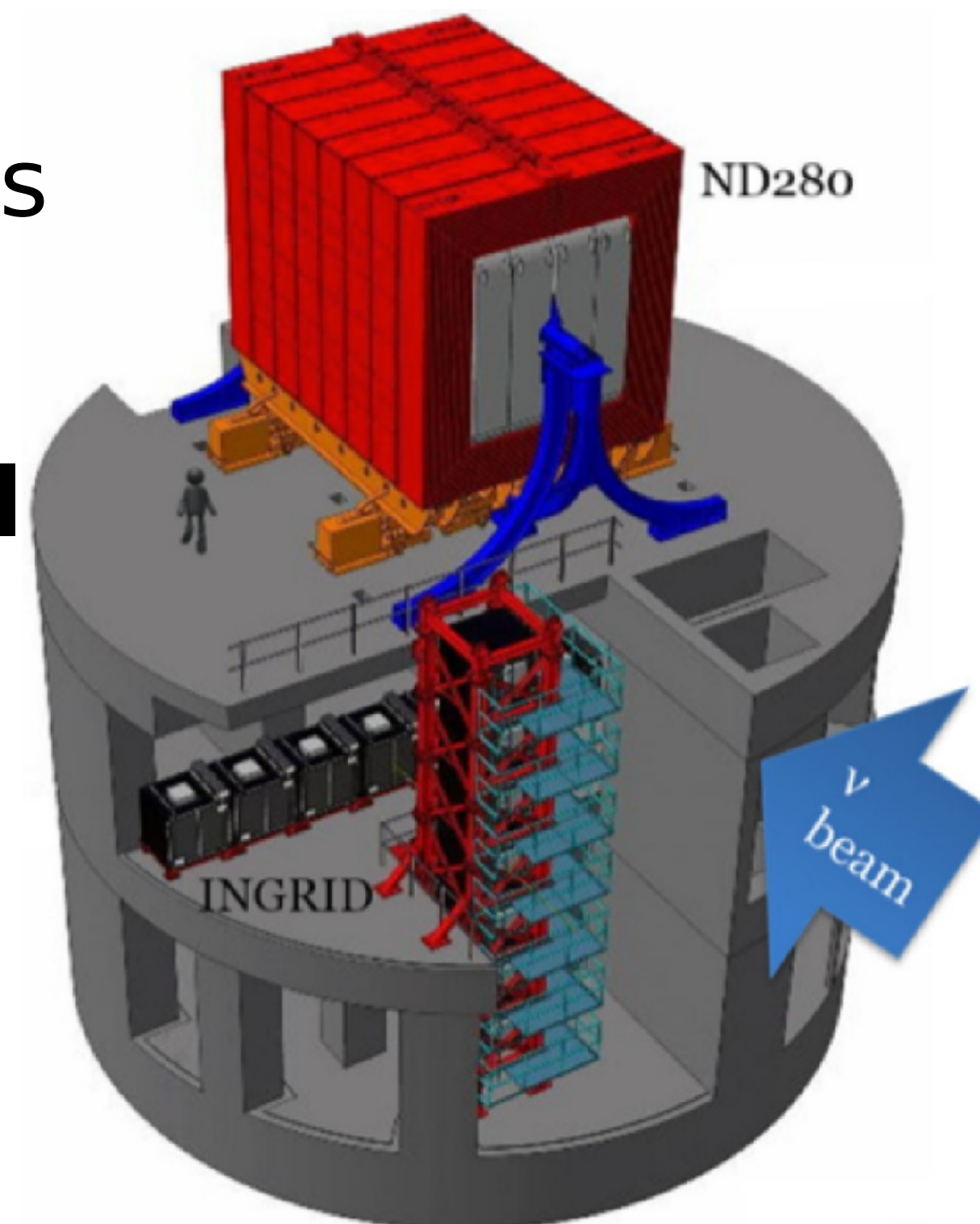
Being upgraded now for T2K-II

(crucial contributions and strong support from IN2P3)

**Systematics uncertainties under control
from Day-1 of HK**



FEC for HA-TPC readout



FEB for SuperFGD readout

Tokai to HK: what will be new

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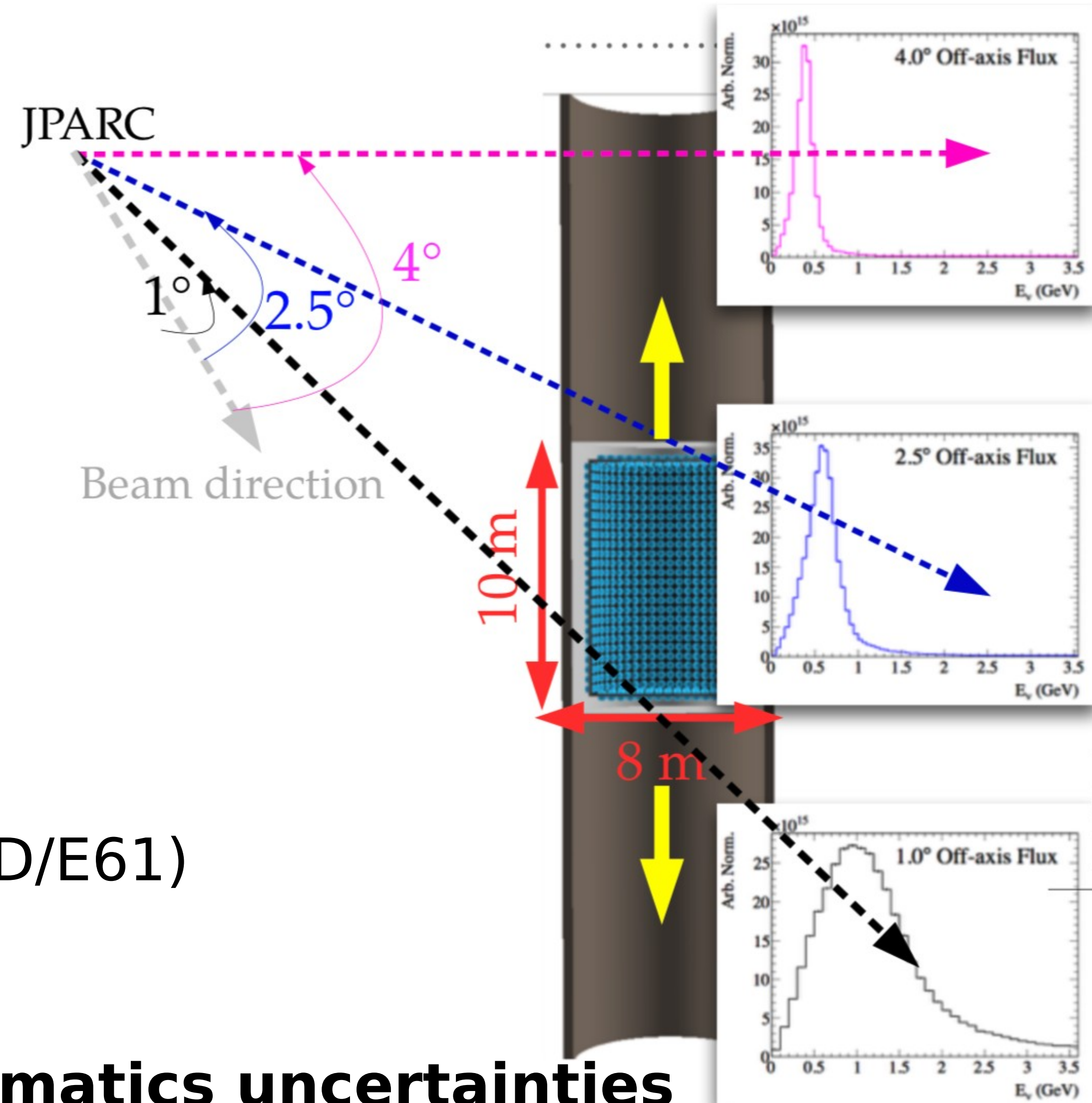
Intermediate Water Cherenkov Detector (IWCD/E61)

Measure ν interactions on Water

NEW High stats. sample of ν_e interactions

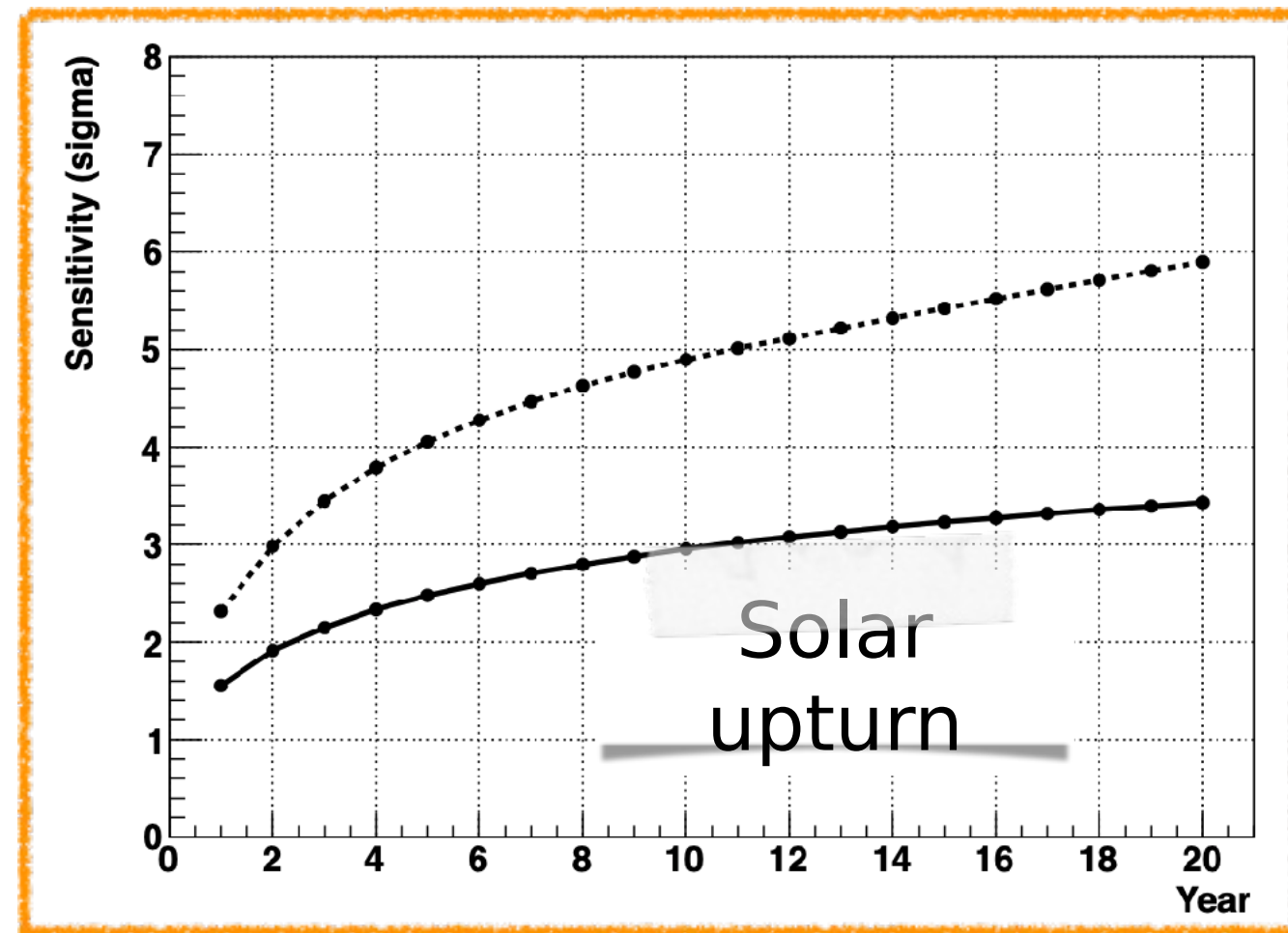
Needed to reach final HK goal for systematics uncertainties

(if IWCD is delayed, ND280 will be the only near detector on day 1 of HK)

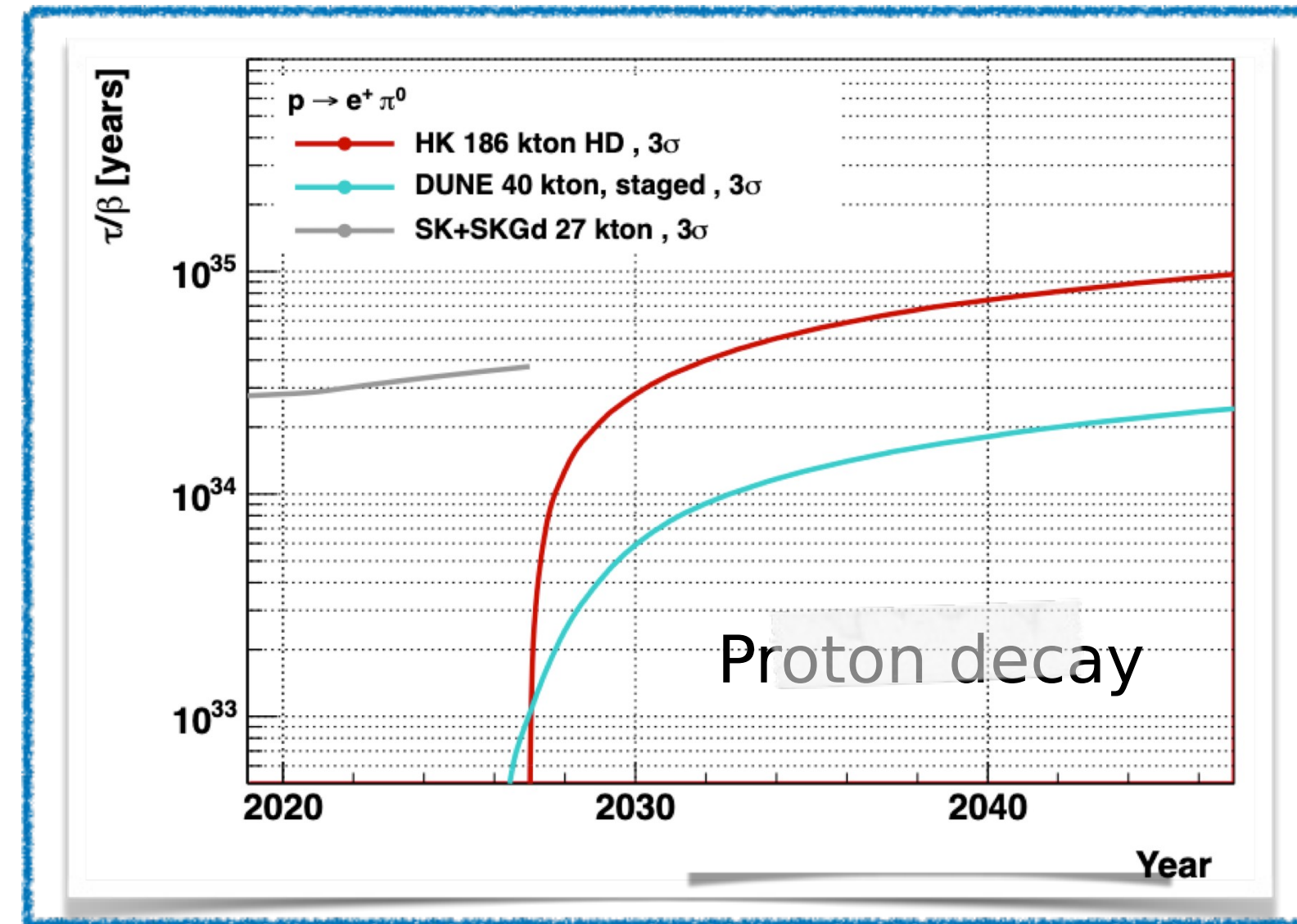


Hyper-Kamiokande Physics

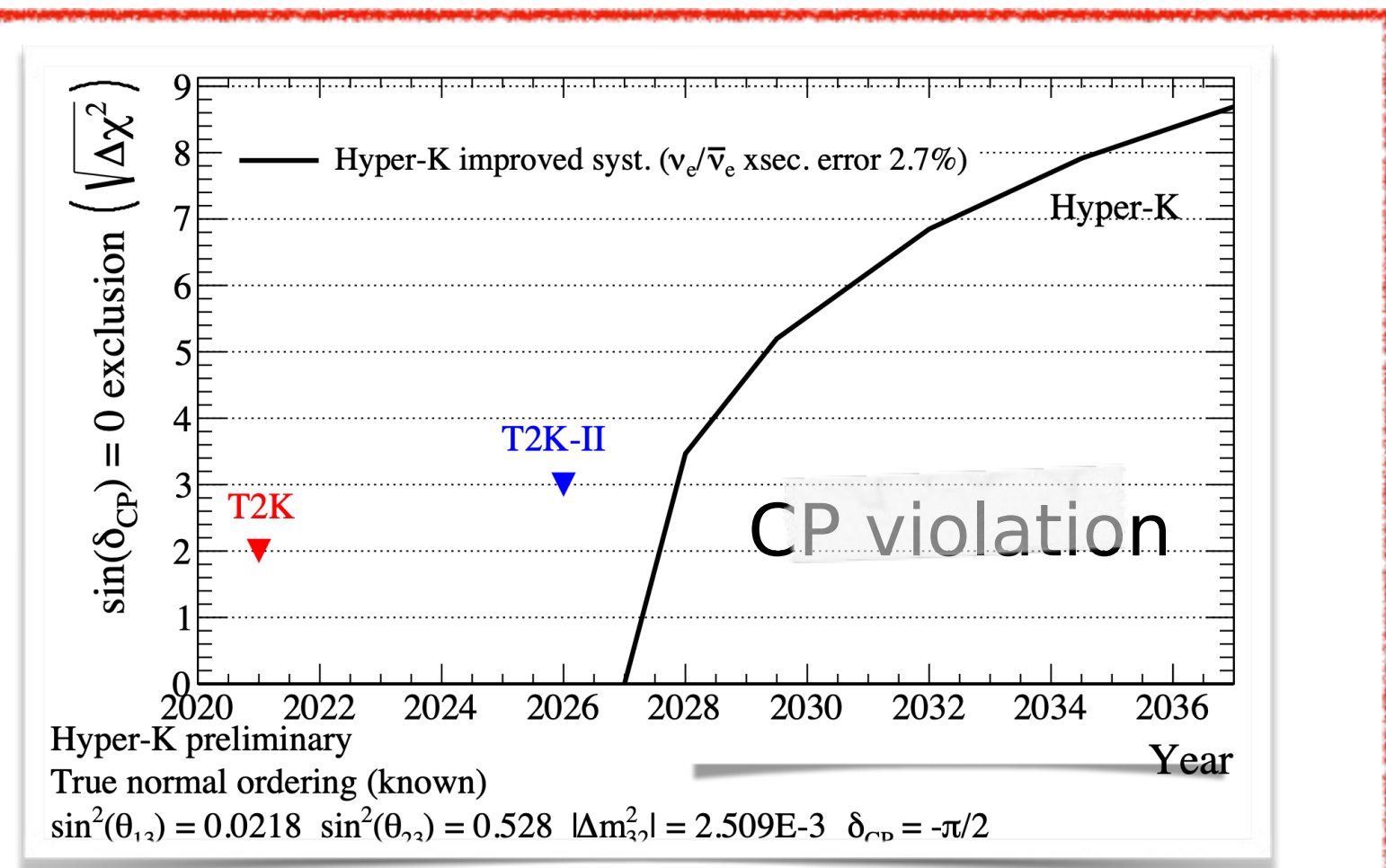
Solar physics



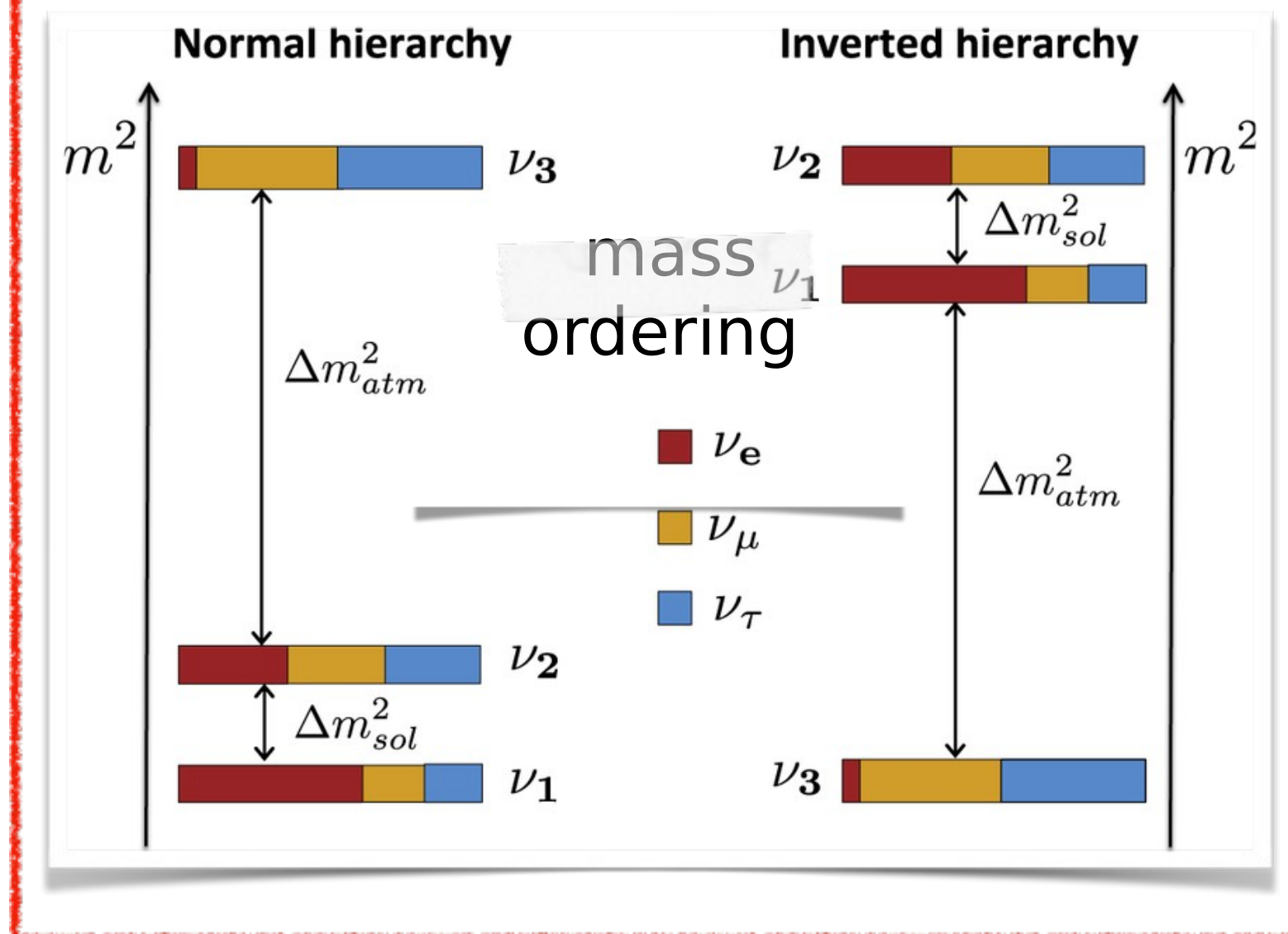
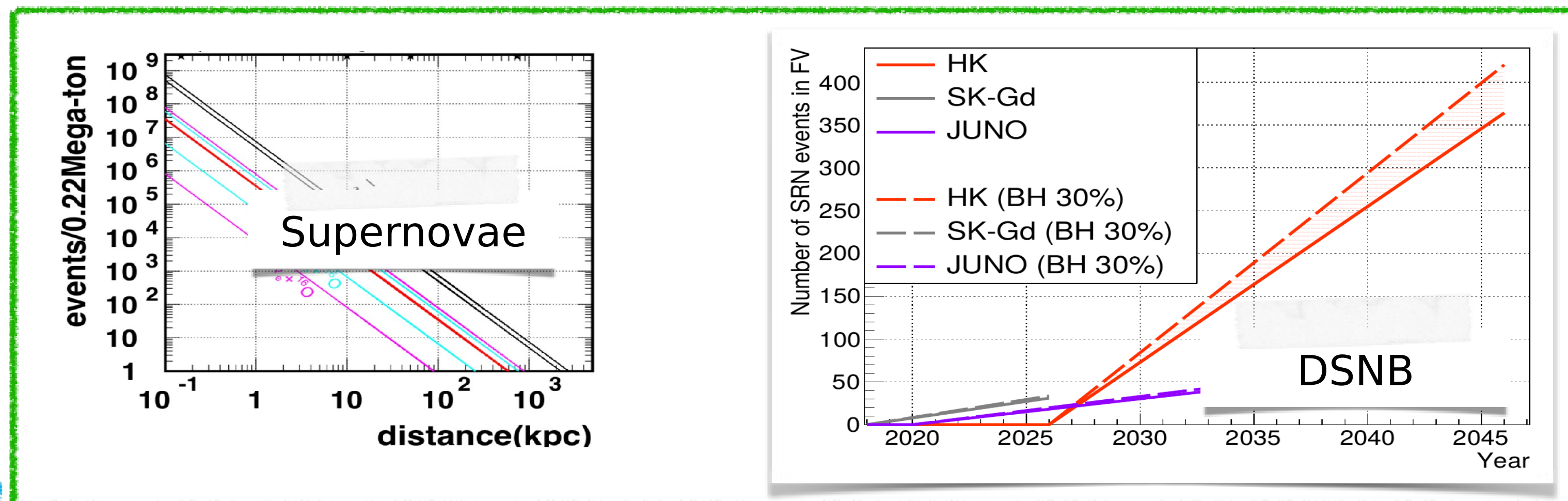
Rare events



Neutrino oscillations

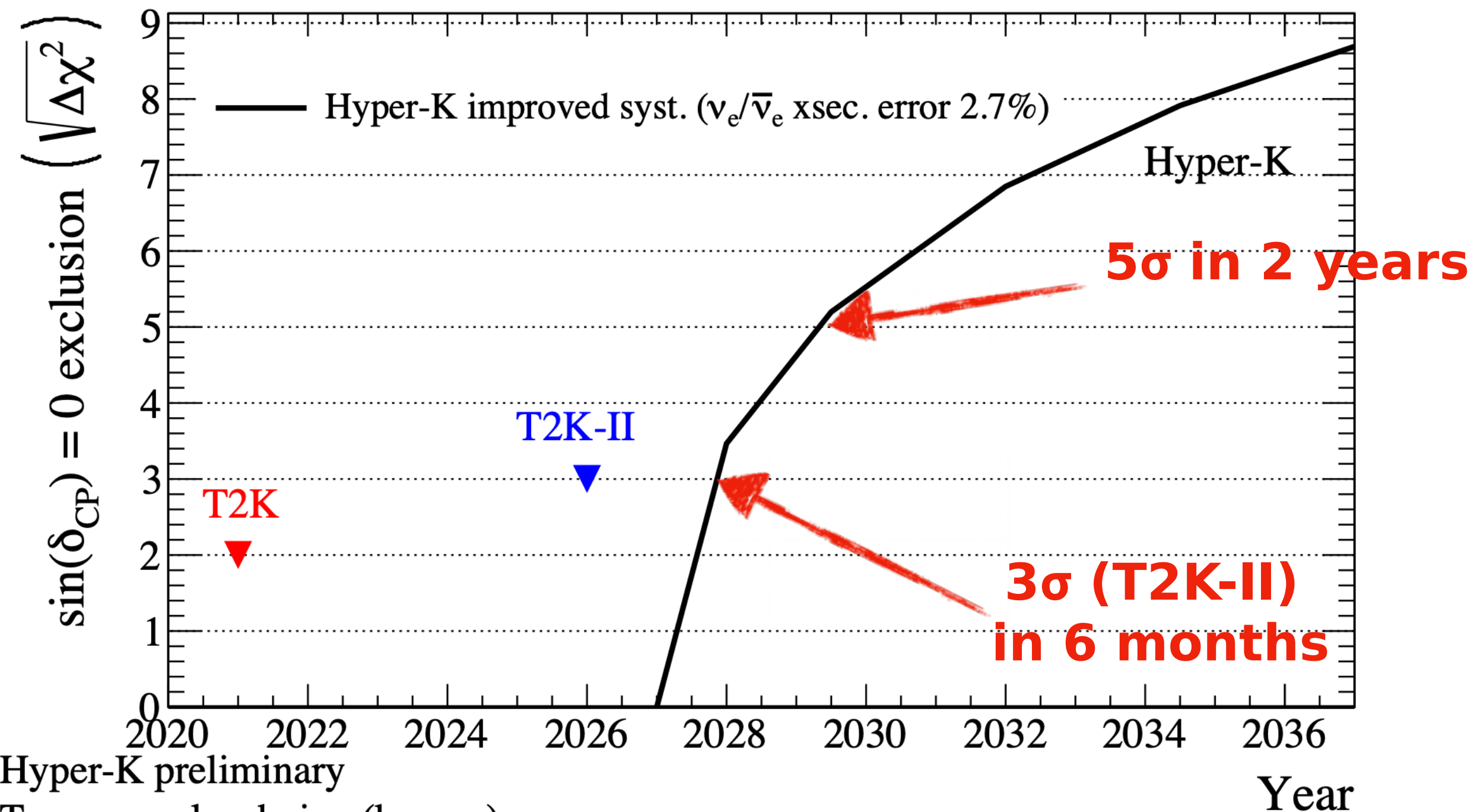


Supernovae modeling and Early Universe



Fast CP-violation discovery

Known mass ordering



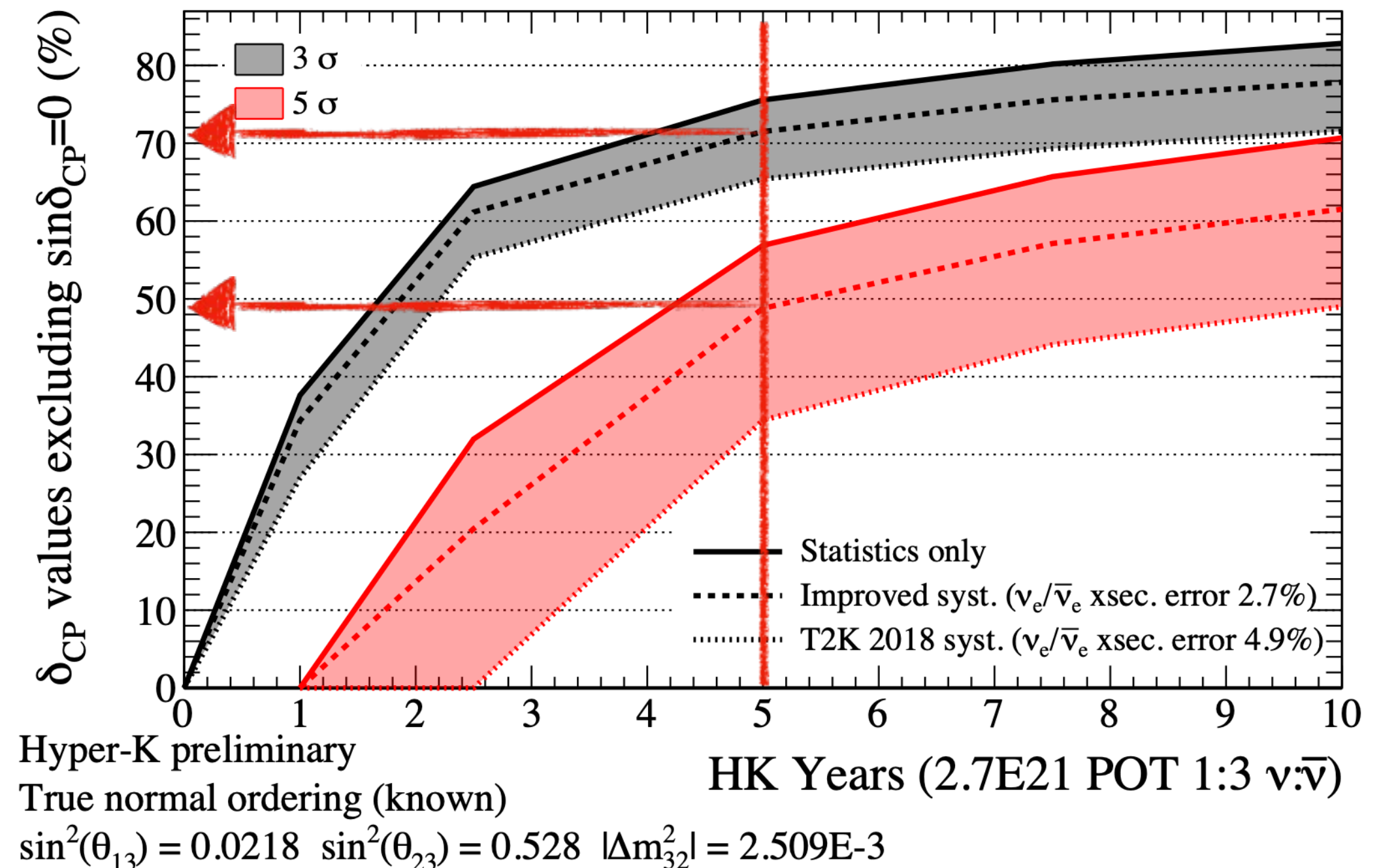
Hyper-K preliminary

True normal ordering (known)

$$\sin^2(\theta_{13}) = 0.0218 \quad \sin^2(\theta_{23}) = 0.528 \quad |\Delta m_{32}^2| = 2.509\text{E-}3 \quad \delta_{CP} = -\pi/2$$

If $\delta_{CP} = -\pi/2$, CP violation discovered before any other LBL- ν experiment

Fastest experiment to survey possible δ_{CP} values



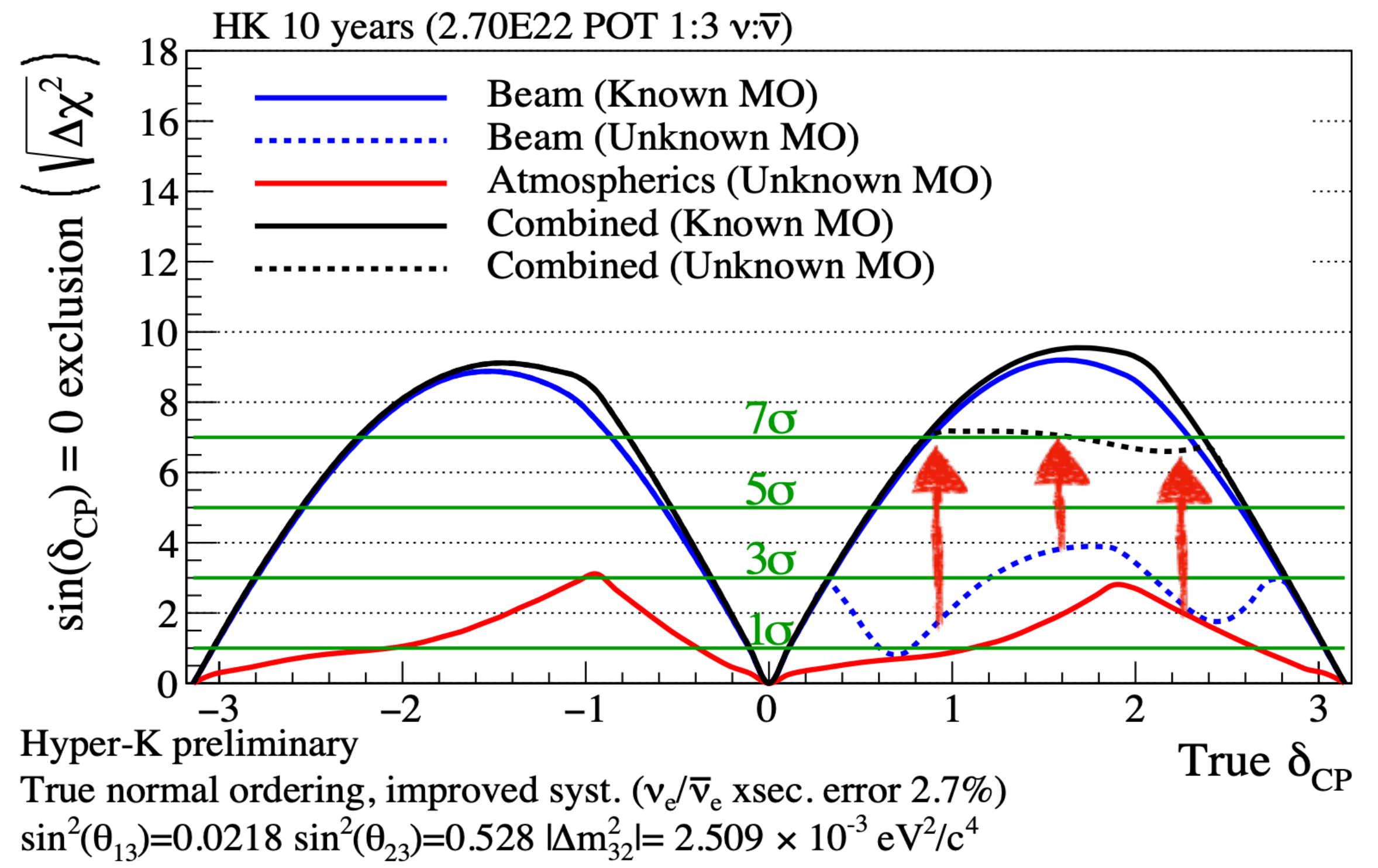
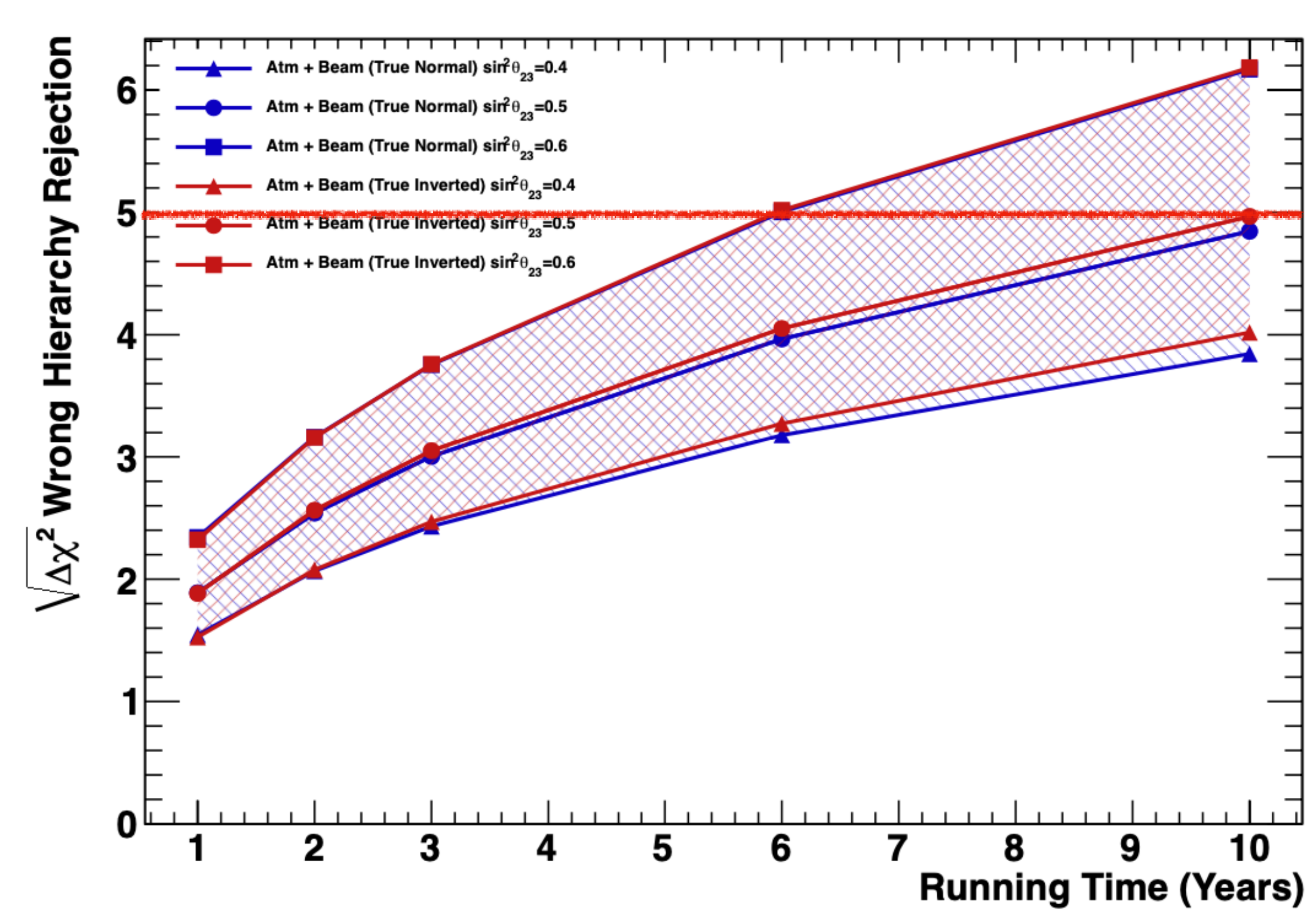
	$\delta_{CP} = -\pi/2$		All δ_{CP}	
	3 σ	5 σ	50 % 5 σ	70 % 3 σ
Hyper Kamiokande	0.5 y	2 y	5 y	5 y
DUNE (staged*)	4 y	8 y	10 y	13 y

* 2 modules@1.2 MW y1; 3 modules y2; 4 modules y4; @2.4 MW y7

DUNE CDR [arXiv:2002.03005](https://arxiv.org/abs/2002.03005)

IUPAP Neutrino panel [report](#)

Mass ordering sensitivity with atmospheric

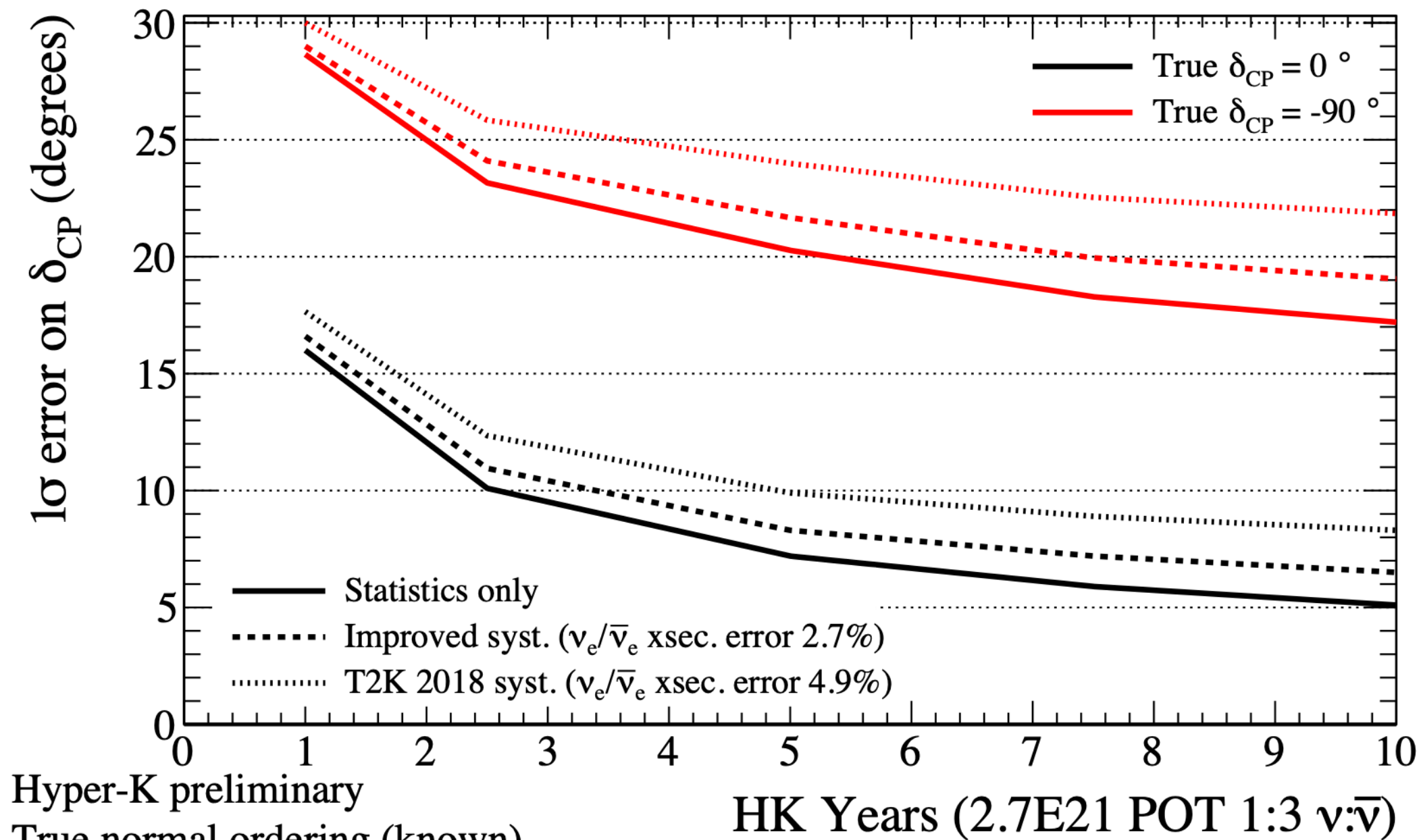


If not discovered by T2K/SK, NOvA, ORCA or JUNO before 2027, HK can determine MO after 6-10 years via atmospheric ν

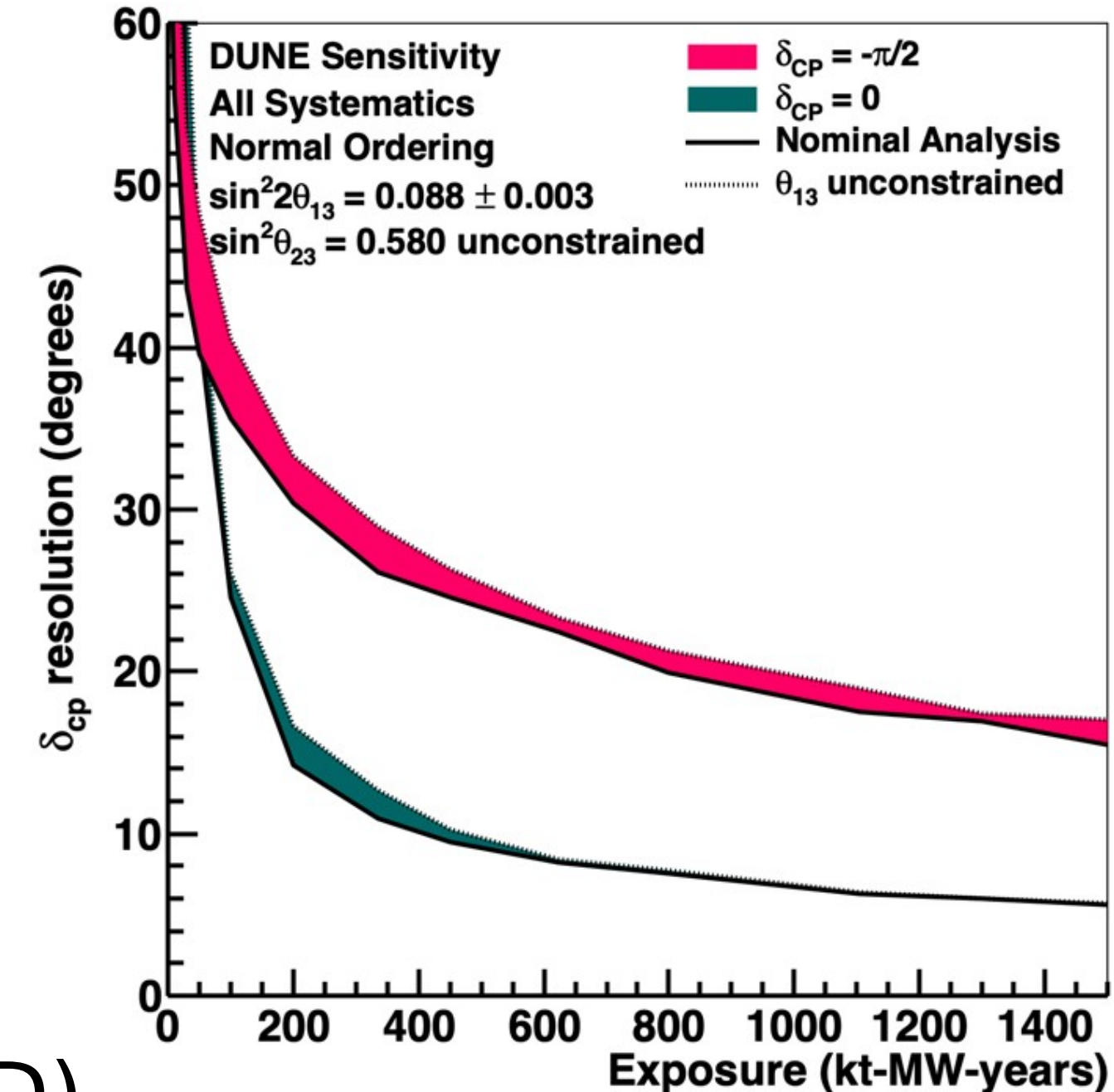
	$\sin^2 \theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	2.2 σ	→ 3.8 σ
	0.60	4.9 σ	→ 6.2 σ

Sensitivity to CPV is little affected if we add atmospheric ν
 → MO prior knowledge not really required to explore δ_{CP}

δ_{CP} measurement resolution



	$\delta_{CP} = -\pi/2$		$\delta_{CP} = 0$	
	30°	20°	15°	10°
Hyper Kamiokande	1 y	7 y	1 y	3 y
DUNE	5 y	12 y	5 y	8 y



Precision = sensitivity to matter-antimatter models

→ **HK will quickly reach precision on δ_{CP} of $30^\circ(15^\circ)$ for $\delta_{CP} = -\pi/2$ (0)**

For the ultimate precision on δ_{CP} it will be important to further reduce systematics uncertainties w.r.t. T2K (ND280 Upgrade + IWCD)

Proton decay

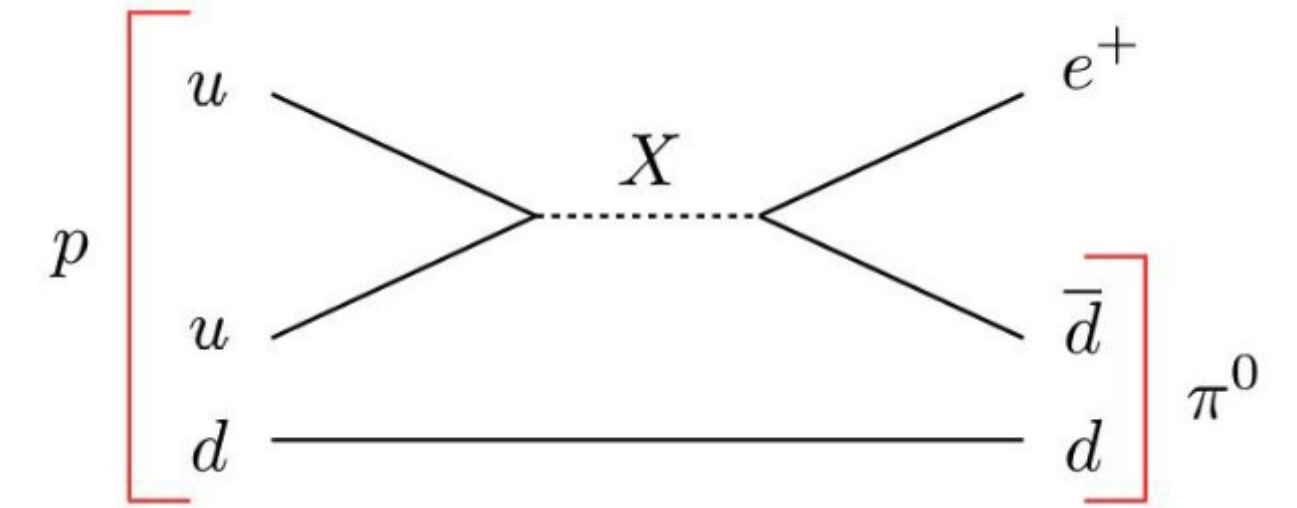
Motivated by Grand-Unification Theories

HK will have the best limit on $p \rightarrow e^+ \pi^0$ for bound protons

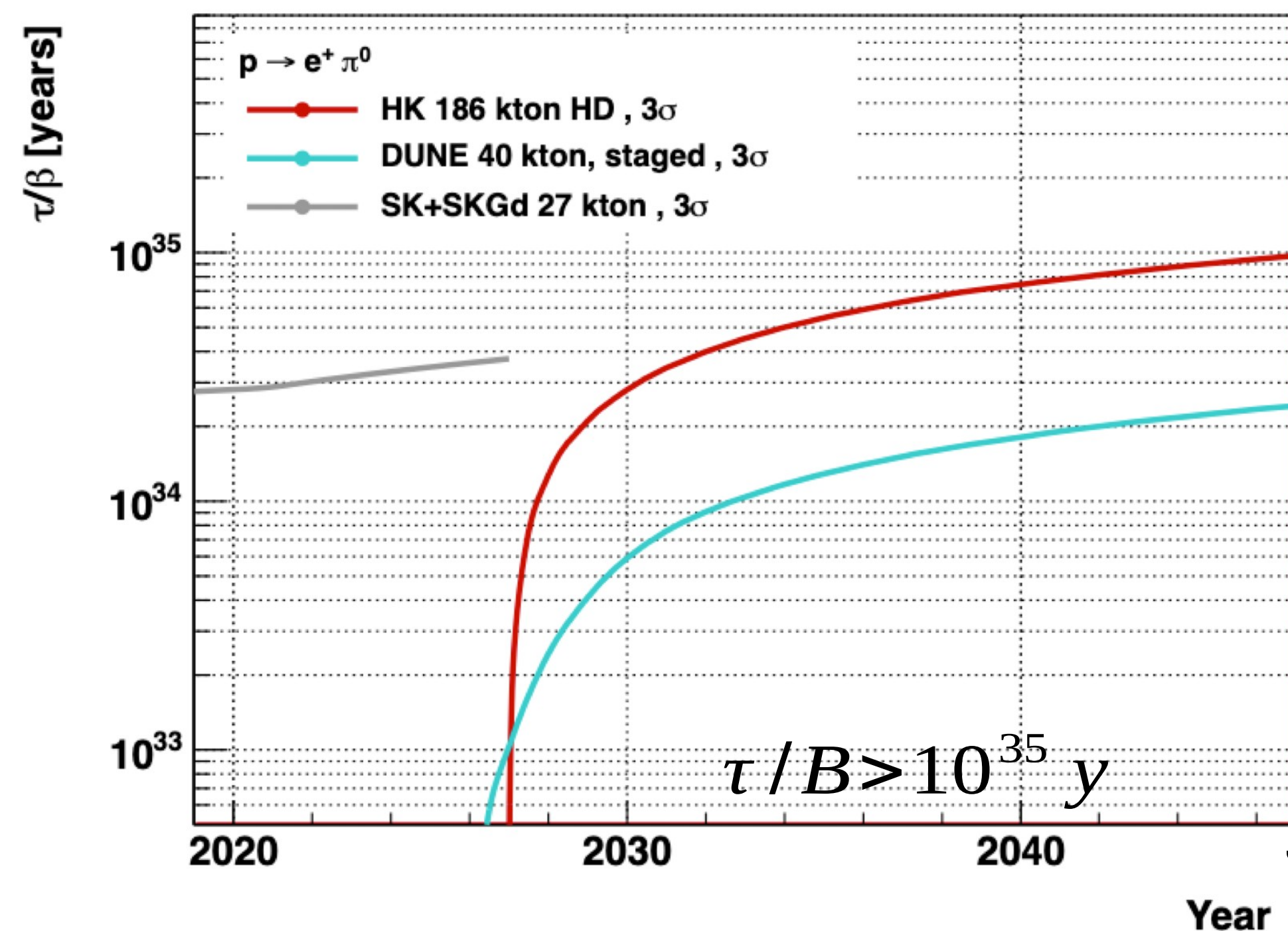
→ about 1 order of magnitude better than current limits

Thanks to its huge mass, HK will also have leading sensitivity to channels with invisible particles ($p \rightarrow \bar{\nu} K^+$)

HK is sensitive to free proton decay

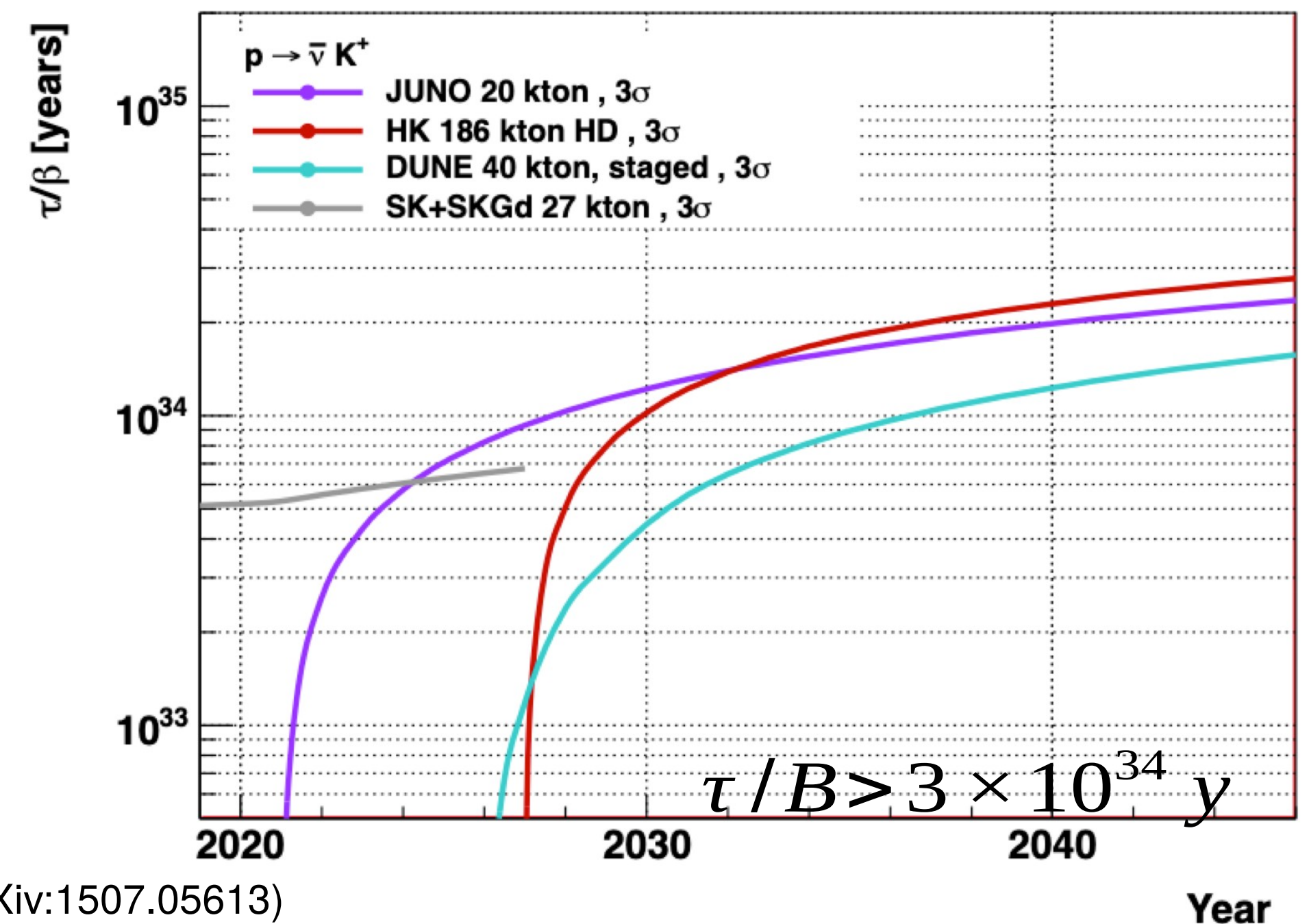


Phys. Lett. B 233 (1-2) 178-182



JUNO: J. Phys. G 43 (2016) 030401 (arXiv:1507.05613)

DUNE: FERMILAB-PUB-20-025-ND (arXiv:2002.03005)



Astrophysical neutrinos

Supernova neutrinos [arXiv:2101.05269](https://arxiv.org/abs/2101.05269)

Increase by ~ 10 in stat sensitivity w.r.t. SK

SN1987A type ~ 2500 events

Galactic center: $\sim 50000+$ events

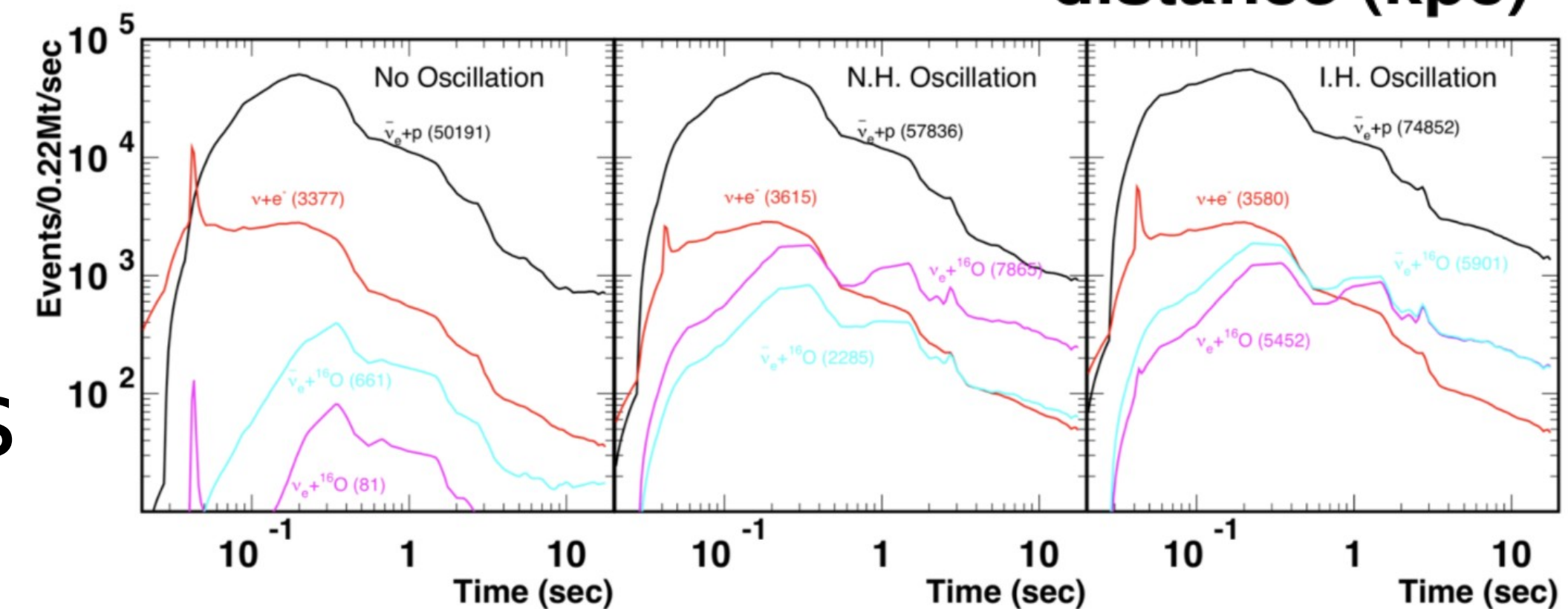
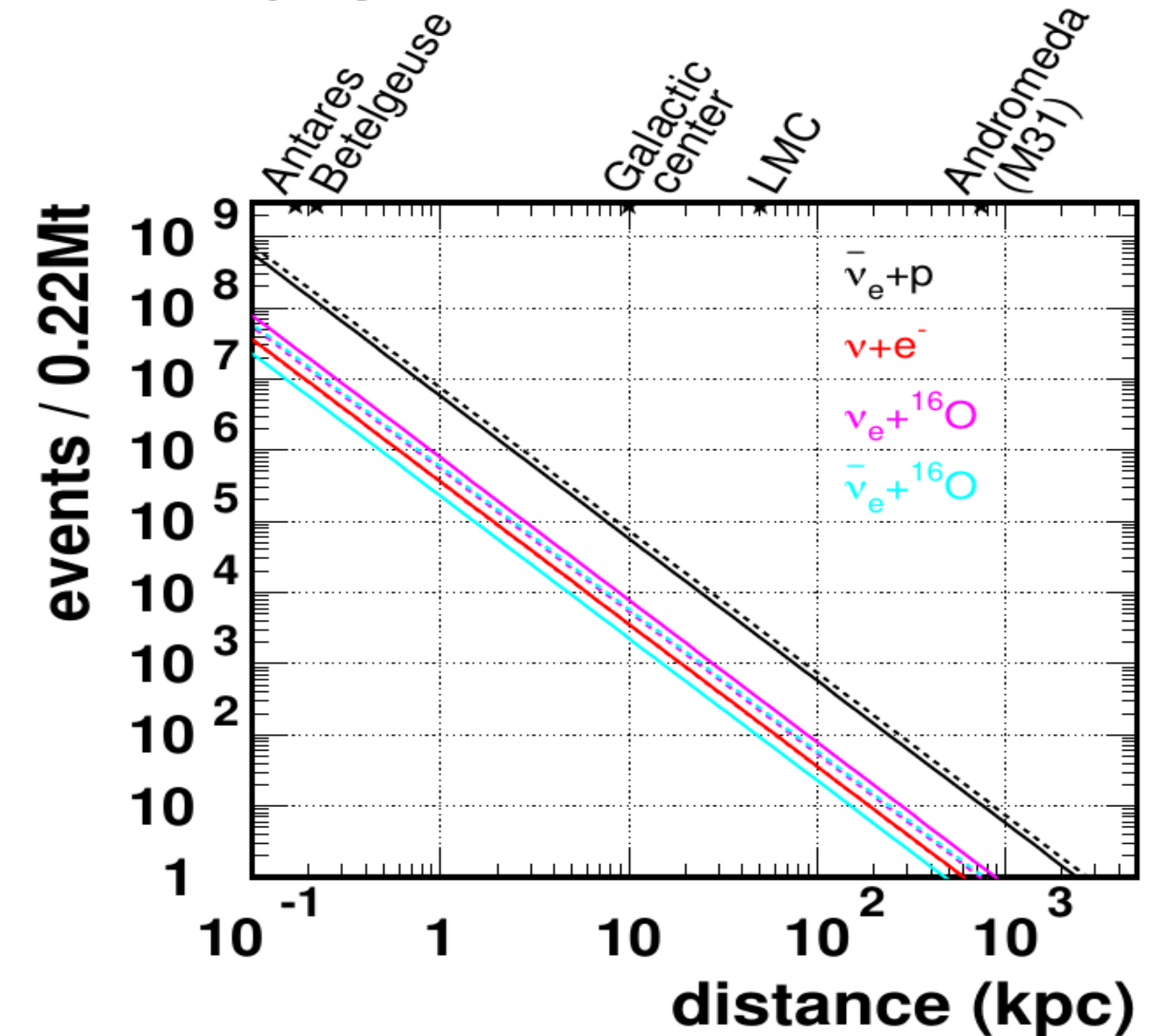
Direction (1° @ 10kpc) \rightarrow triangulation

Time profile: collapse models

SN ν expected every 3 years in HK!
(if HK is sensitive up to 4 Mpc)

Gravitational waves sources

Nearby (10Mpc) neutron star mergers



\rightarrow Unique multi-messengers observatory

SN-relic neutrinos (DSNB) in HK

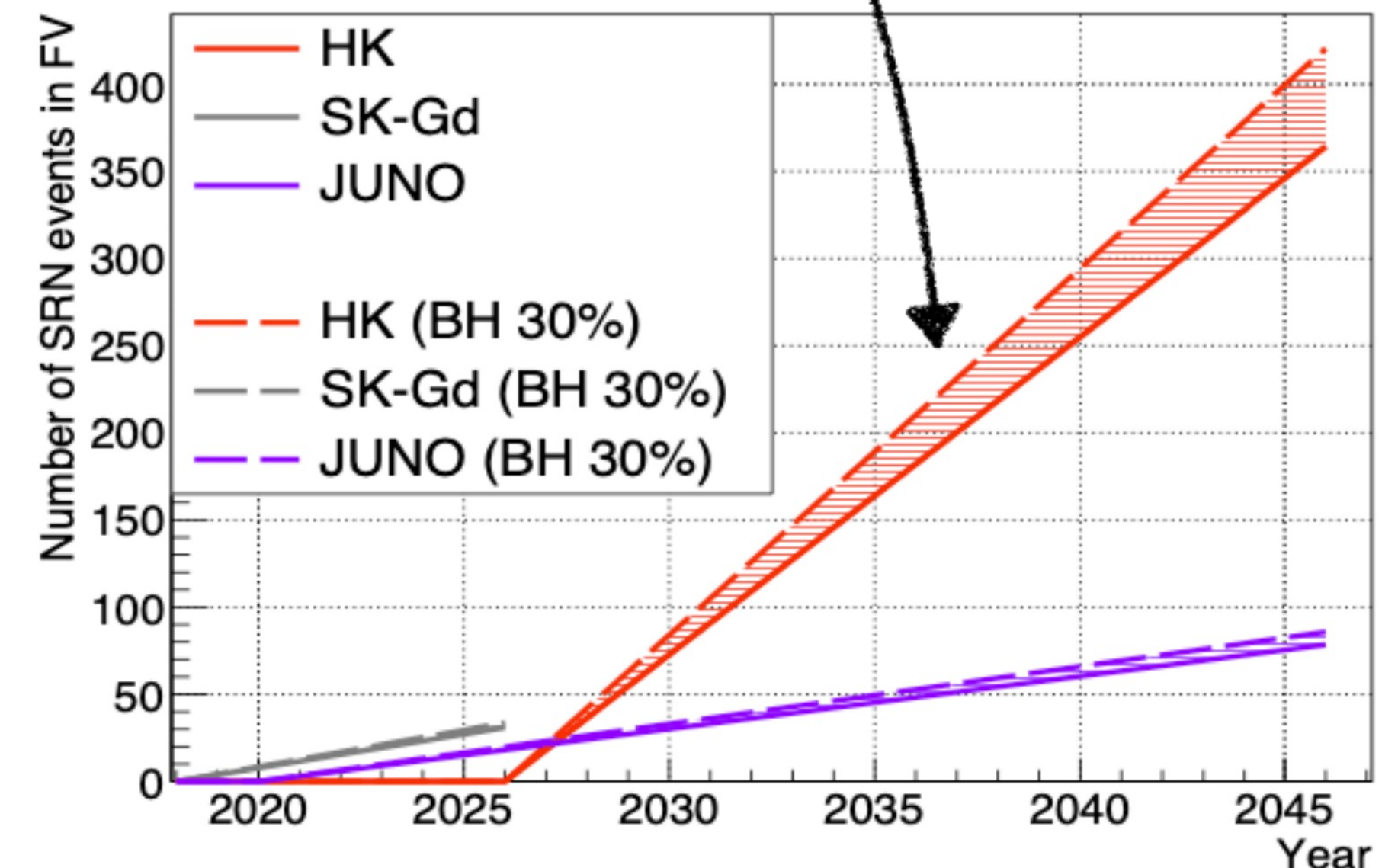
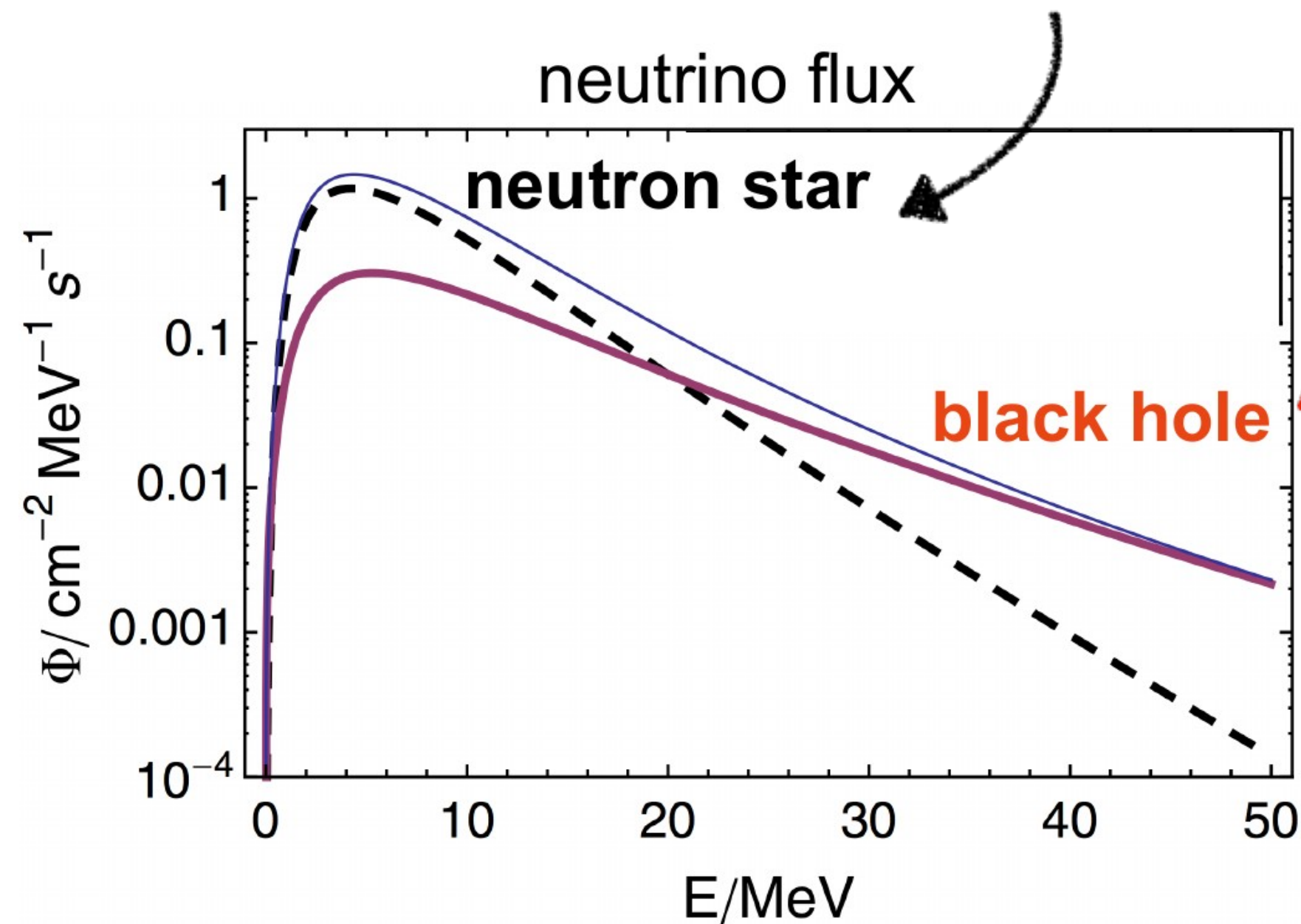
SN-relic neutrinos (SNR ν) offer new constraints on cosmic star history

→ Could be first detected by SK-Gd

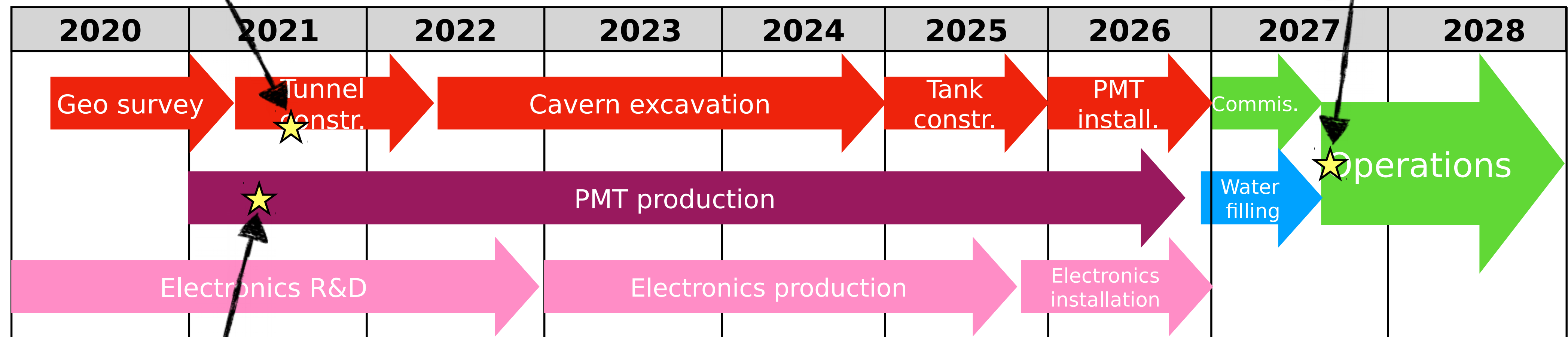
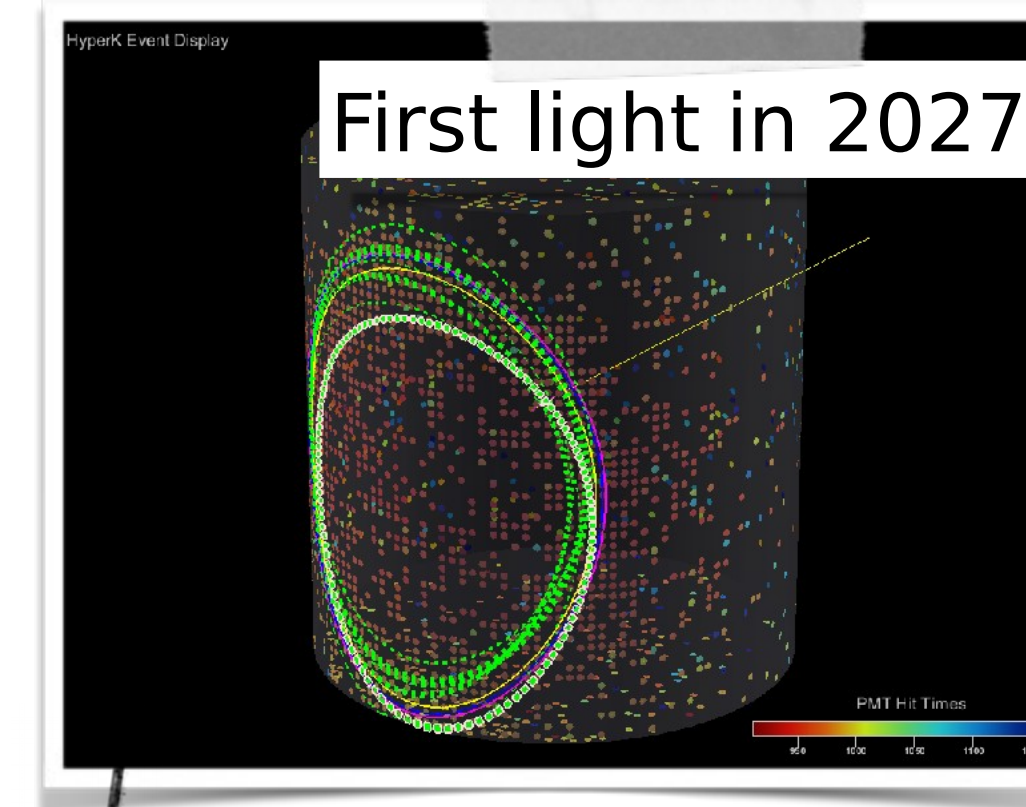
→ The spectrum will be determined by HK

Impact of redshift: low energy \leftrightarrow probe older stars

Sensitivity to neutron star vs **black hole** formation



HK schedule



Strong engagement of Japan: ~500 M\$ for construction
Expected from other countries: ~100 M\$

International contributions are nearly formalized
(proposed IN2P3 contributions presented by Benjamin)

Construction is on schedule

Entrance yard finished (Aug. 2020)



New main building finished (Spring 2022)



Groundbreaking ceremony (May 2021)



Tunnel entrance (June 2021)



Survey completed ✓

Excavation on-going



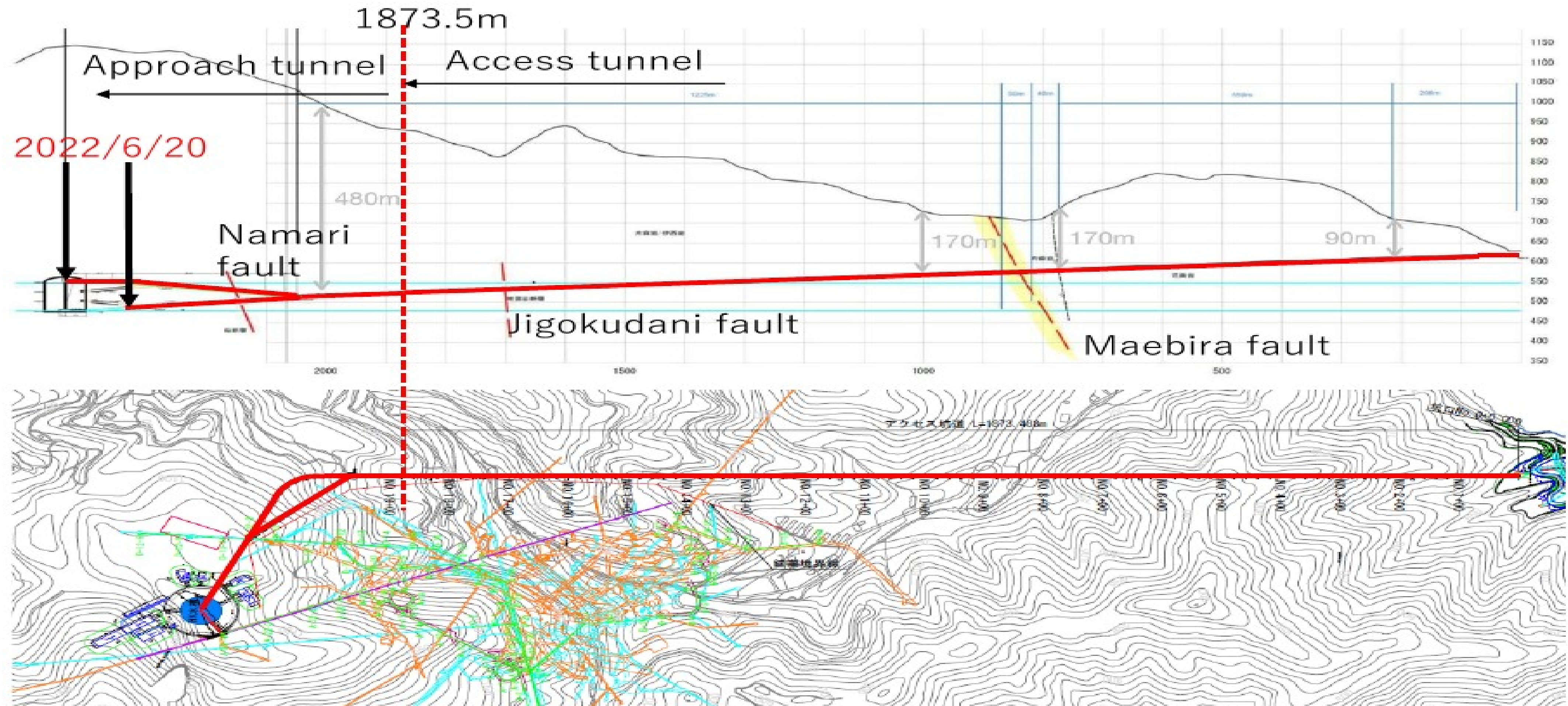
New main building



Everything on track! ✓

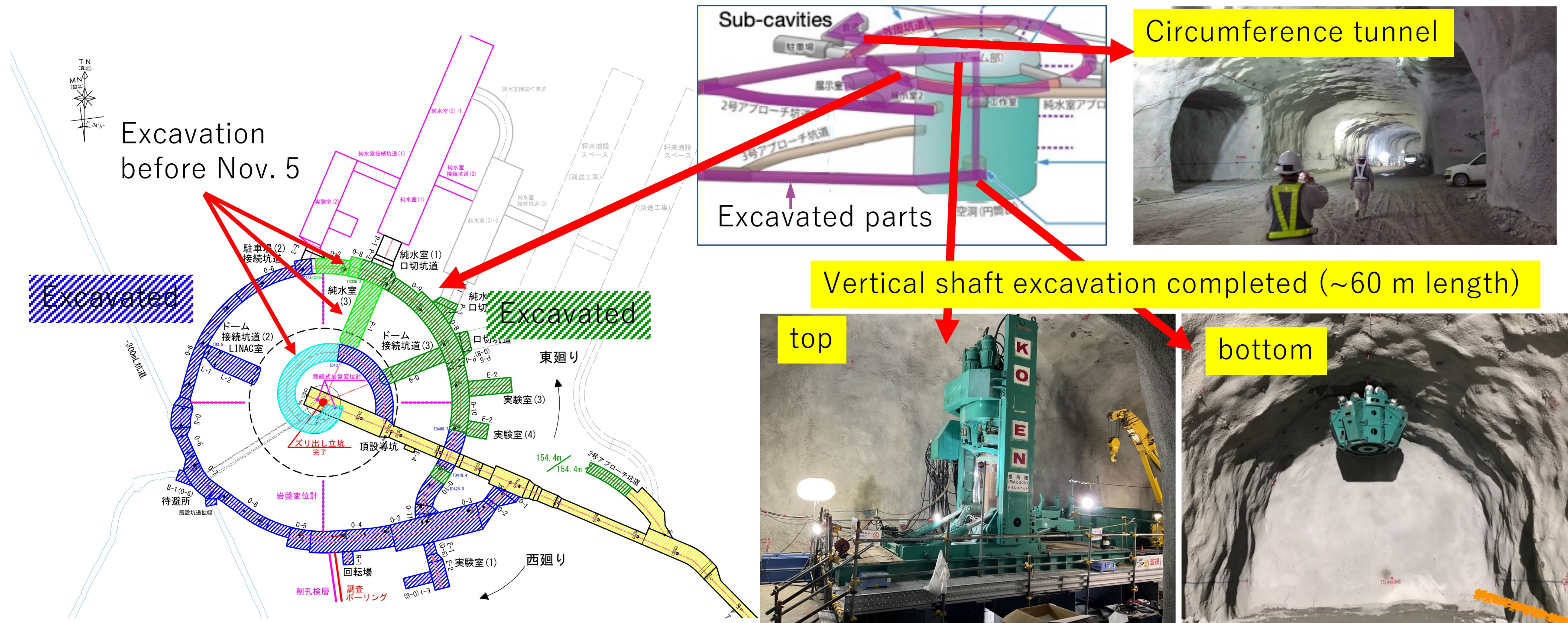
Recent progress: access tunnel excavation

Tunnel excavation overview



The dome center was reached on 24th of June 2022!

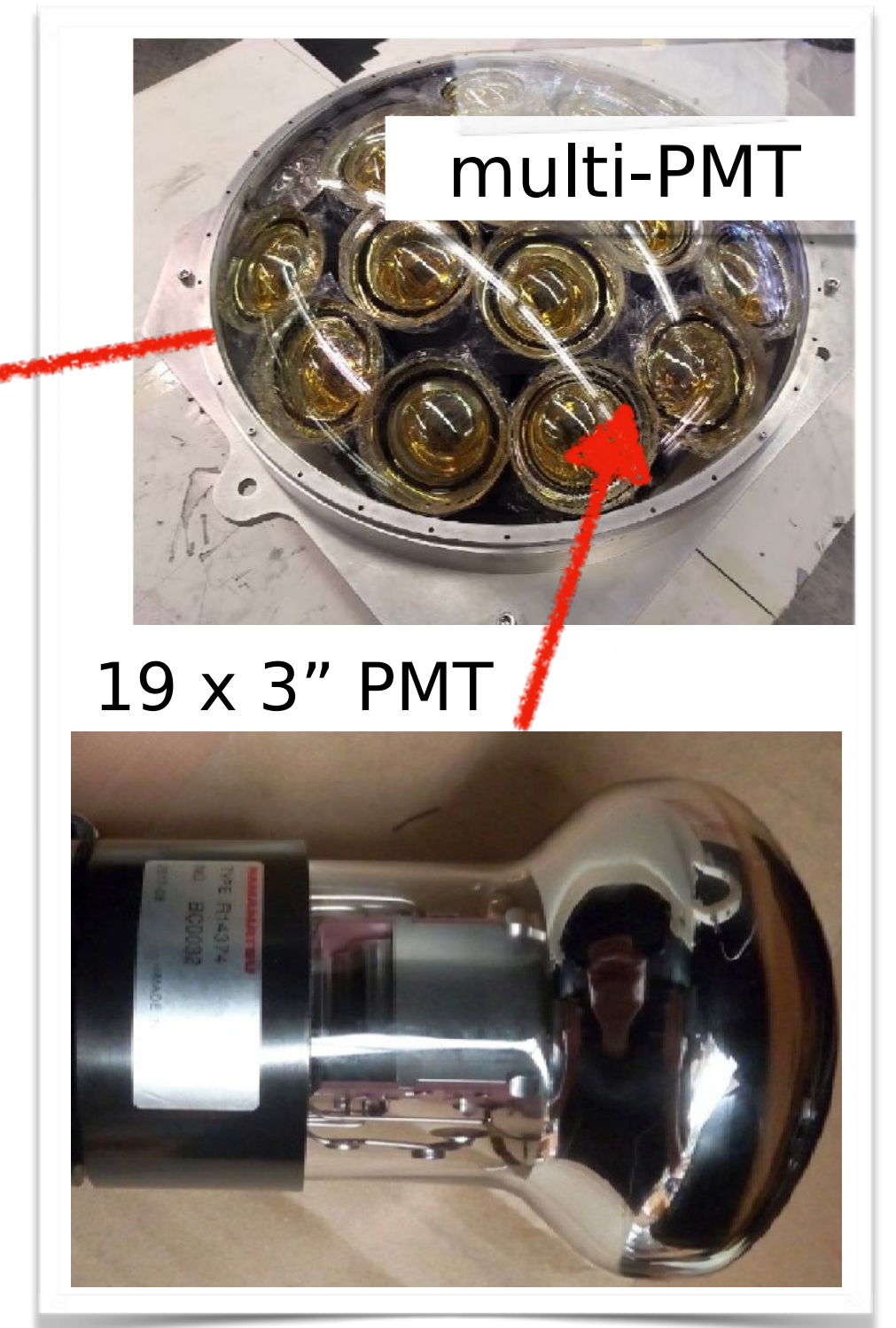
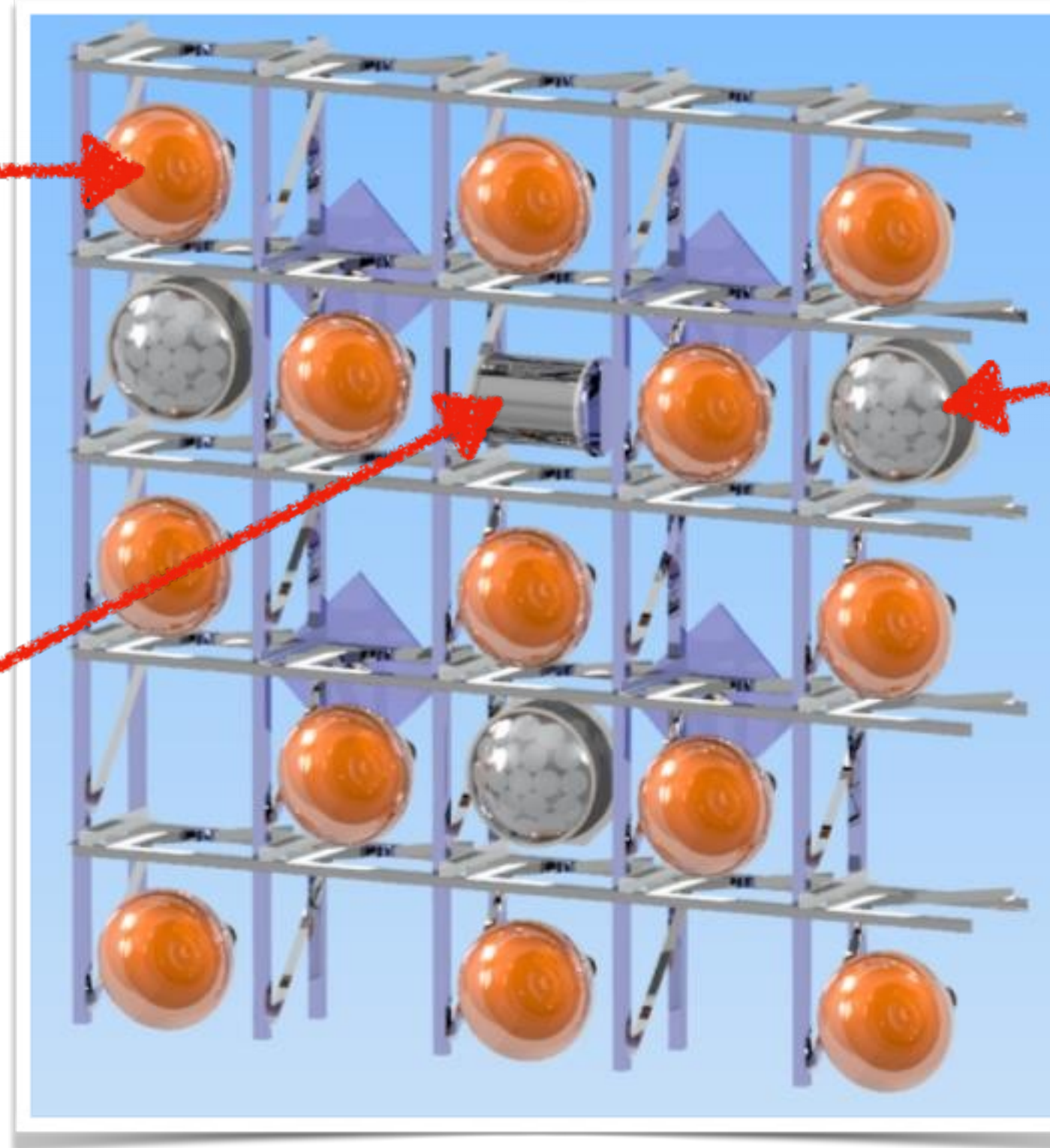
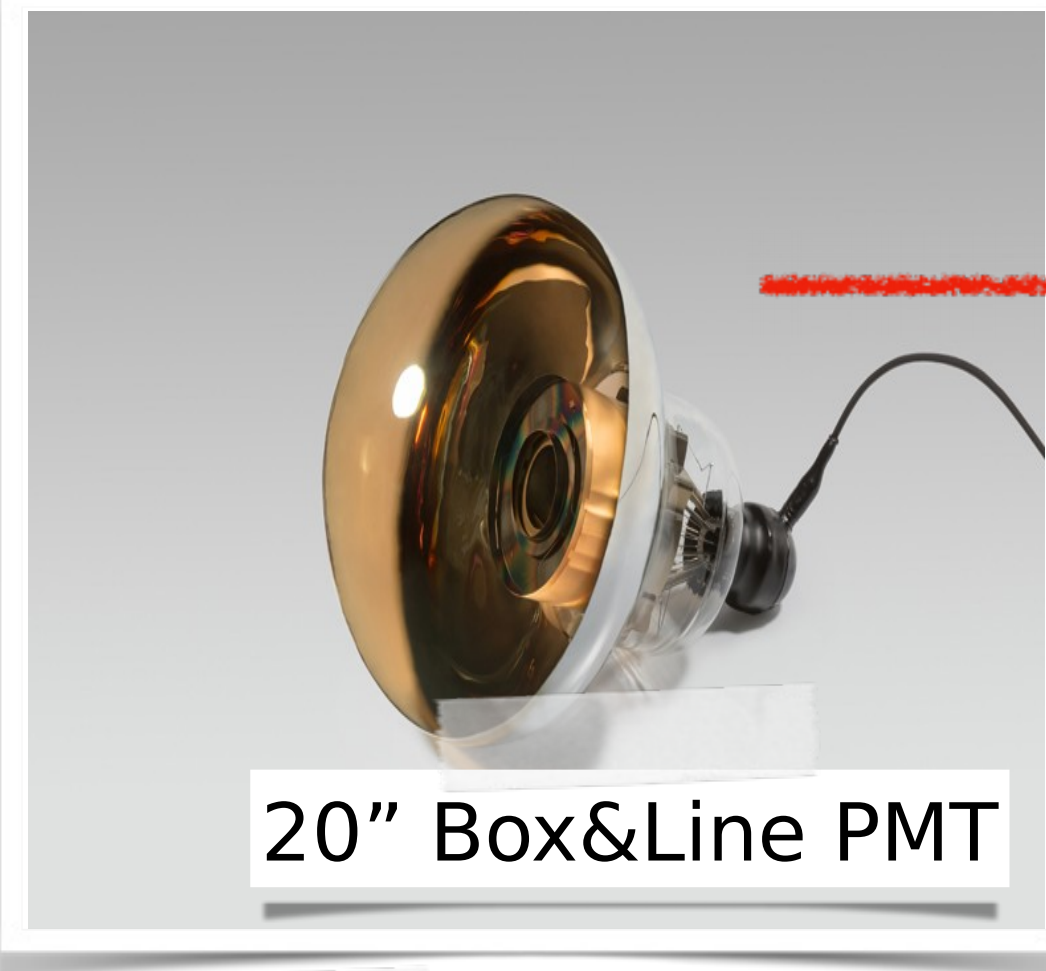
Recent progress: cavern excavation



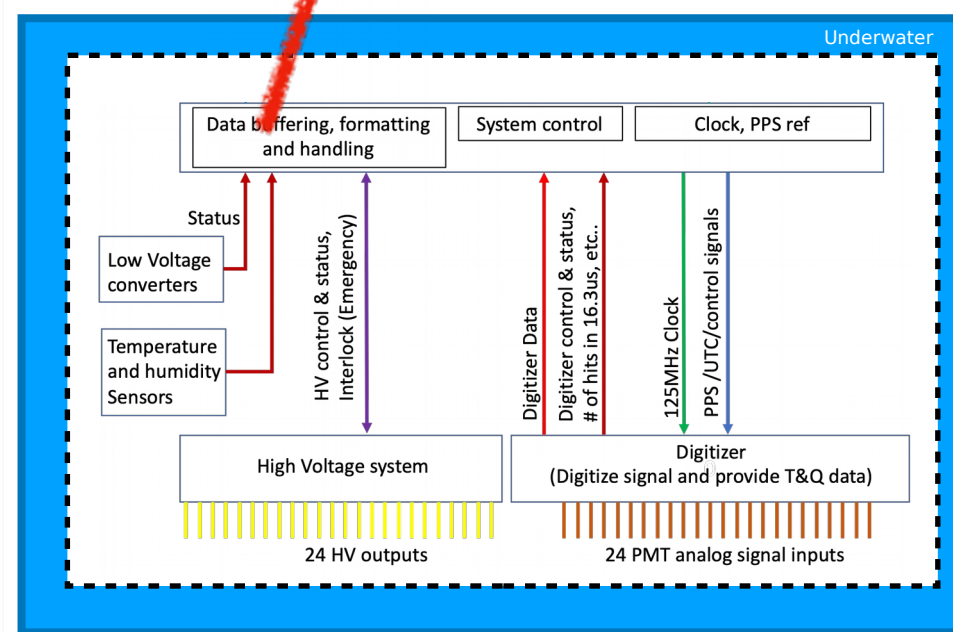
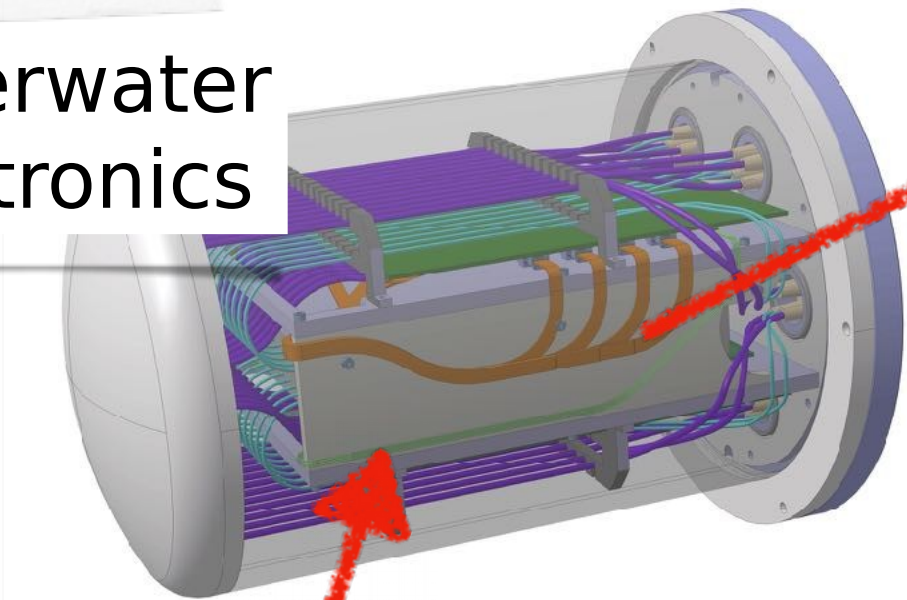
- The excavation work is on schedule. In Oct., a spiral tunnel towards the top of the dome is excavated.
- Ready for excavating the top of the dome in Nov.

Vertical shaft excavation completed on schedule!

20" PMTs, mPMTs and readout



Underwater
electronics

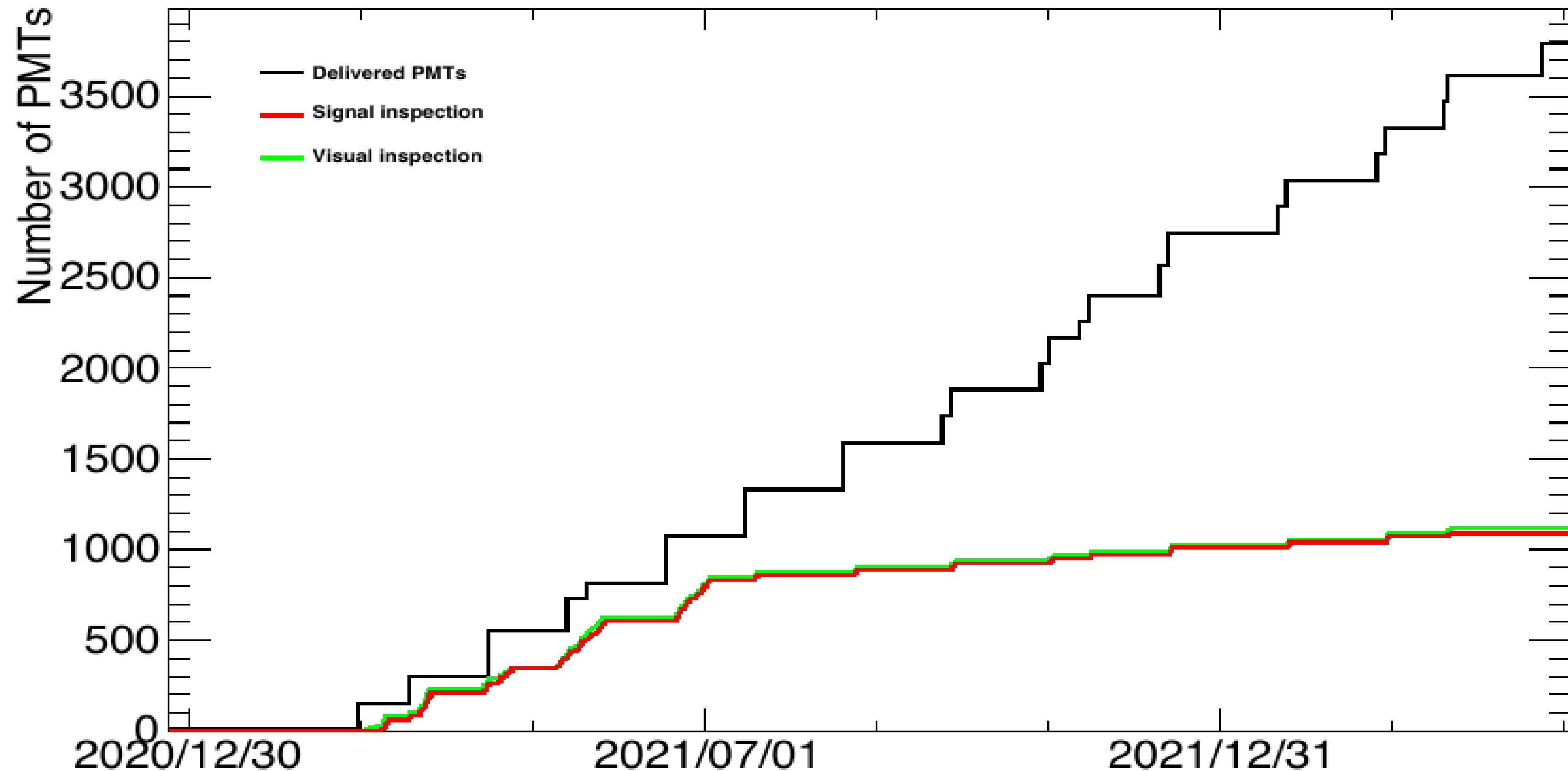


- Inner detector composed of
- 20k+ 20" PMTs (Hamamatsu R12860)
 - ~1k mPMTs (19 3" R12199-02 PMTs)

NEW

Better signal-to-noise ratio, directionality, timing
Size of detector requires an in-water electronics

Recent progress: 20'' PMT production



> 3700 20'' PMTs already produced (at the beginning the signal and visual inspection was done for almost all PMTs). Since July 2021 the inspection rate is 10%.

Intermediate conclusions

Hyper-Kamiokande has a vast and rich physics program including:

- Precision study of ν oscillations (fast CP-violation discovery, δ_{CP} measurement, etc)

- Rare events observatory (e.g. proton decay)

- Multi-messenger astrophysics

→ **Impressive and quick discovery potential!**

Construction started and on schedule → Operation will start in 2027

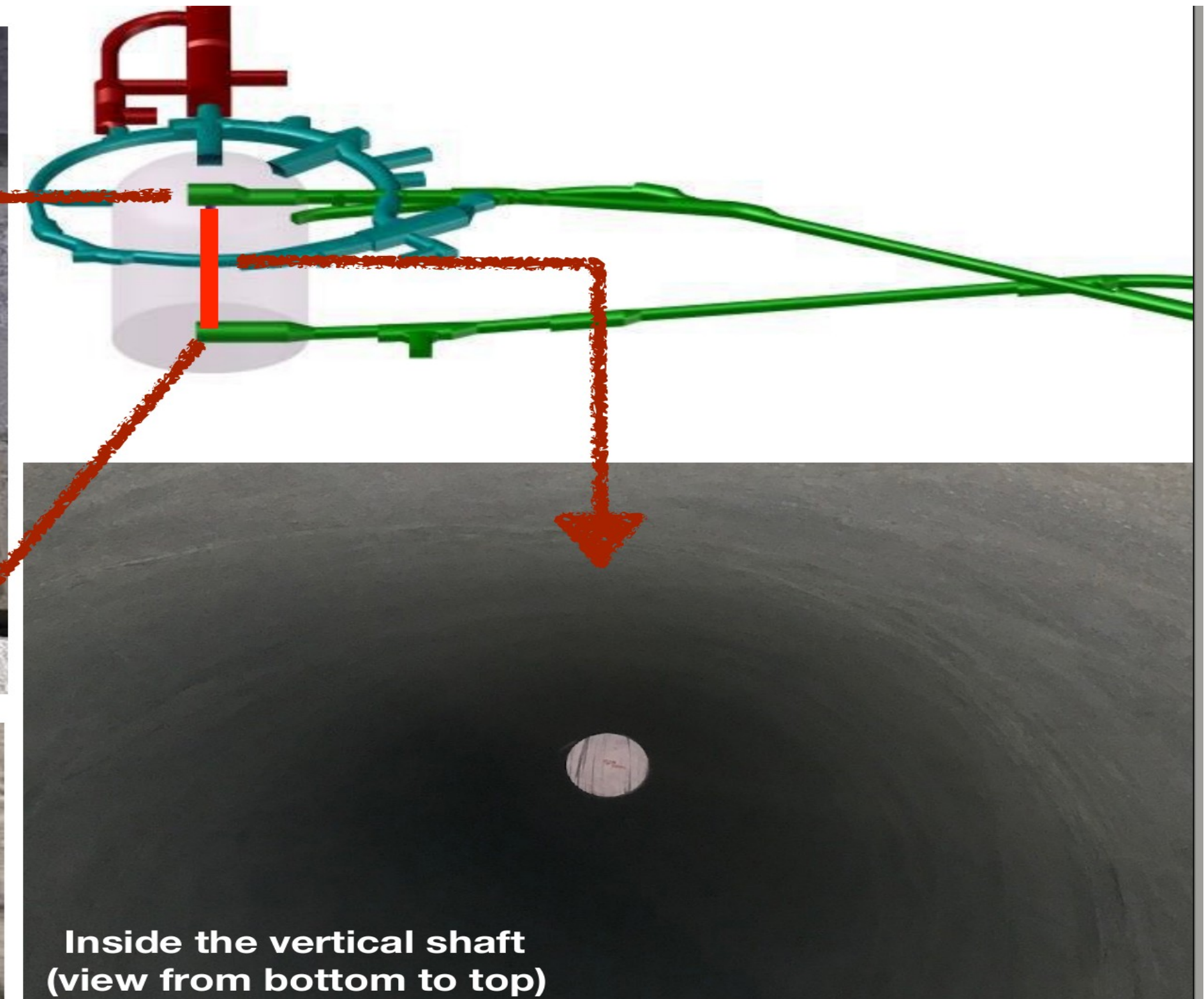
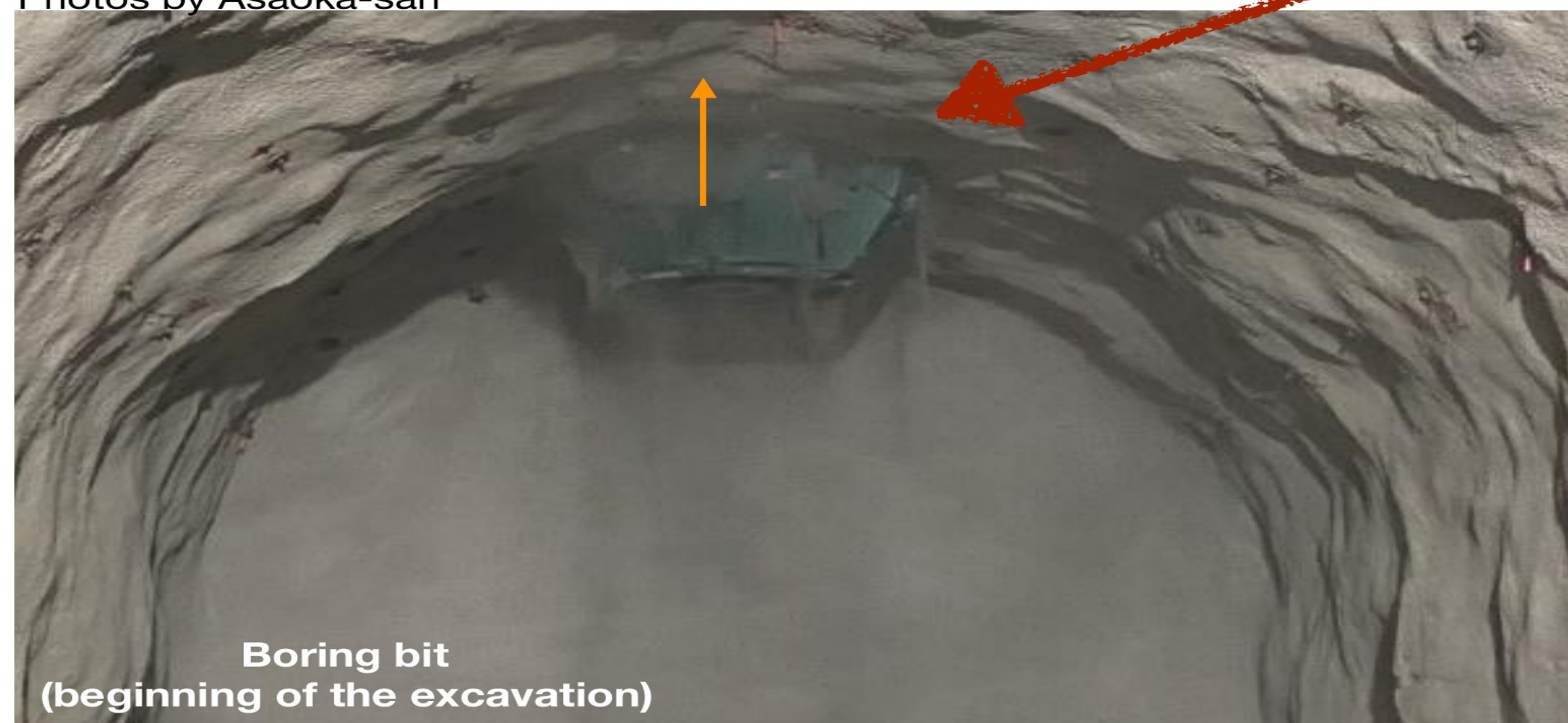
Natural continuation of our involvement in Japanese ν program (T2K/T2K-II and SK)

Upgraded ND280 will be used as the HK near detector starting from day 1

**Unique program of world-leading measurements and discoveries up to
~2040**

Backup slides

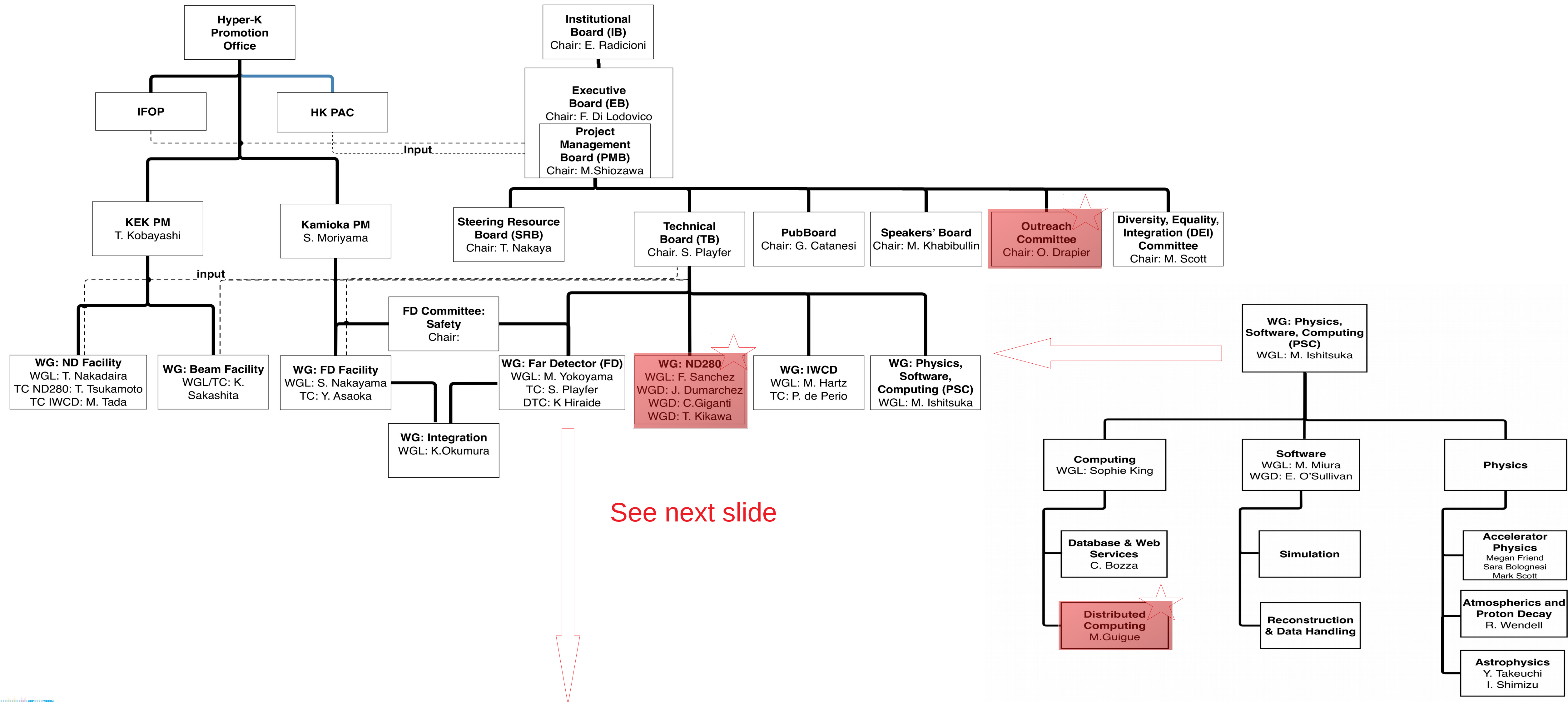
Recent progress: cavern excavation



- The excavation of the vertical shaft completed on schedule
 - Vertical shaft: $\Phi 3.4\text{m}$, 63m-long
- Collect geological data with borehole camera
 - No obvious geological defective throughout the vertical shaft
- No heavy metal content in the excavated rock

Vertical shaft excavation completed on schedule!

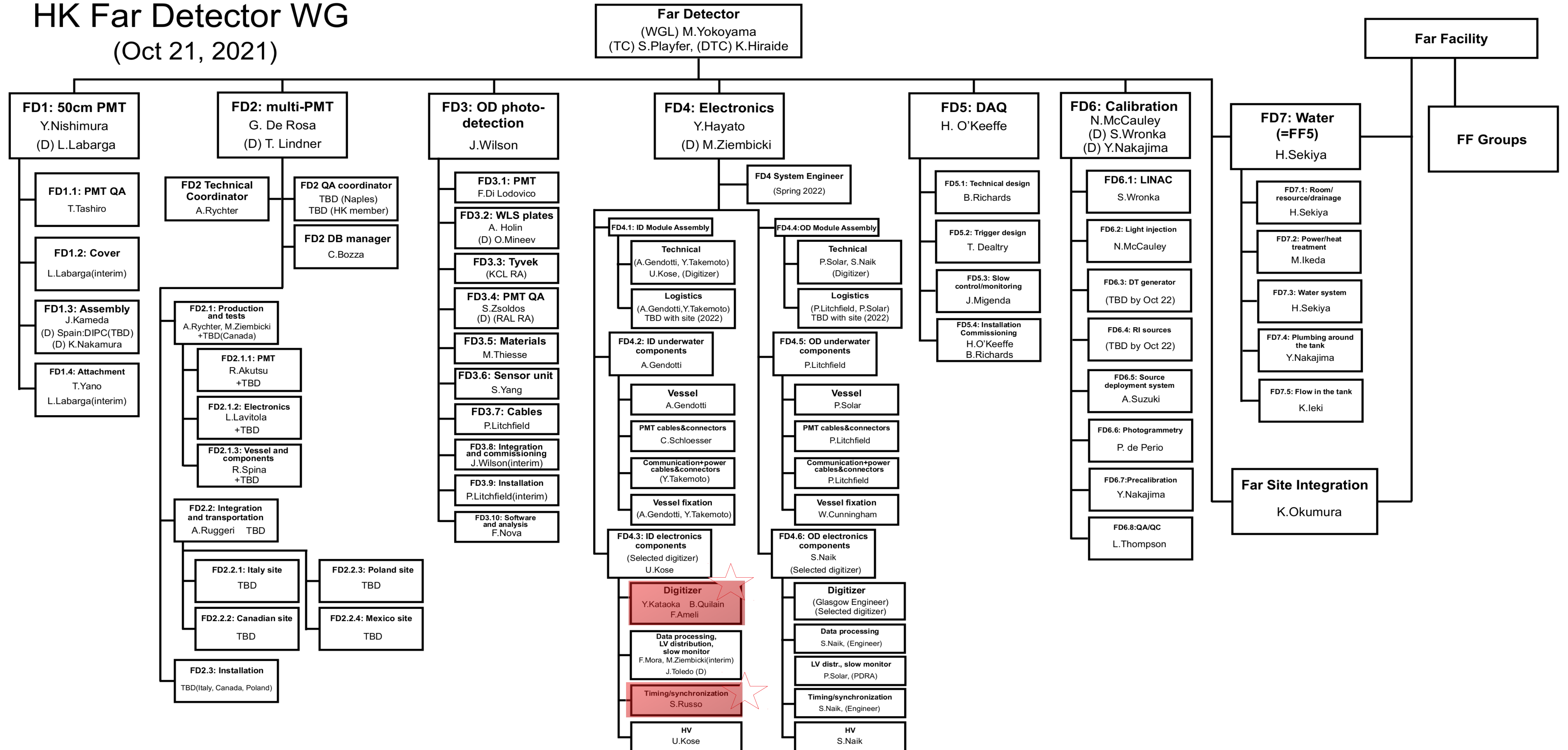
HK organizational chart



See next slide

Far detector Working Groups

HK Far Detector WG (Oct 21, 2021)



IN2P3-CEA technical contributions to HK



- **ND280 Upgrade and maintenance**

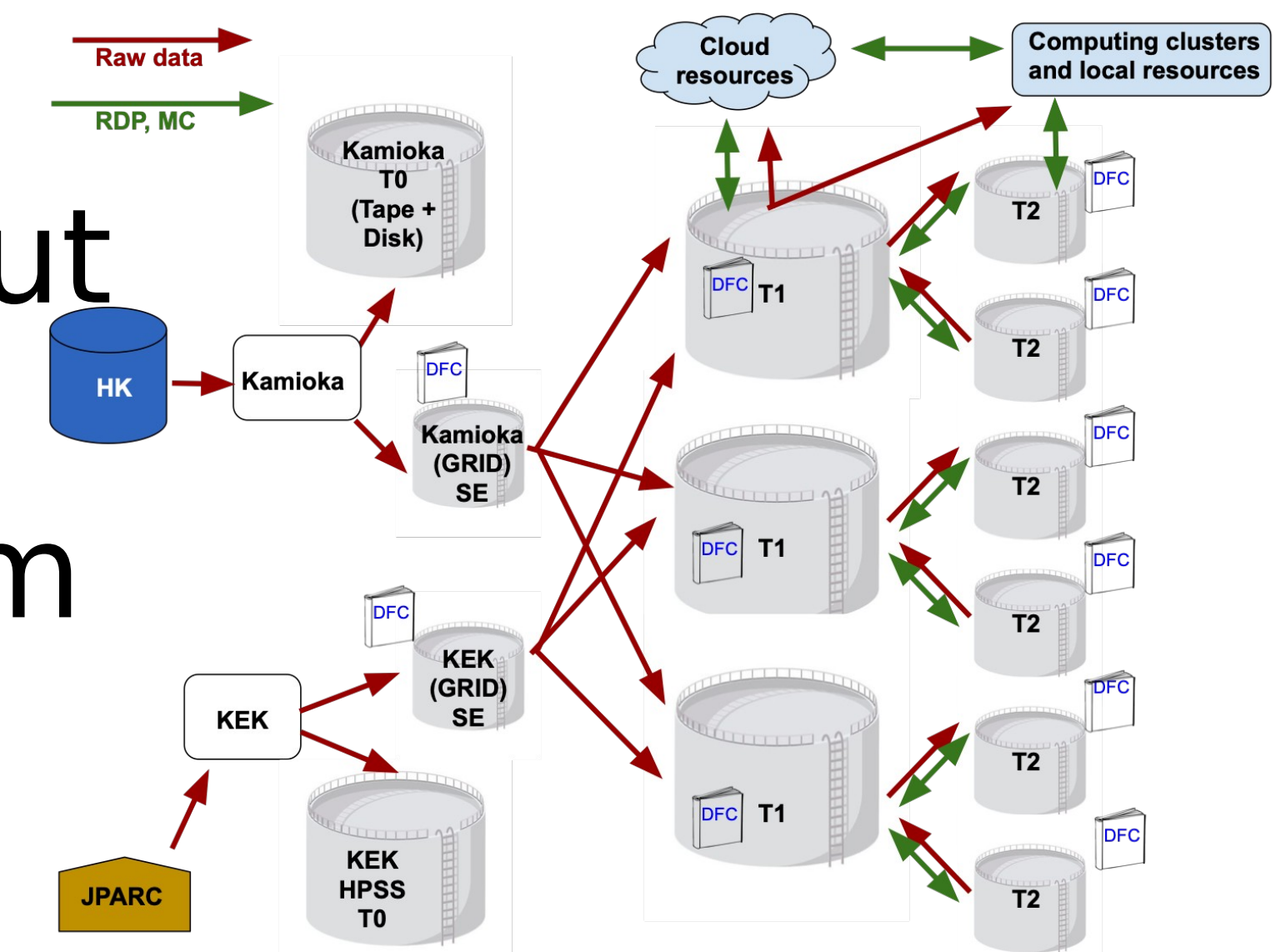
- Super-FGD electronics
- High-Angle TPCs electronics & readout

- **Construction of HK far detector**

- Front-end electronics & timing system

- **International computing effort**

- CC-IN2P3 as T1 for HK



SWOT

Strengths:

- Well-known exceptional Water Cherenkov technology
- Use of existing neutrino beam and near detector complex built for T2K, thus saving large amount of money for the long-baseline program and reducing systematics uncertainties from the first day of the experiment.
- Construction budget for Hyper-Kamiokande have been allocated by Japanese government in 2019 with a budget profile that will allow to start the experiment in 2027.
- Leading roles of French groups and acquired expertise in the ongoing T2K experiment

Weaknesses:

- Small groups at LLR and LPNHE. Mitigated by the large overlap in terms of physics case, technologies and tools between T2K, SK and HK.
- Hyper-Kamiokande is an IN2P3 R&D project since 2022, but not yet an IN2P3 master project, undermining our visibility within the collaboration.

Opportunities:

- Fast measurement of CP violation, before any other experiments.
- Huge target mass, making HK the most sensitive observatory for rare events in the MeV–GeV energy region.
- IN2P3 groups can build on their long standing expertise in the T2K experiment to propose strong contributions in Hyper-Kamiokande. There are still many possibilities to contribute, e.g. electronics of the outer detector, further ND280-upgrade, IWCD.
- Deployment of a similar timing system for the near and intermediate detectors without any additional R&D.

Risks:

- Approval by CS-IN2P3 and allocation of IN2P3 funding is needed to capitalize on the R&D on the digitizer to make a strong contribution to the HK detector in addition to the timing system and computing.
- Since the HKROC digitizer was not selected as the primary option for the HK inner detector, there is still an uncertainty about the outcomes of this contribution.

Financial resources

Item	Cost (M)	Partially covered with external fundings	Funding approval	Construction period	Requested fundings (M)
ND280 Upgrade	6	T2K Collaboration	2019	2019 – 2022	0.6 (obtained)
Far detector timing	0.6	ANR - INFN - CEA	2022	2023 – 2026	0.4
Communication cables	2	European countries	2022	2023 – 2026	0.2-0.4
Chip and Front-end	2.5	CEA - INFN	2022	2023 – 2026	1-2.5
Computing (CC-IN2P3)	3.8	CEA	2021	2021 – 2037	3.8
Note that costs for computing are spread over a much longer period of time (15 years).					
Total	14.9	-	-	-	~6-7.7

External and internal investments:

- 70k€ for R&D towards HK (Sorbonne Université)
- 400k€ (X) + 90k€ (IN2P3) for R&D on HKROC
- 300k€ (ANR) + 150 k€ (IN2P3) for R&D on time generation and clock distribution

Significant efforts to acquire external fundings before asking for IN2P3 investments