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

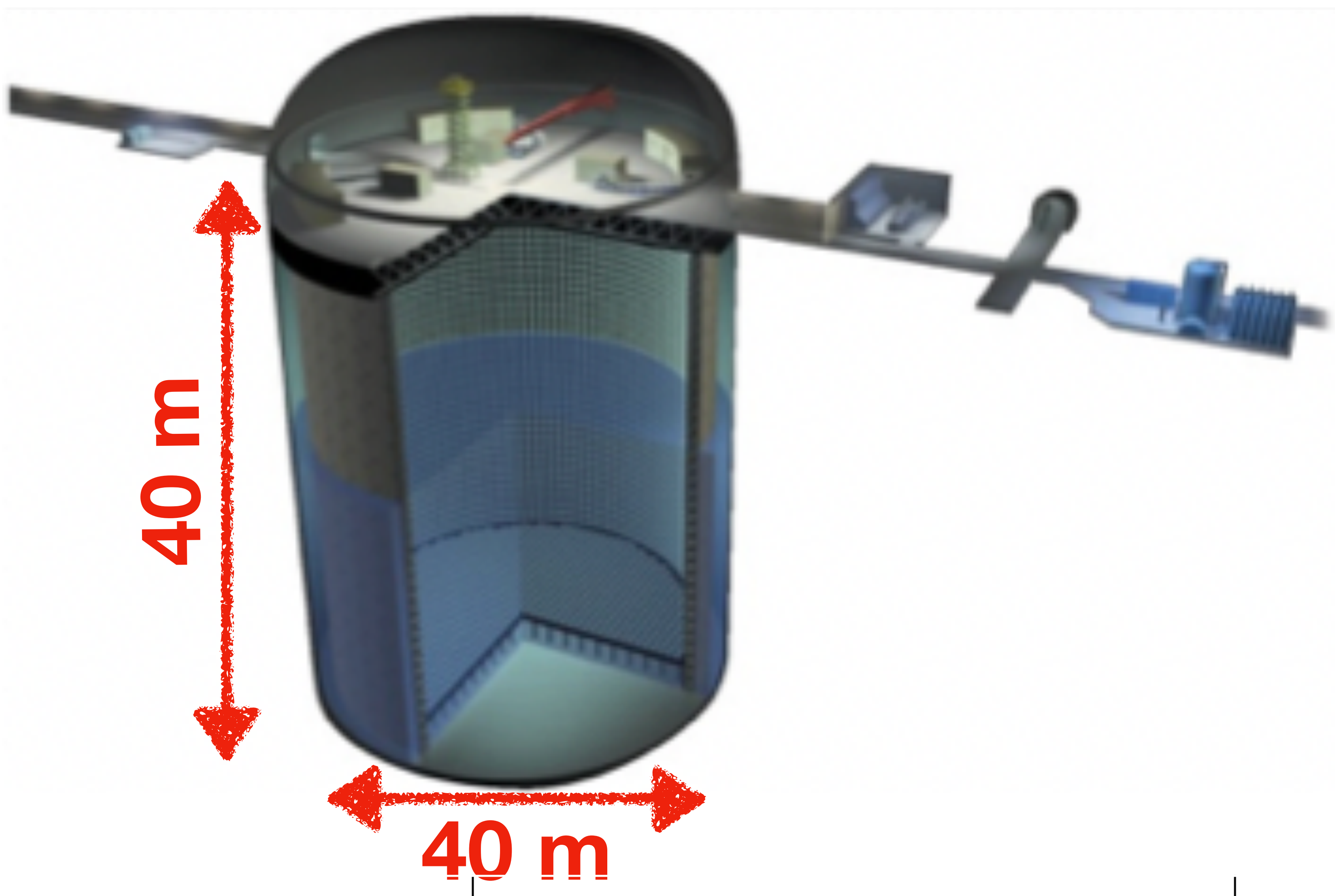
APC: C.Volpe (theoretician)

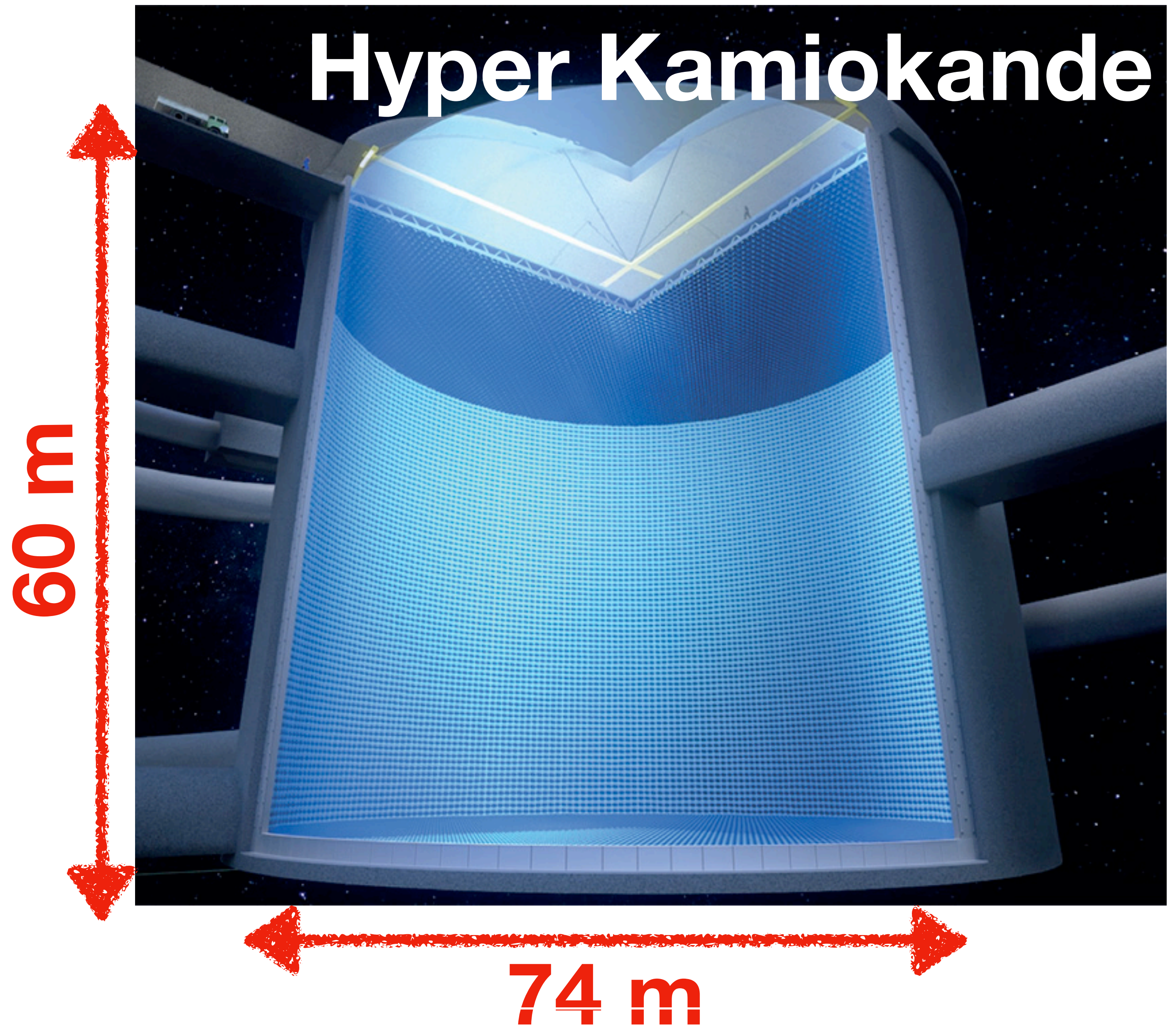
Natural continuation of our participation in the Japanese neutrino program (T2K and SK)
In close collaboration with CEA-IRFU colleagues

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 ($\langle E_\nu \rangle \approx 600 \text{ MeV}$) from J-PARC
- Existing near detector ND280 currently being upgraded for T2K-II
- Vast non-accelerator scientific program

Hyper-Kamiokande vs Super-Kamiokande





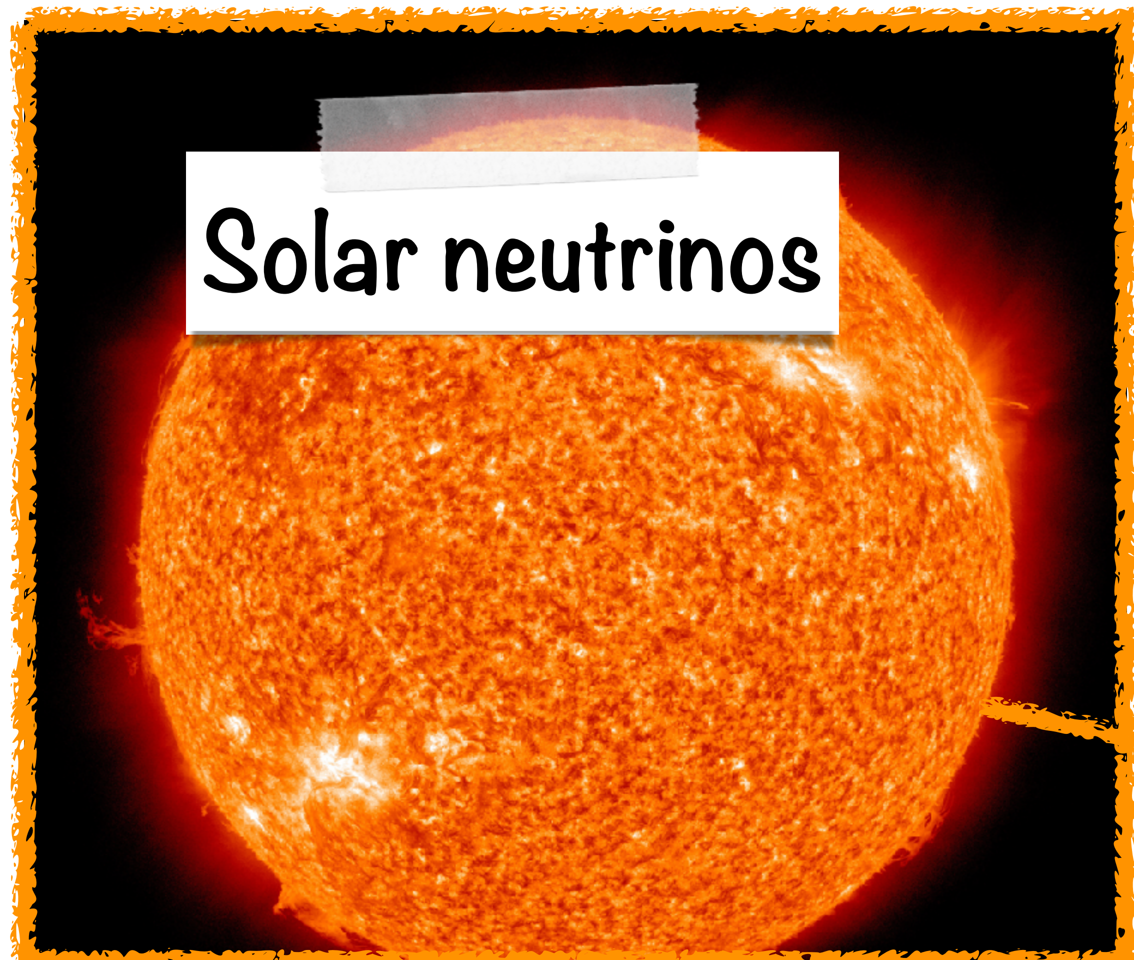
	Super Kamiokande	Hyper Kamiokande
Site	Mozumi-yama	Tochibora-yama
Number of ID 20" PMTs	11 129	>20,000
Photo-coverage	40 %	>20%
Single-photon efficiency/PMT	~12%	~24%
Dark rate/PMT	~4 kHz	~4kHz
Time resolution of 1 photon	~3 ns	~1.1 ns
Total/fiducial mass (kton)	50 / **22.5**	260 / 187

Fiducial volume x8:
→ non-beam ν physics

Beam neutrino event rate x 20:
→ beam ν physics

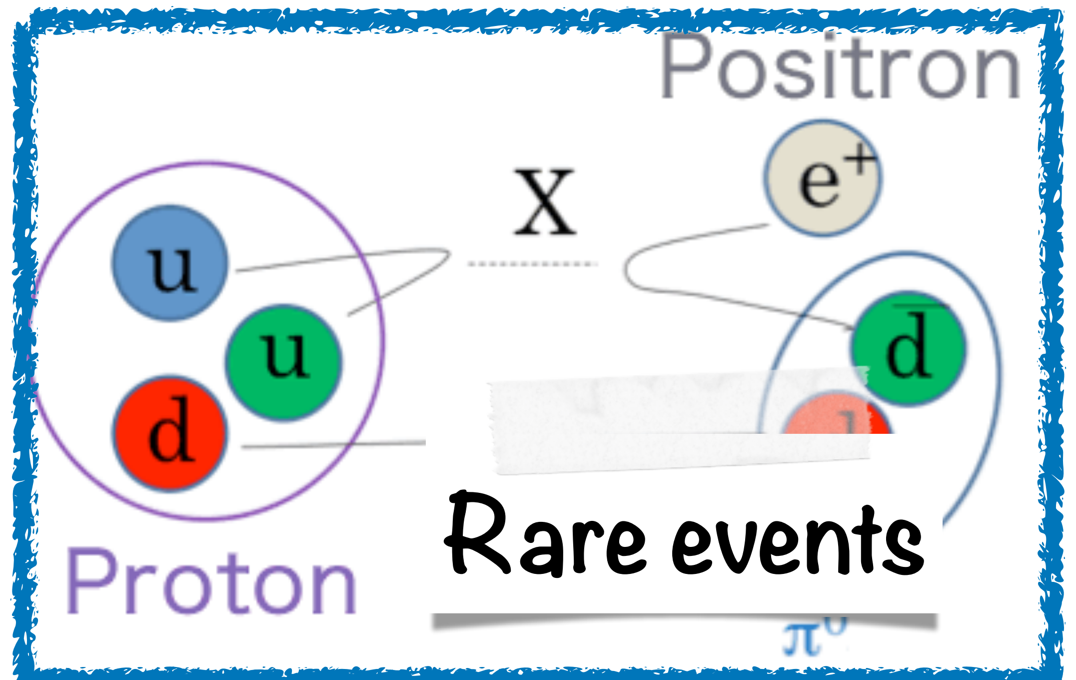
Start operations in 2027 with 240 kt.MW and an assumed runtime 10^7 s per year

Hyper-Kamiokande physics program



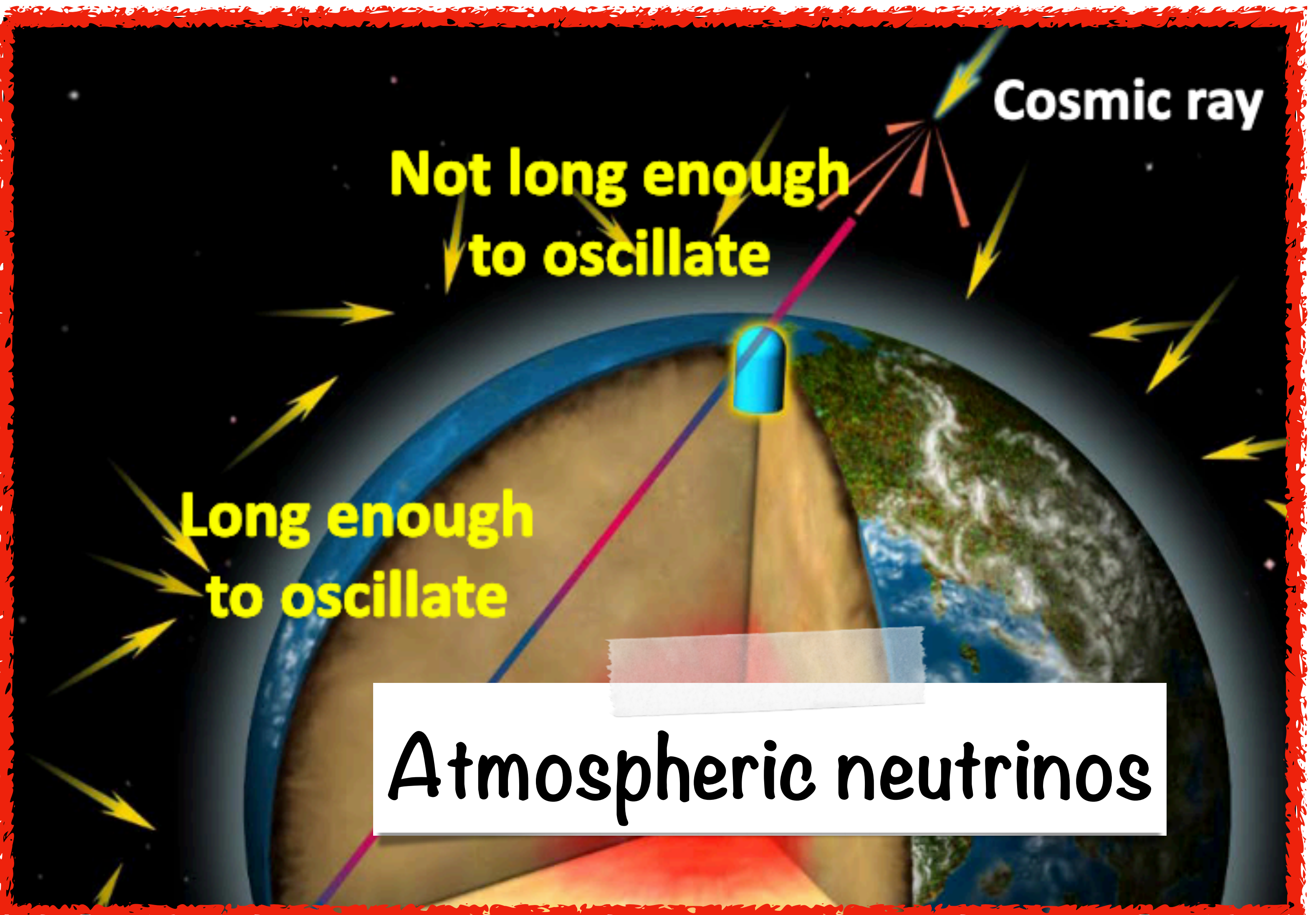
- MSW effect
- Non-standard interactions

ν_e

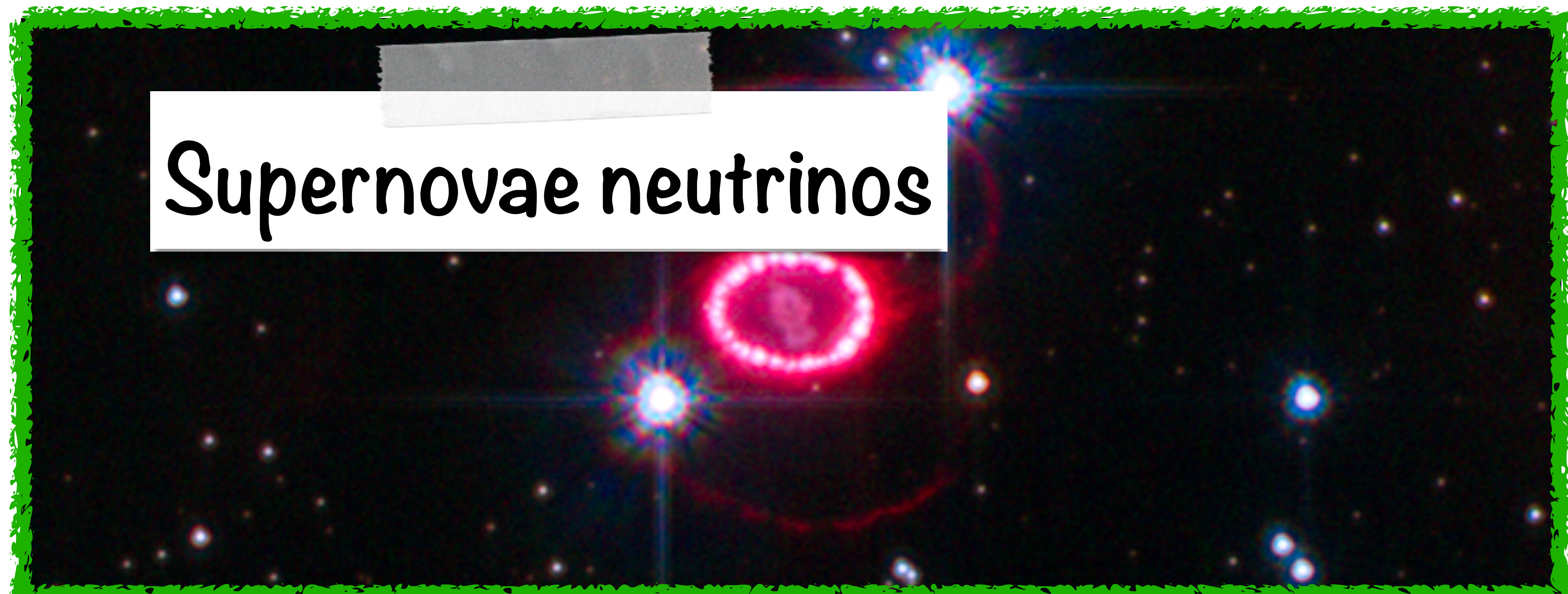


- Probe Grand Unified Theories via p-decay or $n - \bar{n}$ oscillation

ν_e ν_e ν_μ $\bar{\nu}_\mu$

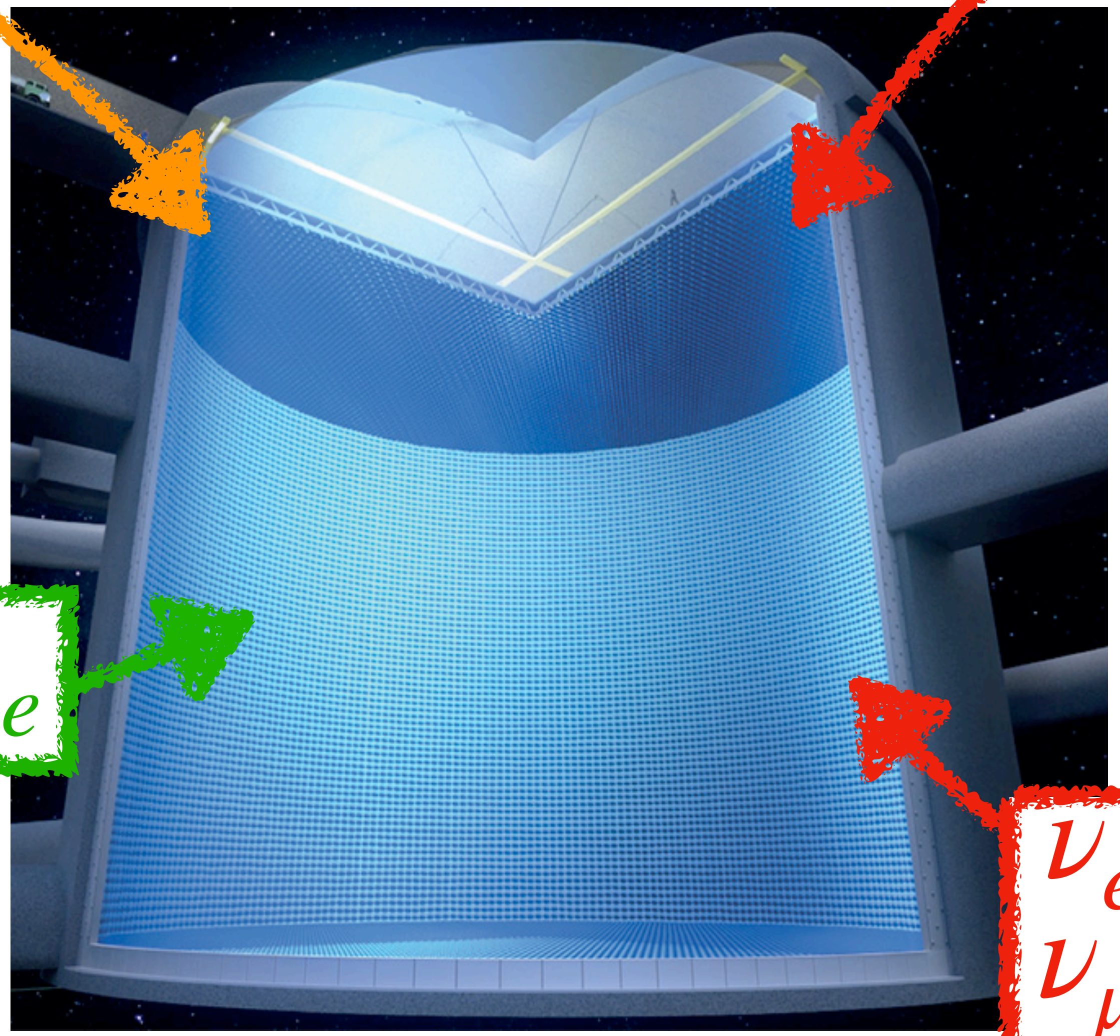


- Observe CP violation for leptons at 5σ
- Precise measurement of δ_{CP}
- High sensitivity to ν mass ordering

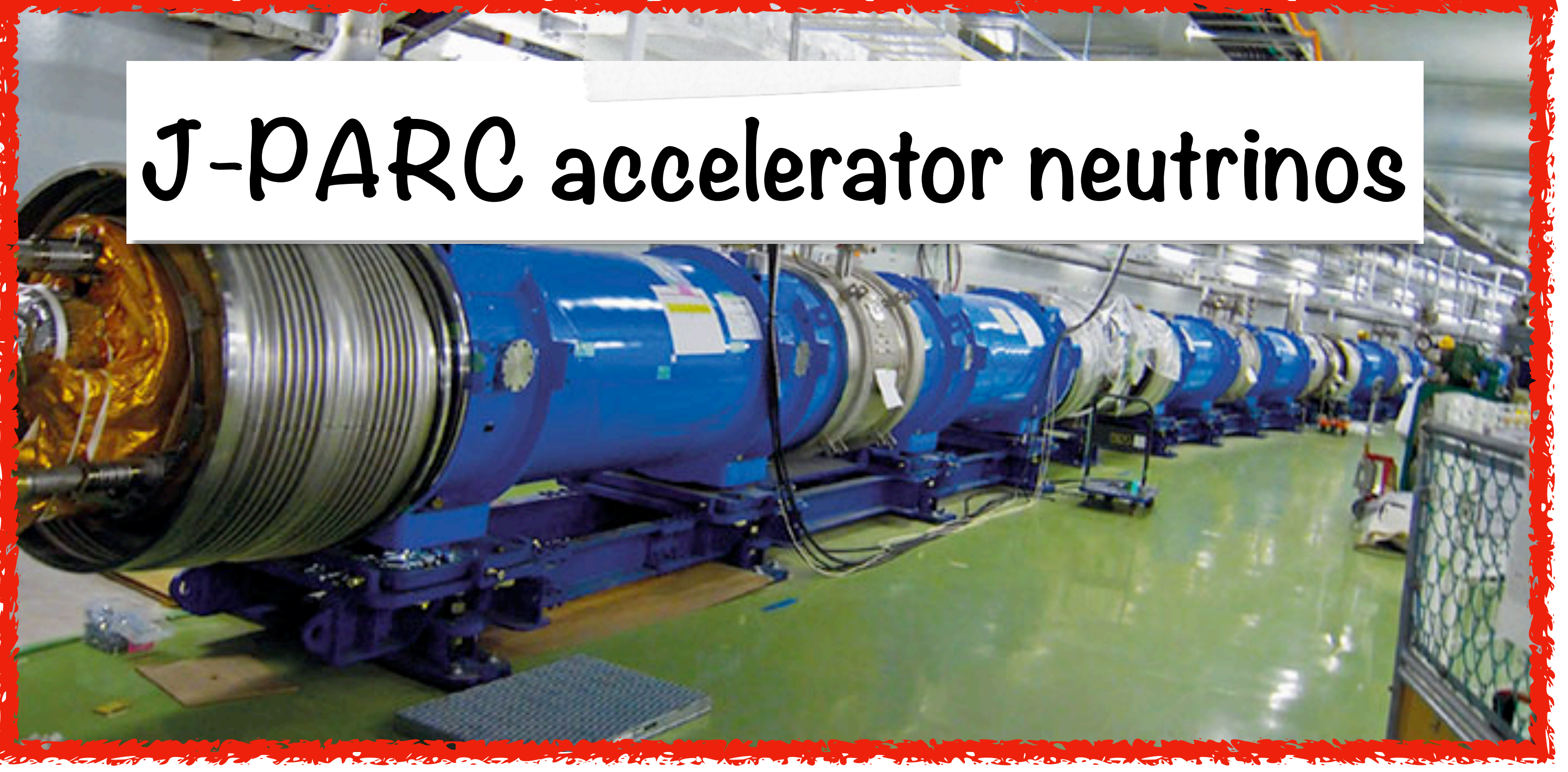


- Transient SN ν: constrain SN profile models
- Relic SN ν: constrain cosmic star formation

$\bar{\nu}_e$

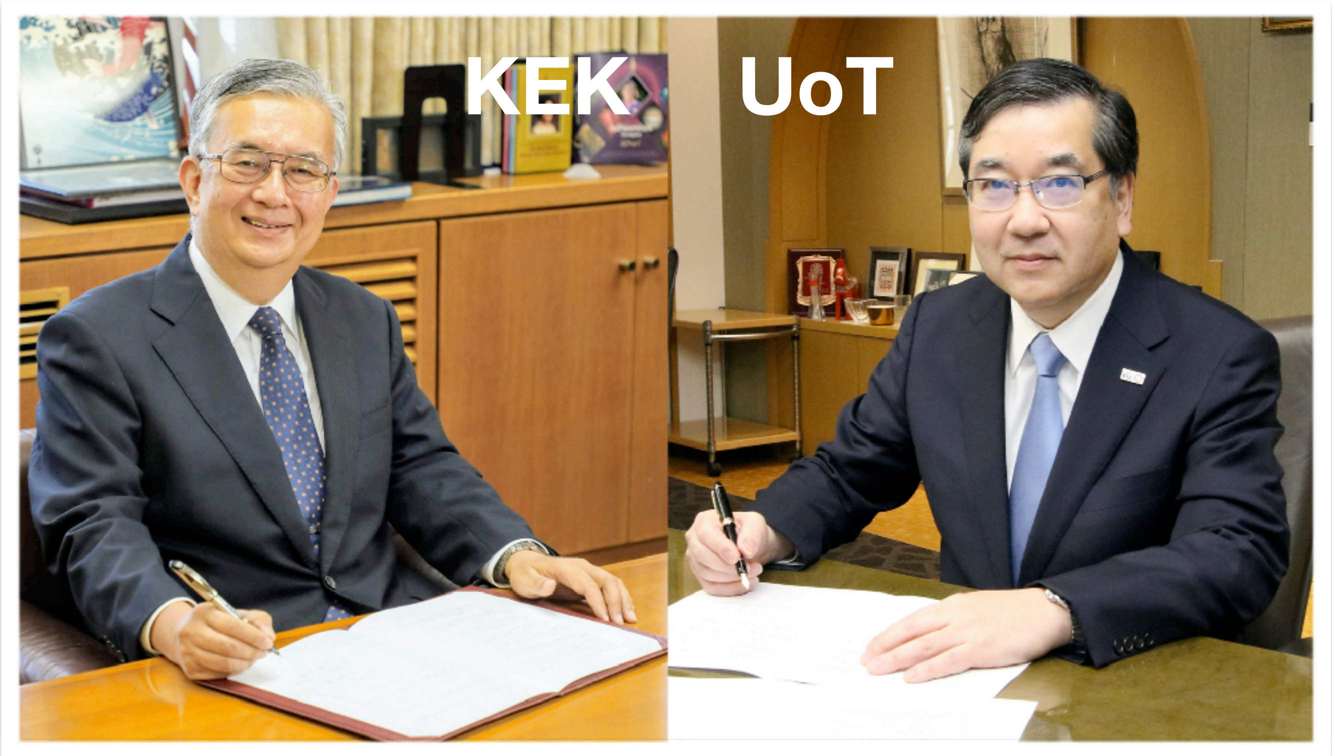


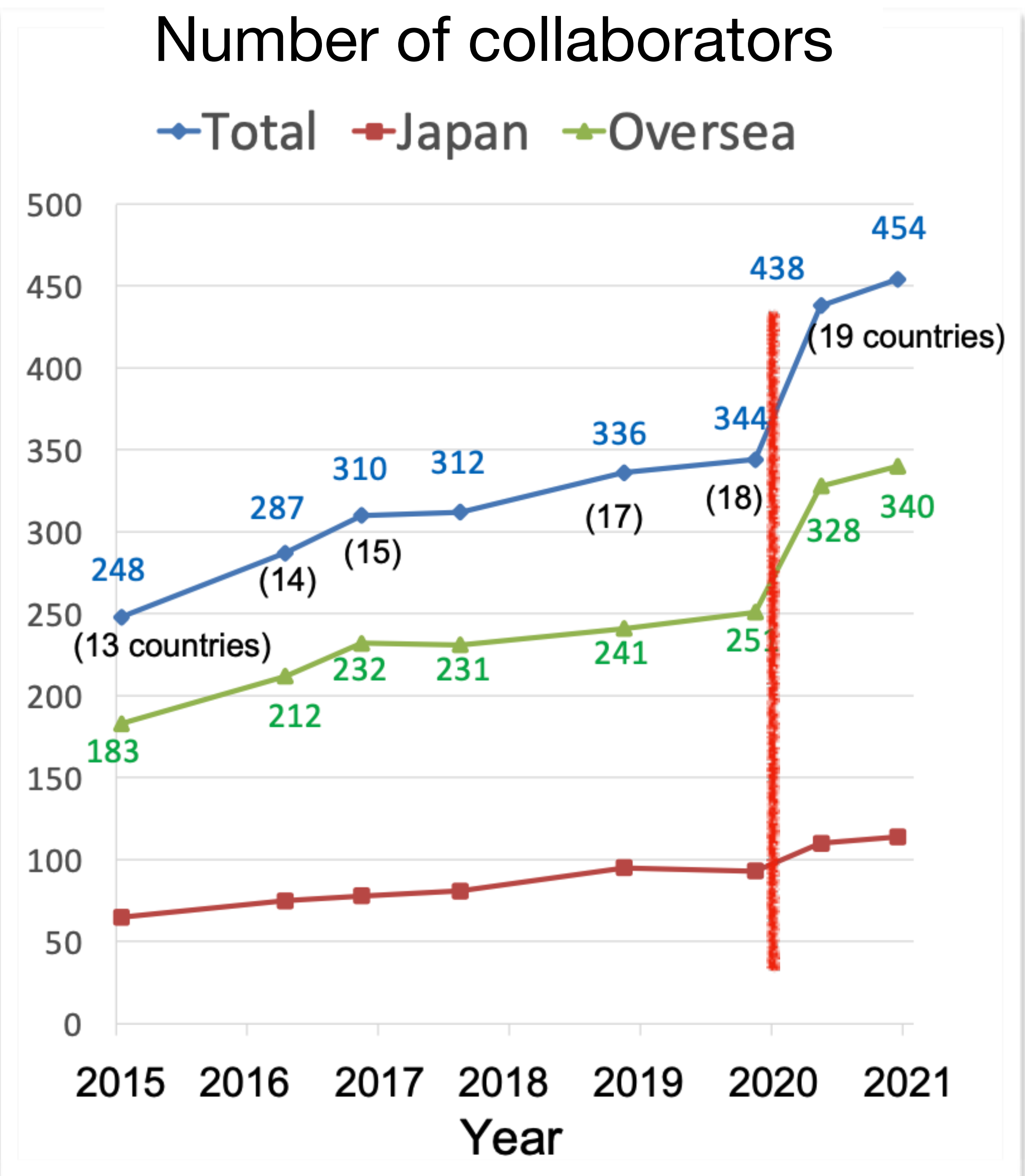
ν_e ν_e ν_μ $\bar{\nu}_\mu$



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.”





Japan timeline:

- Aug. 2019: MEXT approval of HK project
- Feb. 2020: HK budget approved
- May 2020: Signature of MOU
- May 2021: Groundbreaking ceremony

2018 | 2019 | 2020 | 2021

France timeline:

- 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 HK[4], 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)

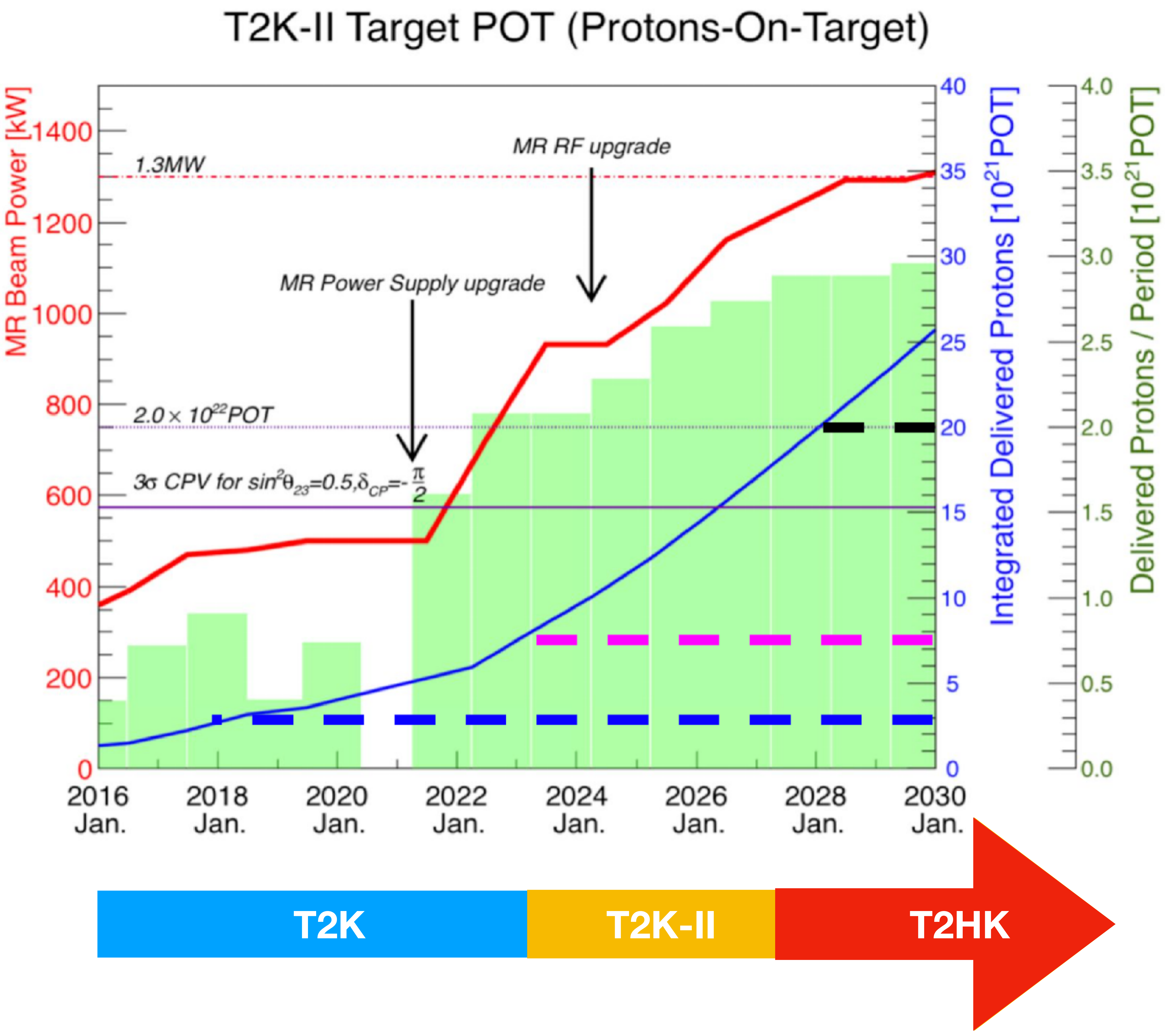
Tokai to HK: heritage from T2K

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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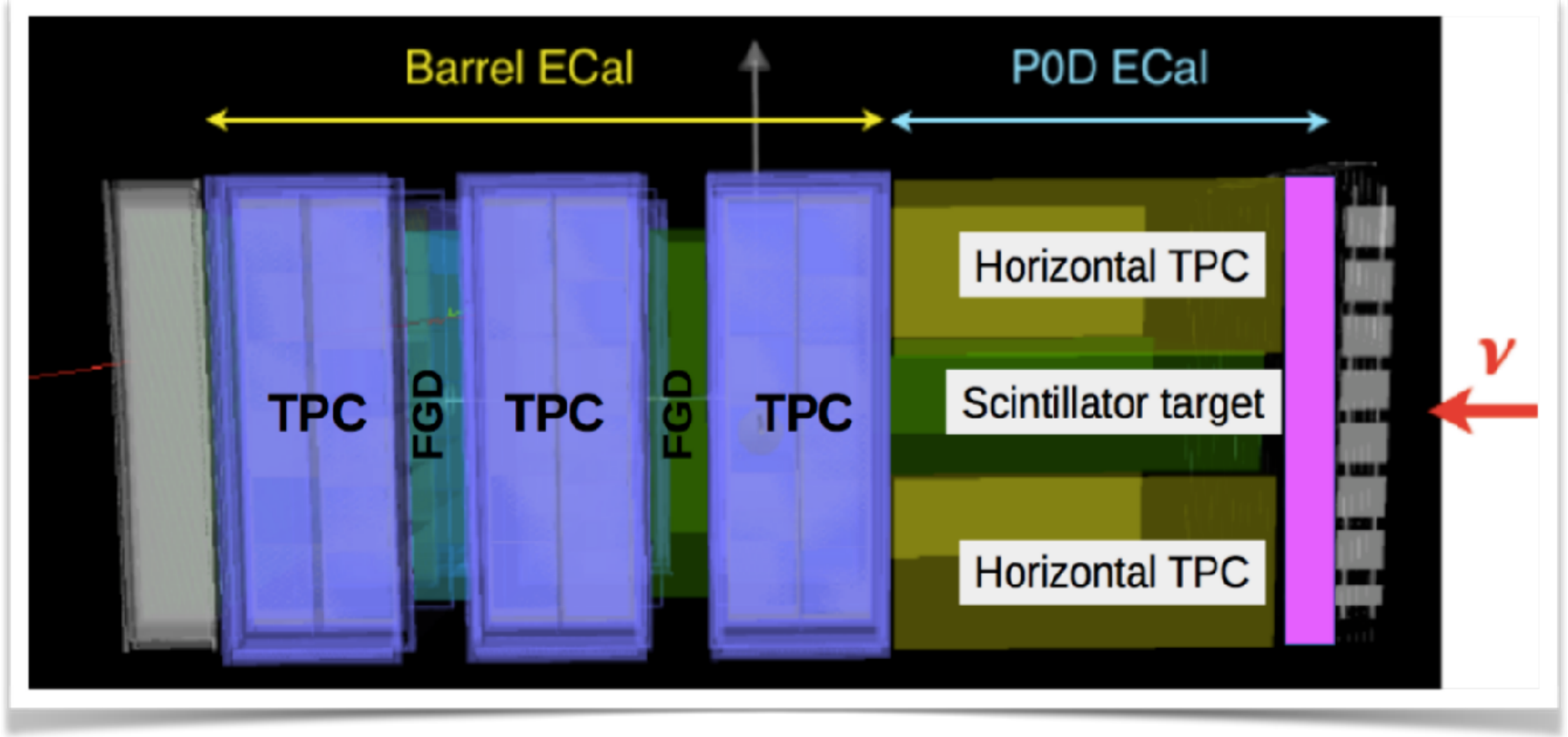
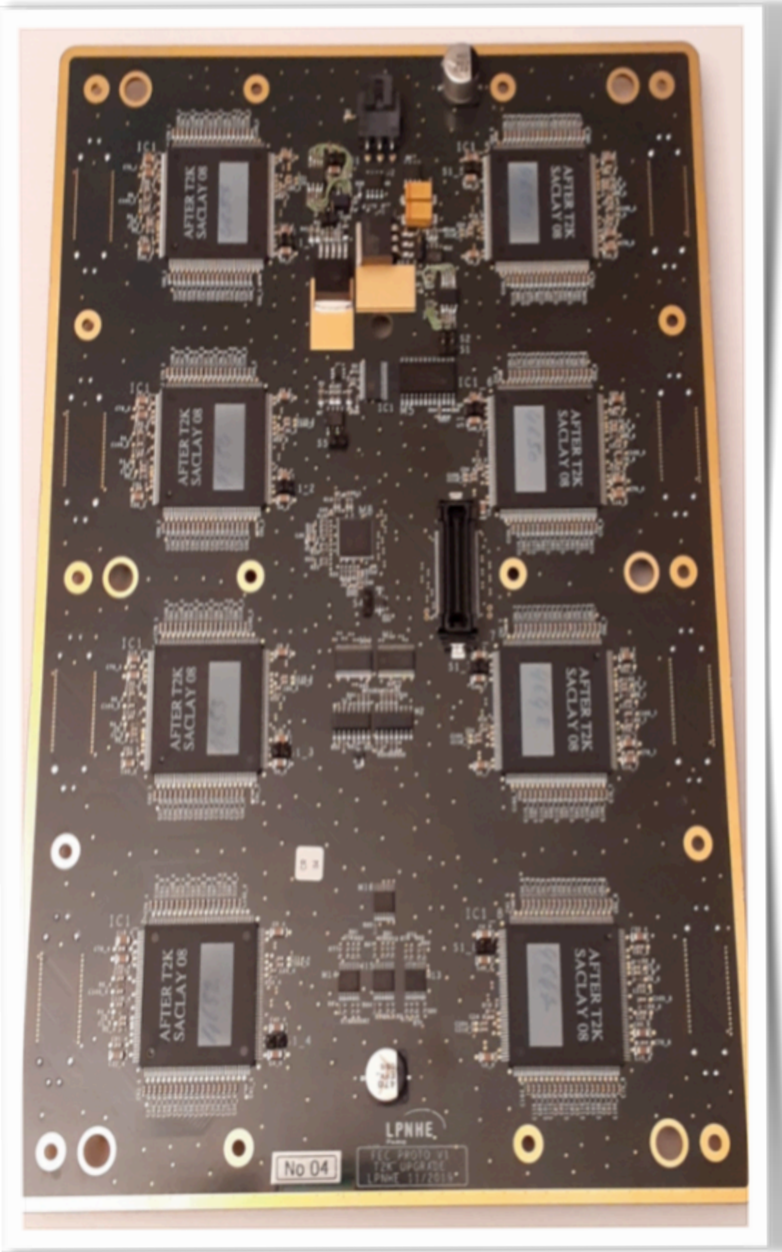
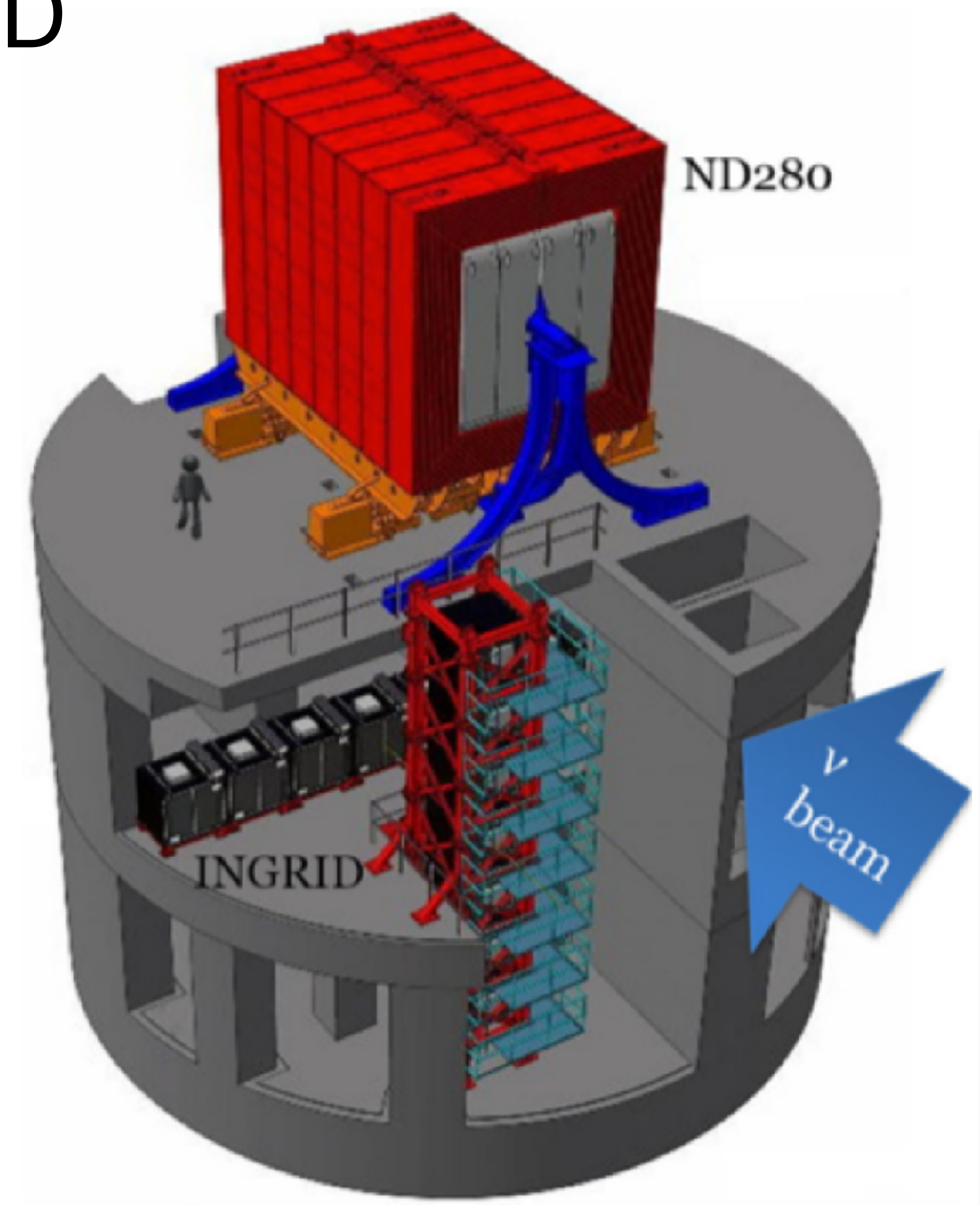
Magnetized near detector @280 m (ND280) + INGRID

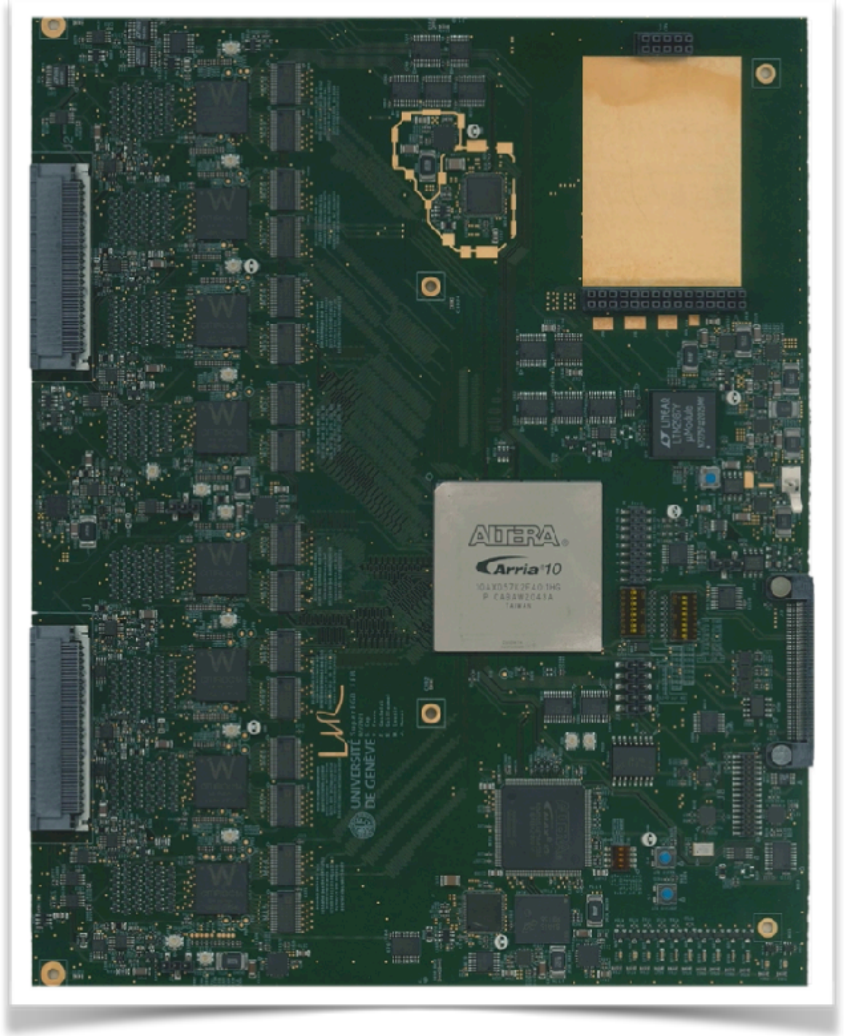
- Used for T2K Oscillation Analysis for >10 years
- Being upgraded now for T2K-II
- (crucial contributions and strong support from IN2P3)
- **Systematics uncertainties under control from Day-1 of HK**





FEC for HA-TPC readout





FEB for SuperFGD readout

Tokai to HK: what will be new

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

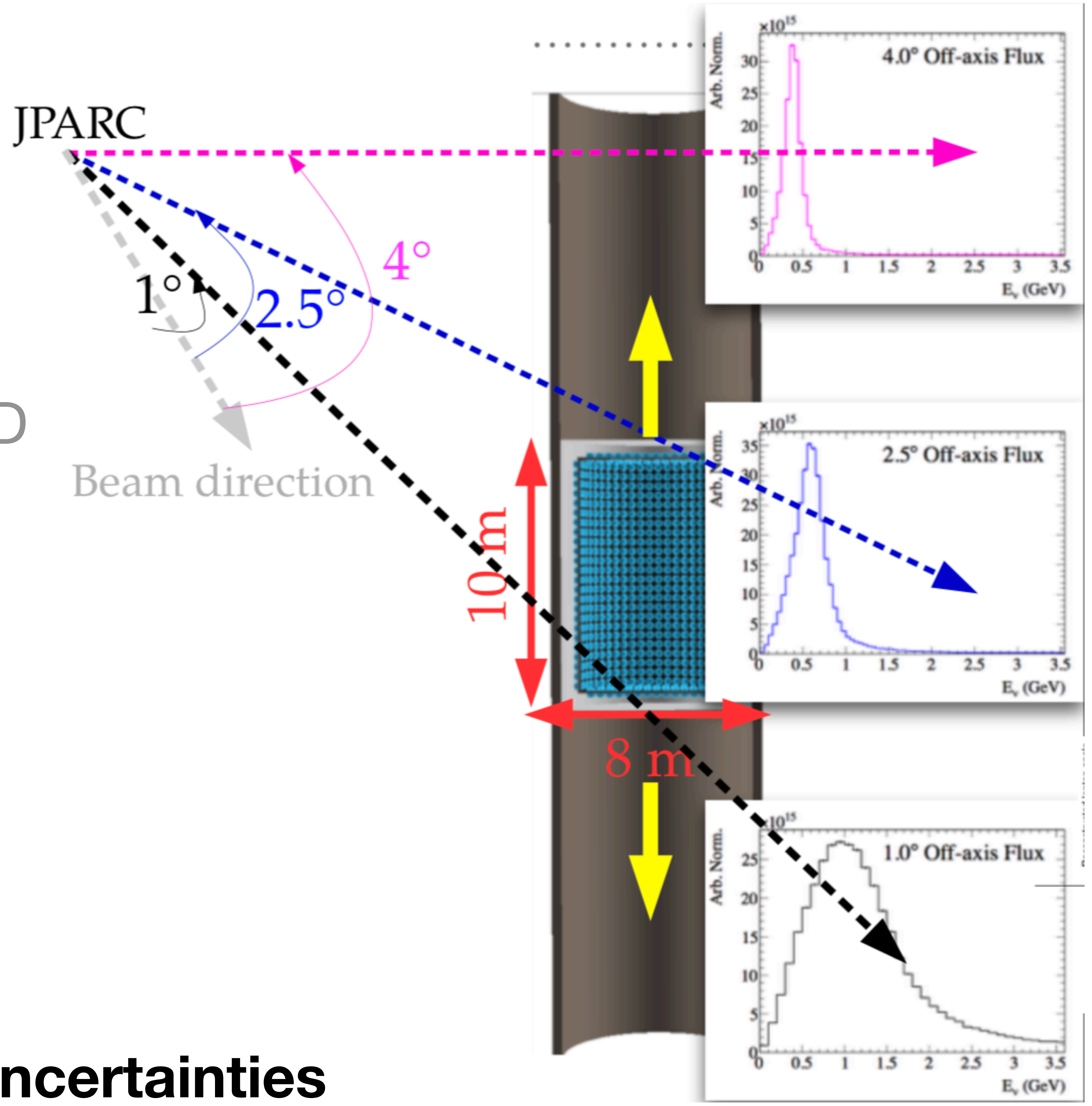
Magnetized near detector @280 m (ND280) + INGRID

- 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

Intermediate Water Cherenkov Detector (IWCD/E61)

NEW

- Measure ν interactions on Water
- High stats. sample of ν_e interactions

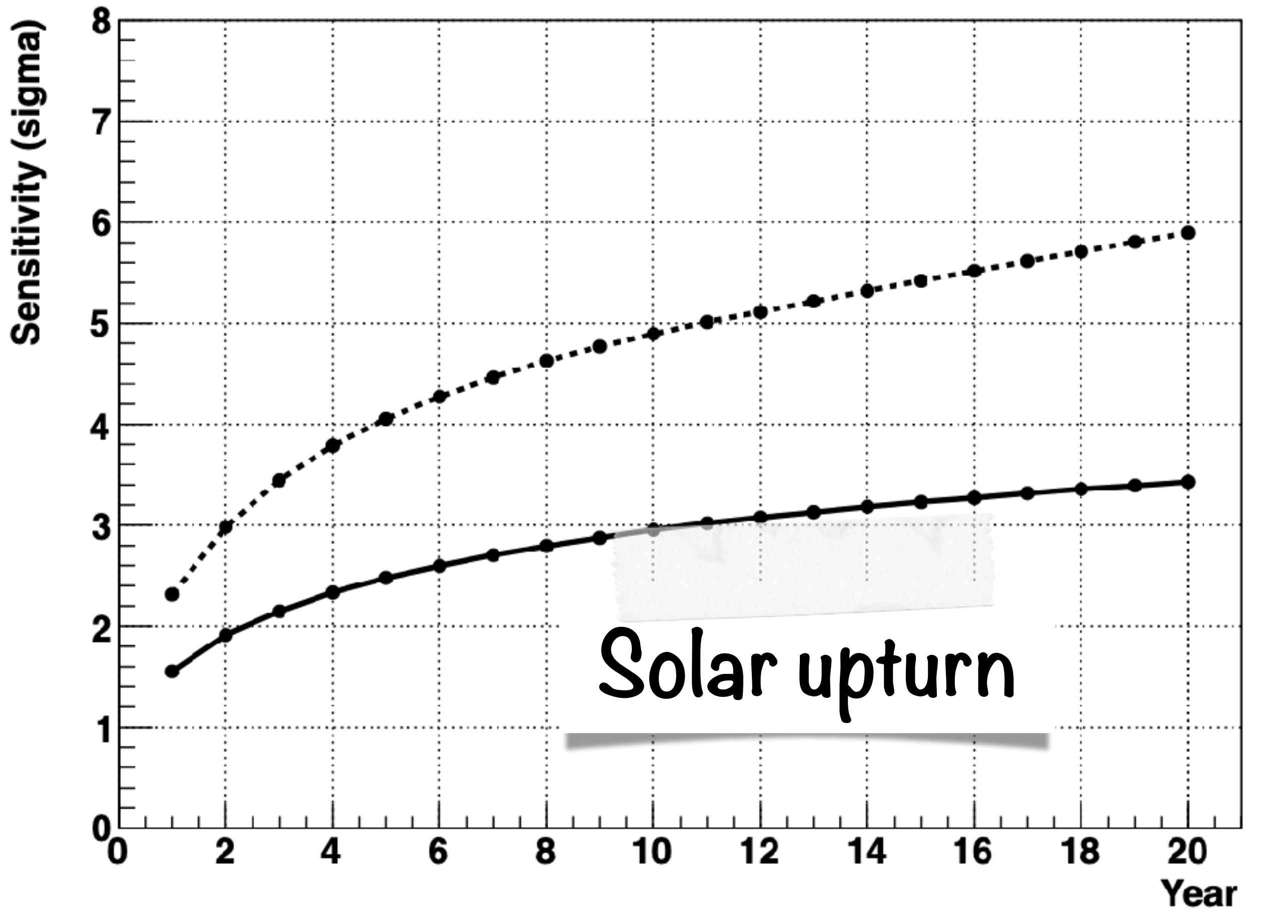


Needed to reach final HK goal for systematics uncertainties

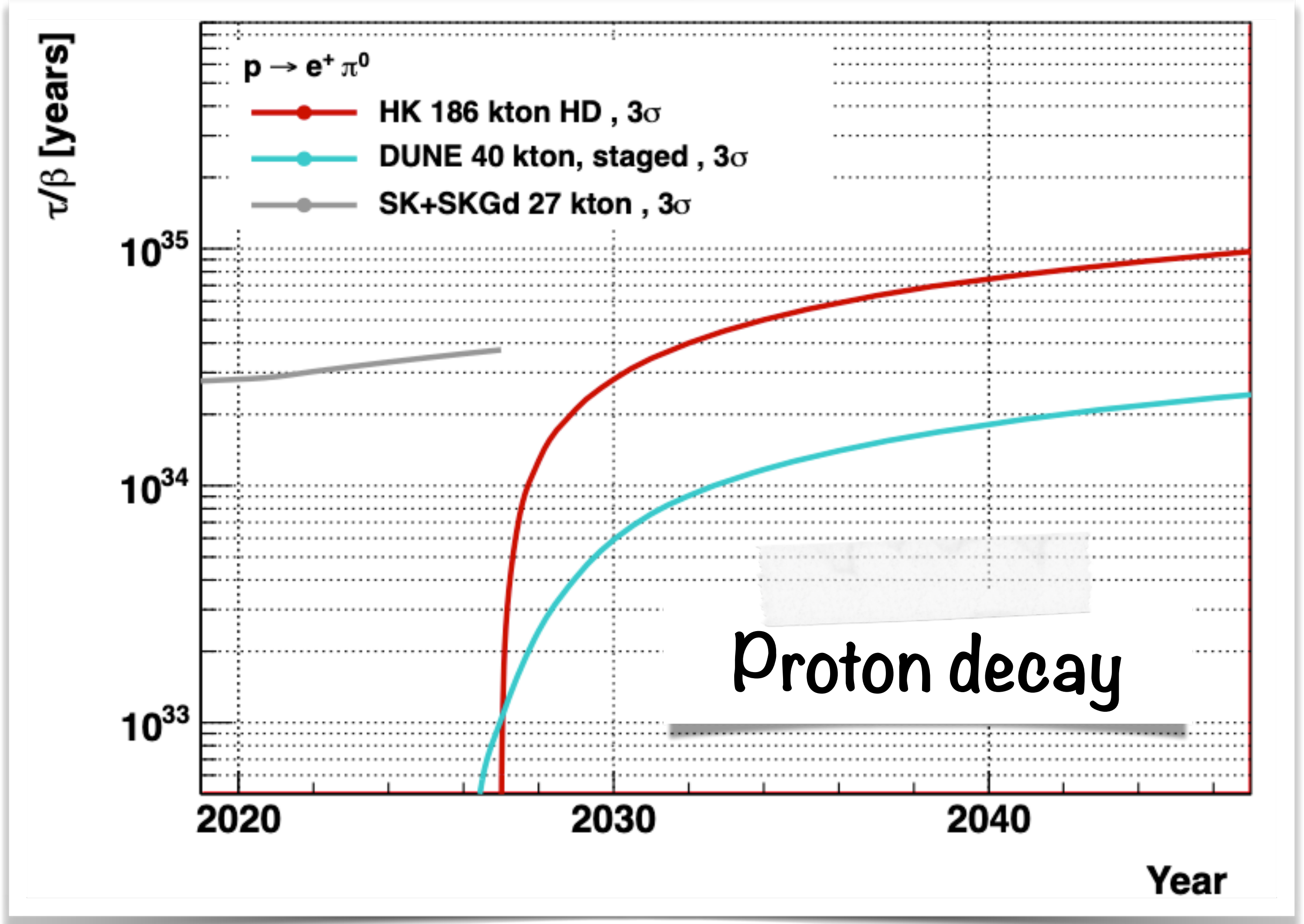
(if IWCD is delayed, ND280 will be the only near detector on day 1 of HK)

Hyper-Kamiokande Physics

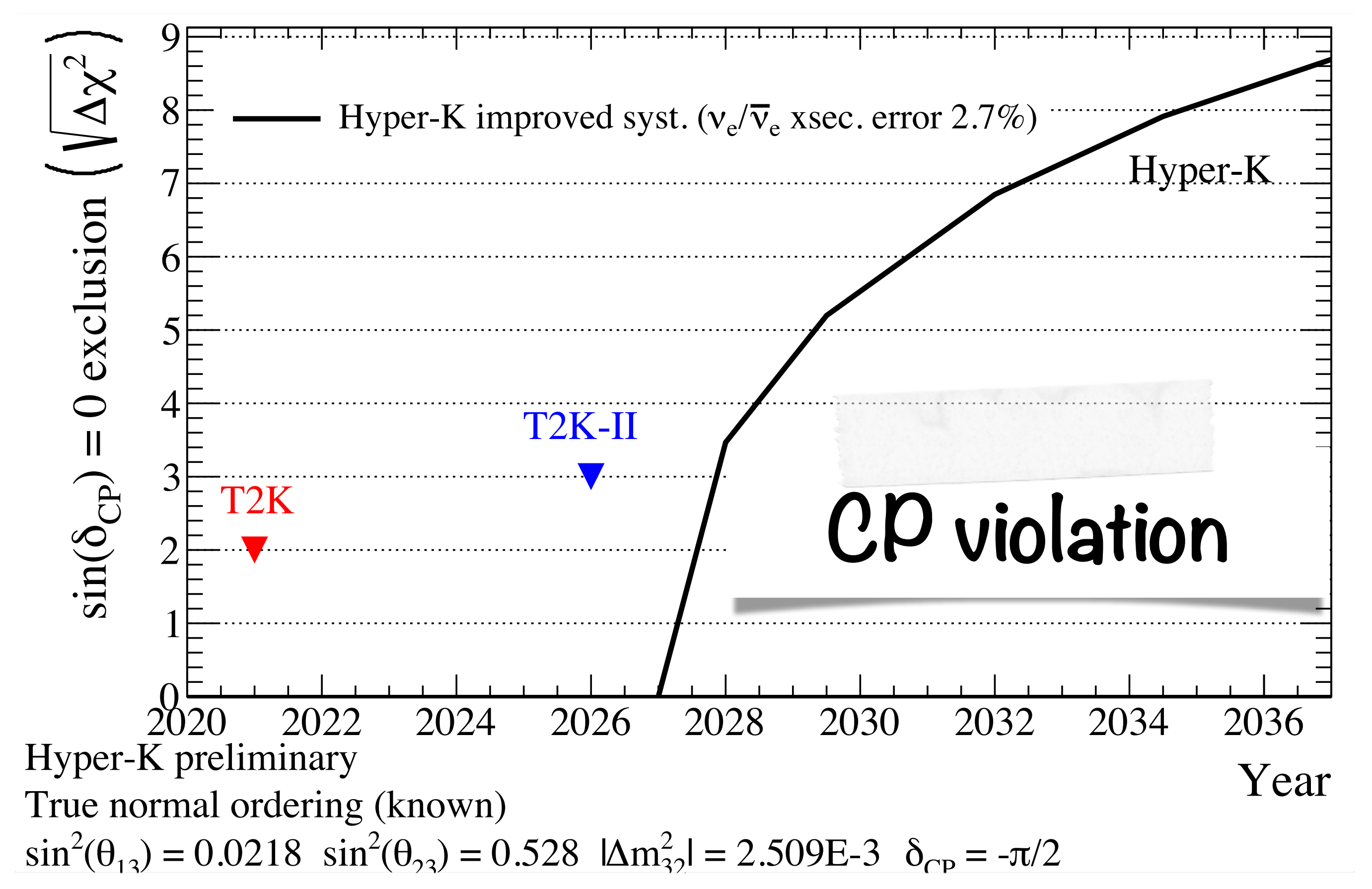
Solar physics

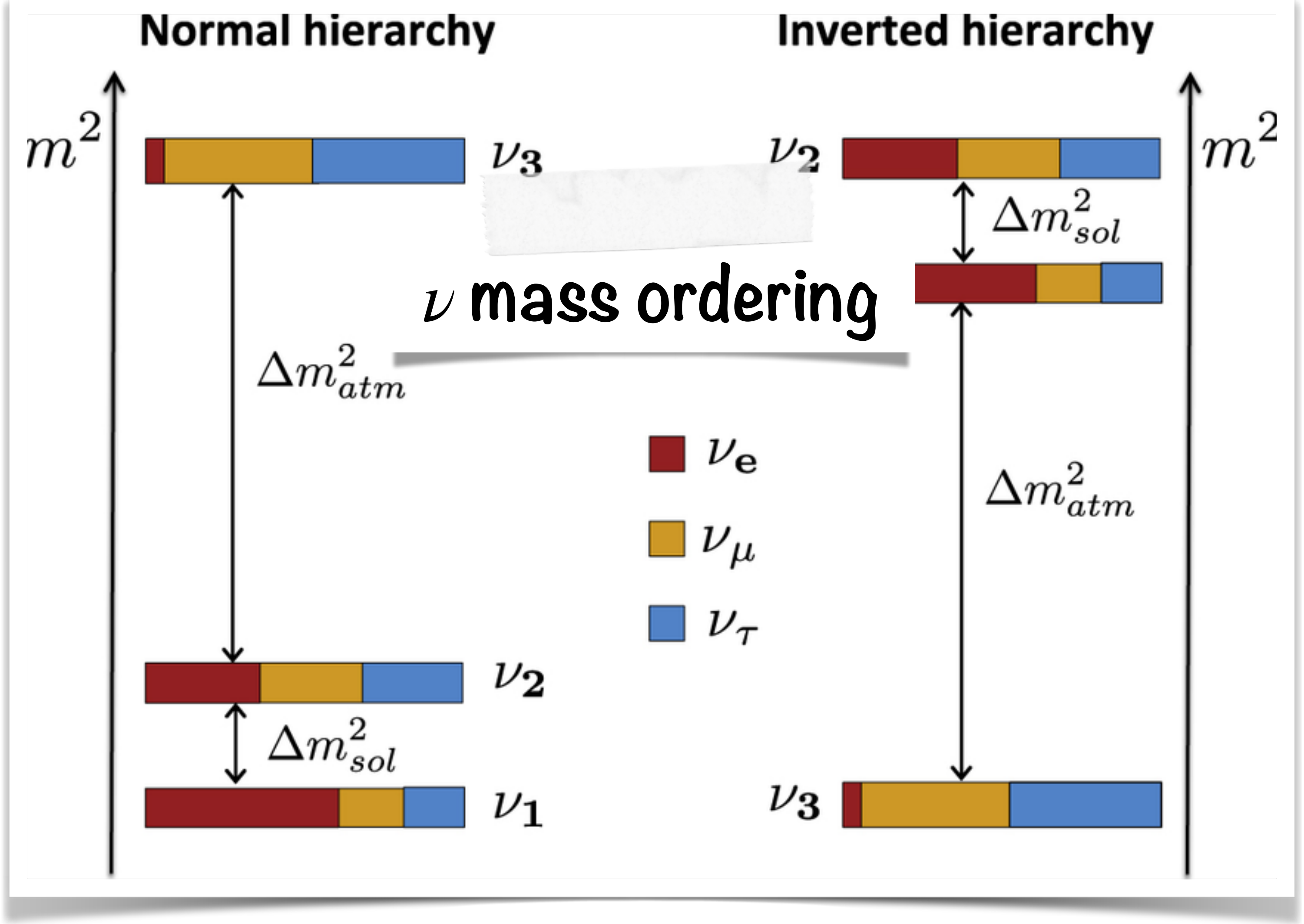


Rare events

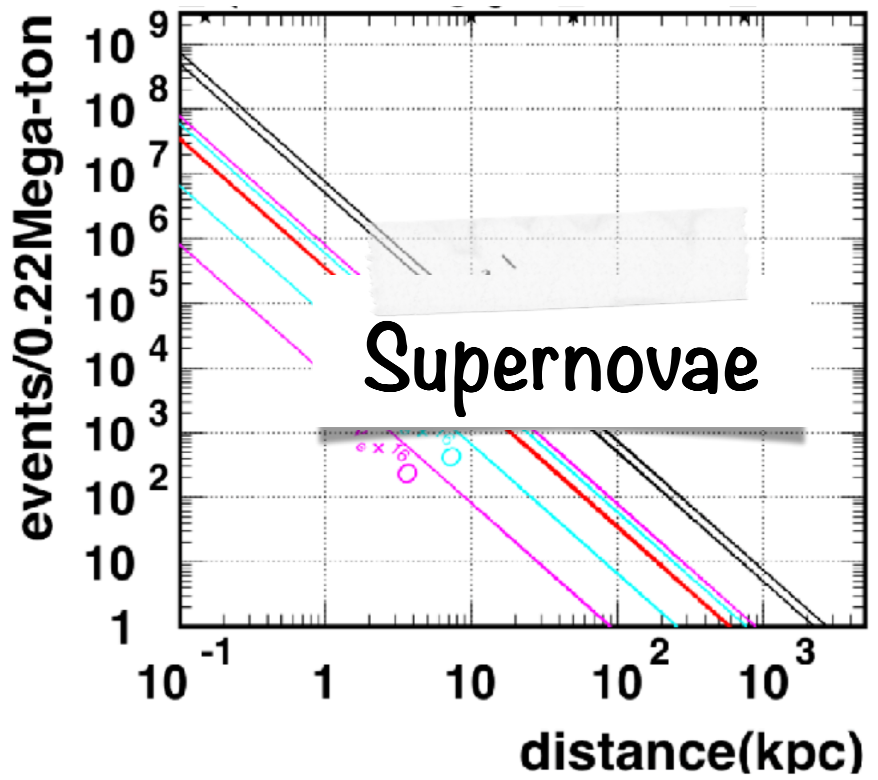


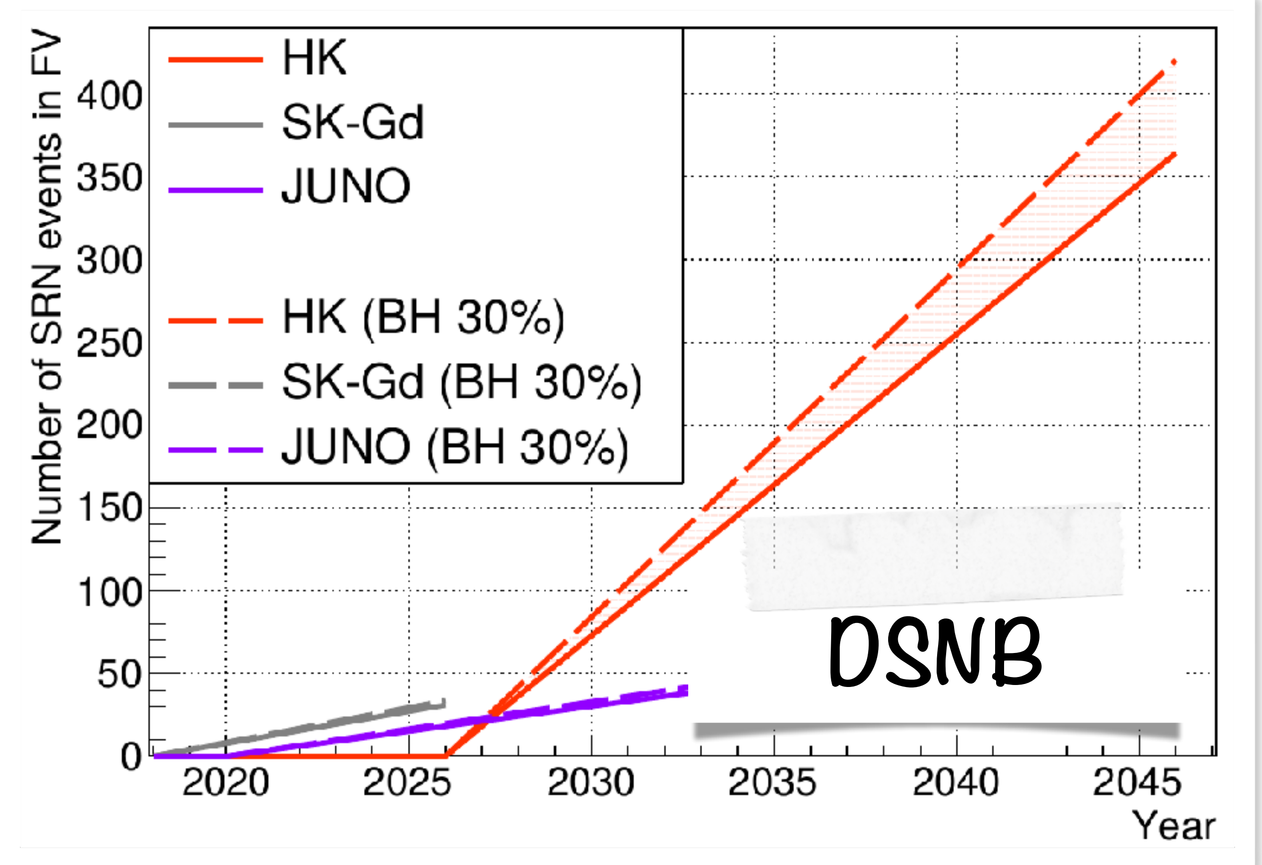
Neutrinos oscillation





Supernovae modeling and Early Universe

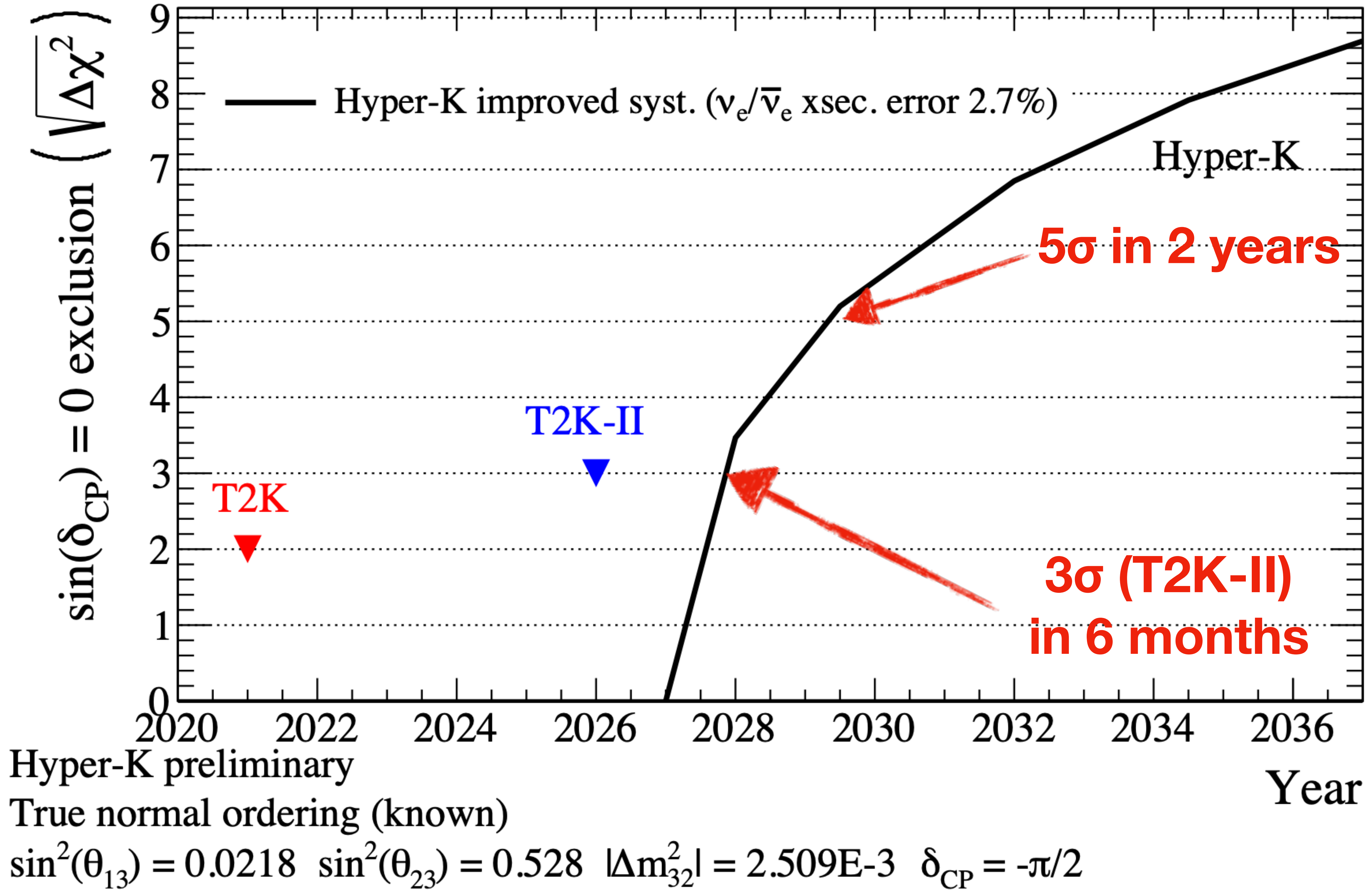


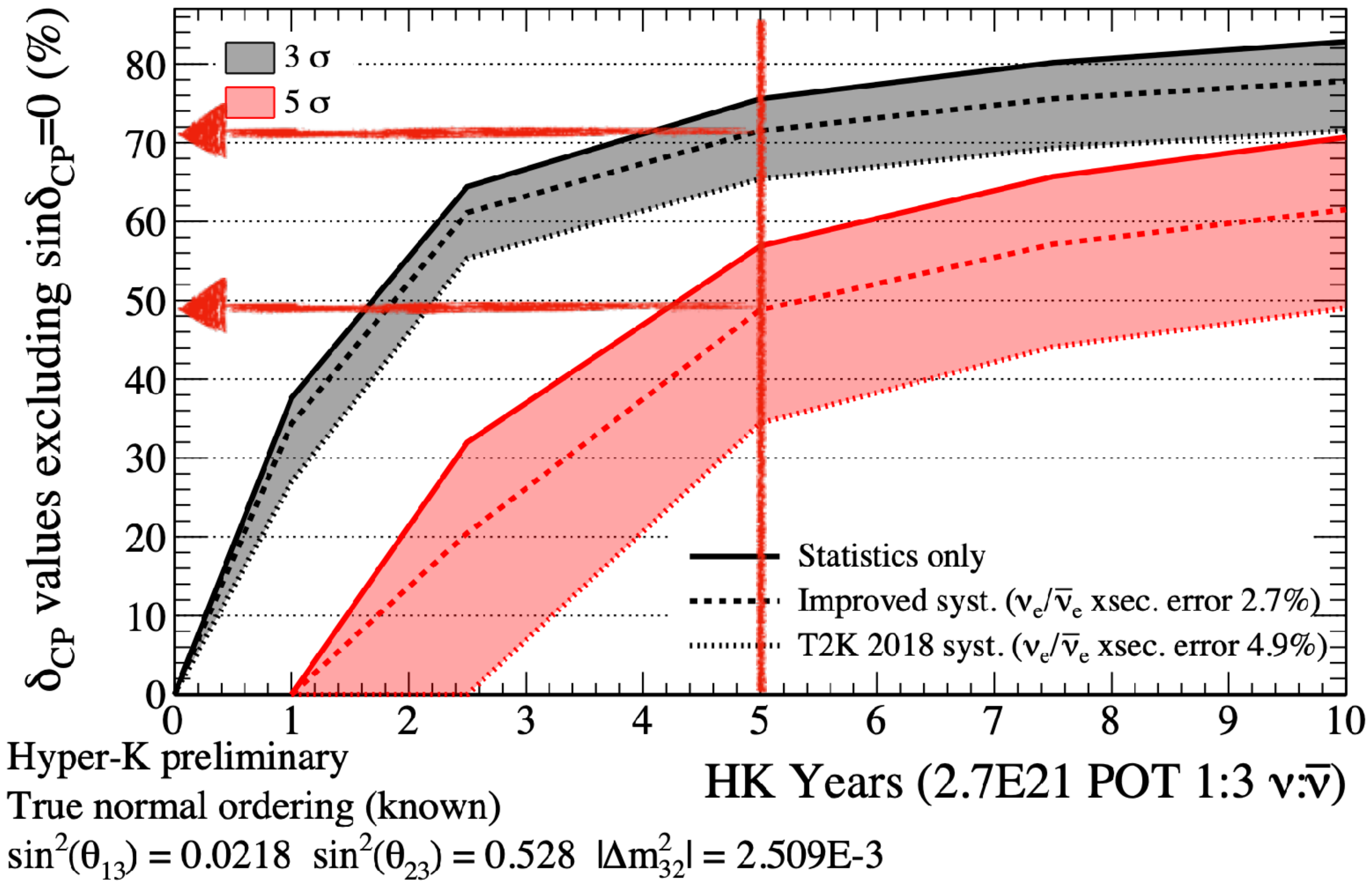


Hyper-Kamiokande

Fast CP-violation discovery

Known mass ordering





If δ_{CP}=-π/2, CP violation discovered before any other LBL-ν experiment

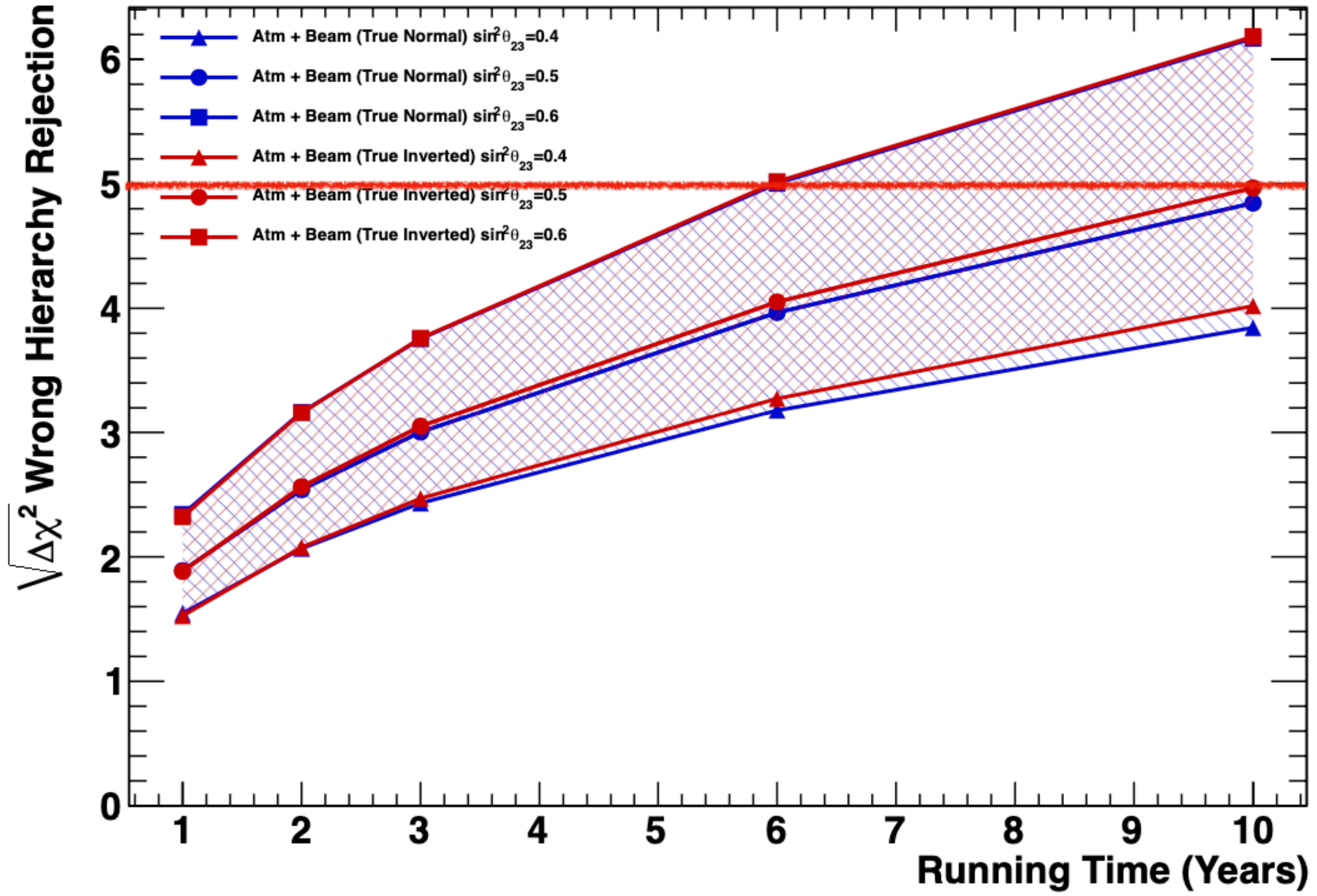
Fastest experiment to survey possible δ_{CP} values

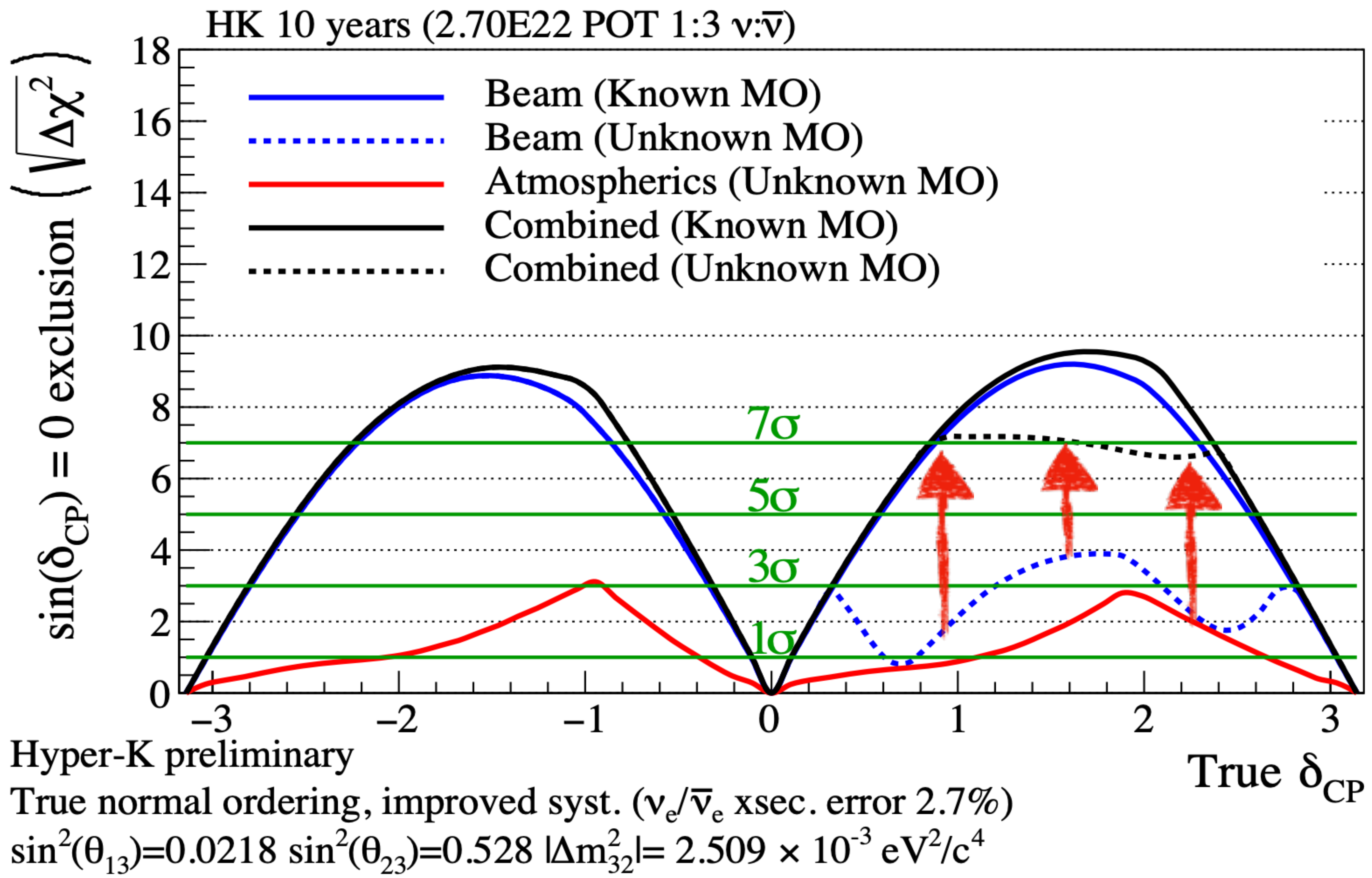
	$\delta_{CP} = -\pi/2$		All δ_{CP}	
	3σ	5σ	50 % 5σ	70 % 3σ
Hyper Kamiokande	0.5 y	2 y	5 y	5 y
DUNE (staged*)	4 y	8 y	10 y	13 y

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

DUNE CDR arXiv:2002.03005
IUPAP Neutrino panel report

Mass ordering sensitivity with atmospherics



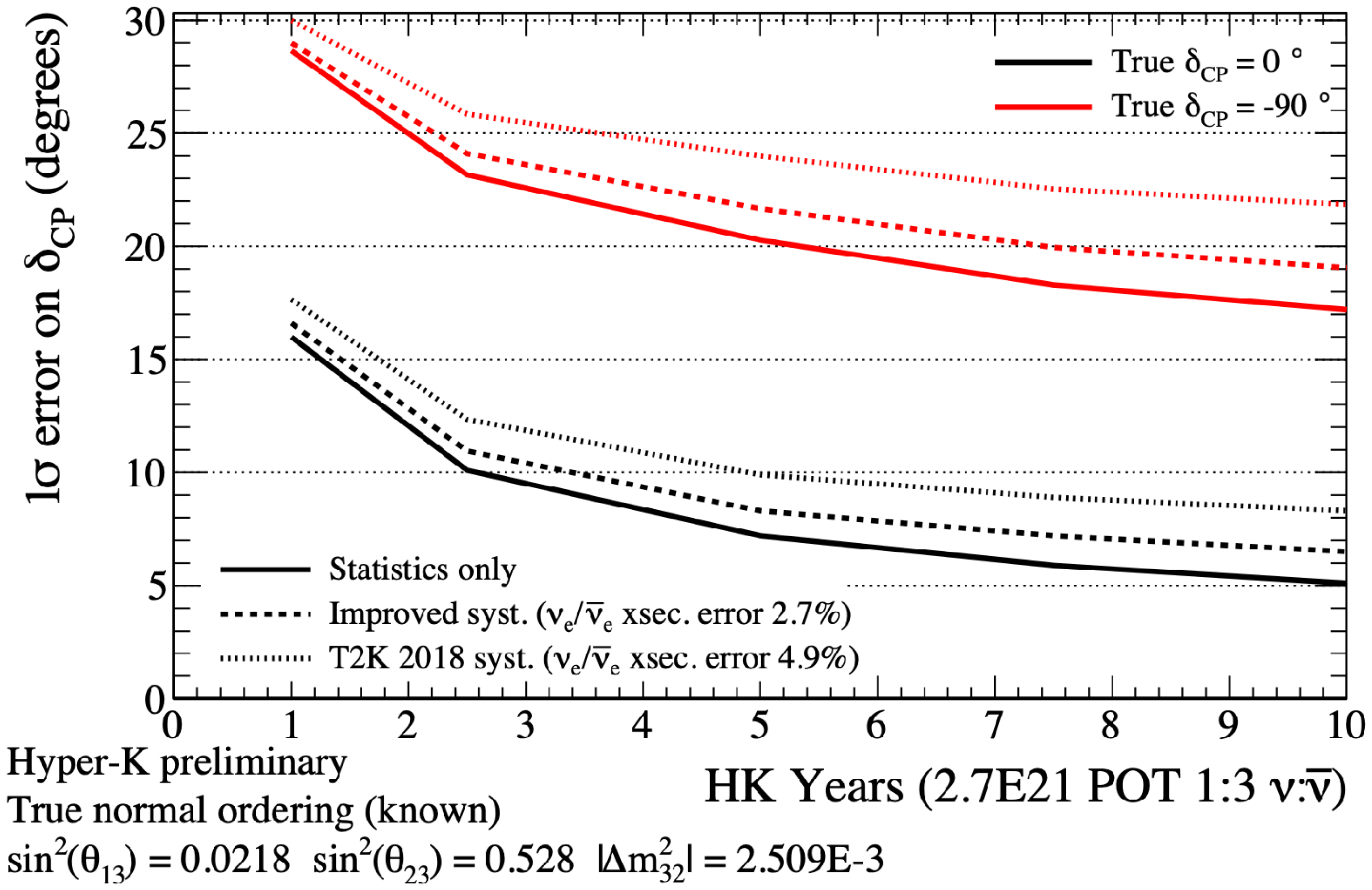


If not discovered by T2K/SK, NOvA, ORCA or JUNO before 2027, HK can determine MO after 6-10 years via atmospheric ν

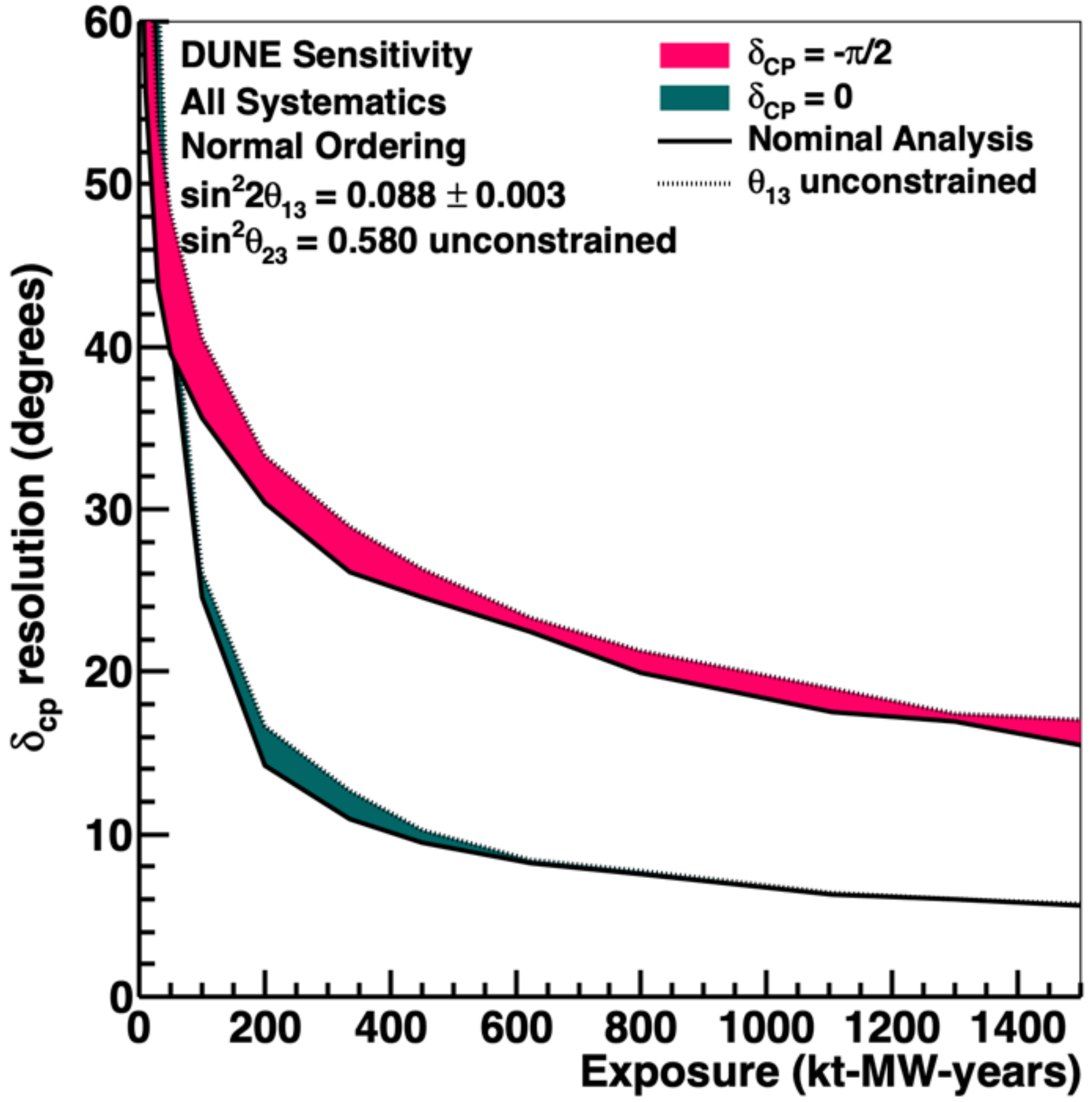
	$\sin^2\theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	2.2 σ	→ 3.8 σ
	0.60	4.9 σ	→ 6.2 σ

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



DUNE CDR arXiv:2002.03005

Precision = sensitivity to matter-antimatter models

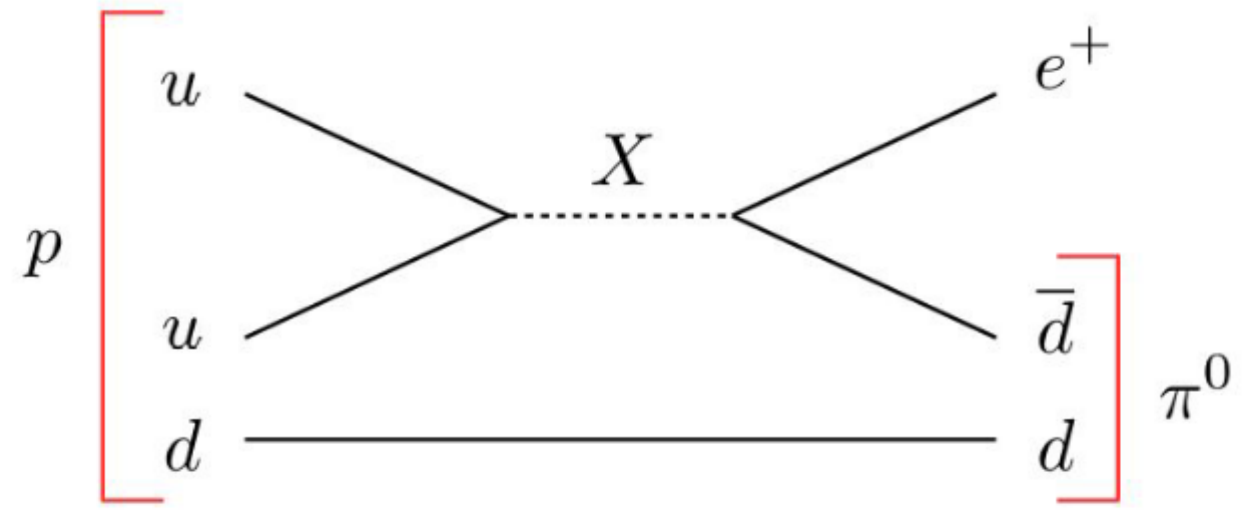
→ **HK will quickly reach precision on δ_{CP} of 30°(15°) for δ_{CP} =-π/2 (0)**

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

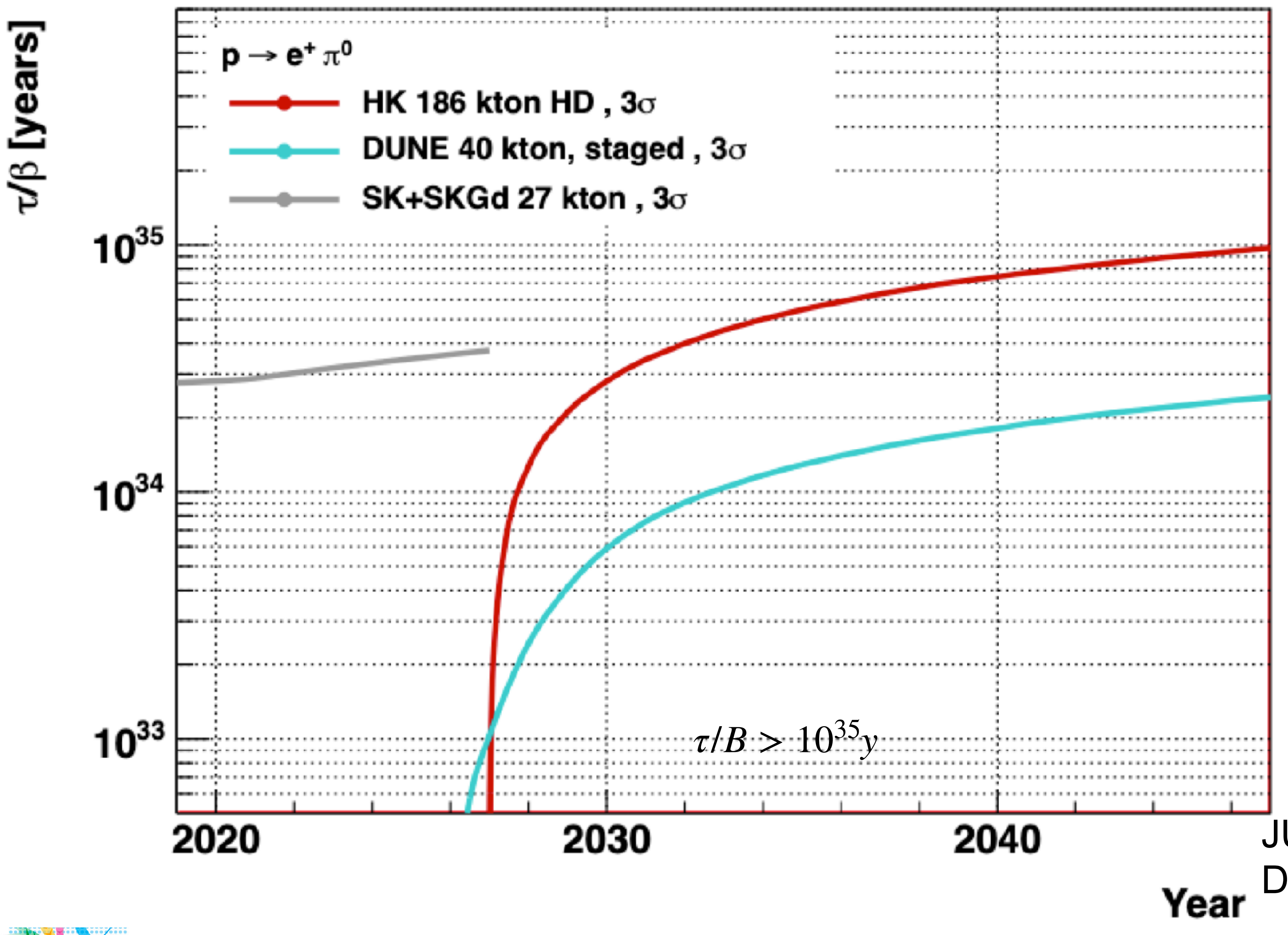
Proton decay

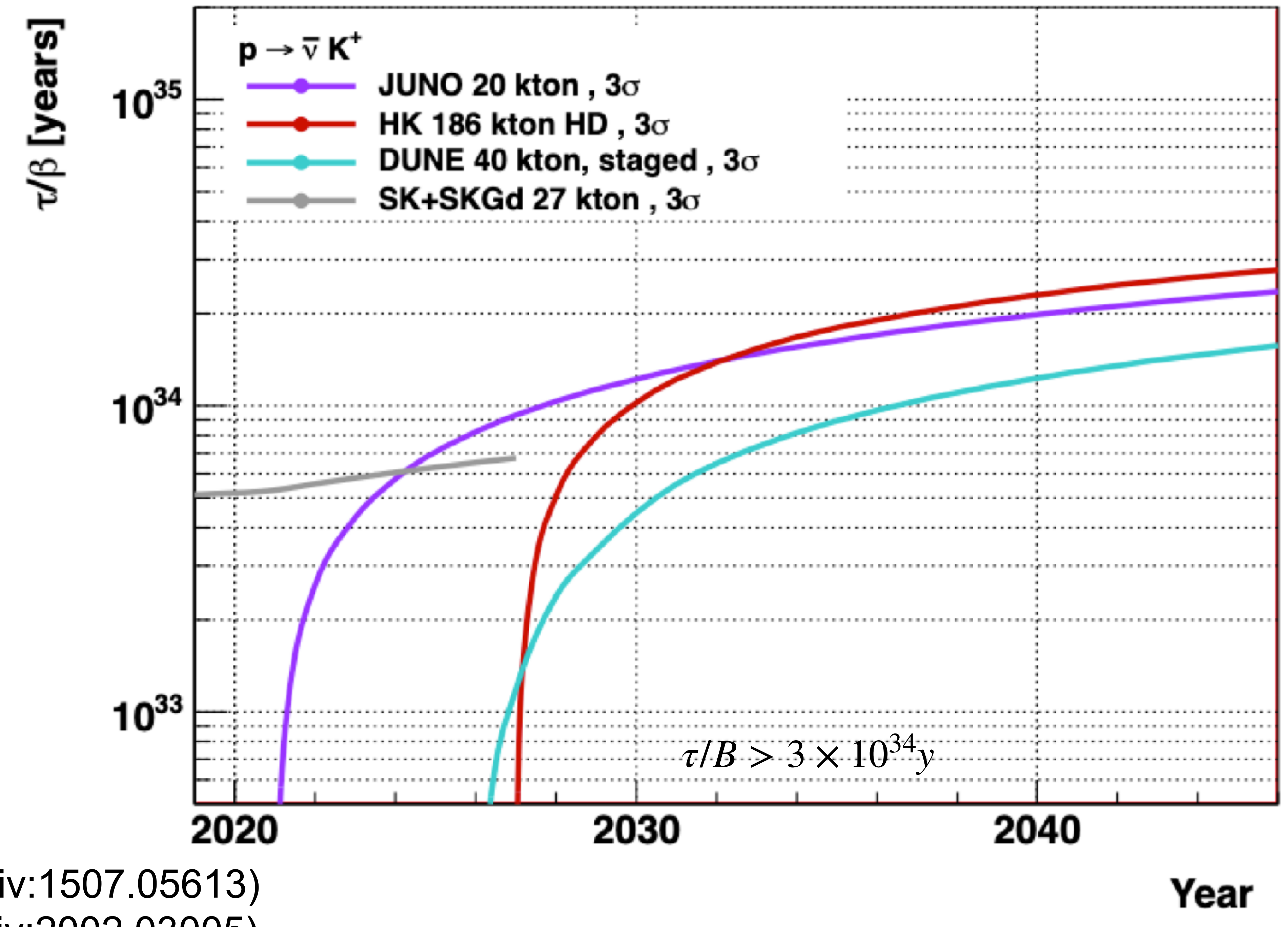
Motivated by Grand-Unification Theories
HK will have the best limit on p → $e^+\pi^0$ for <u>bound</u> protons
→ about 1 order of magnitude better than current limits

Thanks to its huge mass, HK will also have leading sensitivity to channels with invisible particles (p → ν K^+)
HK is sensitive to <u>free</u> 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

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

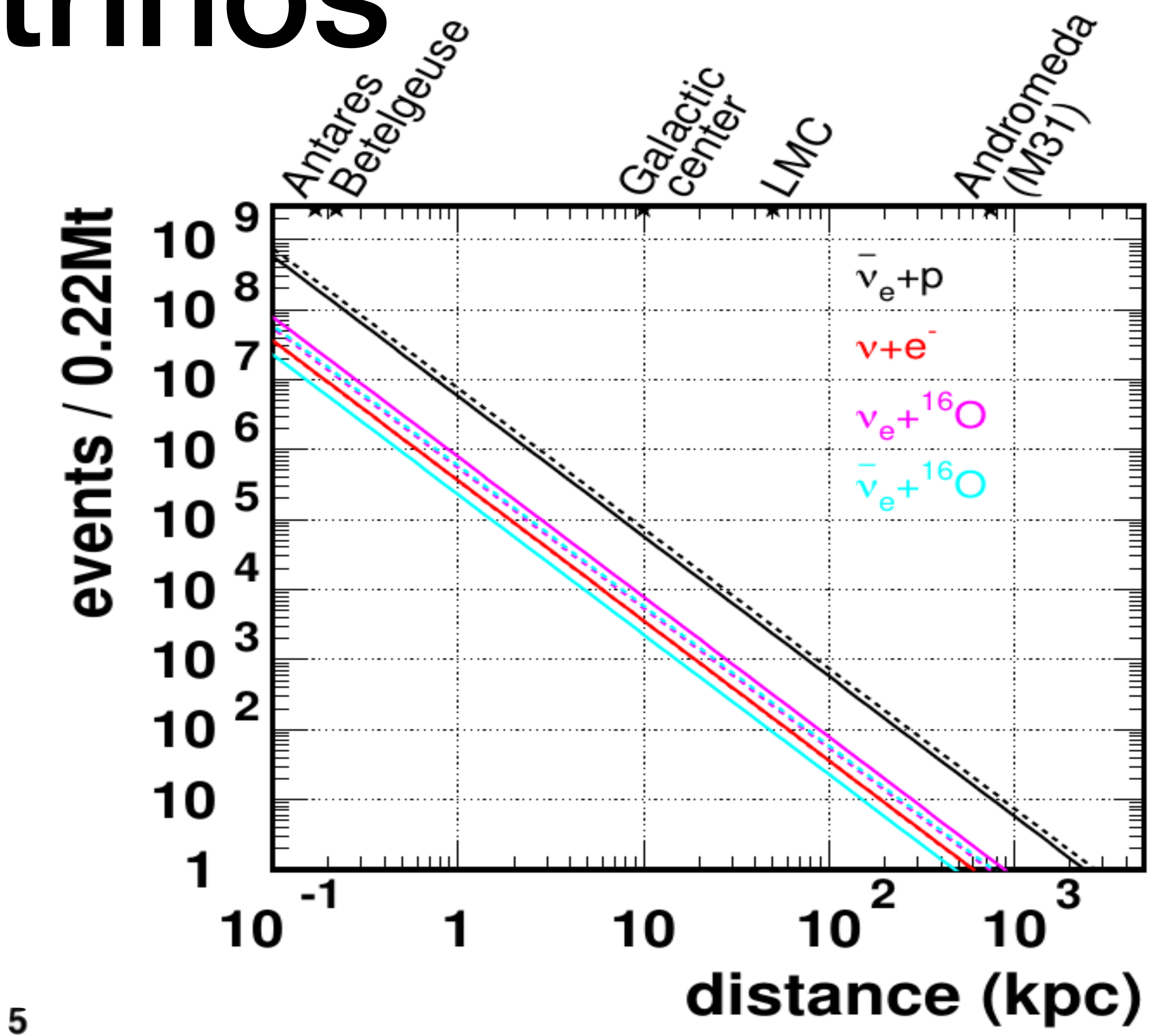
SN1987A type ~2500 events

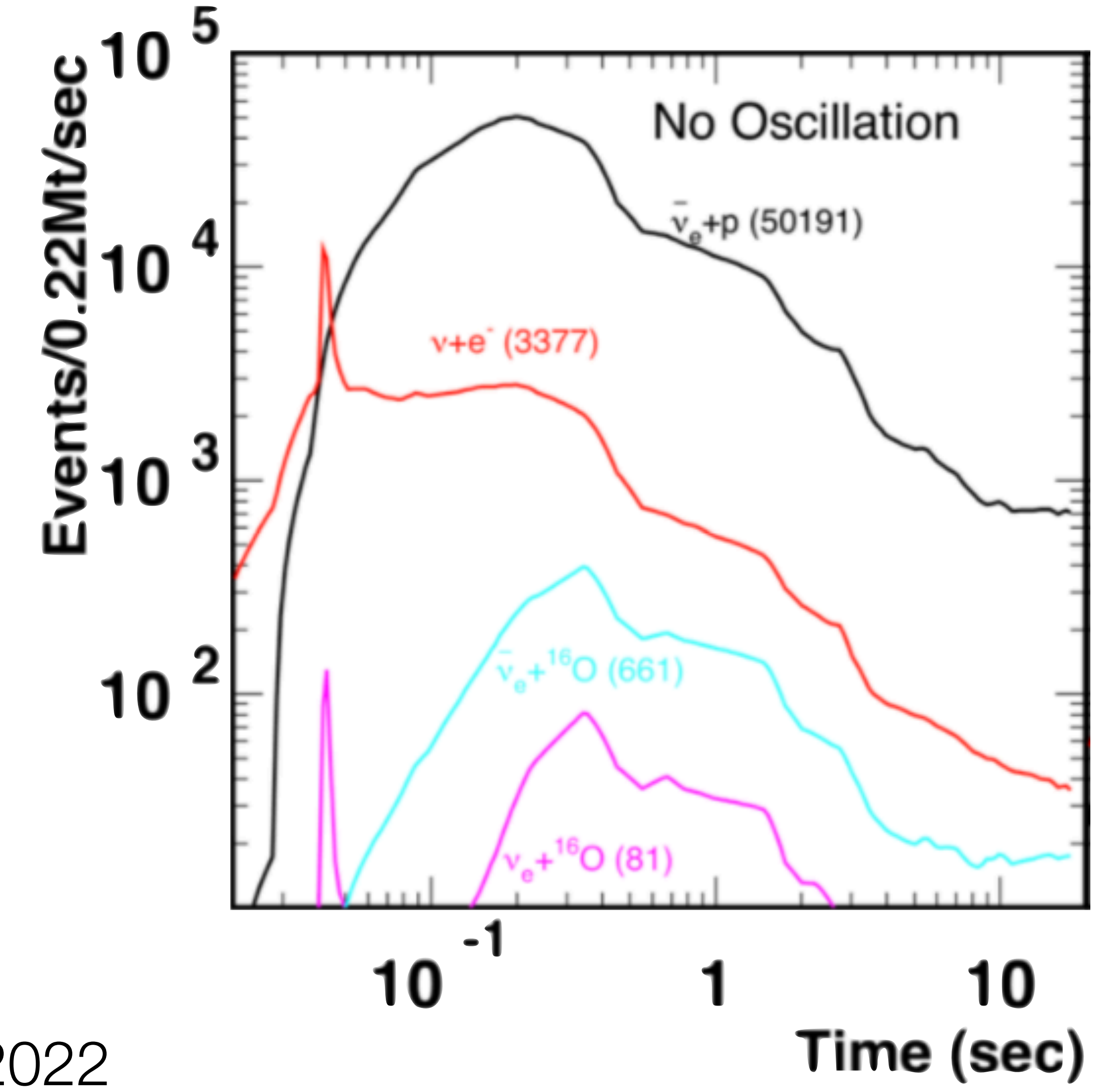
Galactic center: ~50000+ events

Direction (1°@10kpc) → triangulation

Time profile: collapse models

Since HK is sensitive to about 1 Mpc SN, detection of SN explosion expected every 10 y





Gravitational waves sources

Nearby (10 Mpc) neutron star mergers

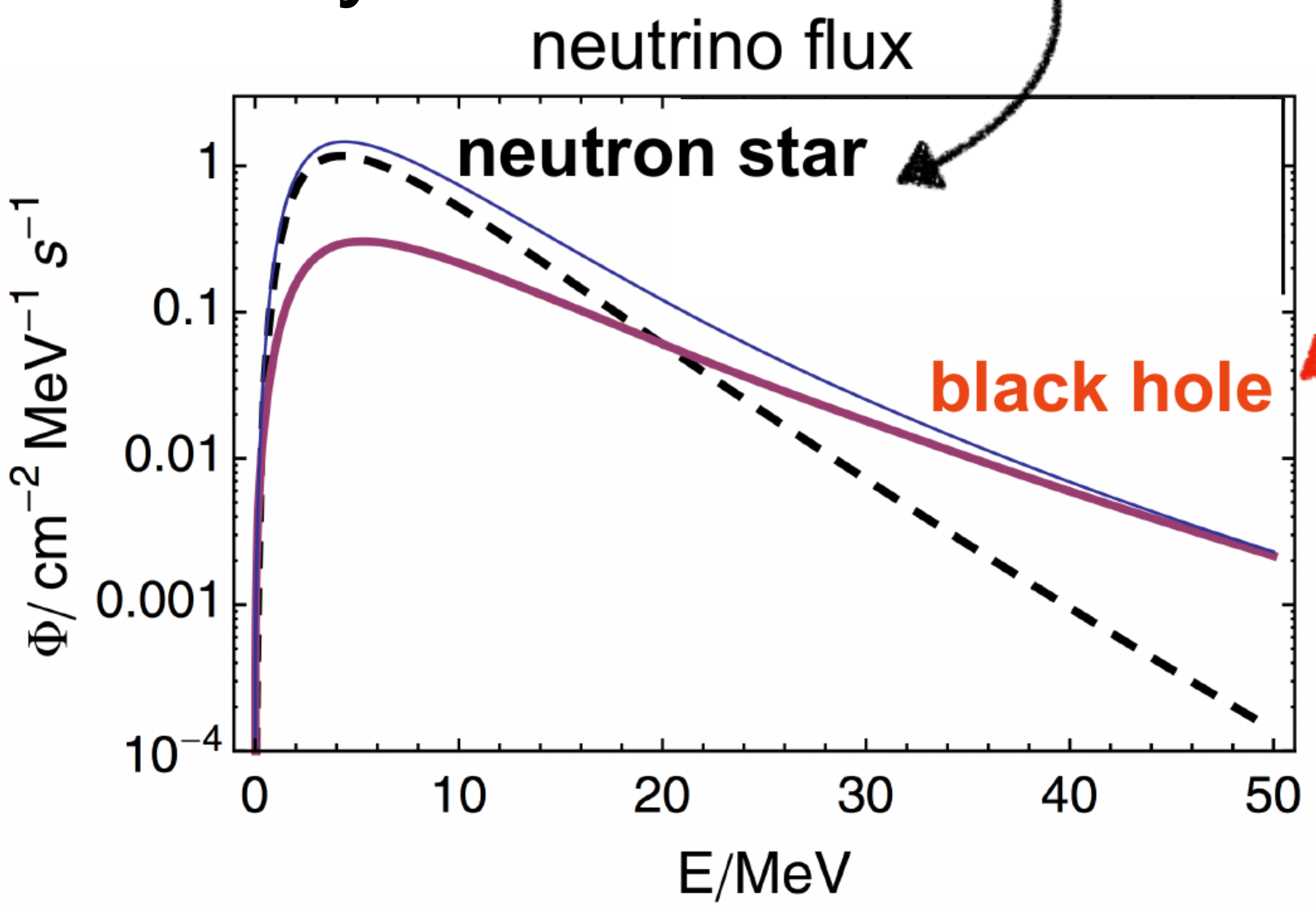
→Unique multi-messengers observatory

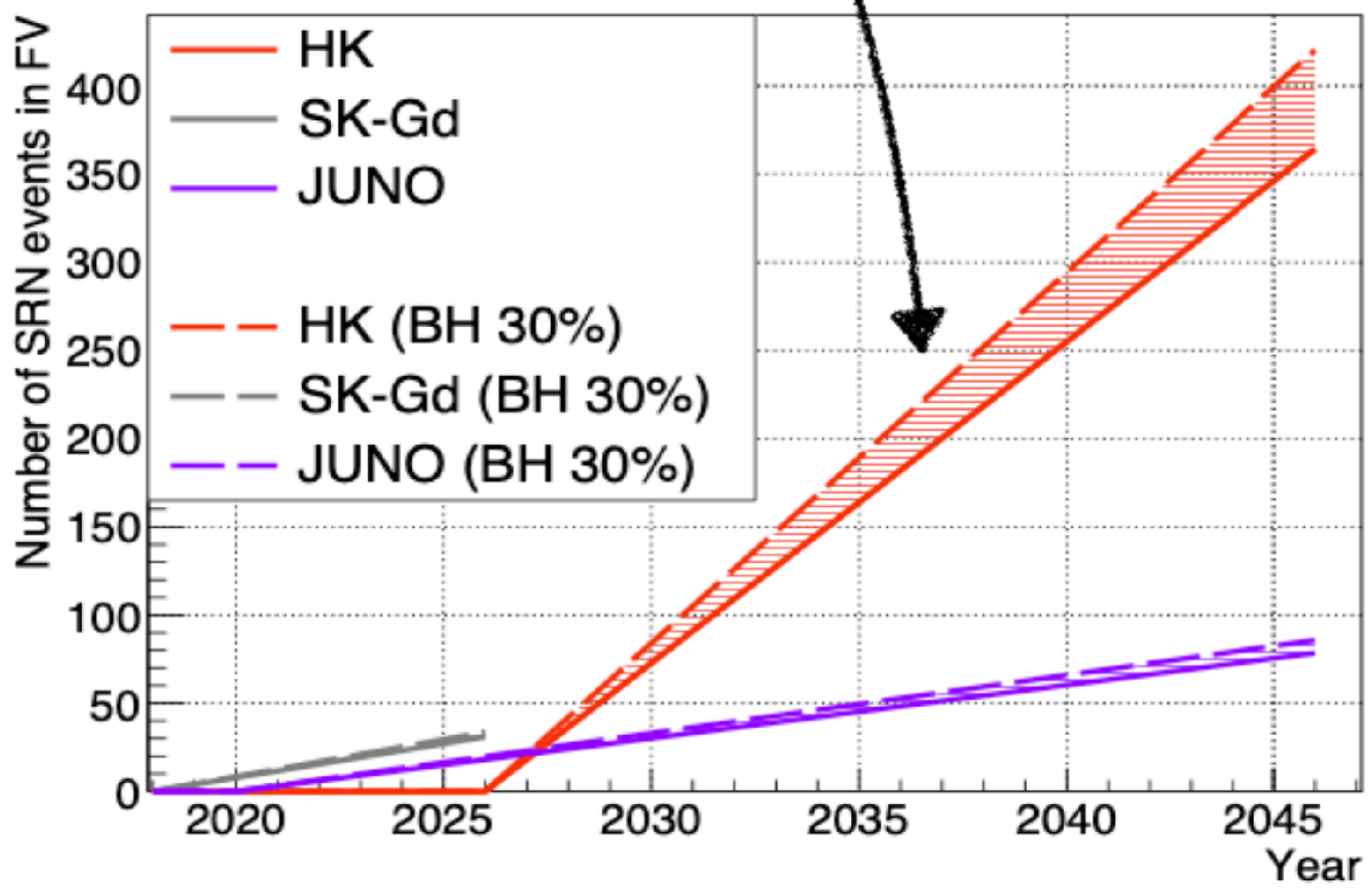
SN-relic neutrinos (DSNB) in HK

SN-relic neutrinos (SNRν) offer new constraints on cosmic star history
→ Could be first detected by SK-Gd
→ The spectrum will be determined by HK

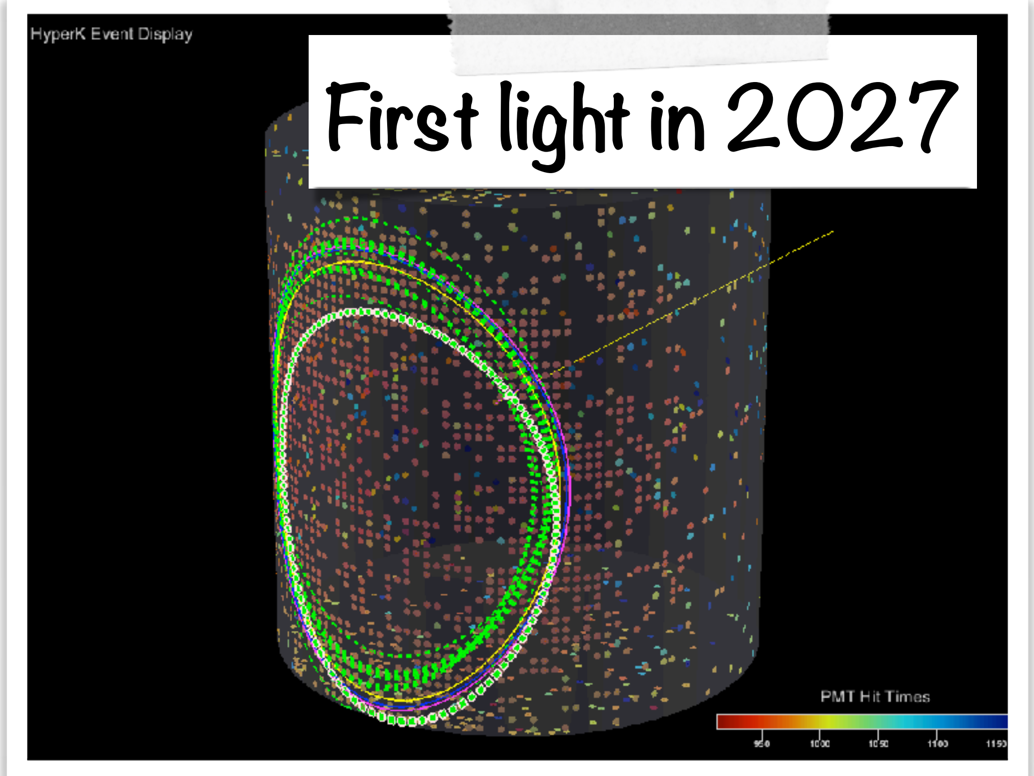
Impact of redshift: low energy ↔ probe older stars

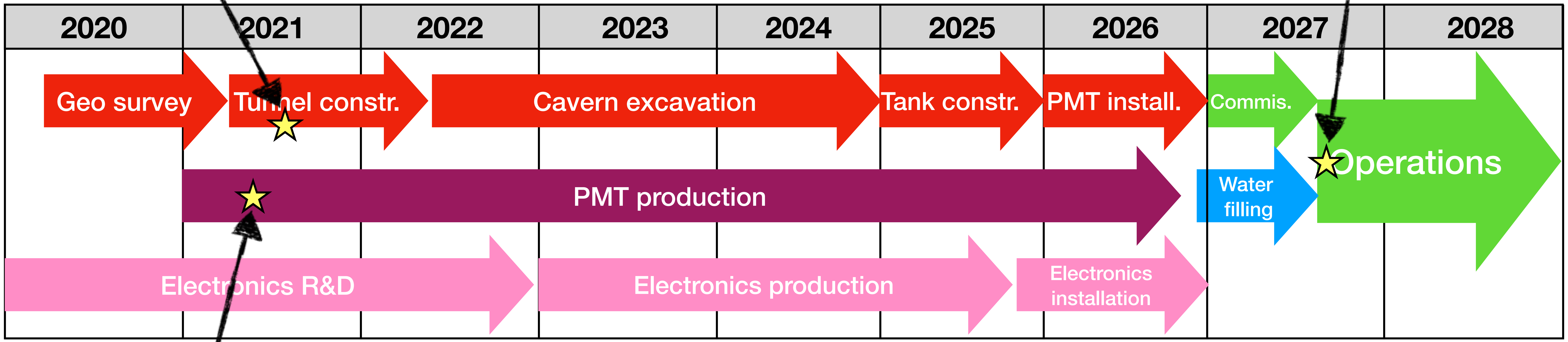
Sensitivity to neutron star vs black hole formation





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

Survey completed ✓

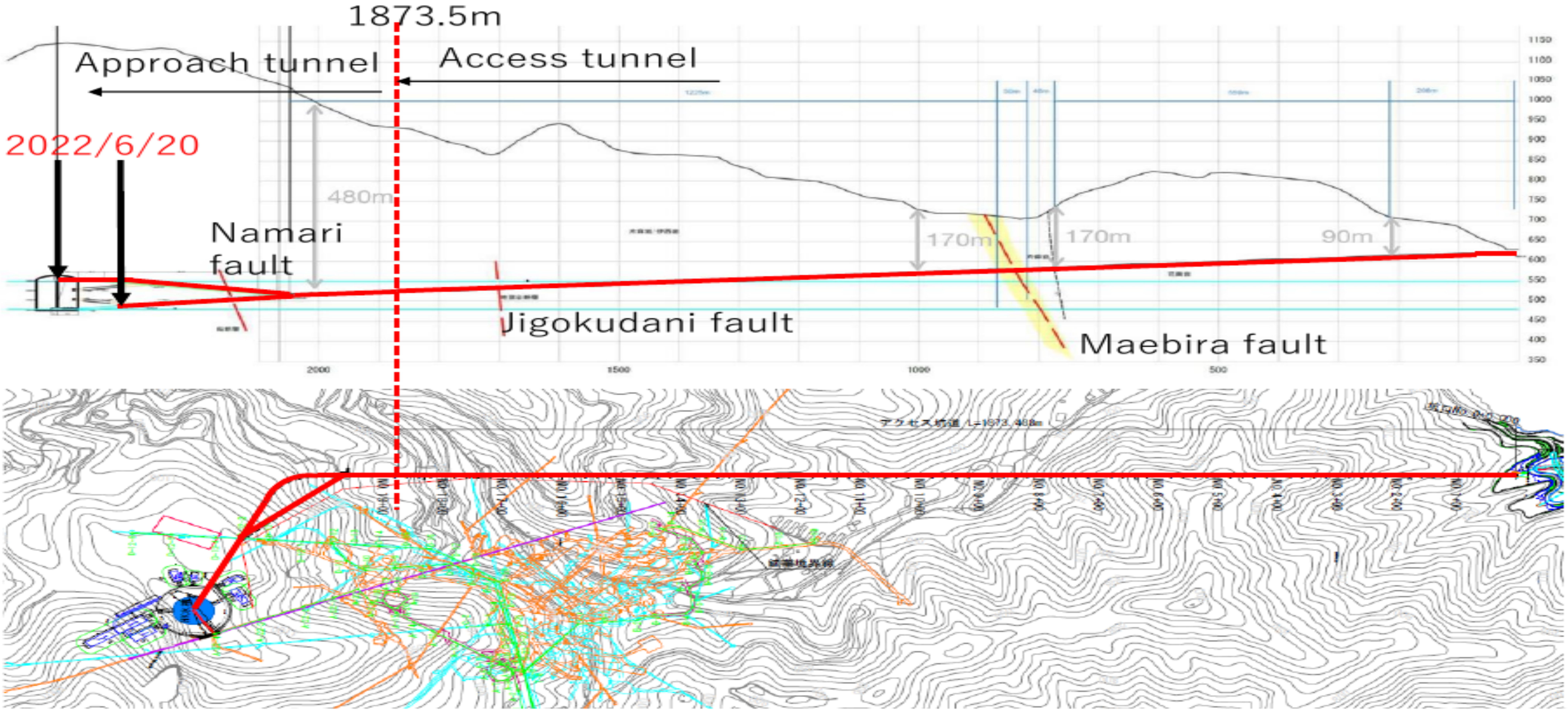
Excavation on-going (WORK IN PROGRESS)

New main building ✓

Everything on track! ✓

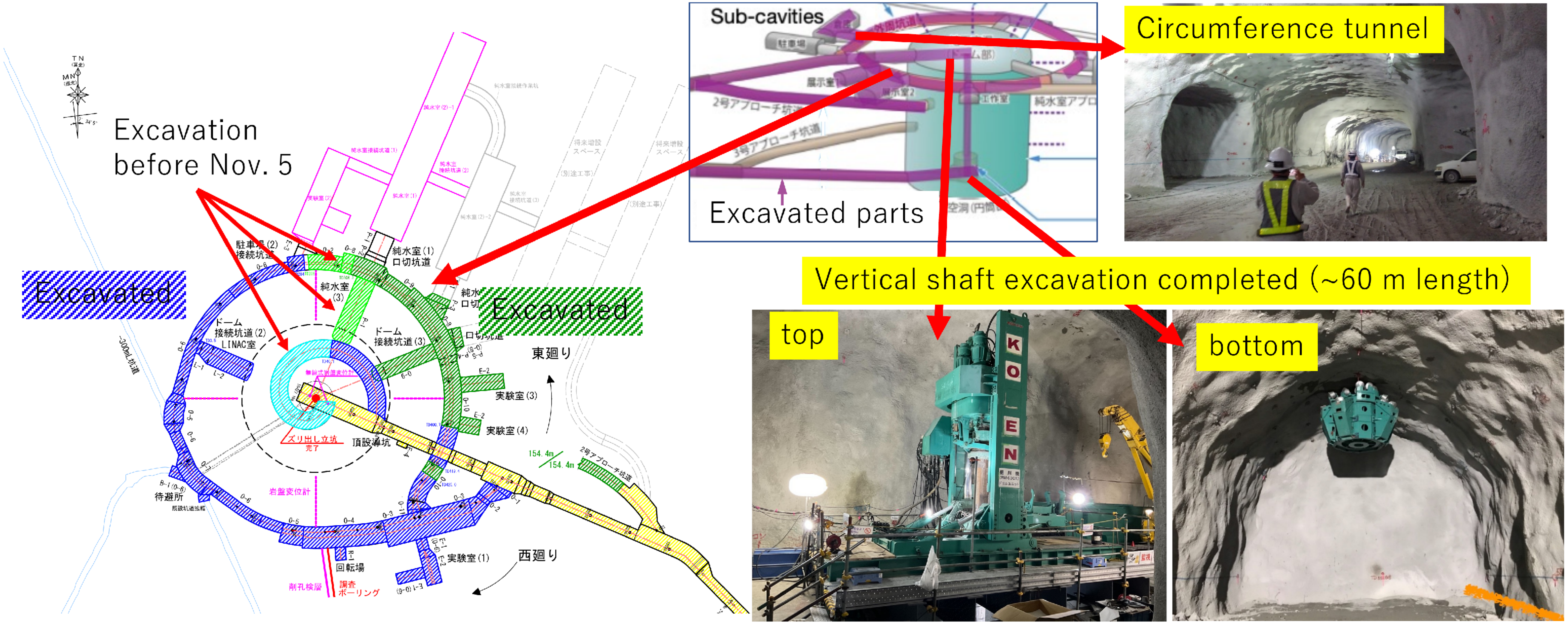
Recent progress: access tunnel excavation

Tunnel excavation overview



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

Recent progress: cavern excavation

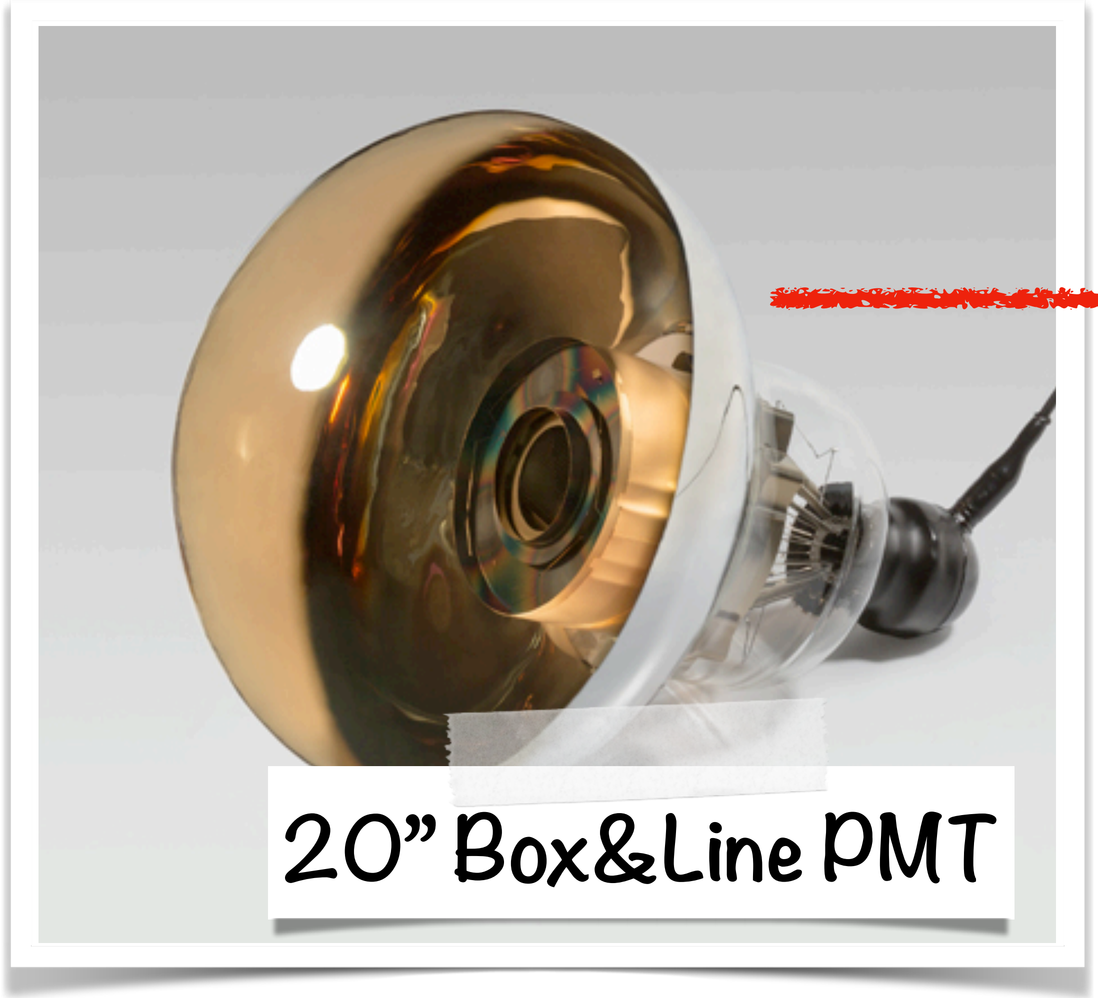


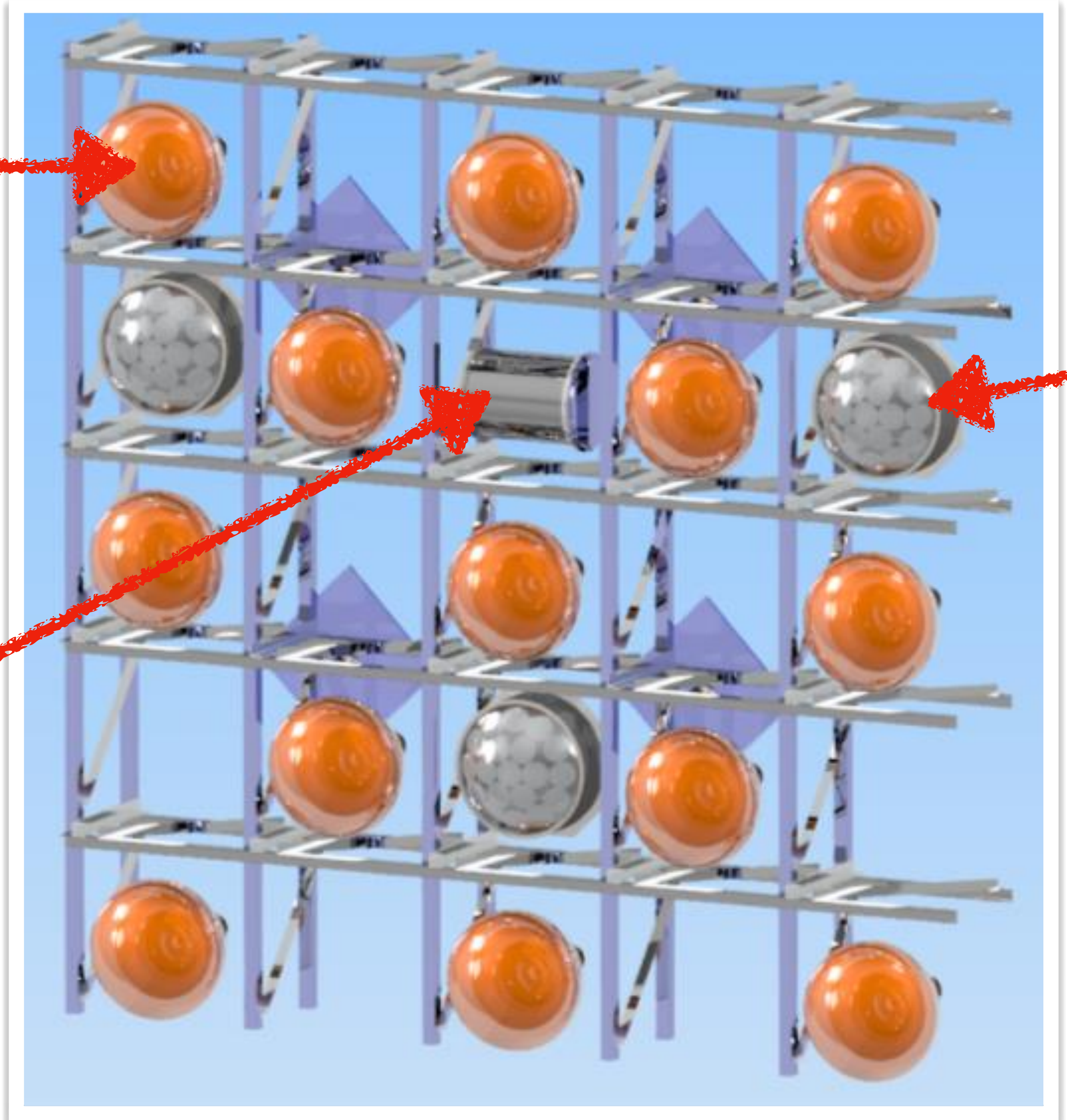
- The excavation work is on schedule. In Oct., a spiral tunnel towards the top of the dome is excavated.
- Ready for excavating the top of the dome in Nov.

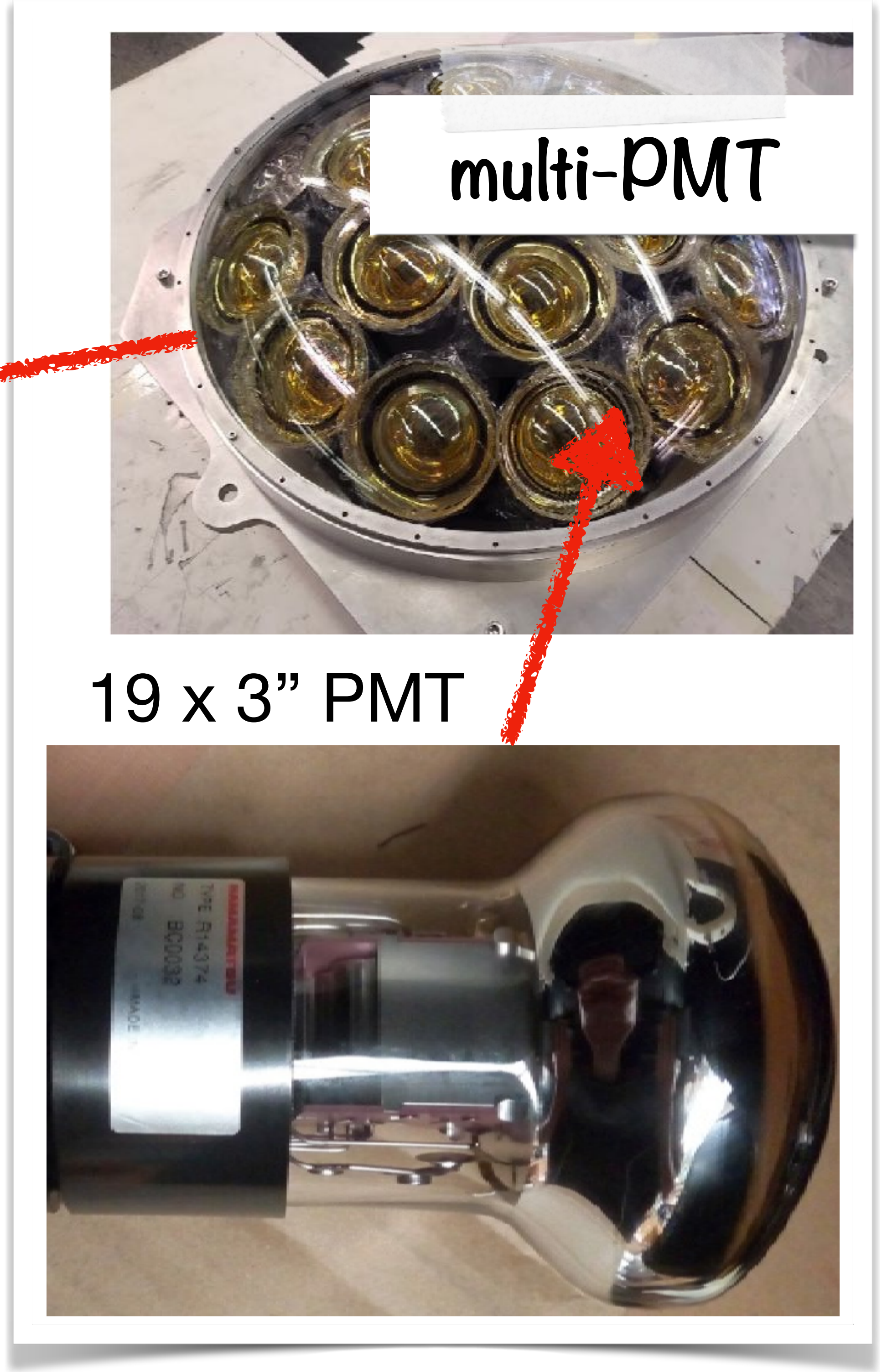
9

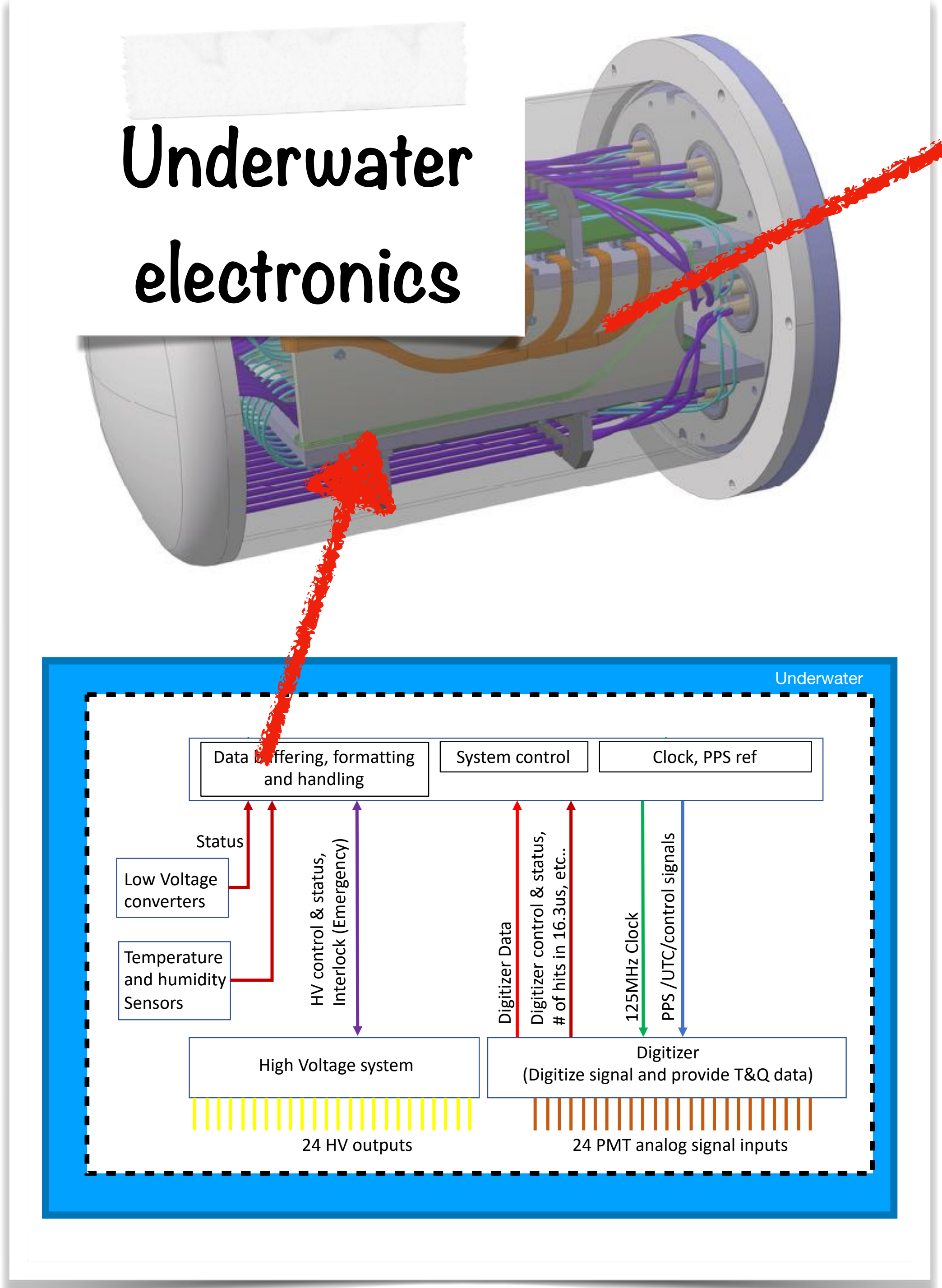
Vertical shaft excavation completed on schedule!

20” PMTs, mPMTs and readout









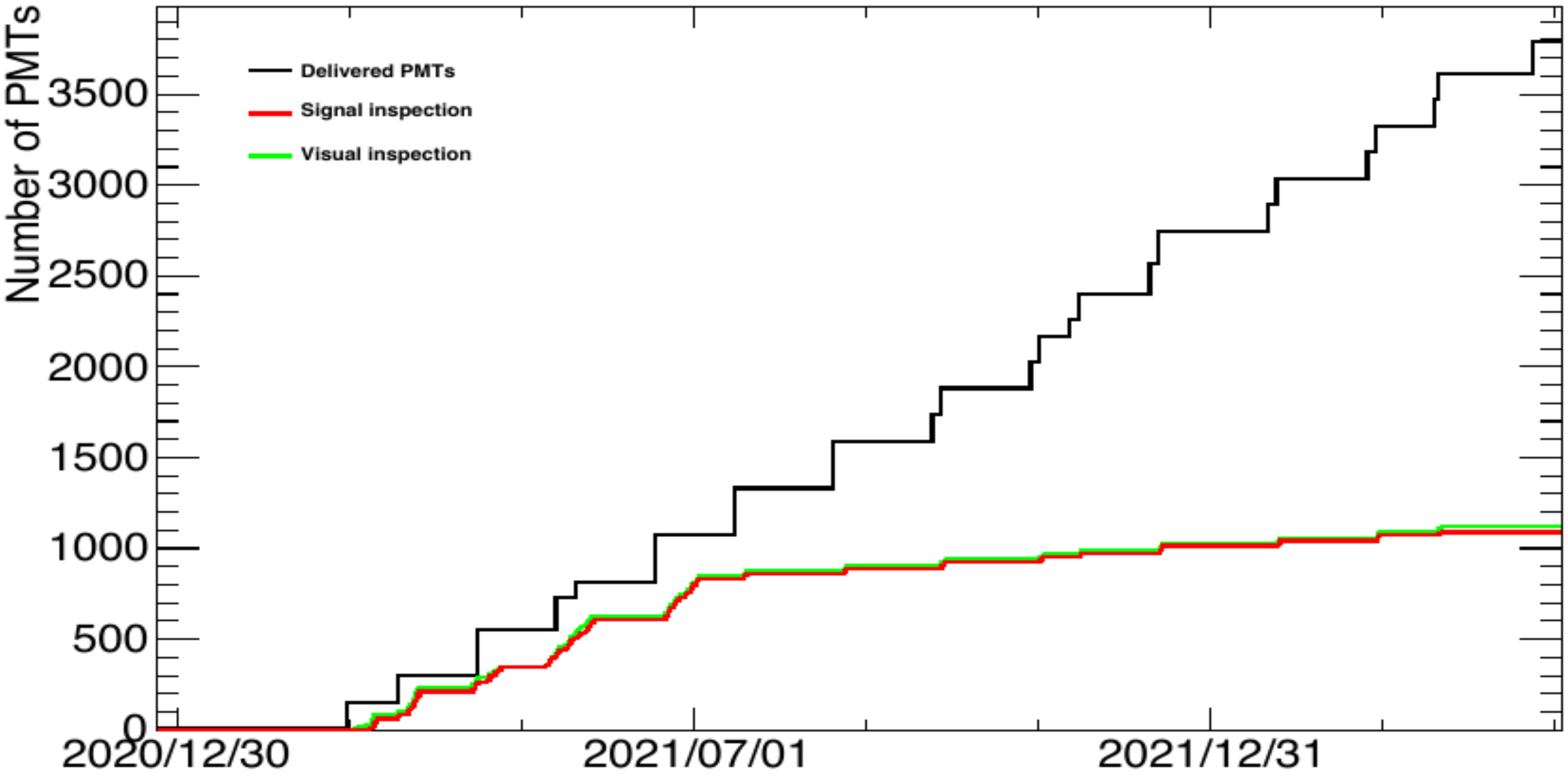
Inner detector composed of

- 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

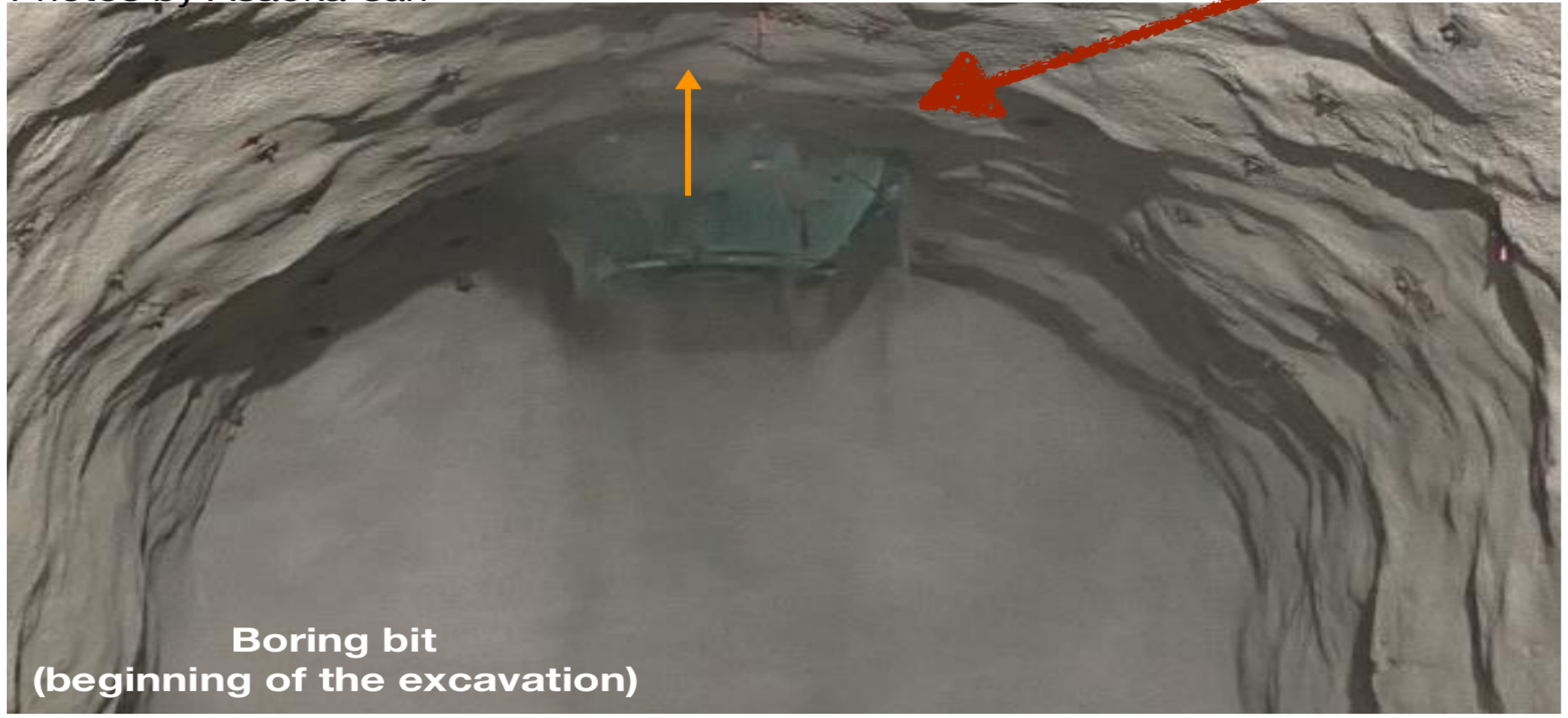
Unique program of world-leading measurements and discoveries up to ~2040

Backup slides

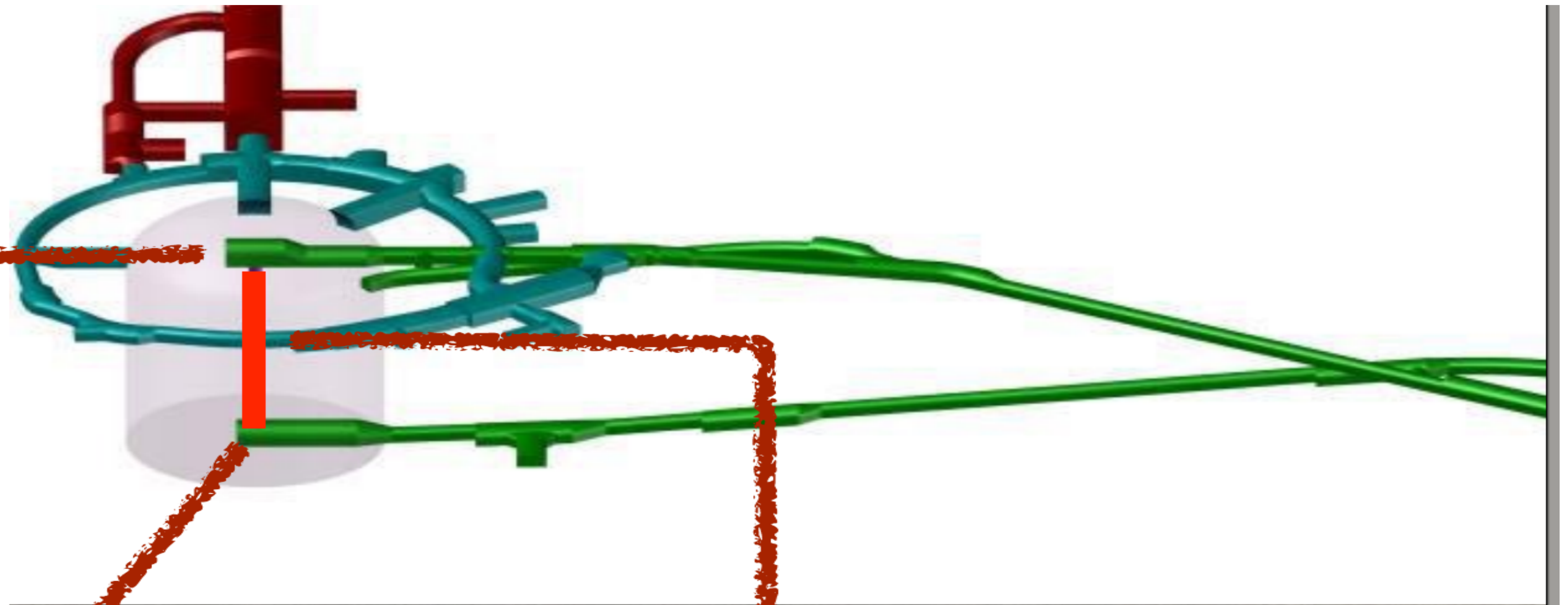
Recent progress: cavern excavation

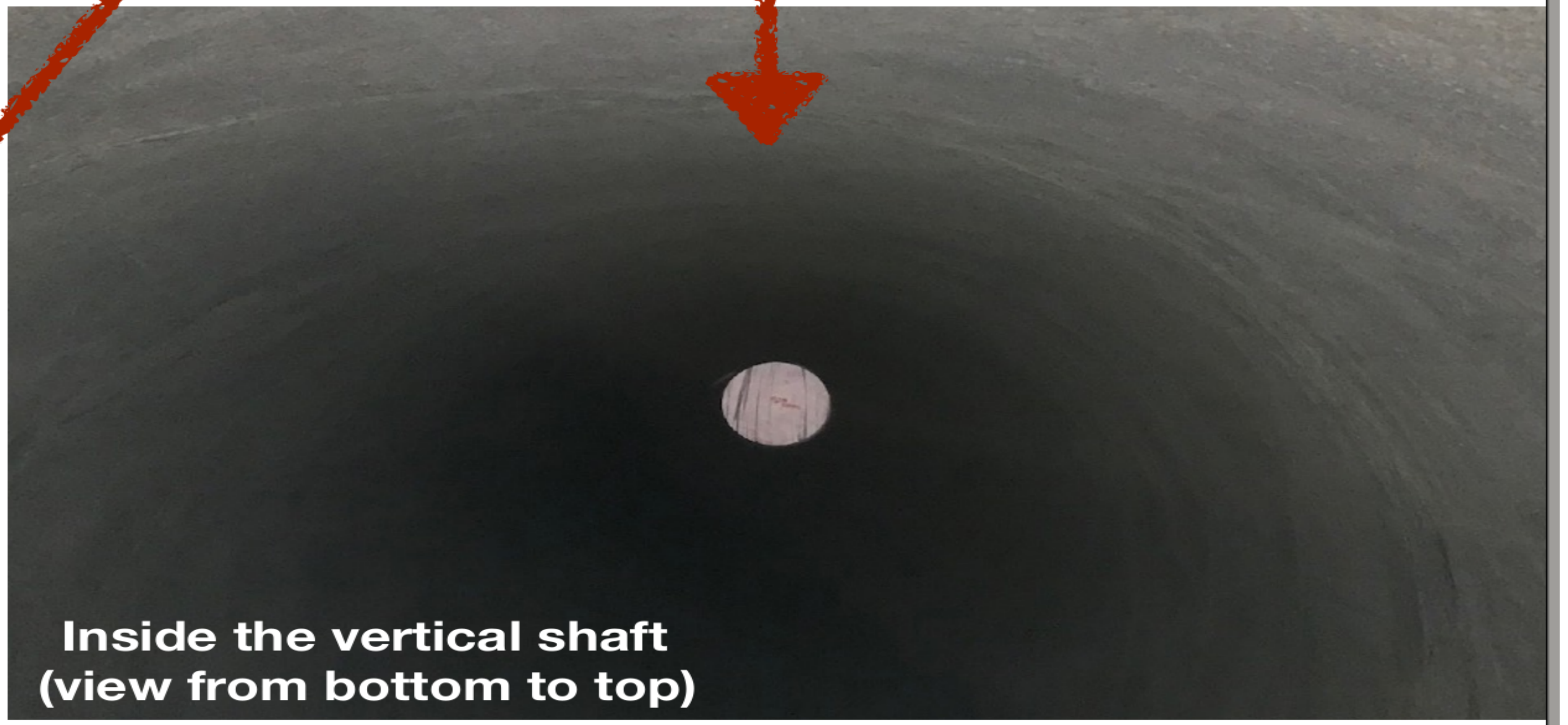
Boring bit
(right after excavation complete)

Photos by Asaoka-san



Boring bit
(beginning of the excavation)





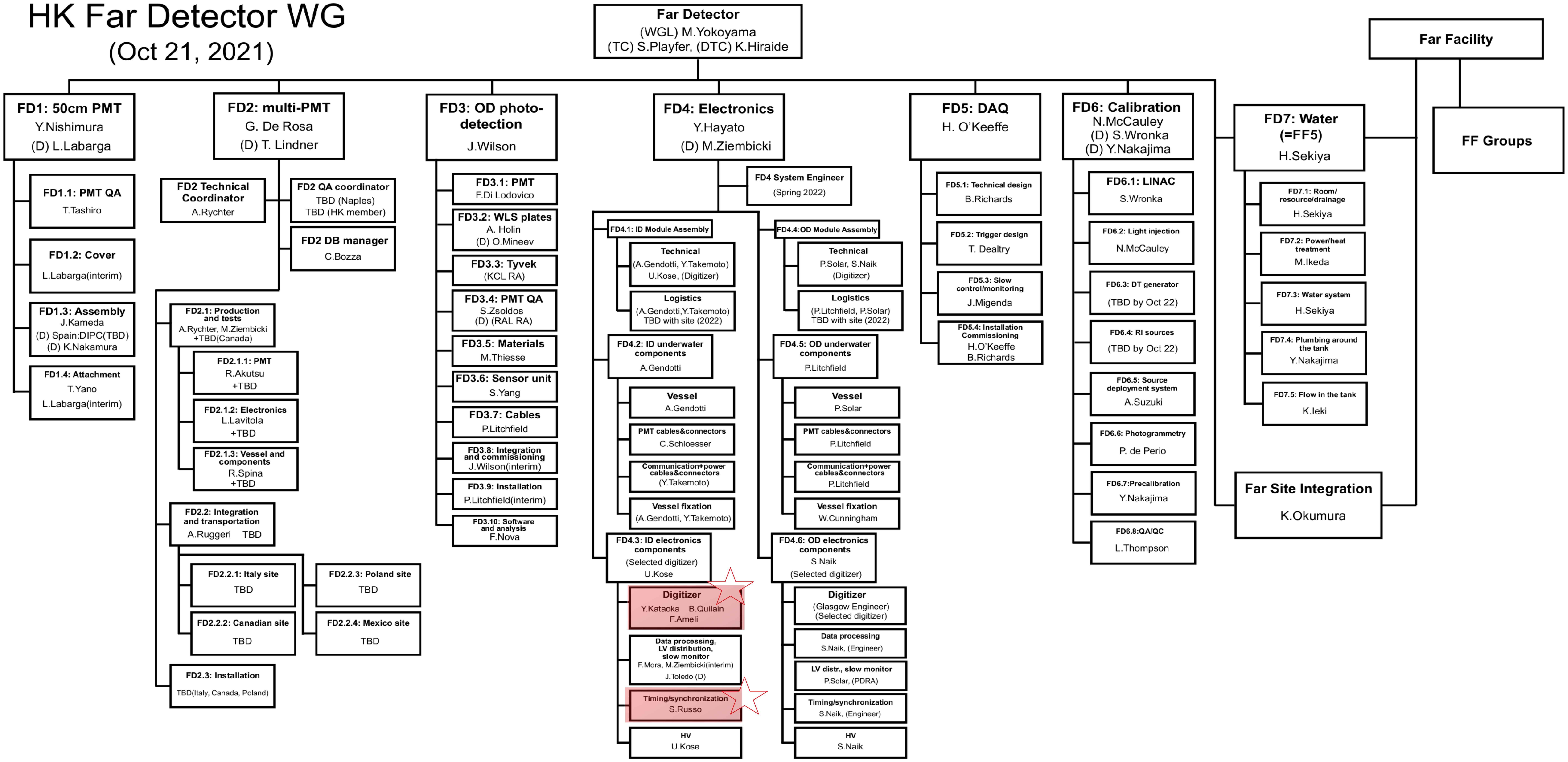
Inside the vertical shaft
(view from bottom to top)

- The excavation of the vertical shaft completed on schedule
  - Vertical shaft: Φ3.4m, 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!

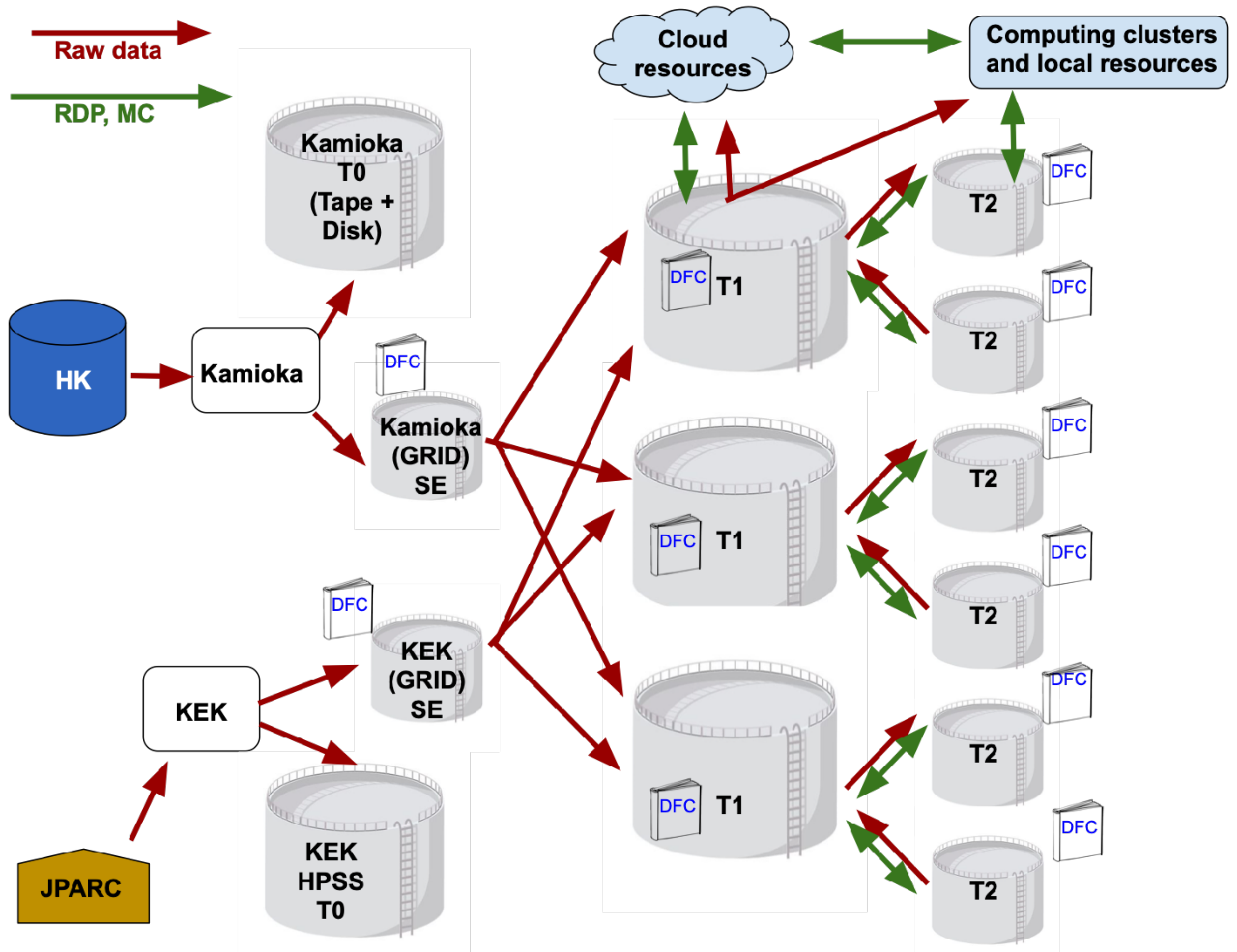
HK organizational chart

Far detector Working Groups



IN2P3-CEA technical contributions to HK

- **<u>ND280 Upgrade and maintenance</u>**
  - Super-FGD electronics
  - High-Angle TPCs electronics & readout
- **<u>Construction of HK far detector</u>**
  - Front-end electronics & timing system
- **<u>International computing effort</u>**
  - 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 externals fundings before asking for IN2P3 investments