

Participation of IN2P3 physicists in the **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)

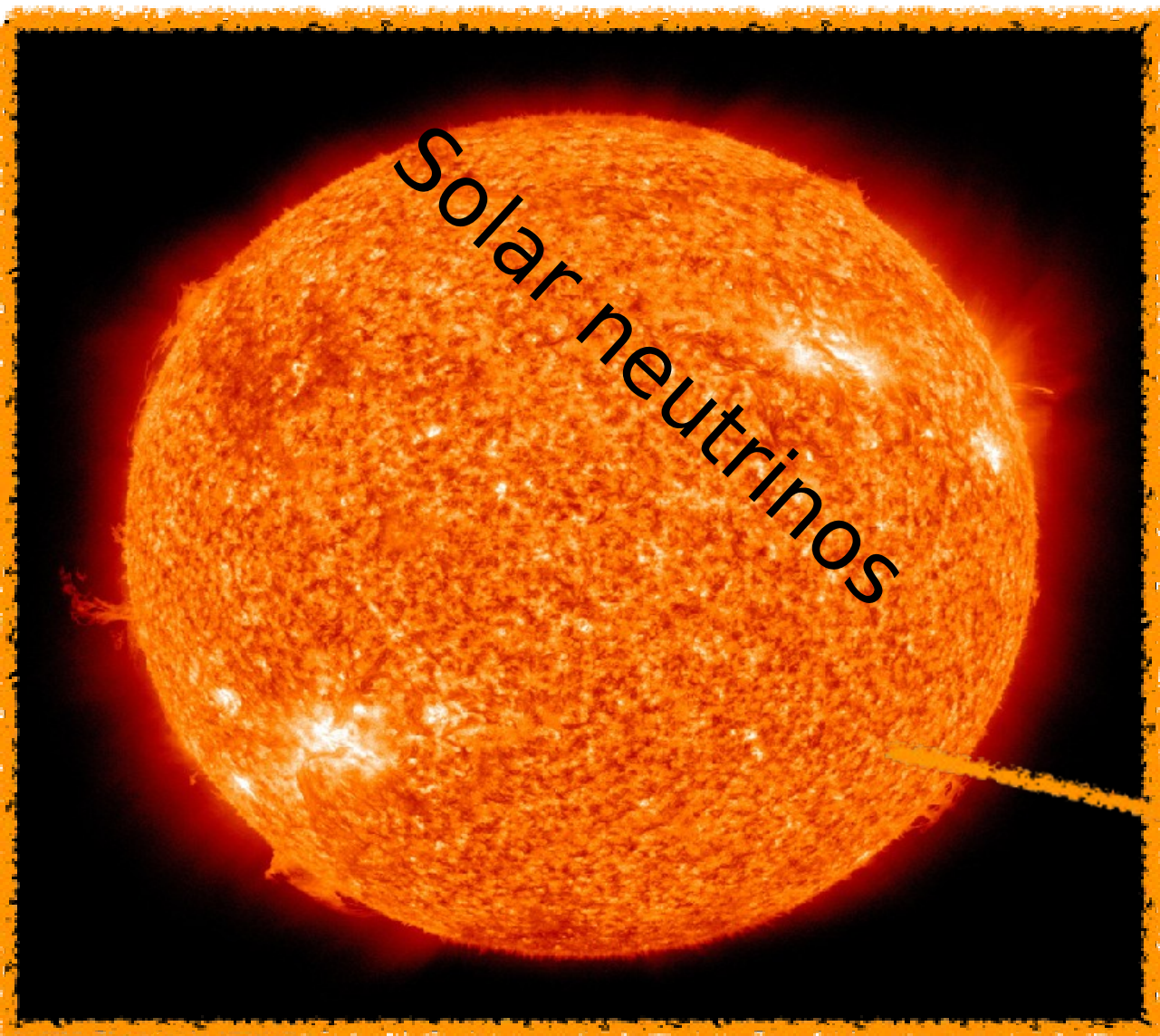
LPNHE: A. Blondel, J. Dumarchez, C. Giganti, M. Guigue, M. Martini, B. Popov, S. Russo, V. Voisin, M. Zito, W. Saenz (postdoc ANR), L. Mellet (PhD student), C. Dalmazzone (PhD student) + one more ANR postdoc starting from 2023

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

APC: C. Volpe

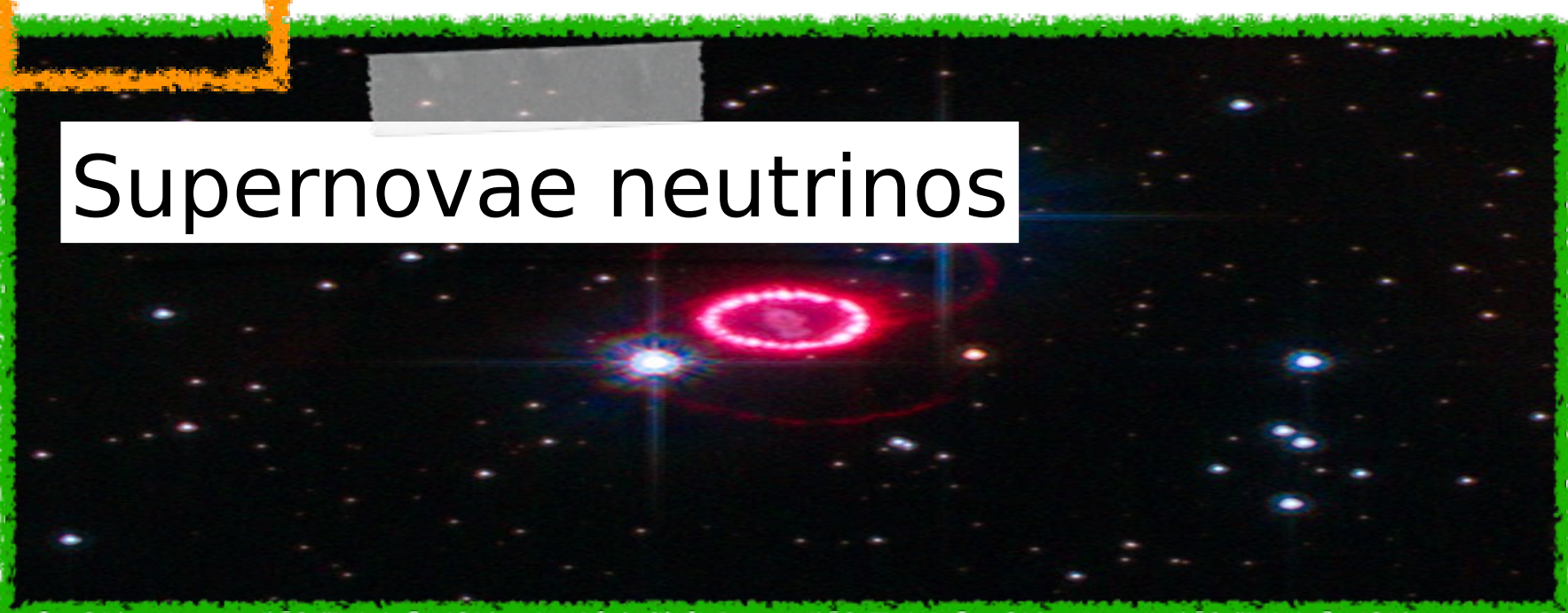
Natural continuation of our participation in the Japanese neutrino program (T2K and SK)

Hyper-Kamiokande physics program

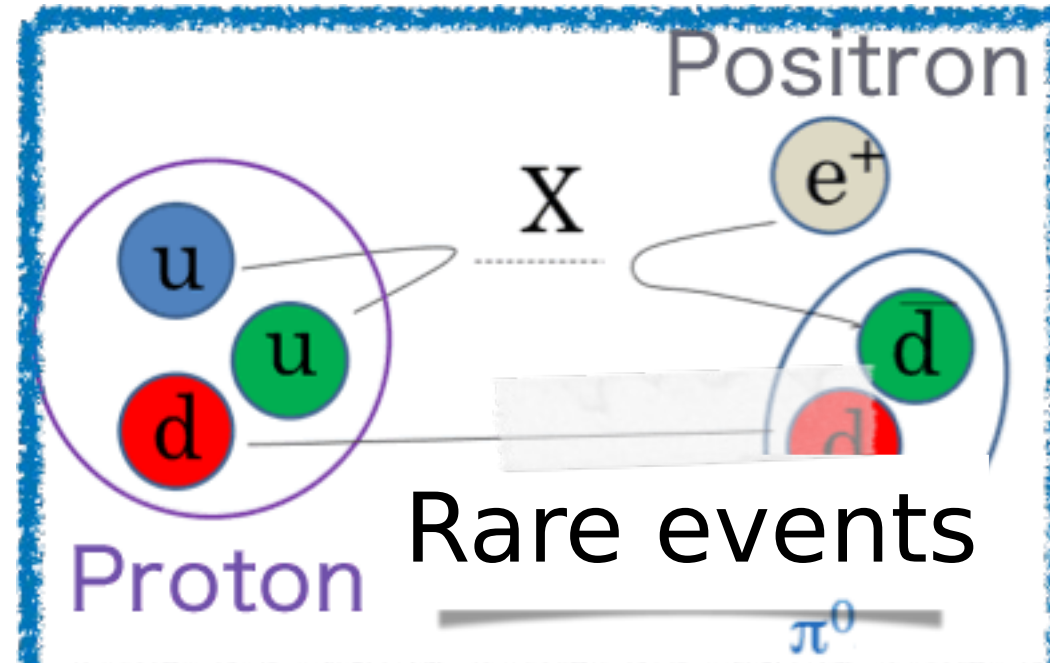


ν_e

MSW effect
Non-standard interactions

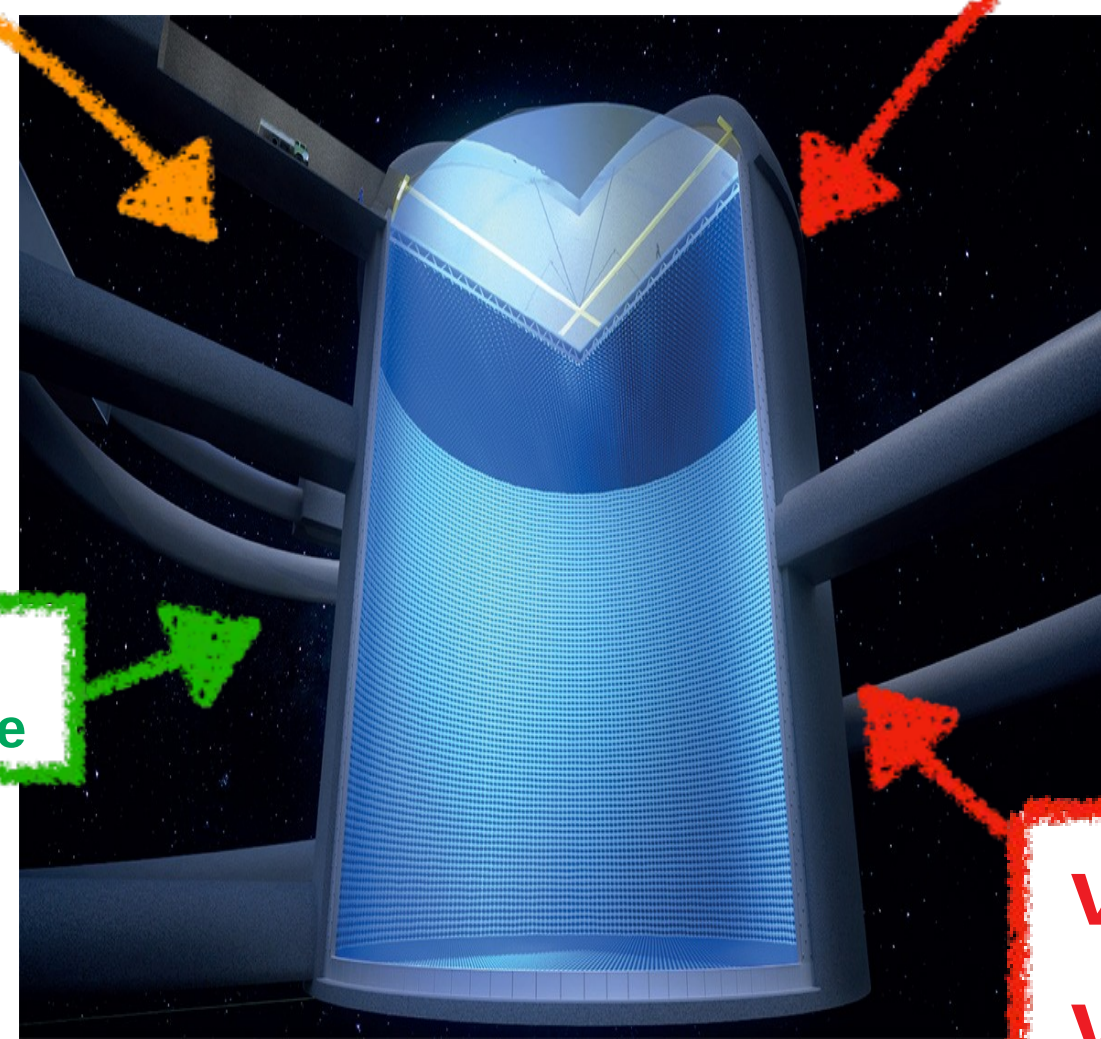


- Transient SNv : constrain SN profile models
- Relic SNv : constrain cosmic star formation



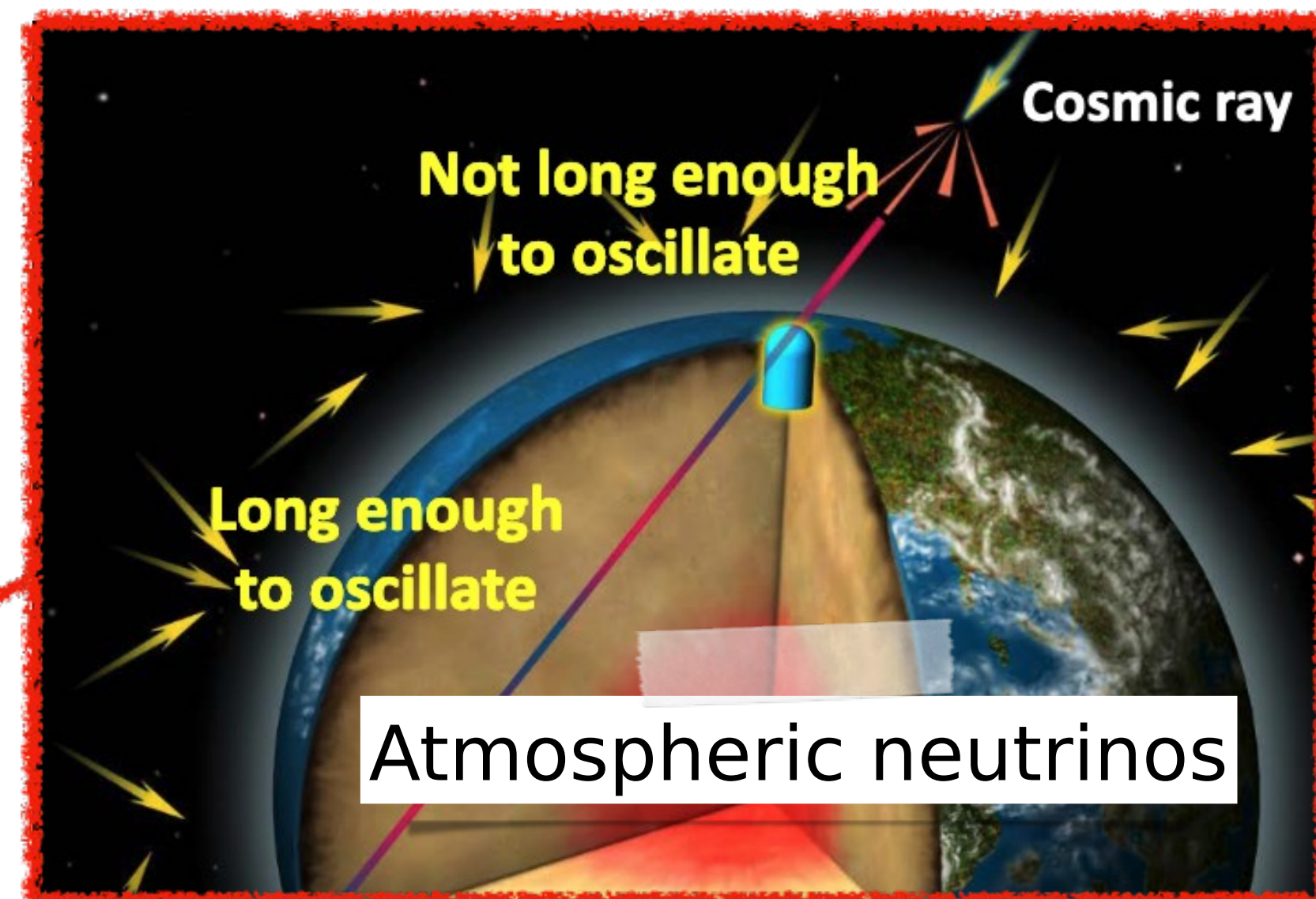
- **Probe Grand Unified Theories via p-decay or n- $\bar{n}$ oscillation**

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

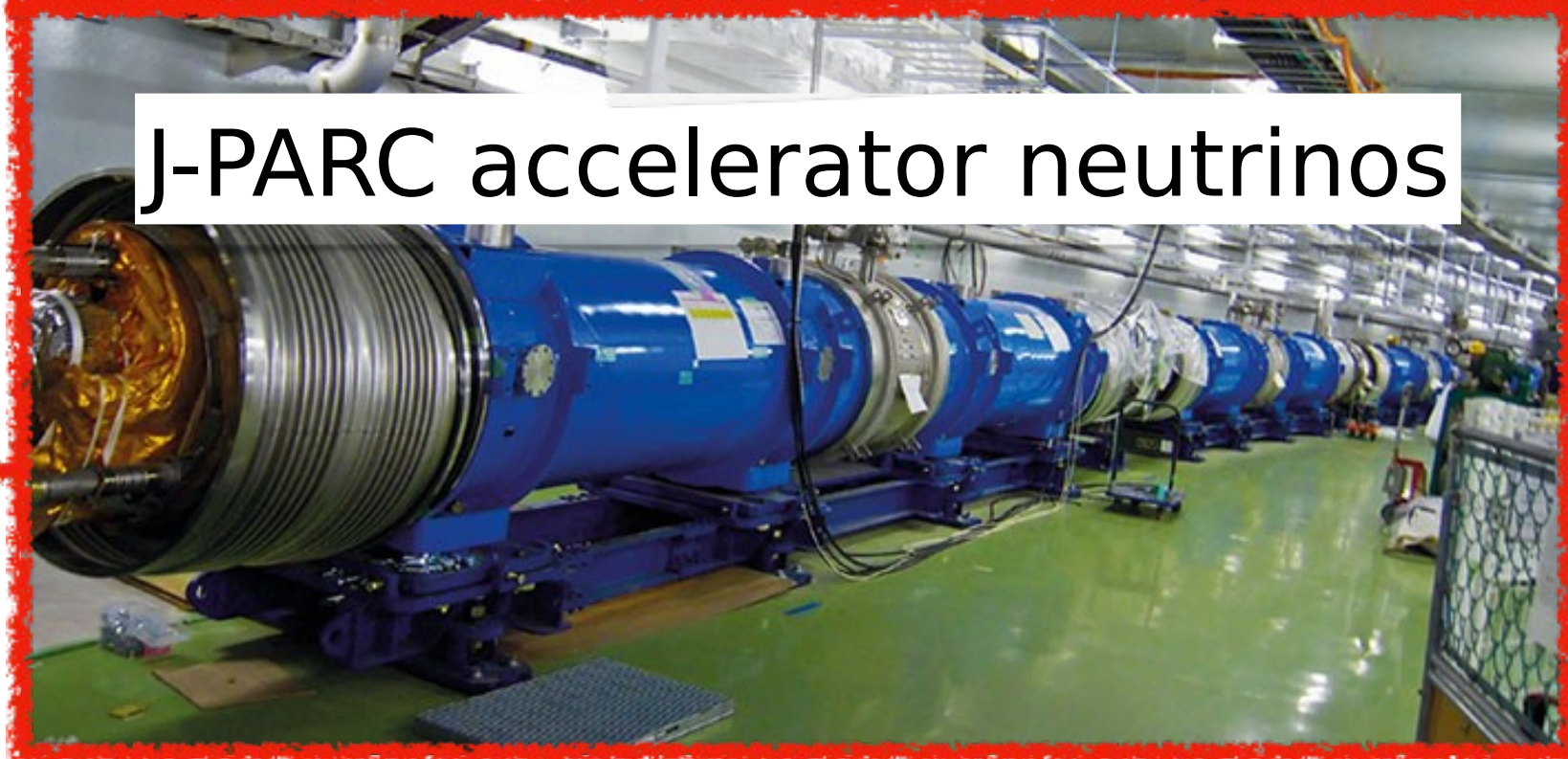


$\bar{\nu}_e$

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

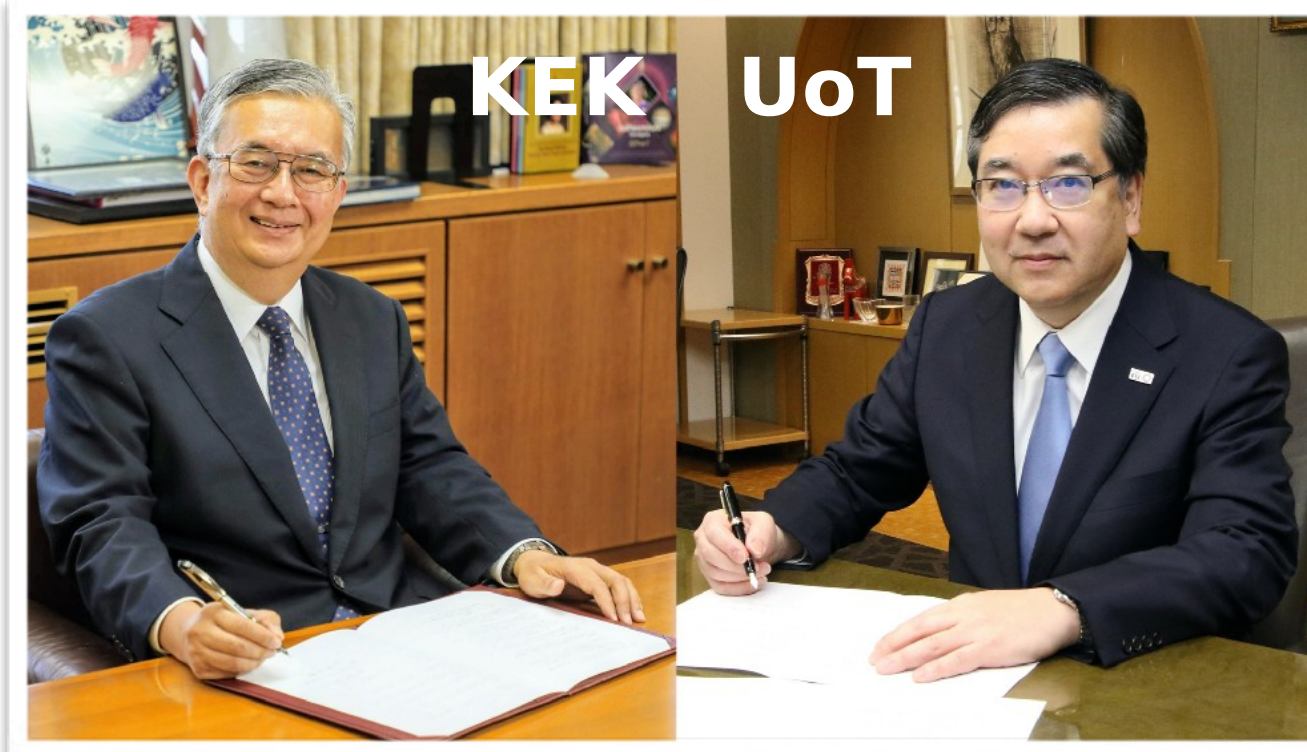


- **Observe CP violation for leptons at 5σ**
- **Precise measurement of δ_{CP}**
- **High sensitivity to ν mass ordering**



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.”

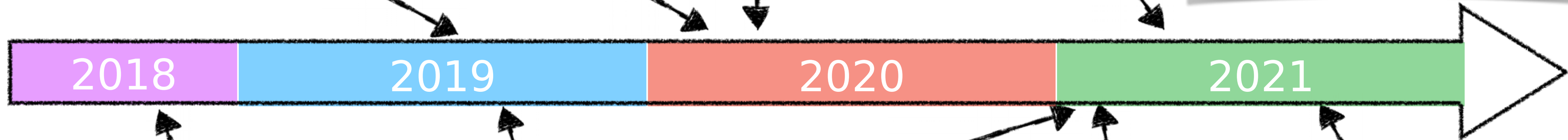
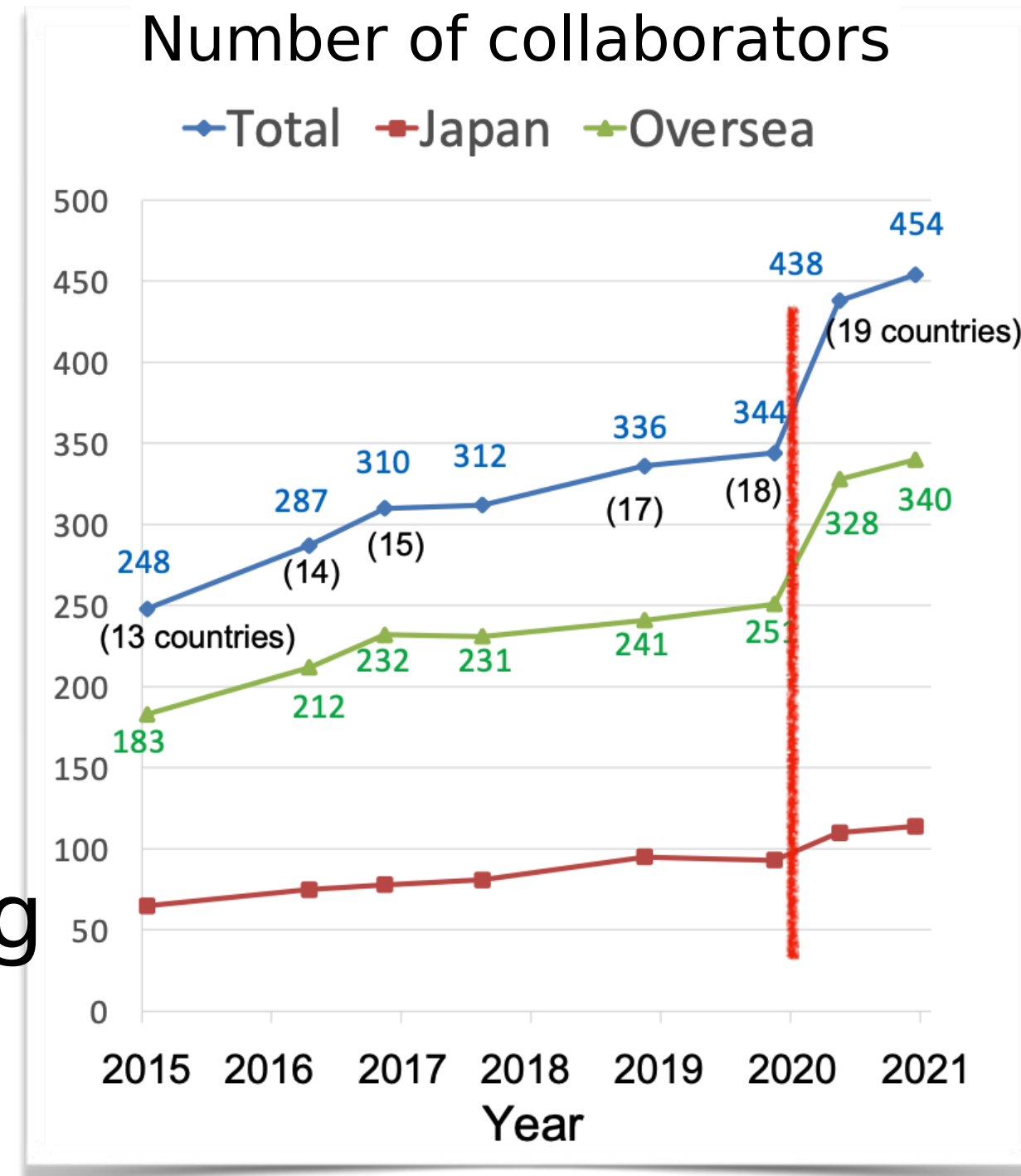


May 2020:

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

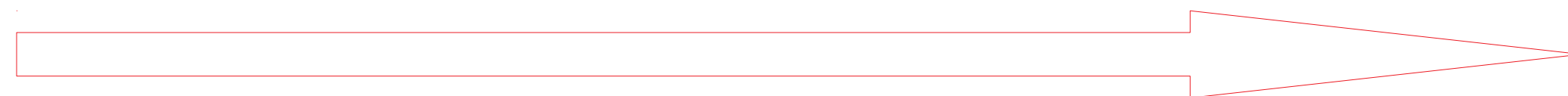
6.3. Avis du Conseil

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.

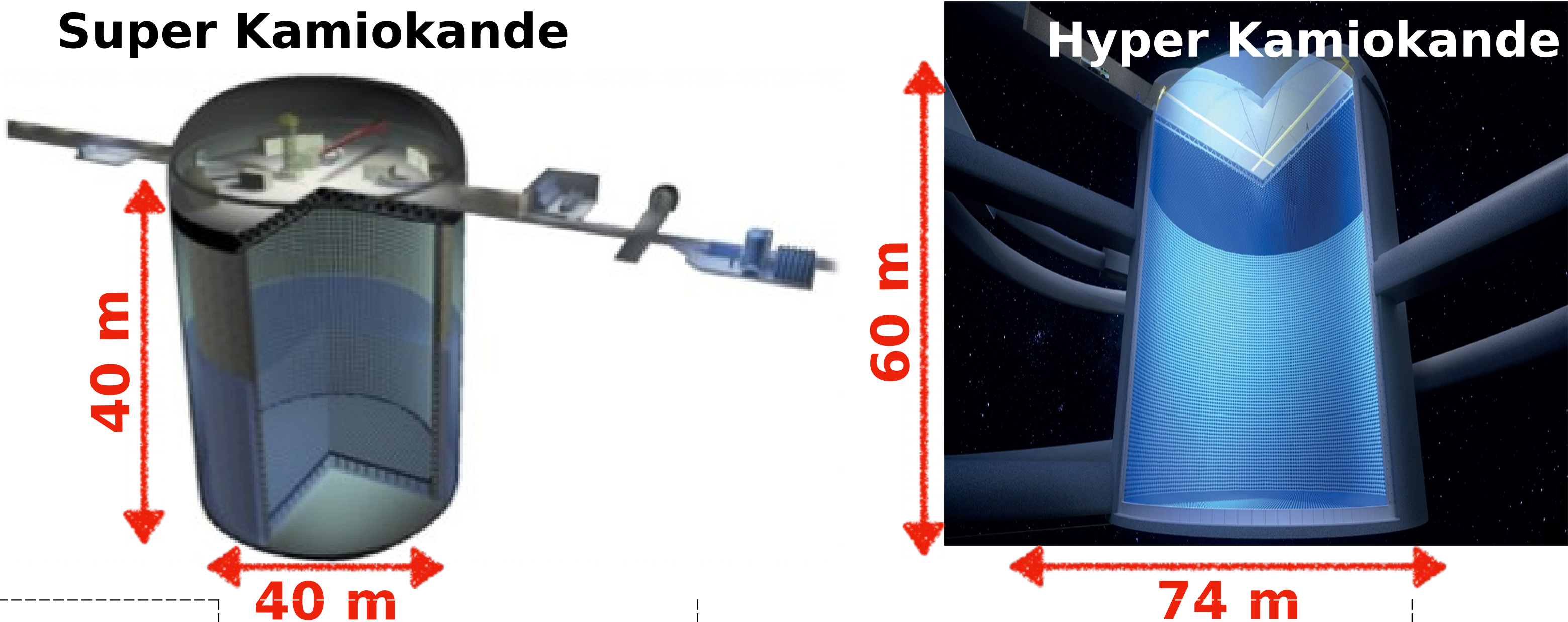
...

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

Hyper-Kamiokande vs Super-Kamiokande



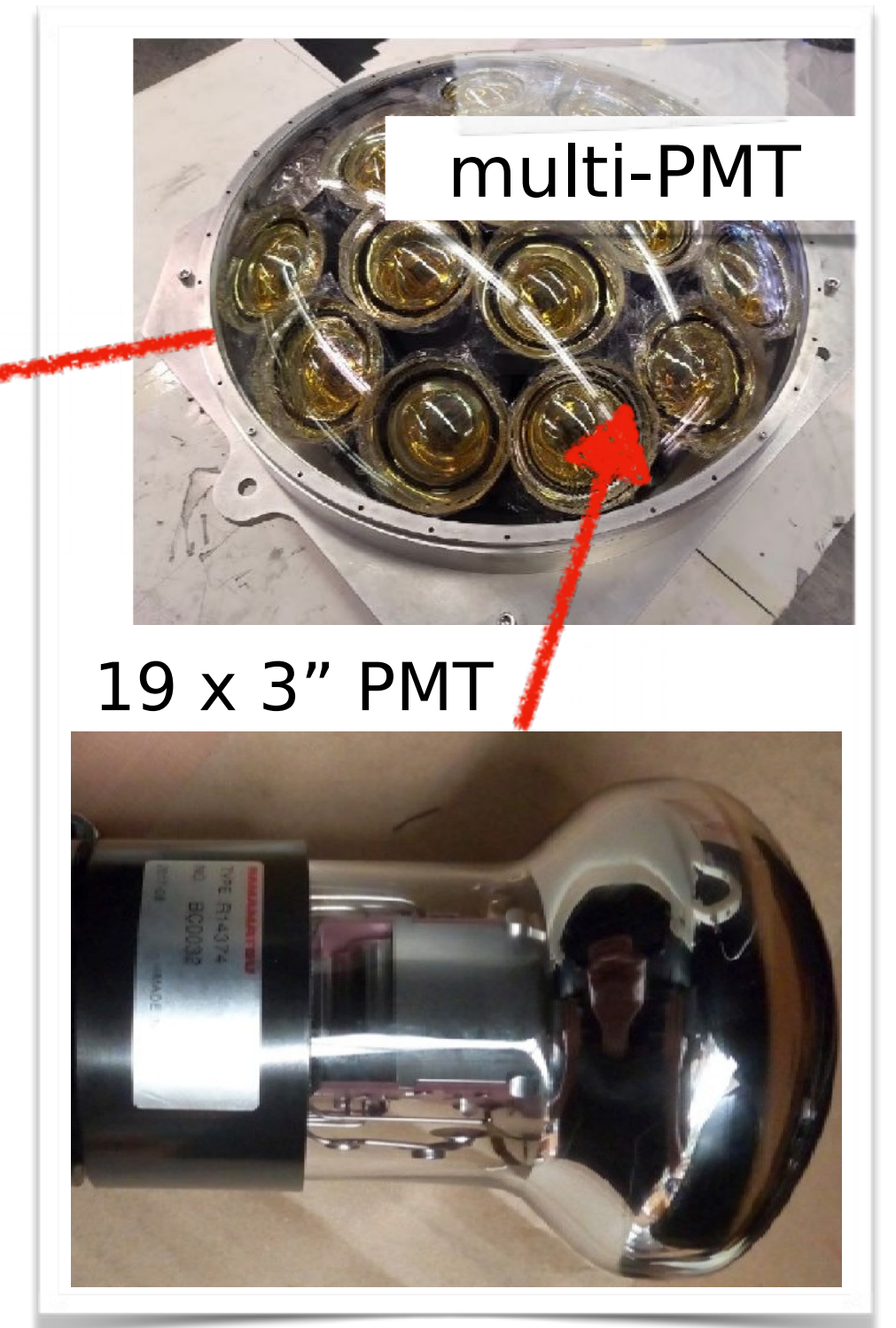
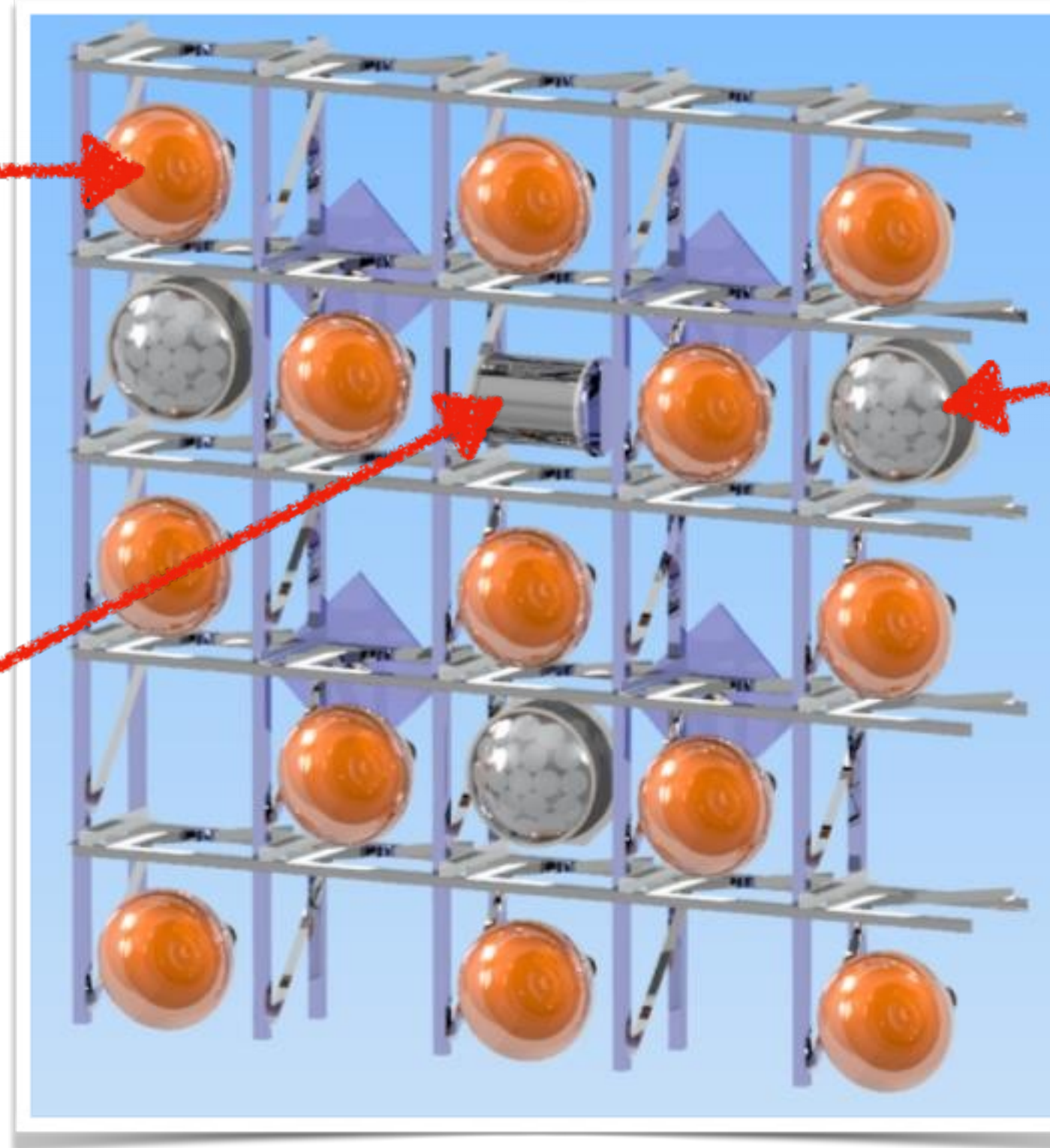
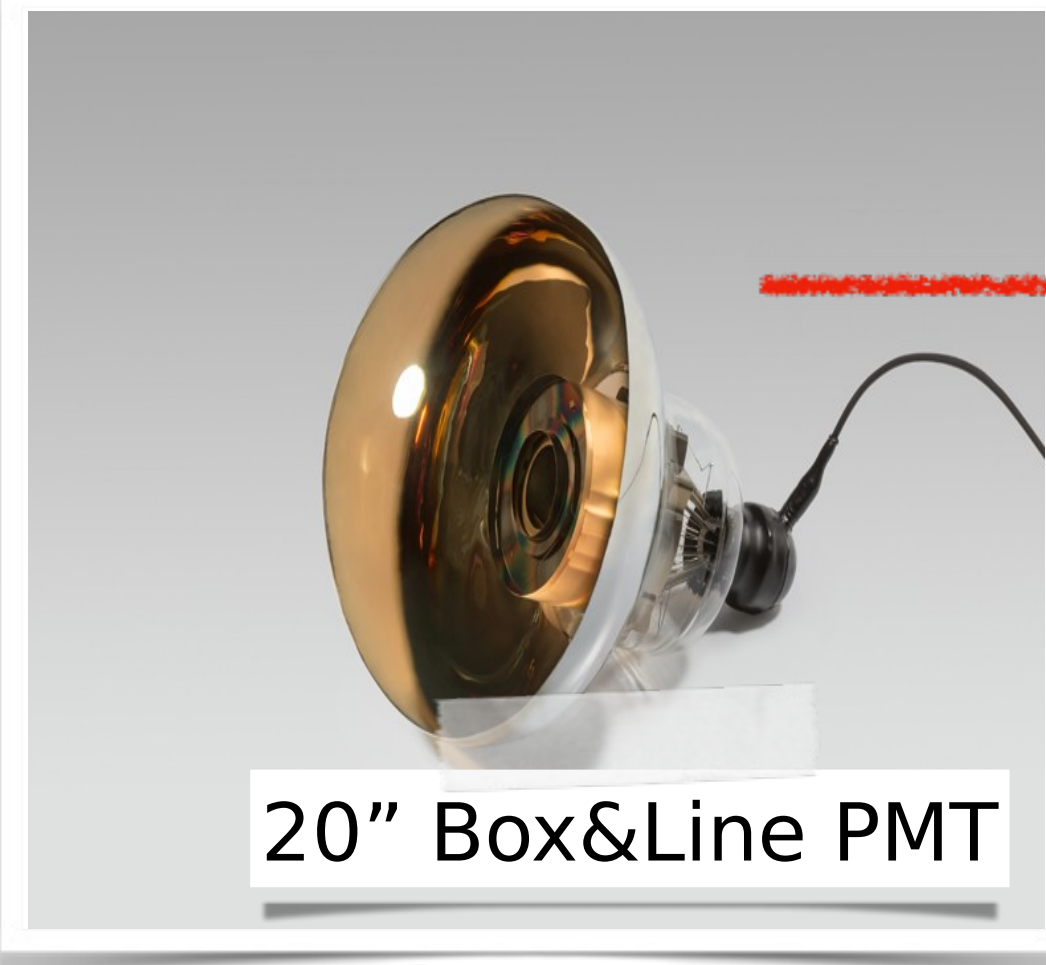
	Super Kamiokande	Hyper Kamiokande
Site	Mozumi-yama	Tochibora-yama
Number of ID 20'' PMTs	11 129	>20,000
Photo-coverage	40 %	>20%
Single-photon efficiency/PMT	~12%	~24%
Dark rate/PMT	~4 kHz	~4kHz
Time resolution of 1 photon	~3 ns	~1.5 ns
Total/fiducial mass (kton)	50 / 22.5	260 / 187

Fiducial volume x8:
→ non-beam ν physics

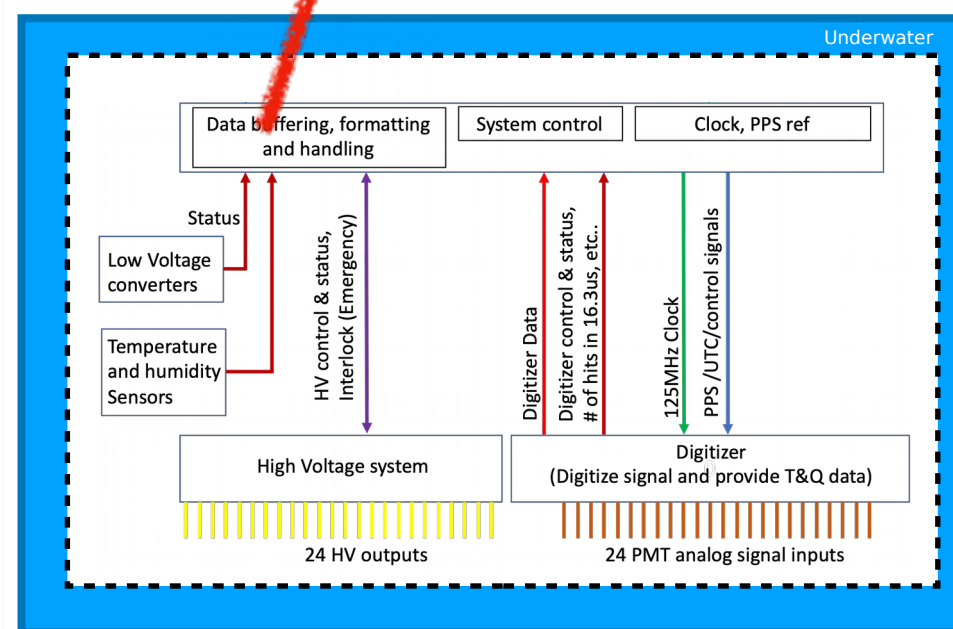
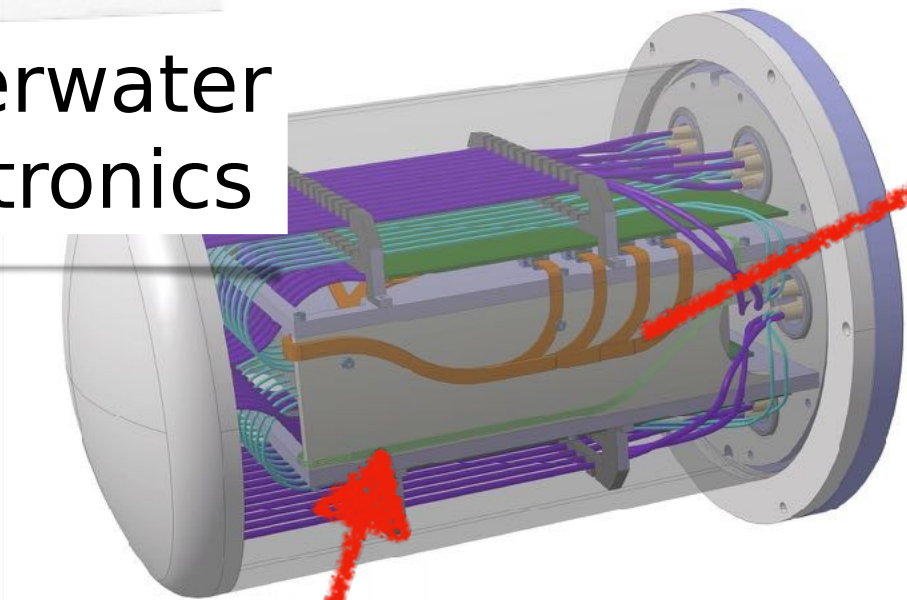
Beam neutrino event rate x 20:
→ beam ν physics

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

20" PMTs, mPMTs and readout



Underwater
electronics



Inner detector composed of

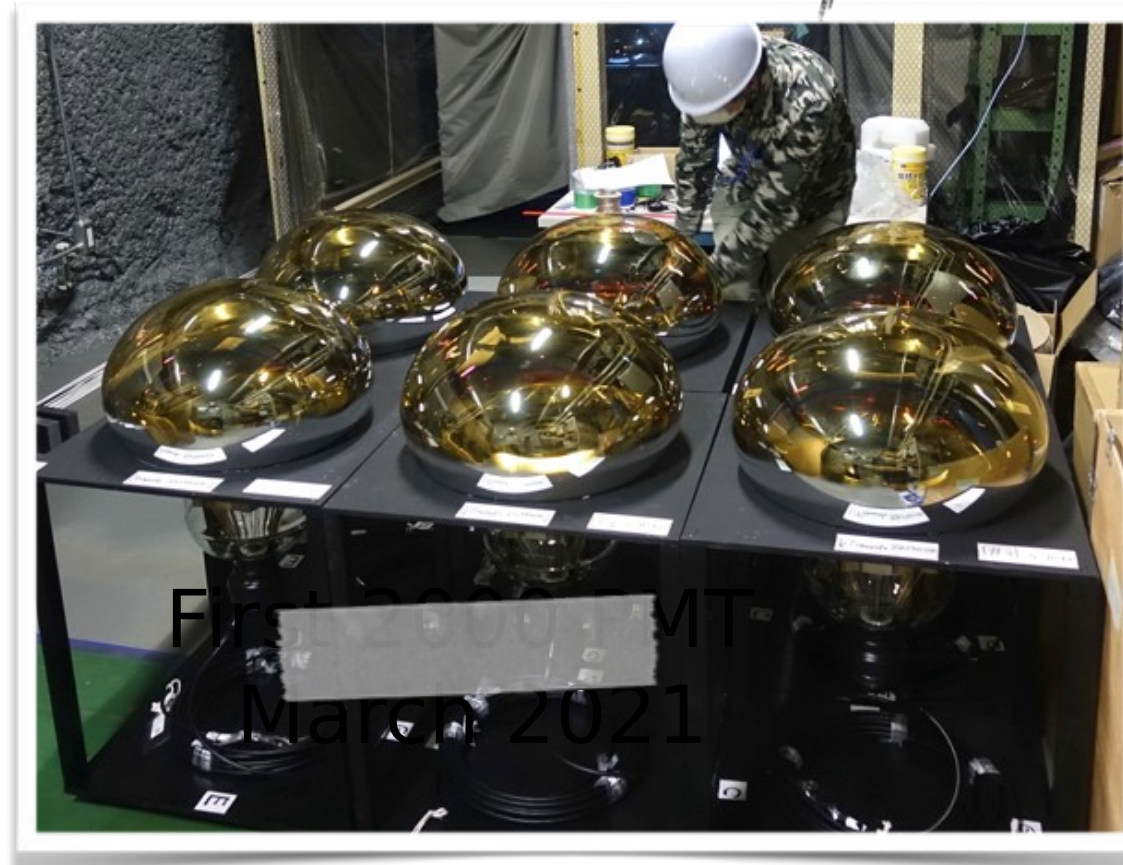
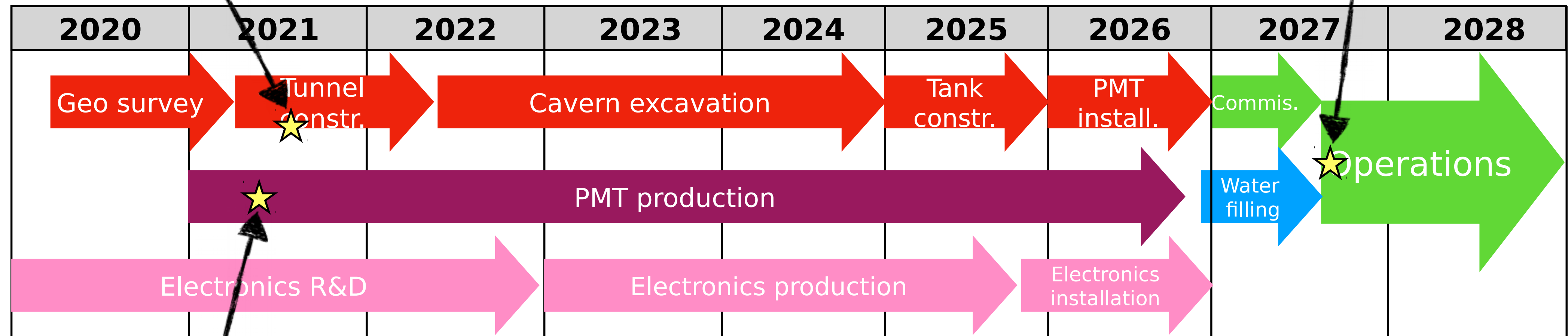
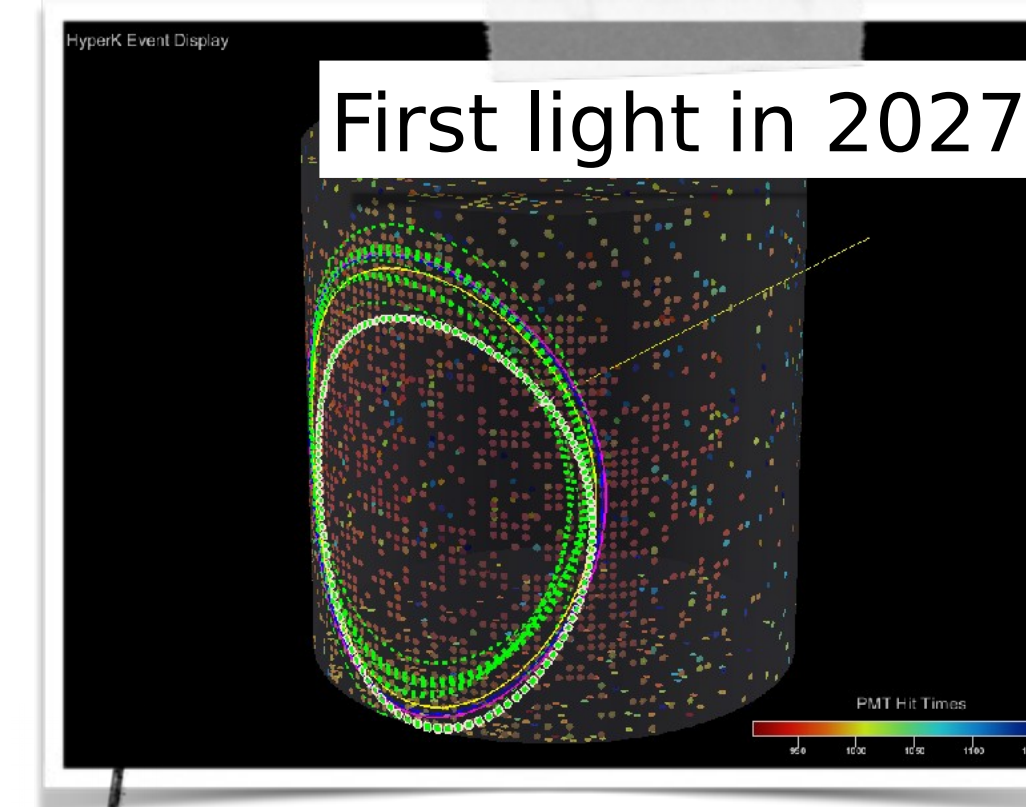
- 20k+ 20" PMTs (Hamamatsu R12860)
- ~1k mPMTs (19 3" R12199-02 PMTs)

NEW

Better signal-to-noise ratio, directionality, timing

Size of detector requires an in-water electronics

HK schedule



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

International contributions are nearly formalized

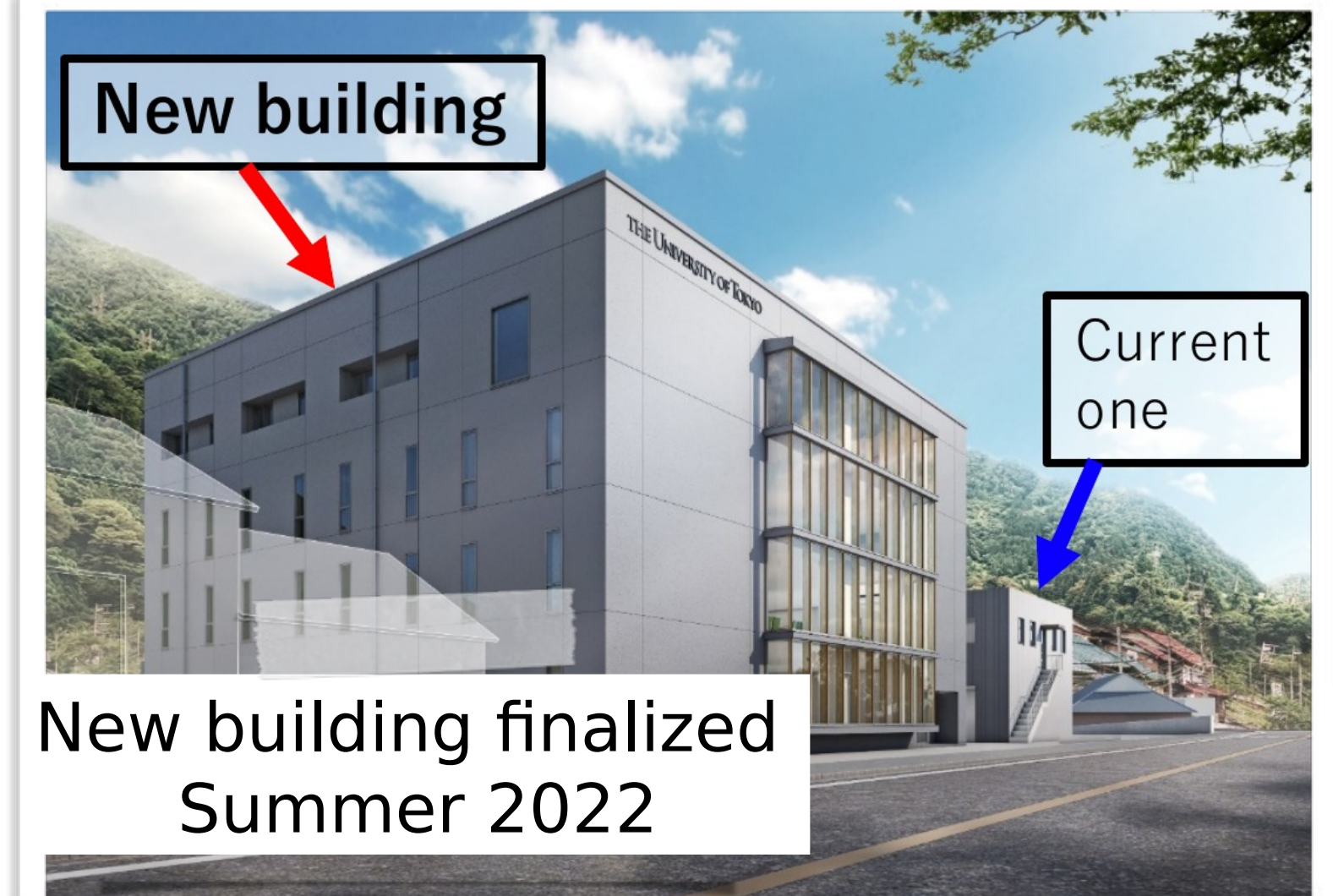
Construction is on schedule

Entrance yard finished (Aug. 2020)



New building

Current one



New building finalized
Summer 2022

Groundbreaking
ceremony
(May 2021)



Tunnel entrance (June 2021)



Survey completed ✓

Excavation on-going

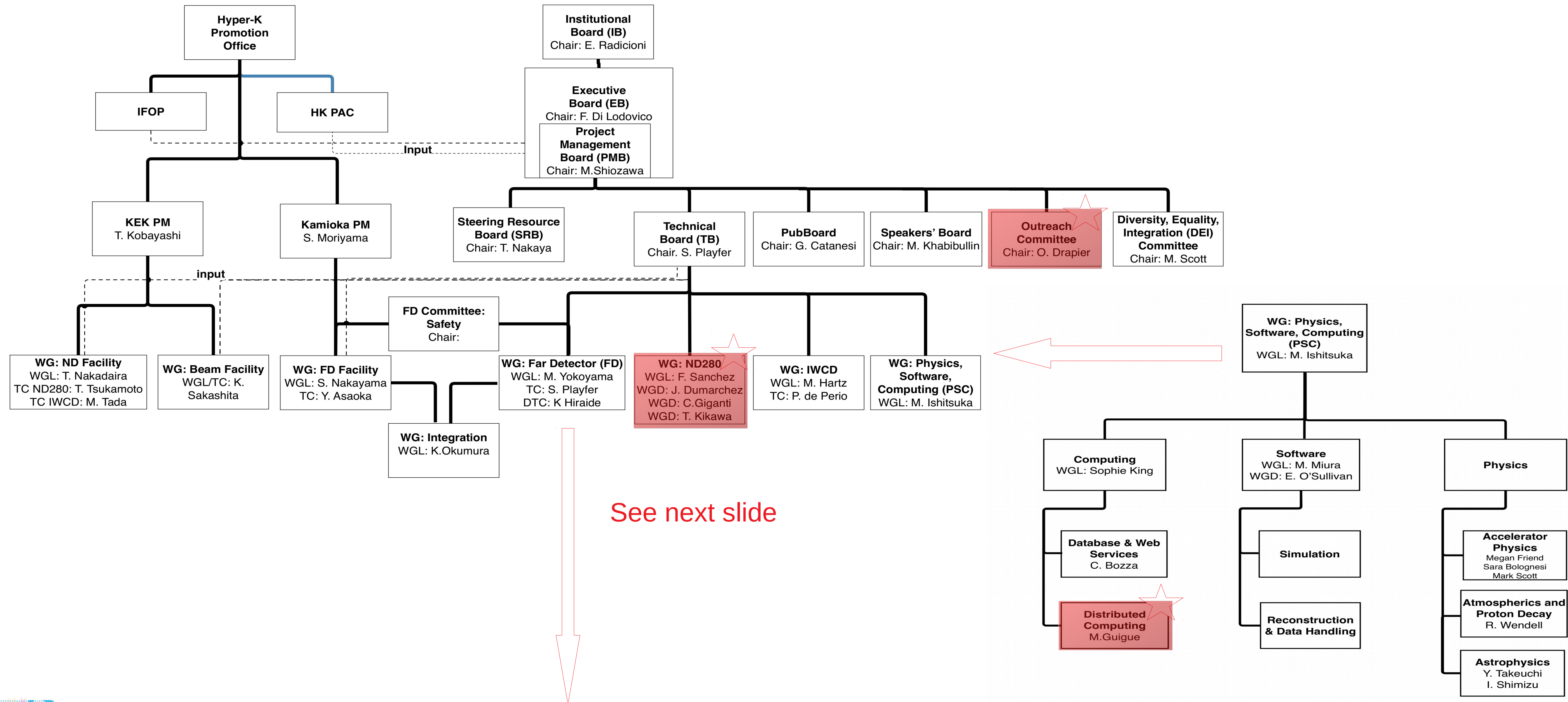


New main building



Everything on track! ✓

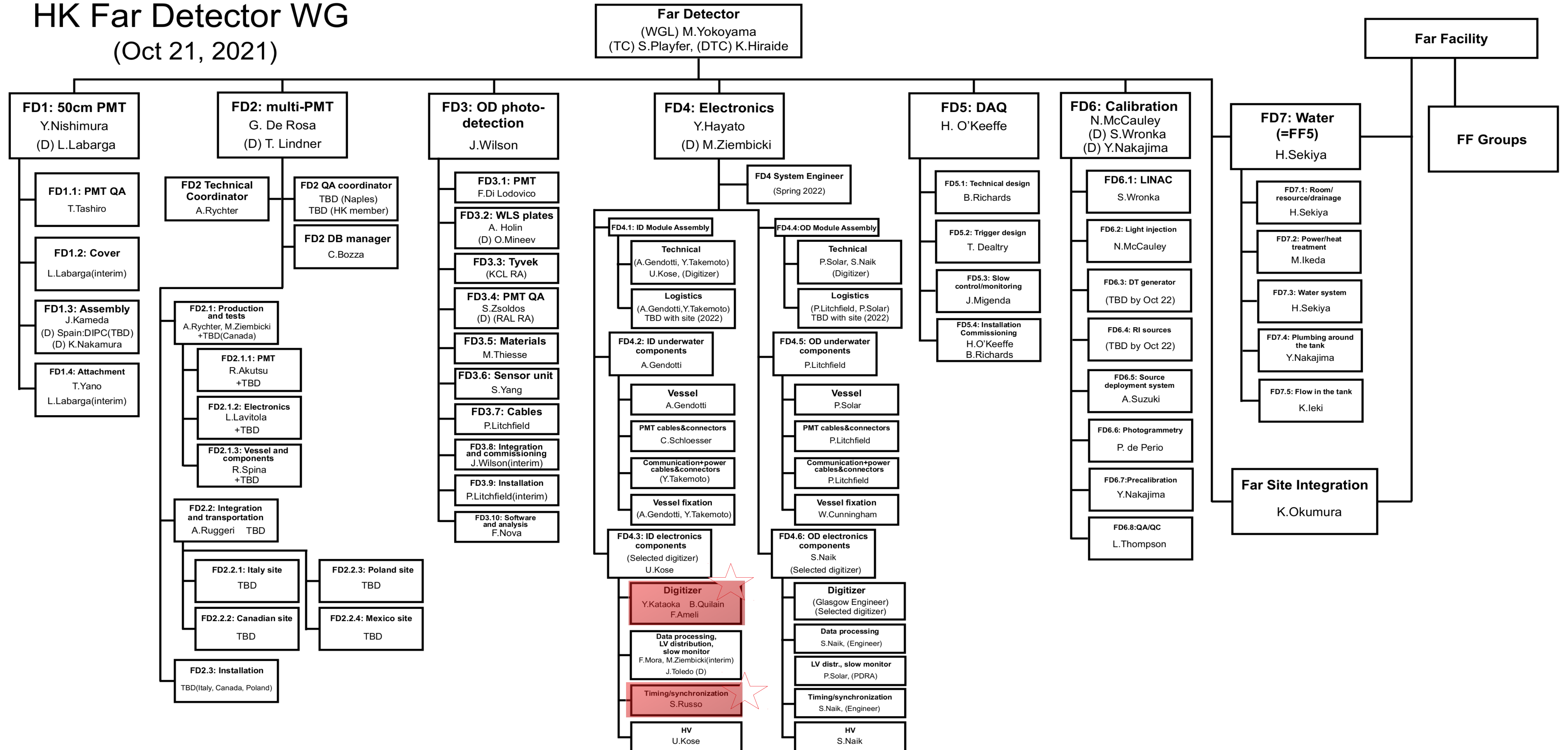
HK organizational chart



See next slide

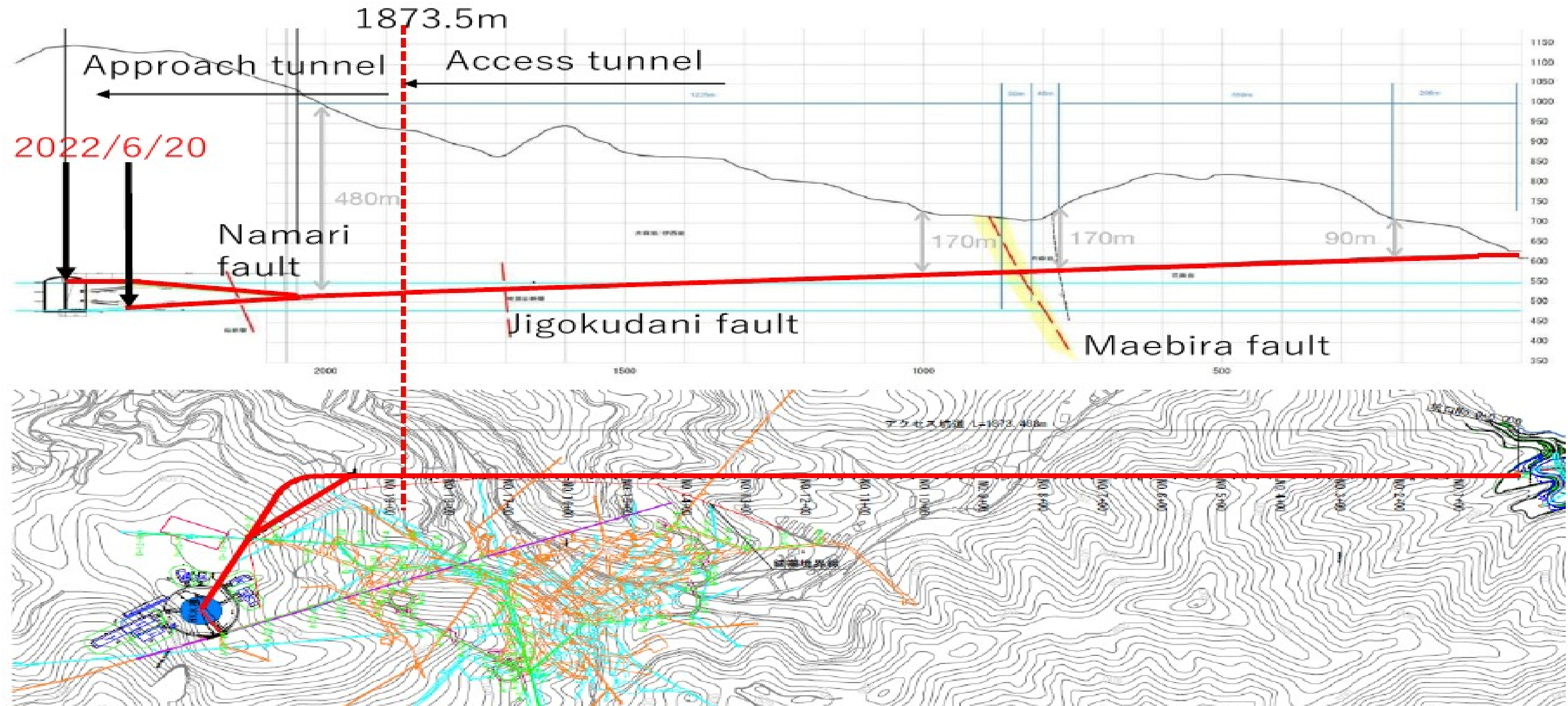
Far detector Working Groups

HK Far Detector WG (Oct 21, 2021)



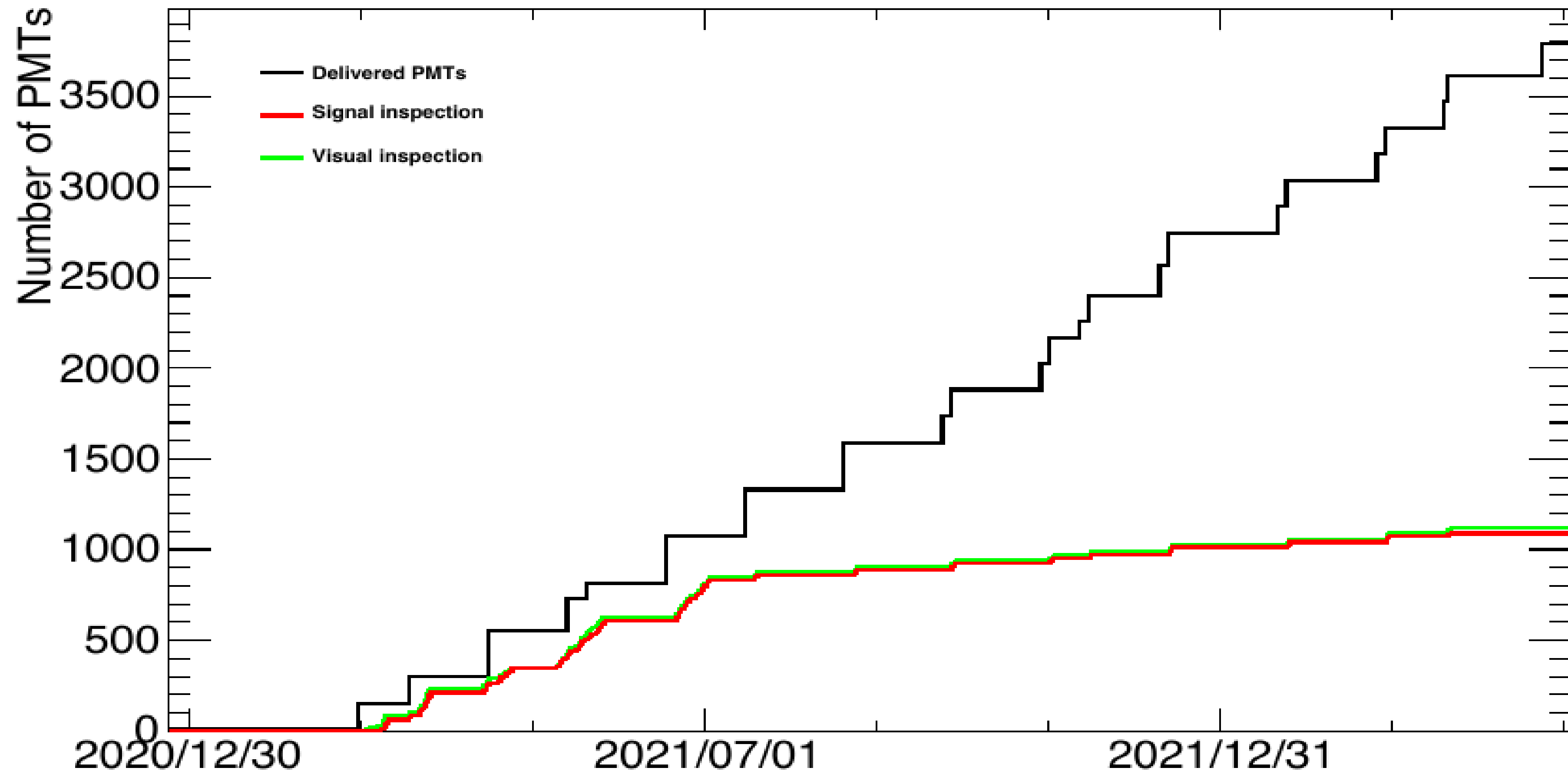
Recent progress: excavation

Tunnel excavation overview



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

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%.

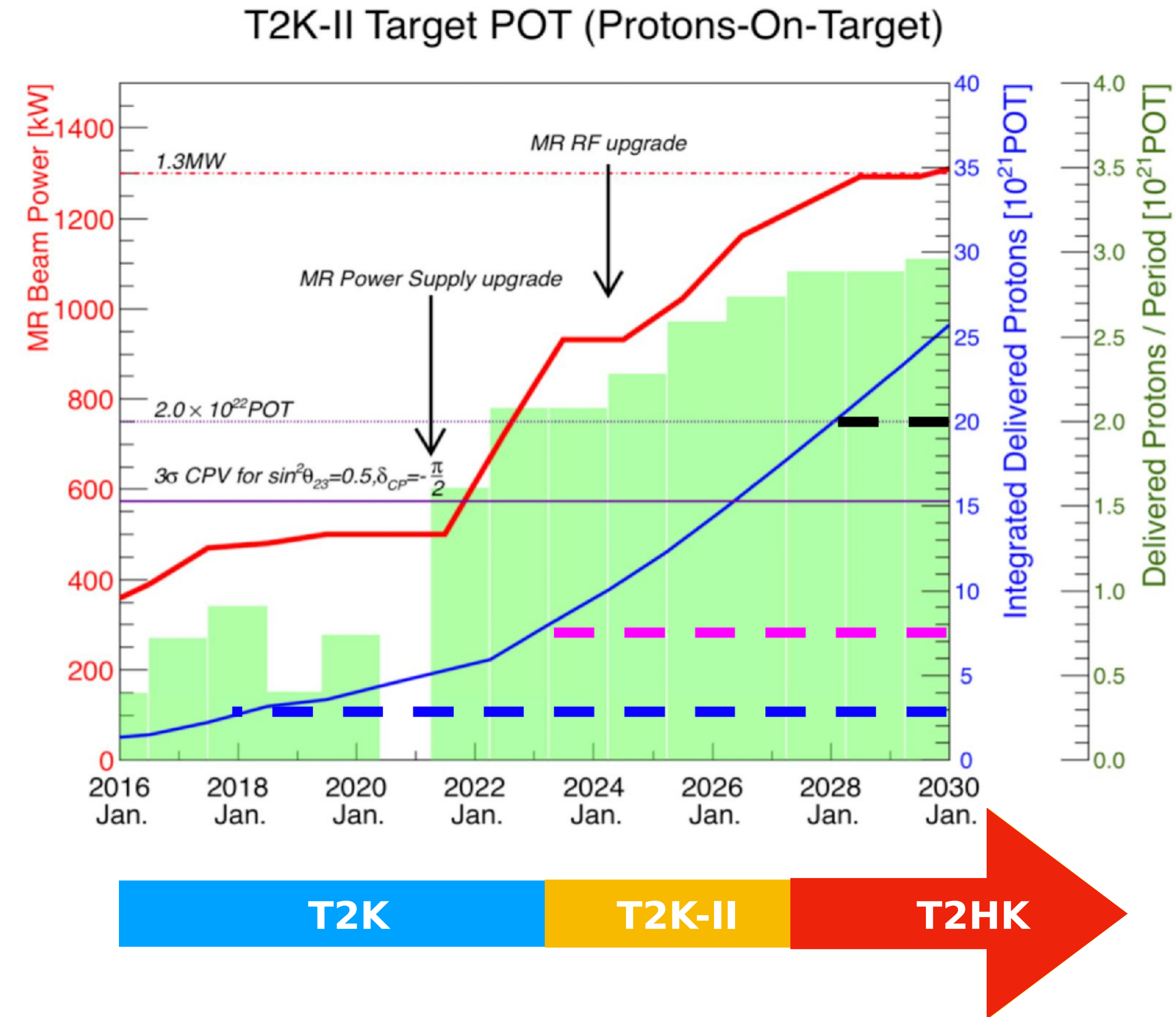
Tokai to HK: heritage from T2K

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



Tokai to HK: heritage from T2K

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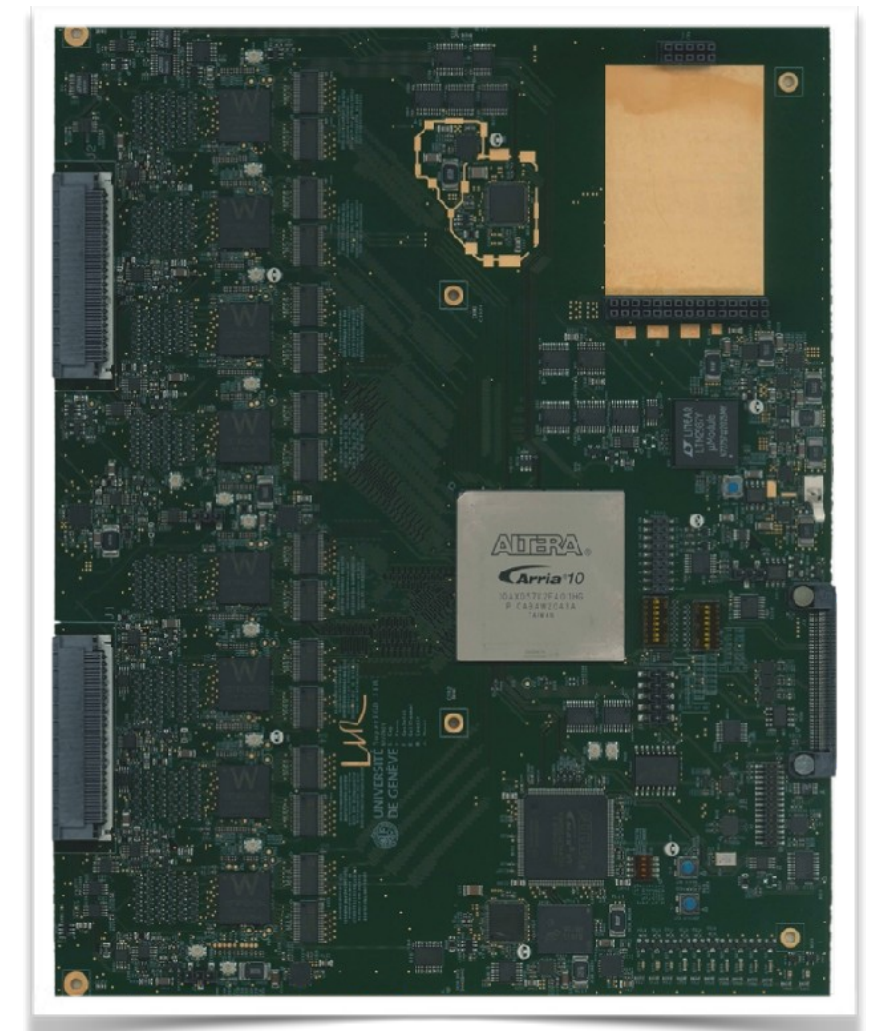
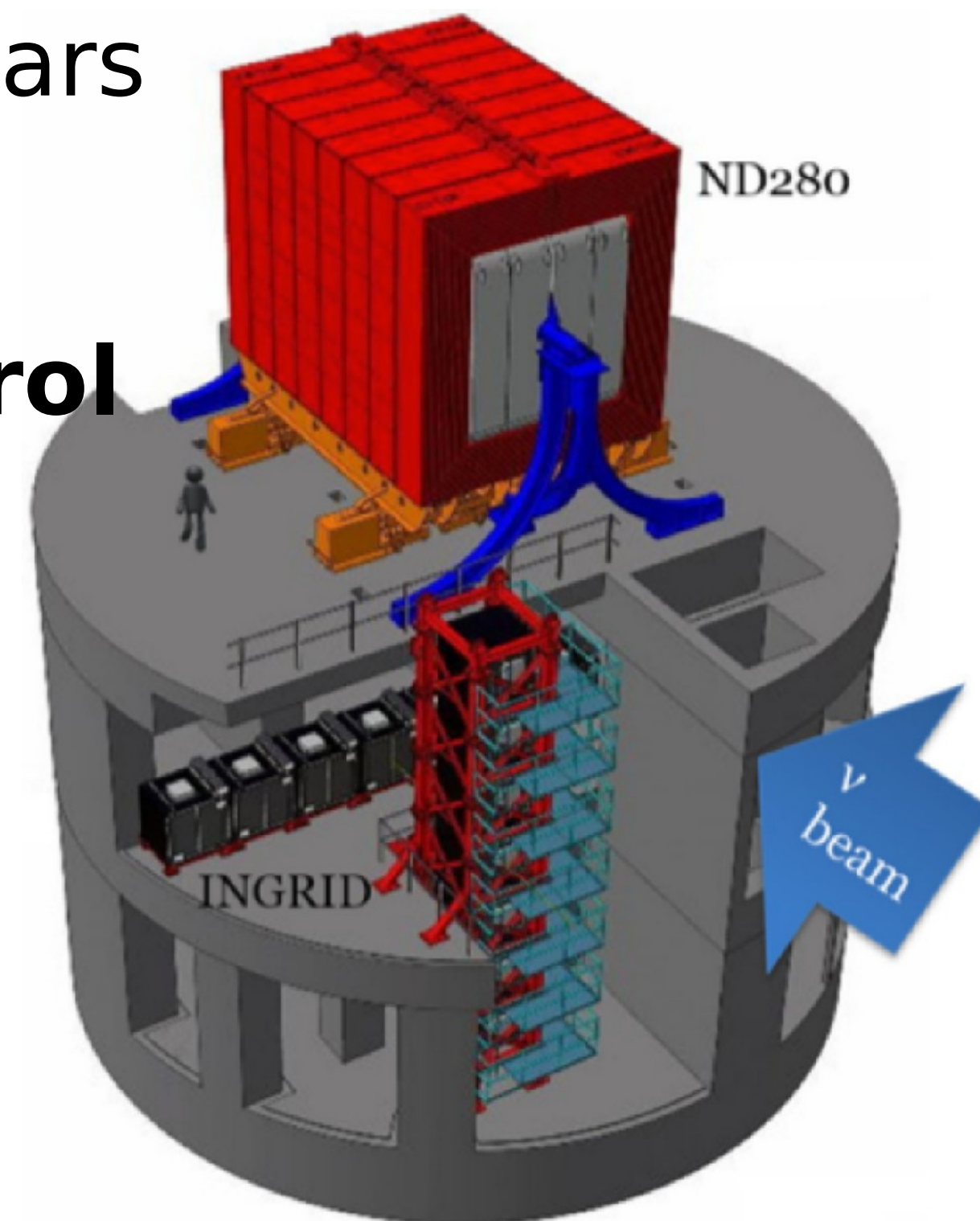
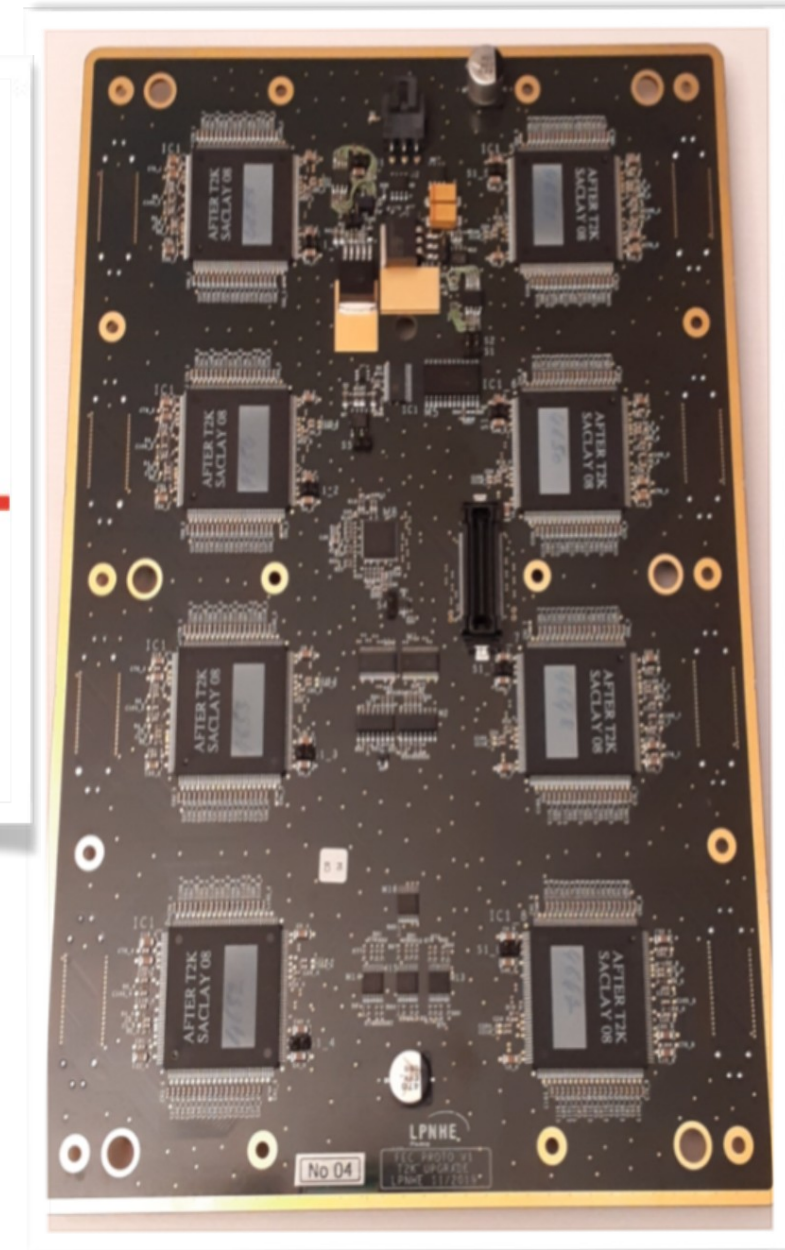
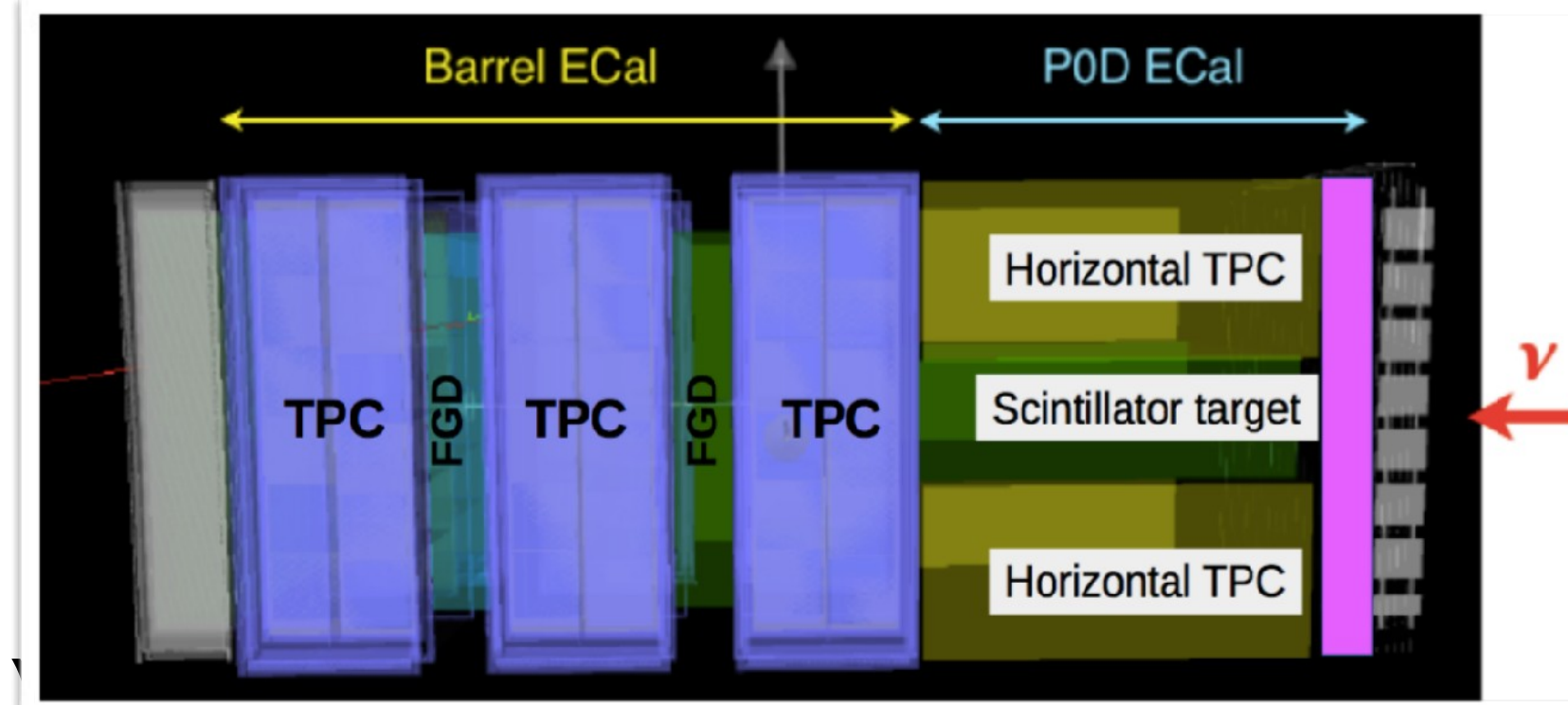
Magnetized near detector @280 m (ND280)

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**



Tokai to HK: what will be new

Accelerator upgrade

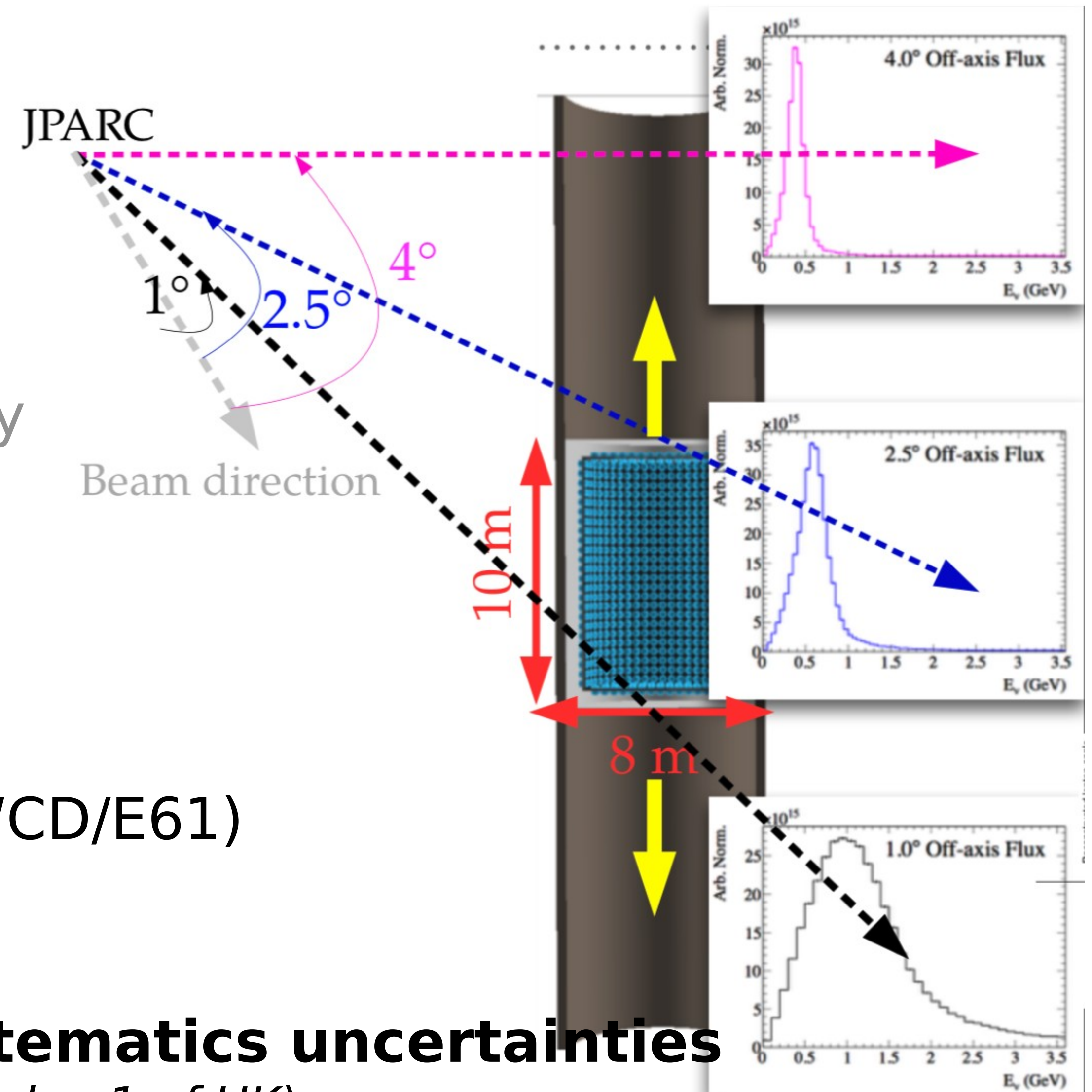
Power increase (500kW 1.3 MW)
x2.7 more stats per s (wrt T2K-I)
 $\nu / \bar{\nu}$ flux uncertainty < 5% thanks to NA61
Magnetized near detector @280 m (ND280)
Used for T2K Oscillation Analysis for >10 y
Being upgraded now for T2K-II
(crucial contributions and strong support from IN2P3)
Systematics uncertainties under control
from day 1 of HK

Intermediate Water Cherenkov Detector (IWCD/E61)

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

Needed to reach final HK goal for systematics uncertainties

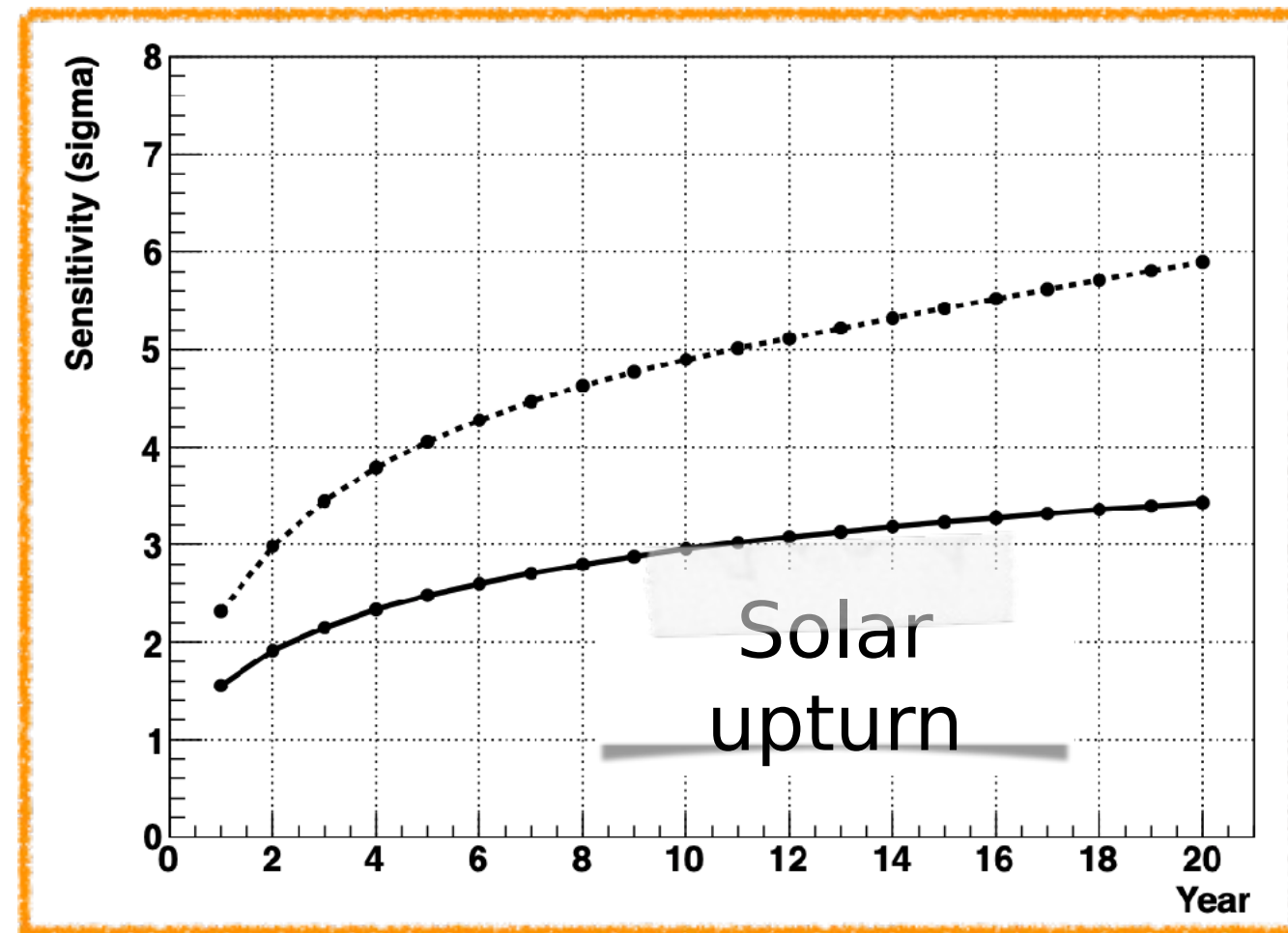
(if delayed ND280 will be the only near detector on day 1 of HK)



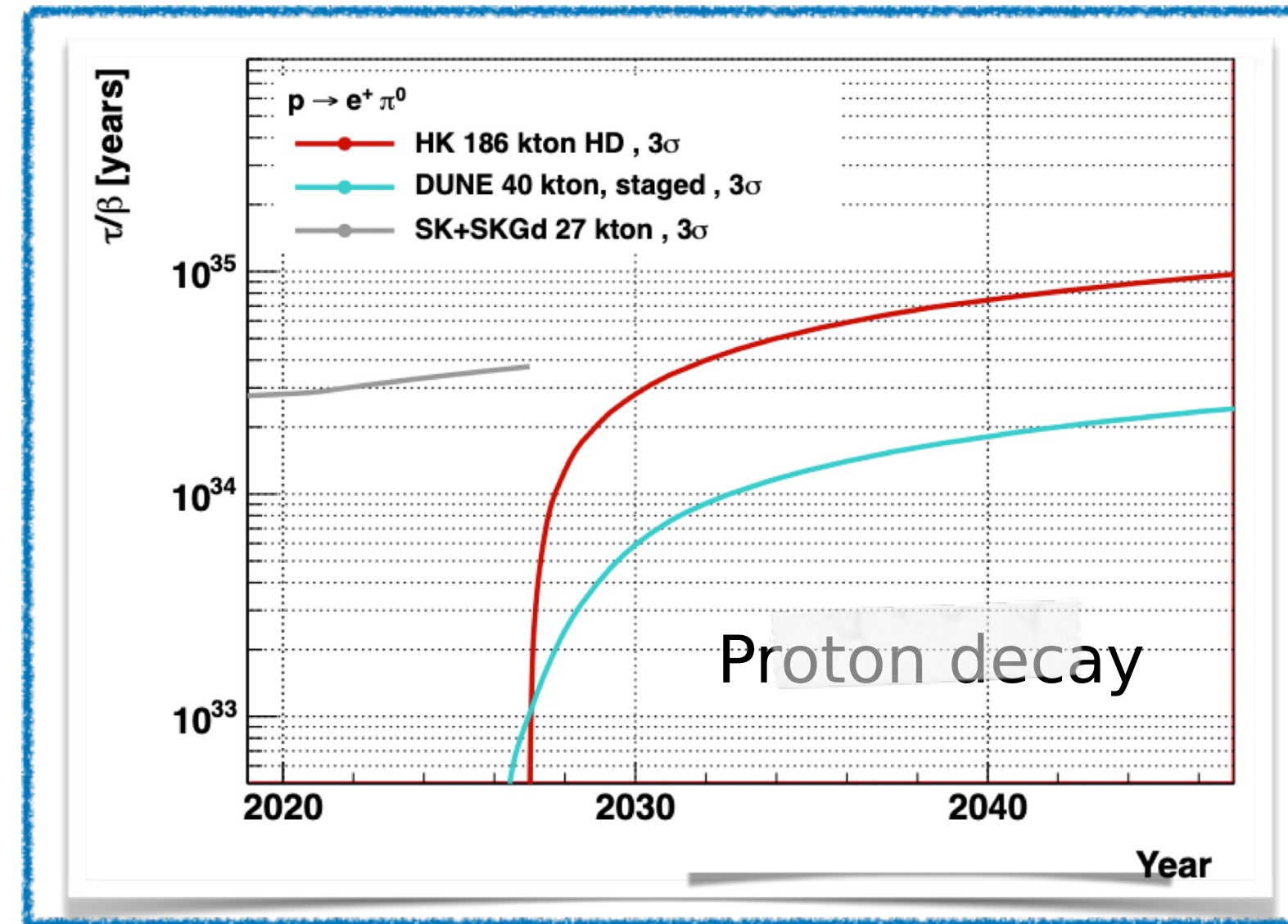
NEW

Hyper-Kamiokande Physics

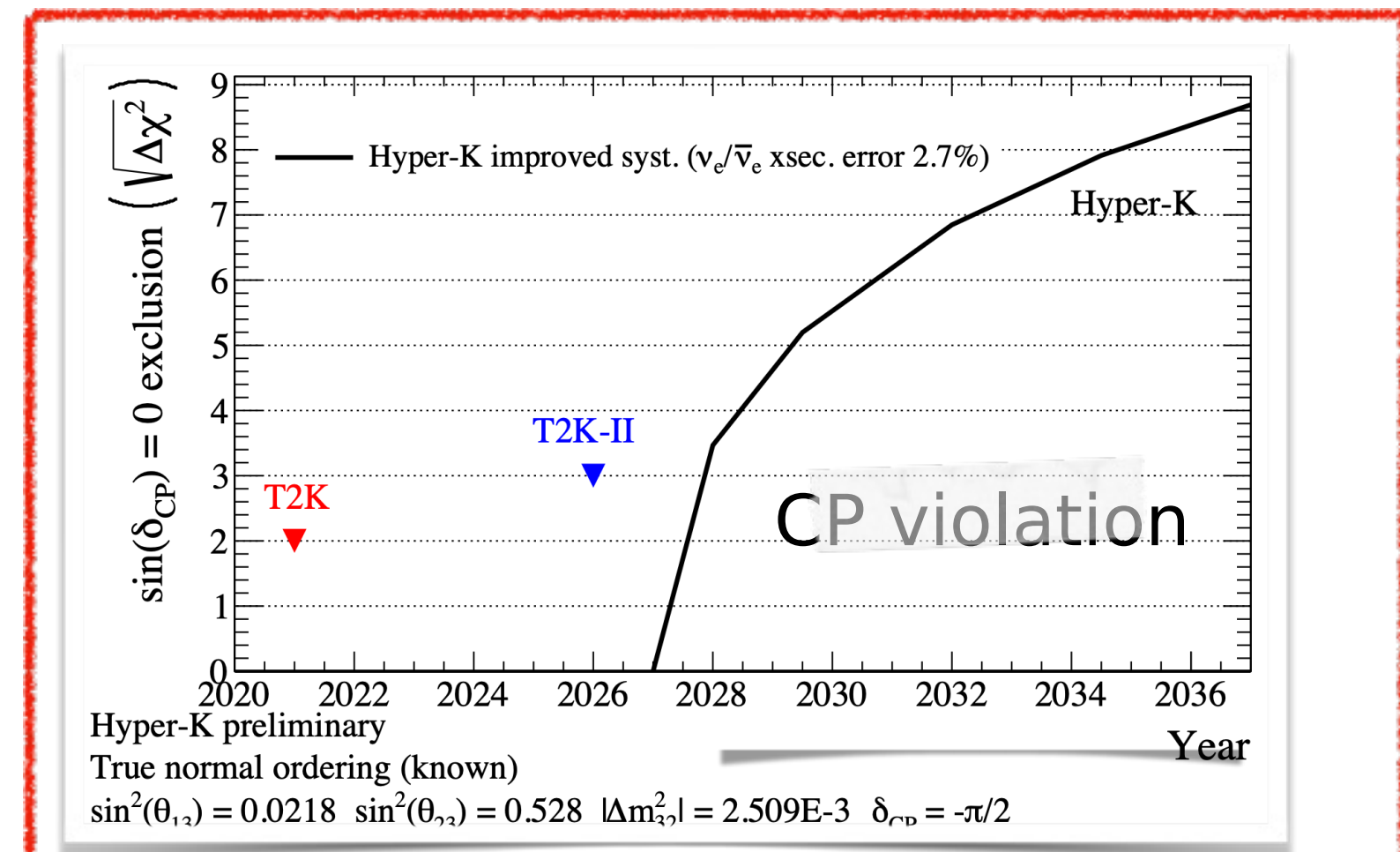
Solar physics



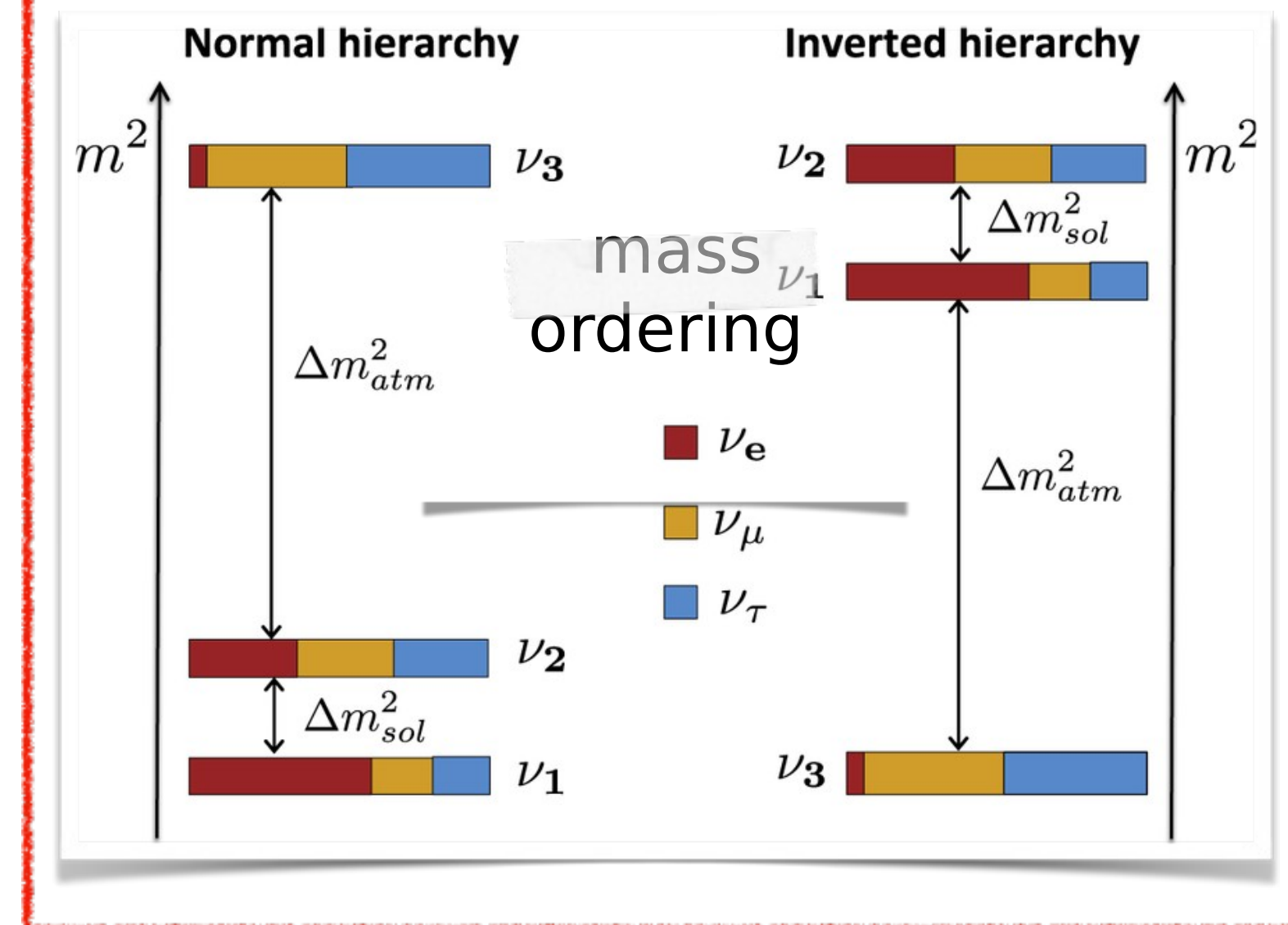
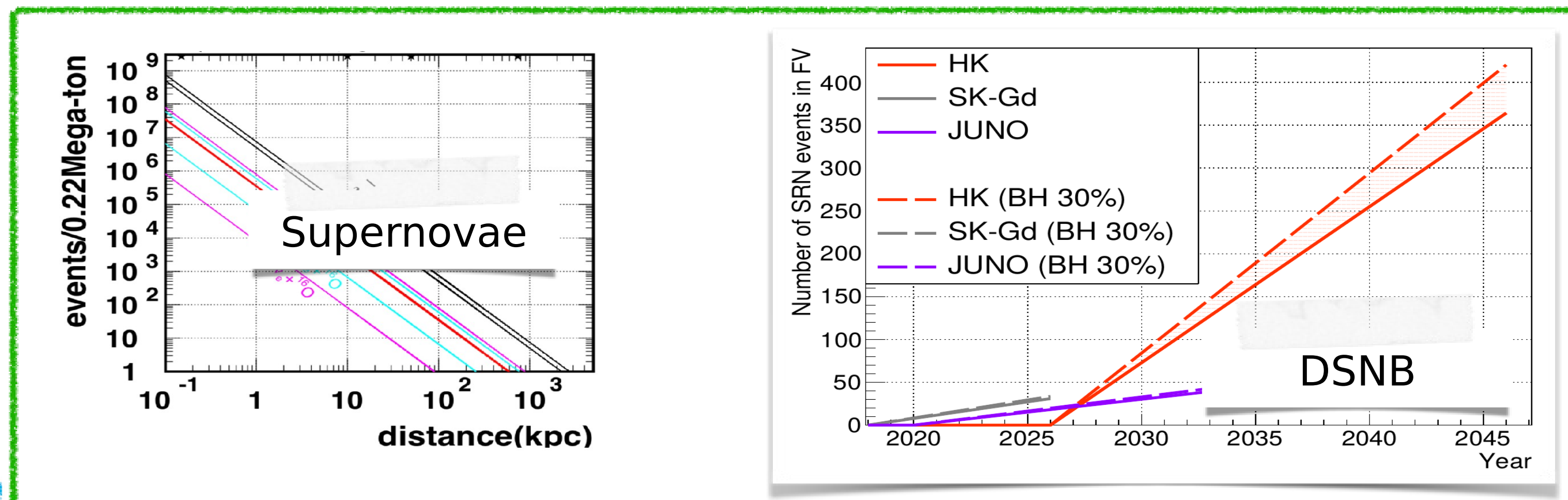
Rare events



Neutrino oscillations

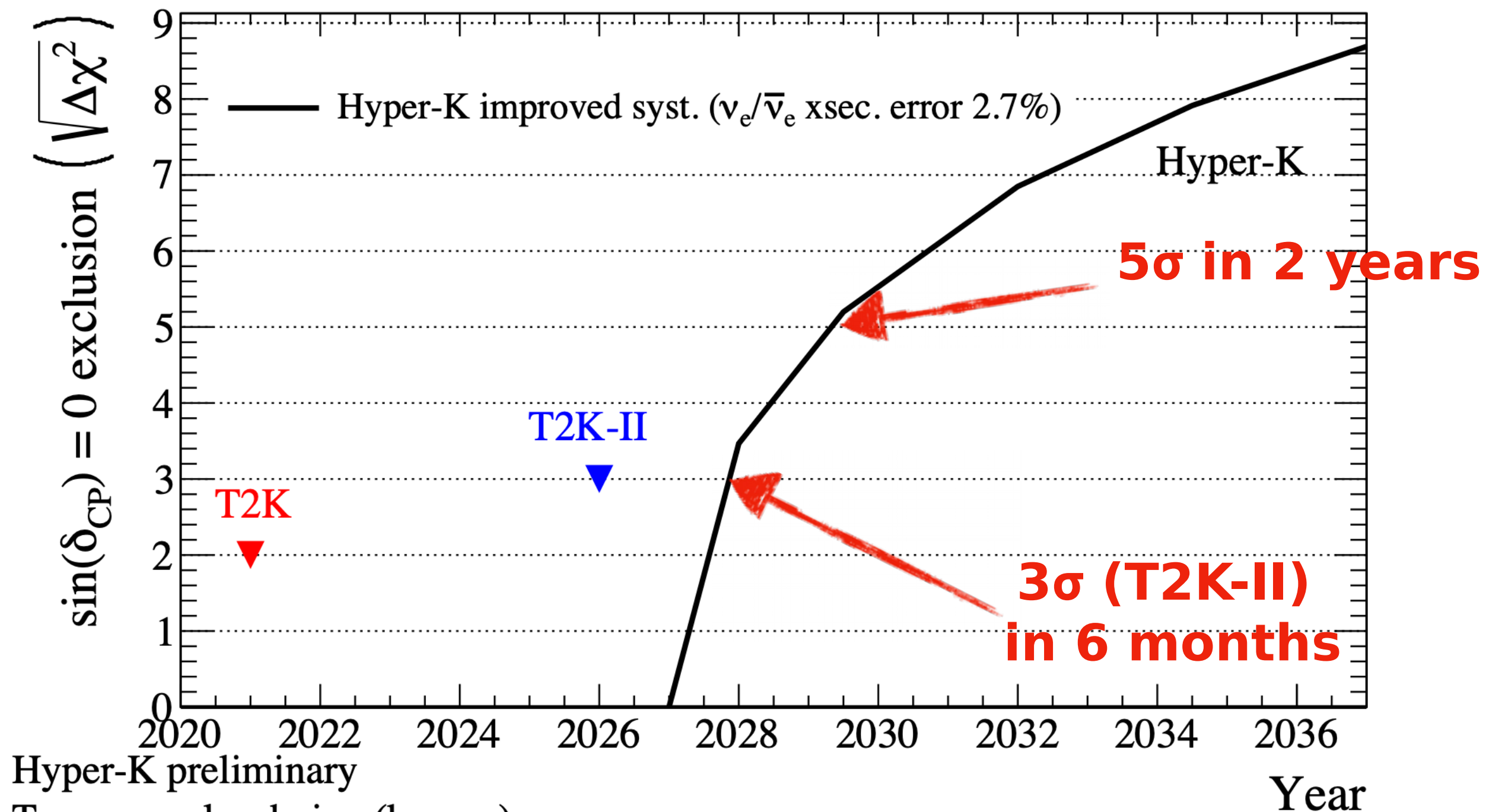


Supernovae modeling and Early Universe



Fast CP-violation discovery

Known mass ordering (KM3NET)

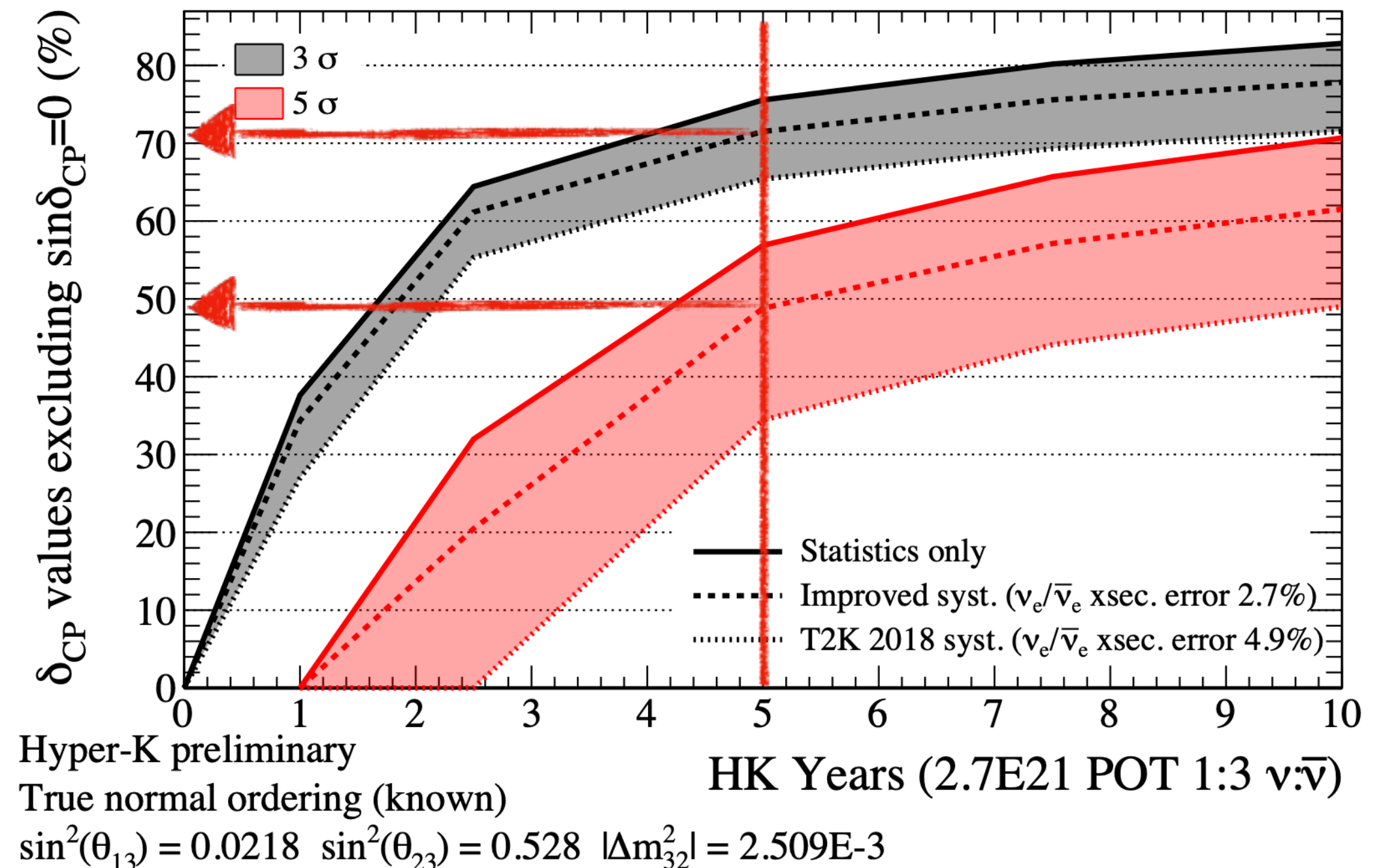


Hyper-K preliminary

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



Hyper-K preliminary

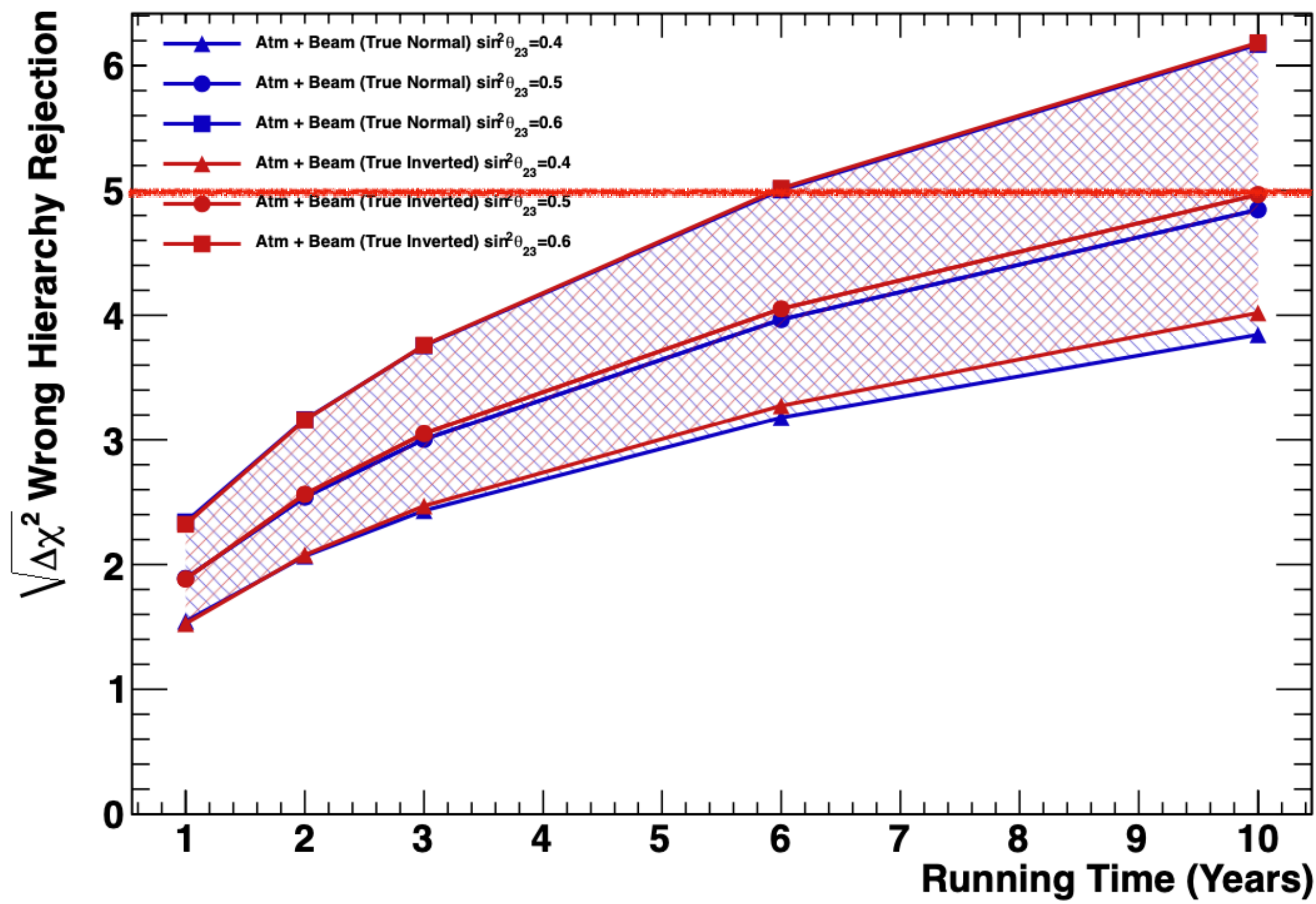
True normal ordering (known)

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

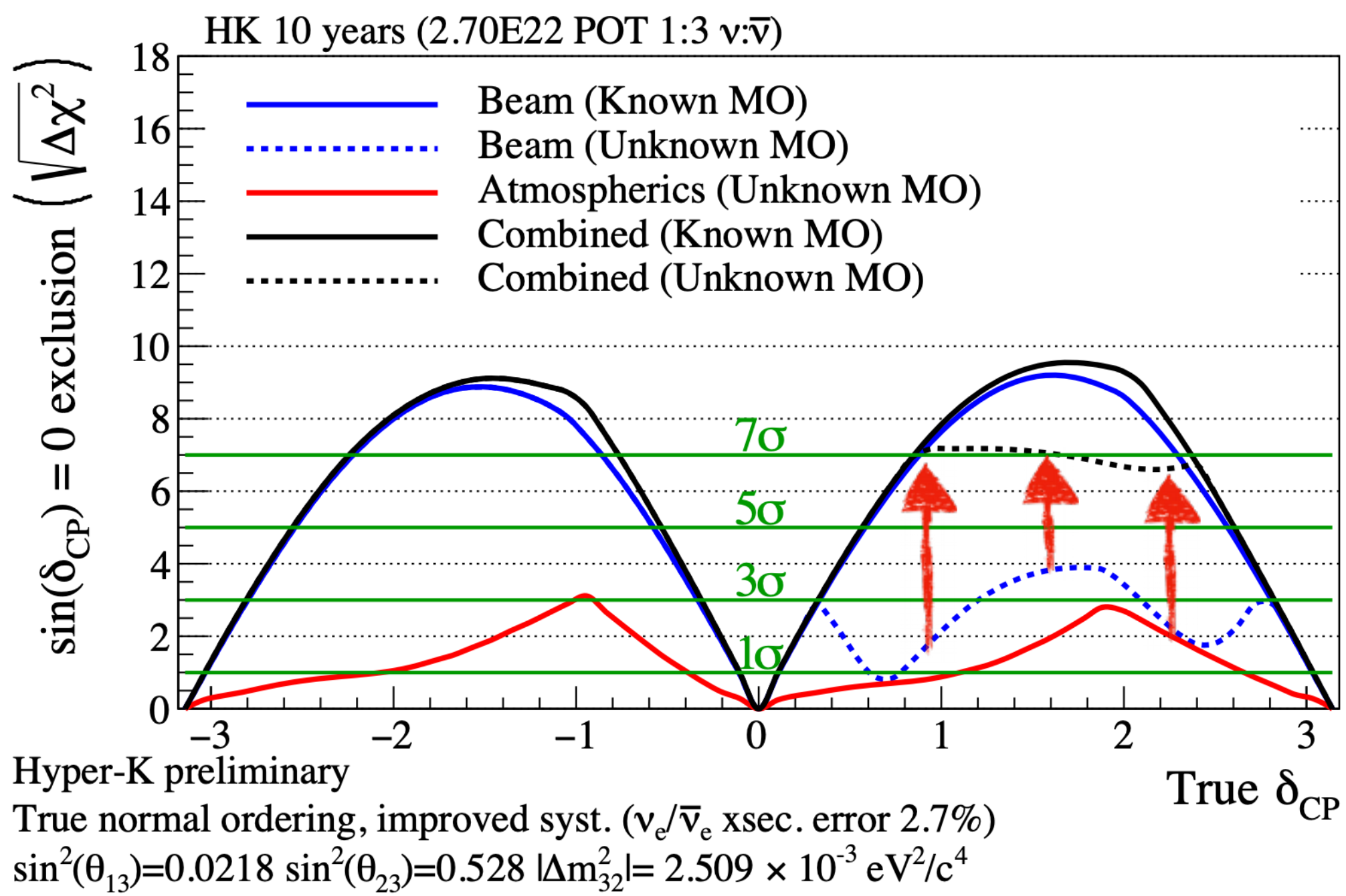
	$\delta_{CP} = -\pi/2$		All δ_{CP}	
	3σ	5σ	50 % 5σ	70 % 3σ
Hyper Kamiokande	0.5 y	2 y	5 y	5 y
DUNE (staged*)	4 y	8 y	10 y	13 y

* 2 modules@1.2 MW y1; 3 modules y2; DUNE CDR [arXiv:2002.03005](https://arxiv.org/abs/2002.03005)
 4 modules y4; @2.4 MW y7
 IUPAP Neutrino panel [report](#)

Mass ordering sensitivity with atmospheric



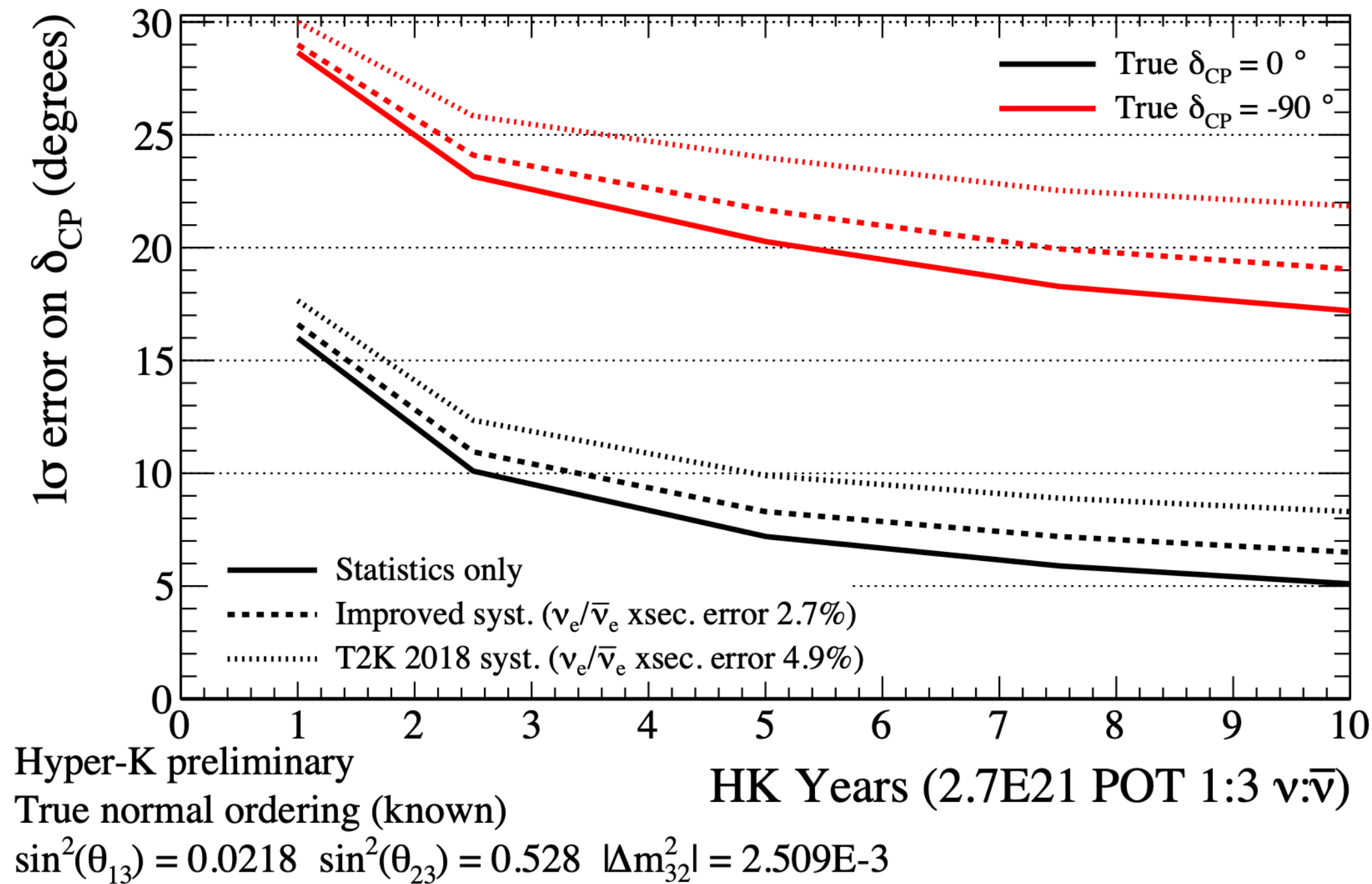
If not discovered by T2K/SK, NOvA, ORCA or JUNO before 2027, HK can determine MO after 6-10 years via atmospheric ν



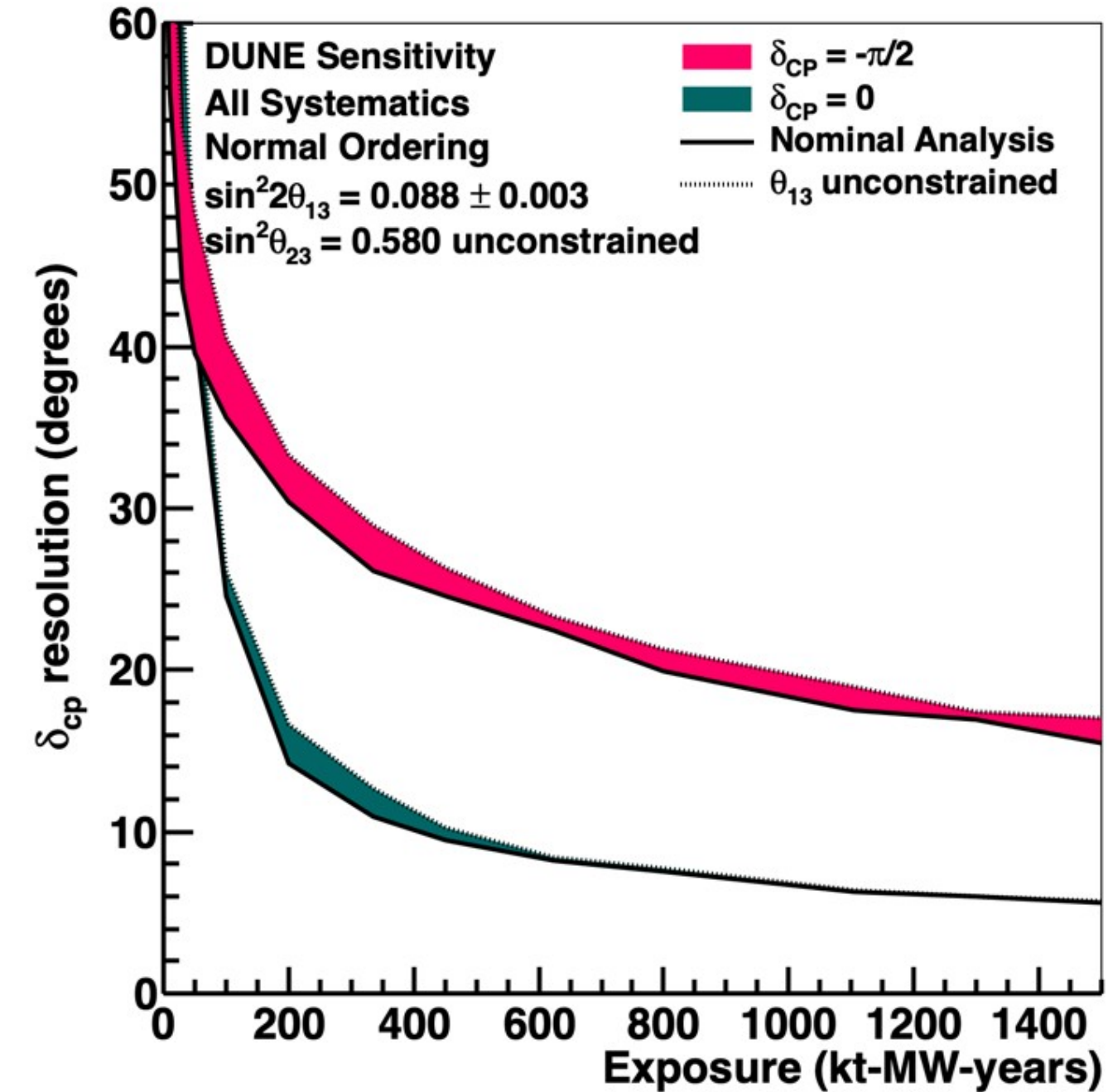
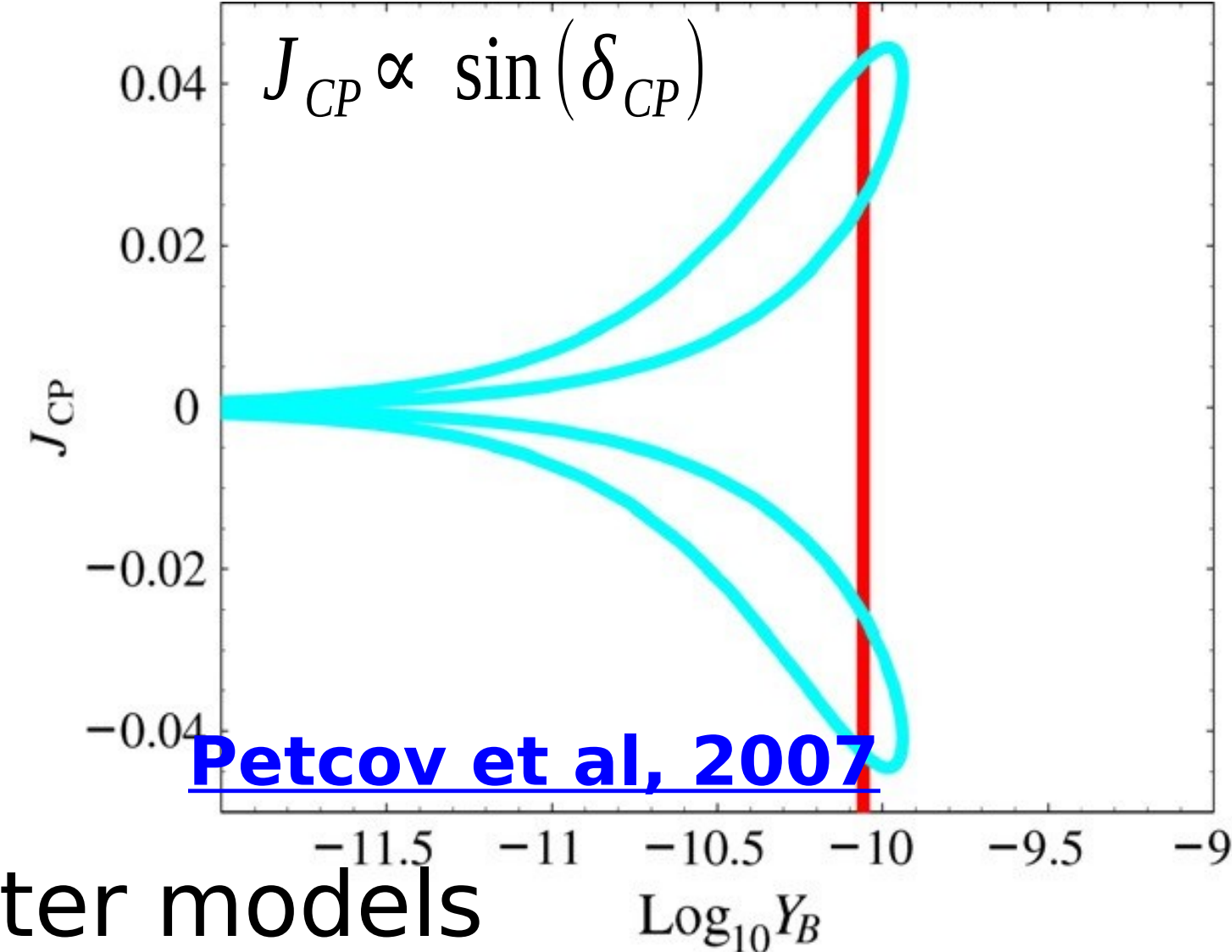
	$\sin^2 \theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	2.2 σ	→ 3.8 σ
	0.60	4.9 σ	→ 6.2 σ

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°(15°) 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)

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

Proton decay

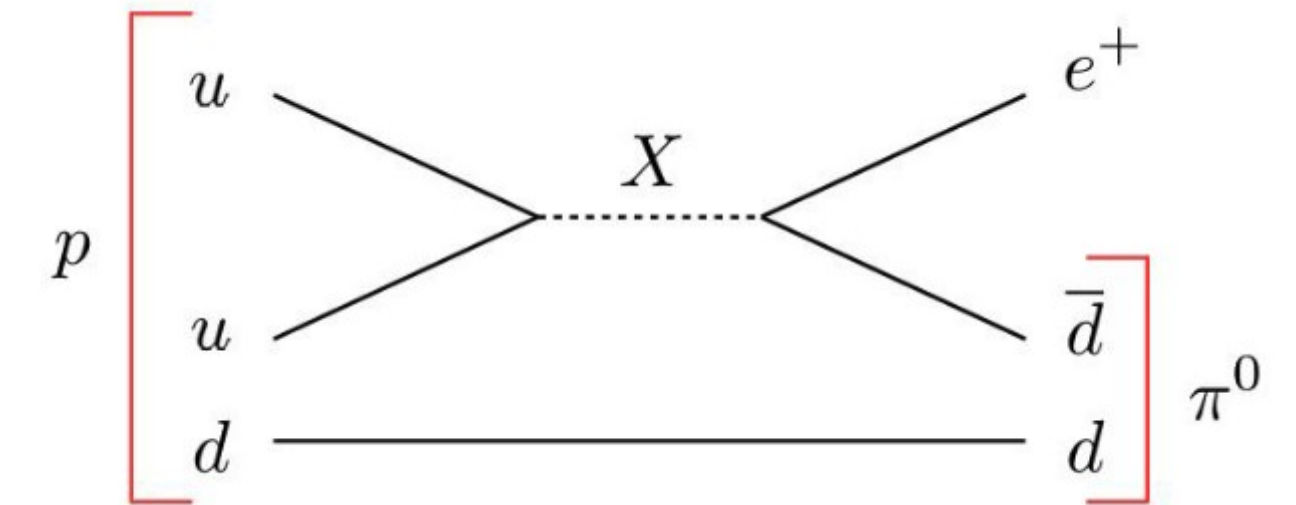
Motivated by Grand-Unification Theories

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

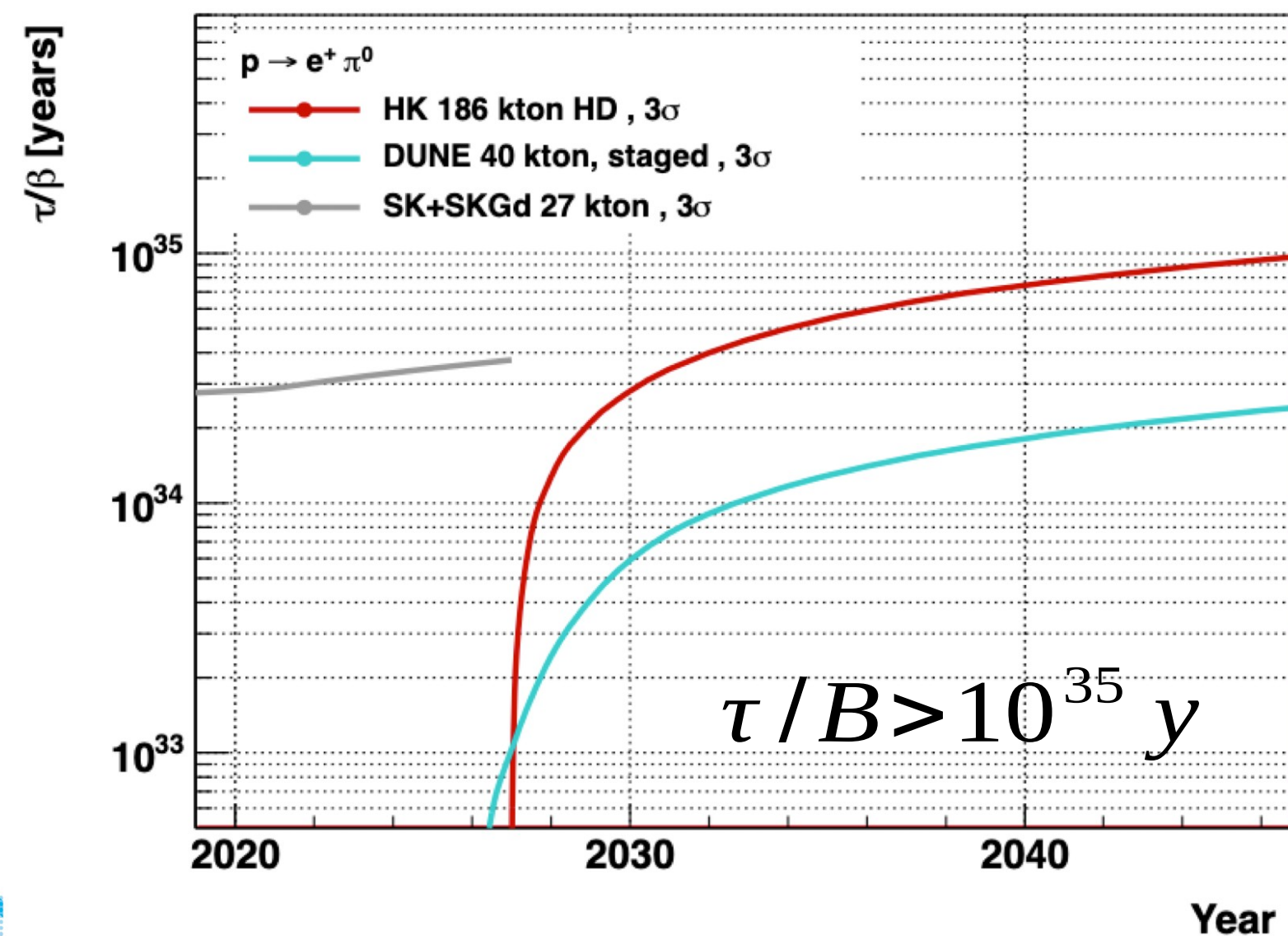
→ about 1 order of magnitude better than current limits

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



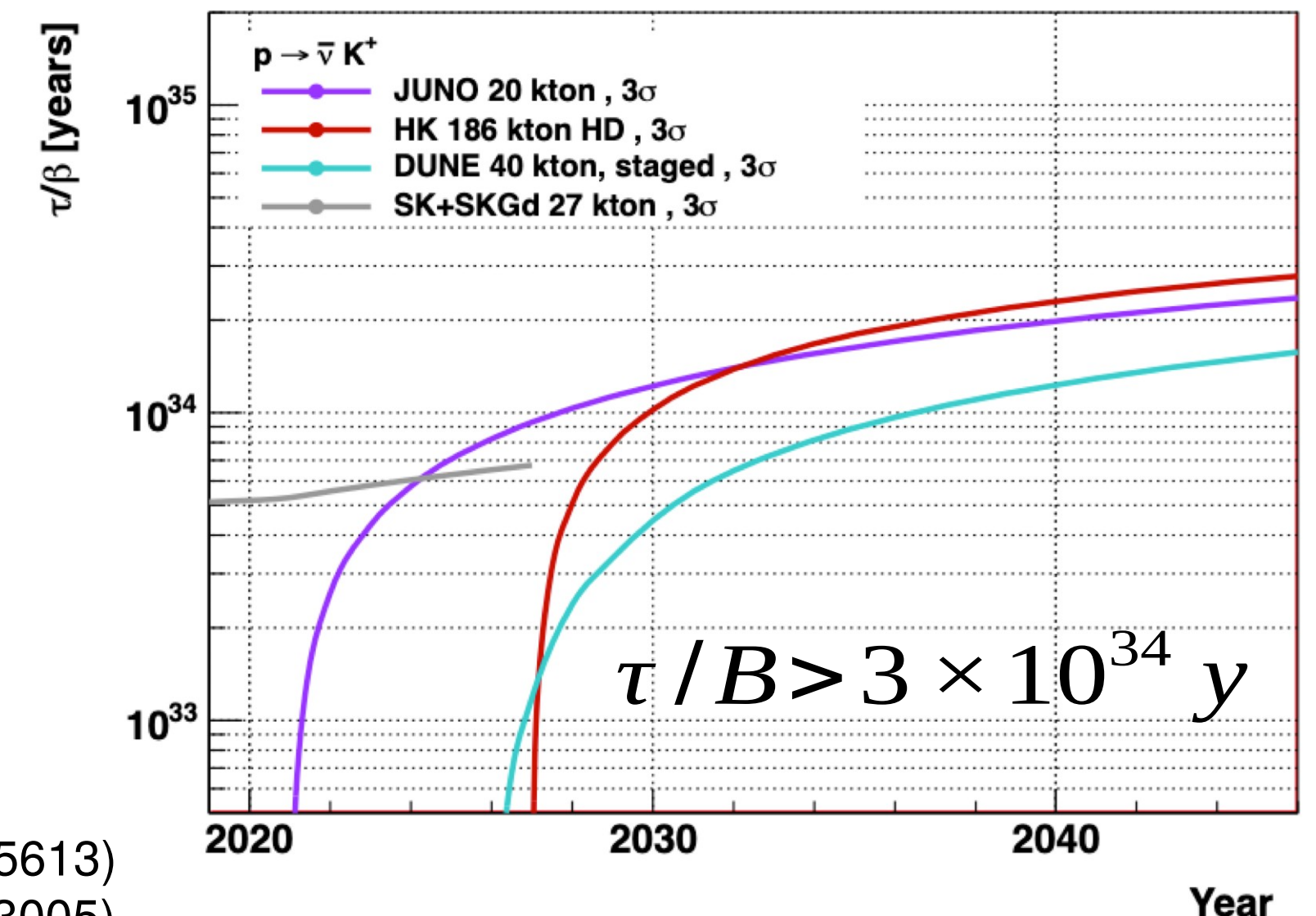
Phys. Lett. B 233 (1-2) 178-182



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

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

Hyper-Kamiokande — CS IN2P3 October 2022



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

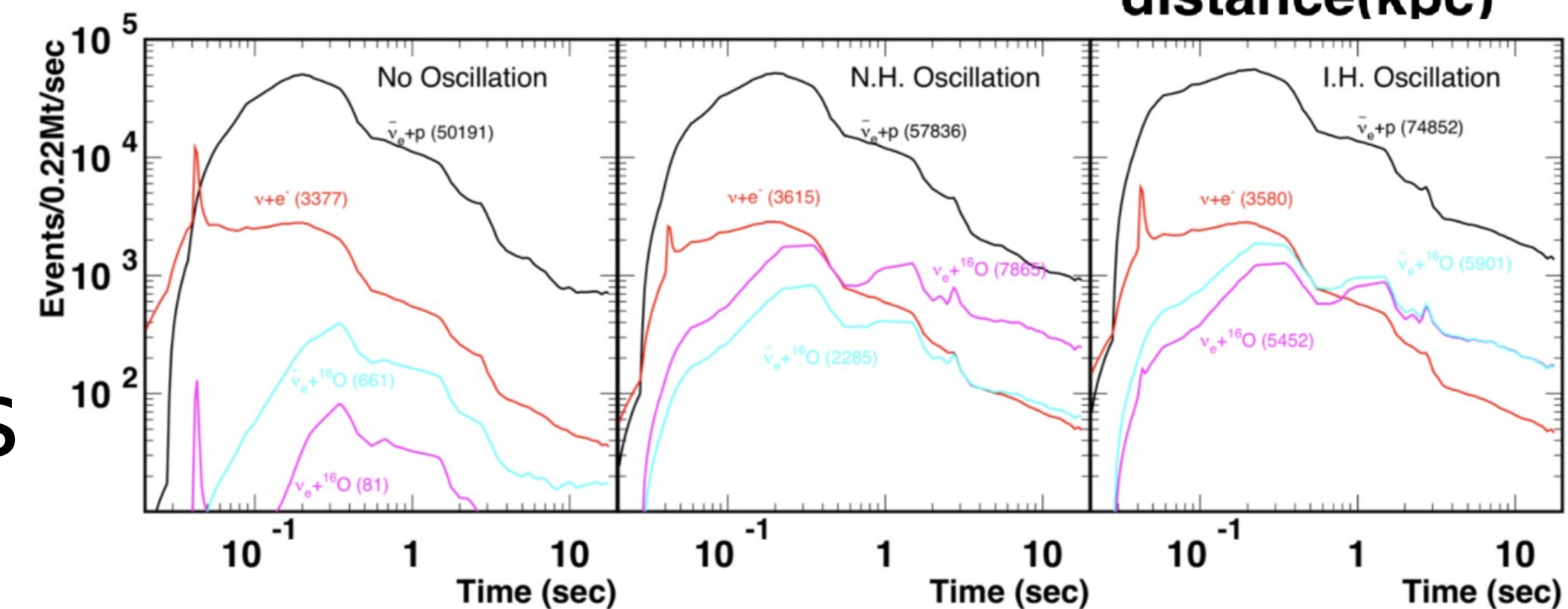
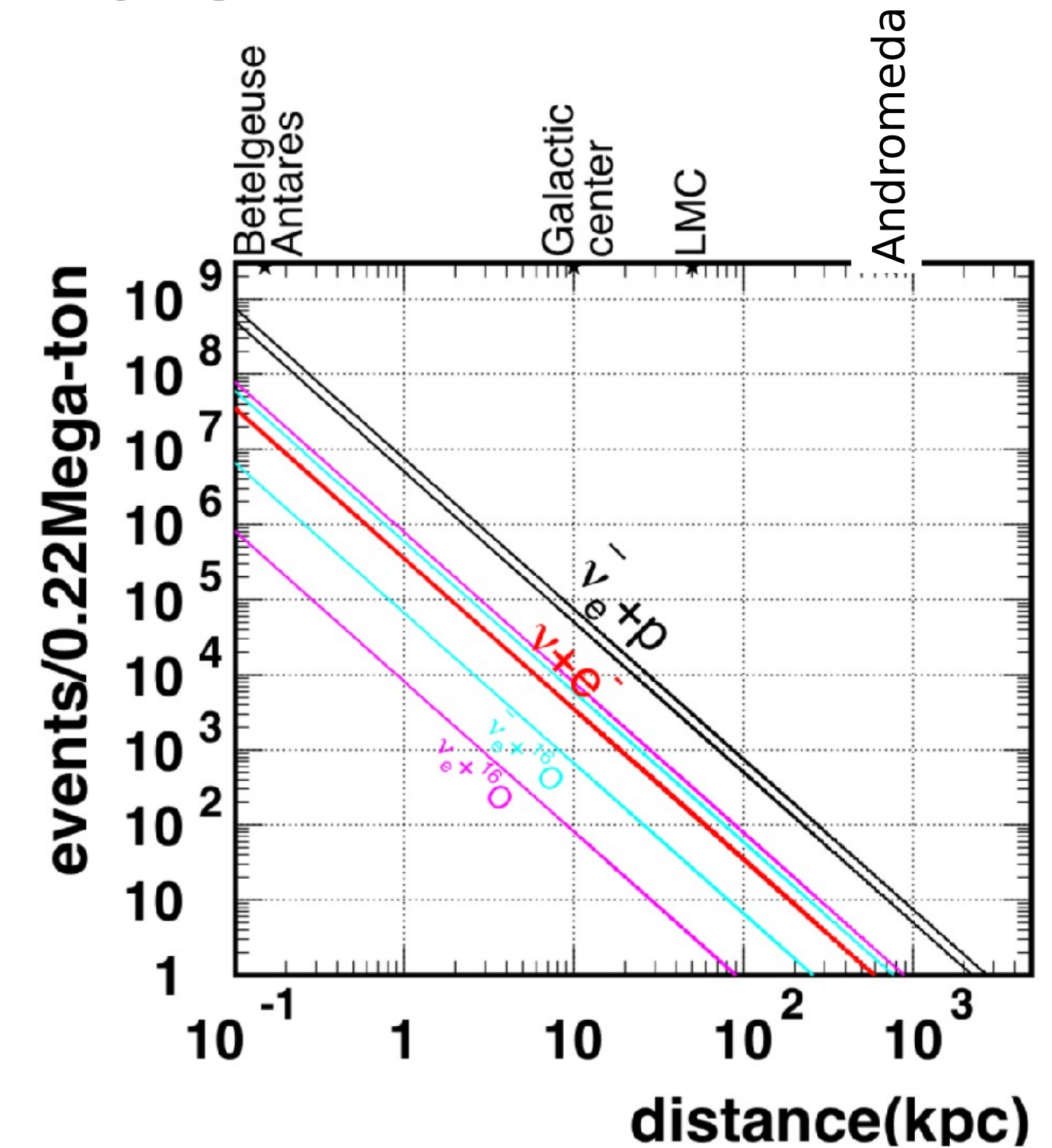
Direction (1° @ 10kpc) $\rightarrow$ triangulation

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

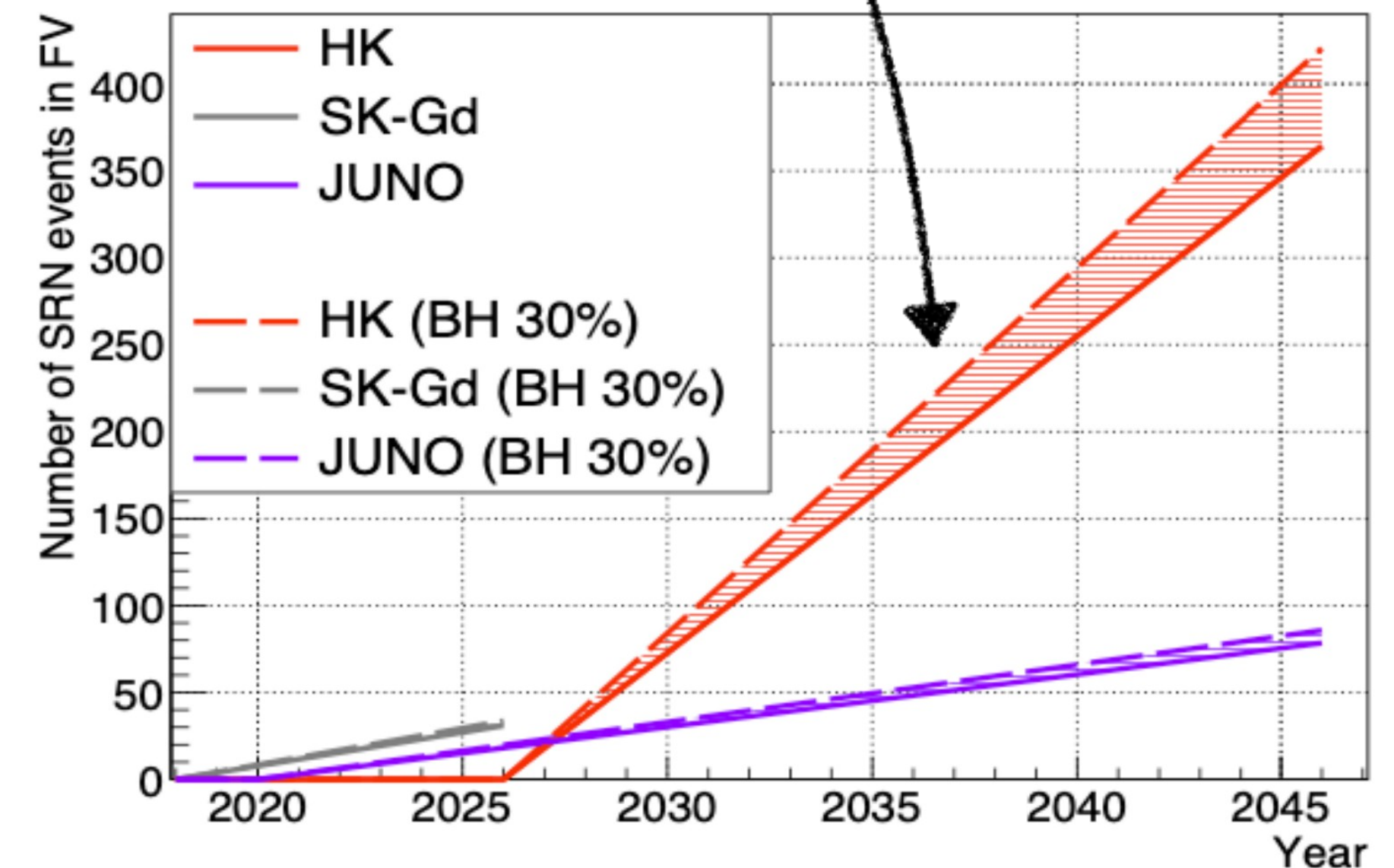
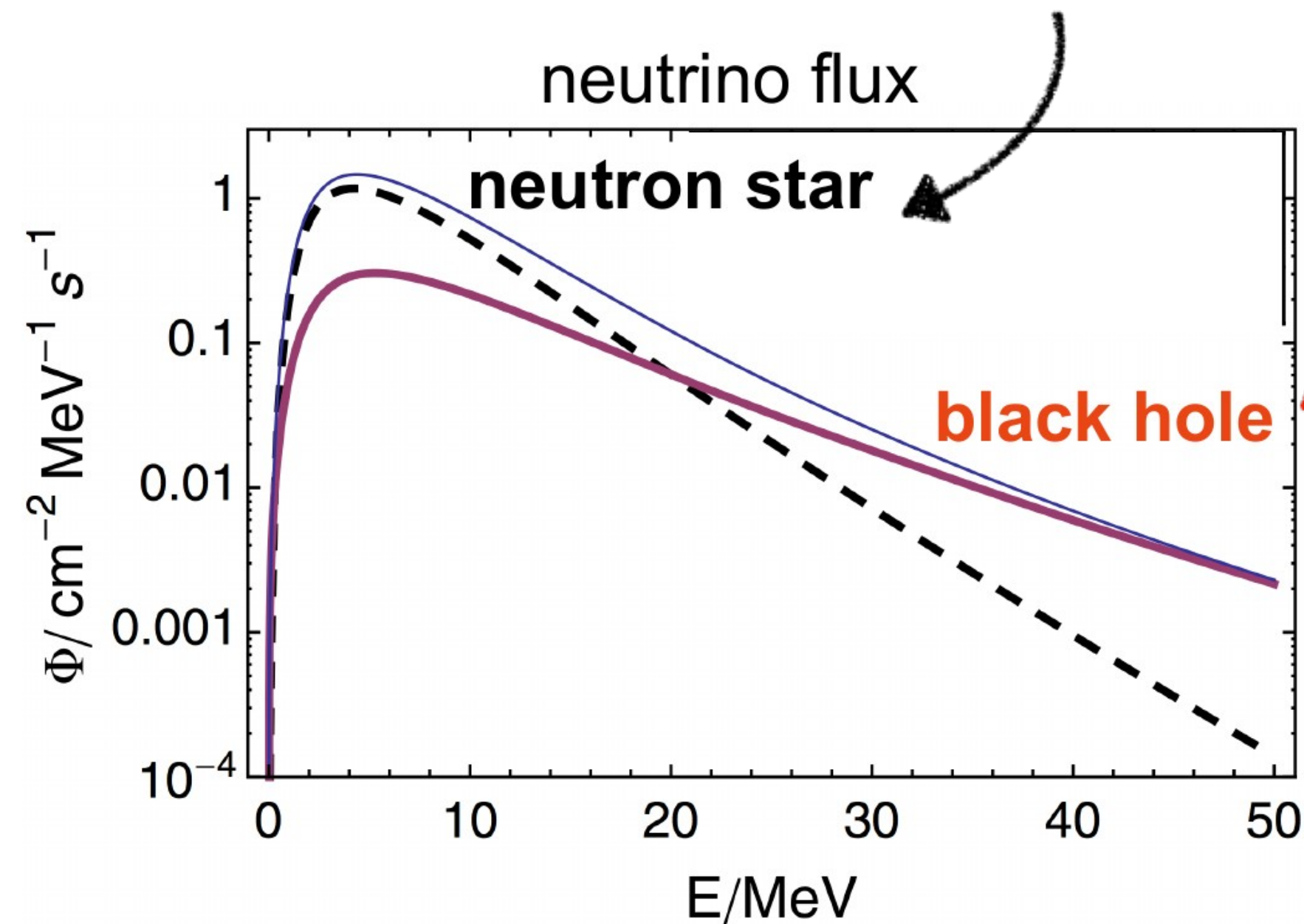
SN-relic neutrinos (SNR ν) offer new constraints on cosmic star history

→ Could be first detected by SK-Gd

→ The spectrum will be determined by HK

Impact of redshift: low energy $\leftrightarrow$ probe older stars

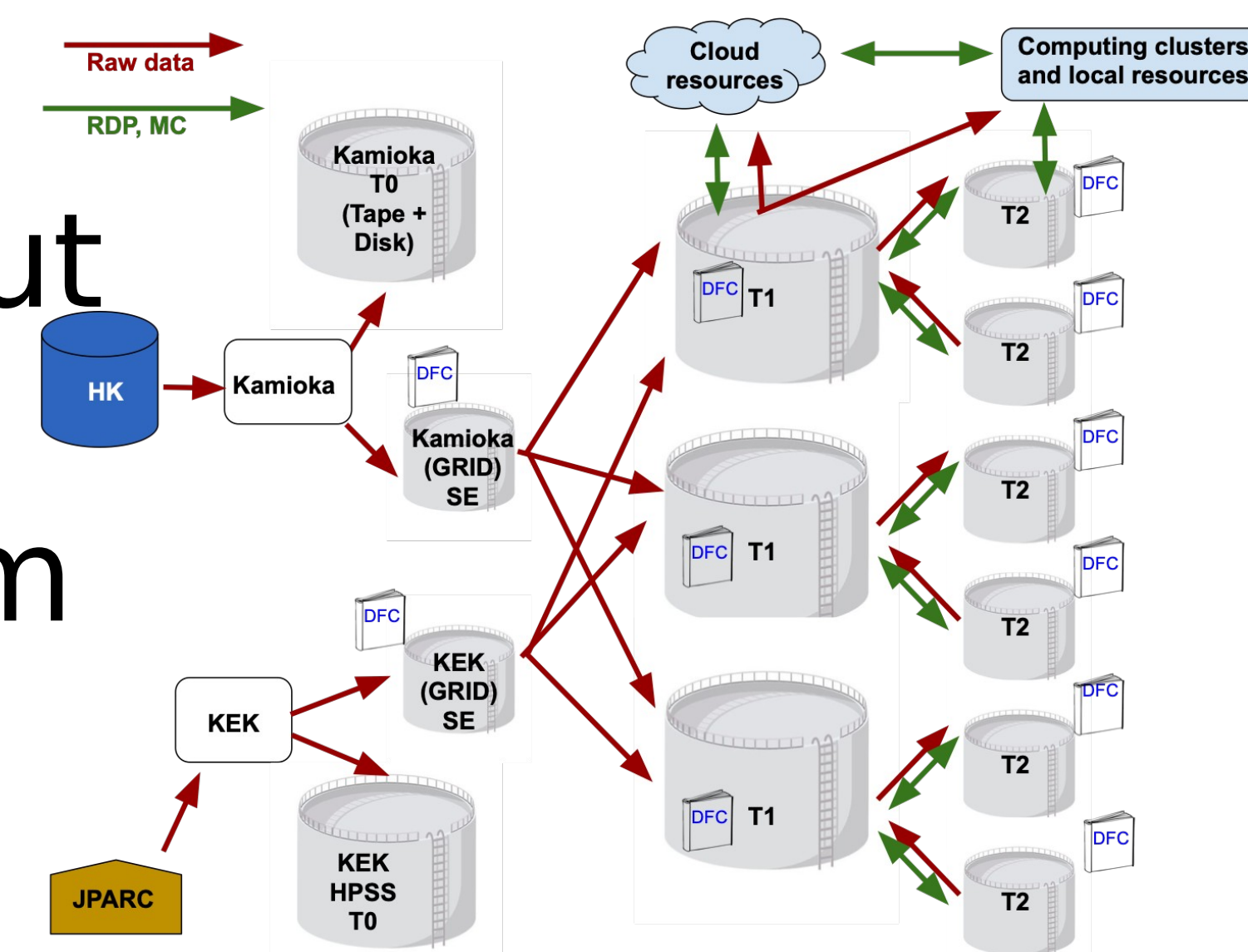
Sensitivity to neutron star vs **black hole** formation



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



Backup slides

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.

Conclusions and outlook

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

Identified contributions on electronics (RD4HK during 2022) and computing

Used funding from external sources (Sorbonne University, Ecole Polytechnique, ANR)

Technological decisions taken in September 2022

→ **approval by CS-IN2P3 & recognition of HK as IN2P3 master project are needed for full-scale participation in the HK experiment**

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

Time Distribution costs estimations

Second stage distribution	Total number of PMTs	PMT per FE	Total number of FE (Time distribution nodes)	Number of nodes per distributor	Number of distributors	Distributor cost per unit	Total distributor's cost
Outer detector	13 300	72	185	16	12	3 000	36 000
Inner detector	20 000	24	833	16	53	3 000	159 000
MultiPMT	2 000	12	167	16	11	3 000	33 000

Total distributor's cost	228 000
Atomic Clock cost	54 000
GNSS recevier	13 000
Antenna + cable	4 000
Clock multiplication board	2 000
Total clock ref cost	73 000
Redundant system	73 000
Grand total clock reference	146 000
Slow Control switch	2 000
Total cost	376 000
Contingency	20%
Gran total	451 200

Time generation estimated cost: 145 k€ (LPNHE)

Time distribution (first and second stages) estimated cost: 250 k€ (LPNHE +CEA)

Time distribution endpoint cost: 80 k€ (INFN)

Total = ~480 Keuros