Hyper-Kamiokande

Participation of IN2P3 physicists in the **Hyper-Kamiokande** experiment

ILANCE, LLR, LPNHE, OMEGA

ILANCE
International Laboratory for Astrophysics, Neutrino and Cosmology Experiments

LLR

LPNHE PARIS

OMEGA Microelectronics

SCIENCES SORBONNE UNIVERSITÉ

l'X ÉCOLE POLYTECHNIQUE

cnrs dépasser les frontières

IN2P3 Les deux infinis

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

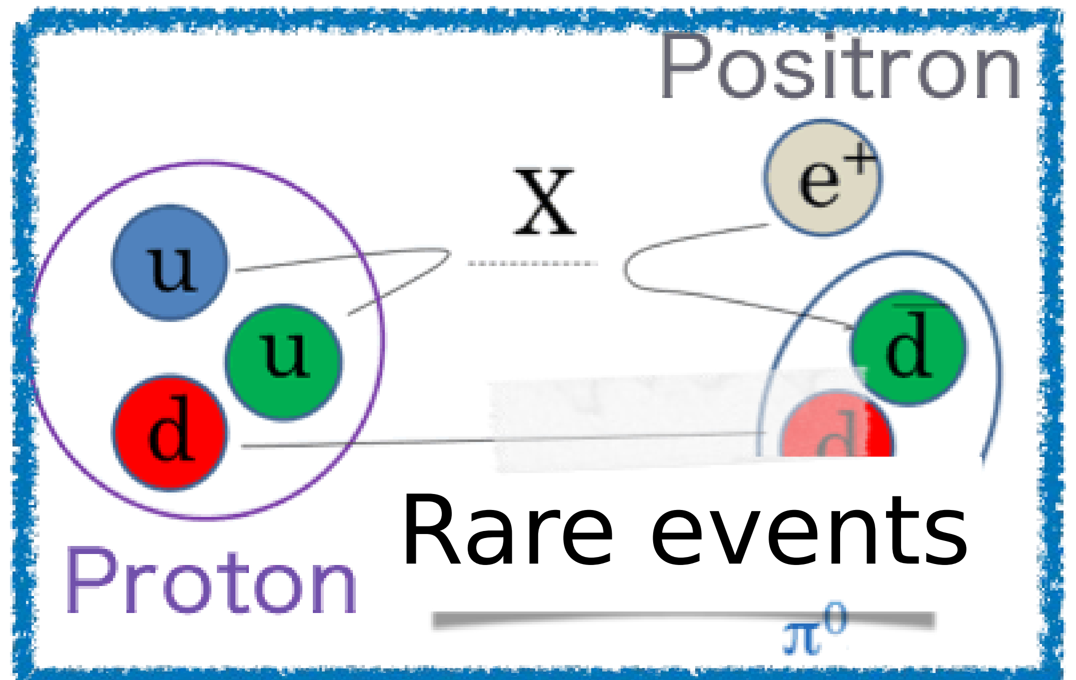
APC: C.Volpe

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

Hyper-Kamiokande physics program

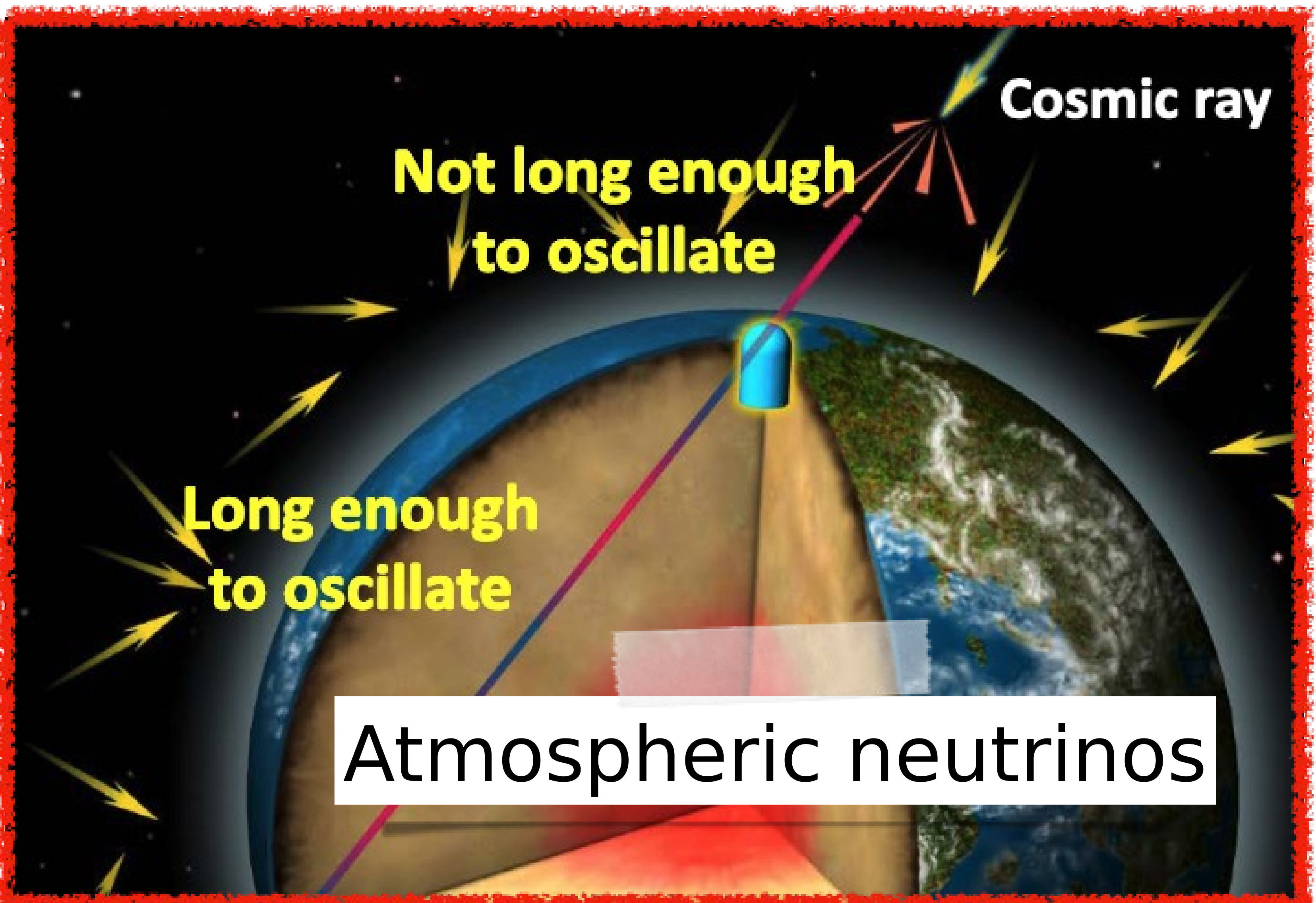
ν_e

MSW effect
Non-standard interactions

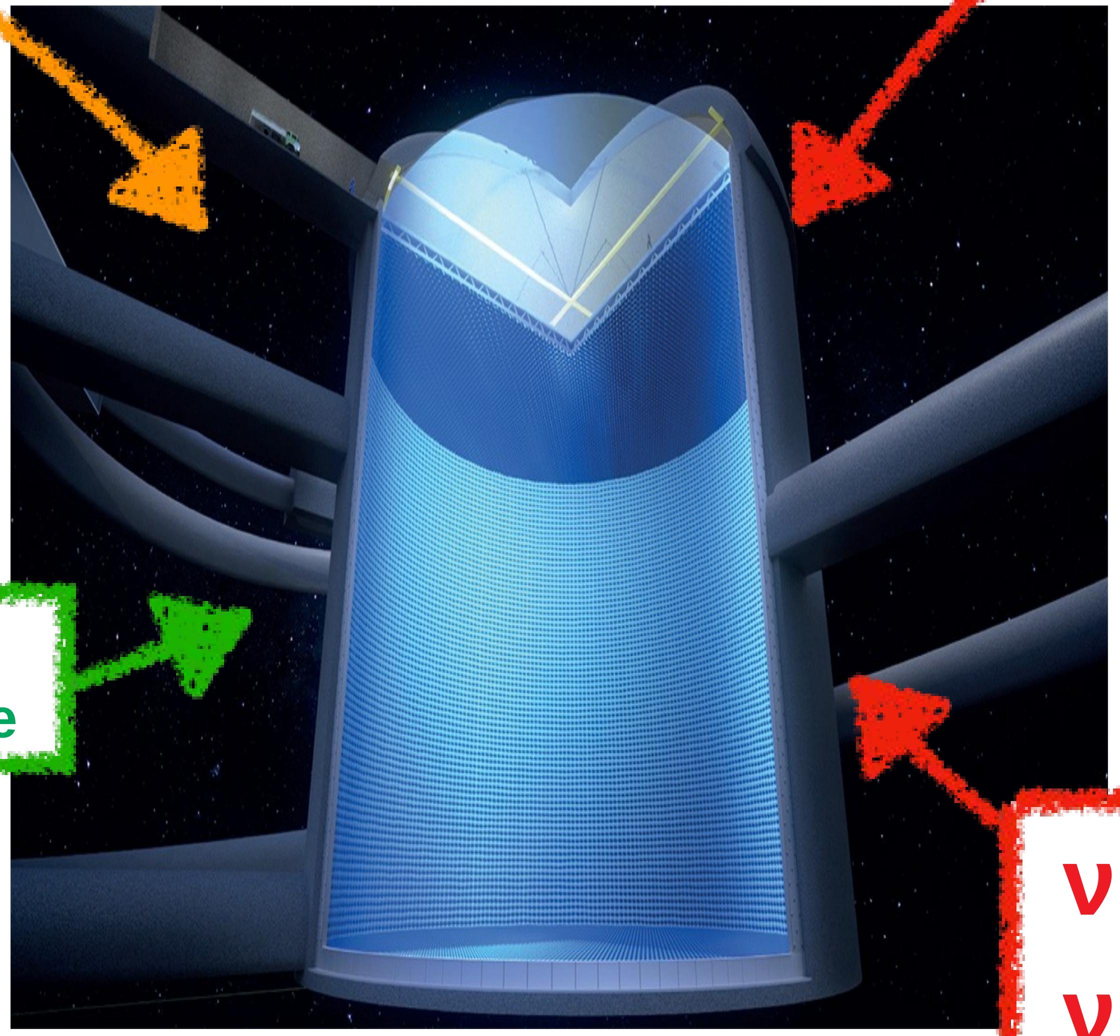


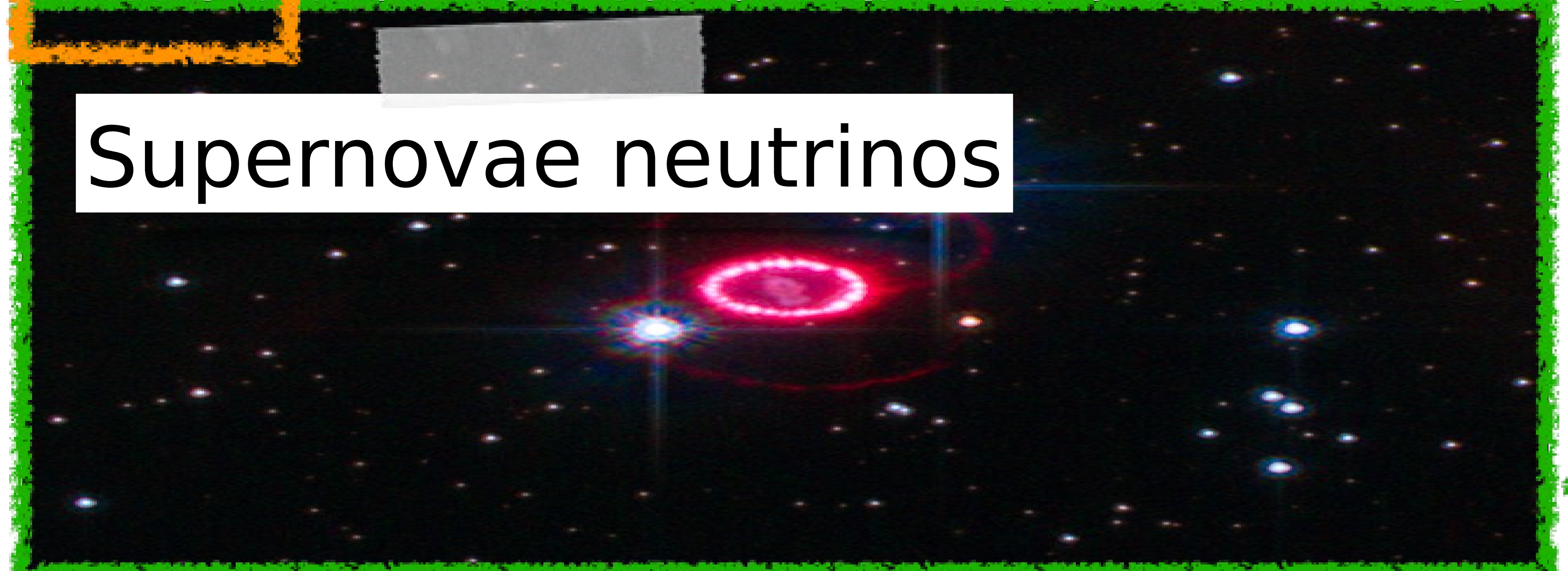
- **Probe Grand Unified Theories via p-decay or n-$\bar{n}$ oscillation**

ν_e $\bar{\nu}_e$
ν_μ $\bar{\nu}_\mu$



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

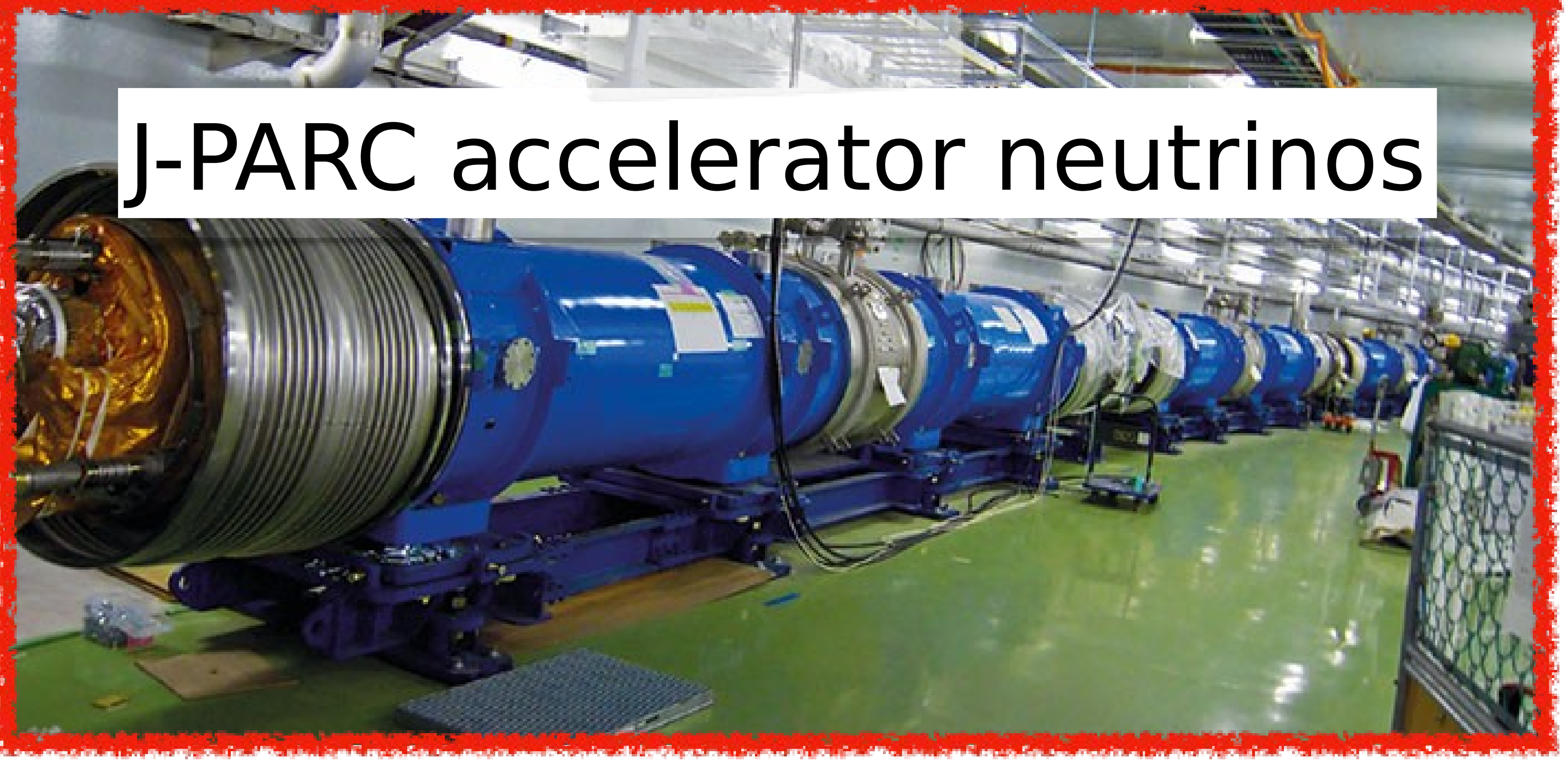




$\bar{\nu}_e$

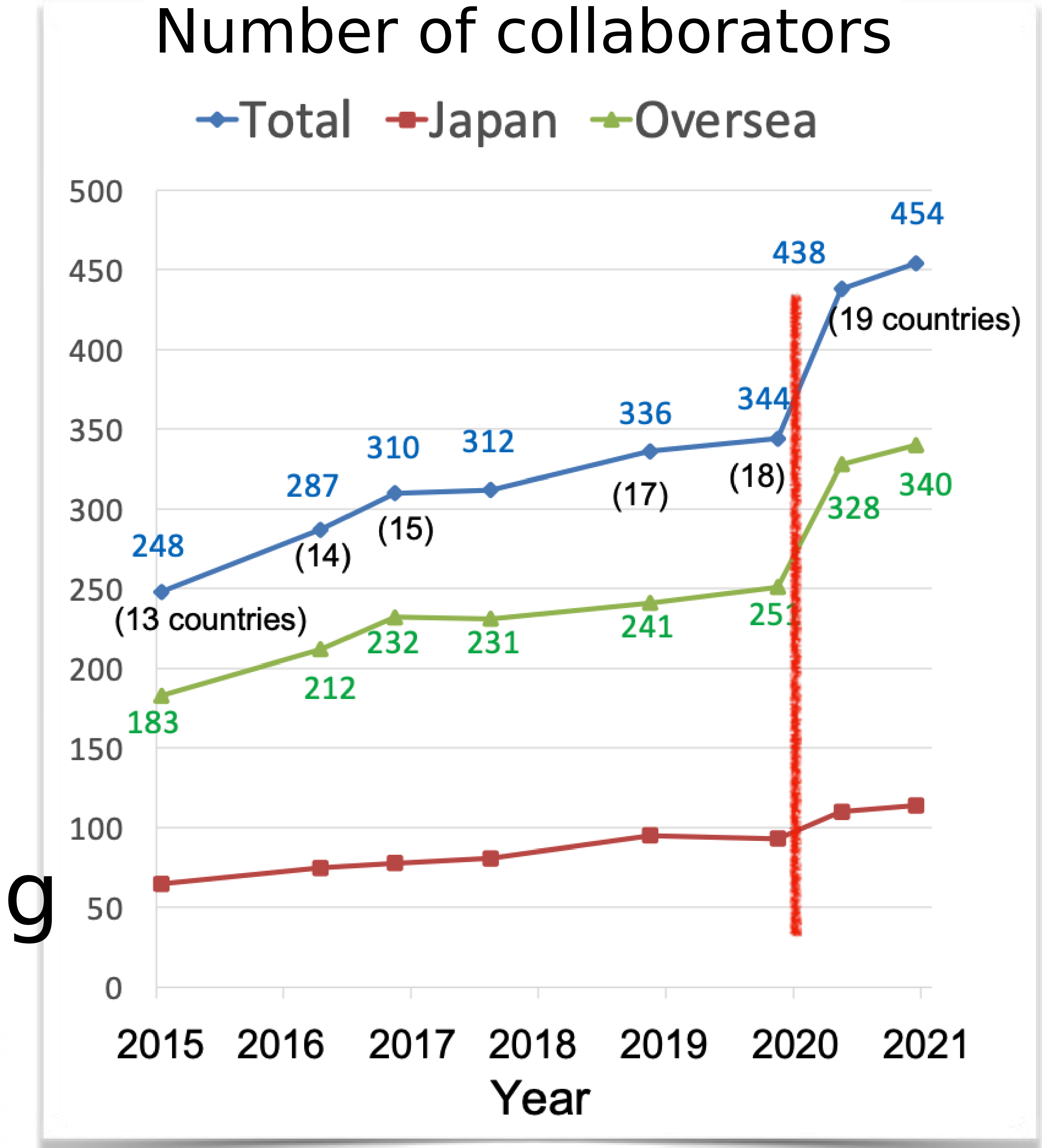
- **Transient SNν :** **constrain SN profile models**
- **Relic SNν :** **constrain cosmic star formation**

ν_e $\bar{\nu}_e$
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.”



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

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.

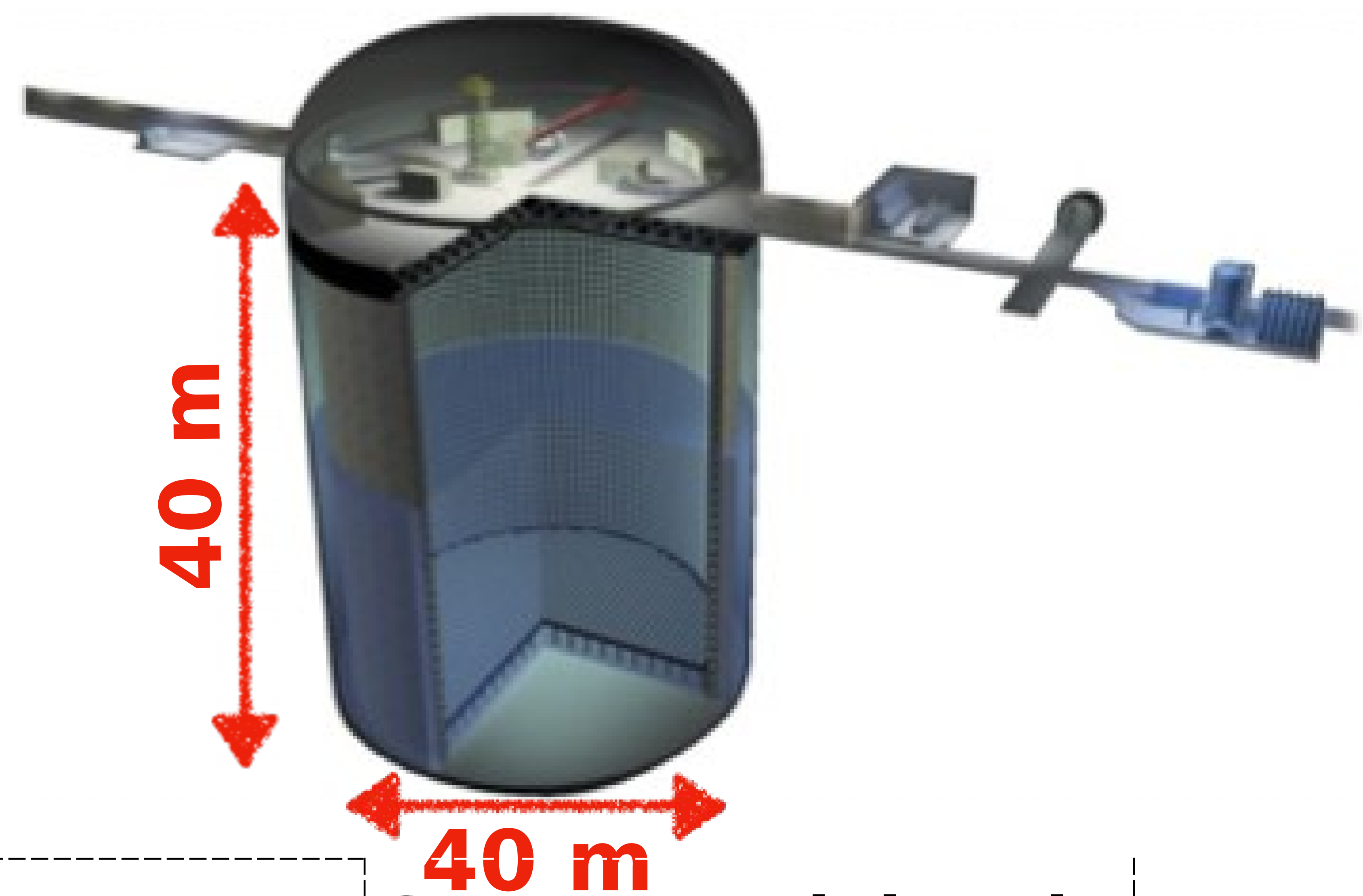
...

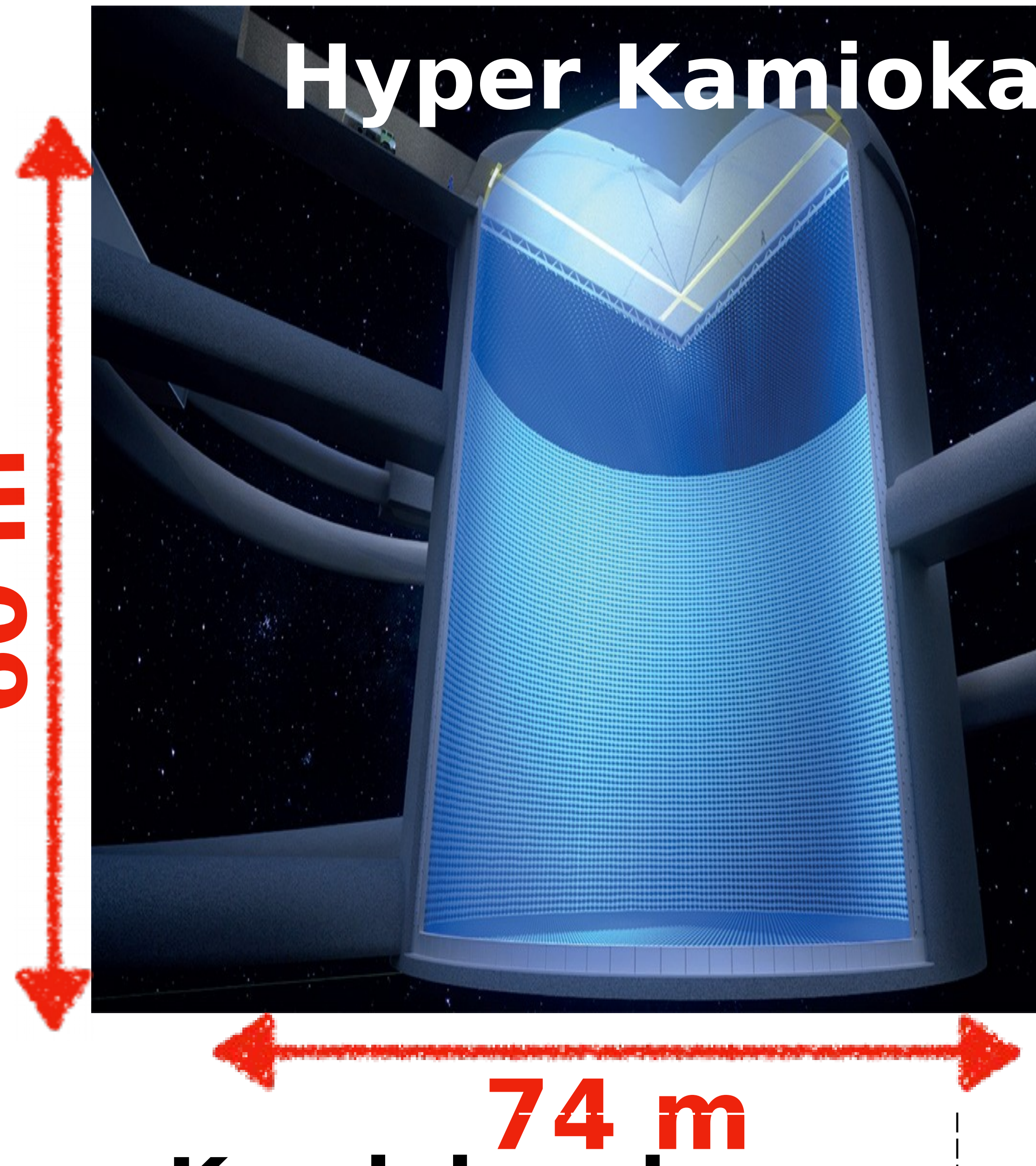
Le Conseil souligne cependant qu'un engagement technique direct sur le détecteur lointain de HK est requis pour confirmer et valider le ticket d'entrée de l'IN2P3 dans HK[4], et considère que la participation centrale proposée par le LPNHE et le LLR en collaboration avec OMEGA sur le digitaliseur HKROC 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 starting from 2022

Hyper-Kamiokande vs Super-Kamiokande

Super Kamiokande





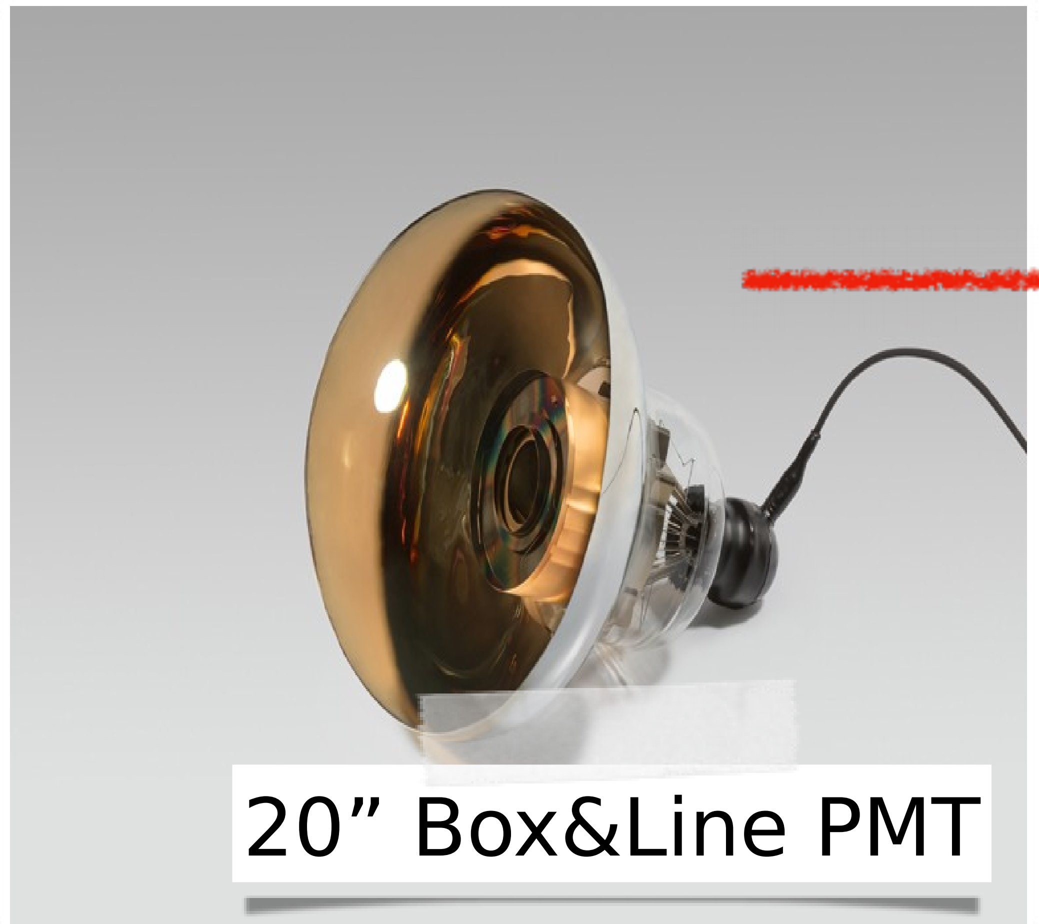
	Super Kamiokande	Hyper Kamiokande
Site	Mozumi-yama	Tochibora-yama
Number of ID 20'' PMTs	11 129	>20,000
Photo-coverage	40 %	>20%
Single-photon efficiency/PMT	~12%	~24%
Dark rate/PMT	~4 kHz	~4kHz
Time resolution of 1 photon	~3 ns	~1.5 ns
Total/fiducial mass (kton)	50 / **22.5**	260 / **187**

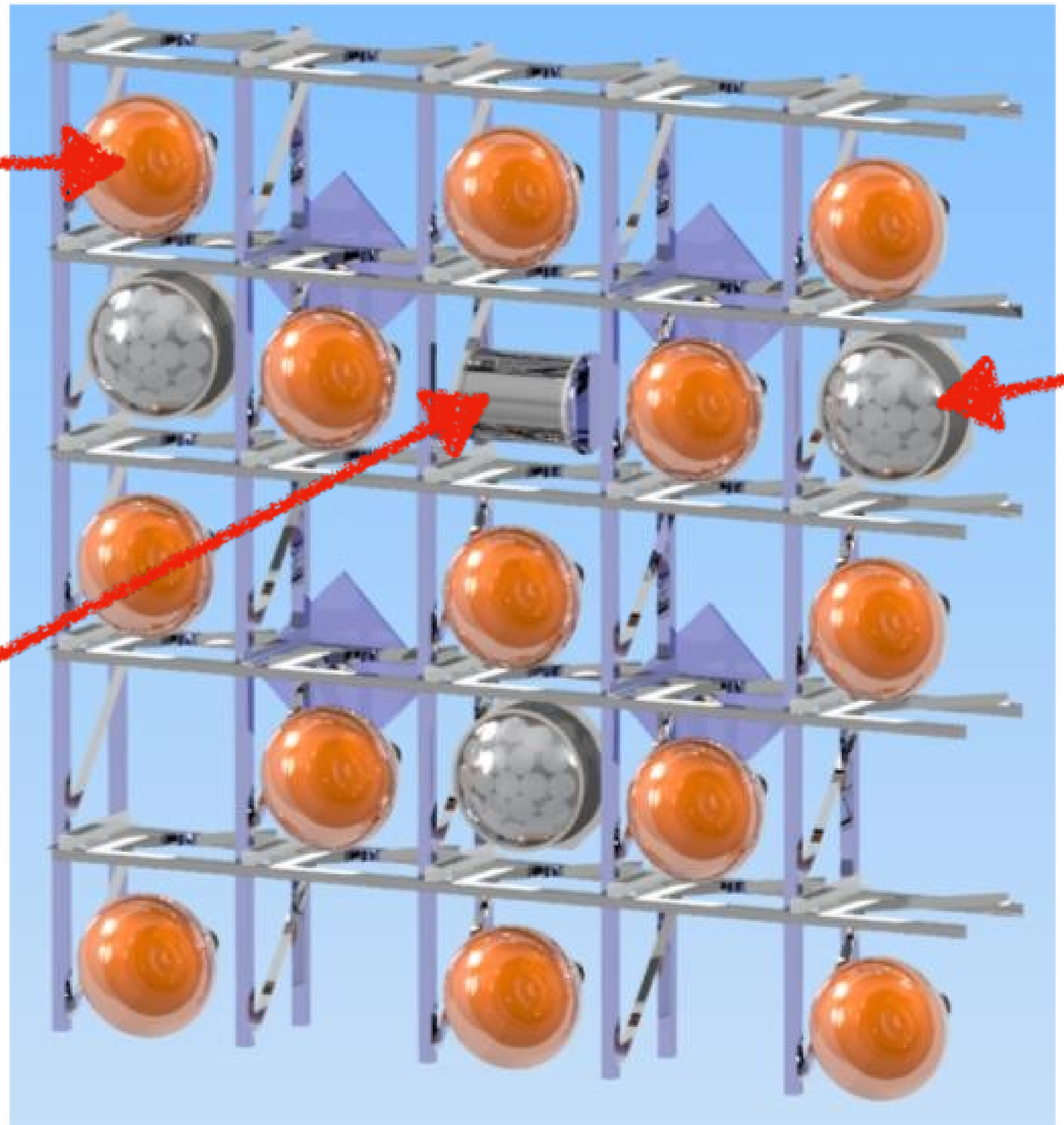
Fiducial volume x8:
→ non-beam ν physics

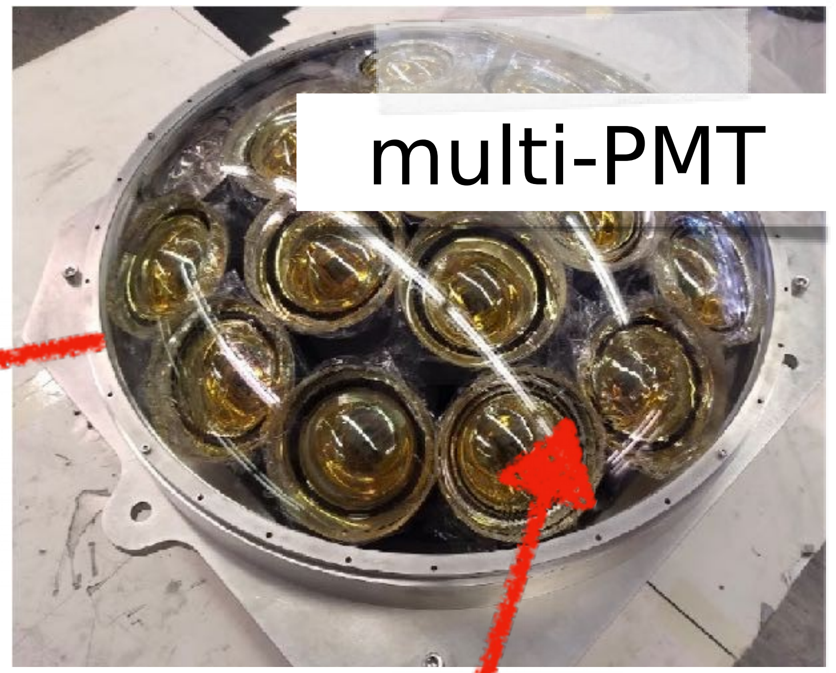
Beam neutrino event rate x 20:
→ beam ν physics

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

20” PMTs, mPMTs and readout

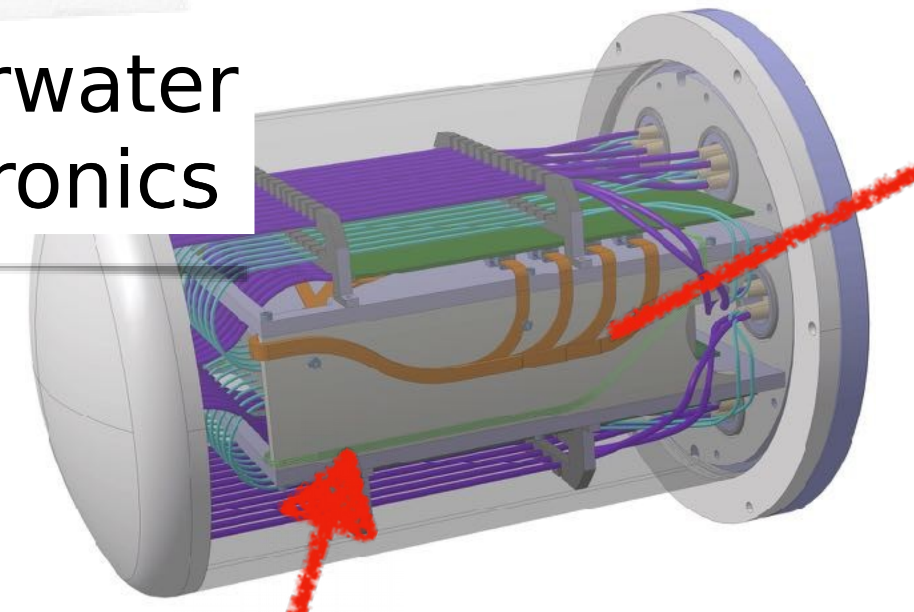


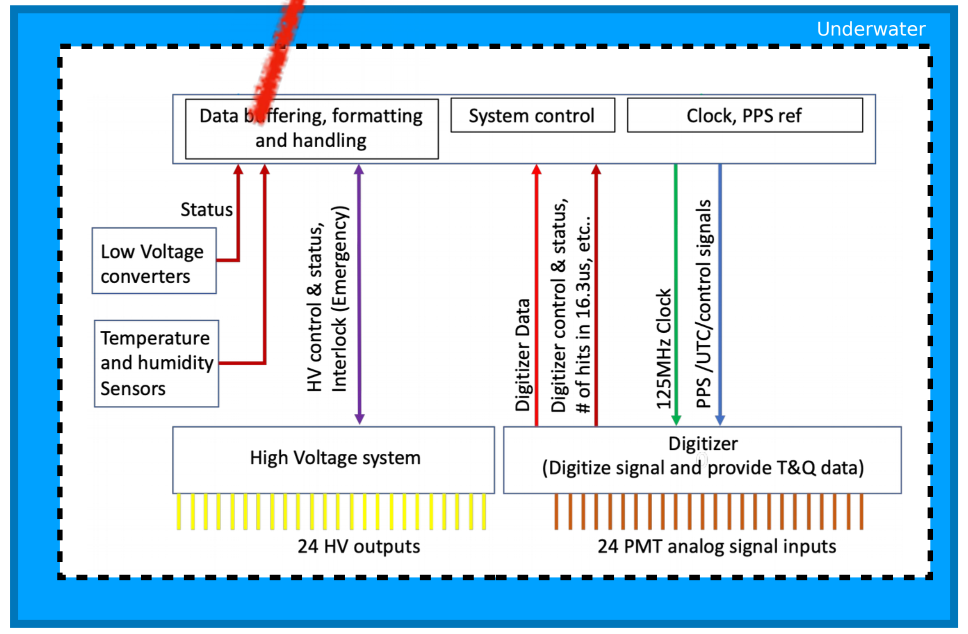




19 x 3” PMT

Underwater electronics





Inner detector composed of

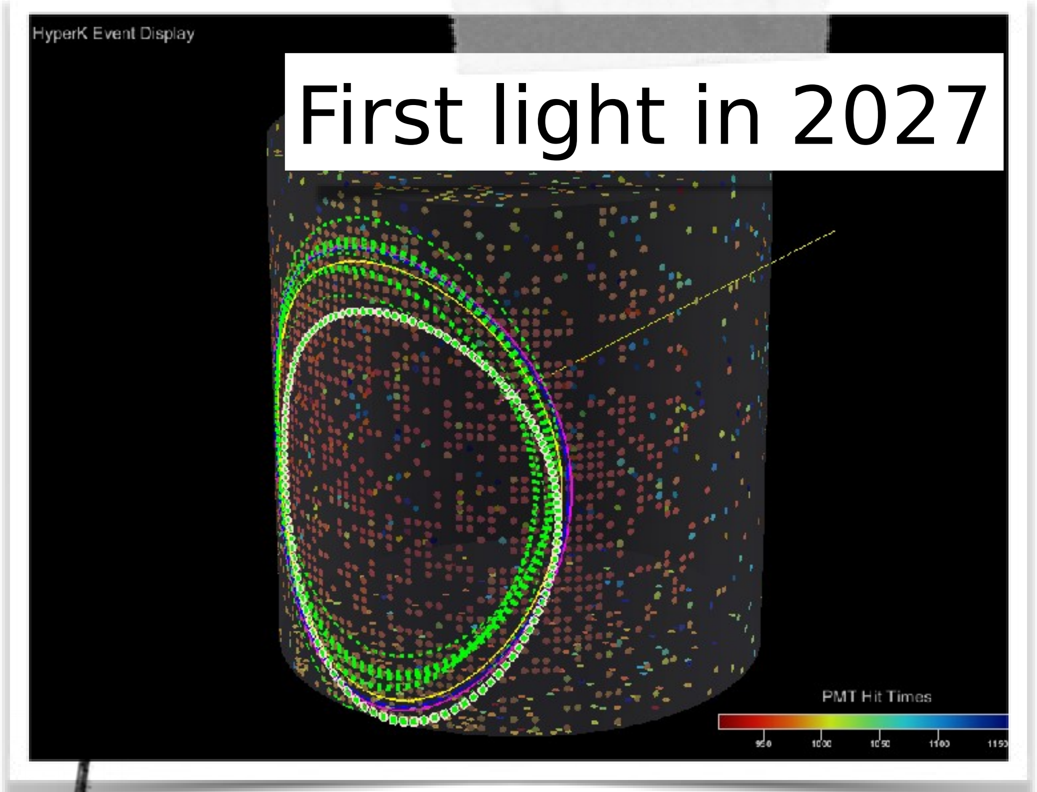
- 20k+ 20” PMTs (Hamamatsu R12860)
- ~1k mPMTs (19 3” R12199-02 PMTs)

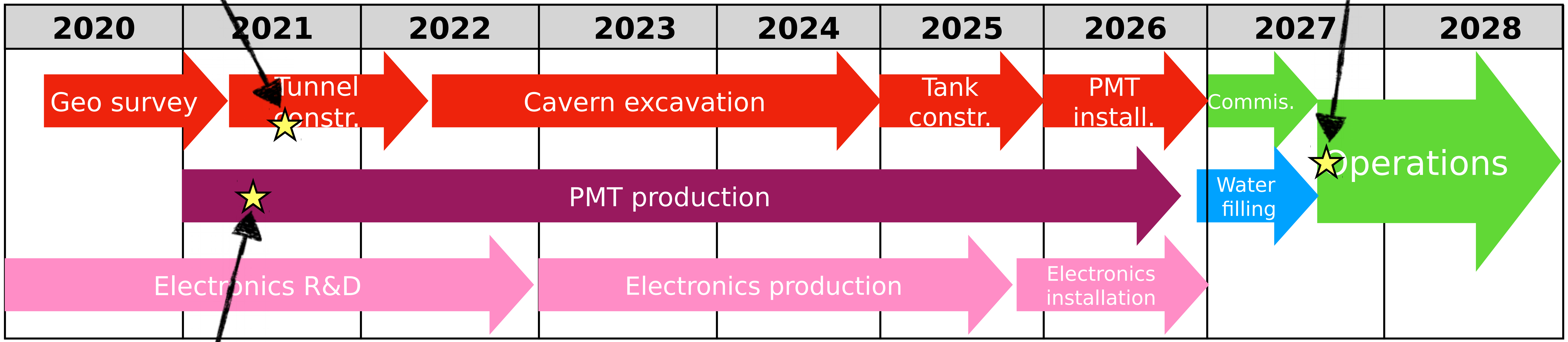
NEW

<u>Better SNR, directionality, timing</u>

Size of detector requires an in-water electronics

HK schedule





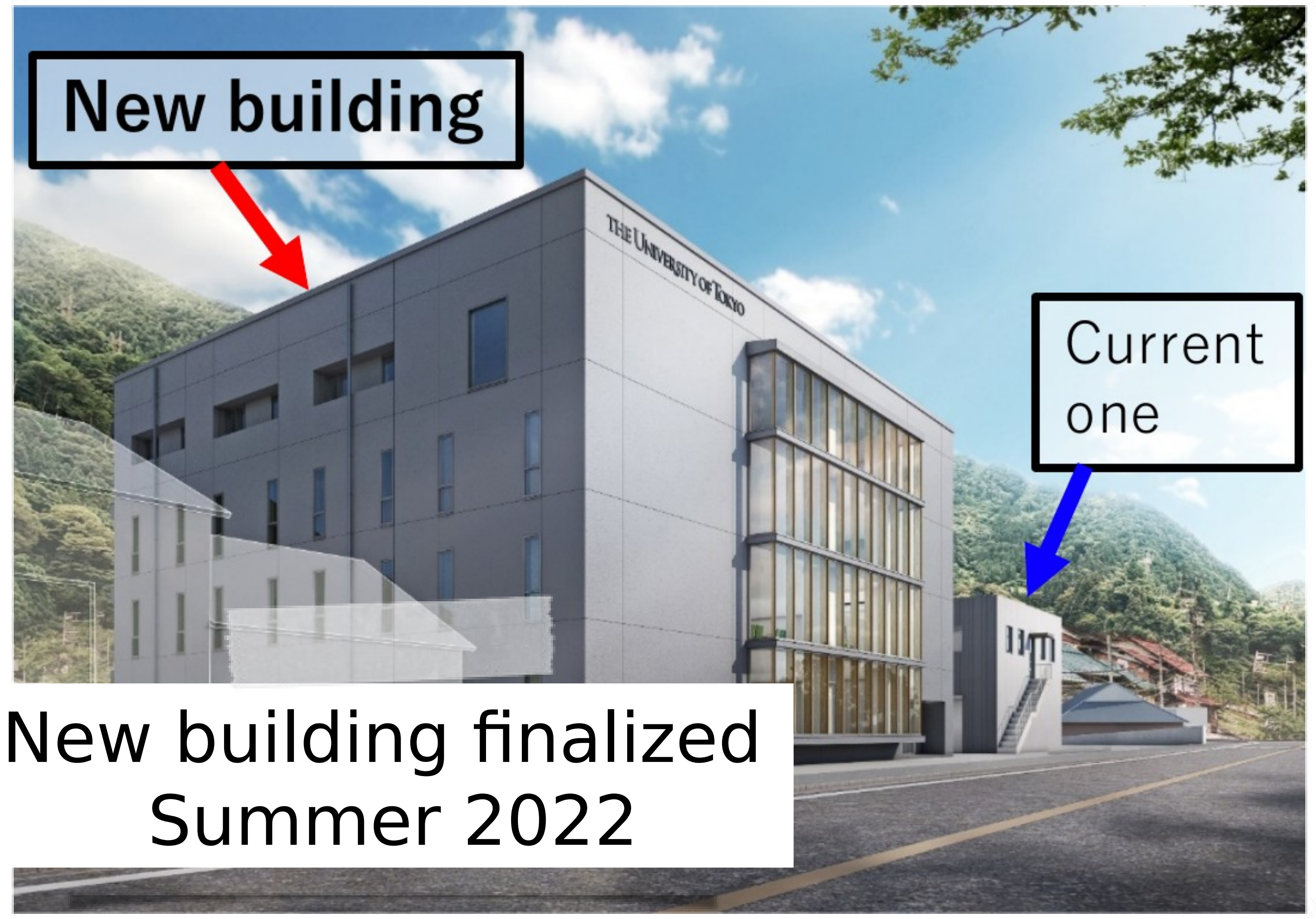
Strong engagement of Japan: ~500 M$ for construction

Expected from other countries: ~100 M$

International contributions are being formalized

Hyper-Kamiokande

Construction is on schedule



Survey completed ✓

Excavation on-going (WORK IN PROGRESS)

New main building (WORK IN PROGRESS)

Everything on track! ✓

HK organizational chart

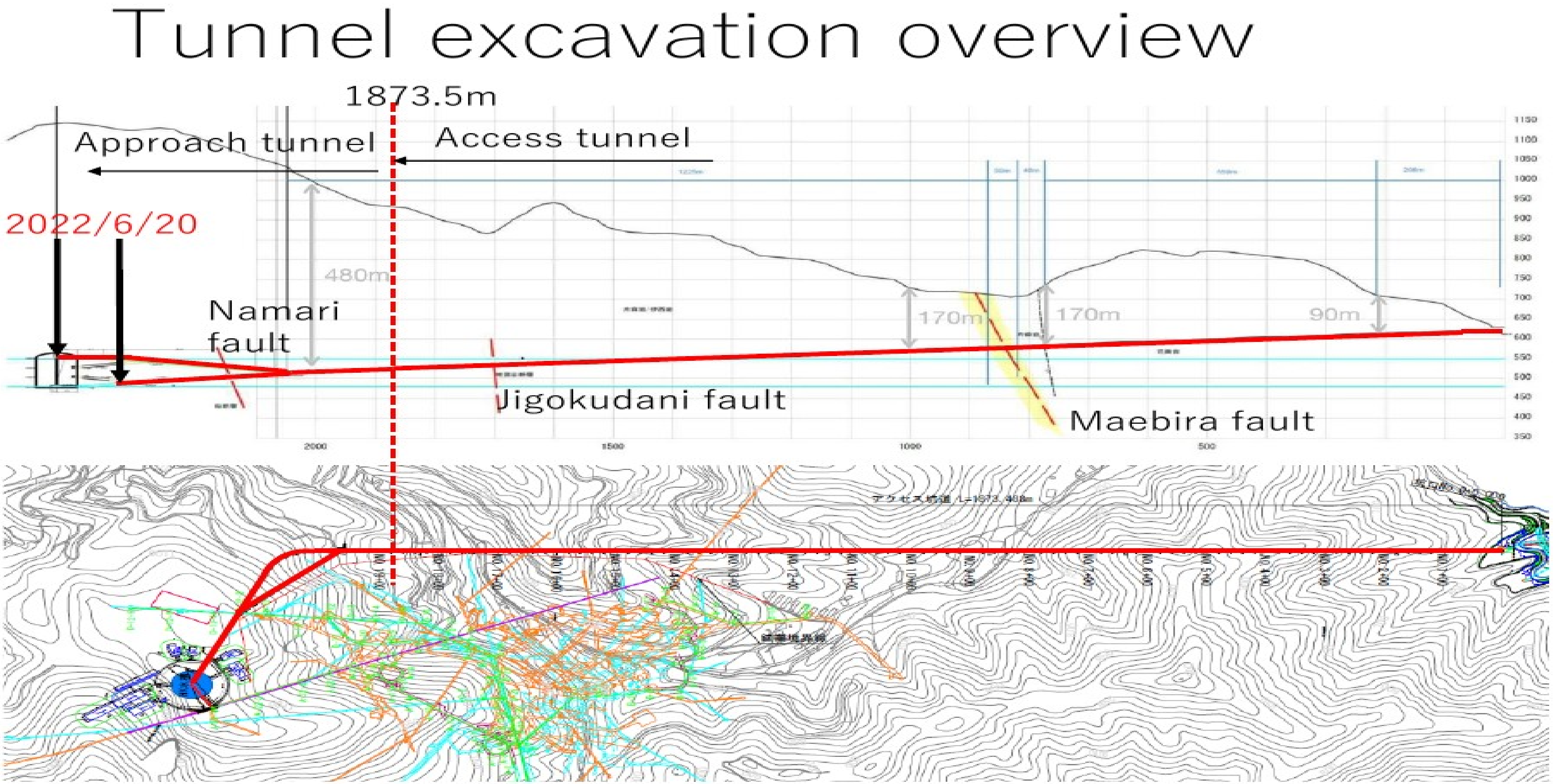
Far detector Working Groups

HK Far Detector WG
(Oct 21, 2021)

- **Far Detector**
  (WGL) M.Yokoyama
  (TC) S.Playfer, (DTC) K.Hiraide
  - **FD1: 50cm PMT** – Y.Nishimura, (D) L.Labarga
    - FD1.1: PMT QA – T.Tashiro
    - FD1.2: Cover – L.Labarga(interim)
    - FD1.3: Assembly – J.Kameda, (D) Spain:DIPC(TBD), (D) K.Nakamura
    - FD1.4: Attachment – T.Yano, L.Labarga(interim)
  - **FD2: multi-PMT** – G. De Rosa, (D) T. Lindner
    - FD2 Technical Coordinator – A.Rychter
    - FD2 QA coordinator – TBD (Naples), TBD (HK member)
    - FD2 DB manager – C.Bozza
    - FD2.1: Production and tests – A.Rychter, M.Ziembicki +TBD(Canada)
      - FD2.1.1: PMT – R.Akutsu +TBD
      - FD2.1.2: Electronics – L.Lavitola +TBD
      - FD2.1.3: Vessel and components – R.Spina +TBD
    - FD2.2: Integration and transportation – A.Ruggeri TBD
      - FD2.2.1: Italy site – TBD
      - FD2.2.2: Canadian site – TBD
      - FD2.2.3: Poland site – TBD
      - FD2.2.4: Mexico site – TBD
    - FD2.3: Installation – TBD(Italy, Canada, Poland)
  - **FD3: OD photo-detection** – J.Wilson
    - FD3.1: PMT – F.Di Lodovico
    - FD3.2: WLS plates – A. Holin, (D) O.Mineev
    - FD3.3: Tyvek – (KCL RA)
    - FD3.4: PMT QA – S.Zsoldos, (D) (RAL RA)
    - FD3.5: Materials – M.Thiesse
    - FD3.6: Sensor unit – S.Yang
    - FD3.7: Cables – P.Litchfield
    - FD3.8: Integration and commissioning – J.Wilson(interim)
    - FD3.9: Installation – P.Litchfield(interim)
    - FD3.10: Software and analysis – F.Nova
  - **FD4: Electronics** – Y.Hayato, (D) M.Ziembicki
    - FD4 System Engineer – (Spring 2022)
    - FD4.1: ID Module Assembly
      - Technical – (A.Gendotti, Y.Takemoto) U.Kose, (Digitizer)
      - Logistics – (A.Gendotti,Y.Takemoto) TBD with site (2022)
    - FD4.2: ID underwater components – A.Gendotti
      - Vessel – A.Gendotti
      - PMT cables&connectors – C.Schloesser
      - Communication+power cables&connectors – (Y.Takemoto)
      - Vessel fixation – (A.Gendotti, Y.Takemoto)
    - FD4.3: ID electronics components – (Selected digitizer) U.Kose
      - Digitizer – Y.Kataoka B.Quilain F.Ameli
      - Data processing, LV distribution, slow monitor – F.Mora, M.Ziembicki(interim) J.Toledo (D)
      - Timing/synchronization – S.Russo
      - HV – U.Kose
    - FD4.4: OD Module Assembly
      - Technical – P.Solar, S.Naik (Digitizer)
      - Logistics – (P.Litchfield, P.Solar) TBD with site (2022)
    - FD4.5: OD underwater components – P.Litchfield
      - Vessel – P.Solar
      - PMT cables&connectors – P.Litchfield
      - Communication+power cables&connectors – P.Litchfield
      - Vessel fixation – W.Cunningham
    - FD4.6: OD electronics components – S.Naik (Selected digitizer)
      - Digitizer – (Glasgow Engineer) (Selected digitizer)
      - Data processing – S.Naik, (Engineer)
      - LV distr., slow monitor – P.Solar, (PDRA)
      - Timing/synchronization – S.Naik, (Engineer)
      - HV – S.Naik
  - **FD5: DAQ** – H. O'Keeffe
    - FD5.1: Technical design – B.Richards
    - FD5.2: Trigger design – T. Dealtry
    - FD5.3: Slow control/monitoring – J.Migenda
    - FD5.4: Installation Commissioning – H.O'Keeffe, B.Richards
  - **FD6: Calibration** – N.McCauley, (D) S.Wronka, (D) Y.Nakajima
    - FD6.1: LINAC – S.Wronka
    - FD6.2: Light injection – N.McCauley
    - FD6.3: DT generator – (TBD by Oct 22)
    - FD6.4: RI sources – (TBD by Oct 22)
    - FD6.5: Source deployment system – A.Suzuki
    - FD6.6: Photogrammetry – P. de Perio
    - FD6.7:Precalibration – Y.Nakajima
    - FD6.8:QA/QC – L.Thompson
  - **FD7: Water (=FF5)** – H.Sekiya
    - FD7.1: Room/ resource/drainage – H.Sekiya
    - FD7.2: Power/heat treatment – M.Ikeda
    - FD7.3: Water system – H.Sekiya
    - FD7.4: Plumbing around the tank – Y.Nakajima
    - FD7.5: Flow in the tank – K.Ieki
  - **Far Site Integration** – K.Okumura
- **Far Facility**
  - FF Groups
  - FD7: Water (=FF5)
  - Far Site Integration

Hyper-Kamiokande

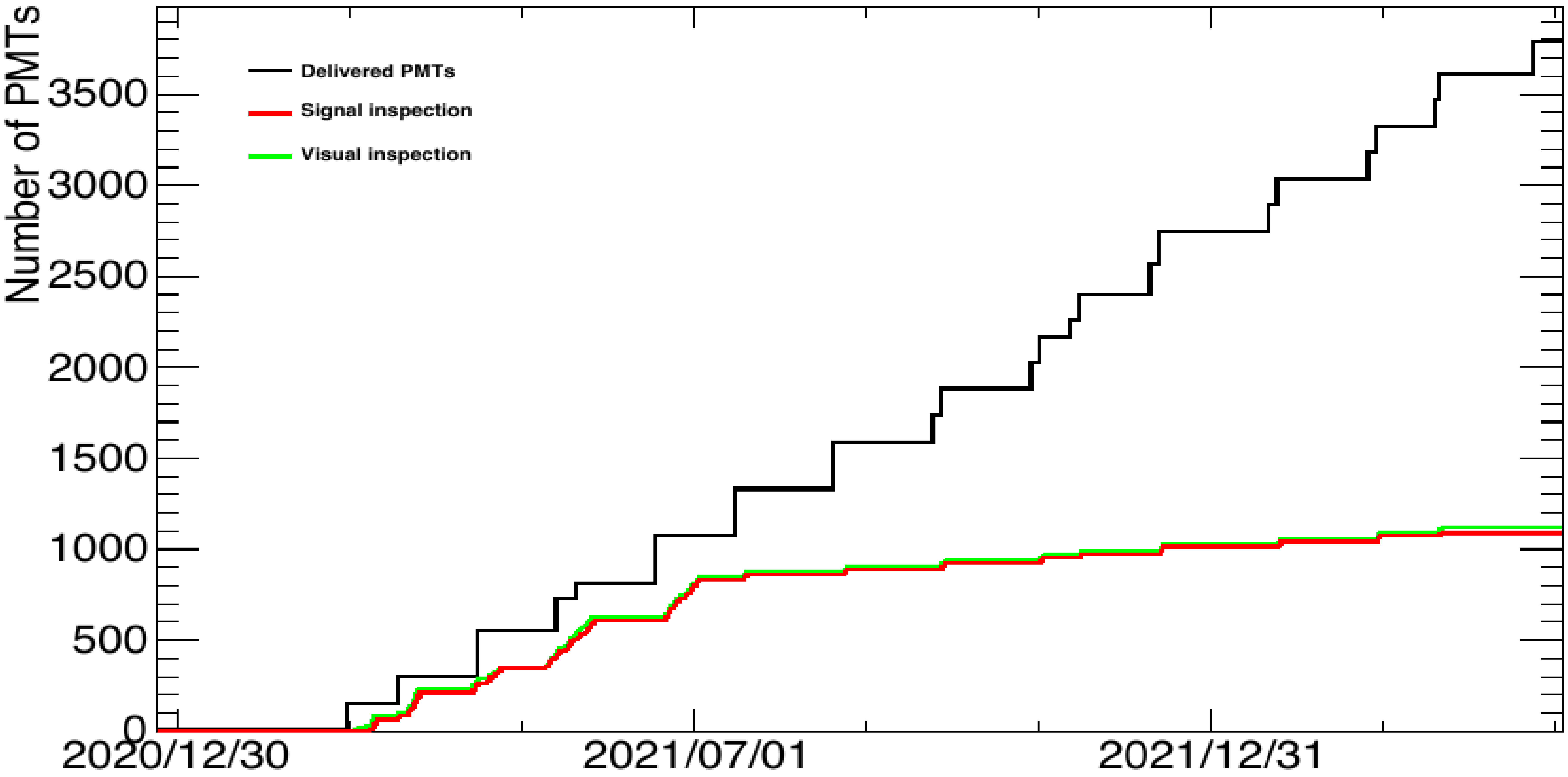
Recent progress: excavation



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

Hyper-Kamiokande

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%.

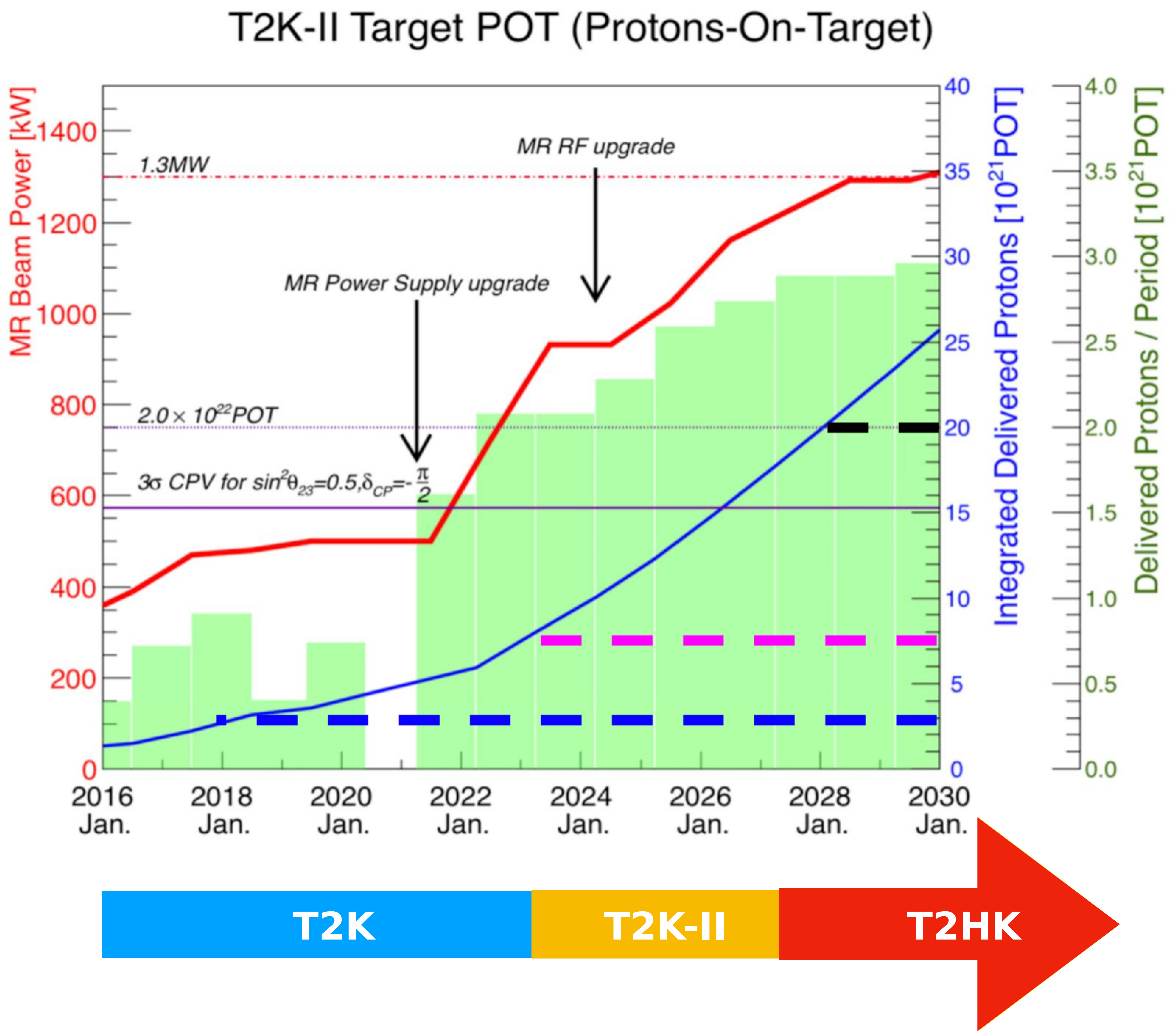
Tokai to HK: heritage from T2K

Accelerator upgrade

Power increase (500kW --> 1.3 MW)

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

ν / $\bar{\nu}$ flux uncertainty < 5% thanks to NA61

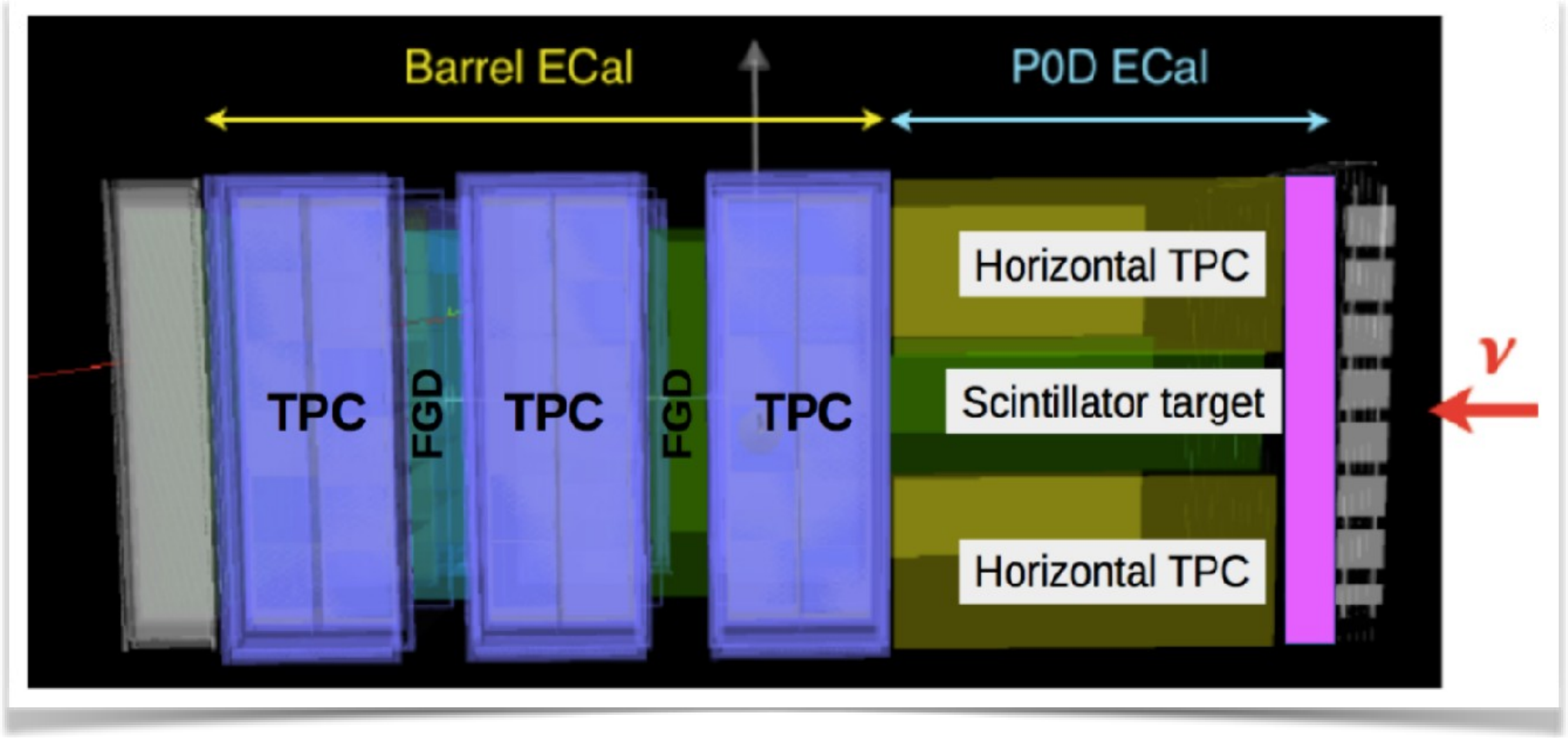


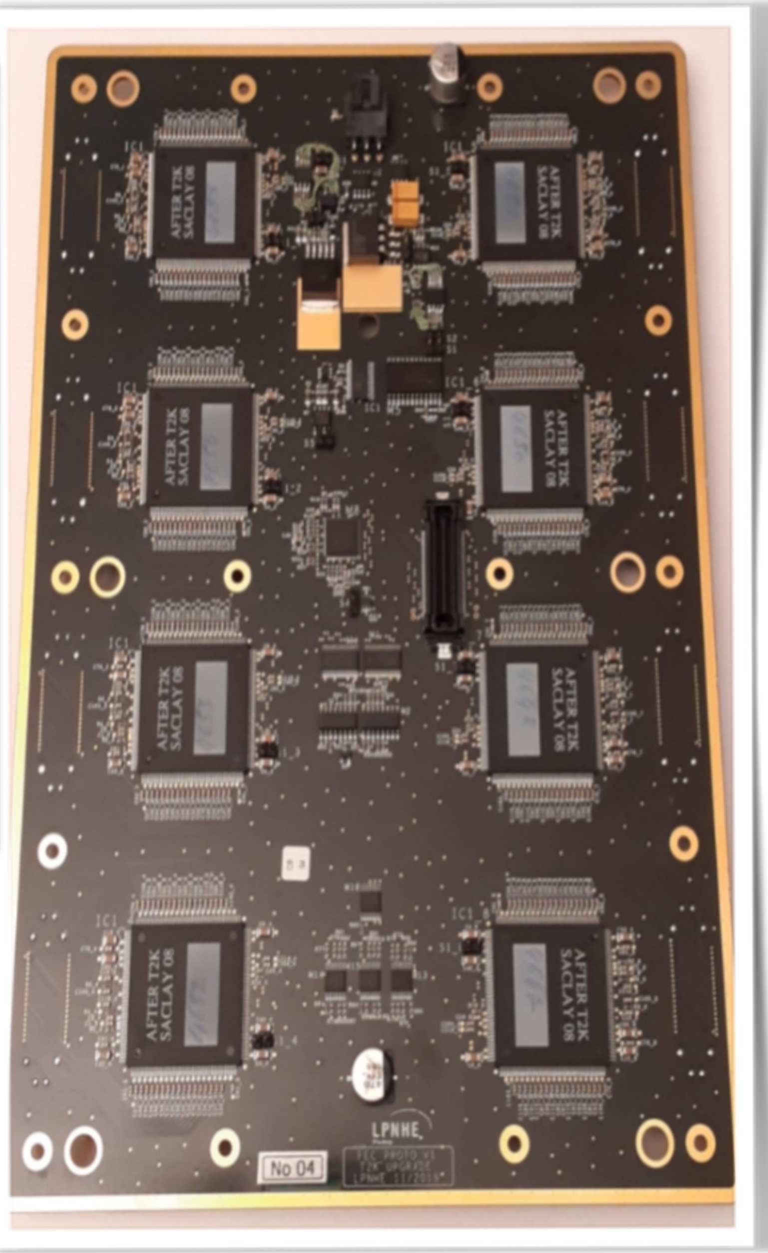
Tokai to HK: heritage from T2K

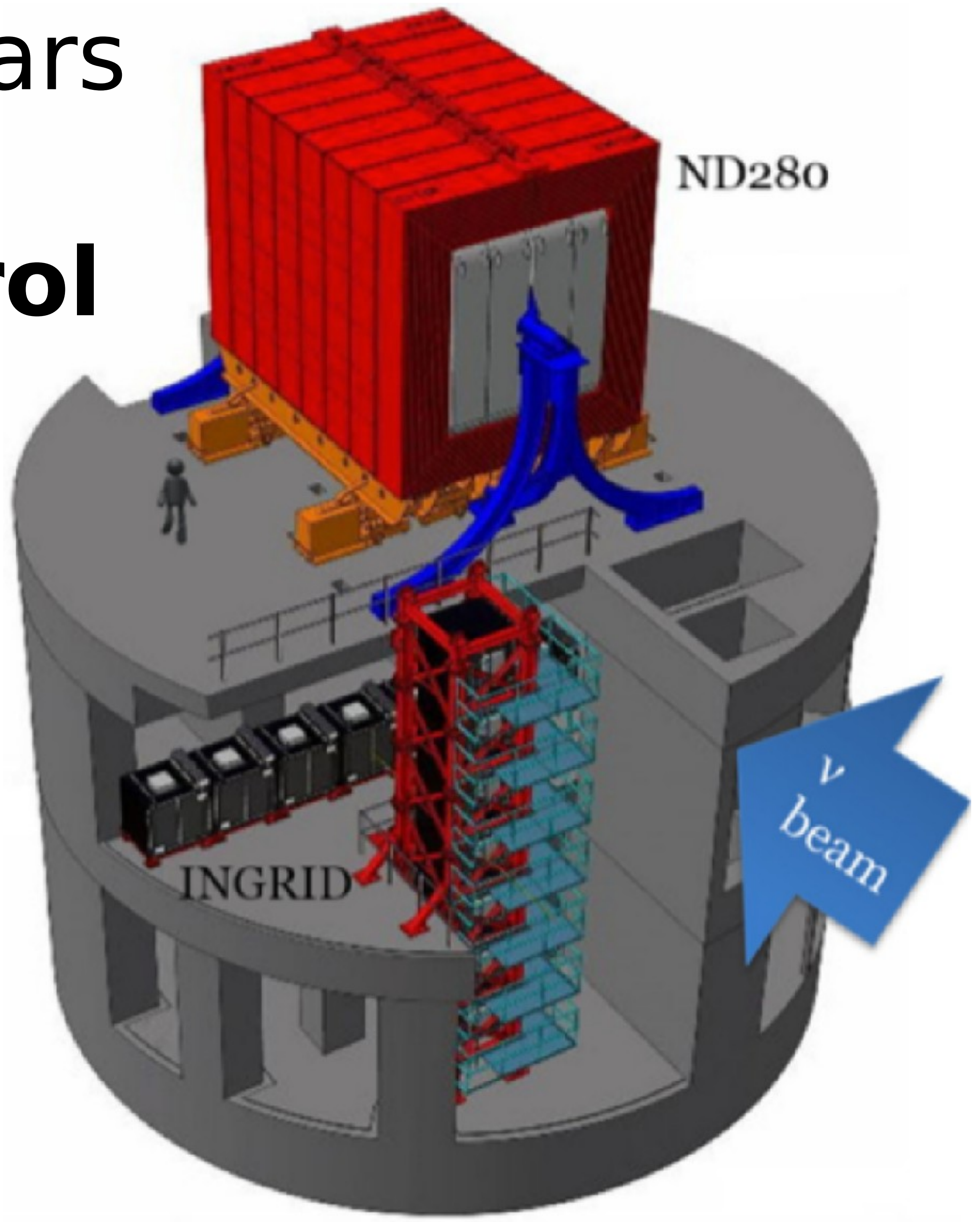
Accelerator upgrade
- Power increase (500kW --> 1.3 MW)
- **x2.7 more stats per s (wrt T2K-I)**

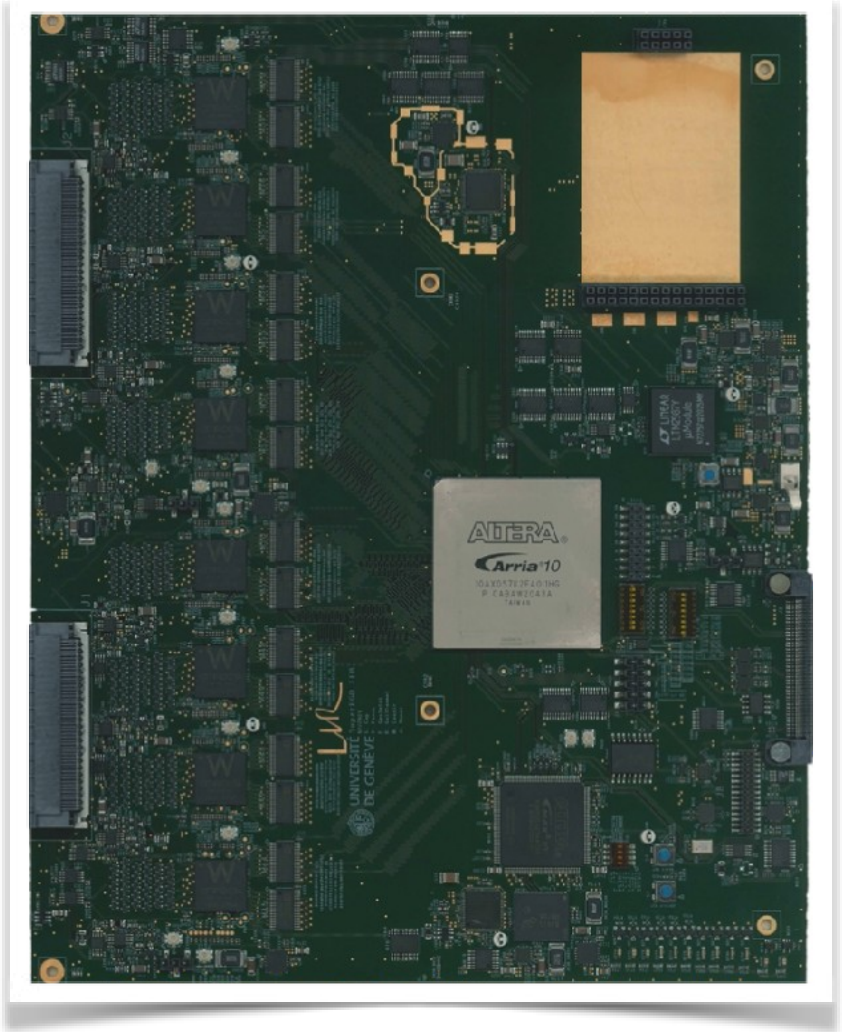
$\nu / \bar{\nu}$ flux uncertainty < 5% thanks to NA61

Magnetized near detector @280 m
- Used for T2K Oscillation Analysis for >10 years
  - Being upgraded now for T2K-II
  - **Systematics uncertainties under control from Day-1 of HK**









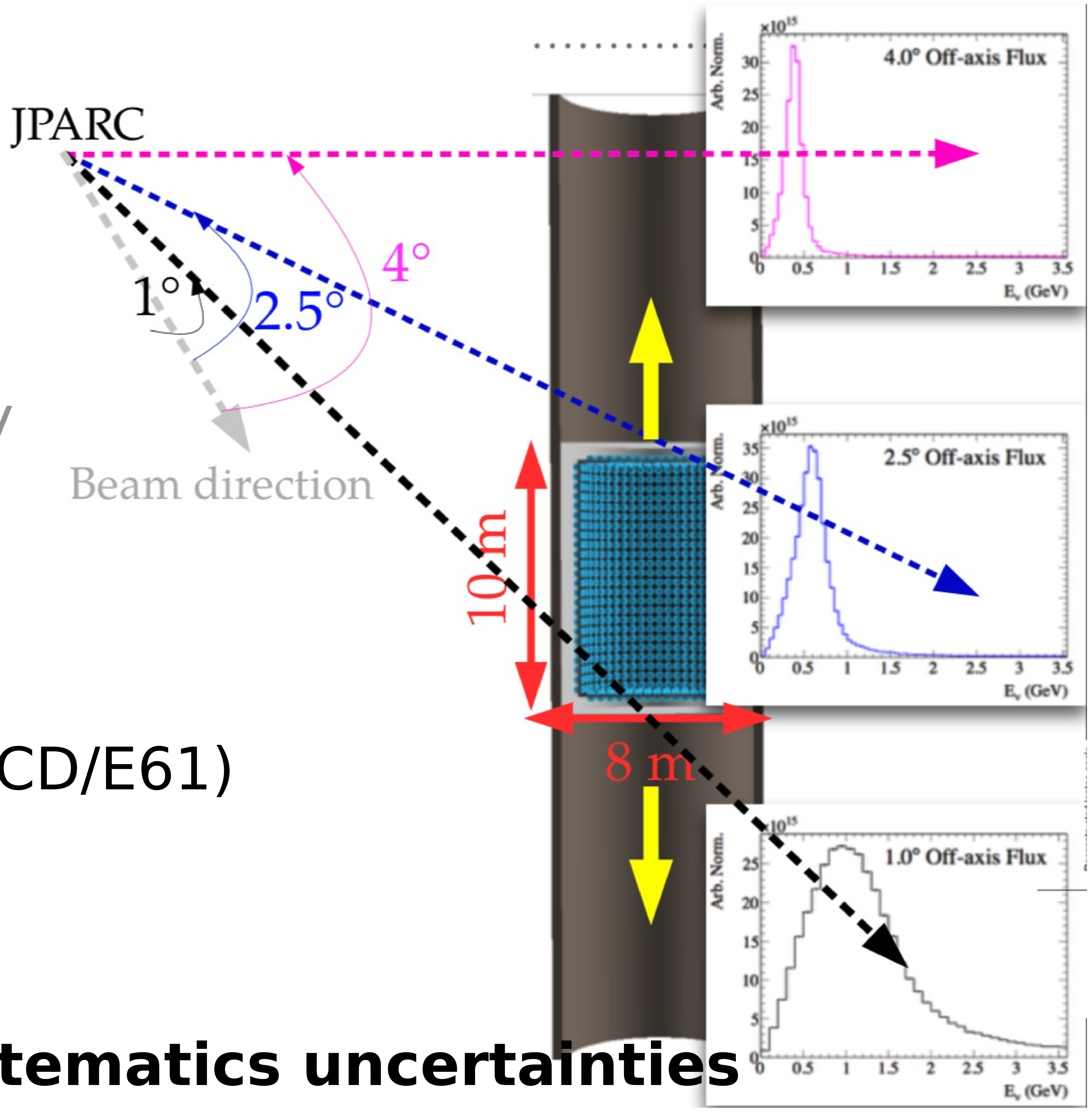
Tokai to HK: what will be new

Accelerator upgrade
- Power increase (500kW 1.3 MW)
- x2.7 more stats per s (wrt T2K-I)

ν / $\bar{\nu}$ flux uncertainty < 5% thanks to NA61

Magnetized near detector @280 m
- Used for T2K Oscillation Analysis for >10 y
- Being upgraded now for T2K-II
- Systematics uncertainties under control

from day 1 of HK



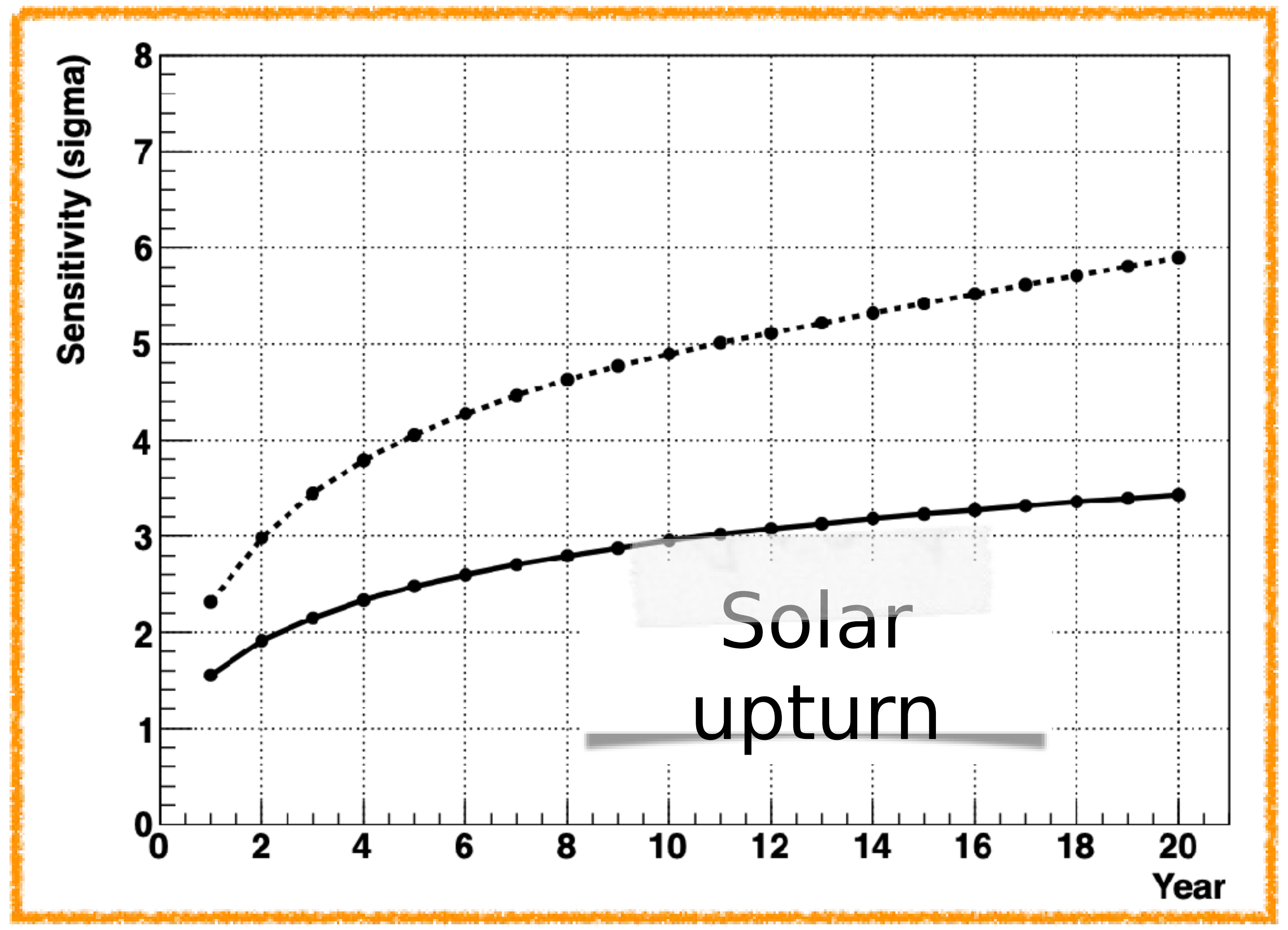
NEW

Intermediate Water Cherenkov Detector (IWCD/E61)
- Measure ν interactions on Water
- High stats. sample of ν_e interactions

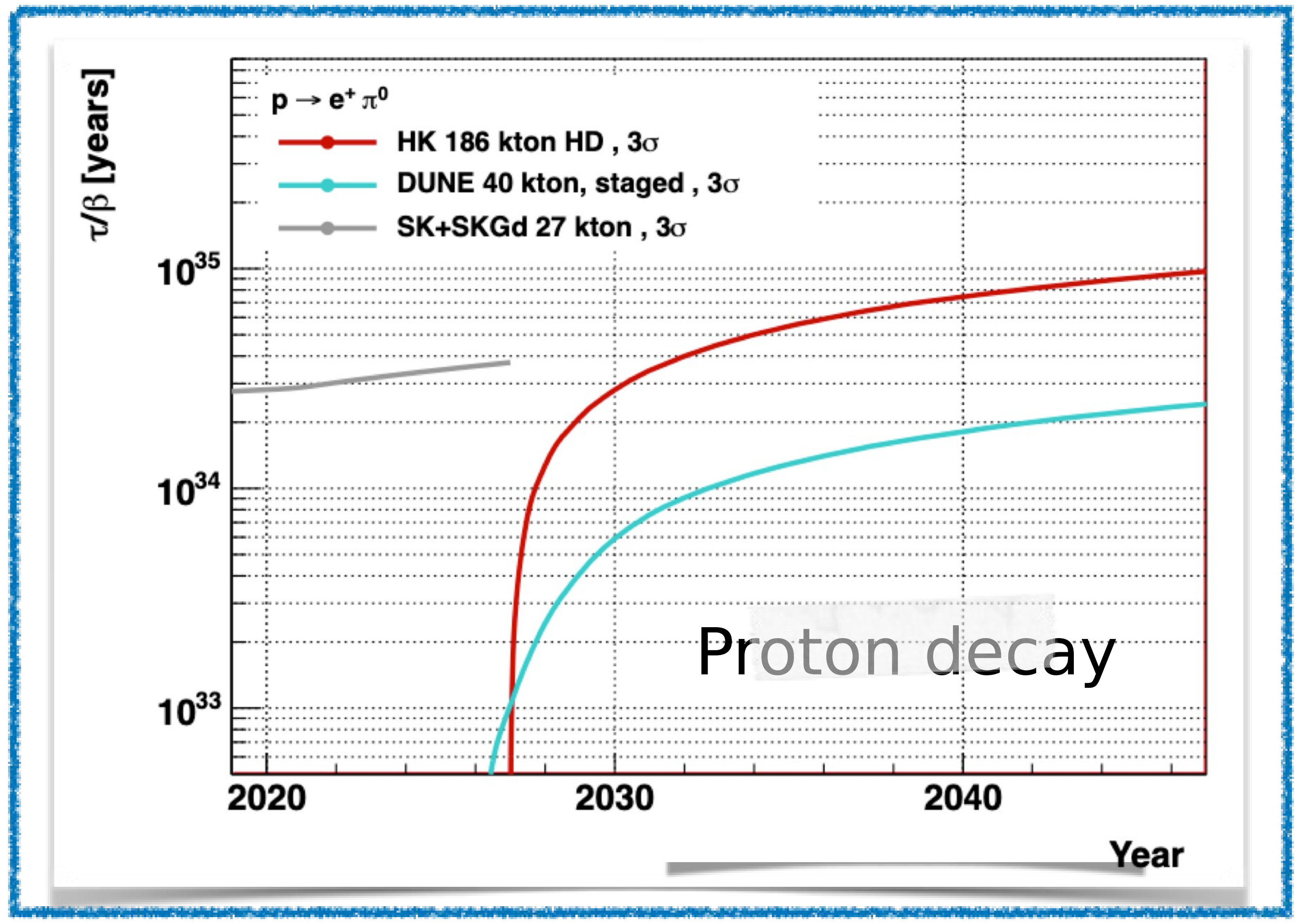
Needed to reach final HK goal for systematics uncertainties

Hyper-Kamiokande Physics

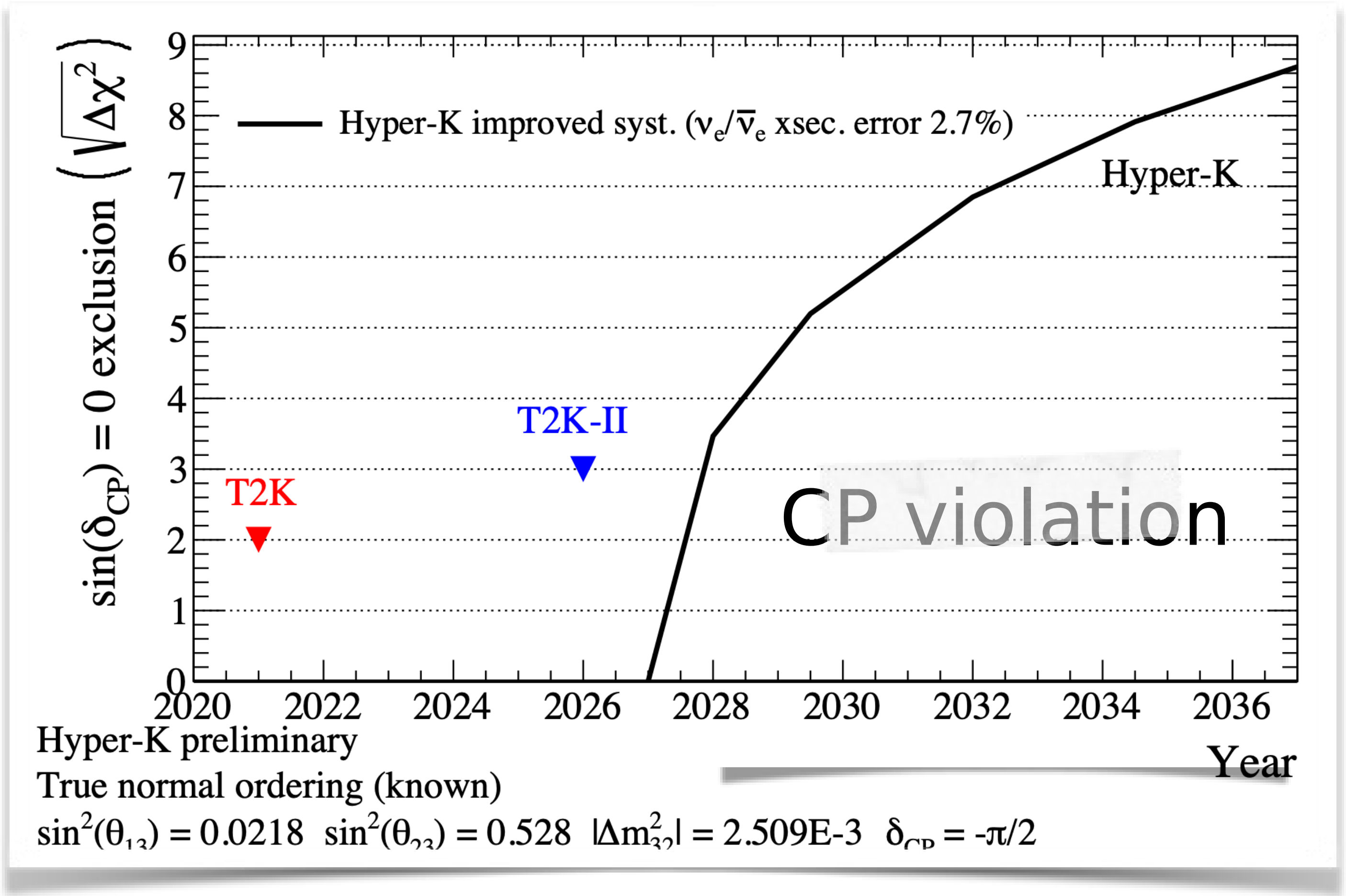
Solar physics

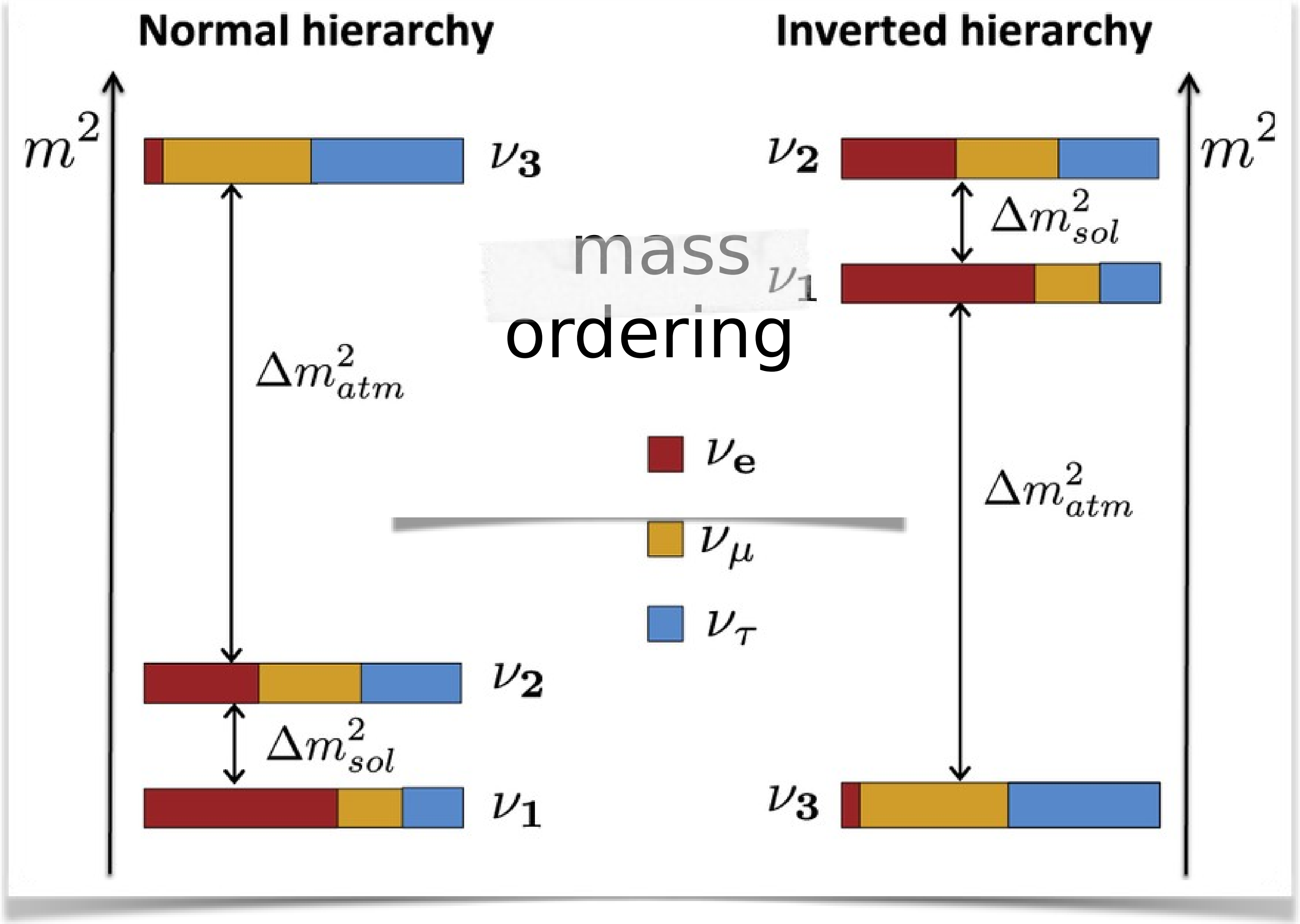


Rear events

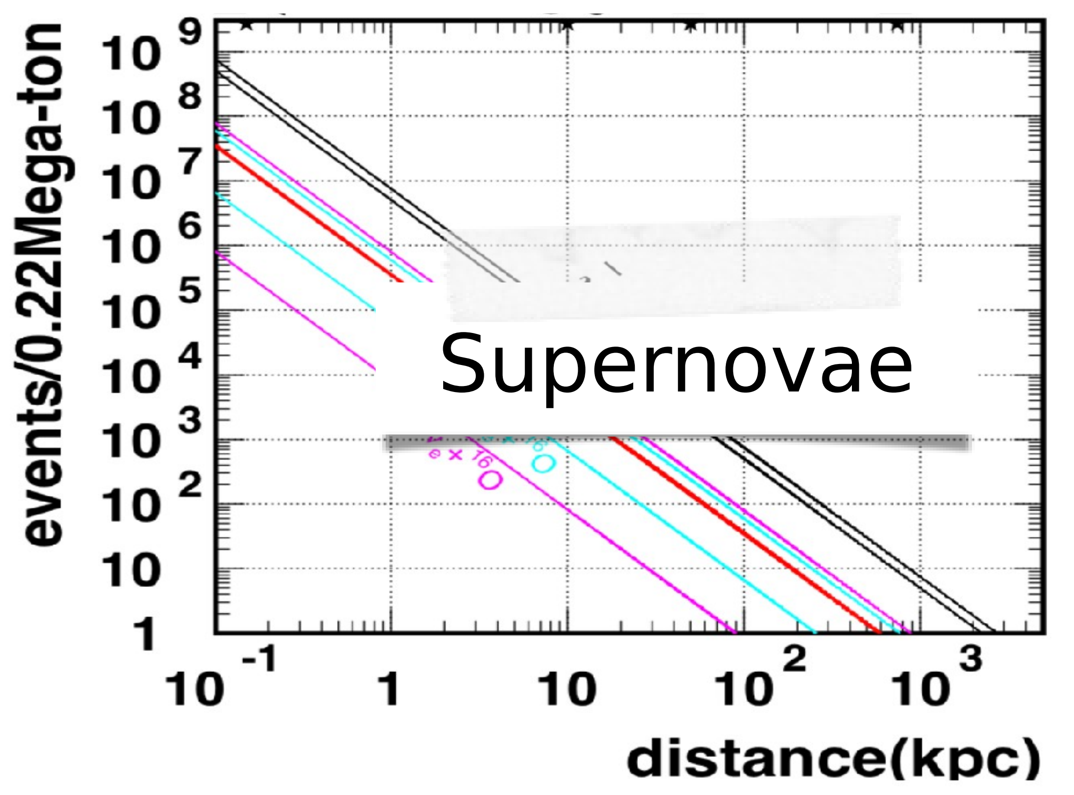


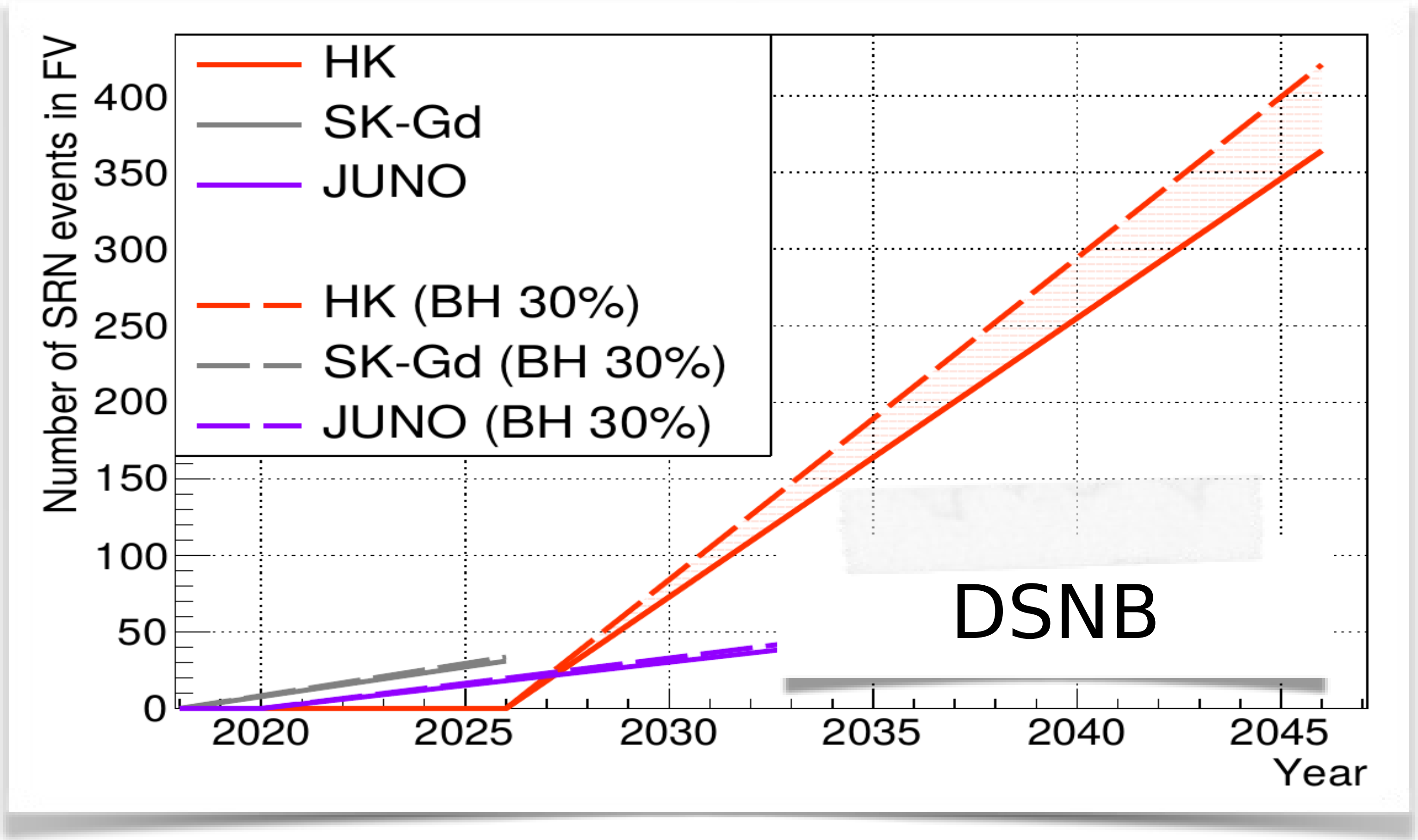
Neutrino oscillations





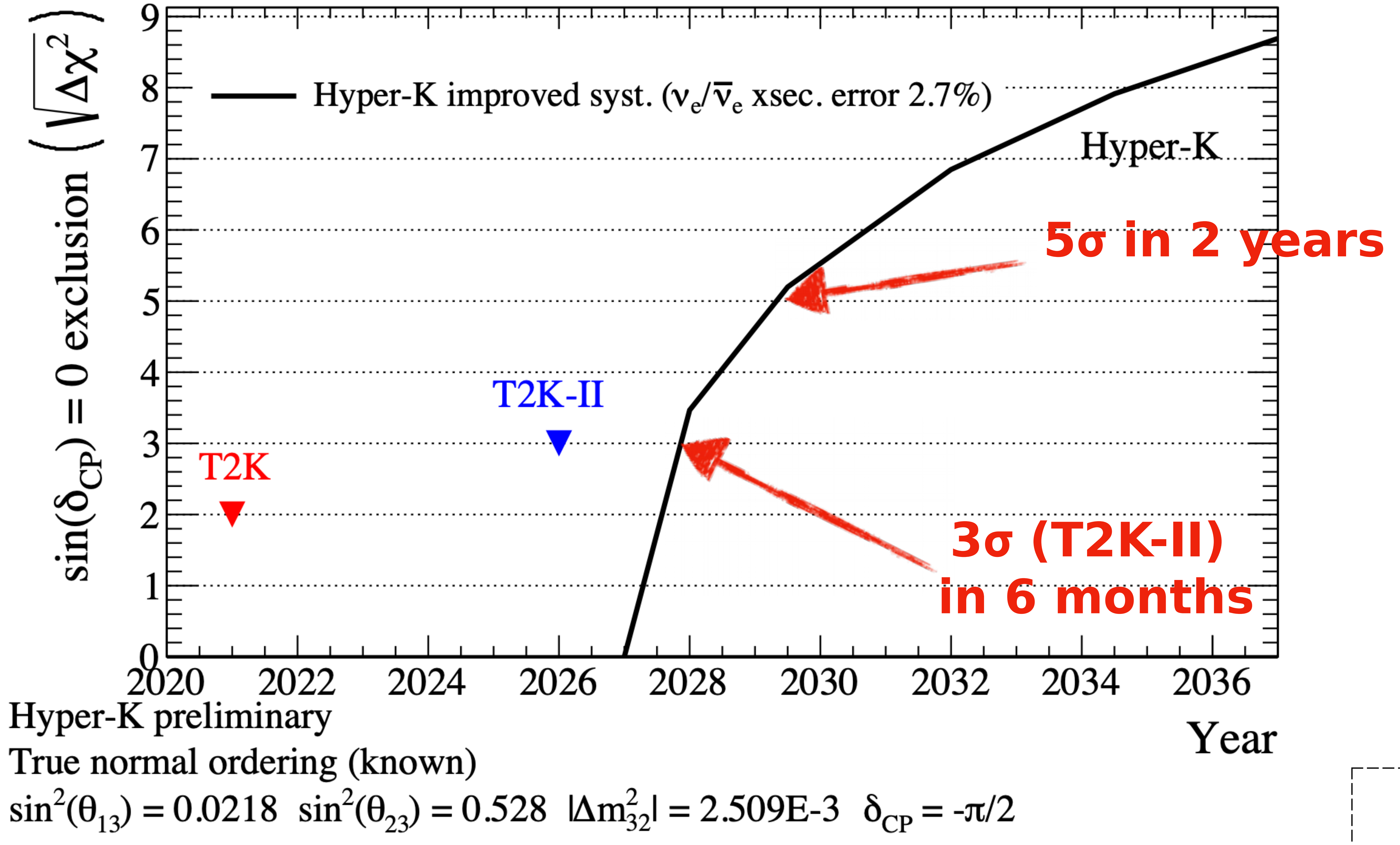
Supernovae modeling and Early Universe

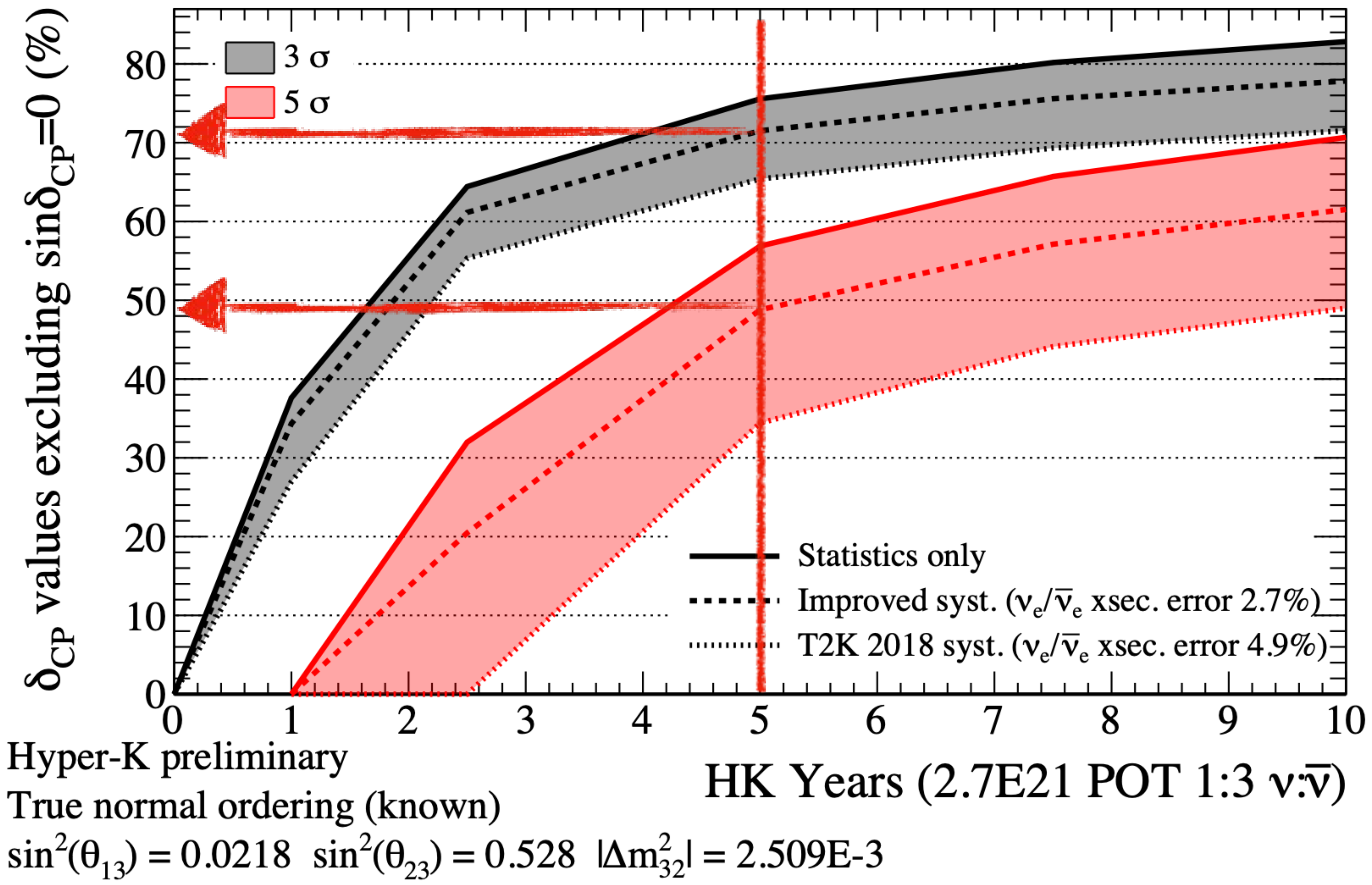




Fast CP-violation discovery

Known mass ordering (KM3NET)





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

Fastest experiment to survey possible δ_{CP} values

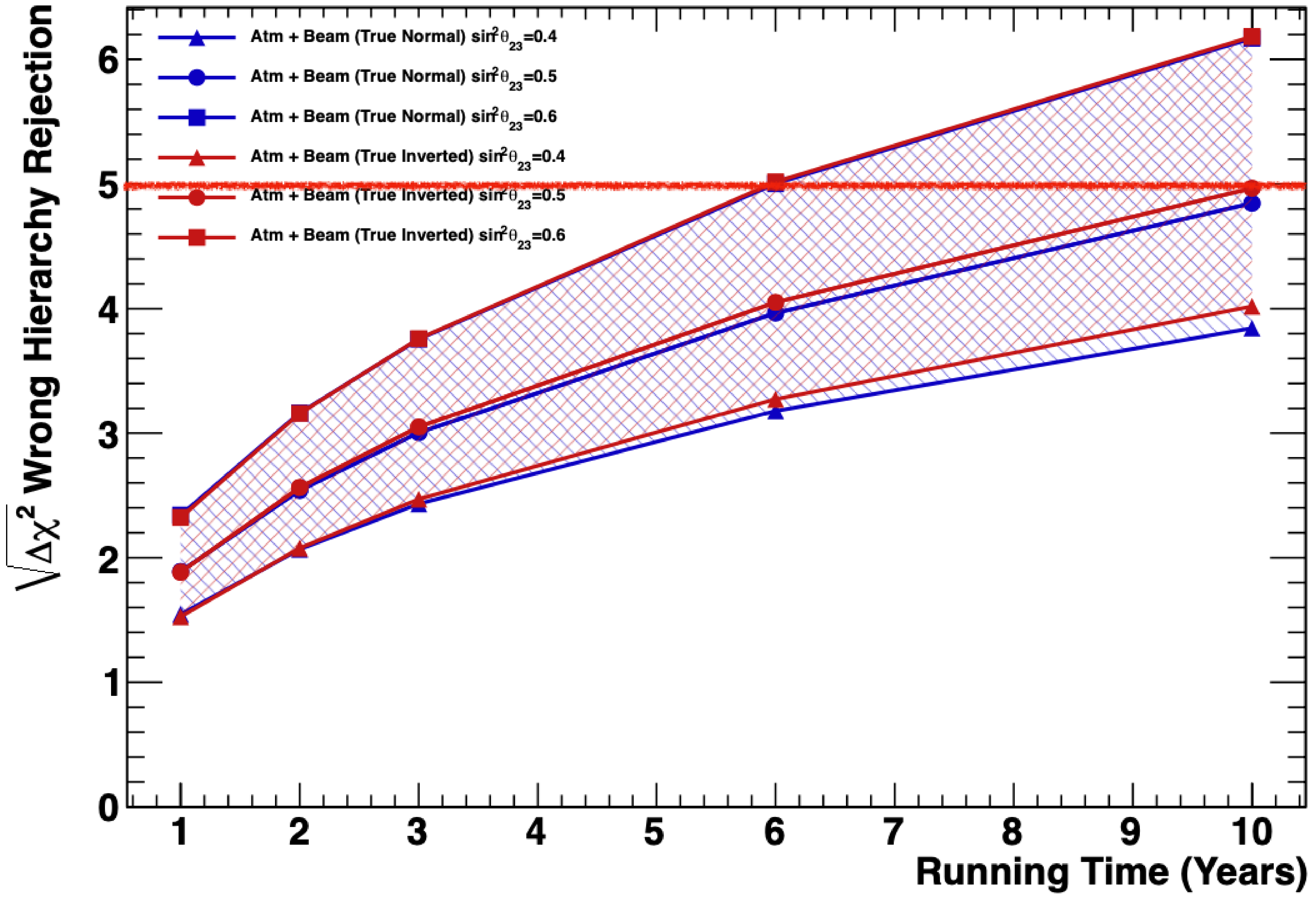
	$\delta_{CP}=-\pi/2$		All δ_{CP}	
	3σ	5σ	50 % 5σ	70 % 3σ
Hyper Kamiokande	0.5 y	2 y	5 y	5 y
DUNE (staged*)	4 y	8 y	10 y	13 y

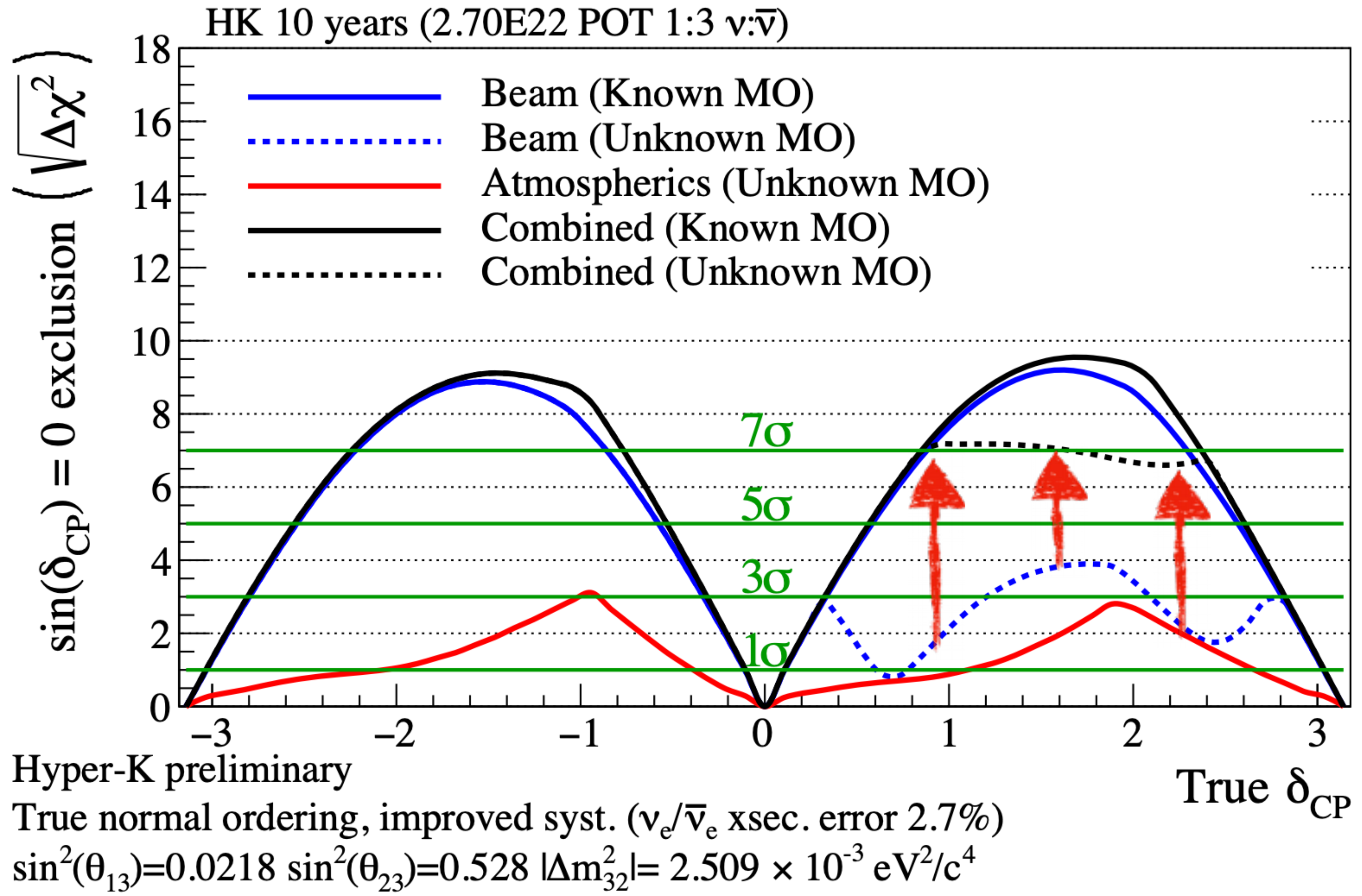
* 2 modules@1.2 MW y1; 3 modules y2; 4 modules y4; @2.4 MW y7

DUNE CDR arXiv:2002.03005

IUPAP Neutrino panel report

Mass ordering sensitivity with atmospherics



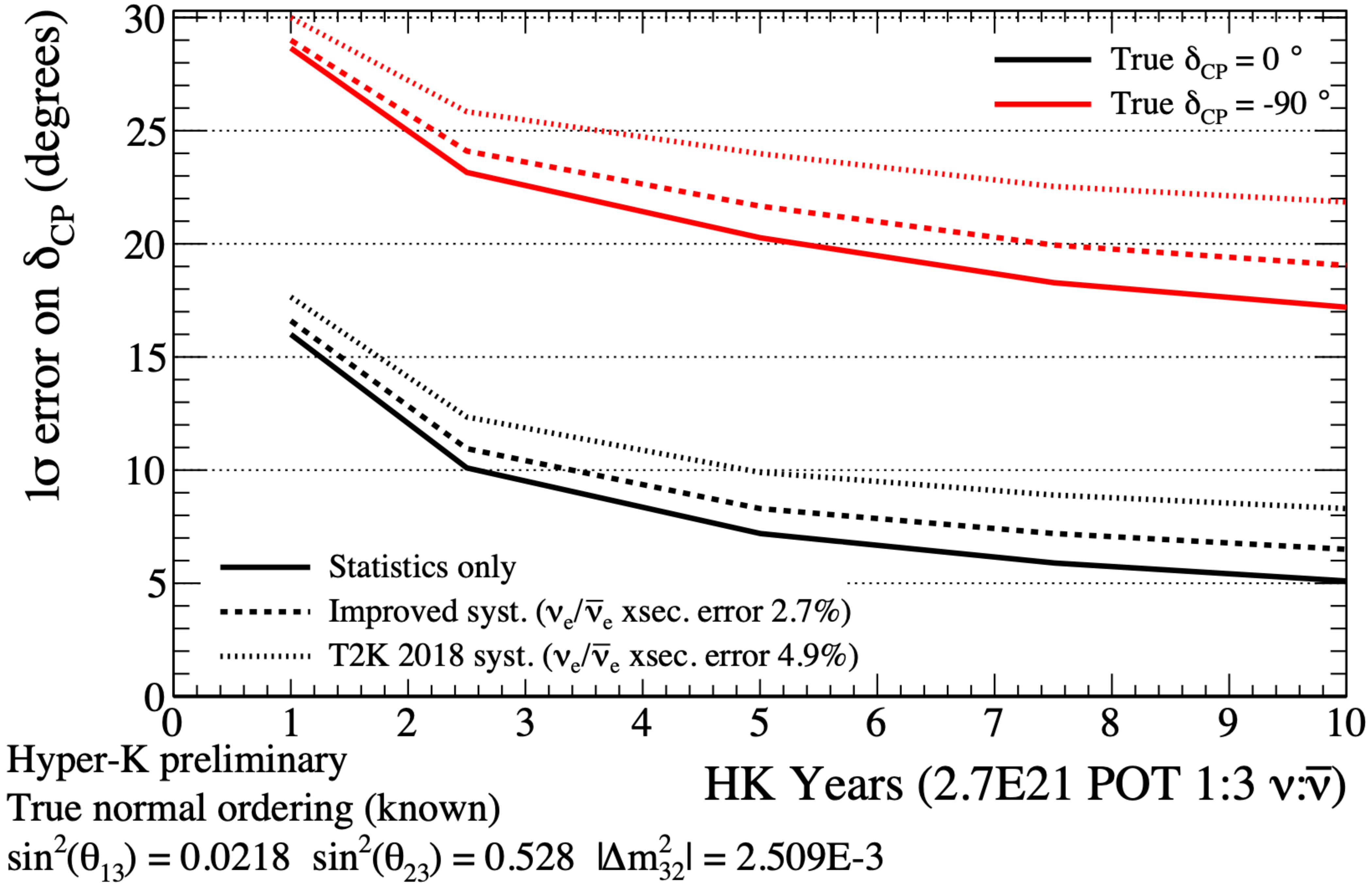


If not discovered by T2K/SK, NOvA, ORCA or JUNO before 2027,
HK can determine MO after 6-10 years via atmospheric ν

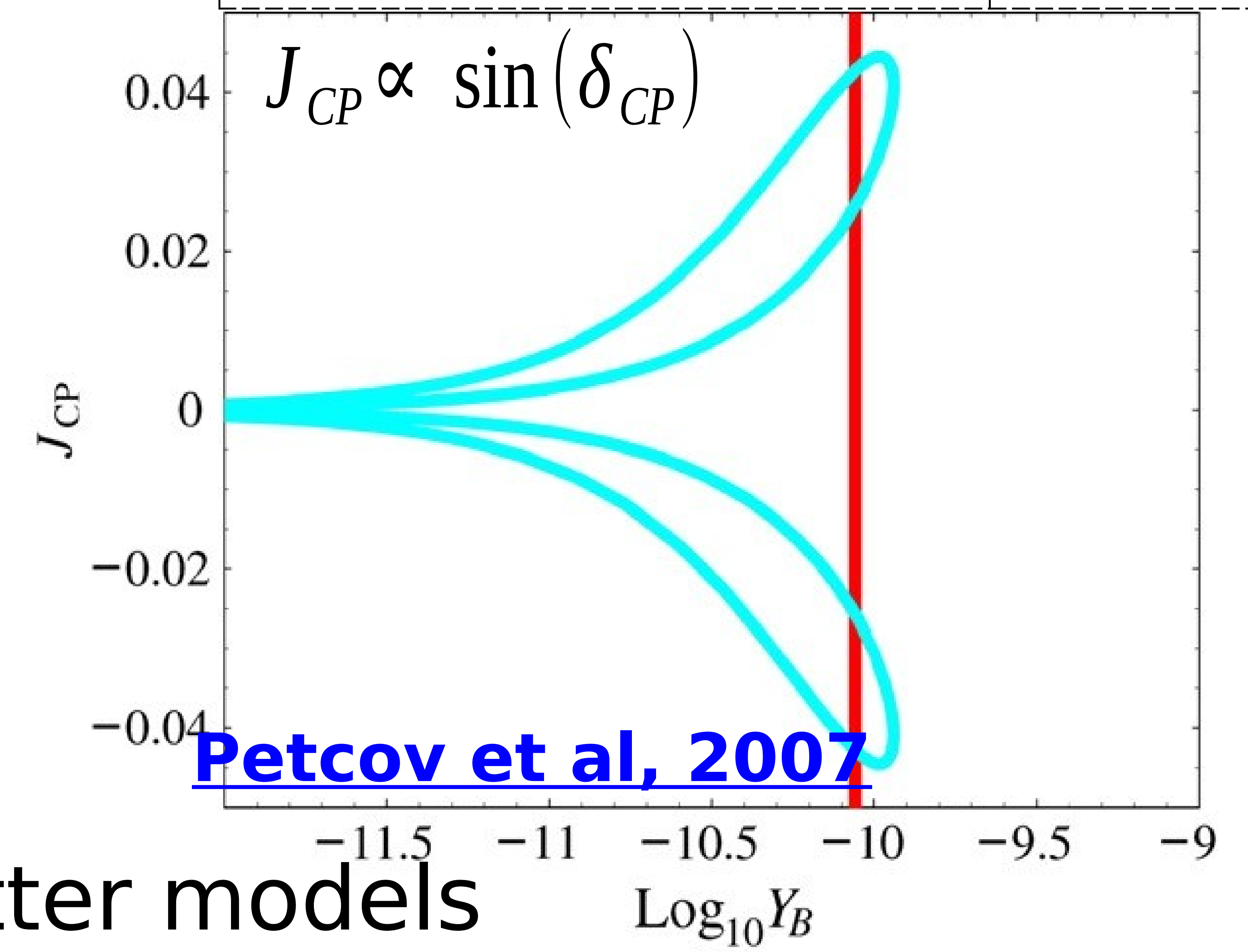
	$\sin^2\theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	2.2 σ →	3.8 σ
	0.60	4.9 σ →	6.2 σ

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

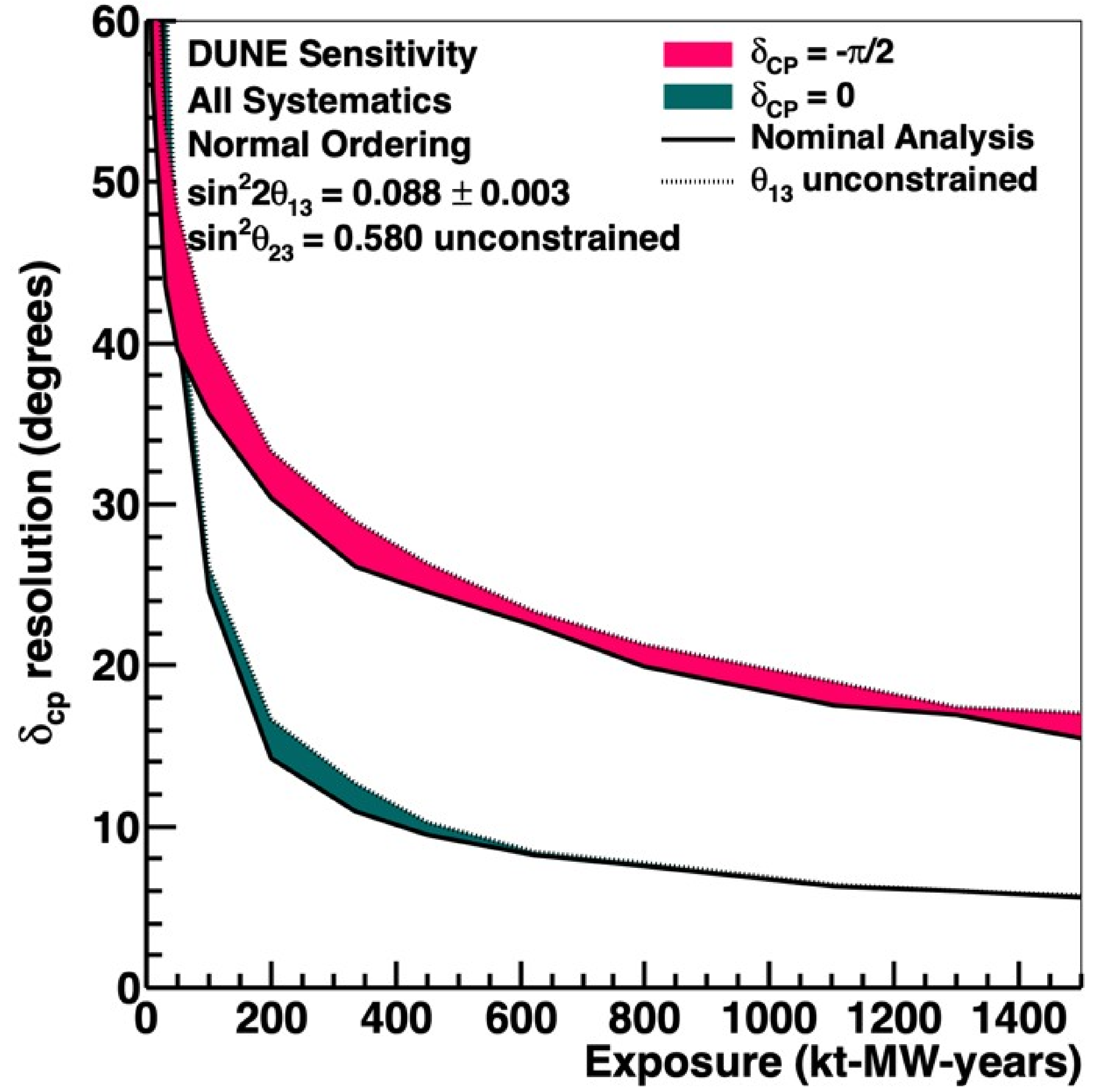
δ_{CP} measurement resolution



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



Petcov et al, 2007



DUNE CDR arXiv:2002.03005

Precision = sensitivity to matter-antimatter models

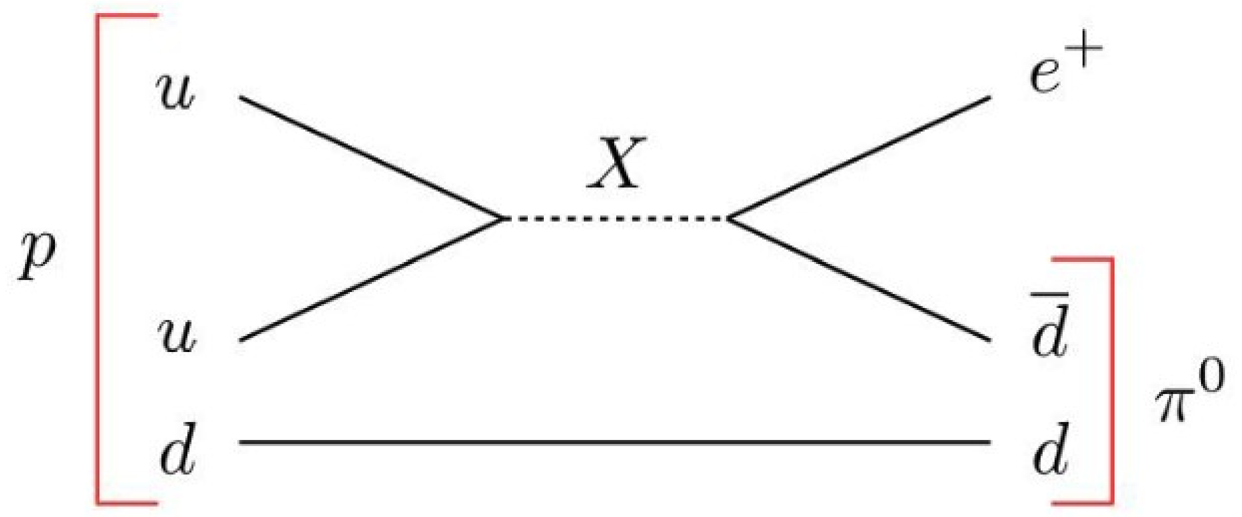
→ **HK will quickly reach precision on δ_{CP} of 30°(15°) for δ_{CP} =-π/2 (0)**

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

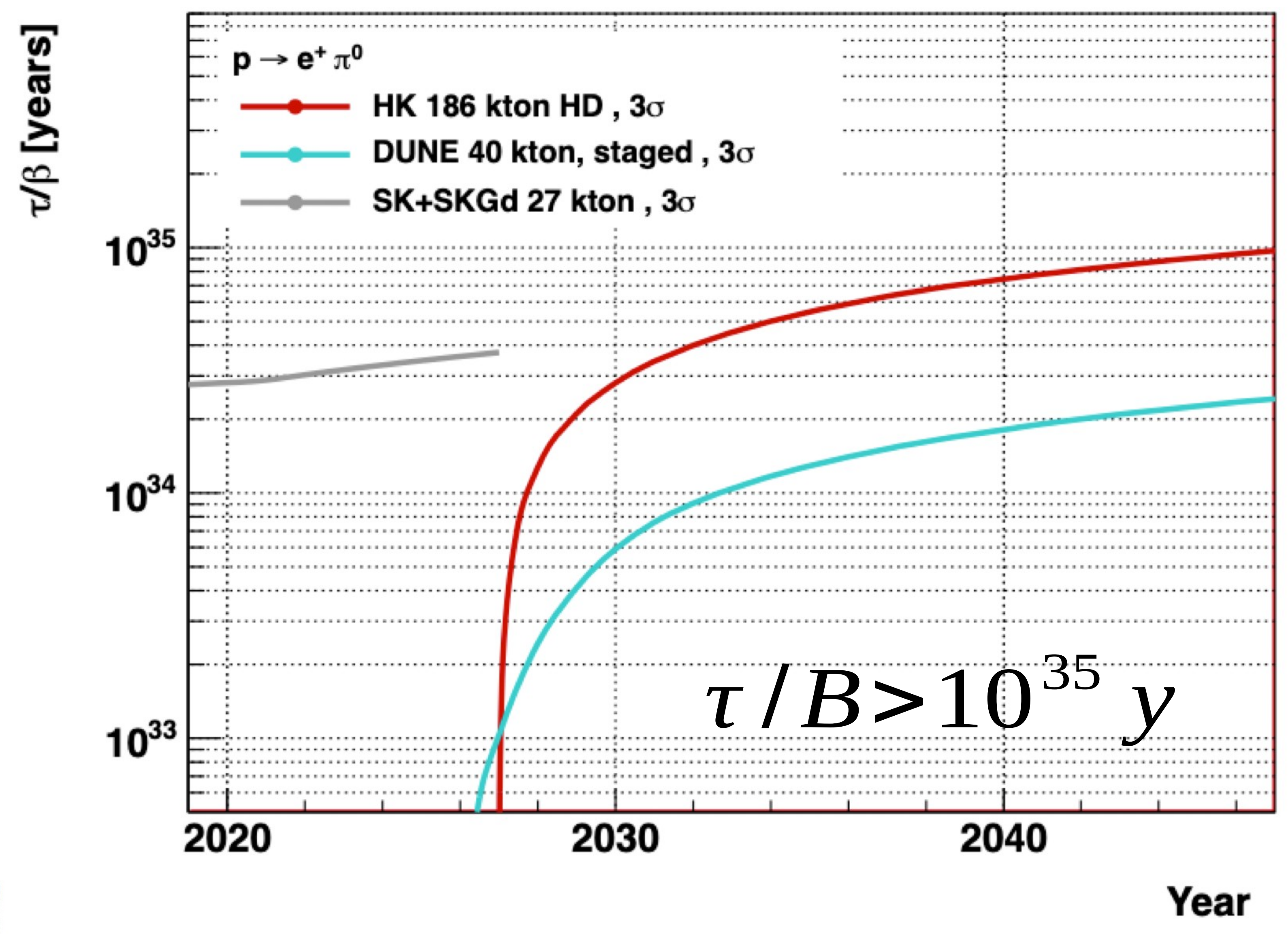
Proton decay

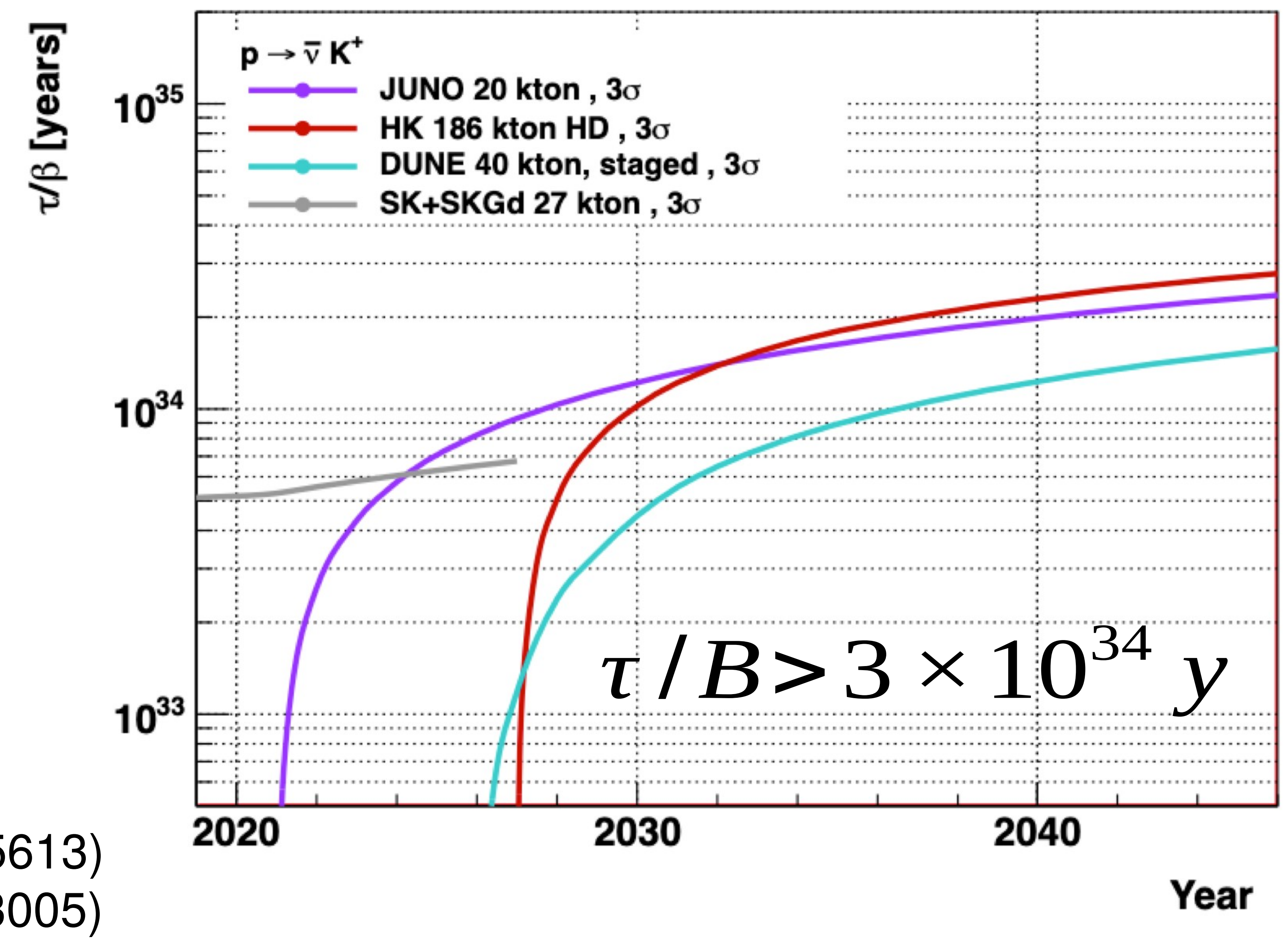
Motivated by Grand-Unification Theories
HK will have the best limit on $p \rightarrow e^+\pi^0$ for <u>bound</u> protons
→ about 1 order of magnitude better than current limits

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

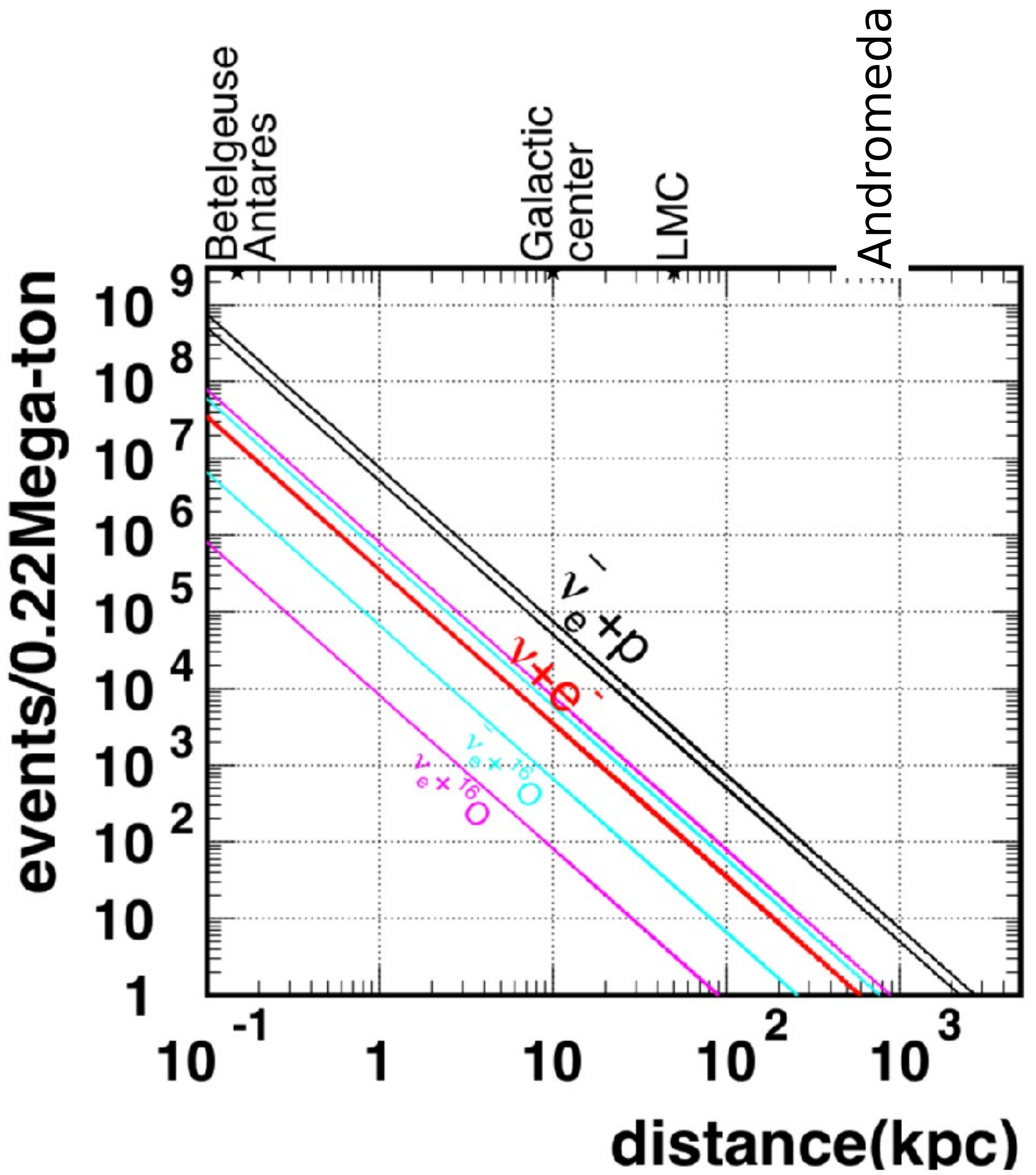
  SN1987A type ~2500 events

  Galactic center: ~50000+ events

Direction (1°@10kpc) → triangulation

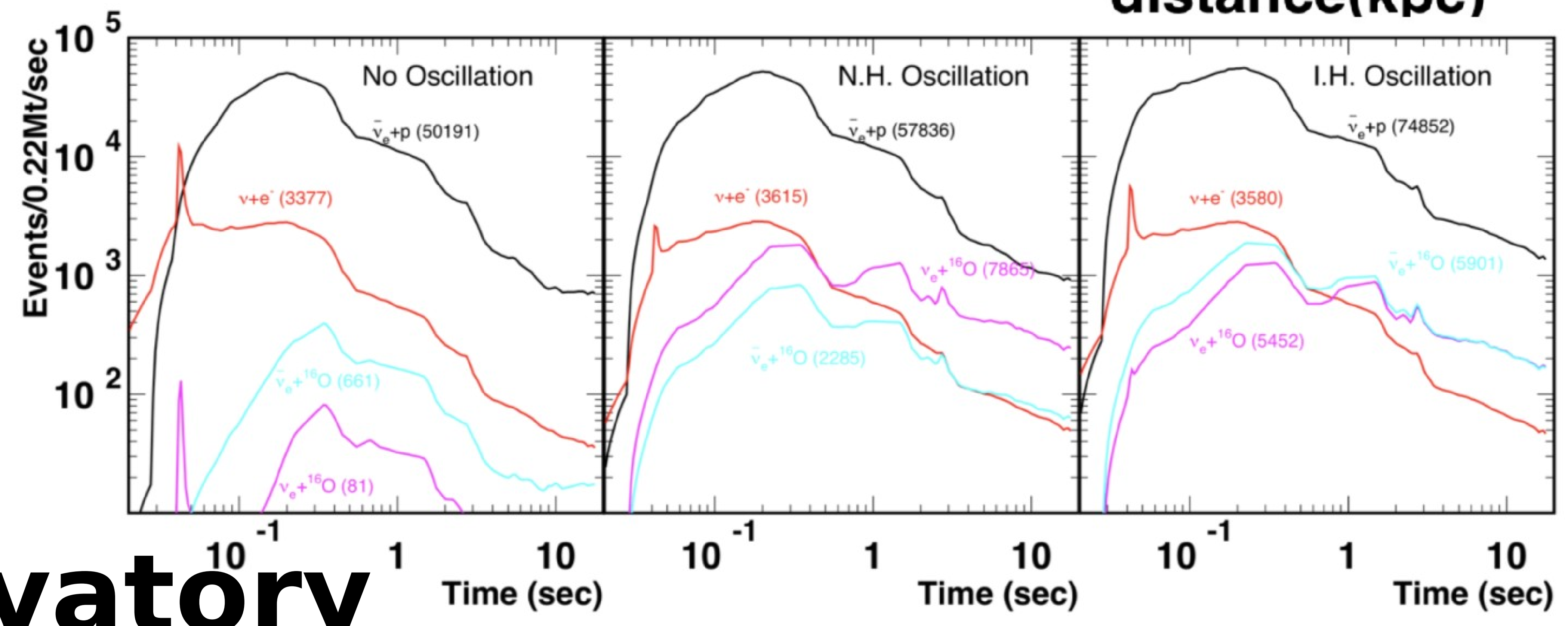
Time profile: collapse models

SN ν detected <u>every 3 years in HK</u>!



Gravitational waves sources

Nearby (10Mpc) neutron star mergers



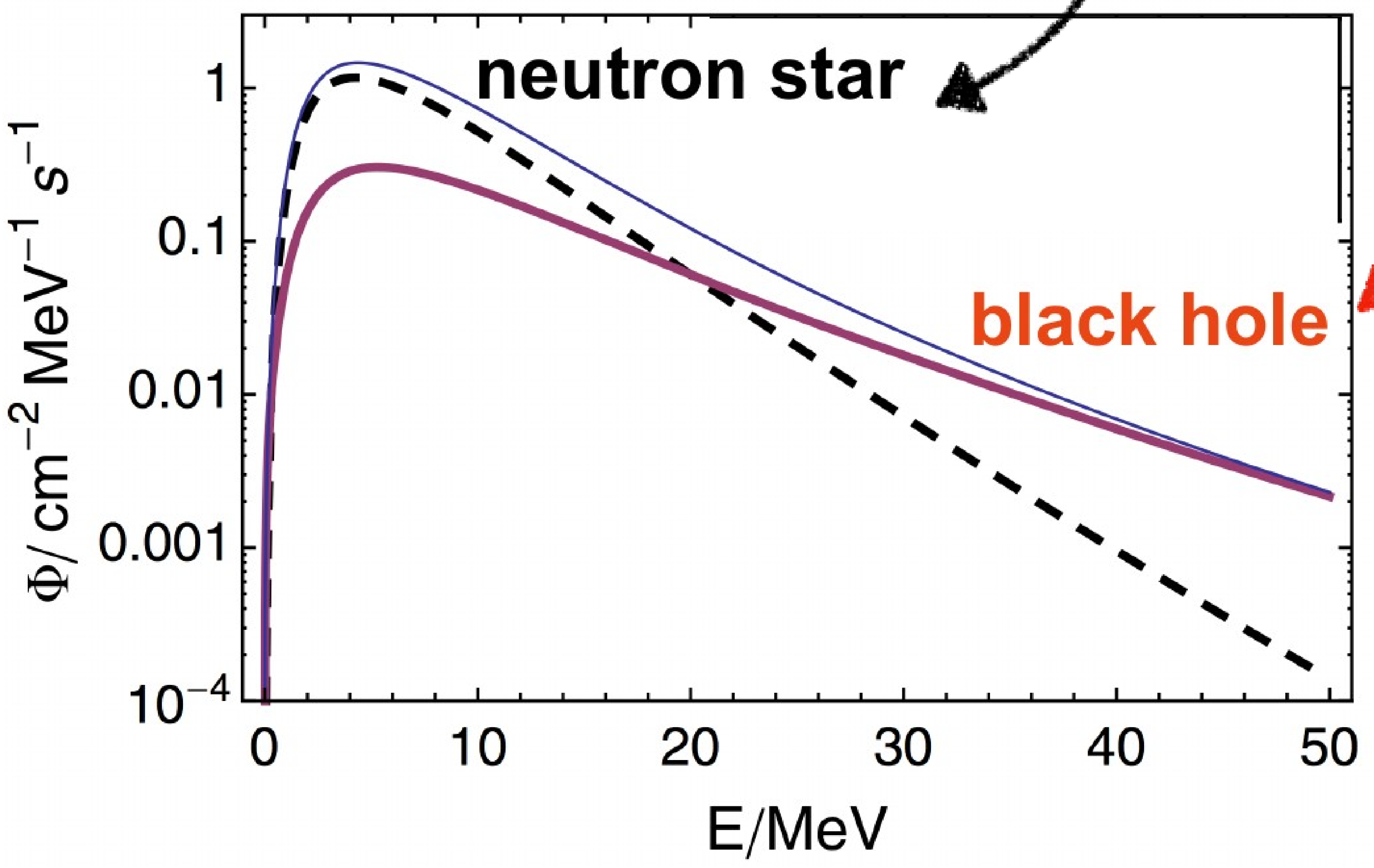
→Unique multi-messengers observatory

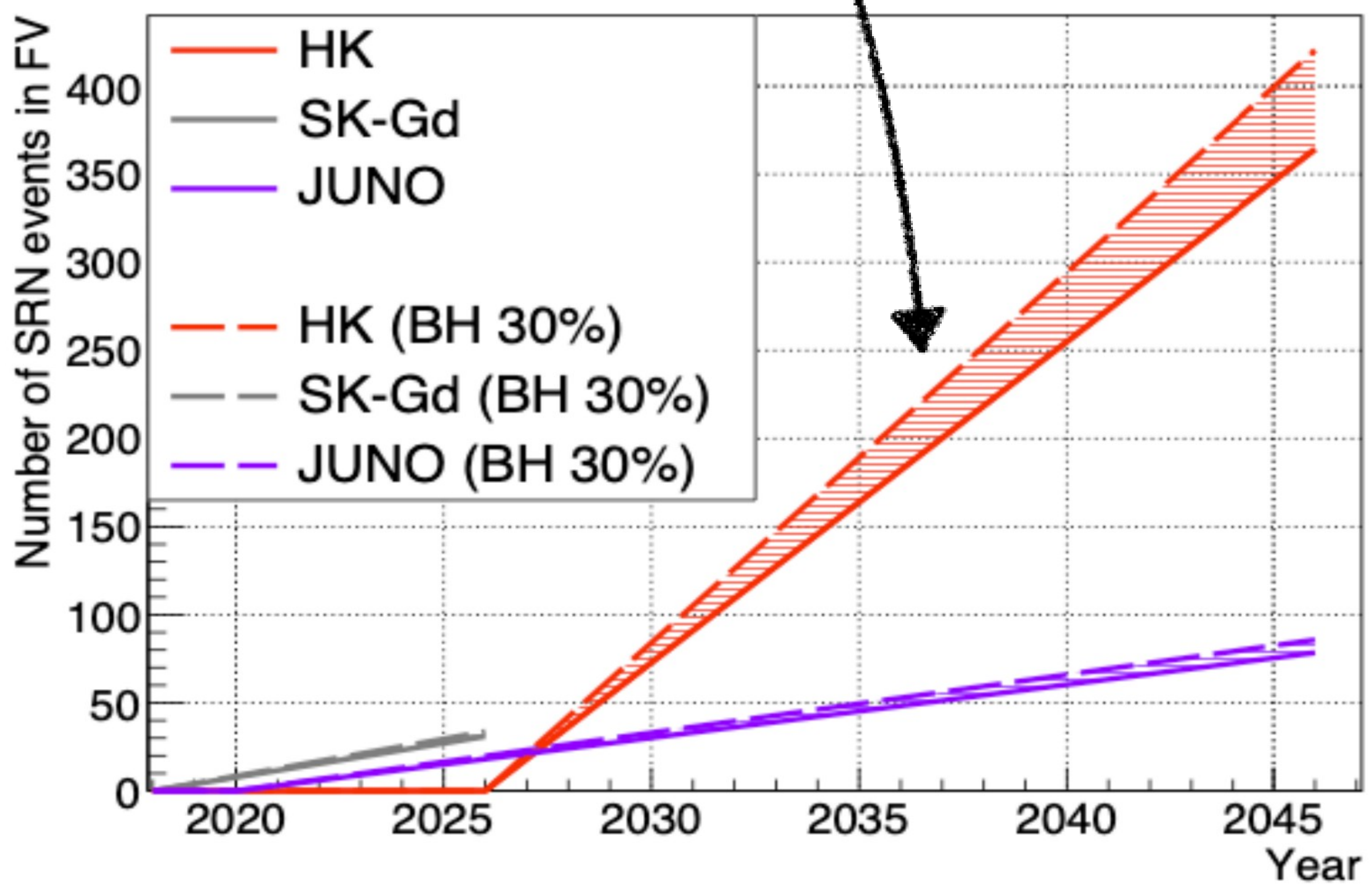
DSNB discovery by HK

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

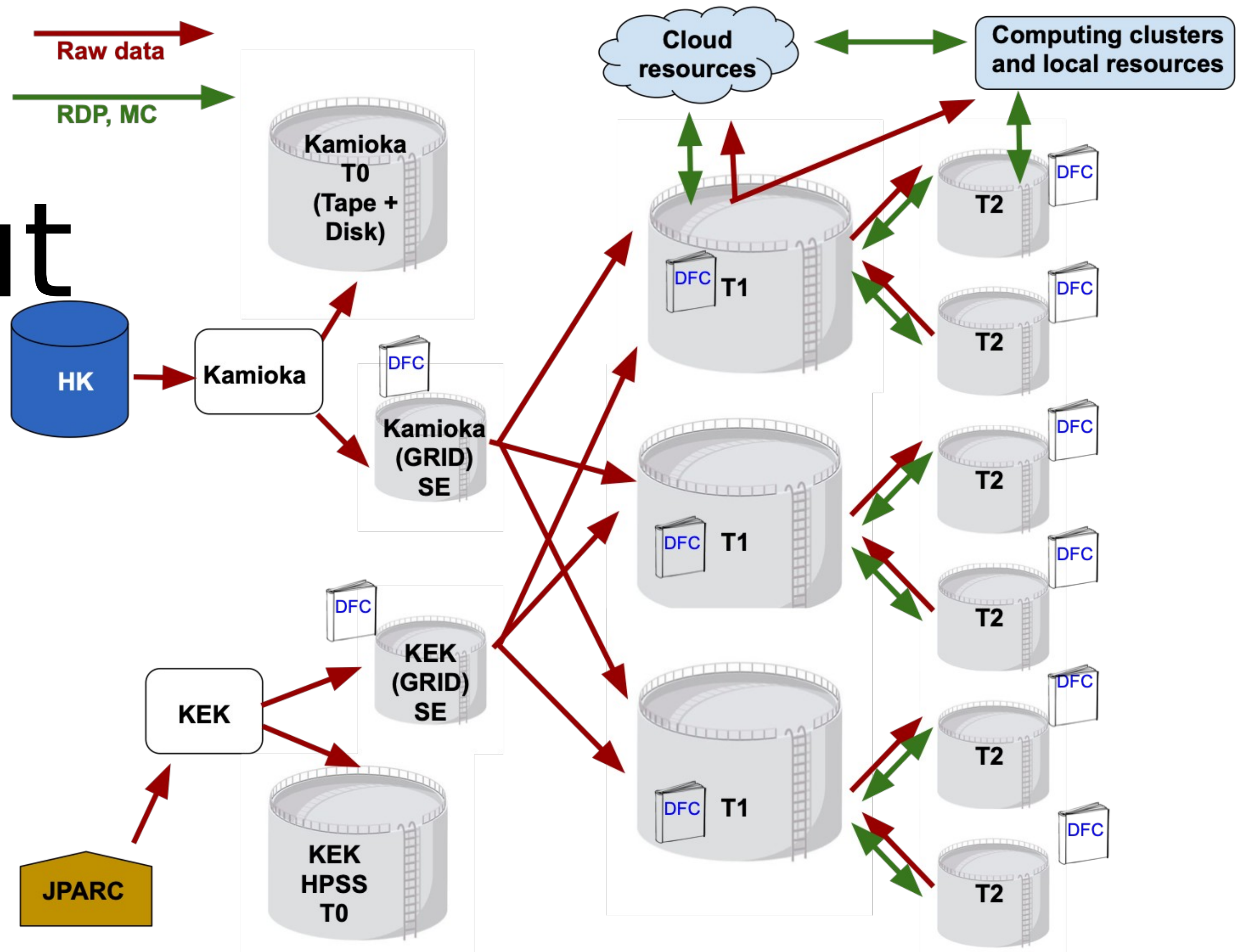
neutrino flux





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
- **<u>International computing effort</u>**
  - CC-IN2P3 as T1 for HK



Hyper-Kamiokande

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.

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.
- So far no other IN2P3 groups decided to join the Hyper-Kamiokande experiment.
- Hyper-Kamiokande not an IN2P3 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 region.
- IN2P3 groups can build on their long standing expertise in the T2K experiment to propose strong contributions in Hyper-Kamiokande. The possibility of using chips developed by OMEGA for the Hyper-Kamiokande far detector is particularly attractive from this point of view.

Risks:

- Dates for the approval by CS-IN2P3 and fundings of our proposed contributions to the HK electronics before collaboration review in Summer 2022. **Missing the Summer 2022 deadline would compromise the French contributions to the Hyper-Kamiokande far detector.**
- If the solutions not selected or not funded, no other planned French contributions to the far detector construction, putting our participation to Hyper-Kamiokande in jeopardy.

Conclusions and outlook

Hyper-Kamiokande has a vast and rich physics program including:
- ν oscillations (fast CP-violation discovery, δ_{CP} precision…)
- Rare events observatory e.g. proton decay
- Multi-messenger astrophysics (transient and diffuse SN detection)

→ **High and quick discovery potential!**

Construction started and on schedule → Operation will start in 2027

Continuation of T2K and T2K-II
- Upgraded ND280 will be used as the HK near detector
- Unique program of world-leading measurements and discoveries from 2010 to ~2040

Almost done: identified contributions on electronics and computing
Used fundings from external sources (SU, Ecole Polytechnique, ANR)
Technological decisions taken in Summer 2022

→ **approval by CS-IN2P3 & recognition of HK as IN2P3 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	1	ANR - INFN - CEA	2022	2023 – 2026	TBD
Communication cables	2	European countries	2022	2023 – 2026	TBD (~0.5)
Chip and Front-end	1.5-3	CEA	2022	2023 – 2026	TBD
Computing (CC-IN2P3)	1.9-3.8	-	2021	2021 – 2037	1.9-3.8
Total	12.4-15.8	-	-	-	~5-7

Table 1: Summary of the costs of the various items for Hyper-Kamiokande. Note that it includes only the production costs (the R&D costs has been already funded). See section 5 for more details about the over investments.

External and internal investments:
- 70k€ for R&D towards HK (Sorbonne Université)
- 400k€ (X) + 90k€ (IN2P3) for R&D on HKROC
- 300k€ (ANR) + 50 k€ (IN2P3) for R&D on time generation and clock distribution

Significant efforts to acquire externals fundings before IN2P3 investments kicks in

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**
Contigency	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