ESS NEUTRINO SUPER BEAM

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

The neutron European Spallation Source and the proposed neutrino Super Beam for CP Violation discovery

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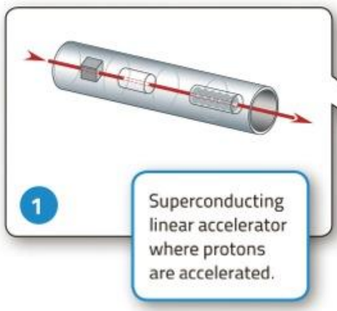
Outlook

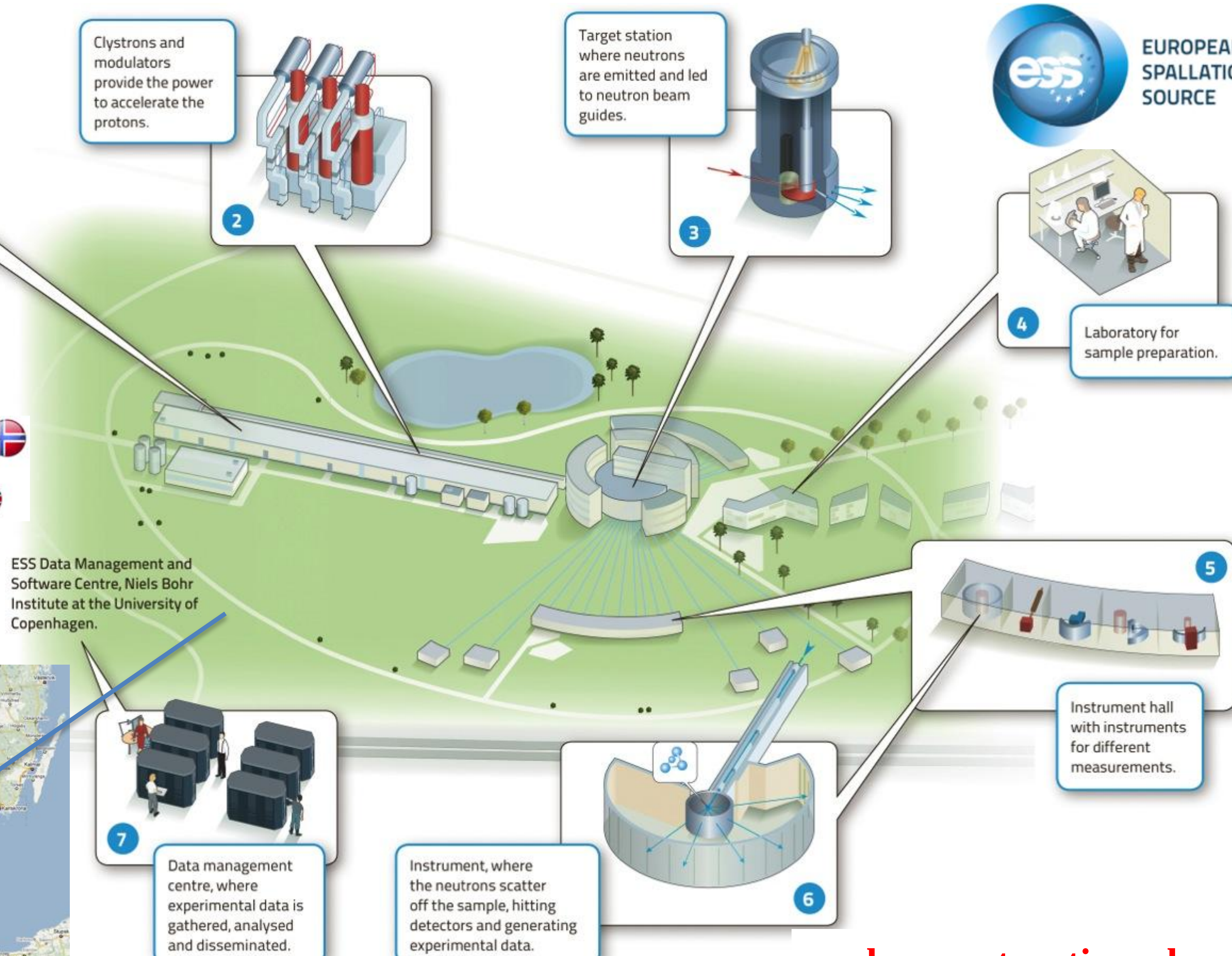
- Brief introduction
- Applications of neutrons
- The ESS neutron facility
- Neutrino Oscillations
- Matter-antimatter asymmetry in the Universe
- How to observe CP violation in the leptonic sector
- The ESS neutrino Super Beam
- Conclusions

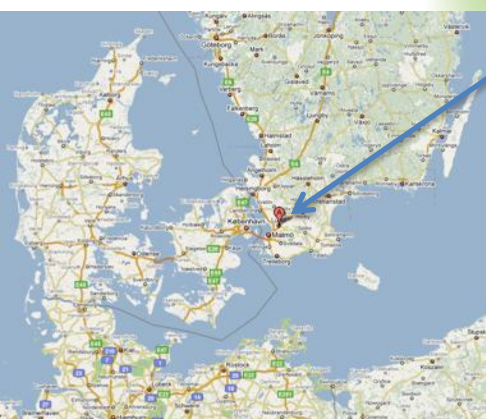
EUROPEAN
SPALLATION
SOURCE

European Spallation Source

Neutron facility



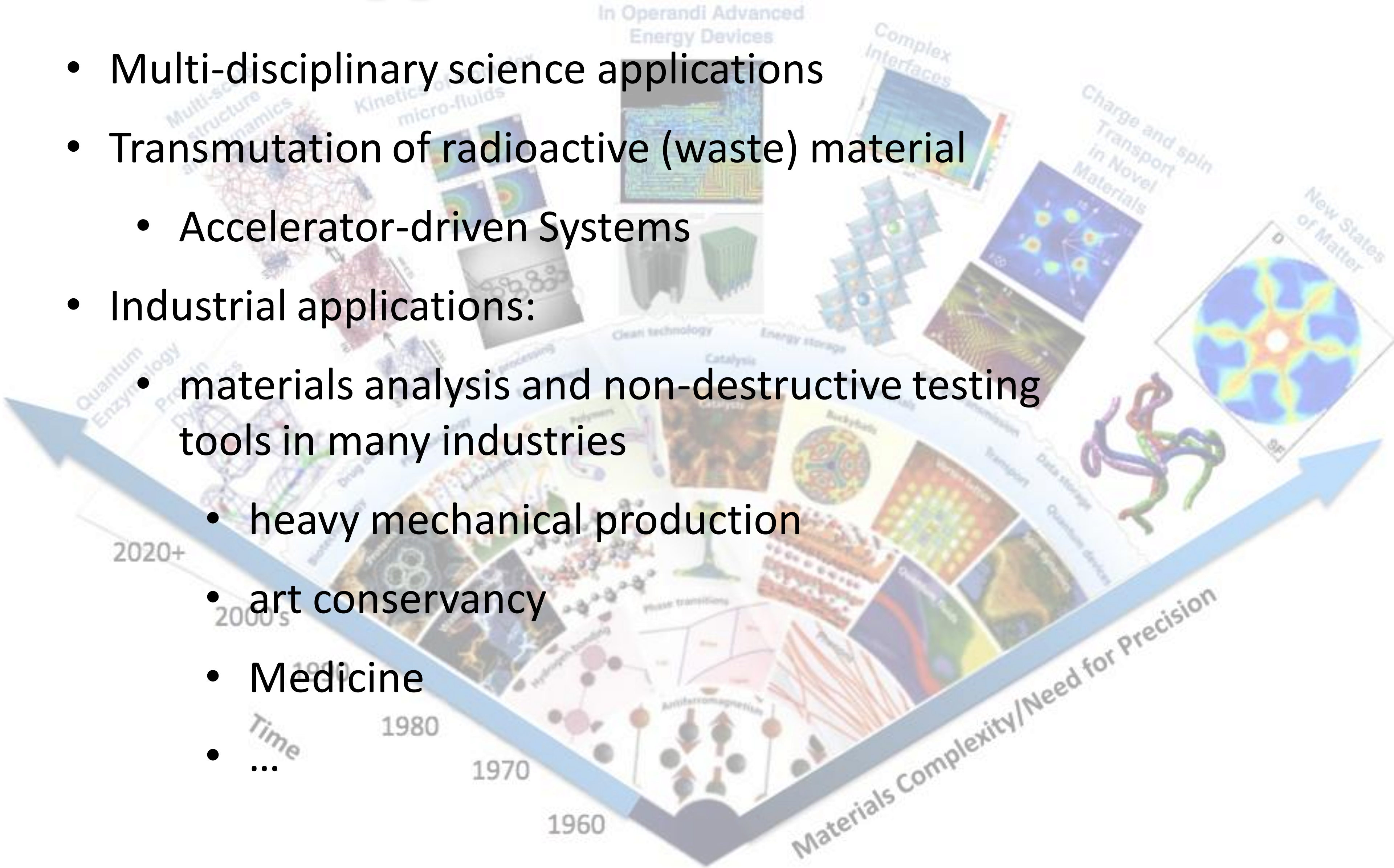




under construction phase (~1.85 B€ facility)

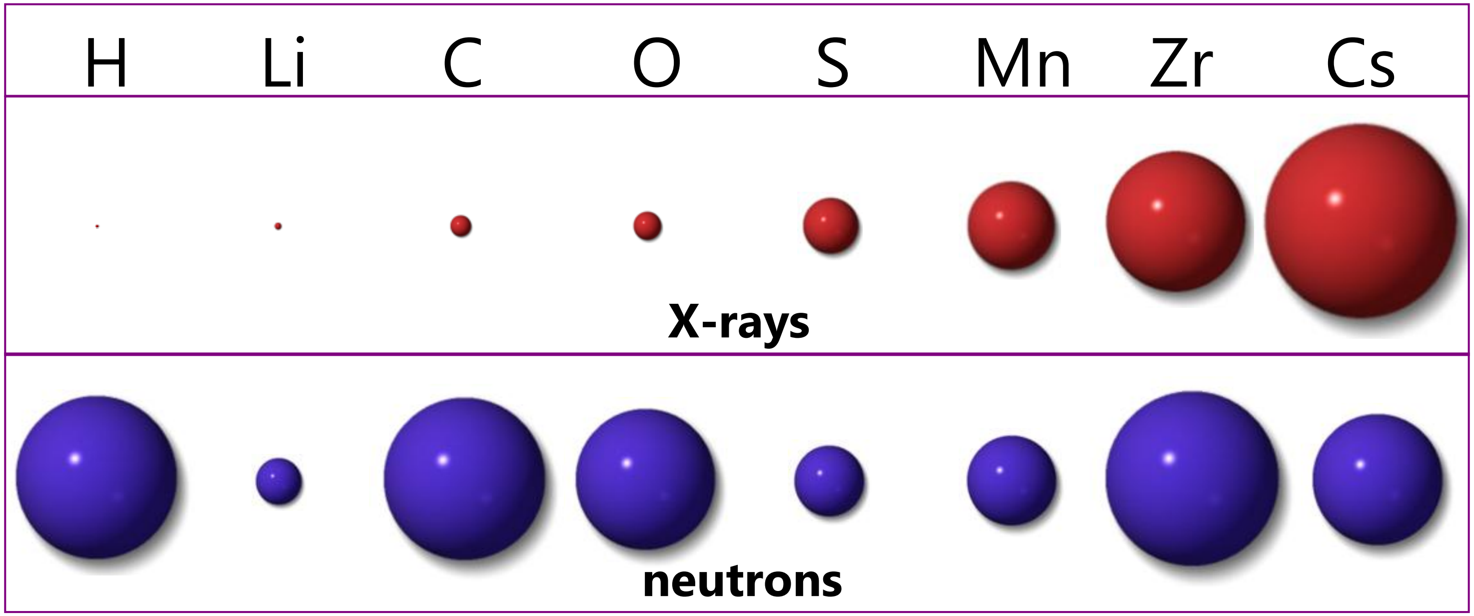
Applications of neutrons

- Multi-disciplinary science applications
- Transmutation of radioactive (waste) material
  - Accelerator-driven Systems
- Industrial applications:
  - materials analysis and non-destructive testing tools in many industries
    - heavy mechanical production
    - art conservancy
    - Medicine
    - …



Science at ESS

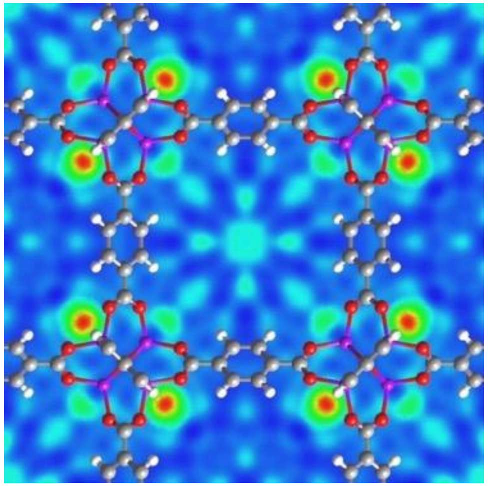
- ESS is a neutron spallation source for neutron scattering measurements.
- Neutron scattering offers a complementary view of matter
  - in comparison to other probes such as x-rays from synchrotron light sources.
  - The scattering cross section of many elements can be much larger for neutrons than for photons.



Neutron Scattering

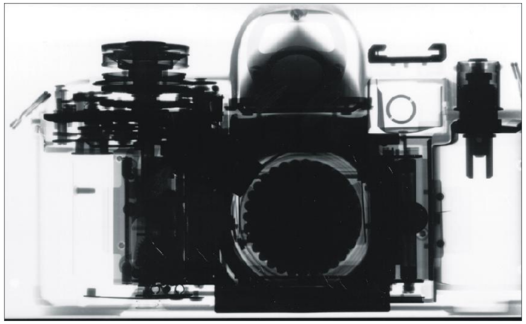
Can reveal the molecular and magnetic structure and behavior of materials, such as:

- Structural biology and biotechnology,
- magnetism and superconductivity,
- chemical and engineering materials,
- nanotechnology,
- complex fluids,
- …

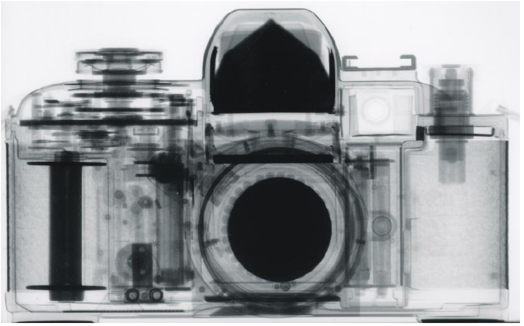


Neutron scattering of hydrogen in a metal organic framework

Neutron radiograph of a flower corsage

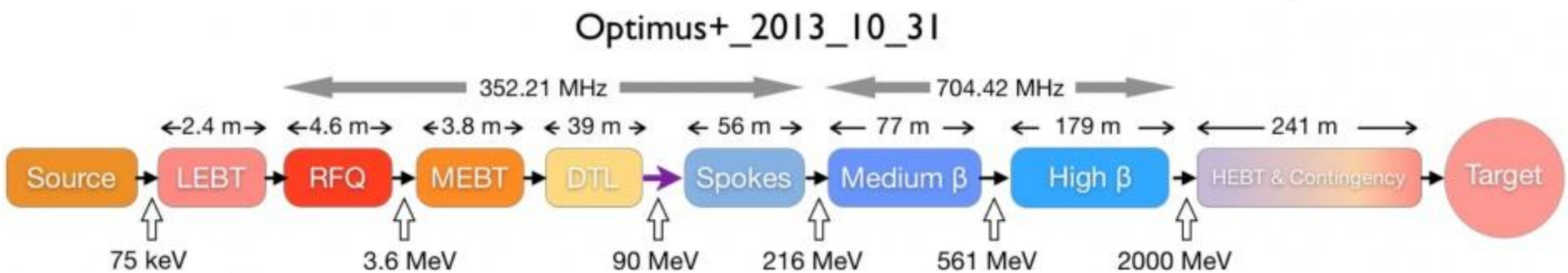


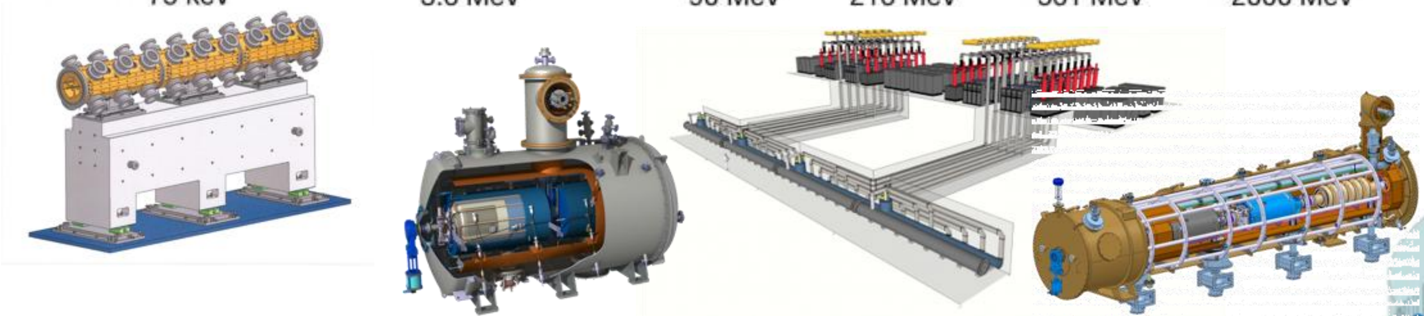
X-Ray Image

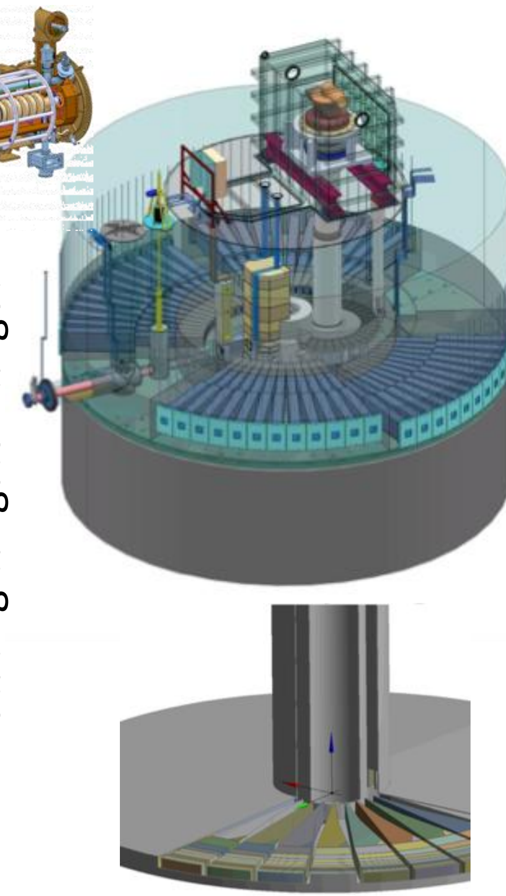


Neutron radiograph

The ESS neutron facility



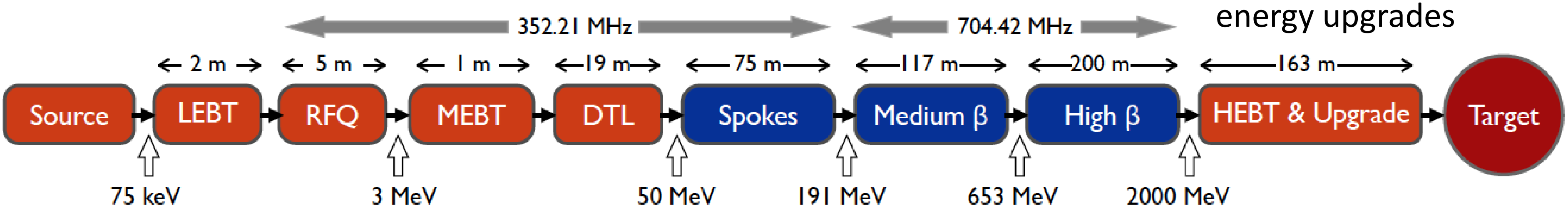




rotating tungsten target

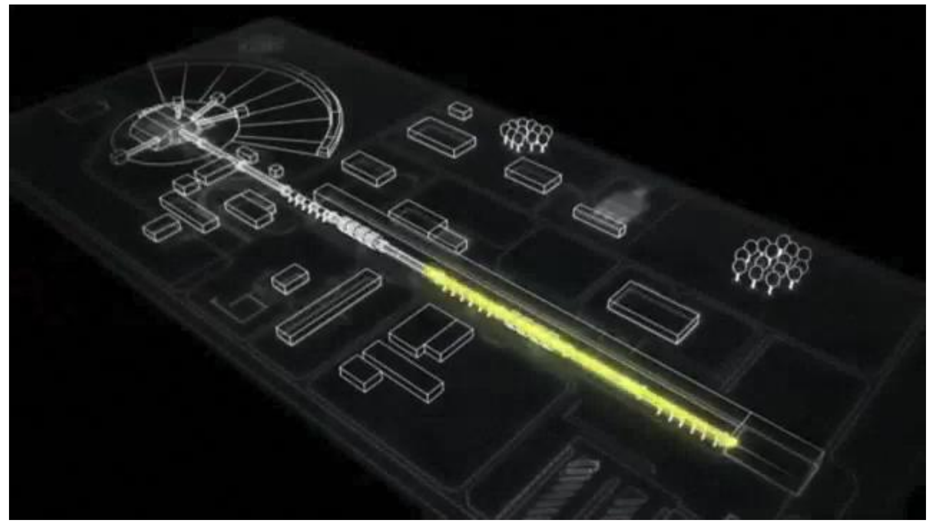
ESS proton linac

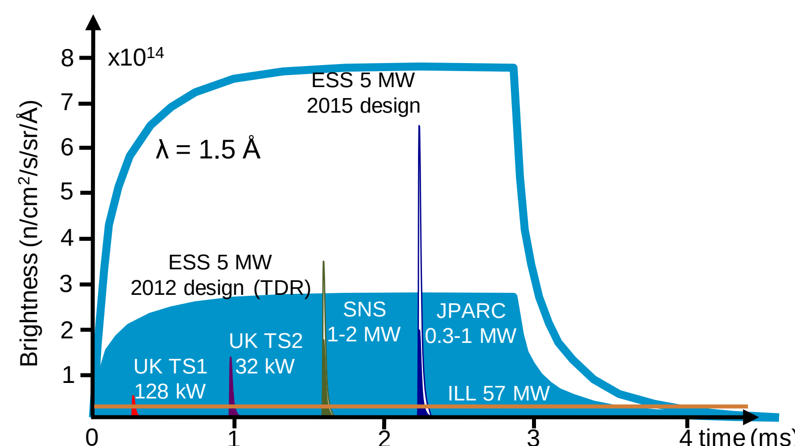
empty space for energy upgrades



- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power.
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4%.
- 2.0 GeV protons
  - up to 3.5 GeV with linac upgrades
- **>2.7x10^{23} p.o.t/year.**

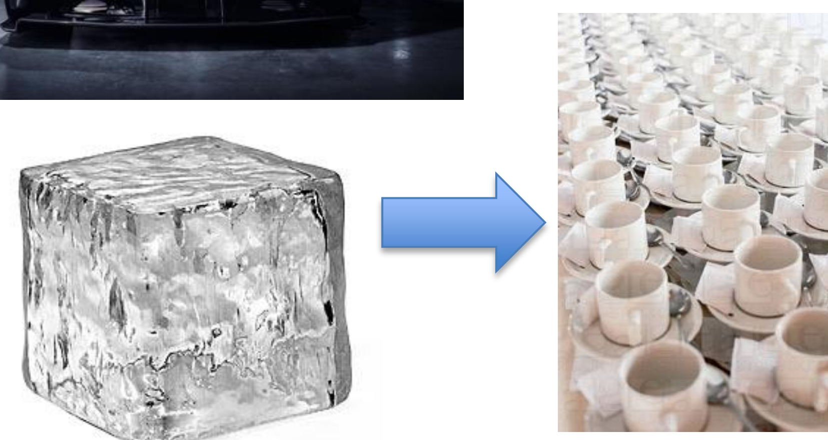
Linac ready by 2023 (full power)





What does it mean 5 MW?

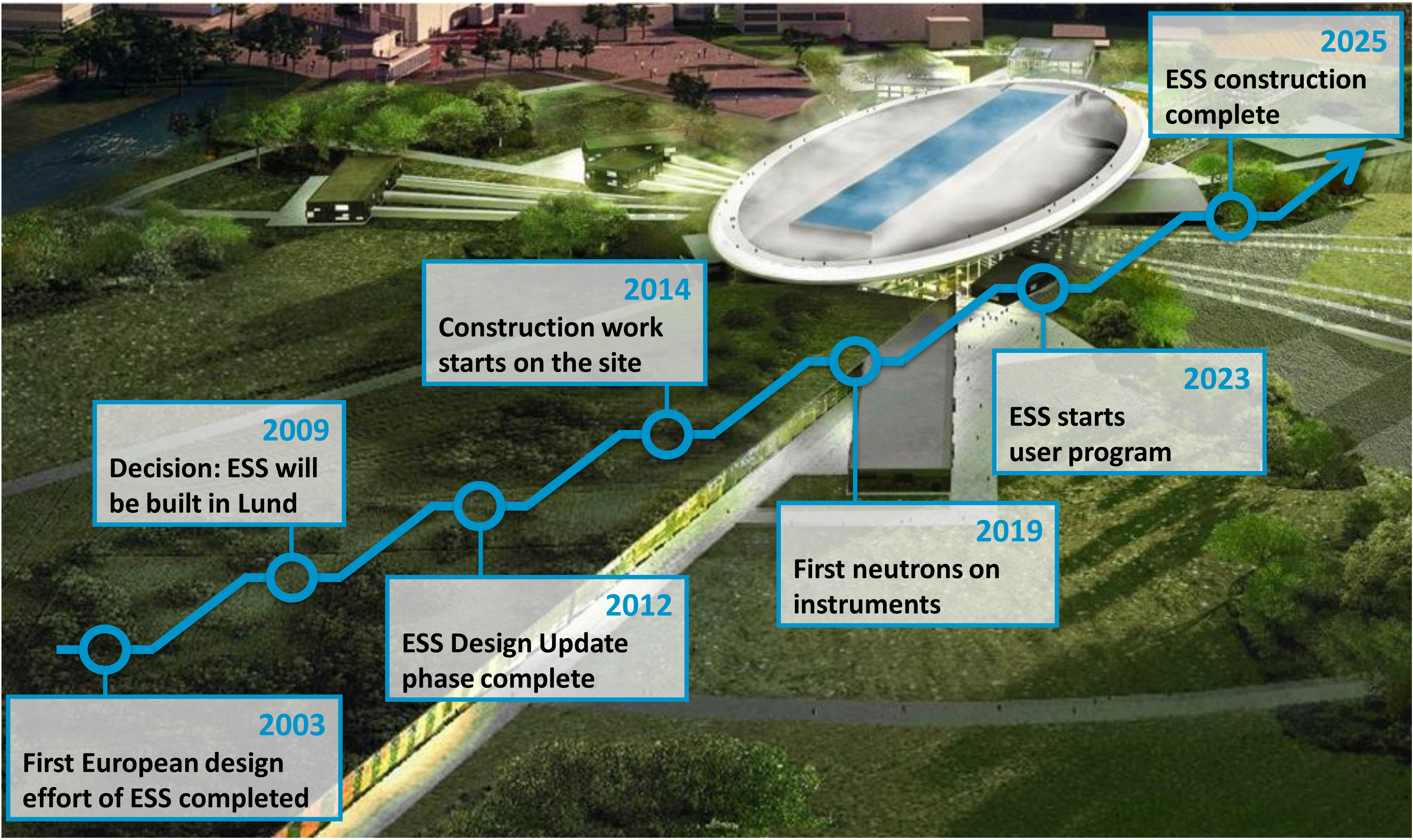
- One beam pulse:
  - has the same energy as a 16 lb (7.2kg) shot traveling at
    - 1100 km/hour
    - Mach 0.93
  - Has the same energy as a 1000 kg car traveling at 96 km/hour
  - You boil 1000 kg of ice in 83 seconds
- And this for 14 pulses/sec…



European Spallation Source

European Spallation Source

ESS schedule



European Spallation Source as Neutrino Facility

ν

Quantum Mechanics and lepton mixing

- The "known" neutrinos are combinations of neutrino mass eigen states, e.g., for the electron neutrino:

$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

- Propagation in time:

$$|\nu_j(t)\rangle = e^{-iHt/\hbar}|\nu_j(0)\rangle$$

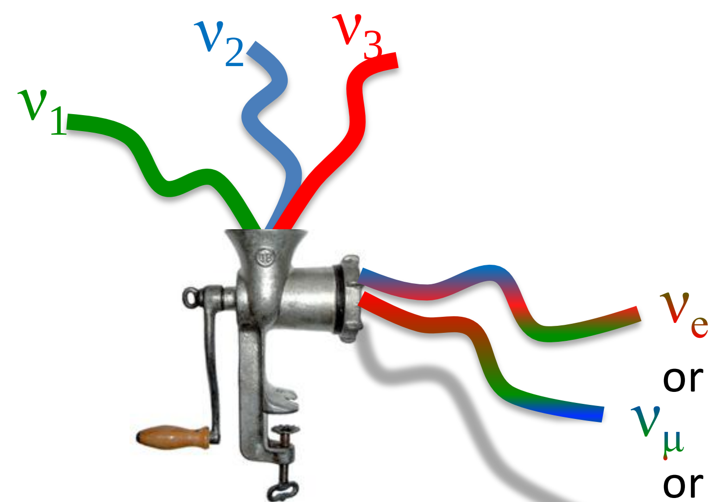
- For all neutrinos, we can write:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{\text{unitary mixing matrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata Matrix

Unitarity: $UU^+=I$

$(U^+=(U^*)^t)$

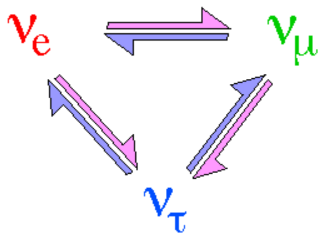


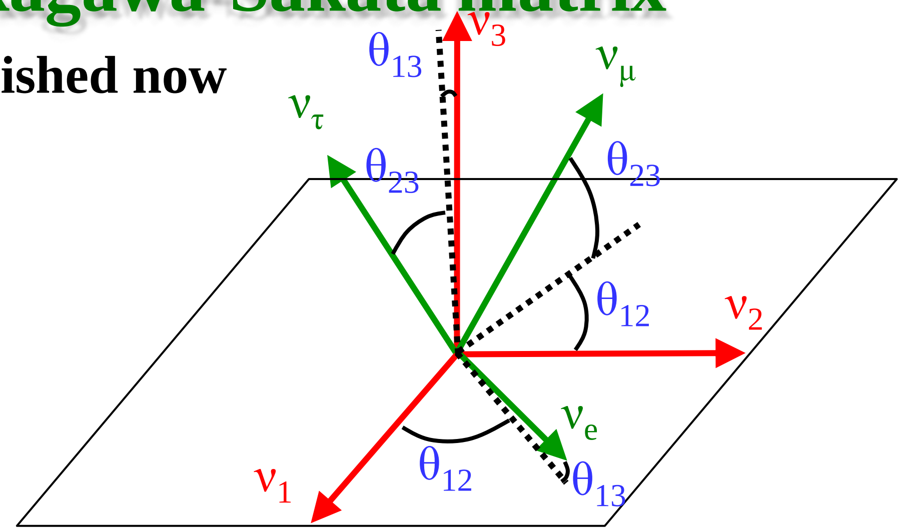
Weak interaction

Neutrino Oscillations

Pontecorvo-Maki-Nakagawa-Sakata matrix

well established now





Usual parametrization

$$U_{\alpha i} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

with $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

rotation around x-axis with angle θ_{23}: atmospheric, accelerators

rotation around y-axis with angle θ_{13}: **reactors,** accelerators, CP violation

rotation around z-axis with angle θ_{12}: solar, **reactors**

- δ_{CP} for neutrinos
- $-\delta_{CP}$ for anti-neutrinos

Transition Probability in vacuum

$$P_{\nu_\alpha \to \nu_\beta} = \left| \delta_{\alpha\beta} + \sum_{k=2}^{3} U_{\beta k} U^*_{\alpha k} \left(e^{-i\frac{\Delta m^2_{k1} L}{2E}} - 1 \right) \right|^2$$

with: $\Delta m^2_{kj} \equiv m_k^2 - m_j^2$

(the time has been replaced by the distance)

the transition probabilities do not depend on the particle masses but on the squared mass differences

Finally, the transition probabilities depend on the mixing matrix elements, the 2 squared mass differences and on the parameter ***L/E***.

No transitions if:

$m_\nu = 0$ or

$\Delta m = 0$ or

$\Delta m^2_{k1} L / E \ll 1$

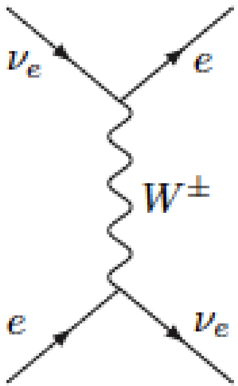
How neutrinos propagate through matter?

(Mikheyev-Smirnov-Wolfenstein effect)

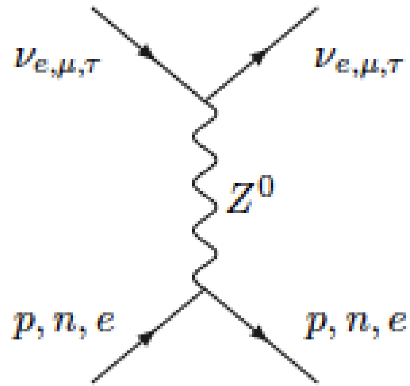
$$\left|\nu_j(t)\right\rangle = e^{-iHt/\hbar}\left|\nu_j(0)\right\rangle$$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H_f\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

only for electron neutrinos



CC



NC

in "ordinary" matter

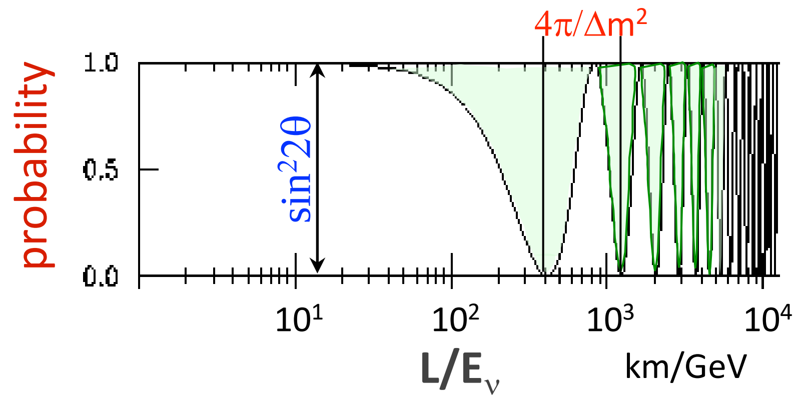
$$H_f = UHU^\dagger = \frac{1}{2E}U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger \rightarrow \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + \begin{pmatrix}a & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right]$$

with: $a = 2EV_{CC} = 2\sqrt{2}EG_F N_e \approx 7.56\times 10^{-5}\,eV^2\left(\frac{\rho}{g/cm^3}\right)\left(\frac{E}{GeV}\right)$ (ρ~3 g/cm^3 for earth crust)

Appearance/disappearance experiments

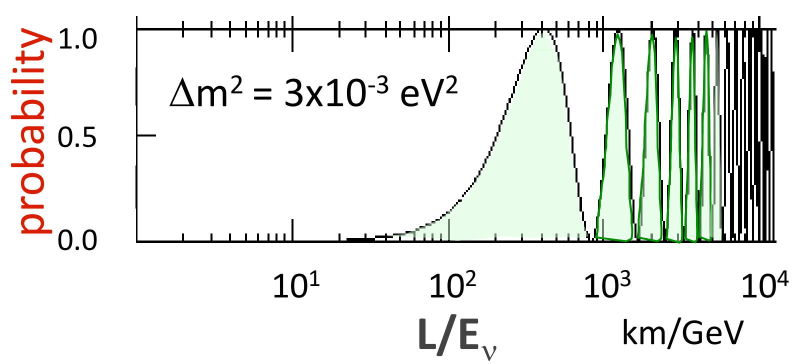
In **disappearance experiments** we count how many initial neutrinos ν_α survive after traveling over a distance *L (case of 2 flavours)*:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \, \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

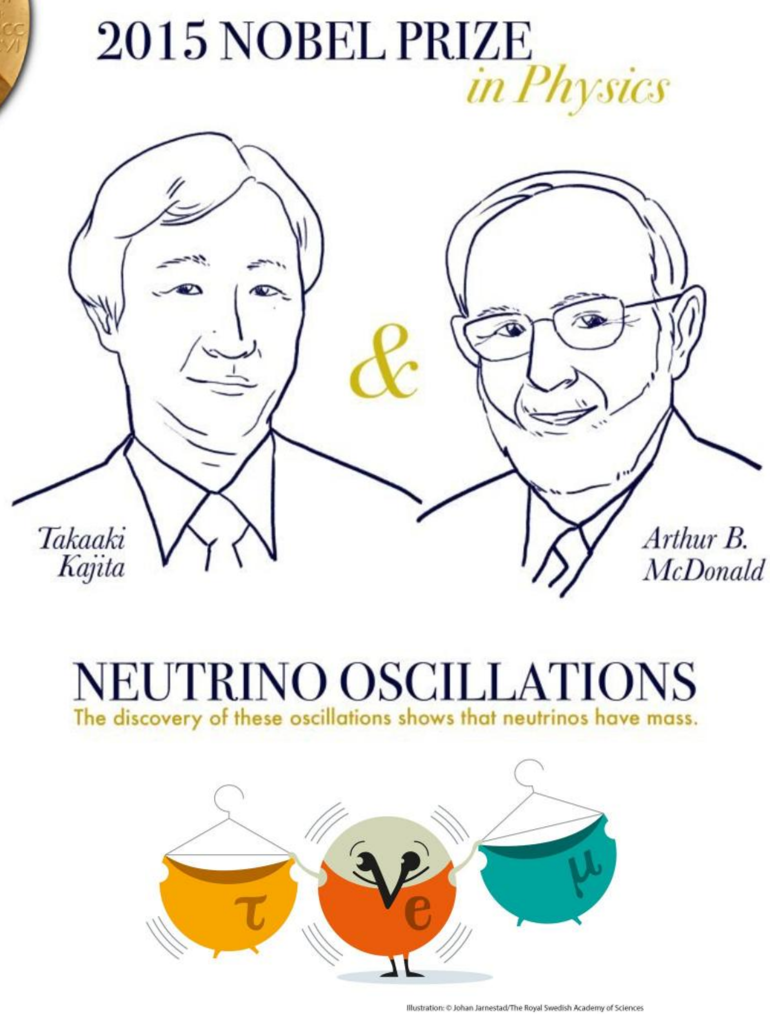


In **appearance experiments** we look for neutrinos ν_β in a ν_α neutrino beam:

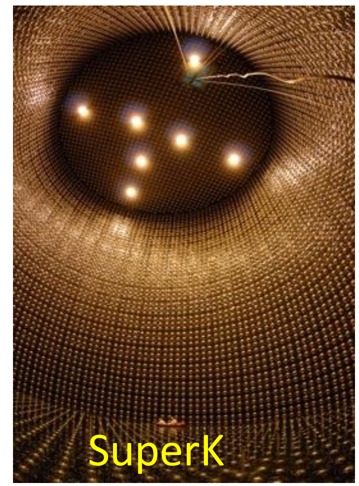
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \, \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$



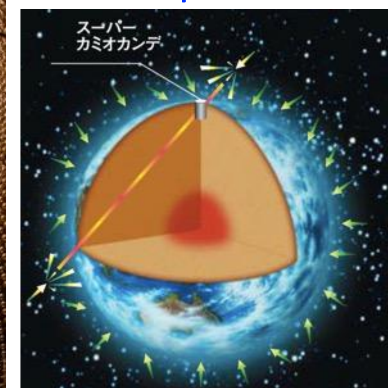
Confirmation of neutrino oscillations

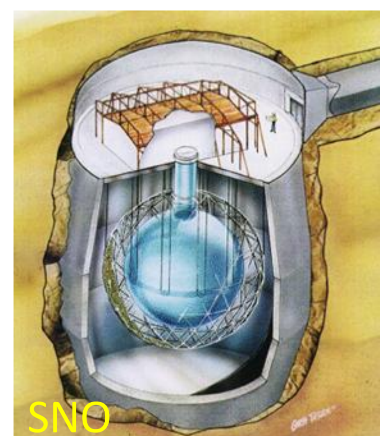


Using SuperK and SNO experiments

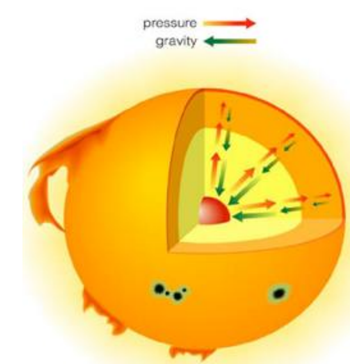


atmospheric ν





solar ν



Present measurements

$\Delta m^2_{32} = |2.52| \pm 0.04 \times 10^{-3}\ \text{eV}^2$

$\Delta m^2_{21} = 7.50^{+0.19}_{-0.17} \times 10^{-5}\ \text{eV}^2$

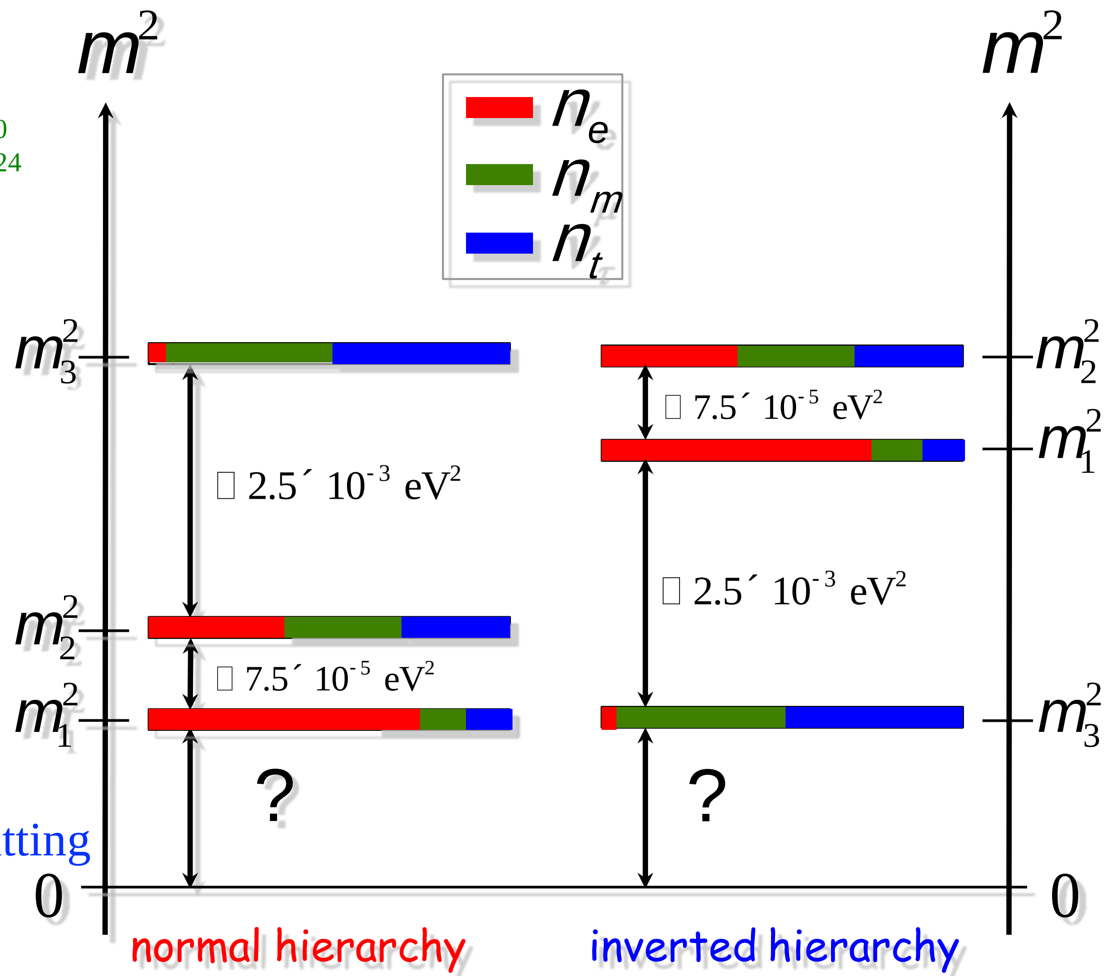
$\sin^2\theta_{23} = 0.441^{0.027}_{-0.021}\ (\approx 41.6°)$ or $0.587^{0.020}_{-0.024}$

$\sin^2\theta_{12} = 0.306^{+0.012}_{-0.012}\ (\approx 33.6°)$

$\sin^2\theta_{13} \leq 0.046\ (<12.4°)$

$\theta_{13} < 12.4°$, 90% CL
up to 2011

~δ_{CP} (almost) unknown



We can then write:

$\Delta m_{13} \approx \Delta m_{23} \equiv \Delta m$ "large" mass splitting

$\Delta m_{12} \equiv \delta m$ "small" mass splitting

$\Delta m \gg \delta m$

Matter/antimatter asymmetry in the Universe

At the very beginning of the Universe:

matter	antimatter
10,000,000,001	10,000,000,000

Matter/antimatter asymmetry in the Universe

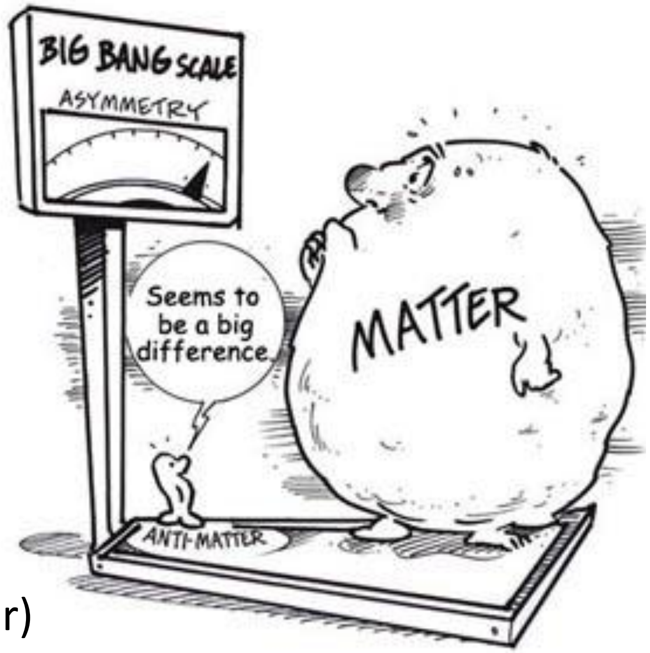
δ_{CP} and Matter-antimatter asymmetry magnitude

$$A^{CP}_{\alpha\beta} = P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$$
$$= J^{PMNS}_{CP} \cdot \sin\delta_{CP}$$

with: J^{PMNS}_{CP} ~3×10^{-3} (Jarlskog invariant)

(for hadrons: J^{CKM}_{CP} ~3×10^{-5}, not enough even if δ_{CP}~70°)

(from the already observed CP violation in the hadronic sector)



Theoretical models predict that if |sinδ_{CP}|≳0.7 (45°<δ_{CP}<135° or 225°<δ_{CP}<315°), this could be enough to explain the observed asymmetry.

(Nucl.Phys.B774:1-52,2007, arXiv:hep-ph/0611338)

Sakharov conditions

In order to generate the needed baryon asymmetry the following conditions must be satisfied:

- **Baryon number violation**
  - If not, no baryon number can be generated (o.k. in SM considering Sphalerons @ ~140 GeV)
- **C and CP violation**
  - Γ(A→B+C)=Γ(A-bar→B-bar+C-bar)
  - CP violation already observed in the quark sector, but not enough
- **Departure from thermal equilibrium**
  - production/destruction rates of baryons are equal if thermal equilibrium Γ(A→B+C)=Γ(B+C→A)
  - expansion of the universe

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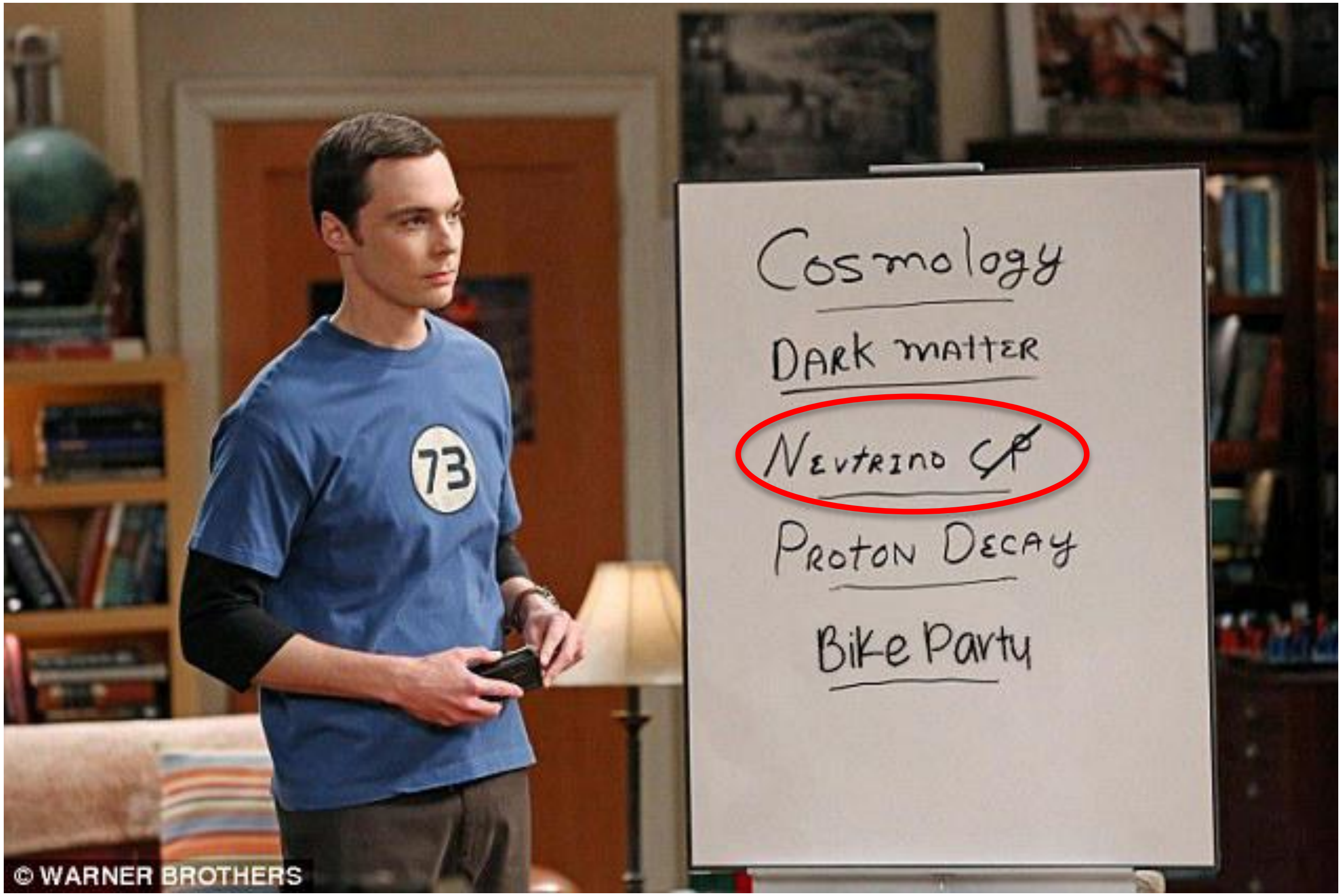
Other sources of CP Violation



Oscillation probability
(neutrino beams)

$$P_{\nu_\mu\to\nu_e(\overline{\nu_\mu}\to\overline{\nu_e})} \simeq 4s_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2}\sin^2\frac{(1-r_A)\Delta L}{2}$$ "atmospheric"

$$+8J_r\frac{r_\Delta}{r_A(1-r_A)}\cos\left(\delta_{CP}-\frac{\Delta L}{2}\right)\sin\frac{r_A\Delta L}{2}\sin\frac{(1-r_A)\Delta L}{2}$$ "interference"

$$+4c_{23}^2 c_{12}^2 s_{12}^2\left(\frac{r_\Delta}{r_A}\right)^2\sin^2\frac{r_A\Delta L}{2}$$ "solar"

$$J_r \equiv c_{12}s_{12}c_{23}s_{23}s_{13},\ \Delta\equiv\frac{\Delta m_{31}^2}{2E_\nu},\ r_A\equiv\frac{a}{\Delta m_{31}^2},\ r_\Delta\equiv\frac{\Delta m_{21}^2}{\Delta m_{31}^2},\ a=2\sqrt{2}G_F N_e E_\nu$$

matter effect

- **for antimatter: $\delta_{CP}\to-\delta_{CP}$ and $a\to-a$**
- fake matter/antimatter asymetry due to matter effect
- for NH: $\Delta m_{31}^2\to|\Delta m_{31}^2|$
- for IH: $\Delta m_{31}^2\to-|\Delta m_{31}^2|$

- δ_{CP} dependence,
- sizable matter effect for long baselines

if $\theta_{13}\sim 0$ → oscillation probability not sensitive to δ_{CP} → impossible to observe CP violation in the leptonic sector.

CP Violating Observables

$$\mathcal{A} = \frac{P_{\nu_\mu \to \nu_e} - P_{\bar{\nu}_\mu \to \bar{\nu}_e}}{P_{\nu_\mu \to \nu_e} + P_{\bar{\nu}_\mu \to \bar{\nu}_e}}$$

$\neq 0 \Rightarrow$ CP Violation
be careful, matter effects also create asymmetry

Matter-antimatter asymmetry

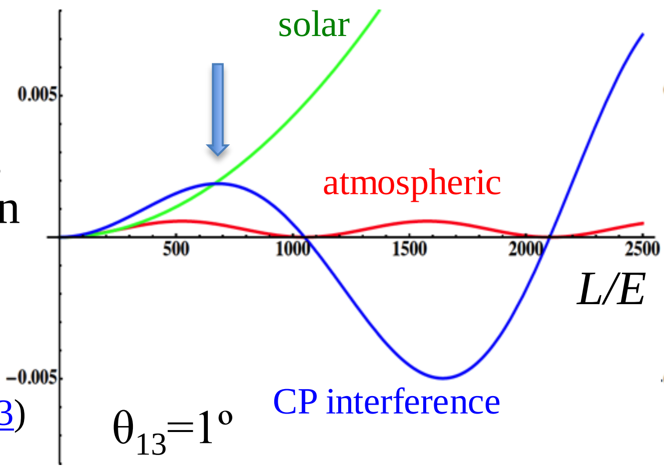
Use all this ESS linac power to go to the second oscillation maximum

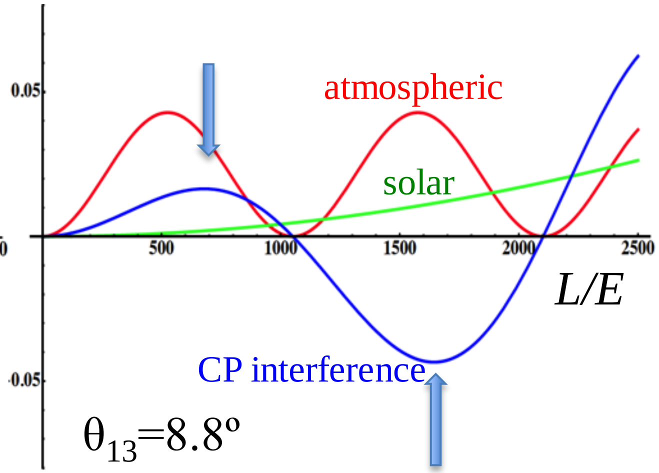
but why?

Neutrino Oscillations with "large" θ_{13}

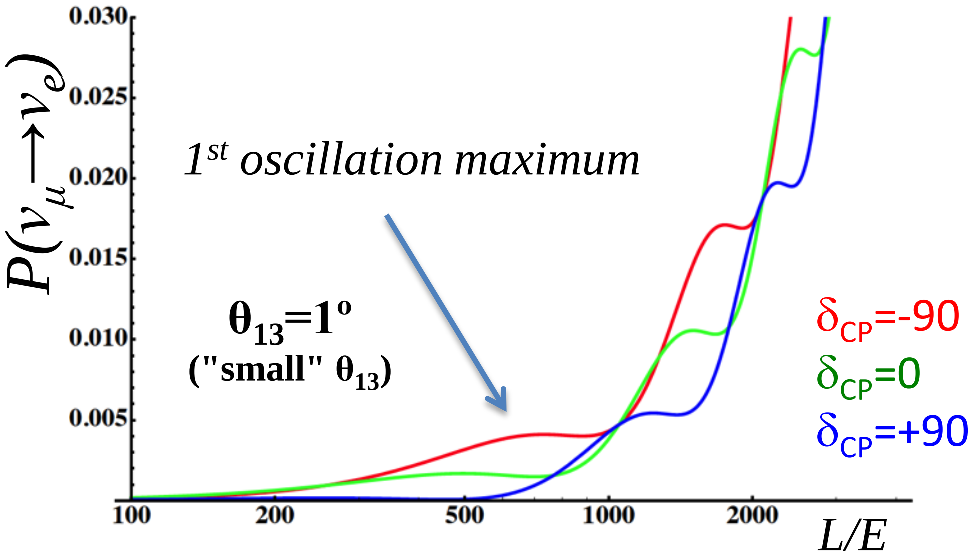
for small θ_{13} 1st oscillation maximum is better

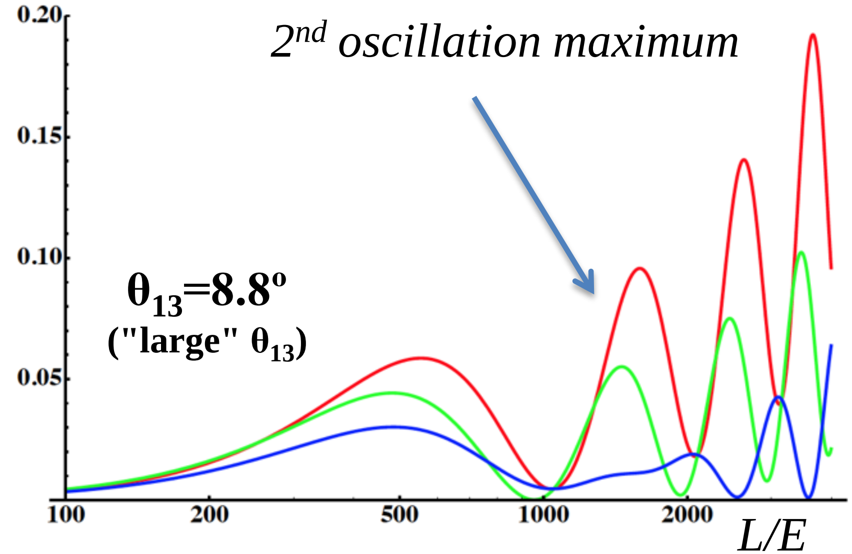
(arXiv:1110.4583)





for "large" θ_{13} 1st oscillation maximum is dominated by atmospheric term





- 1st oscillation max.: $A=0.3\sin\delta_{CP}$
- 2nd oscillation max.: $A=0.75\sin\delta_{CP}$

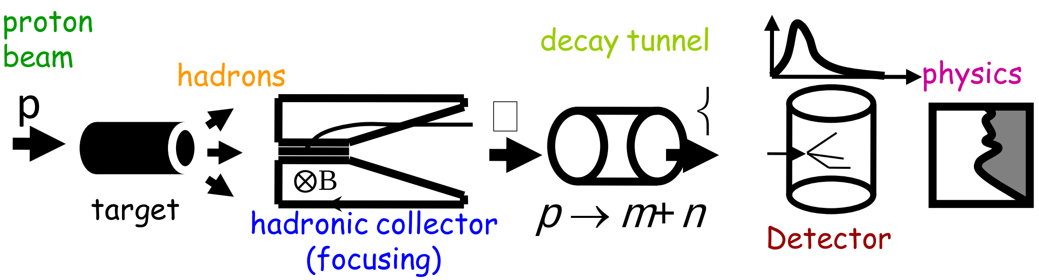
more sensitivity at 2nd oscillation max.

(see arXiv:1310.5992 and arXiv:0710.0554)

Having access to a powerful proton beam…

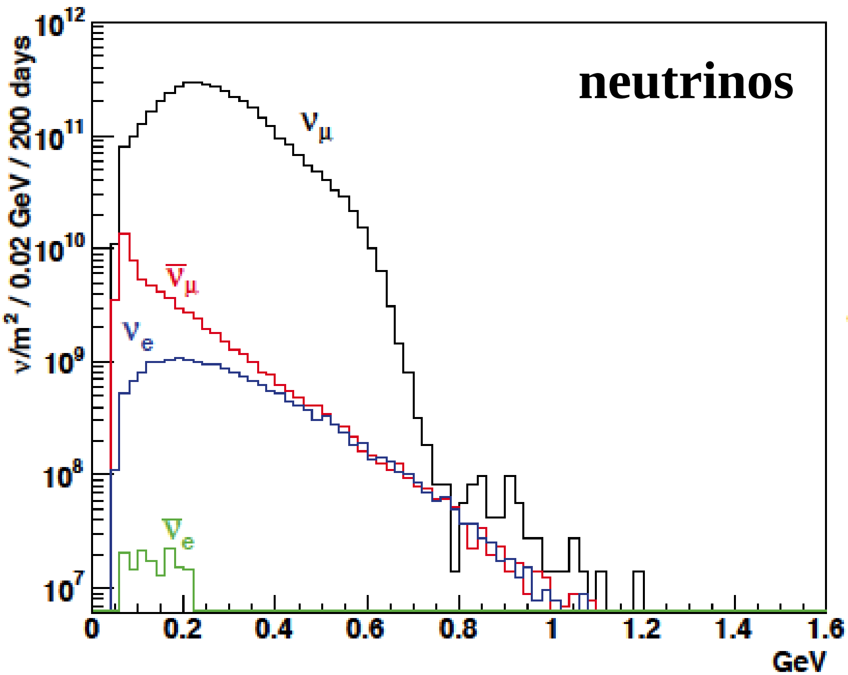
What can we do with:

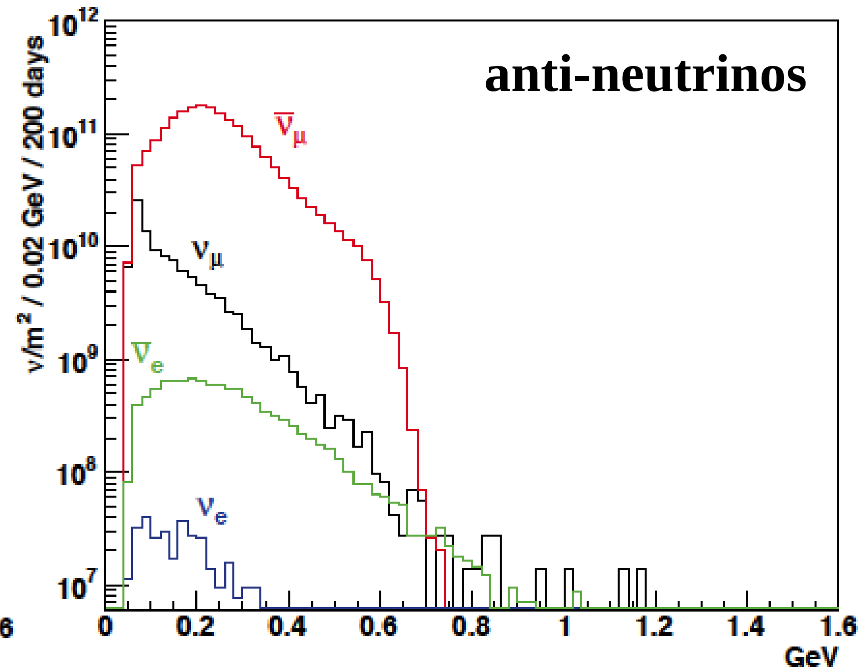
- 5 MW power
- 2 GeV energy
- 14 Hz repetition rate
- 10^{15} protons/pulse
- $>2.7 \times 10^{23}$ protons/year



conventional neutrino (super) beam

ESSνSB ν energy distribution (without optimisation)





- almost pure ν_μ beam
- small ν_e contamination which could be used to measure ν_e cross-sections in a near detector

	positive		negative	
	N_ν $(\times 10^{10})/\text{m}^2$	%	N_ν $(\times 10^{10})/\text{m}^2$	%
ν_μ	396	97.9	11	1.6
$\bar{\nu}_\mu$	6.6	1.6	206	94.5
ν_e	1.9	0.5	0.04	0.01
$\bar{\nu}_e$	0.02	0.005	1.1	0.5

at 100 km from the target and per year (in absence of oscillations)

(Nucl. Phys. B 885 (2014) 127)

Oscillation to be studied

$$\nu_\mu \longrightarrow \nu_e$$

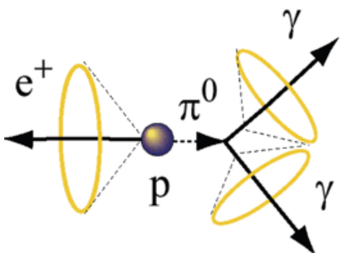
Can we go to the 2nd oscillation maximum using our proton beam?

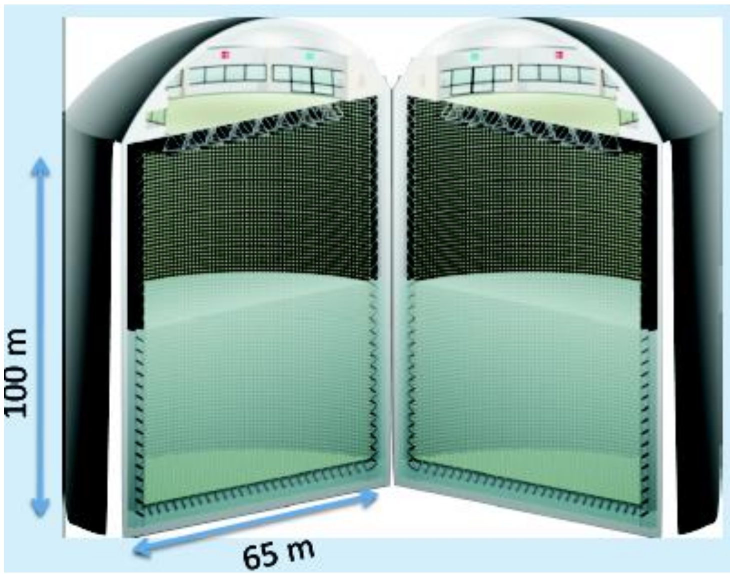
Yes, if we place our far detector at around 500 km from the neutrino source.

MEMPHYS like Cherenkov detector
(MEgaton Mass PHYSics studied by LAGUNA)

(arXiv: hep-ex/0607026)

- Neutrino Oscillations
- Proton decay
- Astroparticles
- Understand the gravitational collapsing: galactic SN
- Supernovae "relics"
- Solar Neutrinos
- Atmospheric Neutrinos

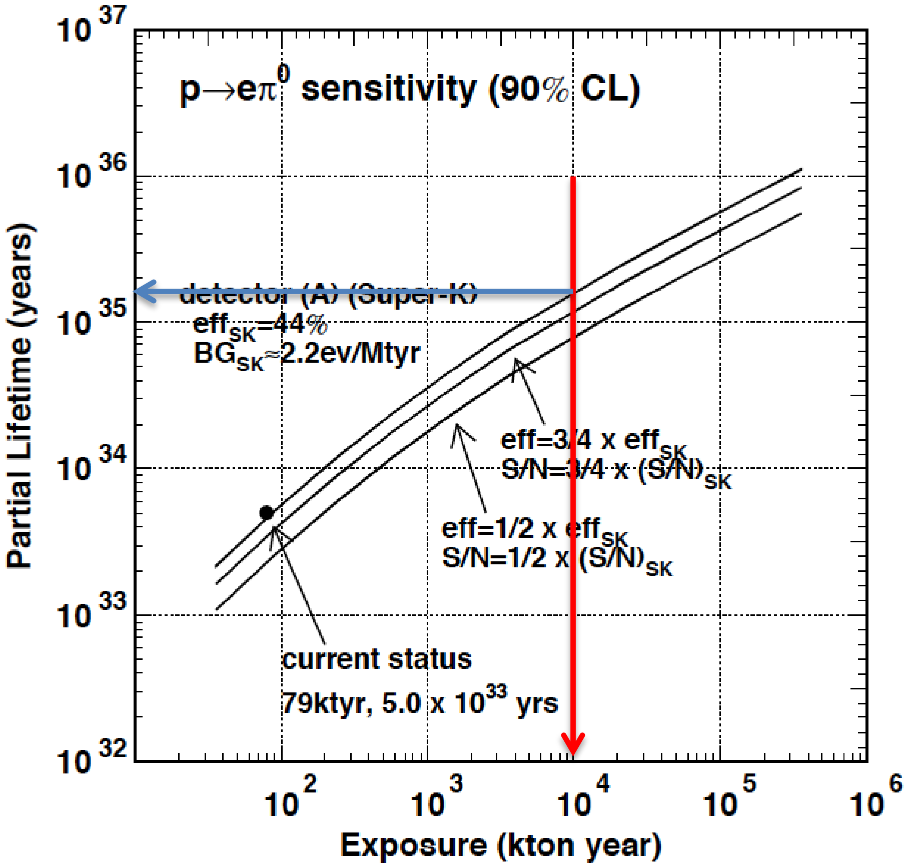


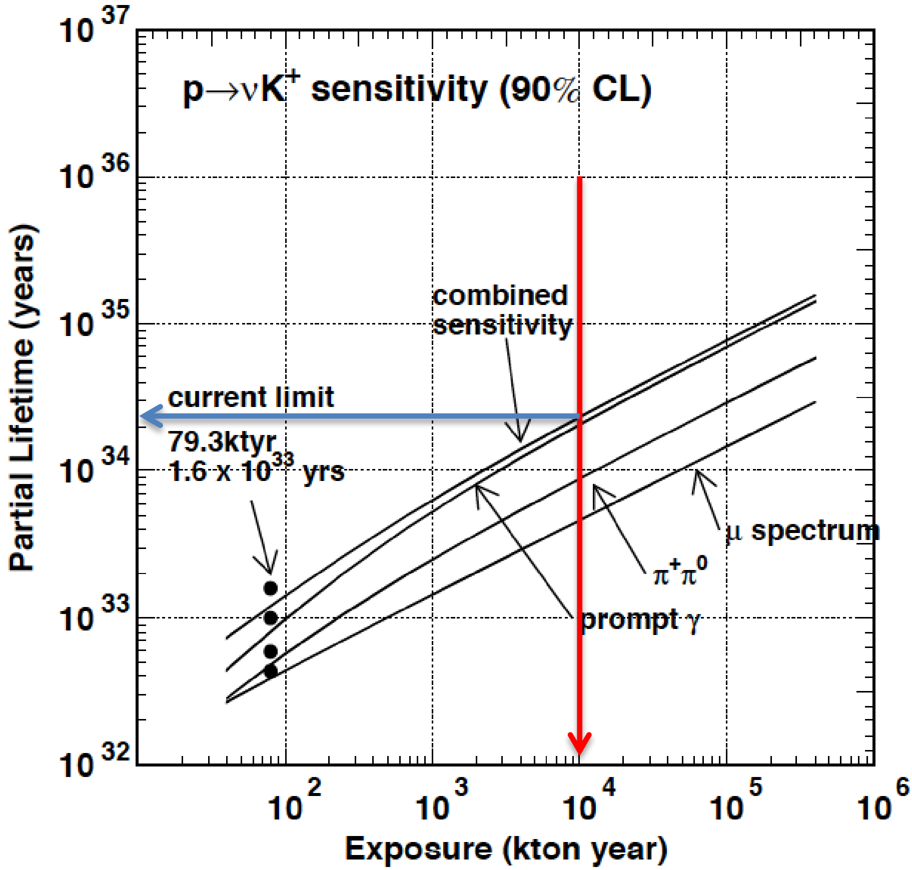


- 500 kt fiducial volume (~20xSuperK)
- Readout: ~240k 8" PMTs
- 30% optical coverage

New 20" PMTs with higher QE and cheaper (see JUNO), the detection efficiency will improve the detector performance keeping the price constant, not yet taken into account.

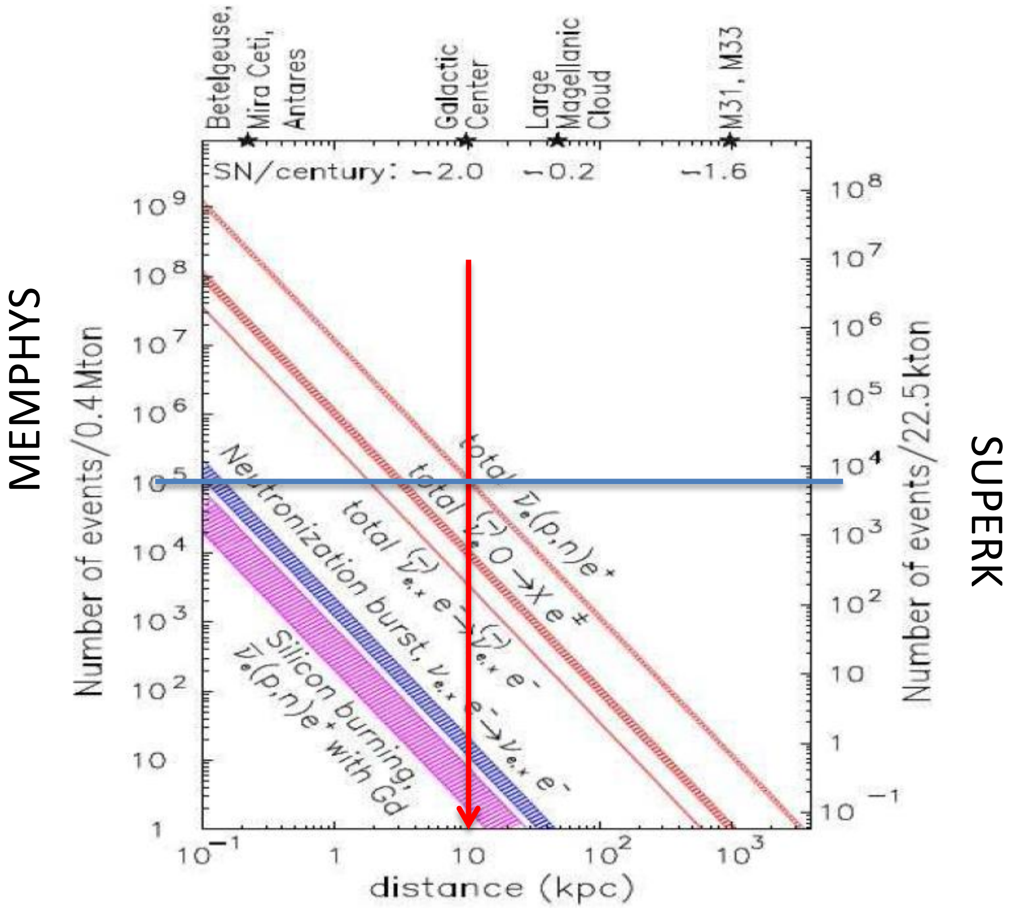
The MEMPHYS Detector (Proton decay)



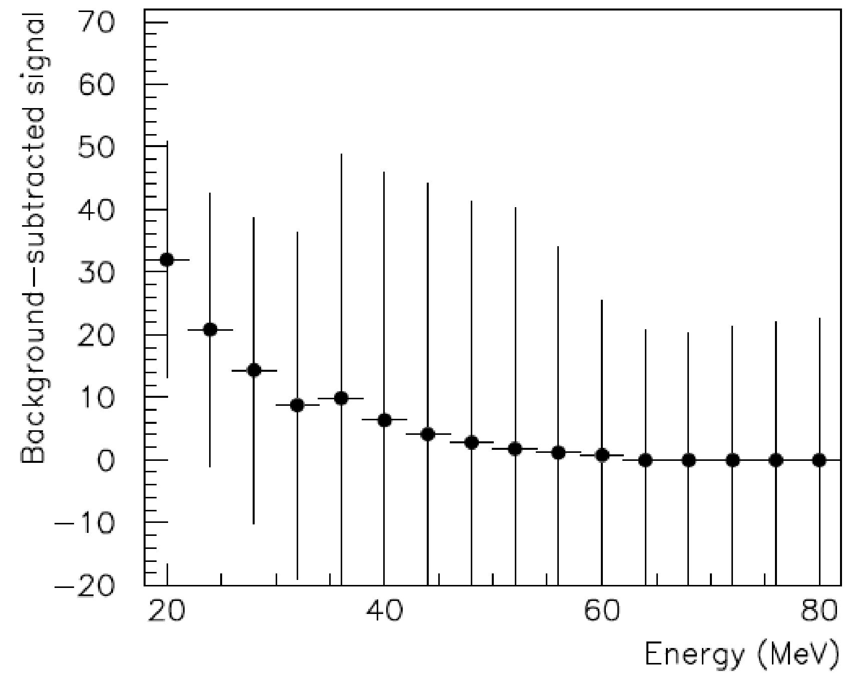


(arXiv: hep-ex/0607026)

The MEMPHYS Detector
(Supernova explosion)

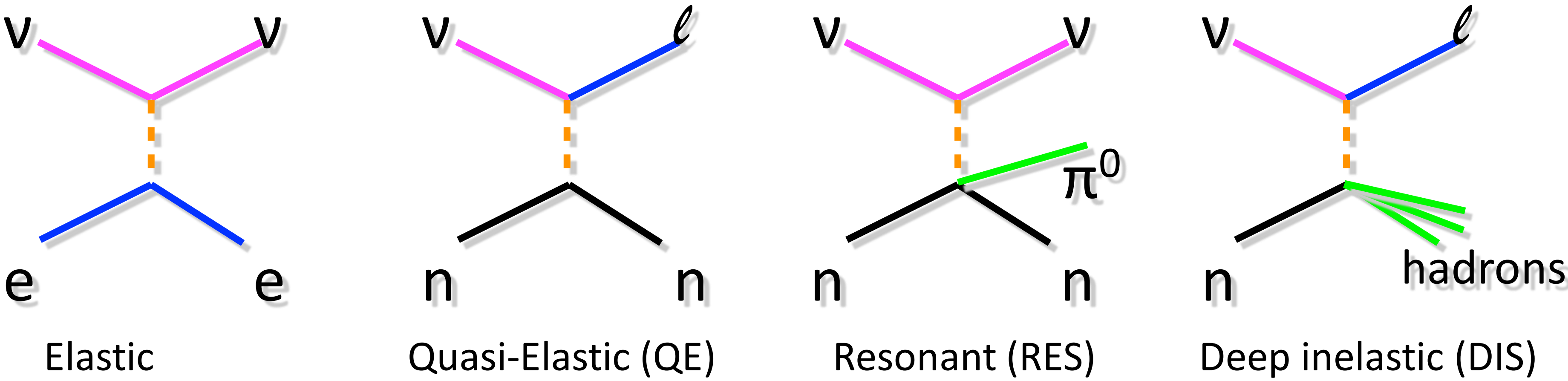


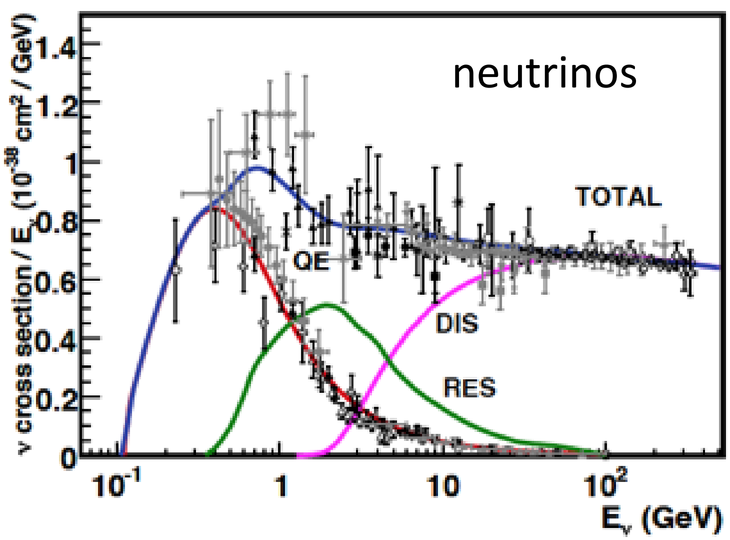
For 10 kpc: ~10^5 events

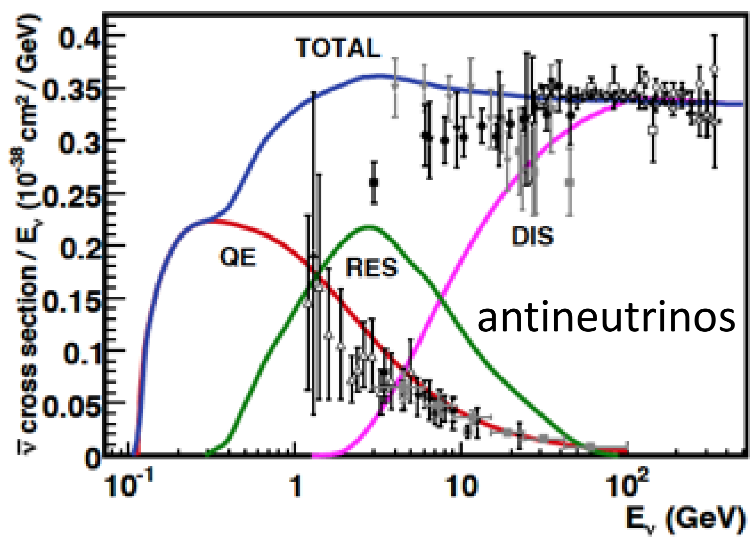


Diffuse Supernova Neutrinos
(10 years, 440 kt)

Neutrino Interactions





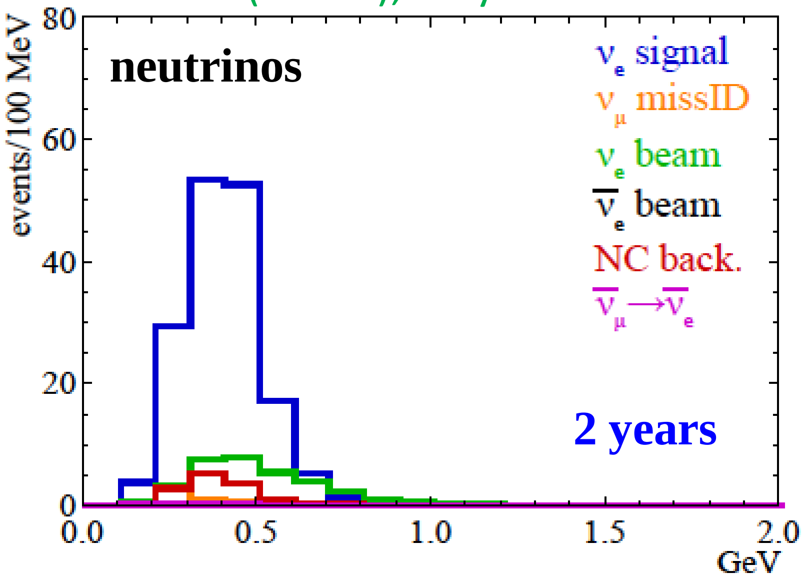


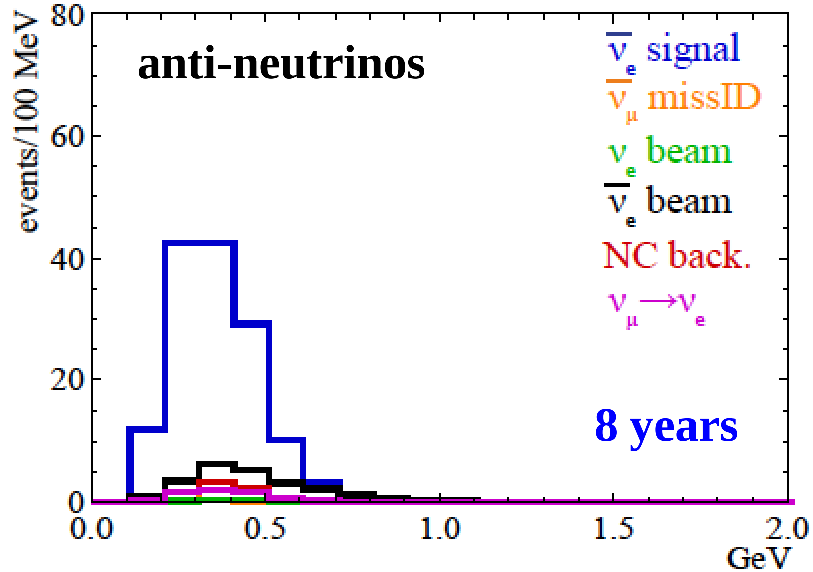
According to neutrinos to be detected their interaction cross-section has to be taken into account.

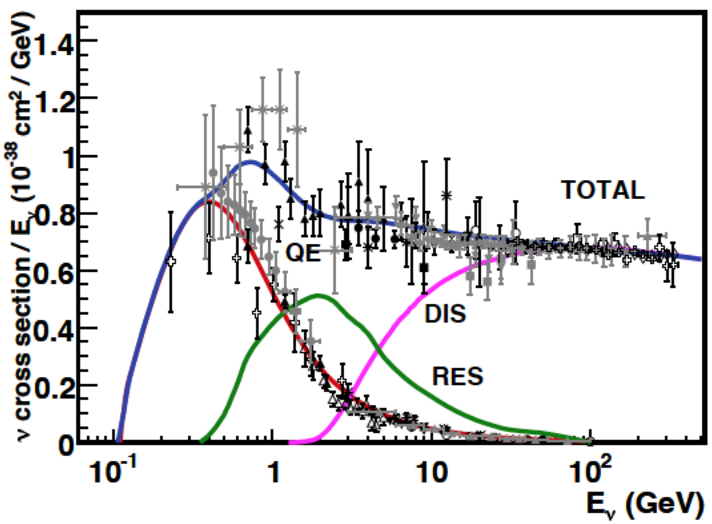
Neutrinos in the far detector

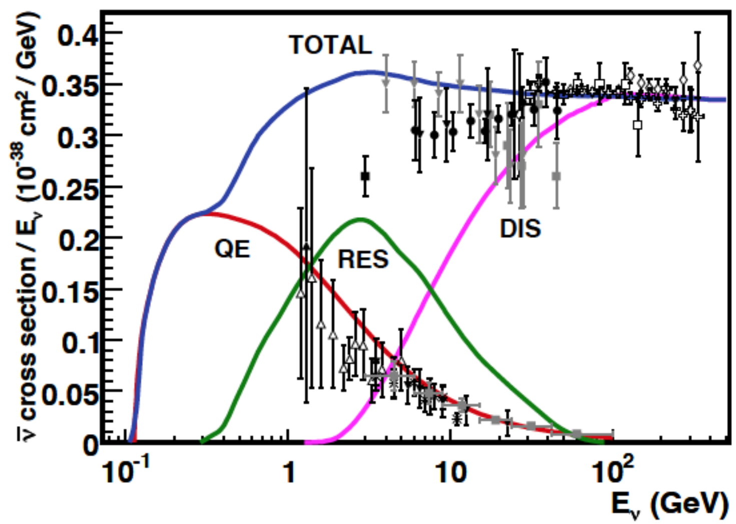
540 km (2 GeV), 10 years

δ_{CP}=0



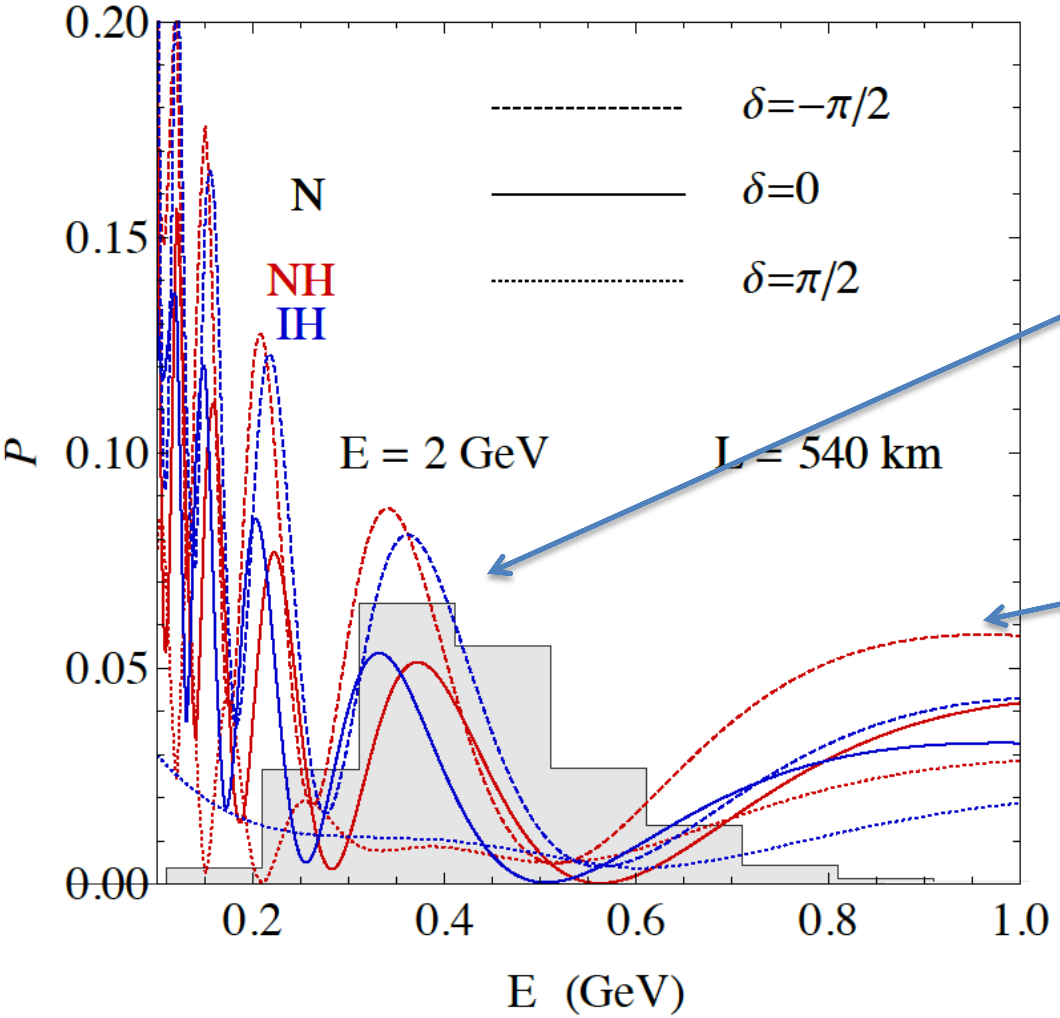






below ν_τ production, almost only QE events, not suffering too much by π^0 background

2nd Oscillation max. coverage



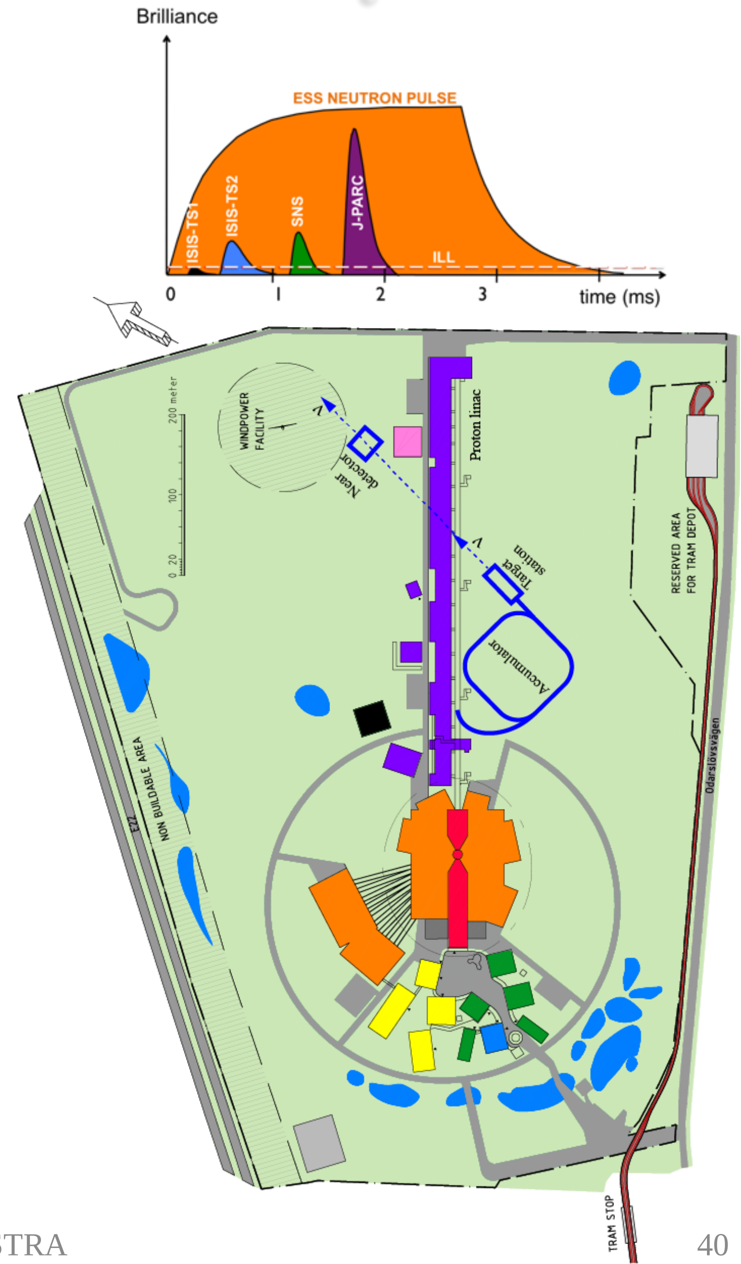
2nd oscillation max. well covered by the ESS neutrino spectrum

1st oscillation max.

ESS Linac modifications to produce a neutrino Super Beam

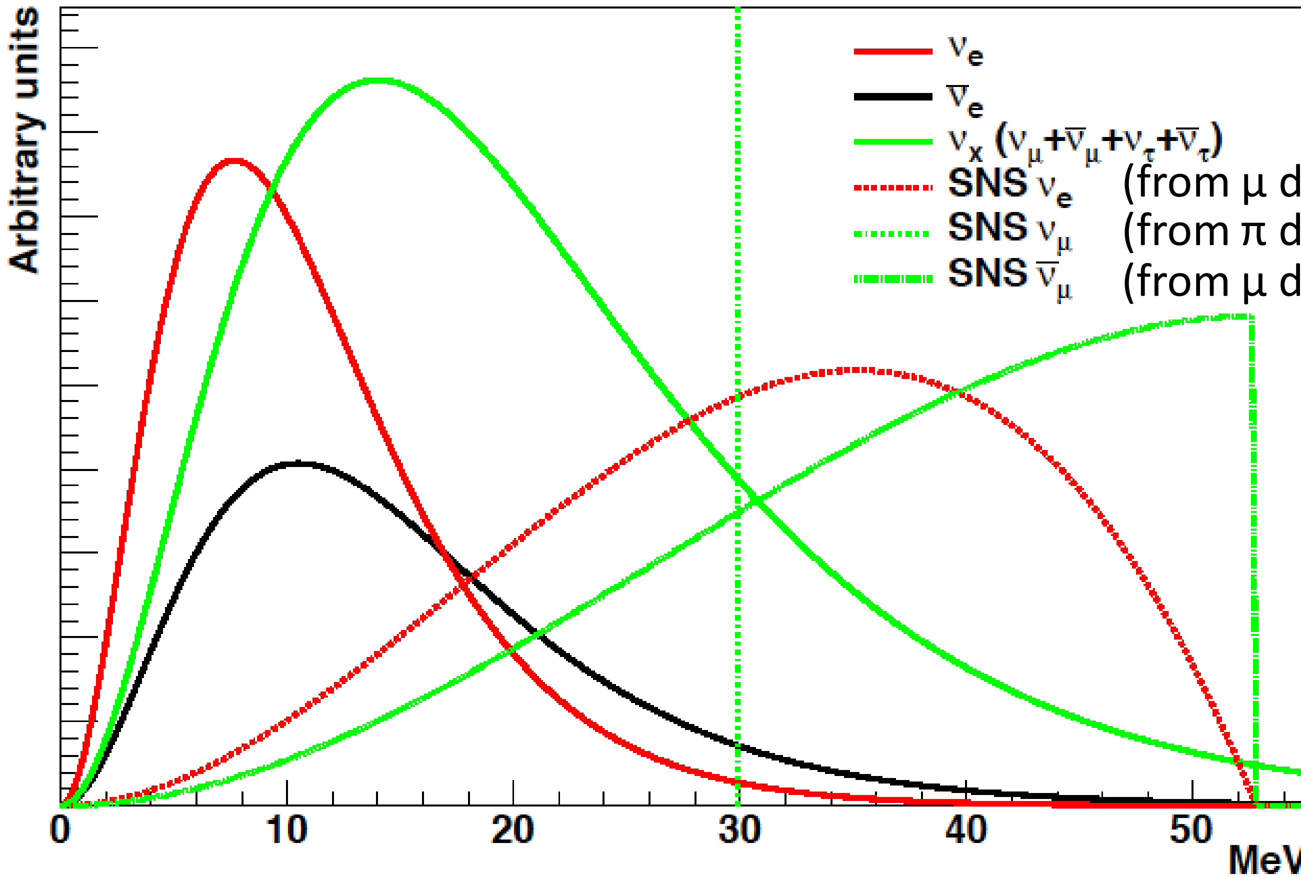
How to add a neutrino facility?

- The neutron program must not be affected and if possible synergetic modifications.
- Linac modifications: double the rate (14 Hz → 28 Hz), from 4% duty cycle to 8%.
- Accumulator (C~400 m) needed to compress to few μs the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA, power consumption, Joule effect)
  - H^- source (instead of protons),
  - space charge problems to be solved.
- ~300 MeV neutrinos.
- Target station (studied in EUROν).
- Underground detector (studied in LAGUNA).
- Short pulses (~μs) will also allow DAR experiments (as those proposed for SNS) using the neutron target.



DAR experiments (ESS/SNS)

using the massive neutron target
(stopping all π and μ)

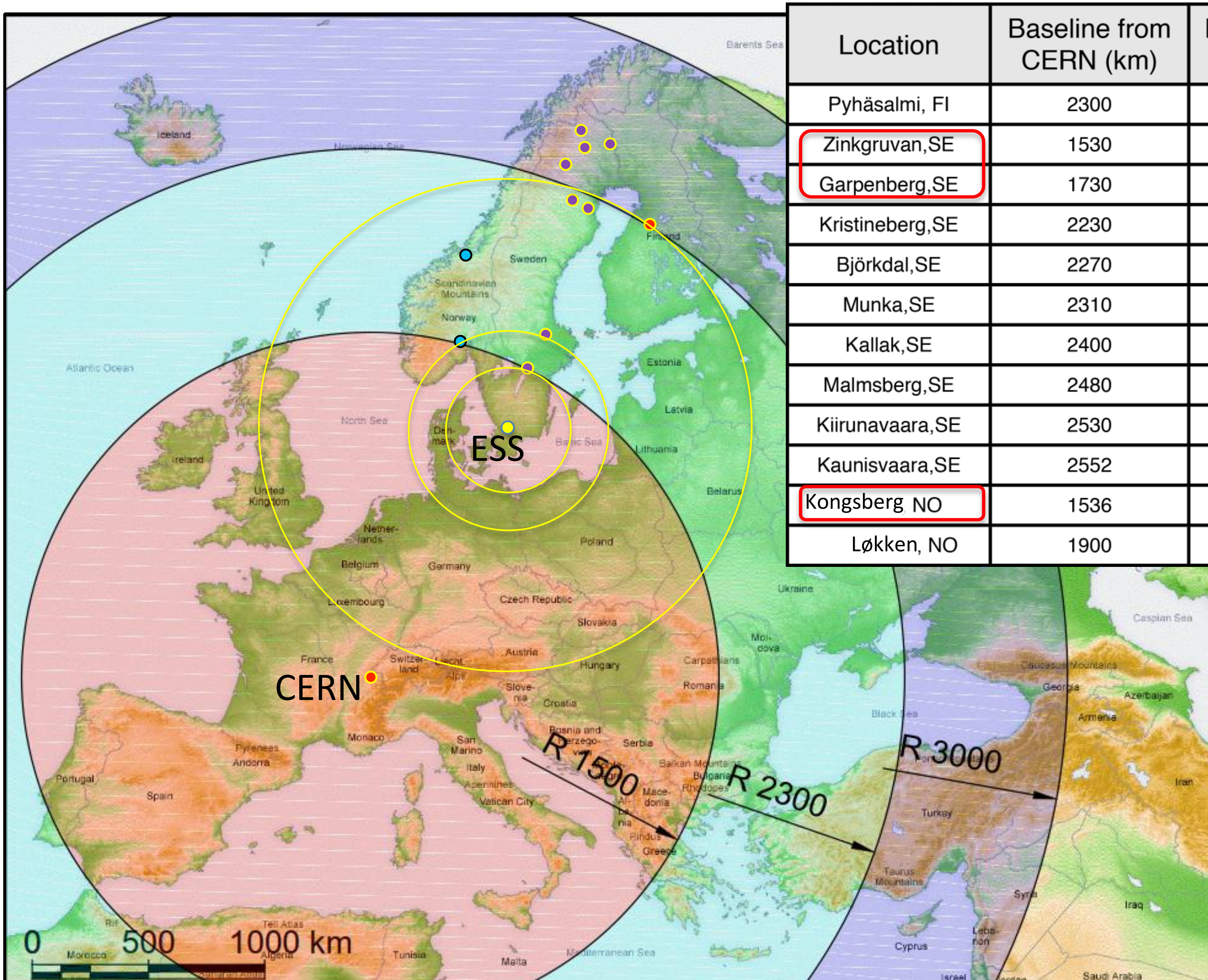


(from SN)
(from μ decays at rest)
(from π decays at rest)
(from μ decays at rest)

Typical expected supernova neutrino spectrum for different flavours (solid lines) and SNS/ESS neutrino spectrum (dashed and dotted lines)

Possible locations for far detector

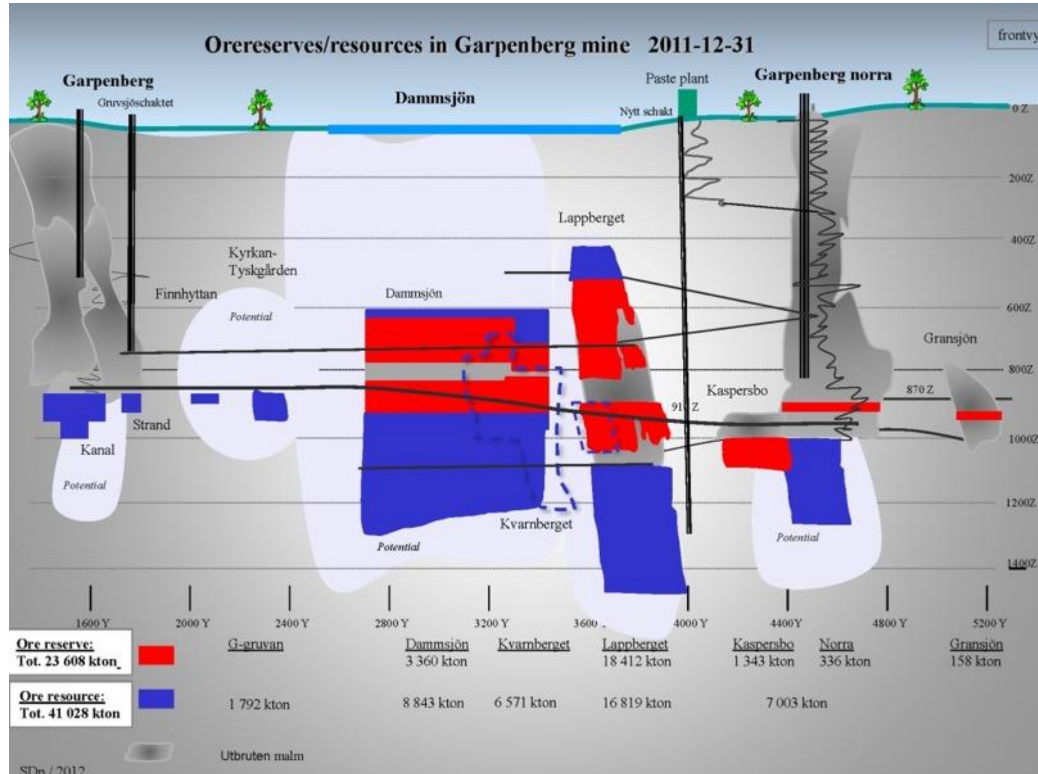
Location	Baseline from CERN (km)	Baseline from Protvino (km)	Baseline from ESS (km)
Pyhäsalmi, FI	2300	1160	1140
Zinkgruvan,SE	1530	1420	360
Garpenberg,SE	1730	1300	540
Kristineberg,SE	2230	1530	1080
Björkdal,SE	2270	1450	1100
Munka,SE	2310	1620	1160
Kallak,SE	2400	1700	1260
Malmsberg,SE	2480	1620	1320
Kiirunavaara,SE	2530	1700	1380
Kaunisvaara,SE	2552	1580	1390
Kongsberg NO	1536	1740	500
Løkken, NO	1900	1800	840



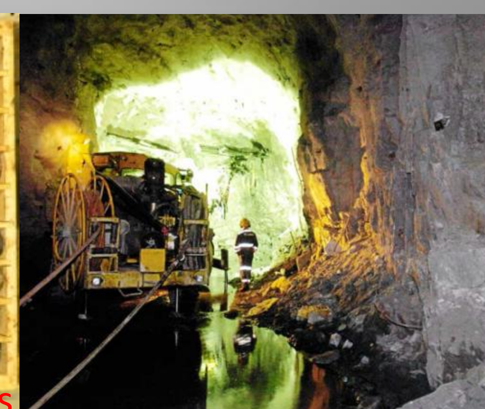
LAGUNA sites

The Garpenberg mine

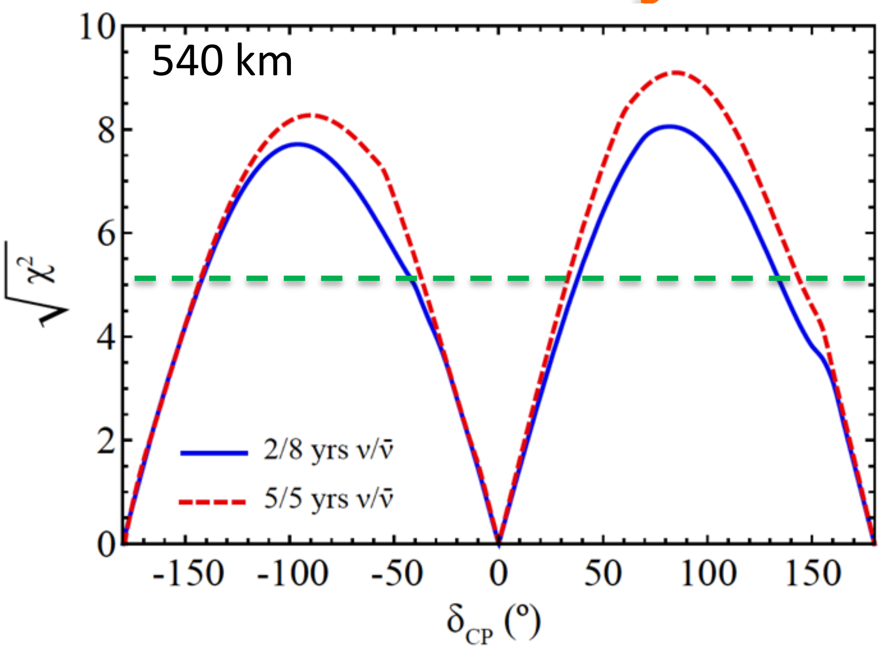
- Distance from ESS Lund **540 km**
- Depth **1232 m**
- Truck **access tunnel**
- **Hoist shaft** free to use by ESSnuSB
- Rock-engineering prospection and studies in the Garpenberg-mine granite-zones

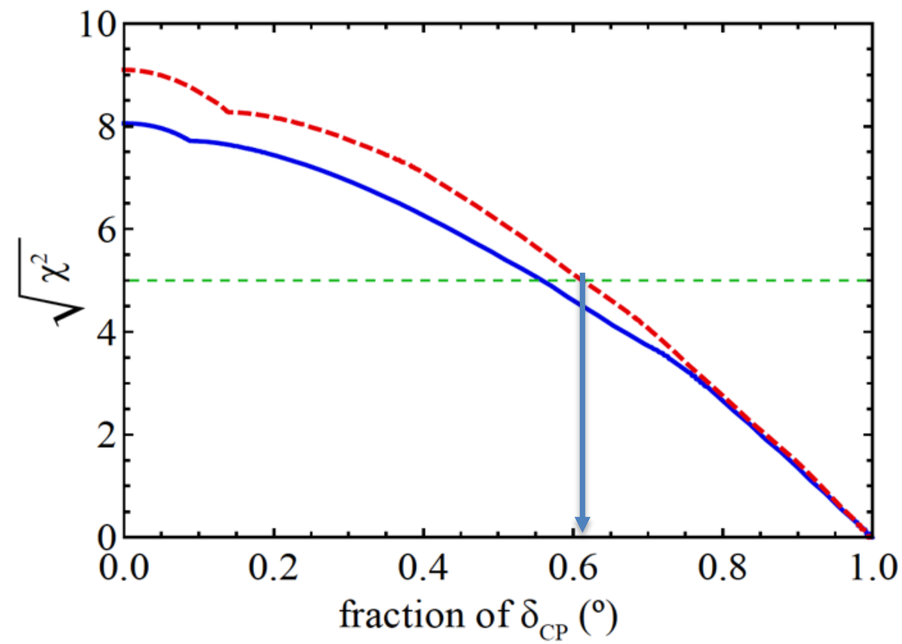


Granite drill cores

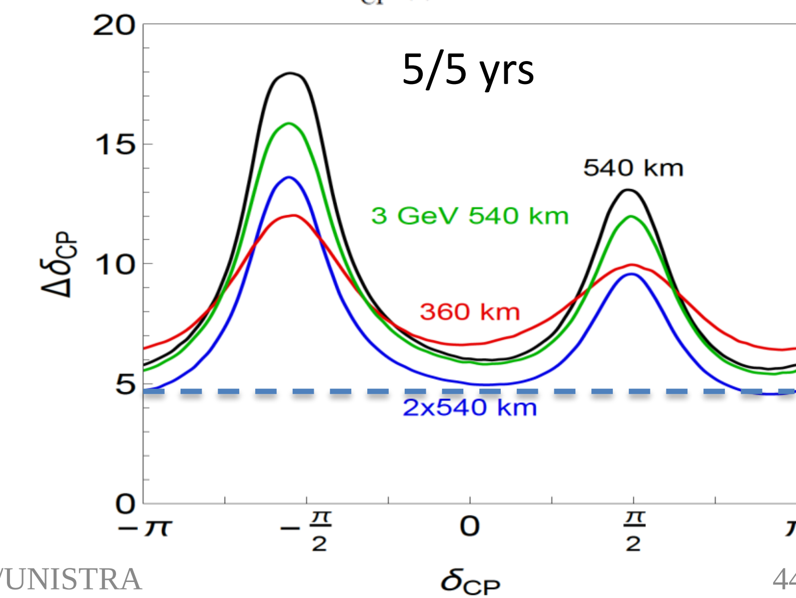


Physics Performance



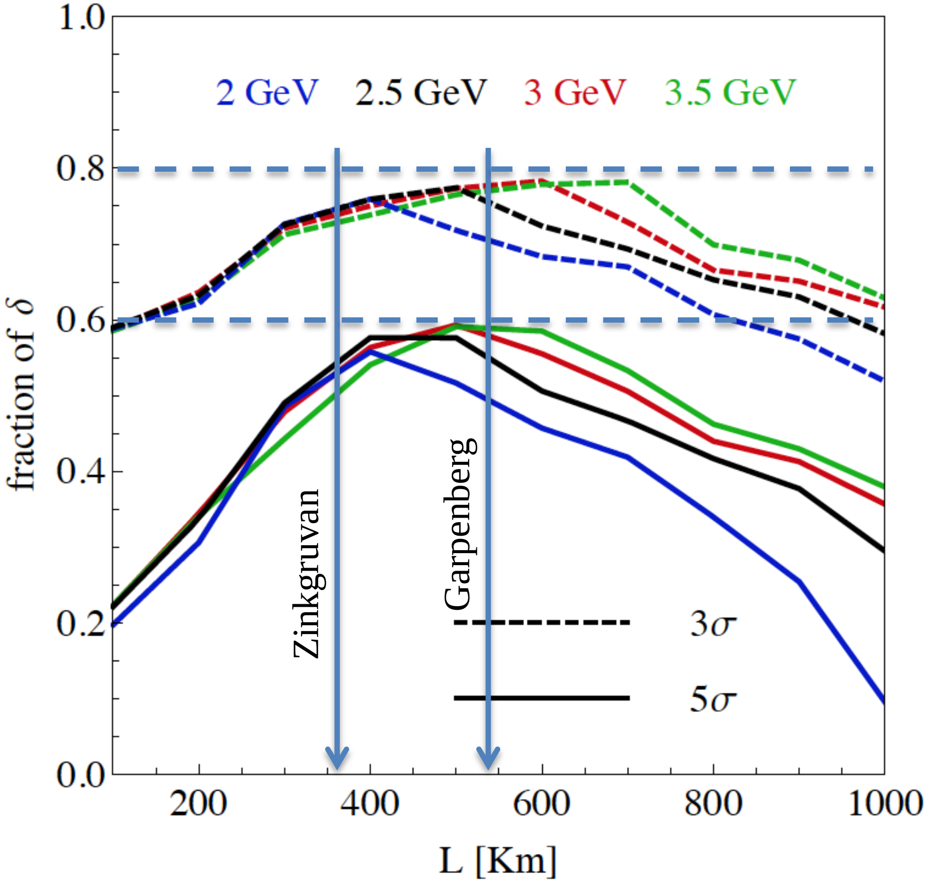


- little dependence on mass hierarchy,
- δ_{CP} coverage at 5 σ C.L. up to **60%**,
- δ_{CP} accuracy down to **6°** at 0° and 180° (absence of CPV for these two values),
- not yet optimized facility,
- **5/10%** systematic errors on signal/background.



Which baseline?

CPV (*Nucl. Phys. B 885 (2014) 127*)



Candidate active mines

- ~60% δ_{CP} coverage at 5 σ C.L.
- >75% δ_{CP} coverage at 3 σ C.L.
- **systematic errors: 5%/10% (signal/backg.)**

Beyond DUNE, JUNO, HyperK: ESSνSB, P2O and Neutrino factory

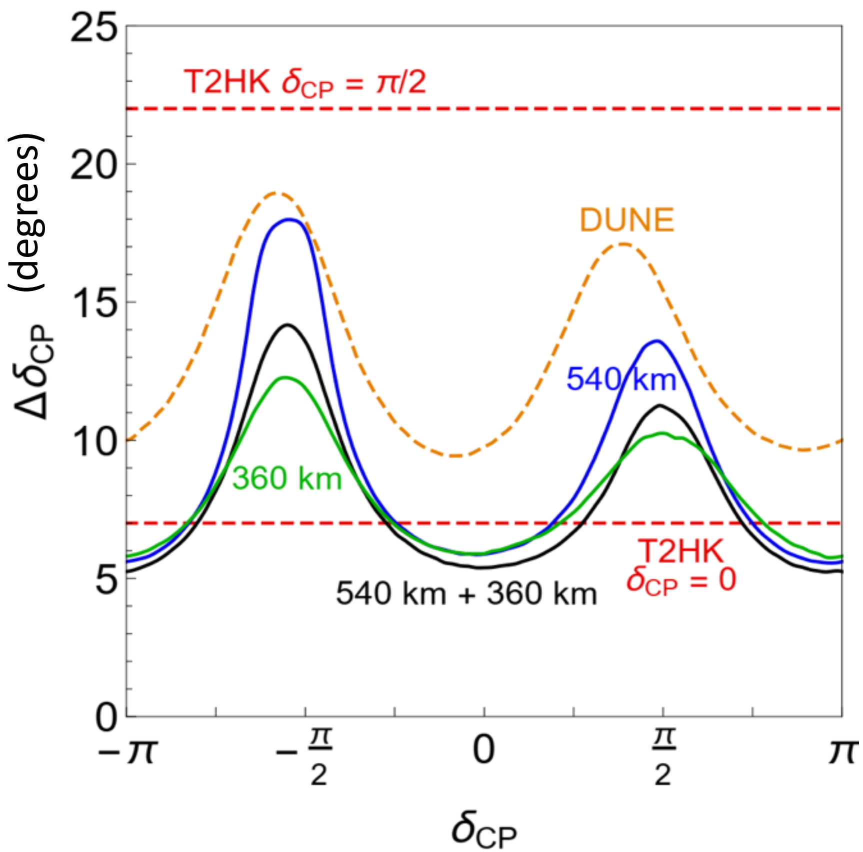
European Neutrino "Town" meeting and ESPP 2019 discussion, CERN, 24.10.2018

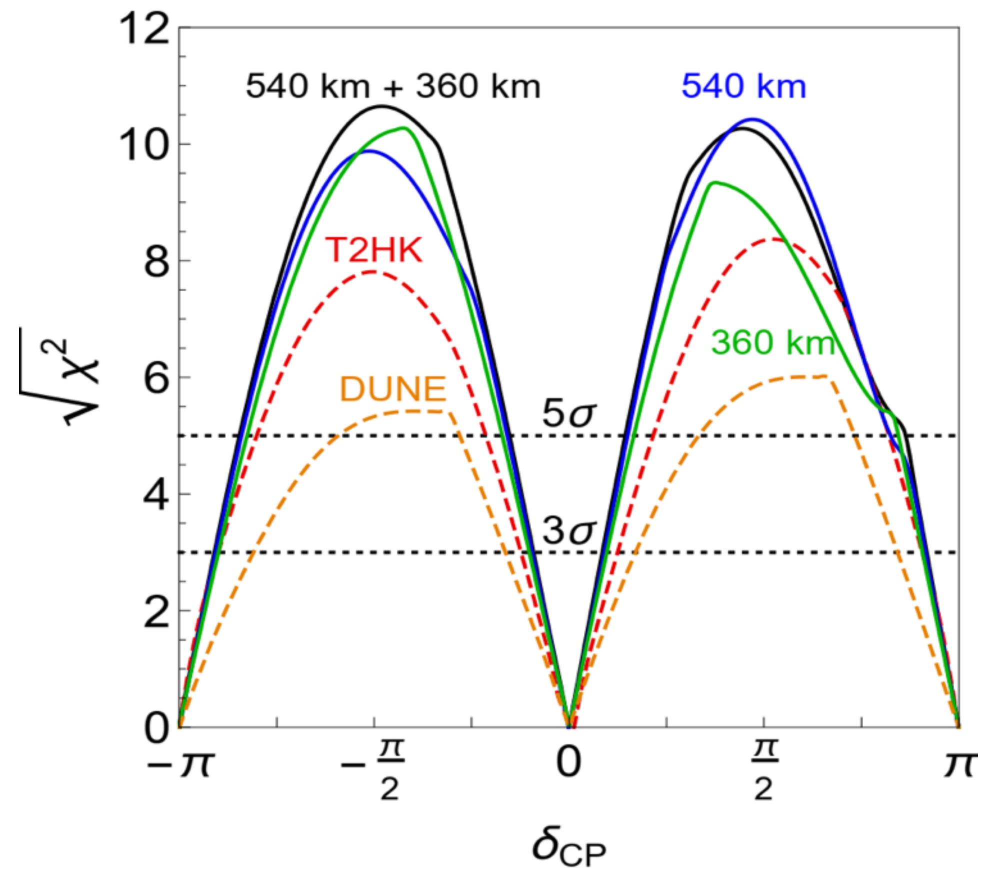
Roumen Tsenov
Department of Atomic Physics, University of Sofia

CPV performance comparison between ESSnuSB, DUNE and Hyper-K assuming 3% systematic errors for ESSnuSB in line with the other two.

ESSνSB 500 kt tank at 540 km.

ESSνSB 500 kt tank at 360 km.

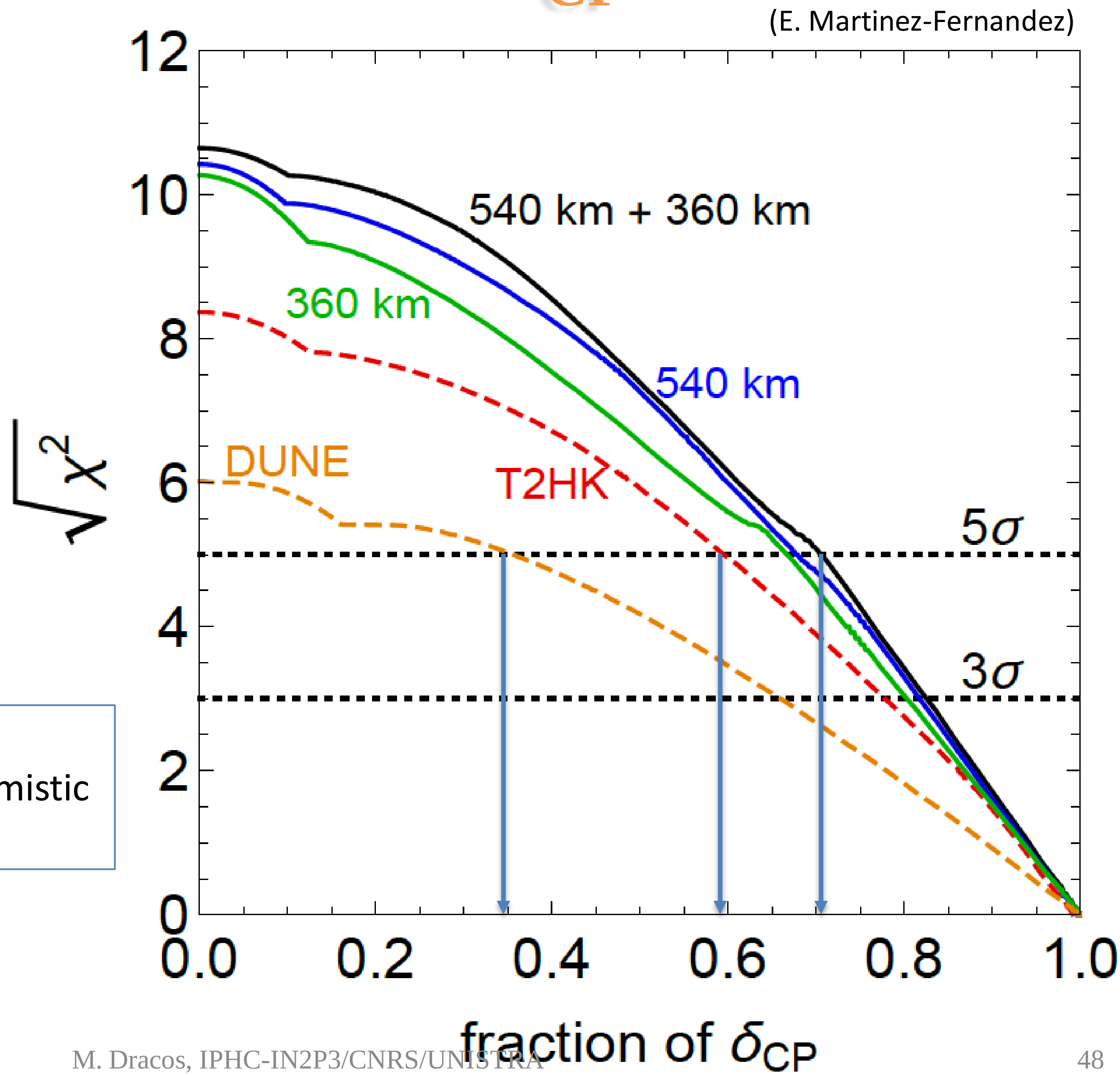




ESSνSB 250 kt tank at 540 km and 250 kt tank at 360 km.

Fraction of δ_{CP}

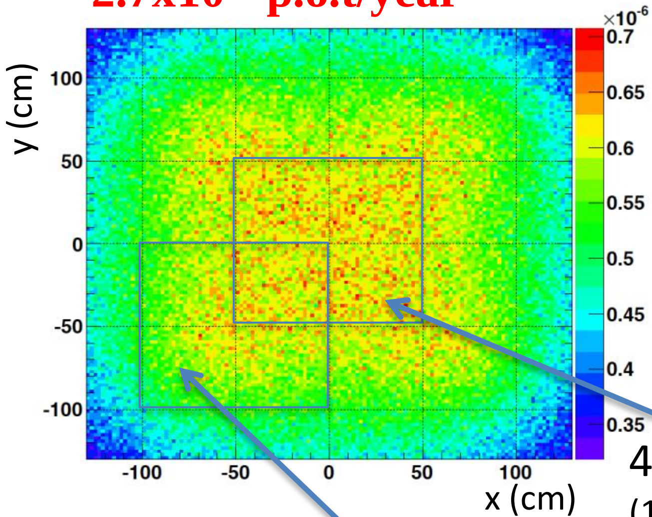
2 active mines aligned…



My personal opinion:
these scenarios are too optimistic for all facilities

Muons at the level of the beam dump

2.7×10^{23} p.o.t/year

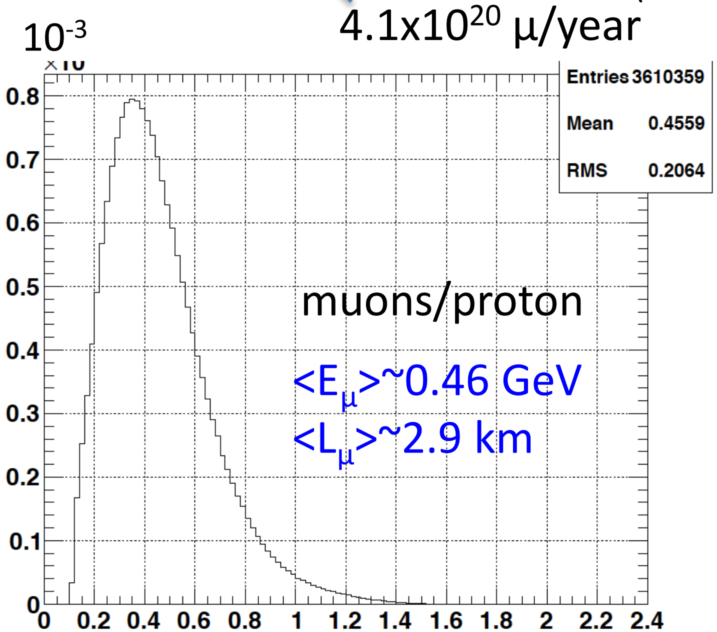


muons at the level of the beam dump (per proton)

4.2×10^{20} μ/year (16.3×10^{20} for 4 m²)

4.1×10^{20} μ/year

more than 4×10^{20} μ/year from ESSS compared to 10^{14} μ used by all experiments up to now (10^{18} μ for COMET in the future).

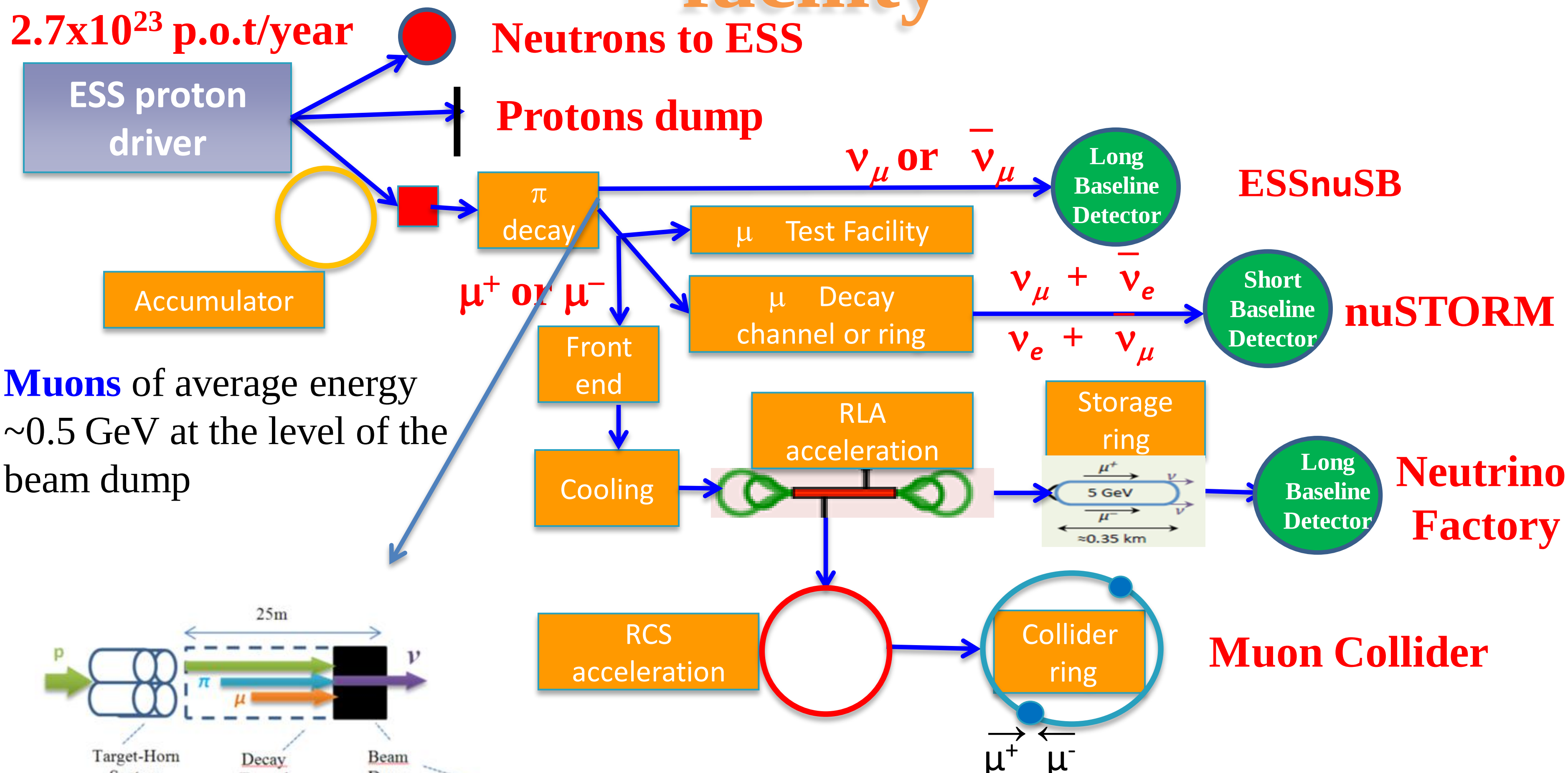


- input beam for future 6D μ cooling experiments (for muon collider),
- low energy nuSTORM,
- Neutrino Factory,
- **Muon Collider**.

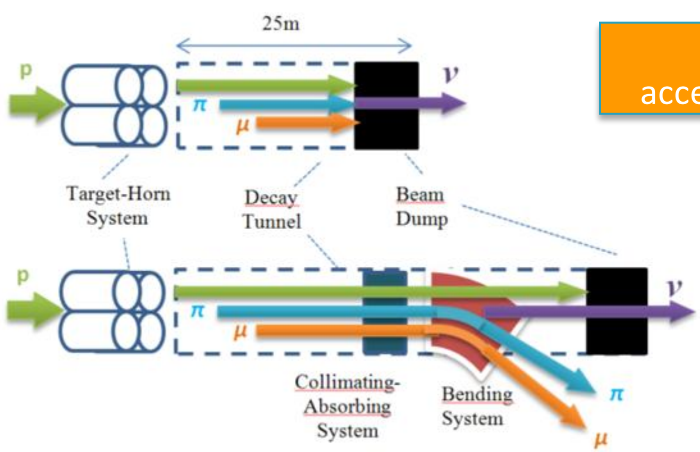
- From 3.3×10^{14} p/pulse 3.5×10^{13} μ+ and 2.4×10^{13} μ- are generated. The cooling process efficiency is 0.4 and the acceleration efficiency to $\sqrt{s}$ = 125 GeV is 0.6.
- The luminosity is given by a formula where: $L = f \frac{N^+ N^-}{4\pi\varepsilon_{rms}\beta}$
  - $N^+ = N^- = 7 \times 10^{12}$ μ/pulse
  - f is the number of effective luminosity crossings: 43 x 555 =23'865/s
  - $\varepsilon_{rms} = \varepsilon_N / 589.5 = 0.36 \times 10^{-4}$ rad cm, with H_2 *but no PIC cooling.*
  - B^* = 5 cm is beta at crossing in both dimensions
- Luminosity is $L = 5 \times 10^{32}$ cm^{-2} s^{-1} for one collision crossing
- The cross section at the maximum averaged with ΔE = 3.4 MeV is 1.0×10^{-35} cm^2. Hence the Ho event rate is 18 ev/h or 5×10^4 ev for 10^7 s/y . In 10 y and 2 crossings one million Ho events
- If PIC is successful ε_{rms}/ 10 and 0.5×10^6 events/year/i.p.

(PIC: Parametric Resonance Cooling of muons)

ESS neutrino and muon facility



Muons of average energy ~0.5 GeV at the level of the beam dump



ESS NEUTRINO SUPER BEAM

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Required modifications of the ESS accelerator for ESSνSB

F. Gerigk and E. Montesinos
CERN, Geneva, Switzerland

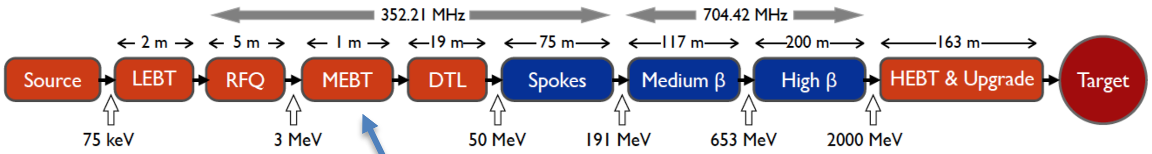
CERN-ACC-NOTE-2016-0050 8 July 2016

Contents

Quotation from "Executive Summary:
"No show stoppers have been identified for a possible future addition of the capability of a 5 MW H- beam to the 5 MW H+ beam of the ESS linac built as presently foreseen. Its additional cost is roughly estimated at 250 MEuros."

Better to go to 2.5 GeV

Preparing the ESS linac for operation at 10 MW with a 8% duty cycle and 28 Hz pulsing

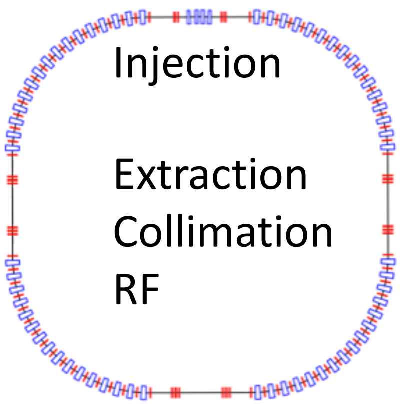


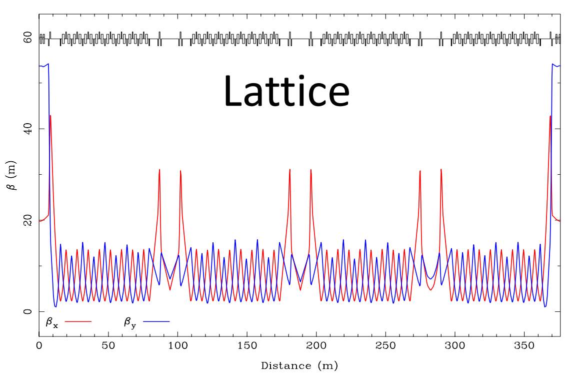
For the medium-beta **elliptical-cavity** part ESS is planning to use tetrodes. Thales has developed a new screen grid with graded wire thickness making operation at **10 % duty cycle** possible.

The picture shows the cryostat and test bunker at the FREIA Lab in Uppsala where a first prototype of the ESS 352 MHz **spoke accelerating cavity** is currently under test at 14 Hz and later on will be tested at 28 Hz.

Accumulation Ring

To compress to few μs the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA, power consumption, Joule effect), but also keeping a reasonable size of the ring.



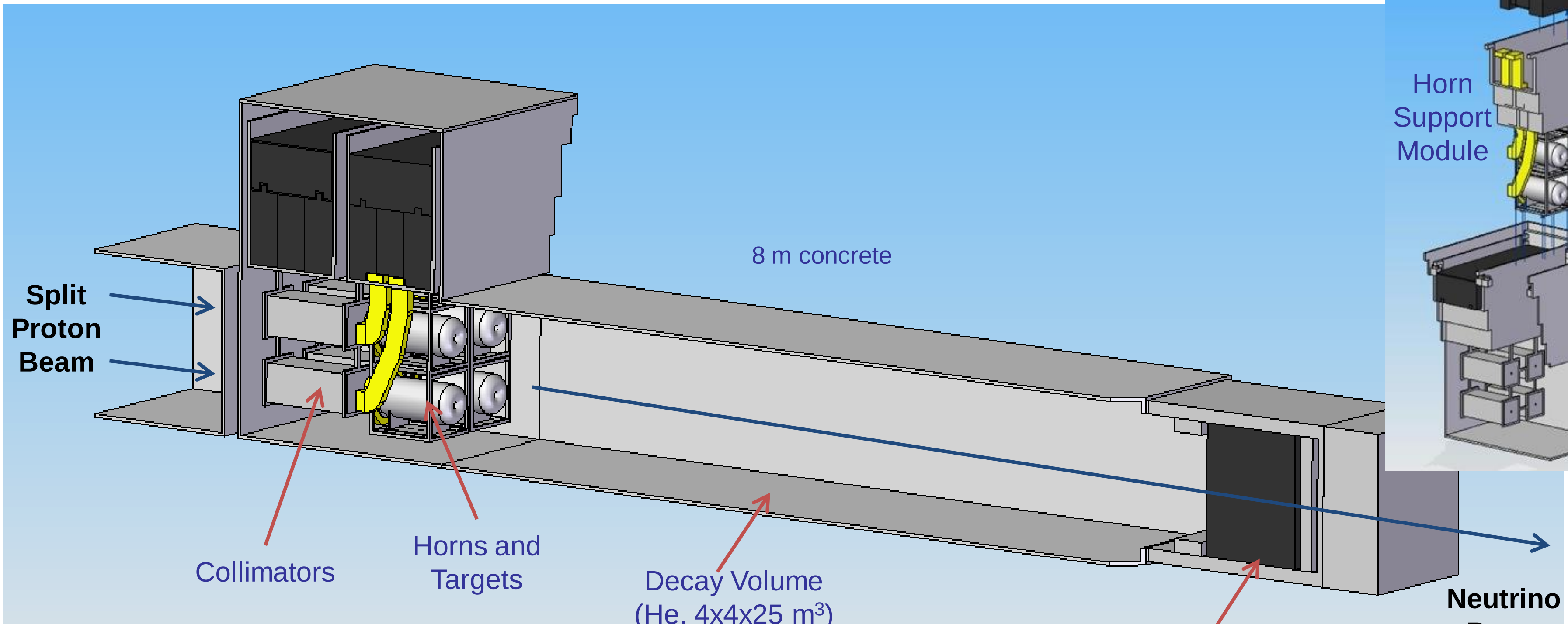


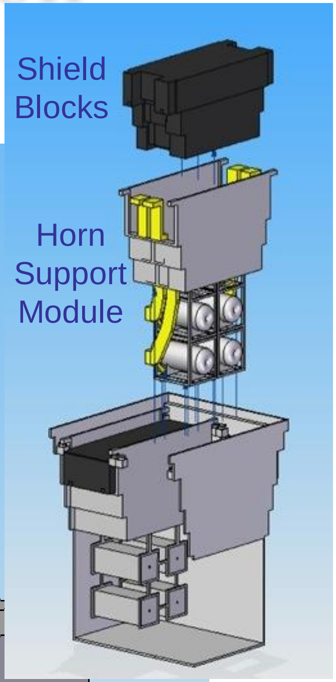
- **Baseline**: **single-ring accumulator**
  - Current studies give a **376 m** circumference accumulator ring 1.32μs.
  - 1 ring leads to a very large space–charge **tune–shift** of about **0.75**.
- **Option: 4 superposed rings** located in the same tunnel,
  - Each ring receives 1/4 of the bunches during the multi–turn injection,
  - Reduction of the **tune shift** to the level of around **0.2** (acceptable for the 2.86 ms storage time),
  - Experience already exists from the CERN PS Booster of using 4 superimposed rings with the aim to avoid high space charge effects.

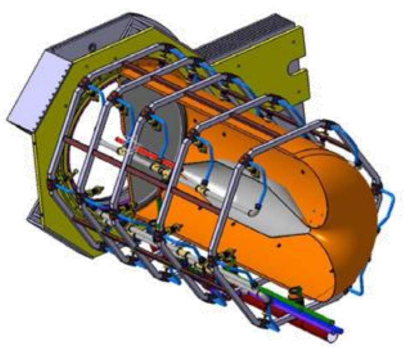
The 4 rings of the CERN PS Booster (1972)

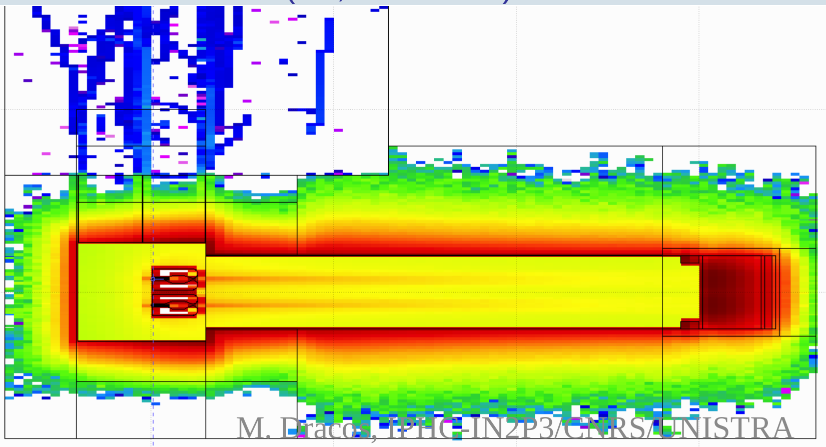
General Layout of the target station

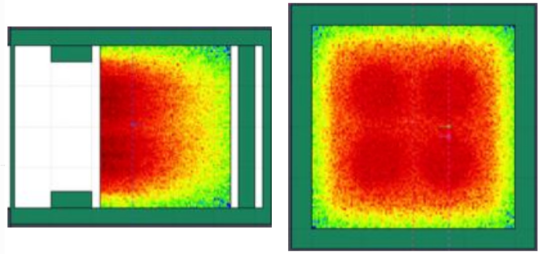
(from EUROν DS)







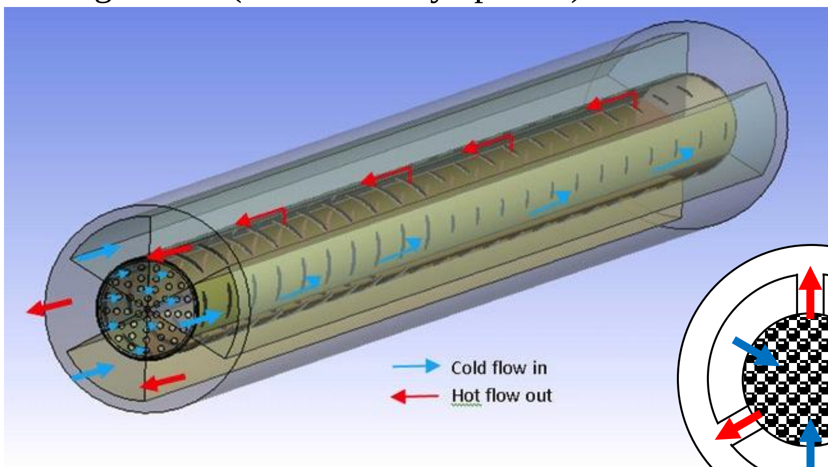


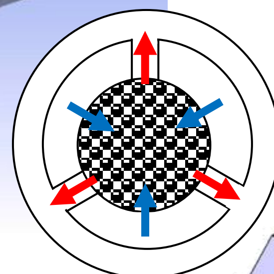


Mitigation of high power effects

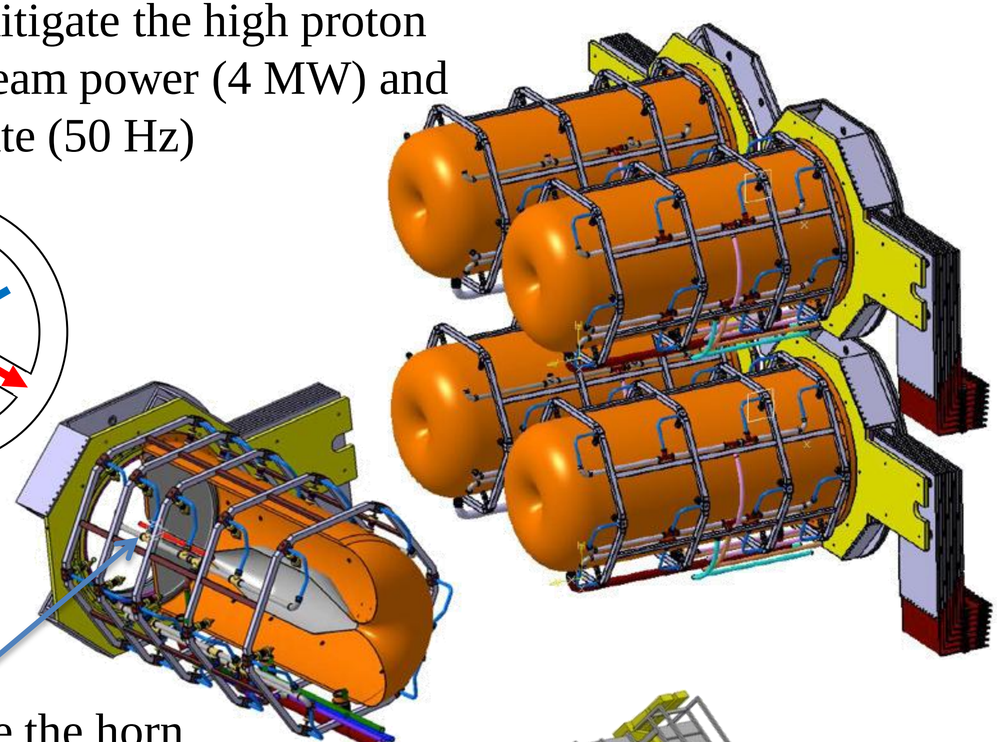
(4-Target/Horn system for EUROnu Super Beam)

Packed bed canister in symmetrical transverse flow configuration (titanium alloy spheres)

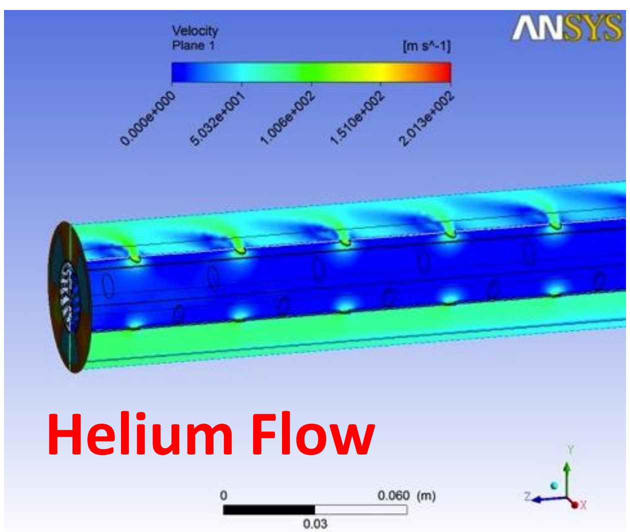


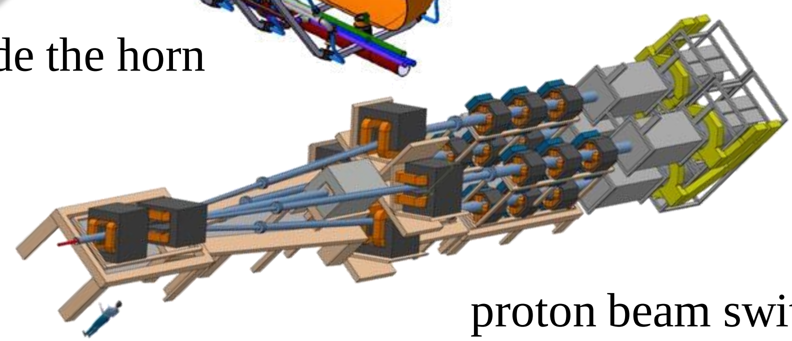


4-target/horn system to mitigate the high proton beam power (4 MW) and rate (50 Hz)



target inside the horn





proton beam switchyard

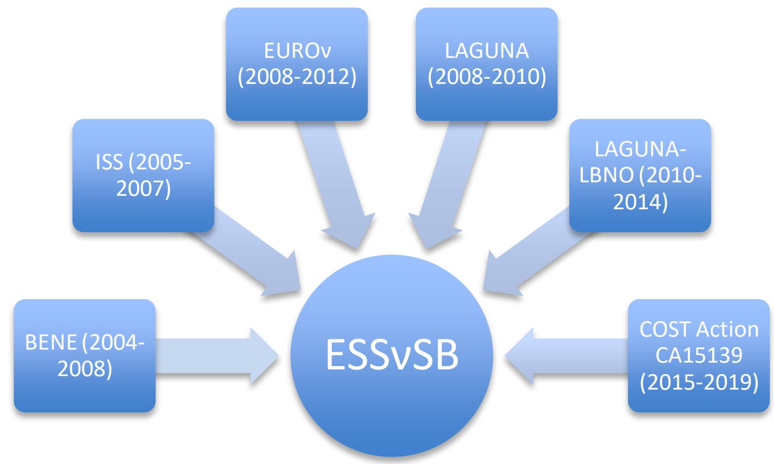
EuroNuNet

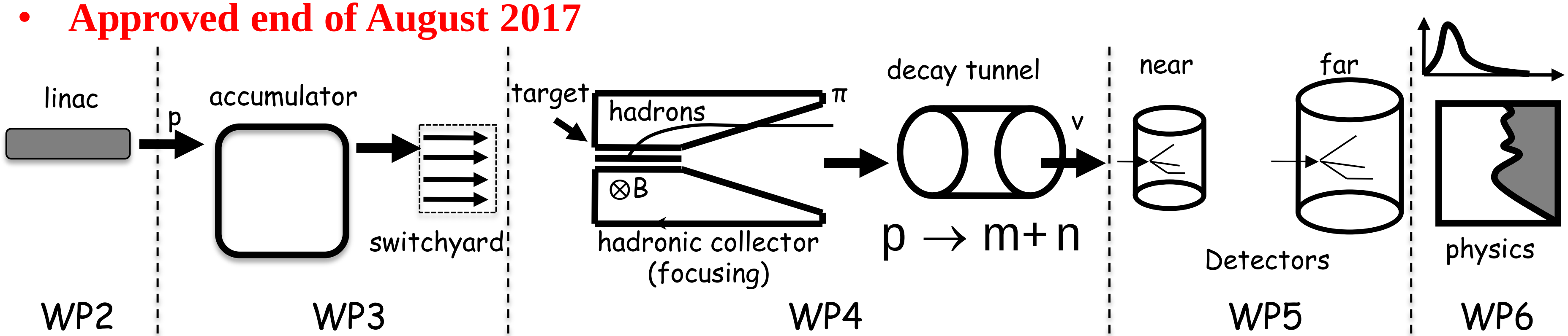
- **COST application for networking: CA15139 (2016-2020)**
  - **EuroNuNet** : *Combining forces for a novel European facility for neutrino-antineutrino symmetry violation discovery* (**http://www.cost.eu/COST_Actions/ca/CA15139**)
  - **Major goals of EuroNuNet**:
    - to aggregate the community of neutrino physics in Europe to study a neutrino long baseline concept in a spirit of inclusiveness,
    - to impact the priority list of High Energy Physics policy makers and of funding agencies to this new approach to the experimental discovery of leptonic CP violation.
  - 13 participating countries (network still growing).
    http://euronunet.in2p3.fr/

The members are countries which signed the Action MoU

ESSνSB at the European level

- A **H2020** EU **Design Study** (Call INFRADEV-01-2017)
  - **Title of Proposal**: Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator
  - **Duration: 4 years**
  - **Total cost: 4.7 M€**
  - **Requested budget: 3 M€**
  - **15 participating institutes from**
    11 European countries including CERN and ESS
  - 6 Work Packages
  - **Approved end of August 2017**





Design Study ESSνSB (2018-2021)

Call:	H2020-INFRADEV-2017-1
Funding scheme:	RIA
Proposal number:	777419
Proposal acronym:	ESSnuSB
Duration (months):	48
Proposal title:	Feasibility Study for employing the uniquely powerful ESS linear accelerator to generate an intense neutrino beam for leptonic CP violation discovery and measurement.
Activity:	INFRADEV-01-2017

Maximum grant amount (proposed amount, after evaluation): **2,999,018.00 EUR**

N.	Proposer name	Country
1	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	FR
2	UPPSALA UNIVERSITET	SE
3	KUNGLIGA TEKNISKA HOEGSKOLAN	SE
4	EUROPEAN SPALLATION SOURCE ERIC	SE
5	UNIVERSITY OF CUKUROVA	TR
6	UNIVERSIDAD AUTONOMA DE MADRID	ES
7	NATIONAL CENTER FOR SCIENTIFIC RESEARCH "DEMOKRITOS"	EL
8	ISTITUTO NAZIONALE DI FISICA NUCLEARE	IT
9	RUDER BOSKOVIC INSTITUTE	HR
10	SOFIISKI UNIVERSITET SVETI KLIMENT OHRIDSKI	BG
11	LUNDS UNIVERSITET	SE
12	AKADEMIA GORNICZO-HUTNICZA IM. STANISLAWA STASZICA W KRAKOWIE	PL
13	EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH	CH
14	UNIVERSITE DE GENEVE	CH
15	UNIVERSITY OF DURHAM	UK
	Total:	

More information on:
http://essnusb.eu/

partners: IHEP, BNL, SCK•CEN, SNS, PSI, RAL

Possible ESSνSB schedule

(2nd generation neutrino Super Beam)

2012: inception of the project

Nucl. Phys. B 885 (2014) 127

2016-2019: beginning of COST Action EuroNuNet

2018: beginning of ESSνSB Design Study (EU-H2020)

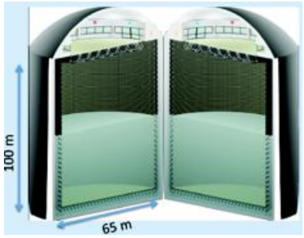
2021: End of ESSνSB Design Study, CDR and preliminary costing

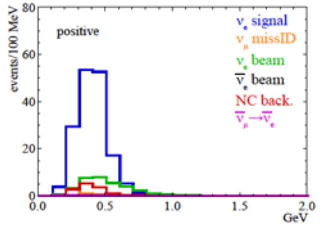
2022-2024: Preparatory Phase, TDR

2025-2026: Preconstruction Phase, International Agreement

2027-2034: Construction of the facility and detectors, including commissioning

2035-: Data taking



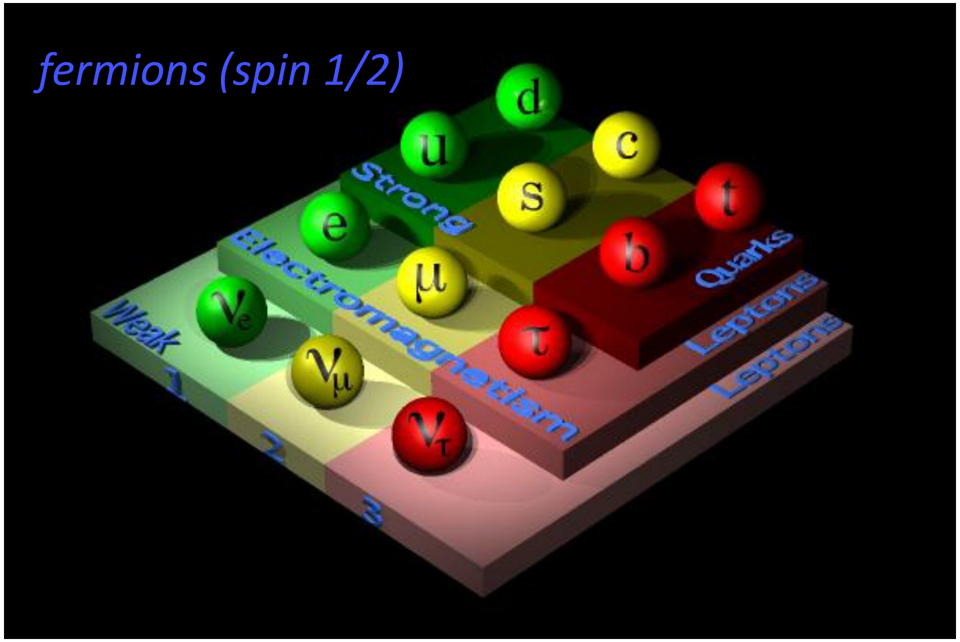


Conclusion

- ESS will be the most powerful neutron facility for many applications.
- ESS can also become a neutrino facility with enough protons to go to the 2^{nd} oscillation maximum and increase the CPV sensitivity.
- CPV: 5 σ could be reached over 60% of δ_{CP} range by ESSνSB with large physics potential.
- Large associated detectors have a rich astroparticle physics program.
- The European Spallation Source Linac will be ready by 2025, upgrade decisions by this moment.
- Rich muon program for future ESS upgrades.
- COST network project CA15139 and a EU-H2020 Design Study supports this project.

Backup

But, what a neutrino is?



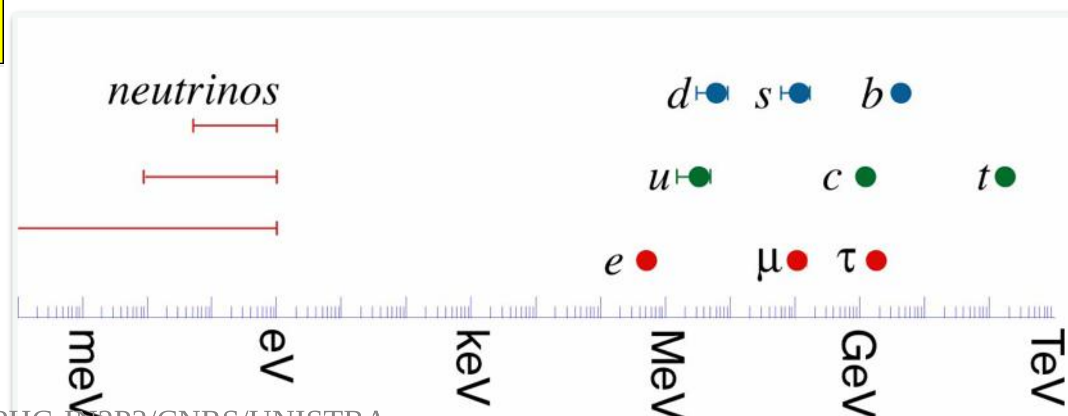
+bosons currying the interactions (spin integer)

g (8 gluons)	γ (photon)	Z^0 boson	$W^{\pm}$ boson

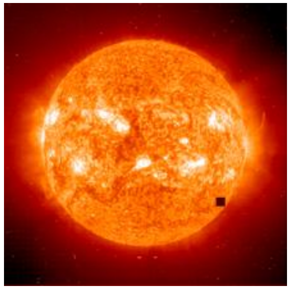
strong *electromagnetic* *weak*

+the fermions' anti-particles
+the Higgs boson

- elementary particles,
- neutral (electrical charge=0)
- interacting only through weak interaction,
- they have massive and charged partners,
- massless up to 90's (this is what was assumed by the Standard Model of elementary particles)



Where can we find neutrinos?



- **Solar Neutrinos** : 2 10^{38} ν/s → 40 billions ν/s/cm^2 on the earth → 400000 billion ν/s/human.

- **Universe** :

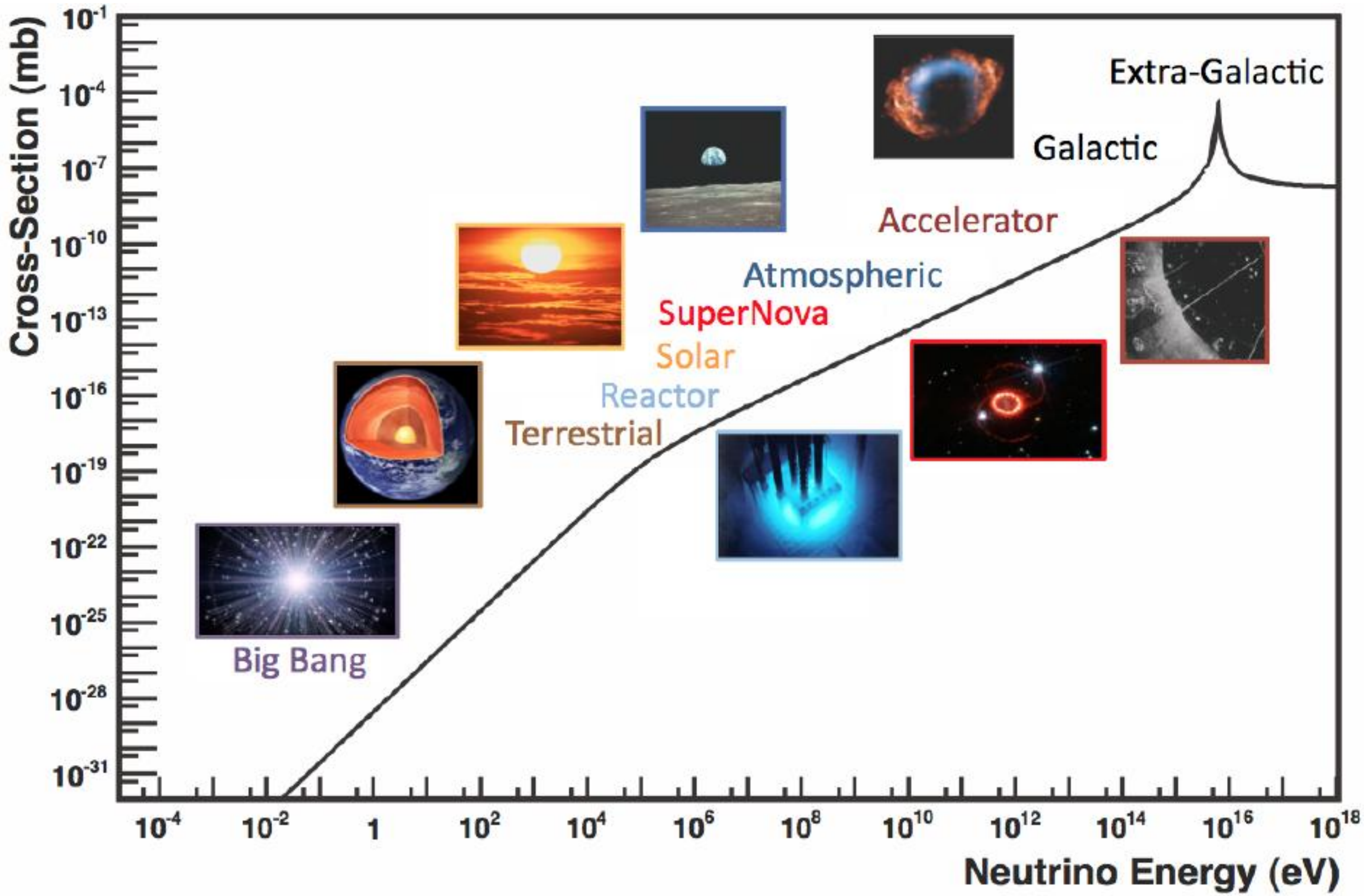
  - Big-Bang : 330 ν/cm^3.
  - Stars : 0.000006 ν/cm^3.
  - Supernovae : 0.0002 ν/cm^3.

- **Earth radioactivity** : 50 billion ν/s human.

- **Nuclear Plants**:10-100 billion ν/s/human.

- **Human body**: 340 million ν/day (20 mg of ^{40}K, β decay).

Neutrino Energy Spectrum



Neutrino interactions

1933 : First estimation of the neutrino interaction cross-section (interaction probability) by Hans Bethe and Rudolf Peierls

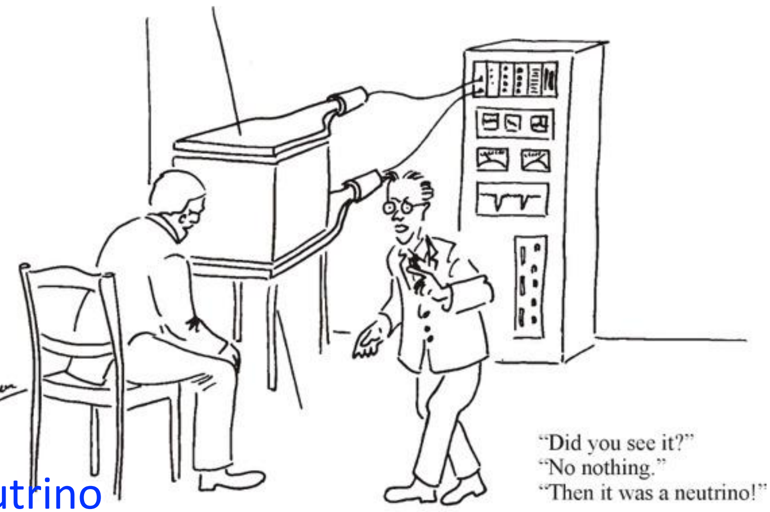
$\sigma_{\nu N} \approx 10^{-10}\,\sigma_{eN}$ (*N* for nucleon), very very weak cross-section!!!

$\sigma_{\bar{\nu} p} \approx 10^{-43}\,cm^2$

$\lambda = \frac{1}{N_A \rho \sigma}$ mean free path

$\lambda(Pb) \approx \frac{1}{6 \times 10^{23}(nucleons/g)(7.9g/cm^3) \times 10^{-43}cm^2}$

$\approx$ 4 light-years! mean free path in lead for 3 MeV neutrino



to stop a neutrino a lot of lead is needed or many neutrinos...

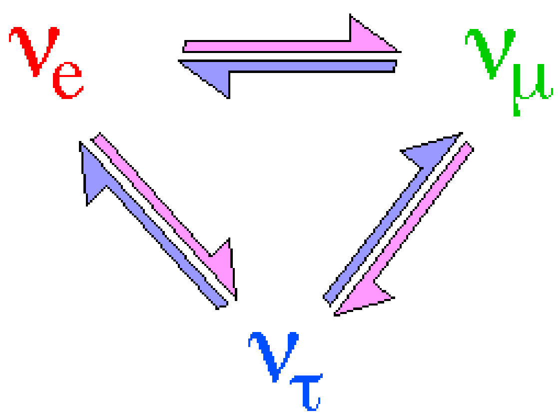
The beginning of a long neutrino hunting which lasted 26 years...

(Pauli: "I *bet a case of champagne that nobody would ever detect the neutrino*")

Neutrino Oscillations

According to Quantum Mechanics, if neutrinos have a non-zero mass they can "oscillate" (change family during travelling).

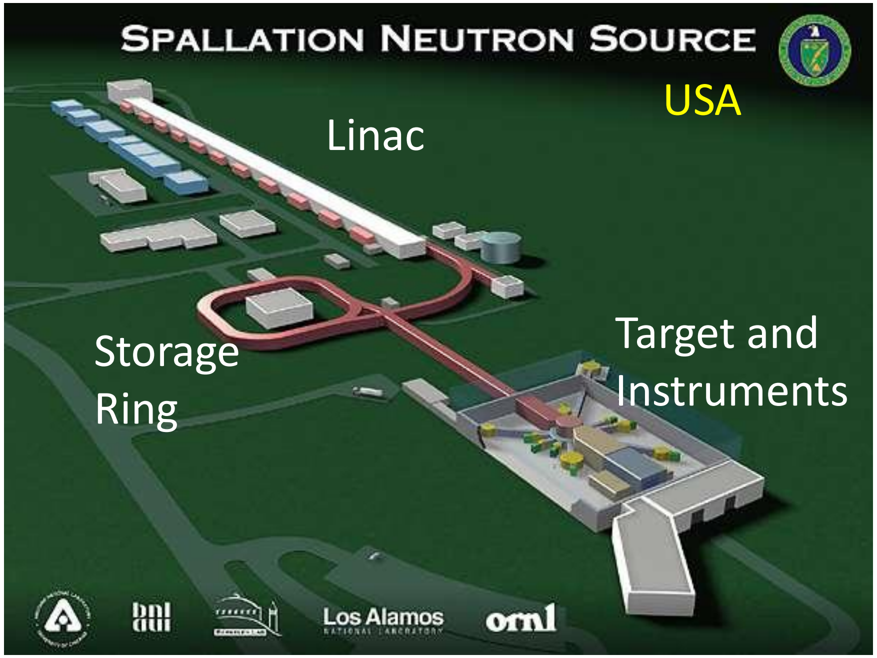
Why? Because their mass eigen states could not coincide with their flavour eigen states (or interaction eigen states).



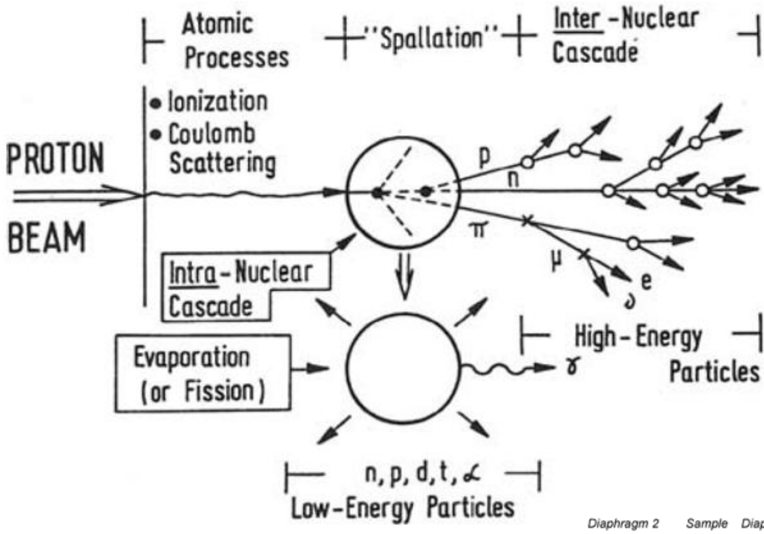
Neutron Spallation Sources

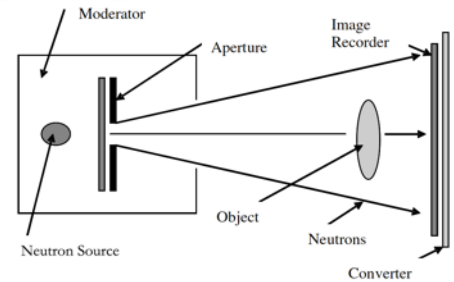
- Traditional neutron sources are reactor based
  - In the long run, reactors will be shut down. Not easy to build new ones
  - Neutron flux is limited by reactor cooling.
  - Neutron energy spectrum is measured by time of flight using neutron choppers.
    - Chopping throws away neutrons and limits neutron brightness.
- Spallation sources consist of a:
  - pulsed accelerator that shoots protons into a metal target to produce the neutrons
- The pulsed nature of the accelerator makes the neutron brightness
  - much higher for a spallation source for the same average neutron flux as a reactor

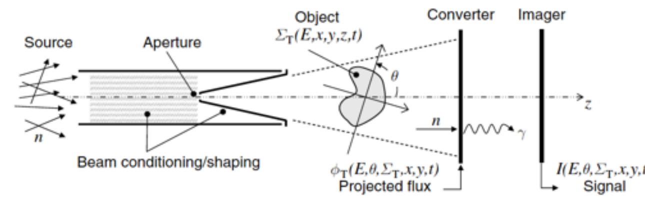
- The accelerator complex of a typical spallation source consists of:
  - A linac to accelerate the protons.
  - A storage ring to compress the linac beam pulse.
- In Europe: ISIS (pulsed), PSI (continuous) and ESS (long pulsed, in construction)



Neutron Production







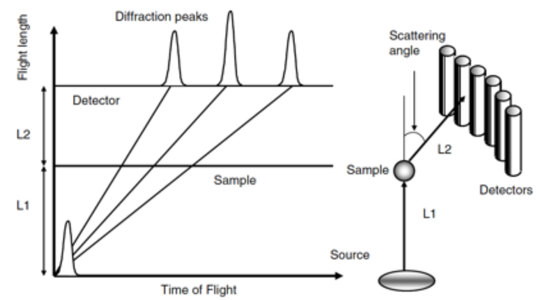
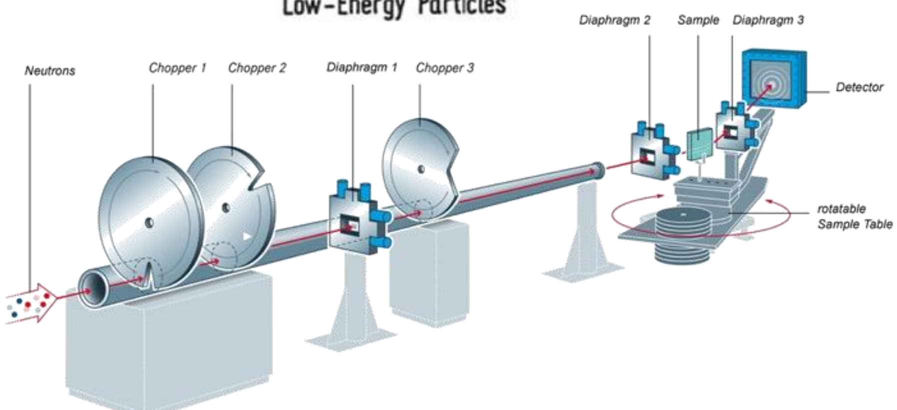


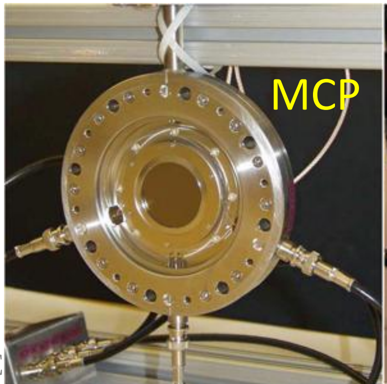
Fig. 2.10 Flight-length/time-of-flight diagram for a diffraction measurement

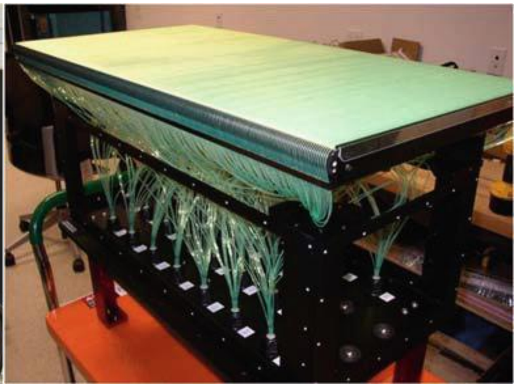


a lot of computing needed…

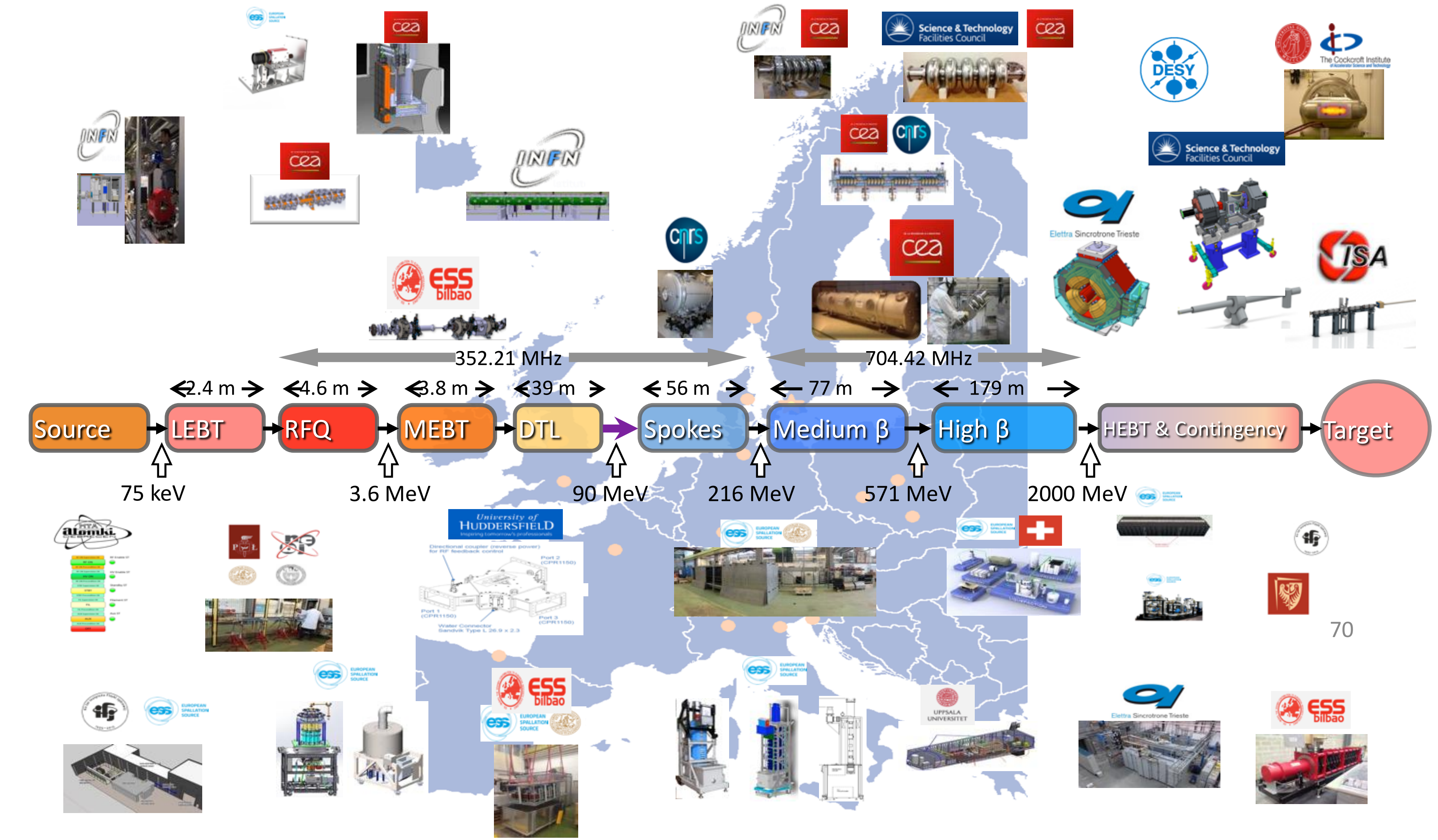
Table 1.1 Neutron characteristics at various energy ranges

Neutron classification	Energy (meV)	Velocity (m/s)	λ (nm)
Ultra-cold	0.00025	6.9	57
Cold	1	437	0.9
Thermal	25	2187	0.18
Epithermal	1000	13,832	0.029





ESS proton linac
(mainly in-kind contributions)

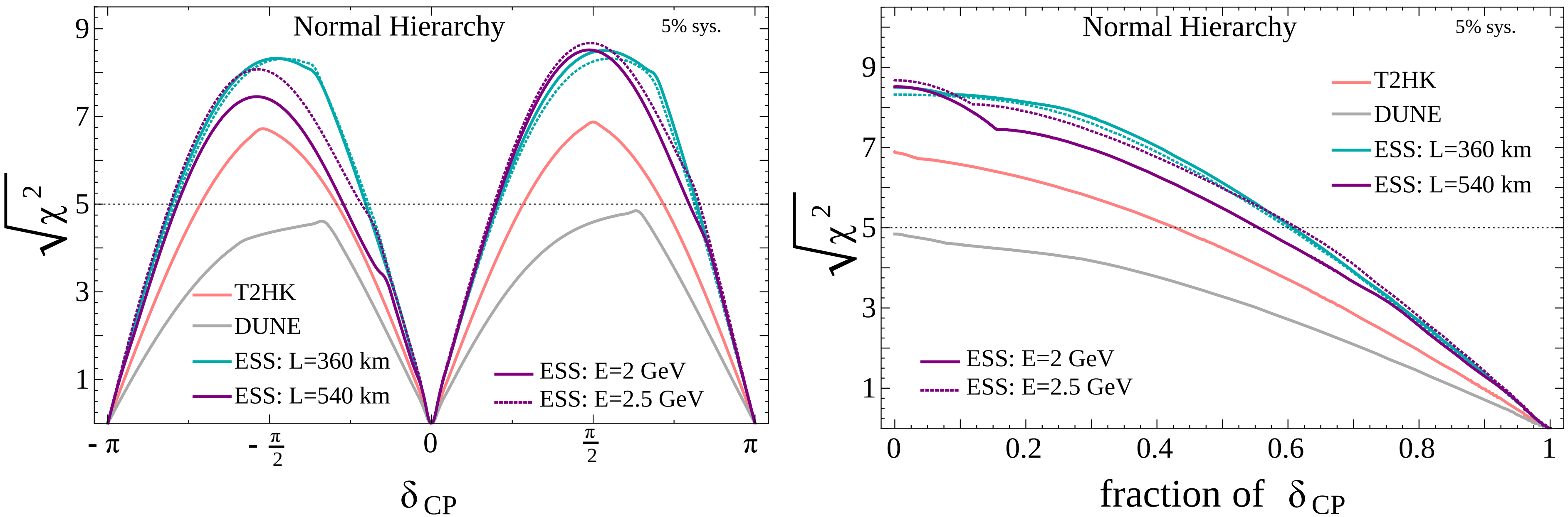


Systematic errors

Systematics	SB Opt.	SB Def.	SB Cons.	BB Opt.	BB Def.	BB Cons.	NF Opt.	NF Def.	NF Cons.
Fiducial volume ND	0.2%	0.5%	1%	0.2%	0.5%	1%	0.2%	0.5%	1%
Fiducial volume FD (incl. near-far extrap.)	1%	2.5%	5%	1%	2.5%	5%	1%	2.5%	5%
Flux error signal ν	5%	7.5%	10%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background ν	10%	15%	20%	correlated			correlated		
Flux error signal $\bar{\nu}$	10%	15%	20%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background $\bar{\nu}$	20%	30%	40%	correlated			correlated		
Background uncertainty	5%	7.5%	10%	5%	7.5%	10%	10%	15%	20%
Cross secs × eff. QE†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs × eff. RES†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs × eff. DIS†	5%	7.5%	10%	5%	7.5%	10%	5%	7.5%	10%
Effec. ratio ν_e/ν_μ QE*	3.5%	11%	–	3.5%	11%	–	–	–	–
Effec. ratio ν_e/ν_μ RES*	2.7%	5.4%	–	2.7%	5.4%	–	–	–	–
Effec. ratio ν_e/ν_μ DIS*	2.5%	5.1%	–	2.5%	5.1%	–	–	–	–
Matter density	1%	2%	5%	1%	2%	5%	1%	2%	5%

Phys. Rev. D 87 (2013) 3, 033004 [arXiv:1209.5973 [hep-ph]]

Comparisons



Comparison using the same systematic errors

Phys. Rev. D 87 (2013) 3, 033004 [arXiv:1209.5973 [hep-ph]]

How the CPV coverage and resolution curves have been produced

- **T2HK**:
  - Same curves that Hyper-K has showed at the Neutrino Town Meeting at CERN and the one that was showed at Neutrino 2018.
  - Systematics are said by T2HK to be between 3% to 4%.
  - $\sin^2 2\theta_{13}$ =0.1 and $\theta_{23}= \pi /2$.
- **DUNE**:
  - Public globes file released by the DUNE collaboration with the CDR, the only change is to increase the number of years from 7 to 10.
  - $\sin^2 2\theta_{13}$ =0.1 and $\theta_{23}=\pi/2$, to be compatible with the T2HK line.
- **ESSnuSB**:
  - Instead of considering as usual "Opt. Snowmass errors" it is only assumed an overall 3% systematic error in the different signal and background channels, more in line with T2HK assumptions.
  - $\sin^2 2\theta_{13}$ =0.1 and $\theta_{23}= \pi /2$, to be compatible with the T2HK line.

What COST is?
(European Cooperation in Science and Technology)

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Growing ideas through networks

The European Cooperation in Science and Technology (COST) provides funding for the creation of research networks, called COST Actions. These networks offer an open space for collaboration among scientists across Europe (and beyond) and thereby give impetus to research advancements and innovation.

COST is bottom up, this means that researchers can create a network – based on their own research interests and ideas – by submitting a proposal to the COST Open Call. The proposal can be in any science field. COST Actions are highly interdisciplinary and open. It is possible to join ongoing Actions, which therefore keep expanding over the funding period of four years. They are multi-stakeholder, often involving the private sector, policymakers as well as civil society.

Since 1971, COST receives EU funding under the various research and innovation framework programmes, such as Horizon 2020.

https://www.cost.eu

Useful links:

- What's in it for researchers? Video
- Growing ideas through networks (brochure)
- 2017 Join an Action booklet
- Annual Report 2017
- Annual Report 2016

Vademecum

http://www.cost.eu/download/COSTVademecum

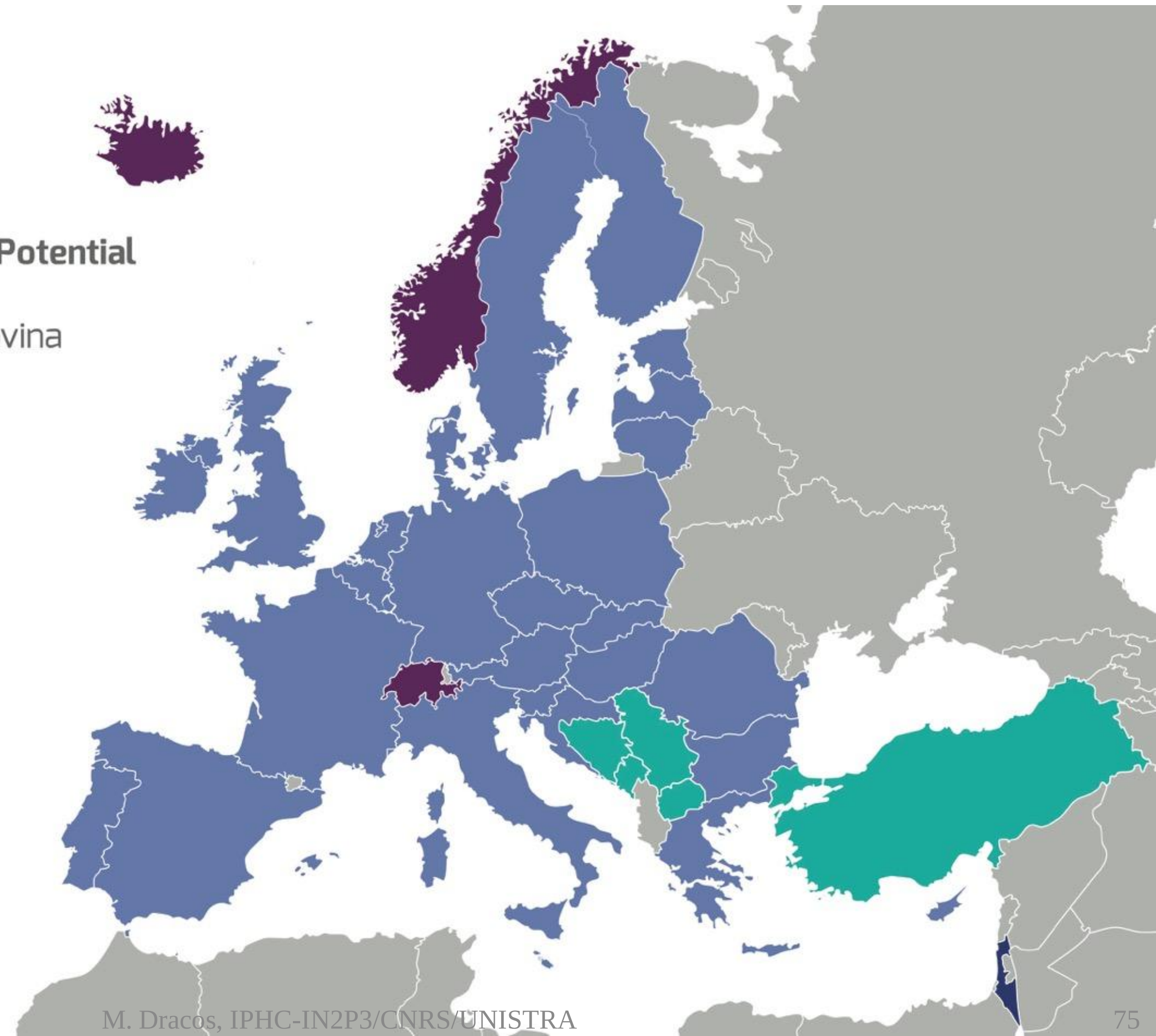
COST Member Countries

EU 28

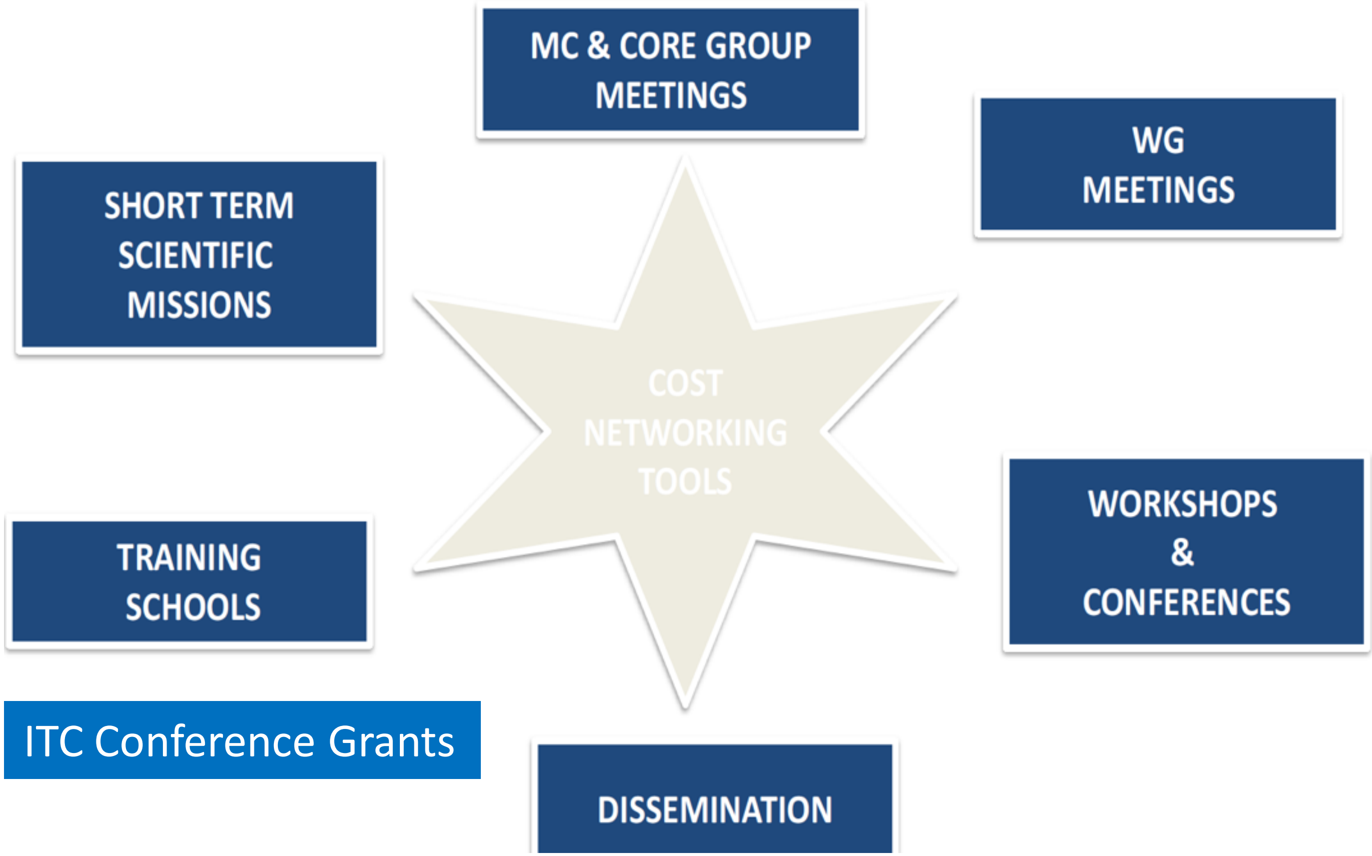
EU Candidates and Potential Candidates
Bosnia and Herzegovina
fYR Macedonia
Montenegro
Republic of Serbia
Turkey

Other countries
Iceland
Norway
Switzerland

COST Cooperating Member
Israel



COST Tools

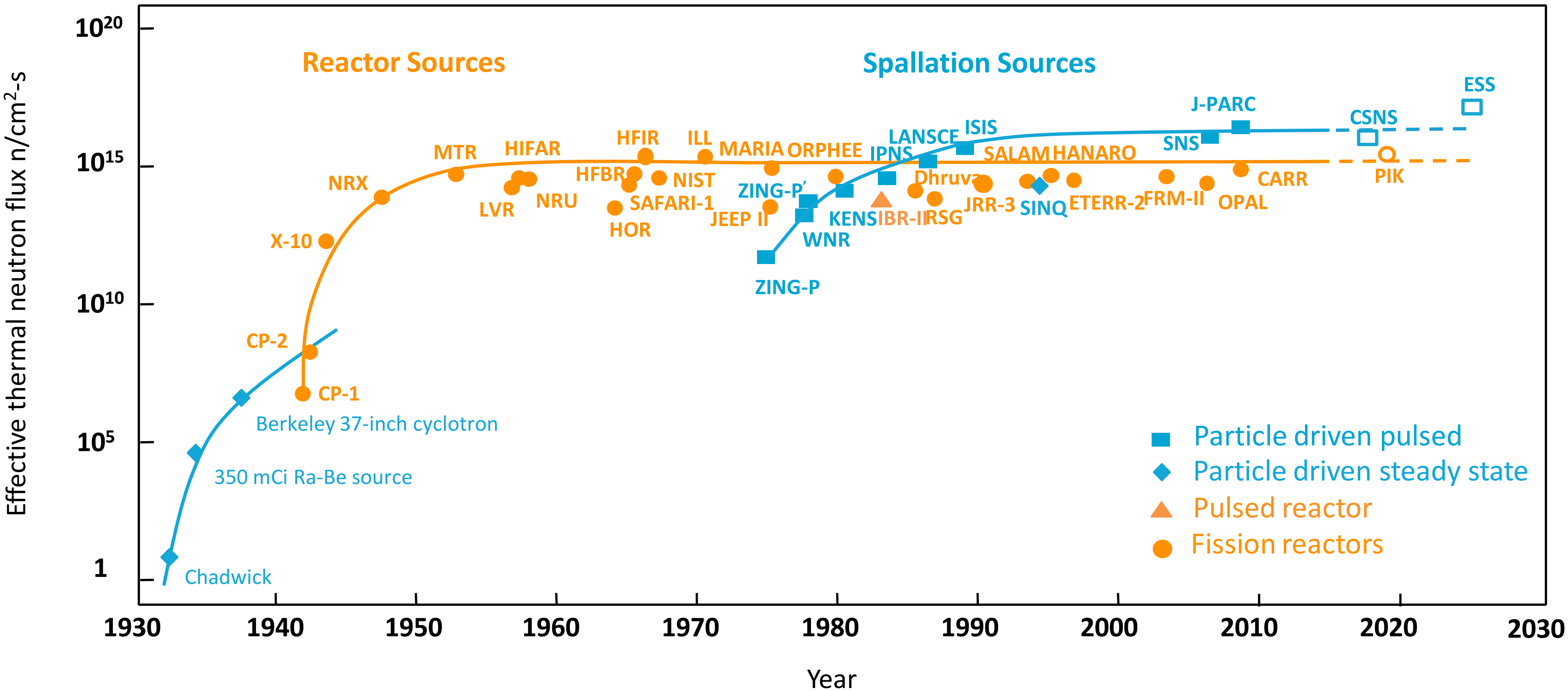


***Inclusiveness Target Countries**: Bosnia-Herzegovina, Bulgaria, Cyprus, Czech Republic, Estonia, Croatia, Hungary, Lithuania, Latvia, Luxembourg, Malta, Montenegro, Poland, Portugal, Romania, Slovenia, Slovakia, the former Yugoslav Republic of Macedonia, Republic of Serbia and Turkey.*

ESS NEUTRINO SUPER BEAM

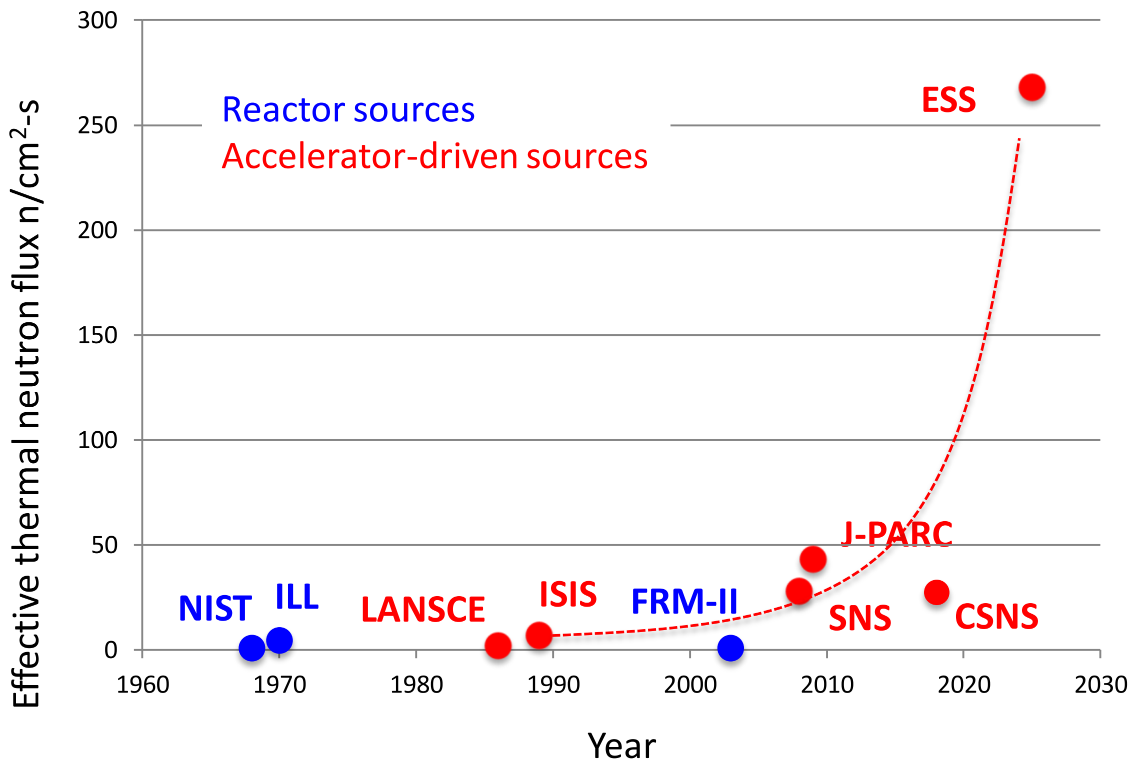
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Neutron facilities – reactors and particle driven



(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

ESS – the sale pitch!



Examples

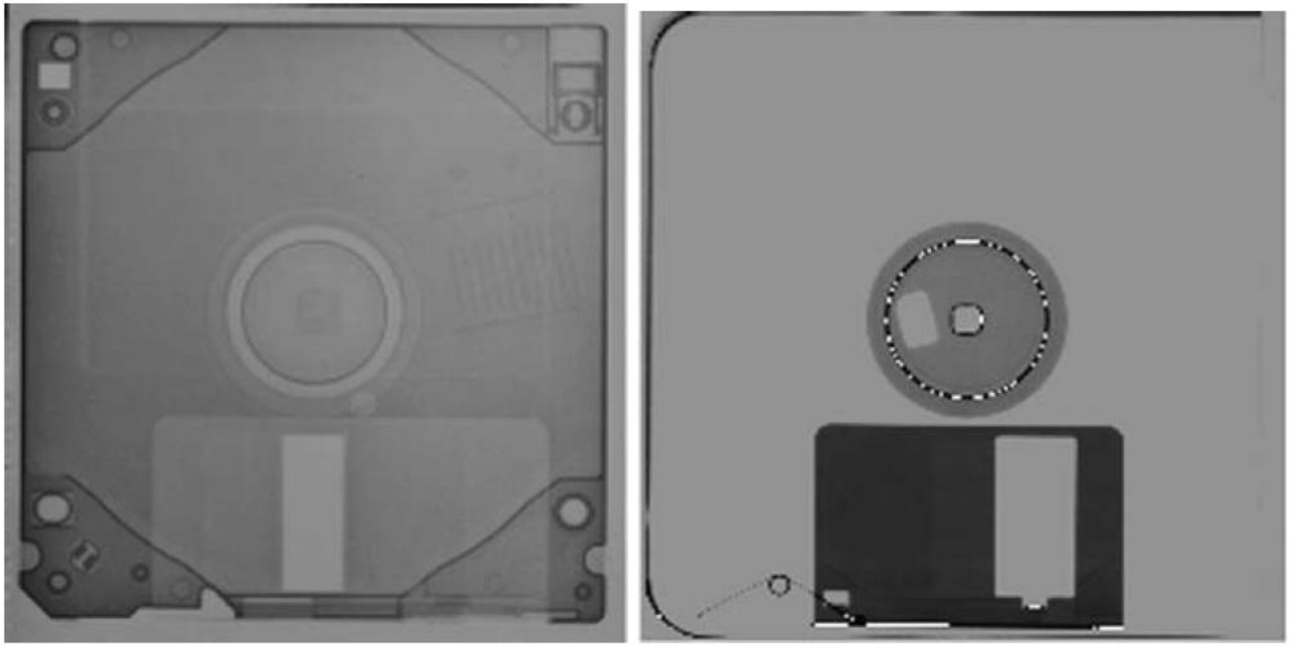
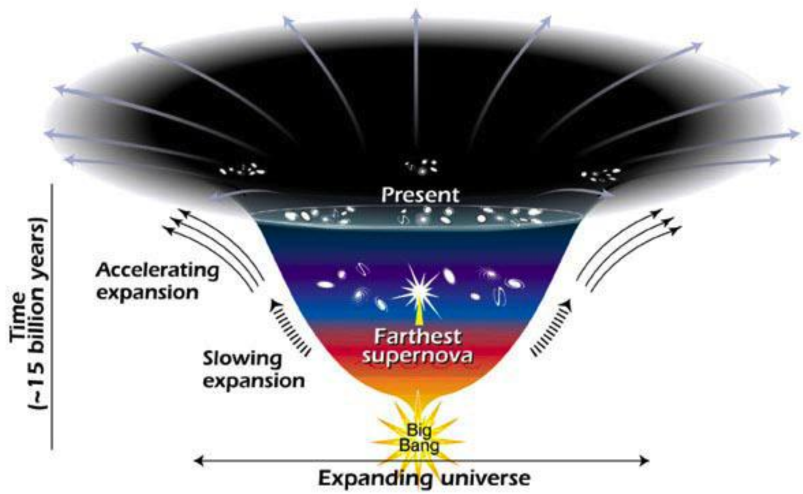
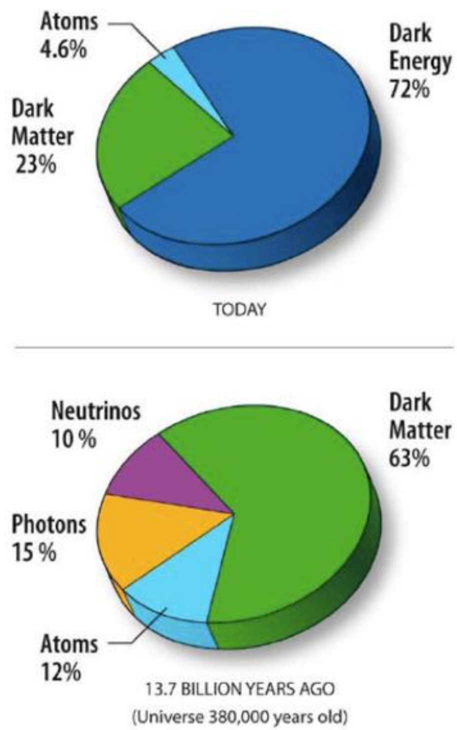
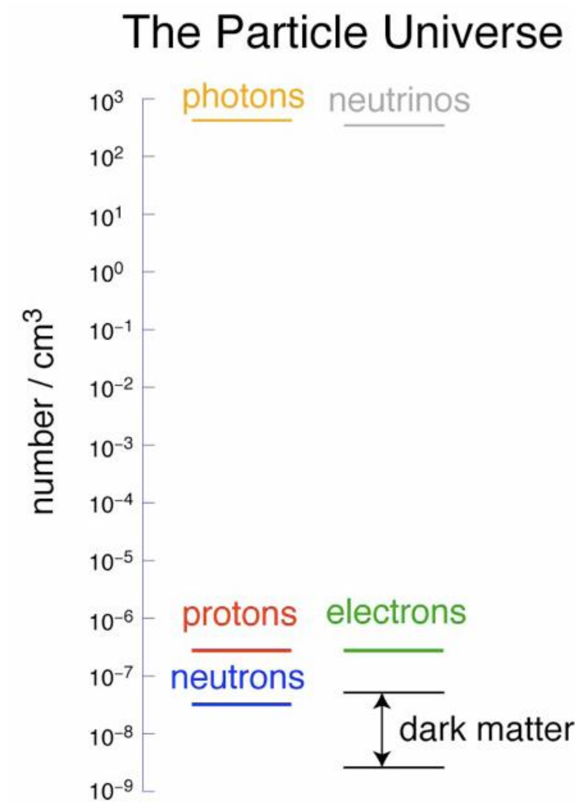

(a) (b)

Fig. 12.1 Radiograph of a computer floppy disk using neutrons (**a**) shows the polymeric components clearly while X-rays (**b**) are sensitive to the metallic components

"cosmological" neutrino mass measurement







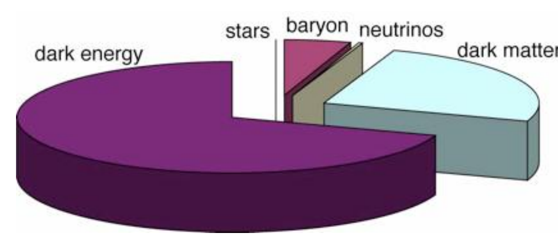
$$\Omega_\nu h^2 = \frac{\sum_i m_{\nu i}}{94 \text{ eV}}$$

neutrino density

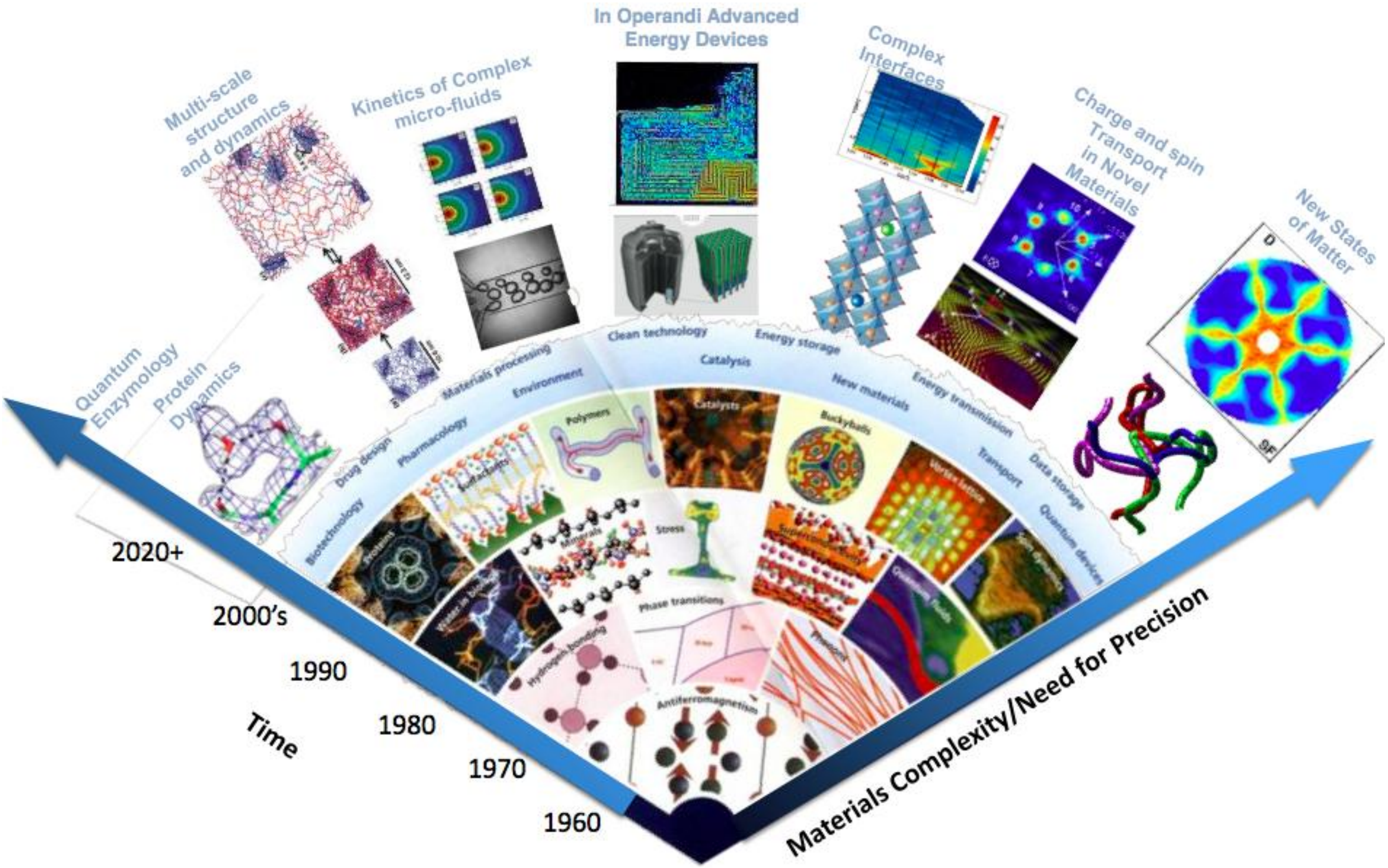
Hubble constant

$\sum m_\nu < 0.18$ eV

(Planck satellite)

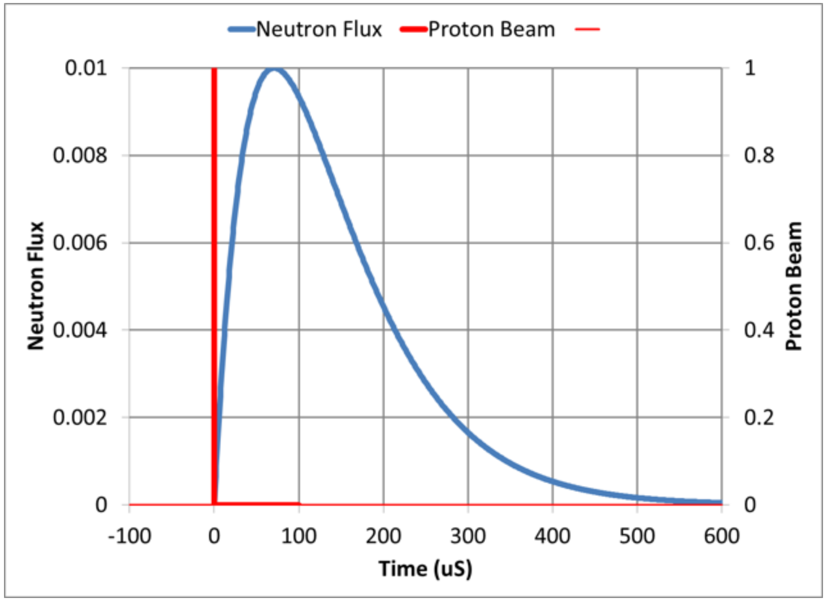


Science at ESS



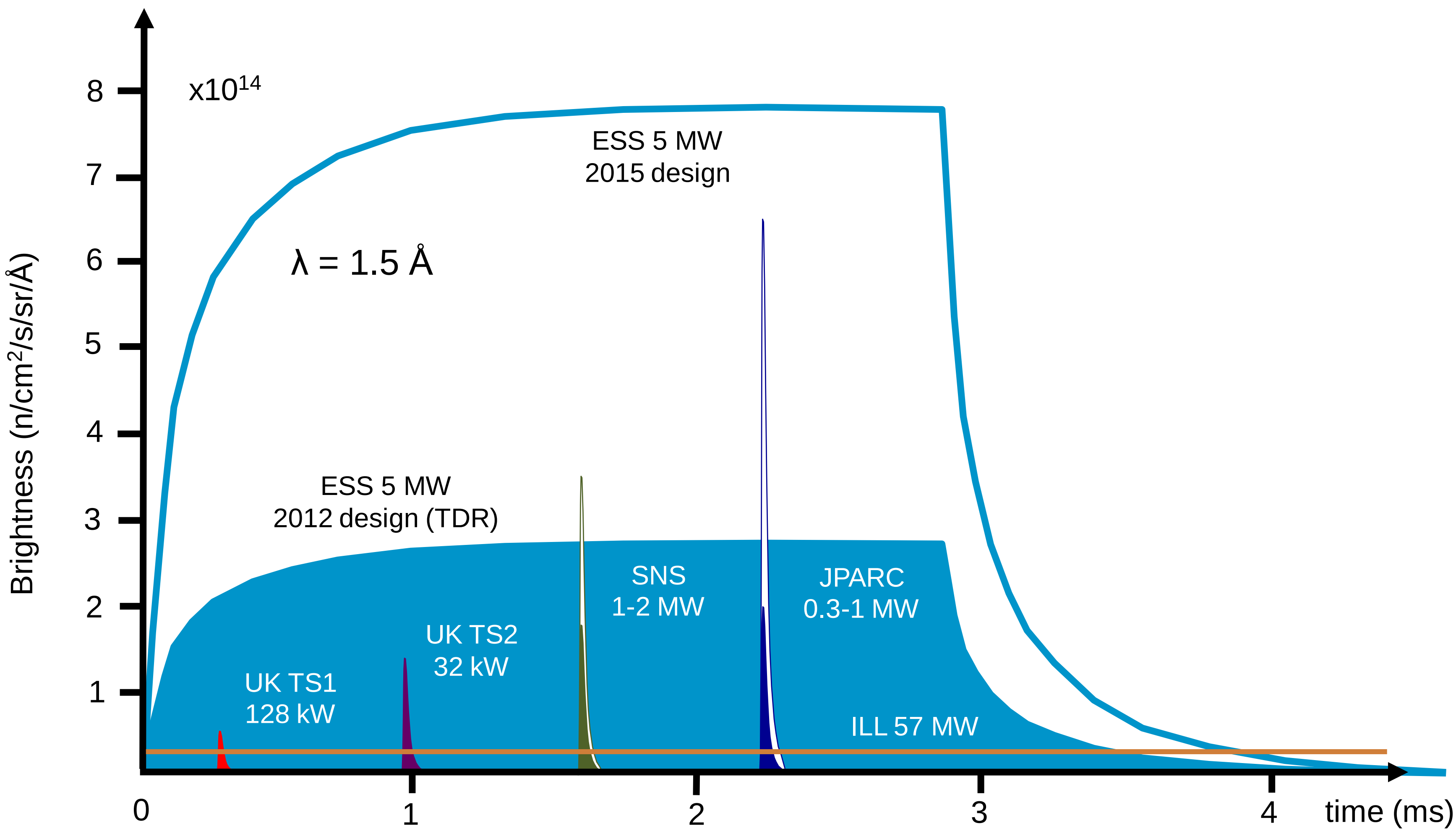
Accelerator Neutron Spallation Sources

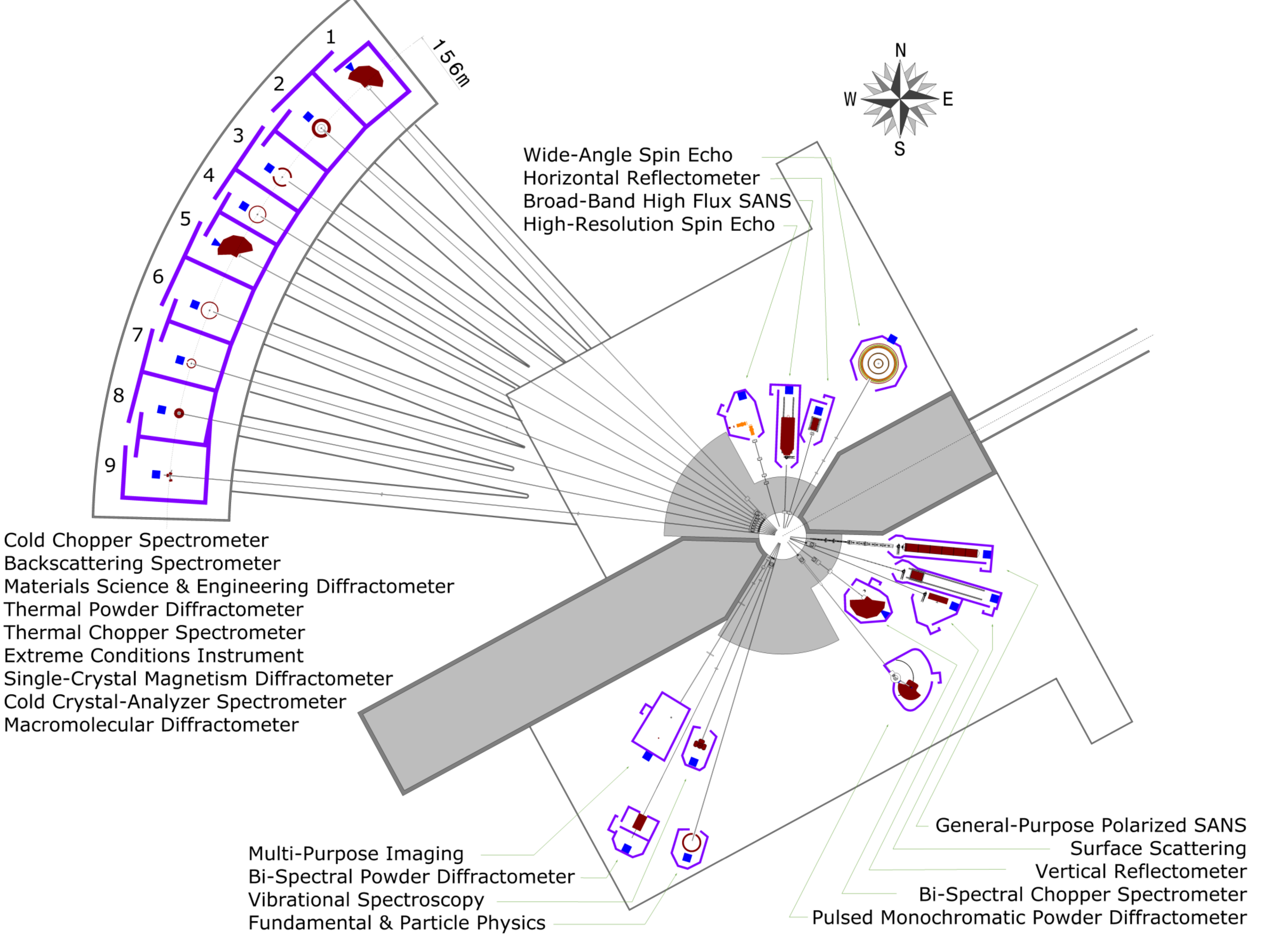
- The neutrons are cooled by a moderator downstream of the target.
- The time constant of the moderation process is about 100 ms.
- Proton beam pulses shorter than 100 µs serve only to stress the metal target and limit the beam power
  - Typical short pulse spallation sources have storage ring circumferences ~300 meters which produce 1 µs beam pulses.
  - To build a storage ring with a 100 ms pulse would require a ring 30 km in circumference.



- The target stress from the short beam pulse places a limit on:
  - proton beam power,
  - neutron flux and brightness,
  - the proton beam power of SNS (Oak Ridge Tennessee, USA) is limited to 1 MW (17 MW peak) for 1 GeV protons.

Comparison of Brightness

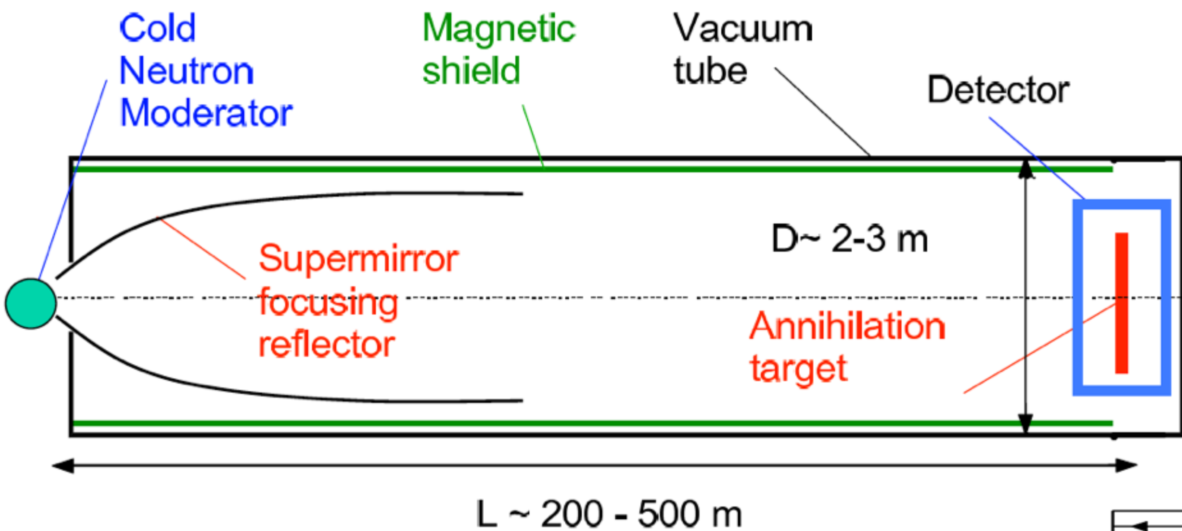


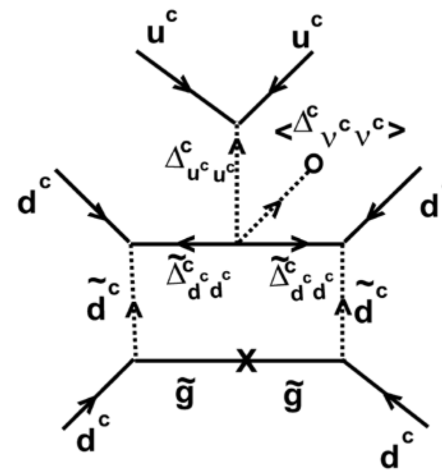


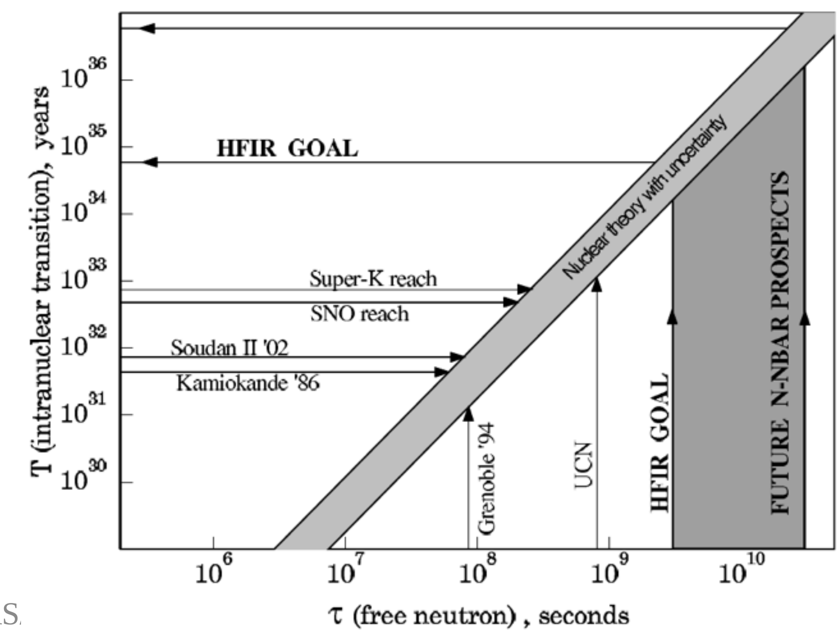
1
2
3
4
5
6
7
8
9
156m
N
E
S
W
Wide-Angle Spin Echo
Horizontal Reflectometer
Broad-Band High Flux SANS
High-Resolution Spin Echo
Cold Chopper Spectrometer
Backscattering Spectrometer
Materials Science & Engineering Diffractometer
Thermal Powder Diffractometer
Thermal Chopper Spectrometer
Extreme Conditions Instrument
Single-Crystal Magnetism Diffractometer
Cold Crystal-Analyzer Spectrometer
Macromolecular Diffractometer
General-Purpose Polarized SANS
Surface Scattering
Vertical Reflectometer
Bi-Spectral Chopper Spectrometer
Pulsed Monochromatic Powder Diffractometer
Multi-Purpose Imaging
Bi-Spectral Powder Diffractometer
Vibrational Spectroscopy
Fundamental & Particle Physics

Neutron-antineutron oscillations

$\Delta B=2$







Neutron-antineutron oscillation will probe physics at scales far below the GUT scales that proton decay will probe.

arXiv:0902.0834