A New Search for Neutron-Anti-Neutron Oscillations

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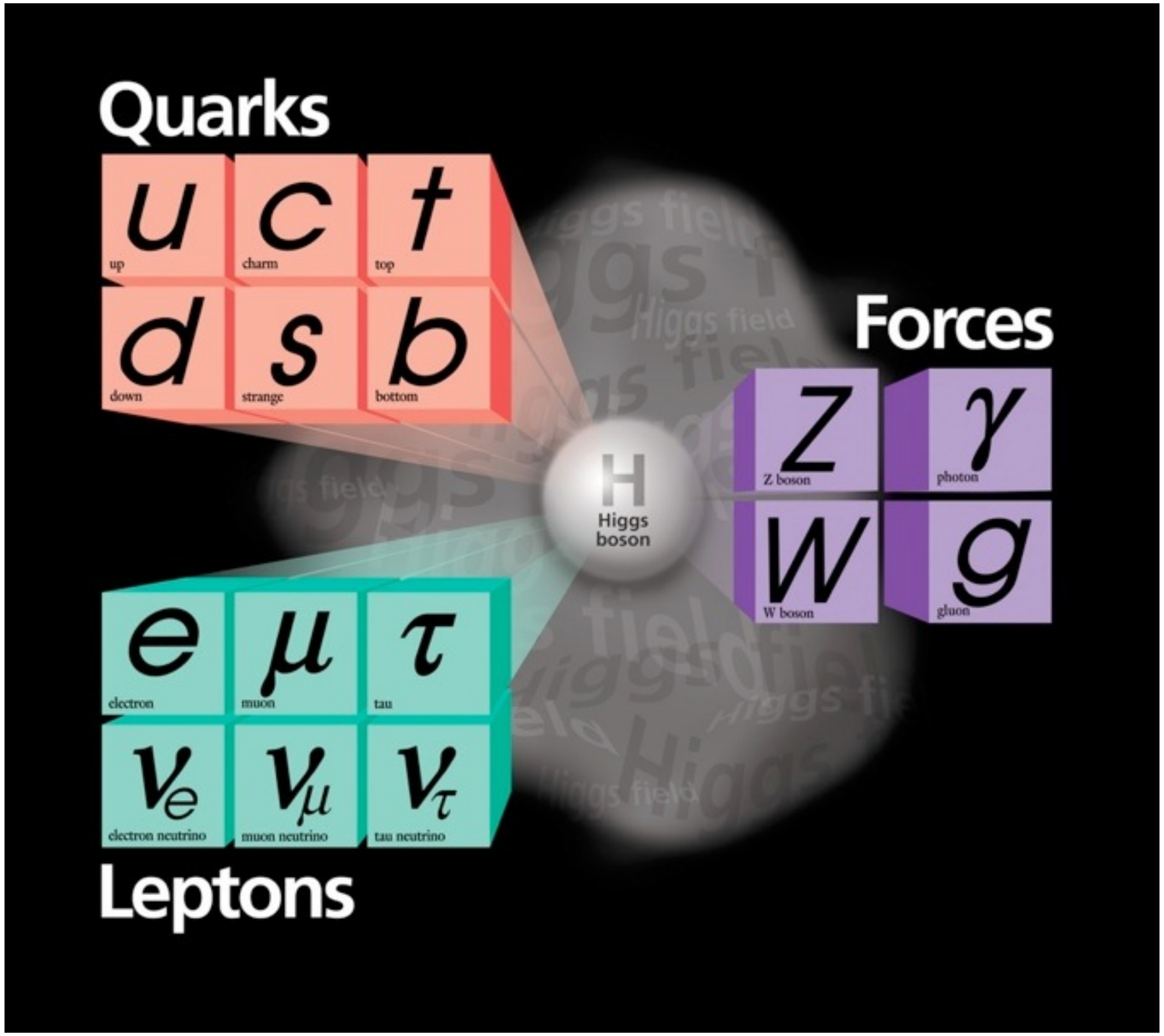
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

DESY
February 10-11, 2014

Outline

- Physics
  - The Standard Model in 2014
  - Oscillations
- Process
  - Key parameters
  - Current limits
- European Spallation Source
- Beamline & Detector
- Building a collaboration

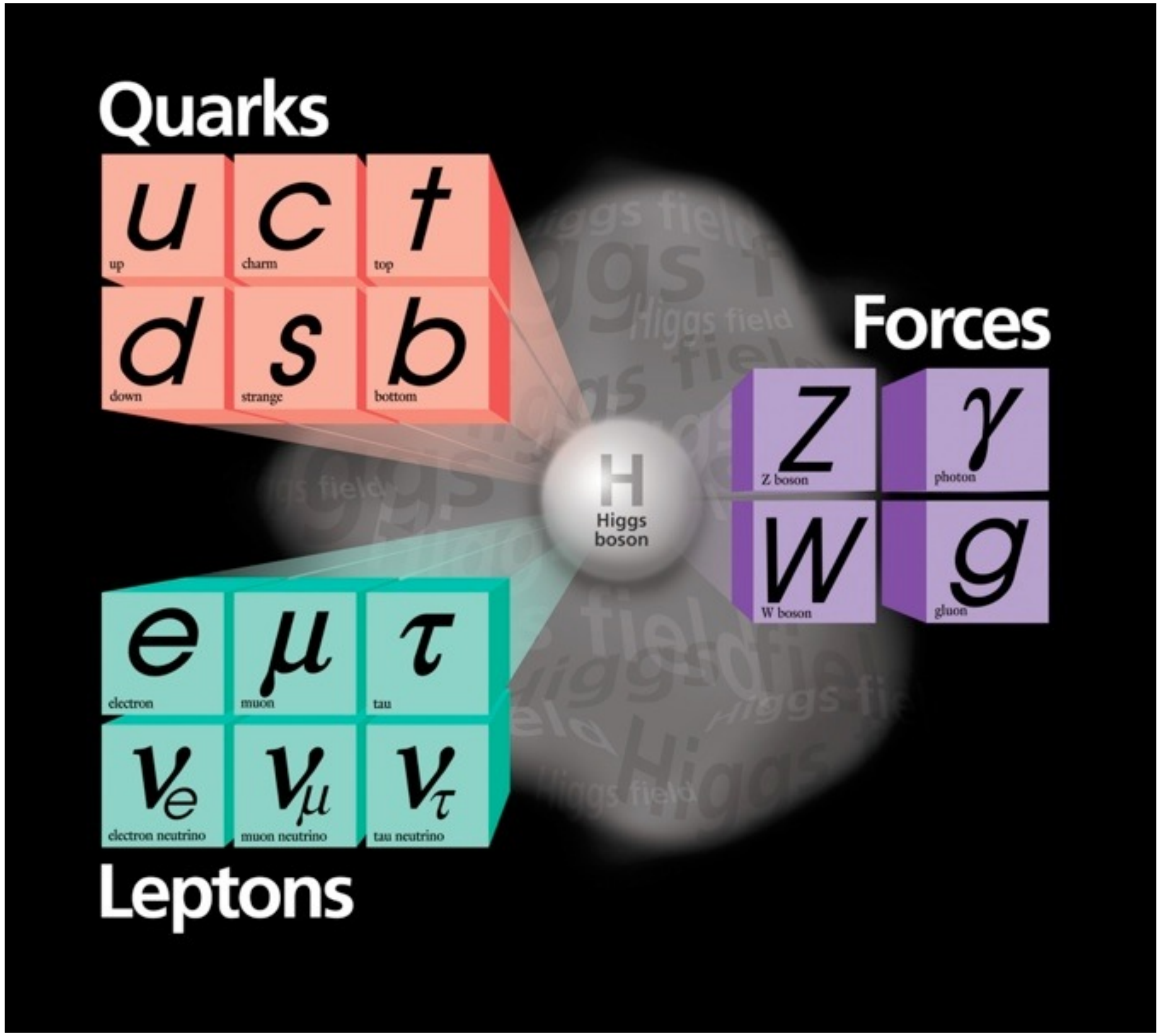
Standard Model in 2014



Triumph of Gauge Theories!

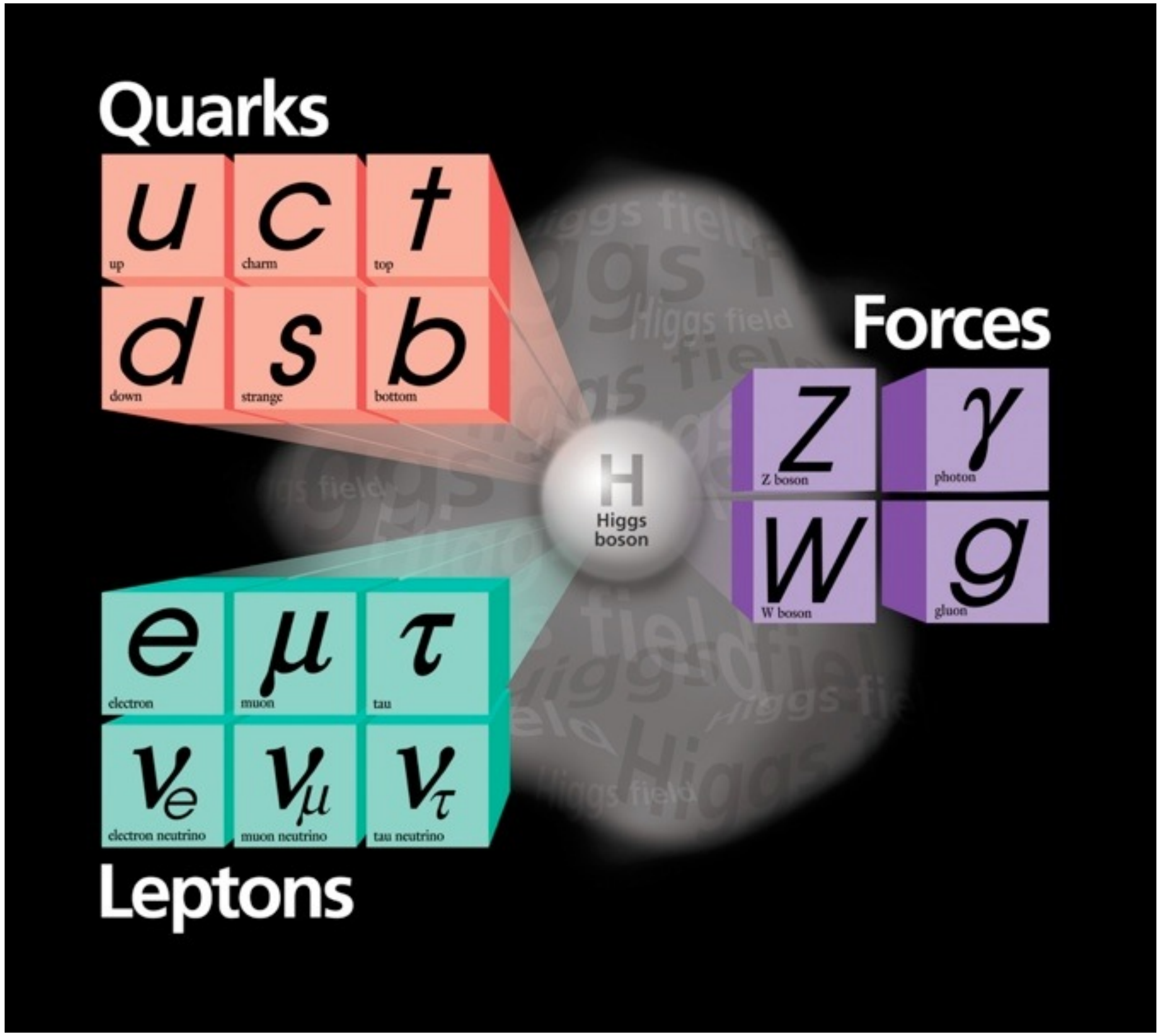
Standard Model in 2014

- Higgs discovery completes the Standard Model
  - Fully consistent, complete, precise description of strong, electromagnetic and weak interactions
- Even generate fermion masses
  - But that is the ***only*** property of fermions we "understand"



Lacking in the Standard Model

- Clear structure in fermionic sector unexplained
  - No understanding of the "charges"
  - Evidence of selective principle(s)
    - E.g. no neutral colored fermions
    - q(down) = q(e)/N_c
  - Interpreted as evidence for (grand) unification
    - Grand or less grand? (One or more scales?)



Lacking in the Standard Model

- Many cosmological issues
  - Dark matter and dark energy
  - Not enough CP violation in the quark sector for baryogenesis
  - Baryon number violation
    - Present in the SM through B-L (sphalerons)
    - Baryogenesis through leptogenesis and B-L?
      - Untestable?

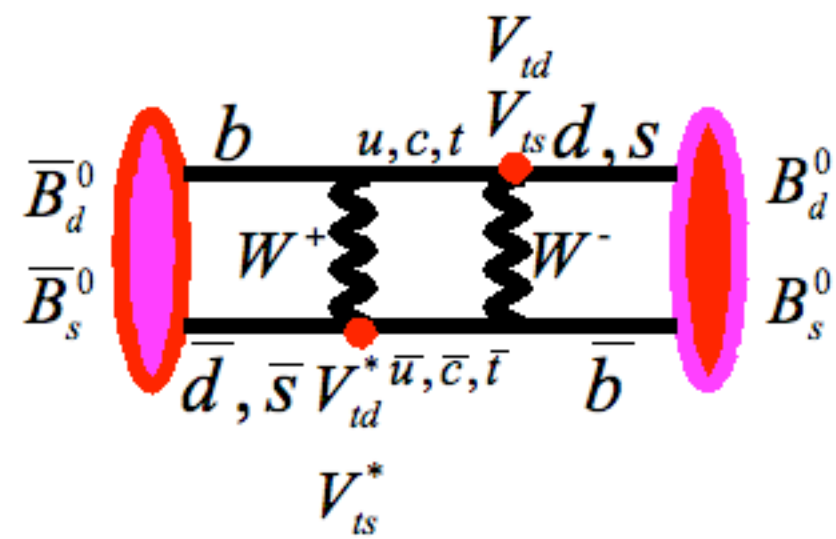
$\Delta B=1$: proton decay $\rightarrow \Lambda > 10^{13}$ TeV

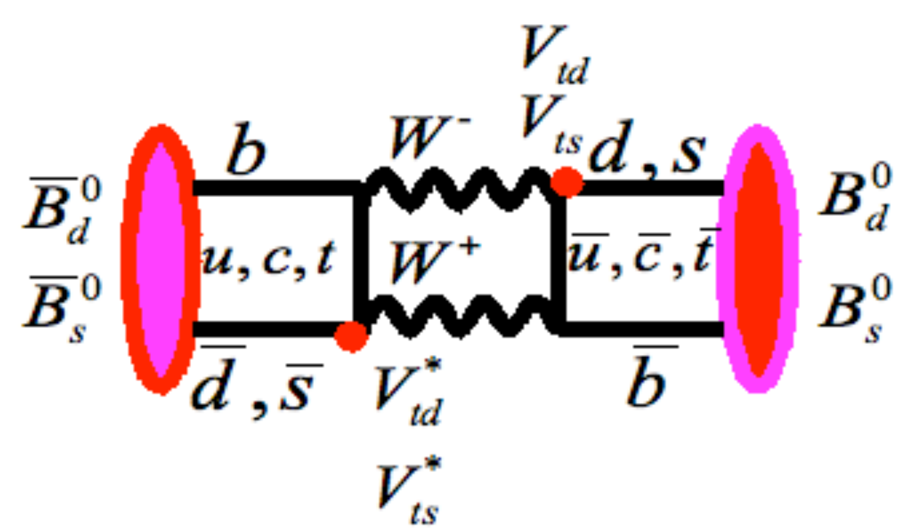
$\Delta B=3$: ~~nucleosynthesis~~

$\Delta B=2$: intriguing!

The Power of Oscillations

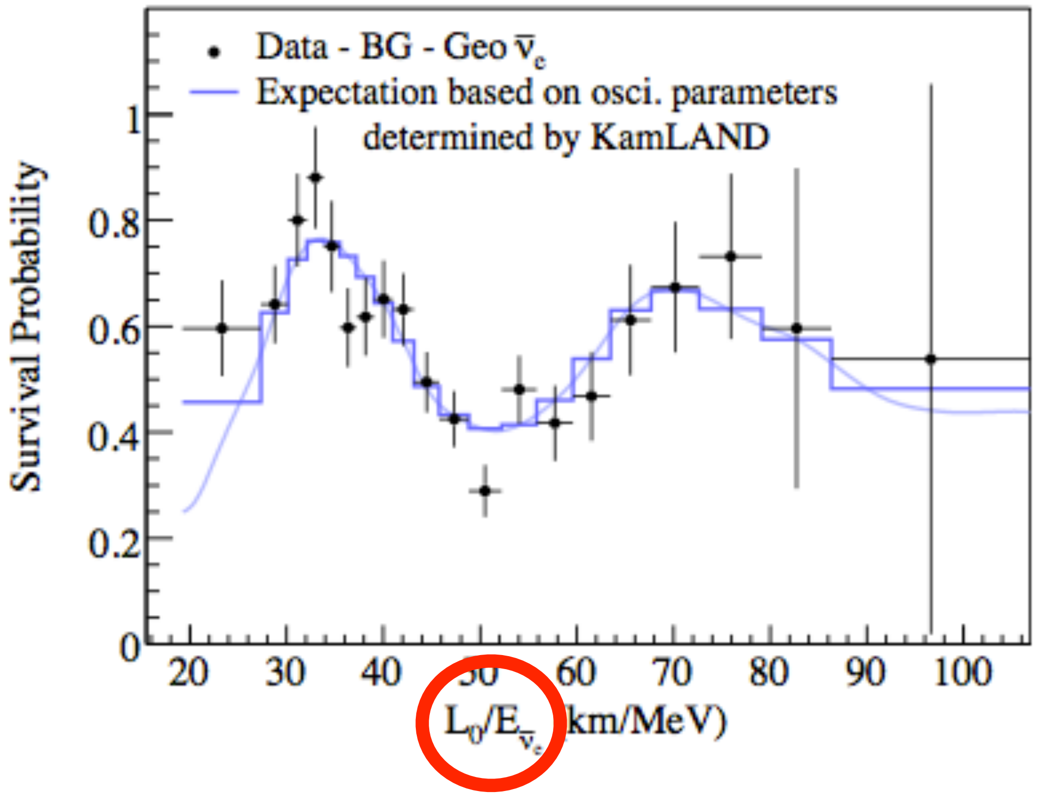
- Neutral particle oscillations have played large role in particle physics
  - K^0-$\bar{K}^0$ oscillations ($\Delta S = 2$) at the core of our initial understanding of CP-violation
  - B meson oscillations (ΔBeauty = 2):
    - Sensitive to CKM elements
    - CP-violation “workhorse”
    - Probe m_t^2/m_W^2
    - ➡ First indication of large top mass! (1987)
- Sensitive probes of high mass scales





Neutrino Oscillations

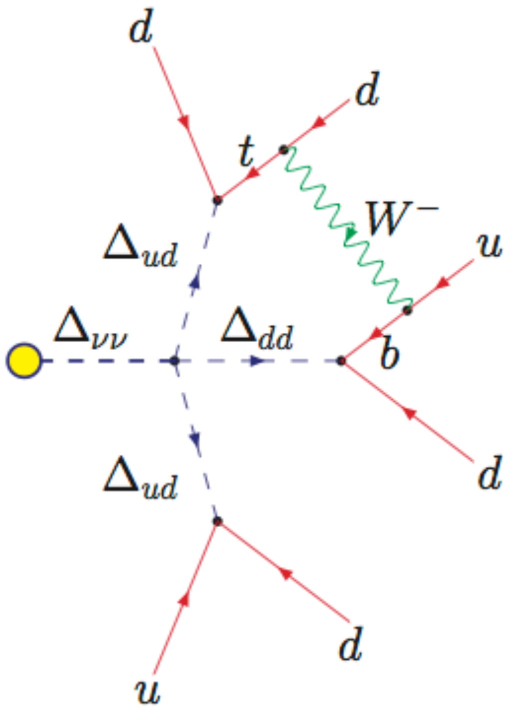
- Neutrino oscillations unambiguously establish neutrinos are massive
  - Since neutral, Majorana mass term allowed
    - If exists, $\Delta L = 2$!
  - If both Dirac and Majorana mass terms, mixing induces see-saw effect, *explaining* small neutrino masses
    - Two scales: Dirac and Majorana mass terms
      - Lead to observed scales $m_\nu \sim m_D^2/M$ and $m_N \sim M$
    - Dirac scale could be close to other fermions
      - Suggests a Majorana ($\Delta L=2$) scale 10^6 - 10^{10} GeV
  - $\Delta B = 2$ in the same range?



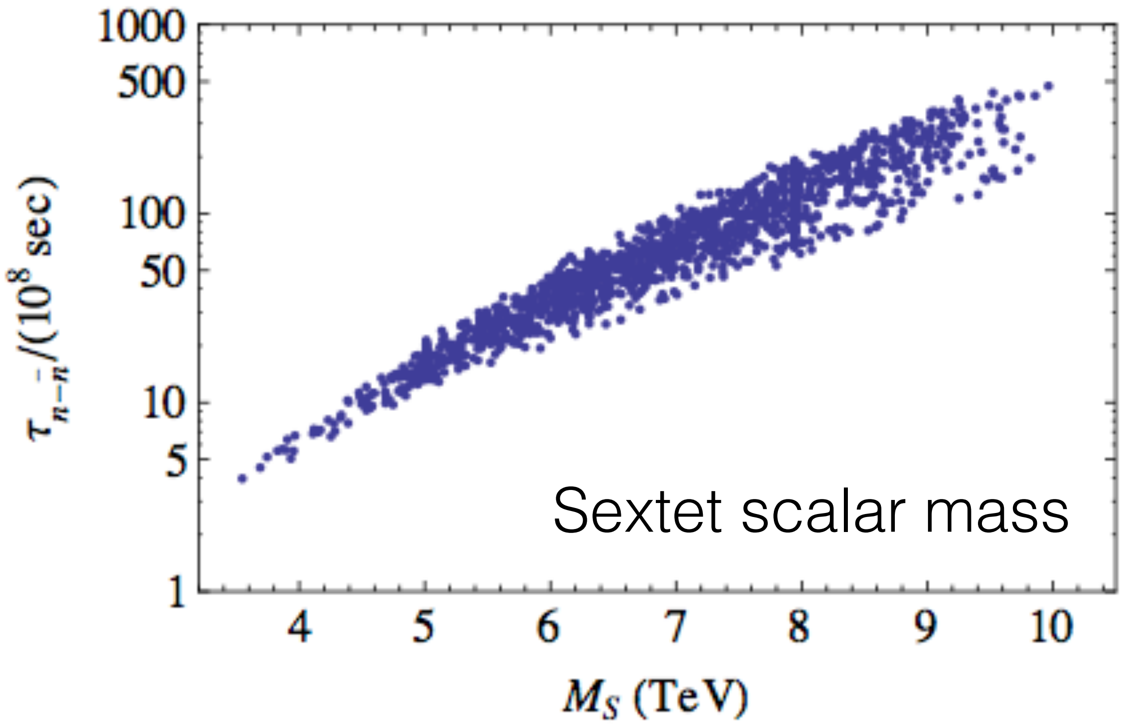
Example: Post-Sphaleron Baryogenesis

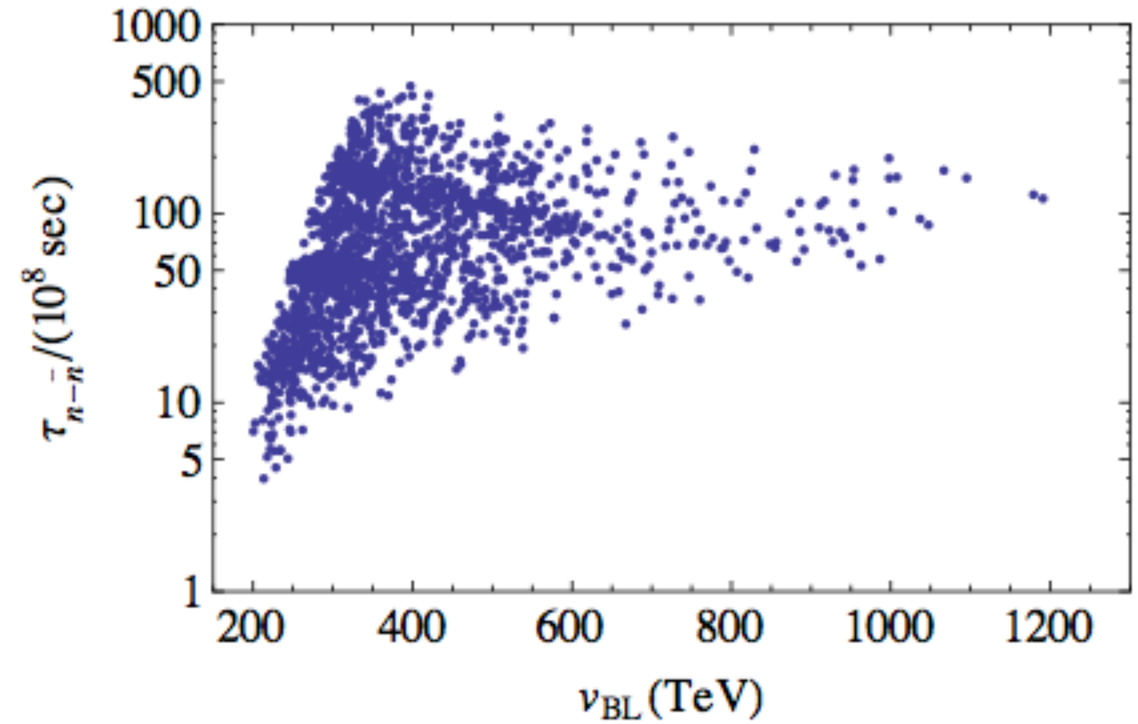
Babu et al., arXiv:1303.6918 (PRD)

- Baryon asymmetry does not rely on electroweak sphaleron process
  - Concrete realizations can be supersymmetric (or not)
  - Embed neutrino see-saw
- Example: $SU(2)_L \times SU(2)_R \times SU(4)_C$, observable consequences:
  - Color sextet scalars in TeV range
  - Neutron oscillations

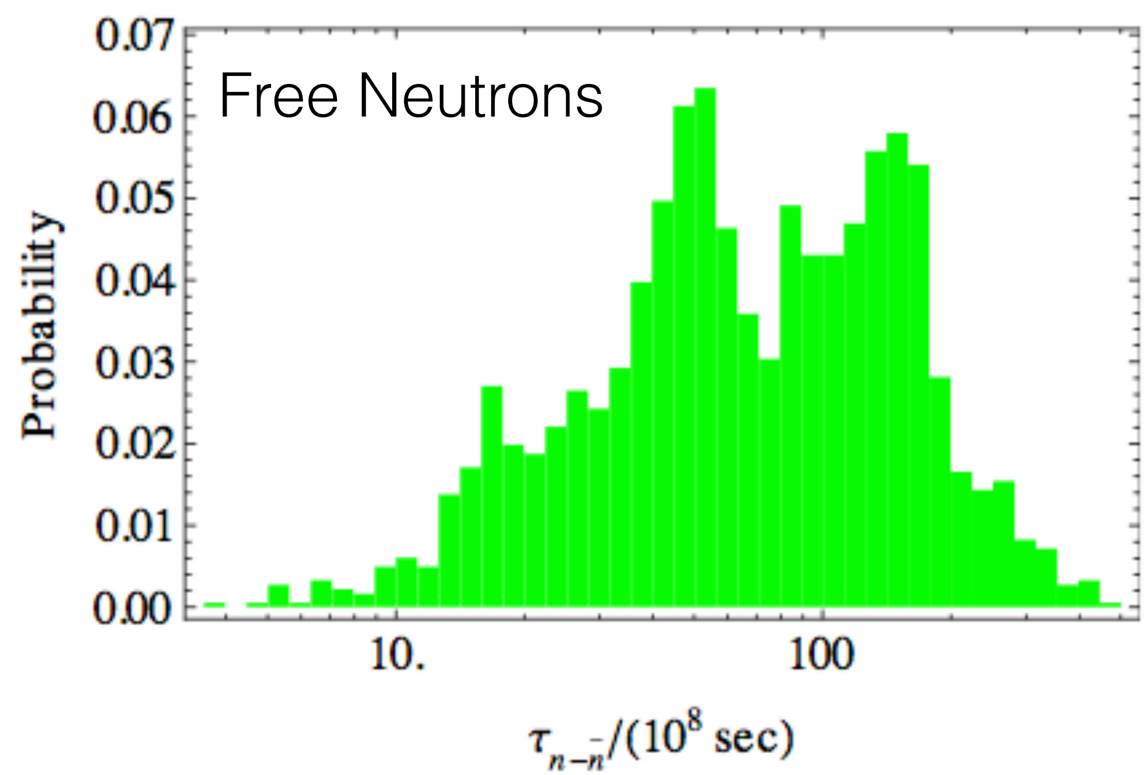


Babu et al., arXiv:1303.6918 (PRD)





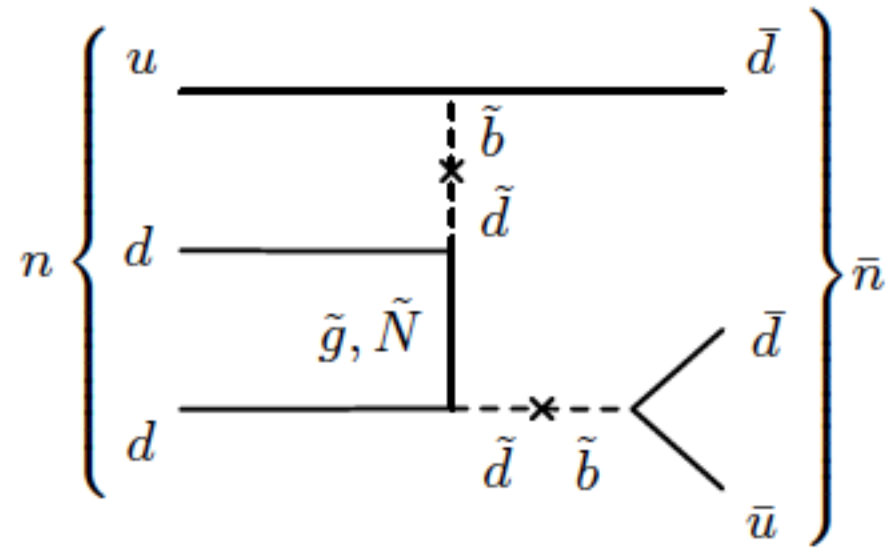
B-L breaking scale



MFV SUSY

Csaki, Grossman, Heidenreich, Phys.Rev. D85 (2012) 095009

- Two big SUSY issues:
  - R-parity often imposed “ad hoc”
  - Why would flavor align with SM?
- If assume minimal flavor violation → can have R-parity as accidental, approximate symmetry
- In limit of $m_\nu = 0$
  - Proton stable
  - No lepton number violation



➡ n-n̄ primary probe of baryon number violation

$$t_{\rm osc} \sim (9 \times 10^9\ {\rm s}) \left(\frac{250\ {\rm MeV}}{\tilde{\Lambda}}\right)^6 \left(\frac{m_{\tilde{q}}}{100\ {\rm GeV}}\right)^4 \left(\frac{m_{\tilde{g}}}{100\ {\rm GeV}}\right) \left(\frac{45}{\tan\beta}\right)^6$$

Other Examples

- Left-right symmetric MSSM

Babu and Mohapatra, hep-ph/0108089 (PLB)

  - Model addresses MSSM issues: SUSY CP, strong CP, μ-problem
  - Majorana neutrinos, $\Delta L=2$ and $\Delta B=2$
  - Through see-saw, find $\tau_{n\bar{n}} \sim m_\nu$
    - Leads to *upper* limit on $\tau_{n\bar{n}}$ of 10^9-10^{10} s (frequency goes *up* with L-R breaking scale)
- Extra dimensions with SM particles in the bulk

Nussinov and Shrock, hep-ph/0112337 (PRL)

  - Current limits already probe effective scale $\geq$ 45 TeV
    - Relevant range for models of that type

Review: Mohapatra arXiv:0902.0834

Particle Physics Strategy

European:

h) Experiments studying quark flavour physics, investigating dipole moments, searching for charged-lepton flavour violation and performing other precision measurements at lower energies, such as those with neutrons, muons and antiprotons, may give access to higher energy scales than direct particle production or put fundamental symmetries to the test. They can be based in national laboratories, with a moderate cost and smaller collaborations. *Experiments in Europe with unique reach should be supported, as well as participation in experiments in other regions of the world.*

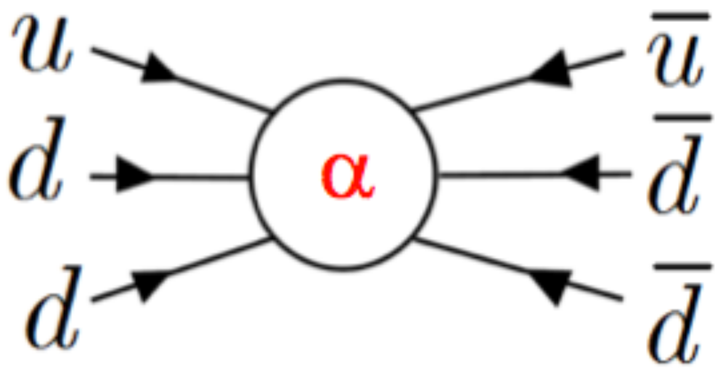
US P5 report:

- With a mix of large, medium, and small projects, important physics results will be produced continuously throughout the twenty-year P5 timeframe. In our budget exercises, we maintained a small projects portfolio to preserve budgetary space for a set of projects whose costs individually are not large enough to come under direct P5 review but which are of great importance to the field. This is in addition to the aforementioned small neutrino experiments portfolio, which is intended to be integrated into a coherent overall neutrino program.

Consensus in the field that we should pursue combination of energy frontier searches (hierarchy) and probing of non-understood symmetries

Experimental Aspects

Process, Critical Parameters



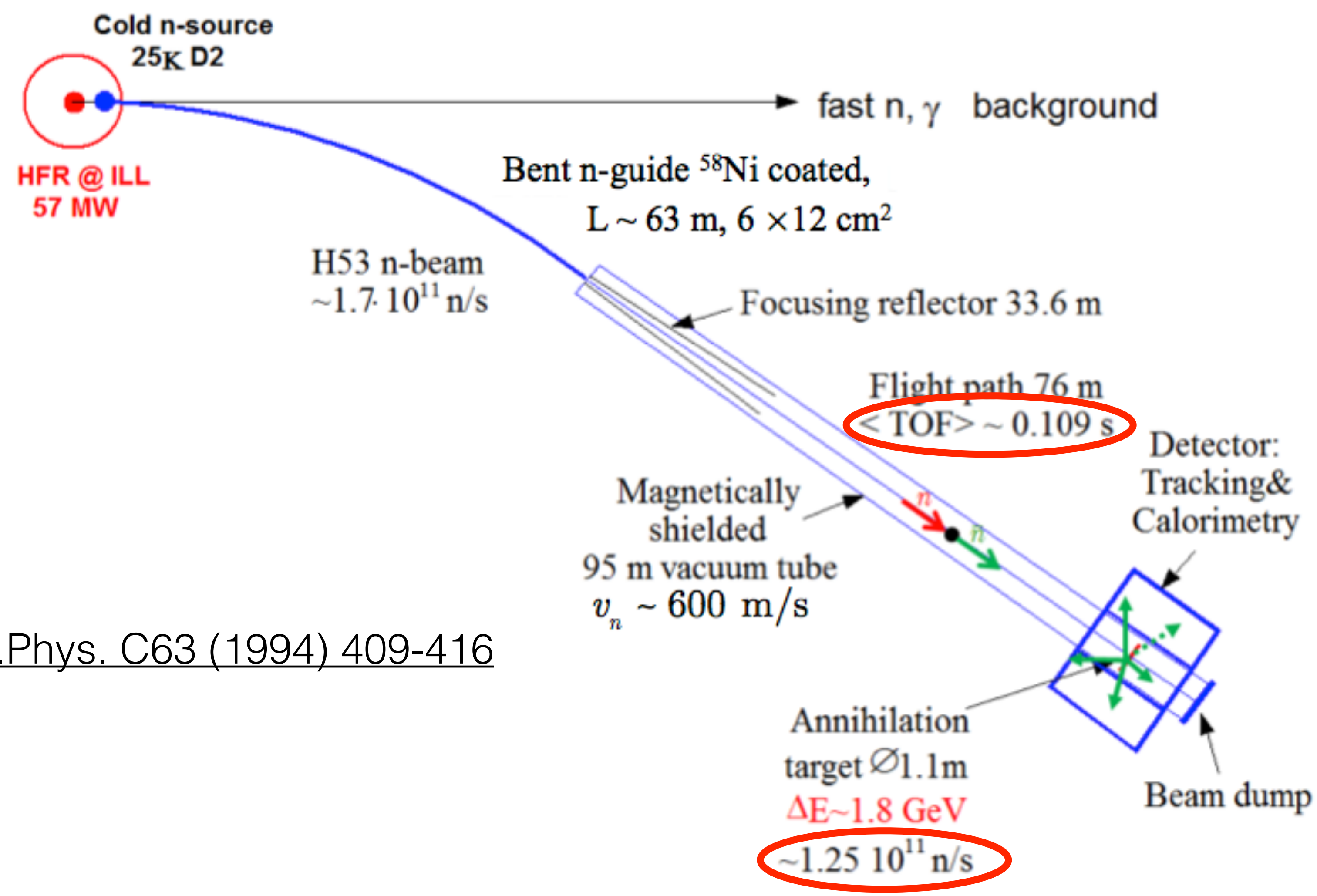
$$P_{n\to\bar{n}}(t) = \frac{\alpha^2}{\alpha^2 + V^2} \cdot \sin^2\left(\frac{\sqrt{\alpha^2 + V^2}}{\hbar} \cdot t\right)$$

- Potential V (if antisymmetric for n vs $\bar{n}$)
  - Nuclear potential ~100 MeV
  - $\mu_n . B_{Earth} \sim 10^{-18}$ MeV
  - Current limit: $\alpha < \sim 10^{-30}$ MeV
- Leads to strong suppression
  - Free neutron experiment requires substantial cancellation of Earth magnetic field, then:

$$P_{n\to\bar{n}} = \left(\frac{\alpha}{\hbar} \times t\right)^2 = \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$$

  - For free neutron experiment, magnetic field can be used to check result if signal is seen

Current Limits

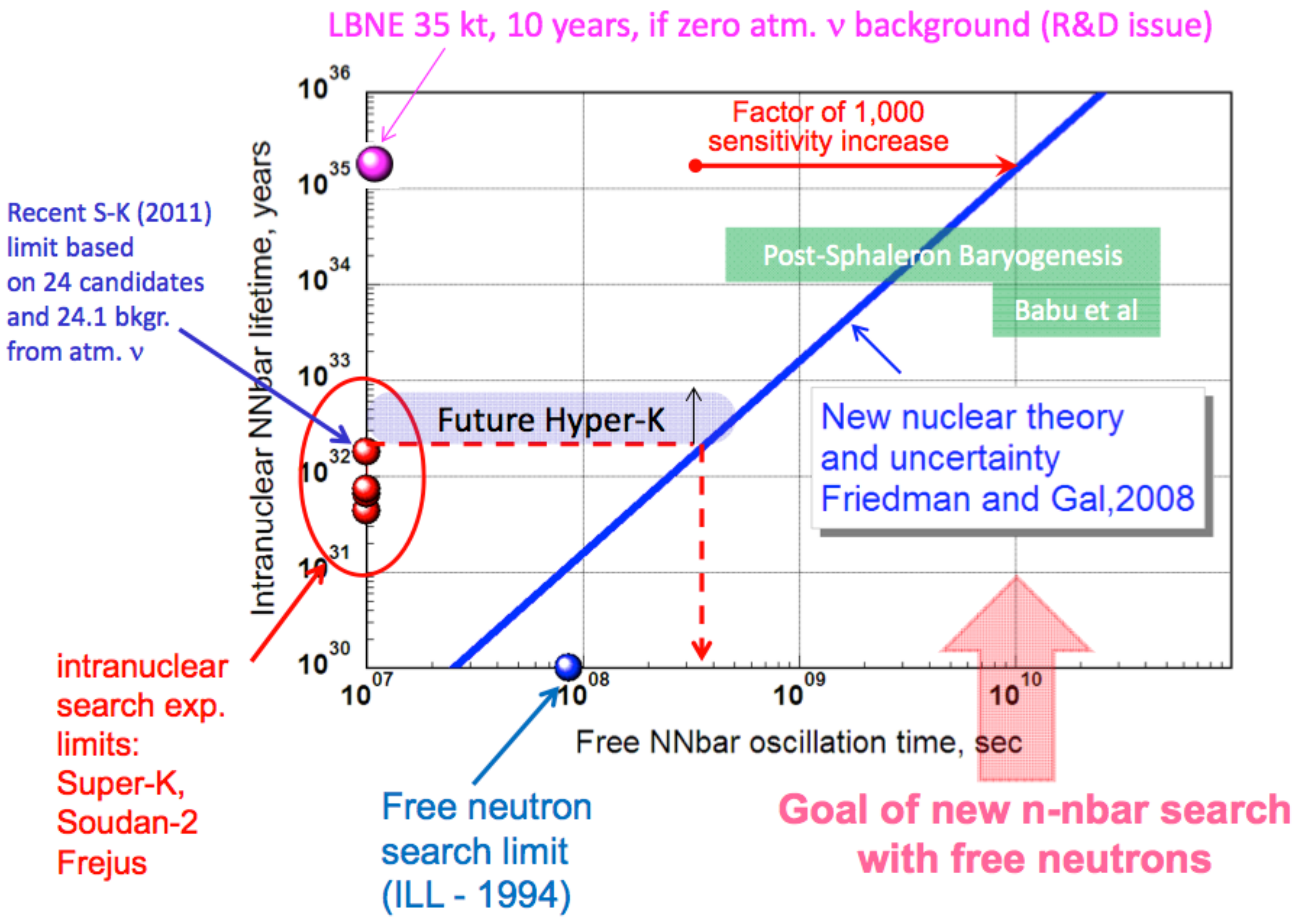


Baldo-Ceolin et al, Z.Phys. C63 (1994) 409-416

- $Nt^2 = 1.5\ 10^9$s, $P < 1.6\ 10^{-18}$ (run lasted ~1 year) and $\tau > 0.86\ 10^8$s
  - Many subtle optimizations to minimize losses and backgrounds
  - Experiment was background-free
- Bound neutron limits ~3 times better
  - But model-dependent, and now limited by atmospheric ν background

$$\tau_{bound} = R \times \tau^2_{free}$$

Free Neutron vs Bound Neutrons NNbar Search Sensitivity Comparison



Next Generation Free Neutron Experiment

- Increase number of neutrons
  - Flux
  - Moderator brightness and area
  - Angular acceptance
  - Longer run
- Increase time-of-flight
  - Colder neutrons
  - Longer beamline
- Keep (or even increase) detection efficiency (~50%), keep background at ~0
  - Exploit current, established hardware and software technologies
- Better B_{Earth} suppression
  - Improved passive (+ active?) shield

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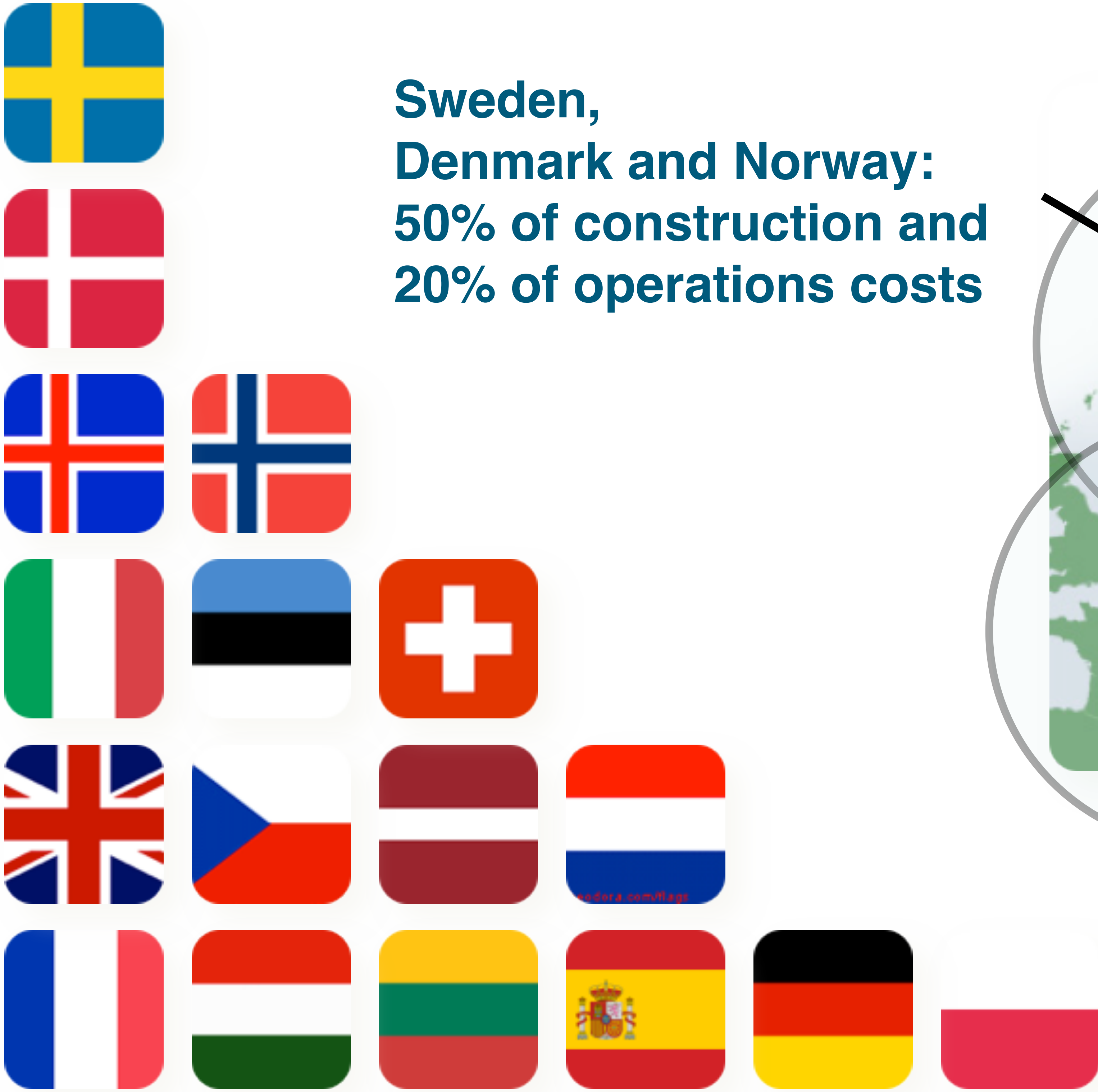
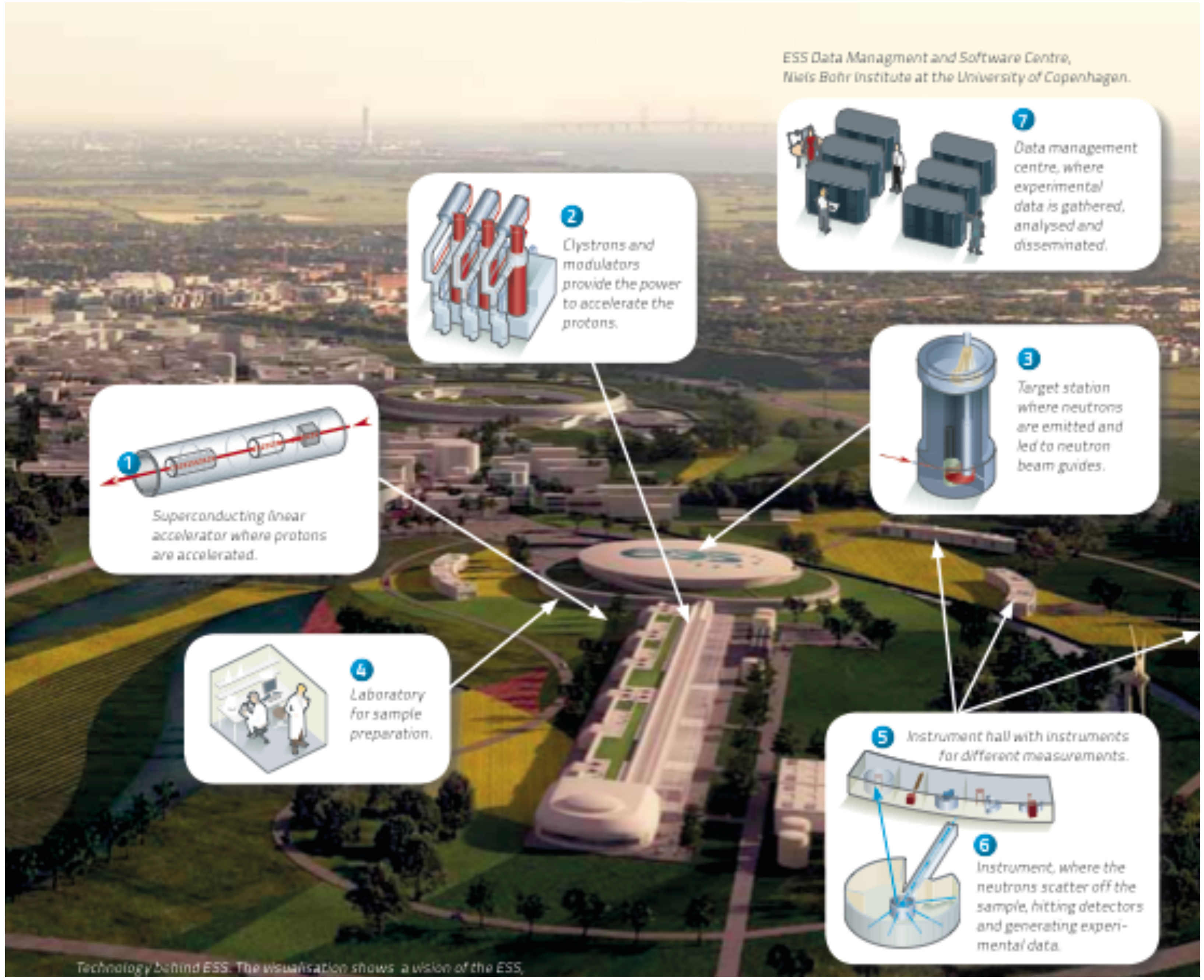
European Spallation Source

An International Collaboration

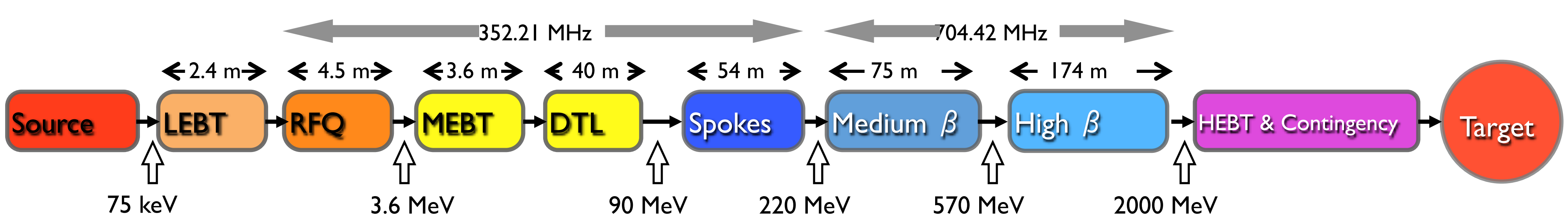


Sweden,
Denmark and Norway:
50% of construction and
20% of operations costs

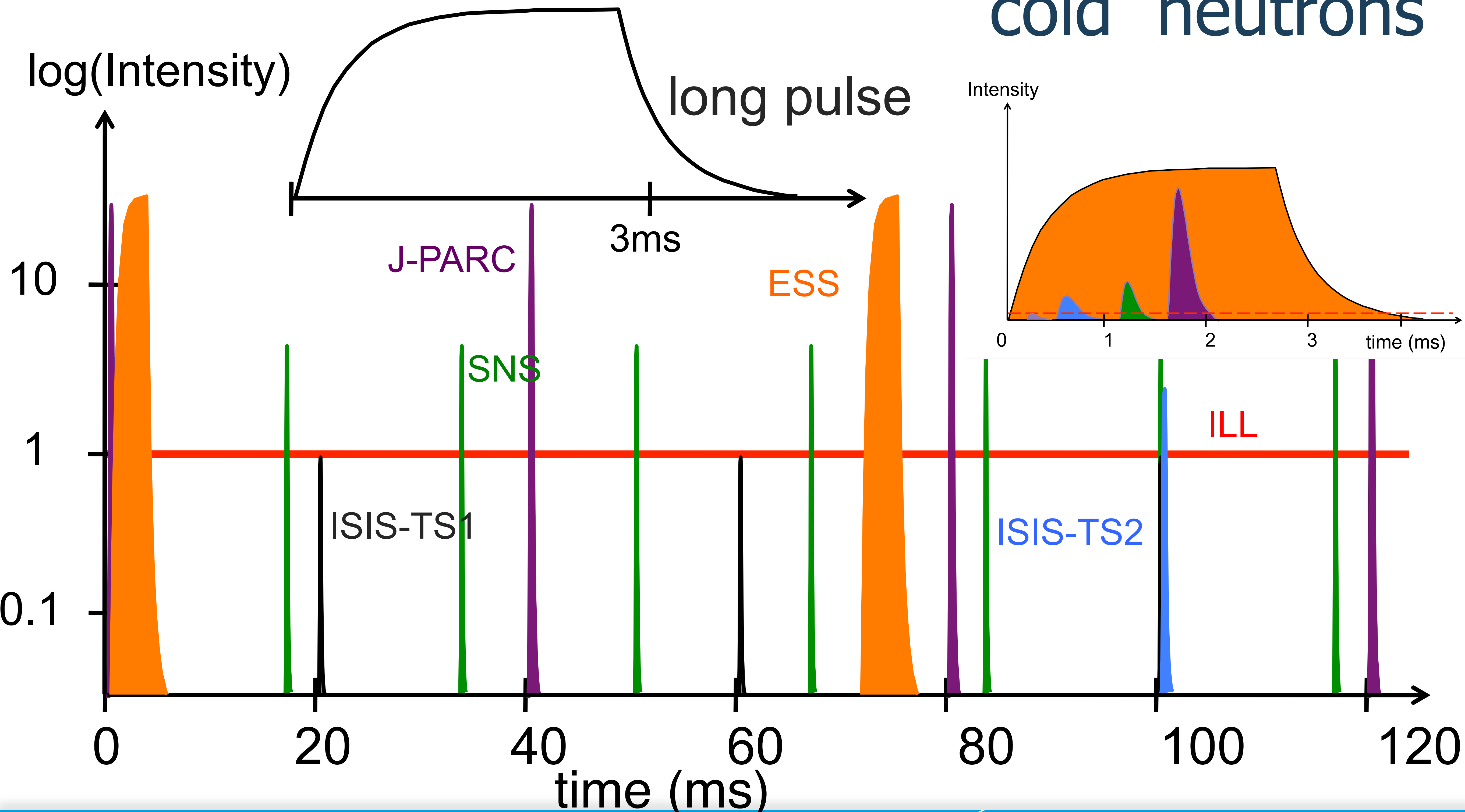
European partners pay the rest



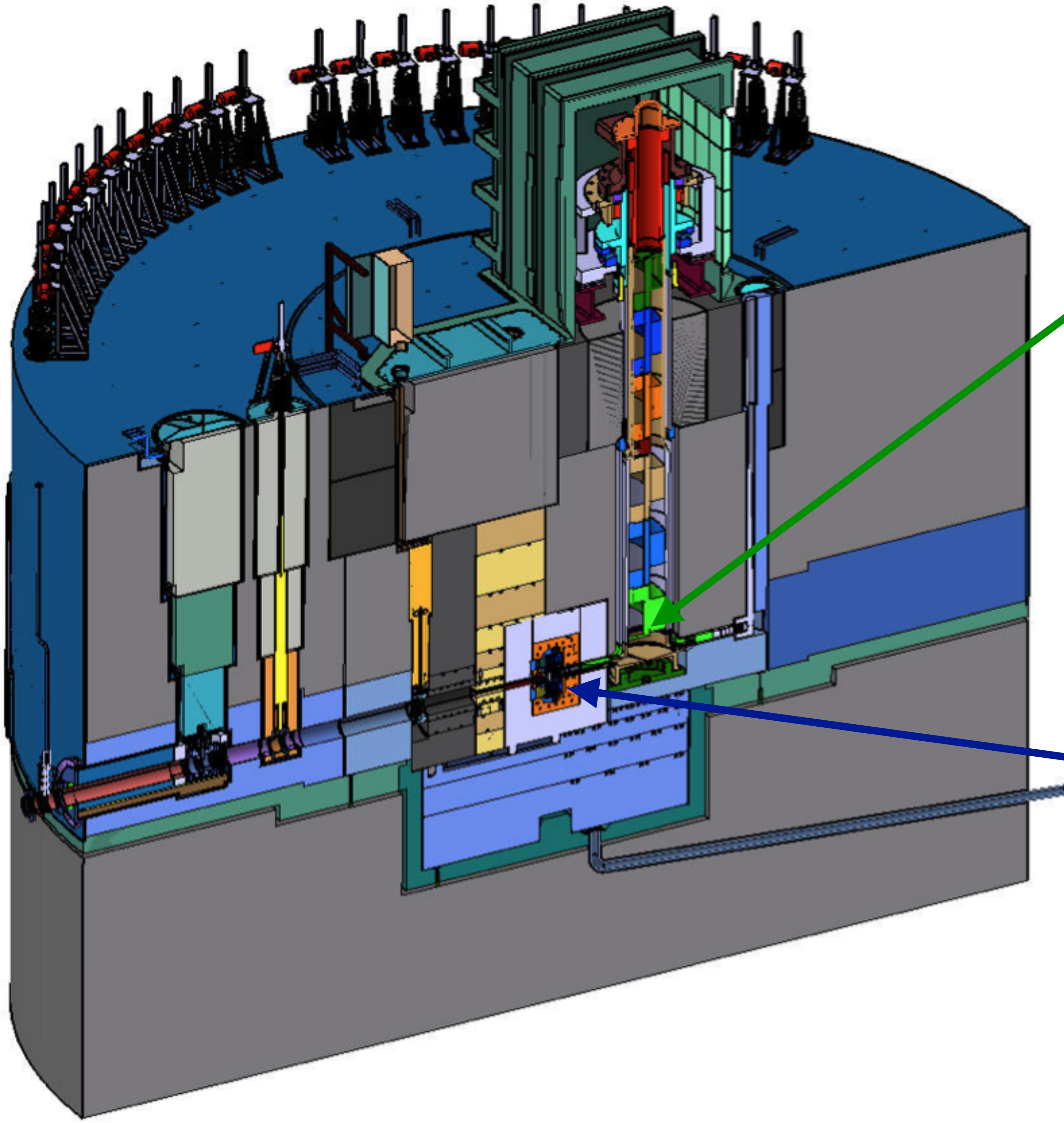
2.3 GeV superconducting linac, 14 Hz, 5 MW



Pulsed-source time structures cold neutrons



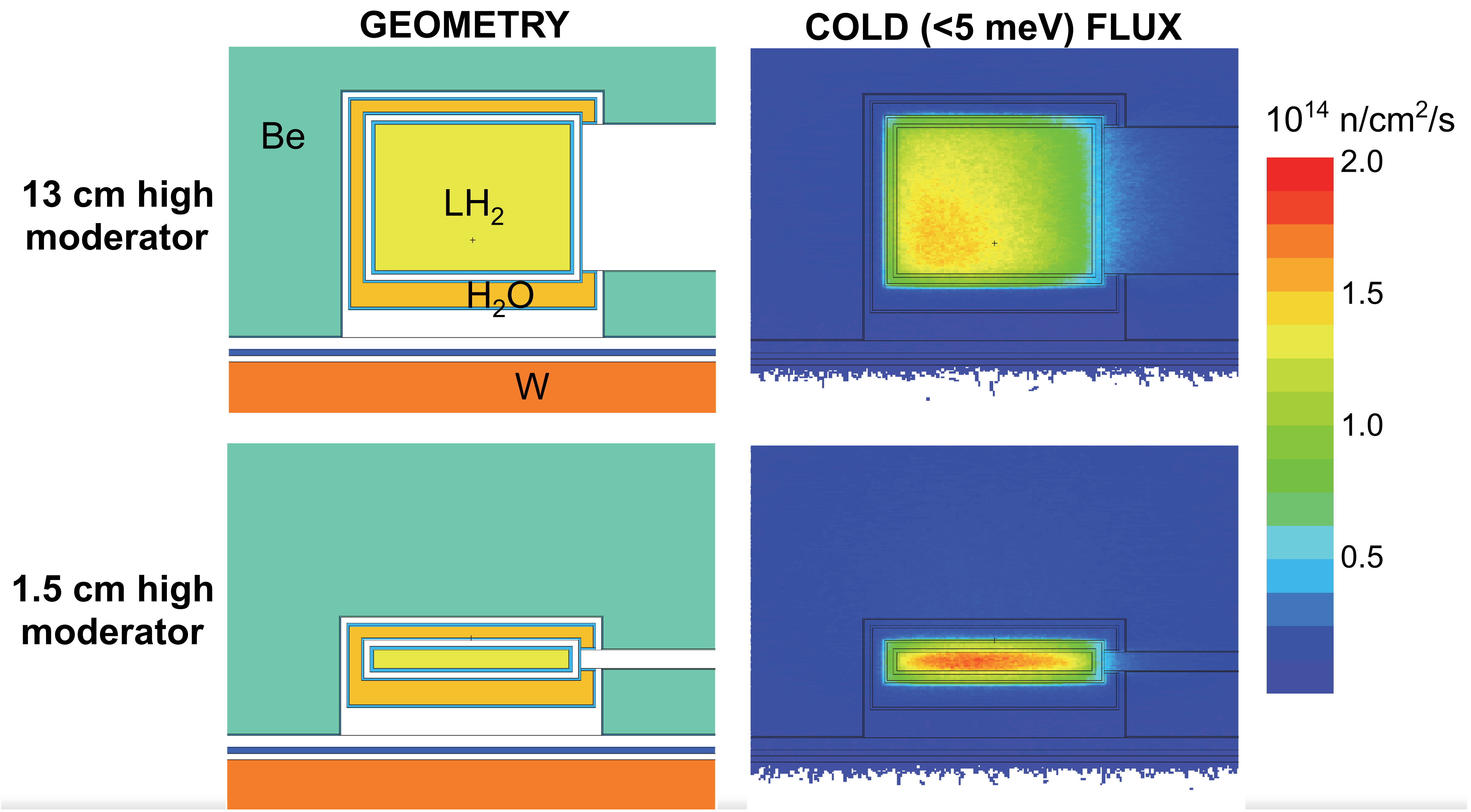
Target station: the monolith



Rotating Tungsten Target: 5 year lifetime

Moderator optimization on-going (Yearly intervention)

- Flat moderator gives higher brightness
  - Better for neutron scattering… but we care mainly about flux



Work in progress

ESS Timeline

- 2014: Construction start
- 2019-2022: Initial phase: commissioning, intensity ramp, experiments by friendly users
  - Experiment completion, commissioning, physics start
- 2023-2025: Initial user program operations: reliable operations with public users; establish basis for future cost sharing
  - Physics run
- 2026+: routine operations, completion of final public instruments

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- Keep (or even increase) detection efficiency (~50%), keep background at ~0
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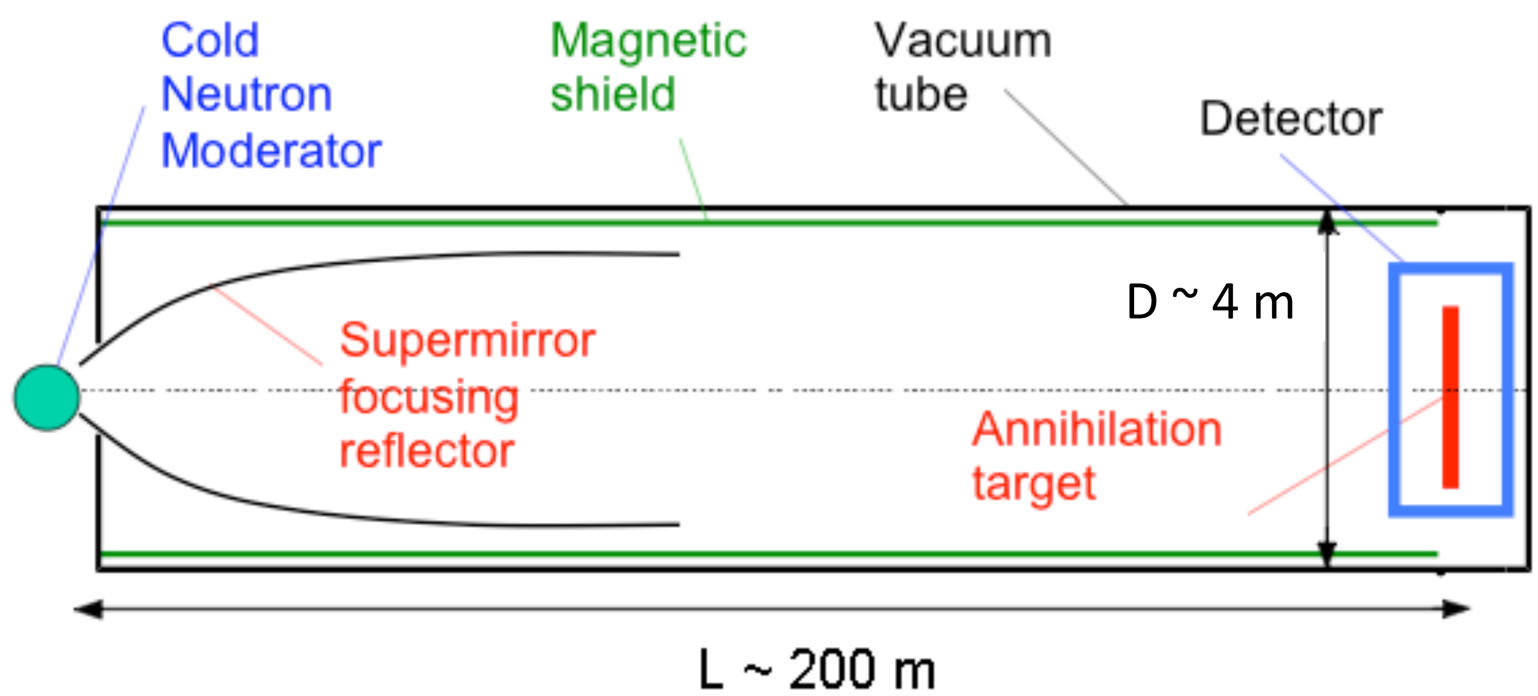
The Experiment

Conceptual Design



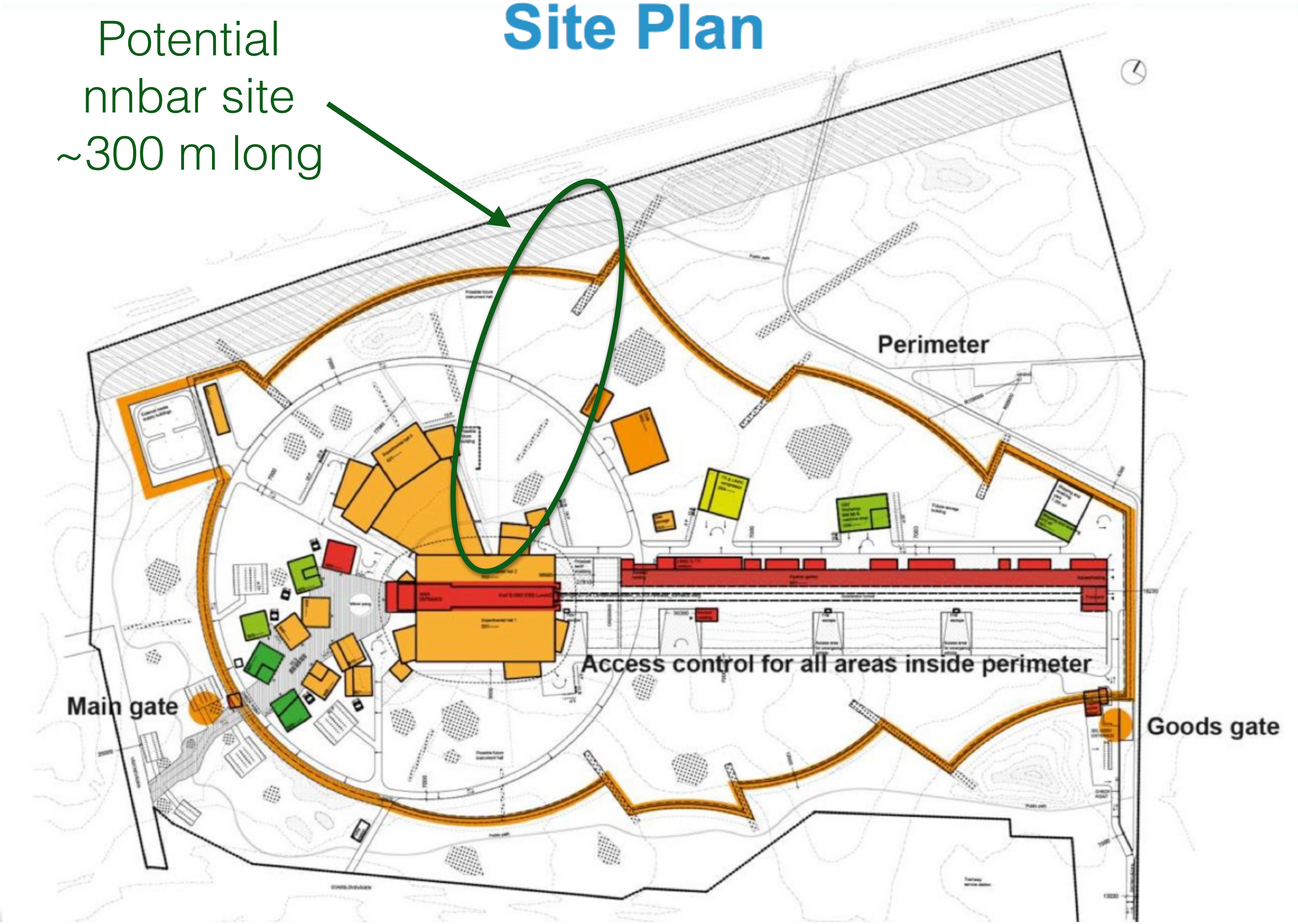
See e.g. NNbarX (Babu et al.), http://arxiv.org/abs/arXiv:1310.8593

- High-m super-mirror
- Residual B field < 5 nT
- Good vacuum < 10^{-5} Pa

MC optimization of parameters ongoing!

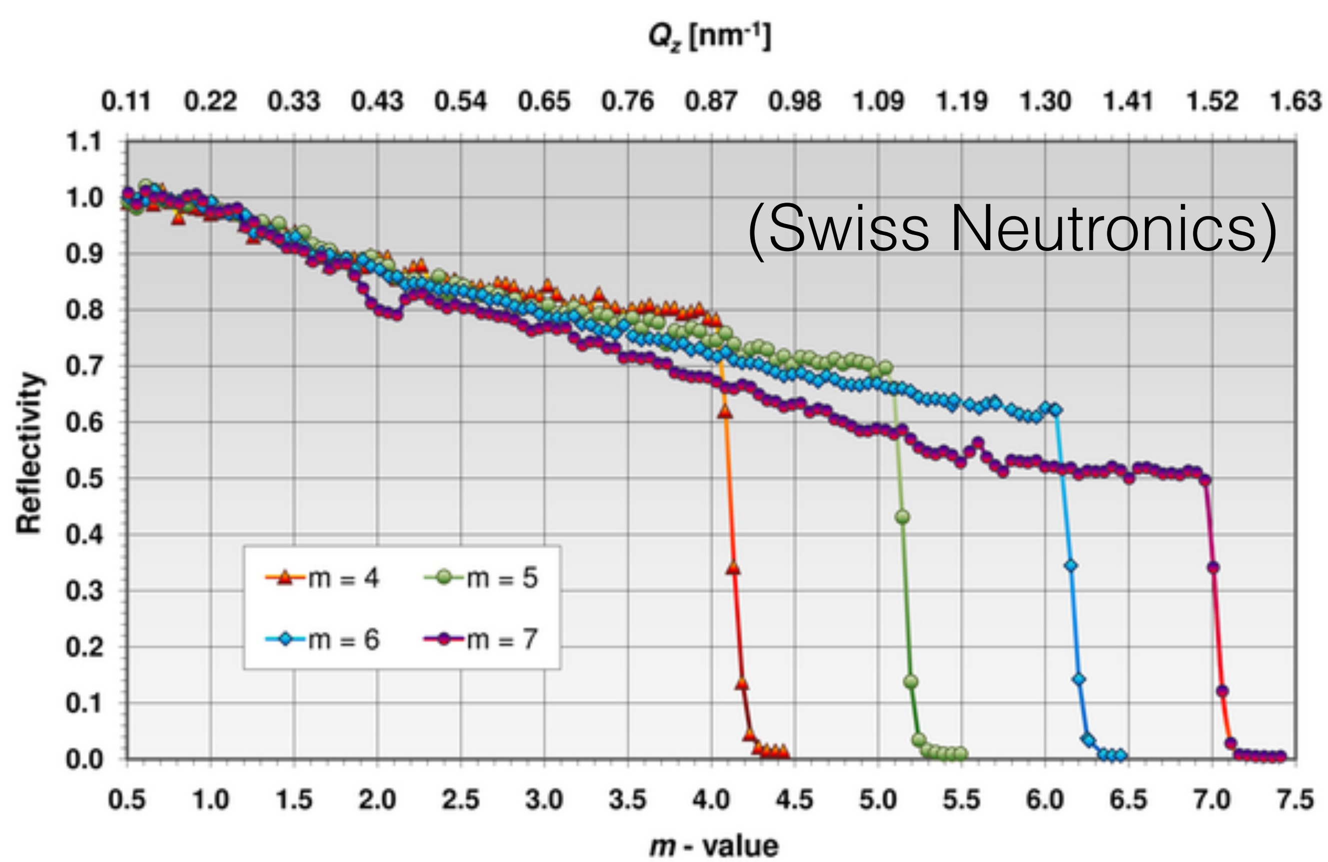
Site Plan

Potential
nnbar site
~300 m long



Supermirror

- Crucial in acceptance gain
  - 2D, so acceptance scales quadratically
  - Modern multi-layer supermirrors have good reflectivity at increasingly large momentum transfers



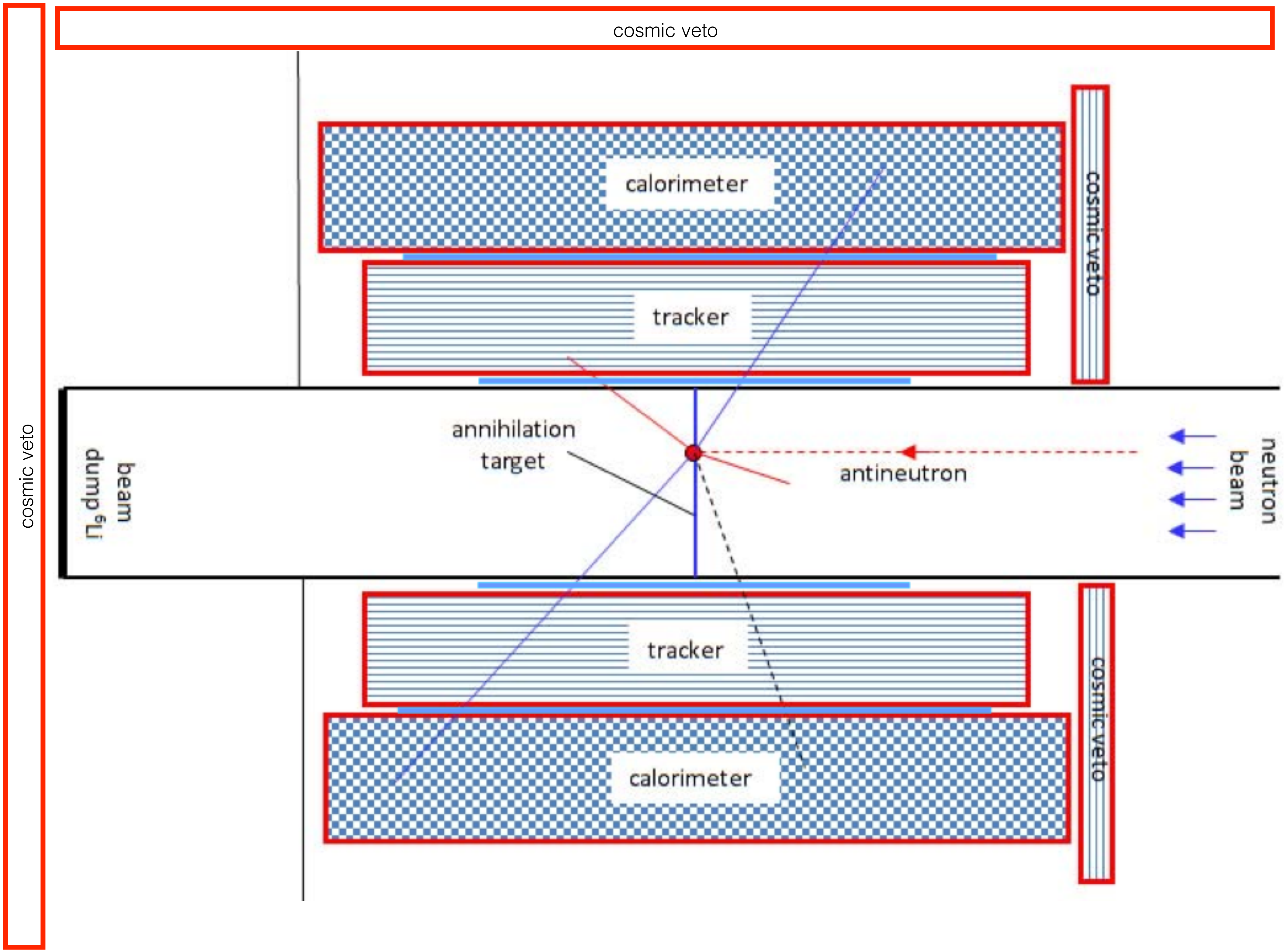
Active R&D at Nagoya University, with devices used at JPARC

Ni reflectivity → 0 defines m=1

Detector

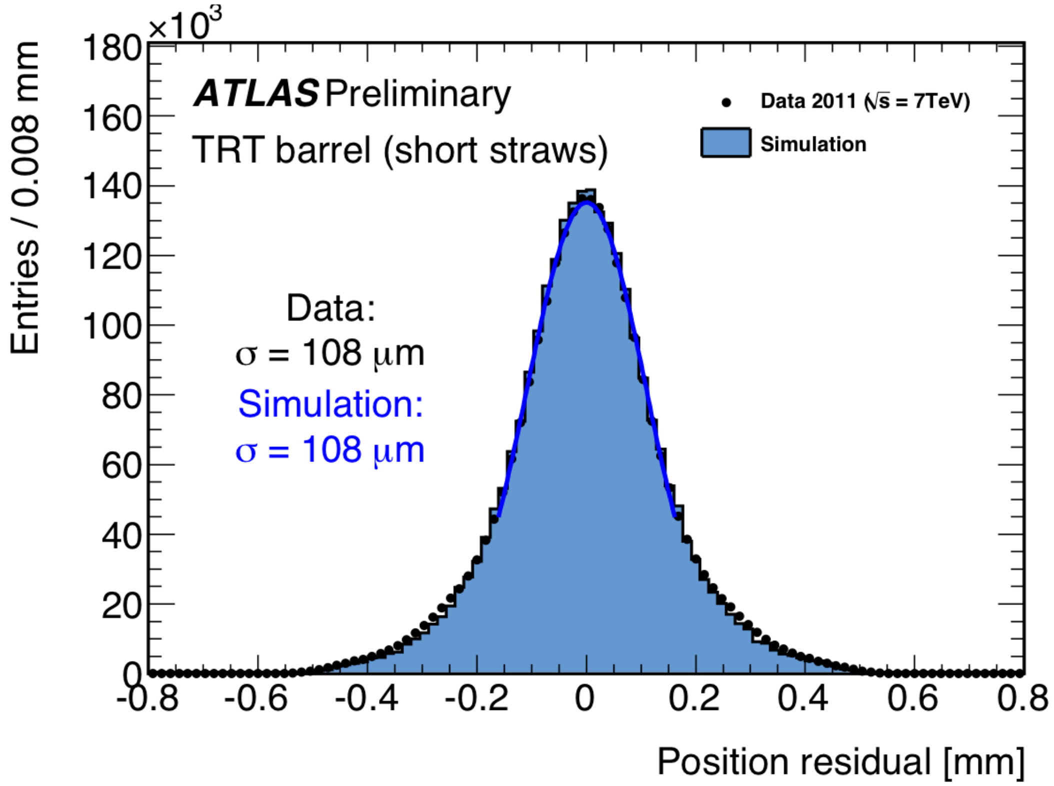
- Anti-neutron annihilation target
  - High annihilation probability, low Z, high transparency to neutrons
    - ILL experiment used a carbon foil, 130 μm thick
- Annihilation produces pions, <n> ~ 5
- Background suppression:
  - Precise annihilation vertex identification
  - Good mass resolution
  - Beam time structure? (If see signal)

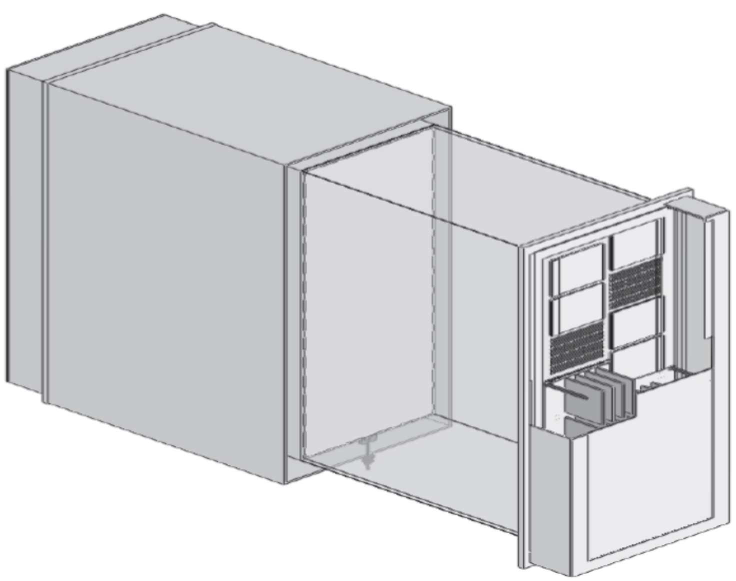
Detector


cosmic veto
cosmic veto
calorimeter
cosmic veto
tracker
annihilation
target
antineutron
neutron
beam
beam
dump
^{6}Li
tracker
calorimeter
cosmic veto

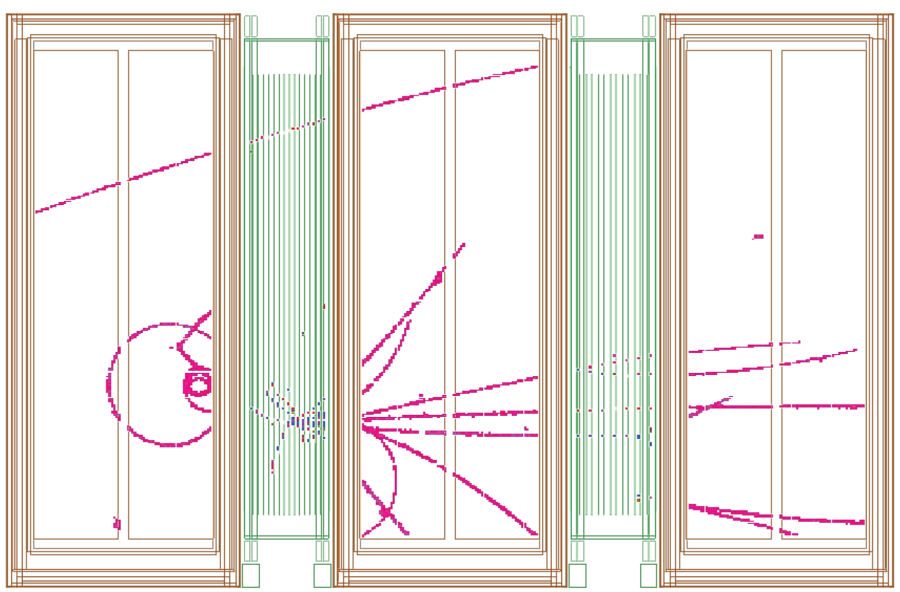
Tracker

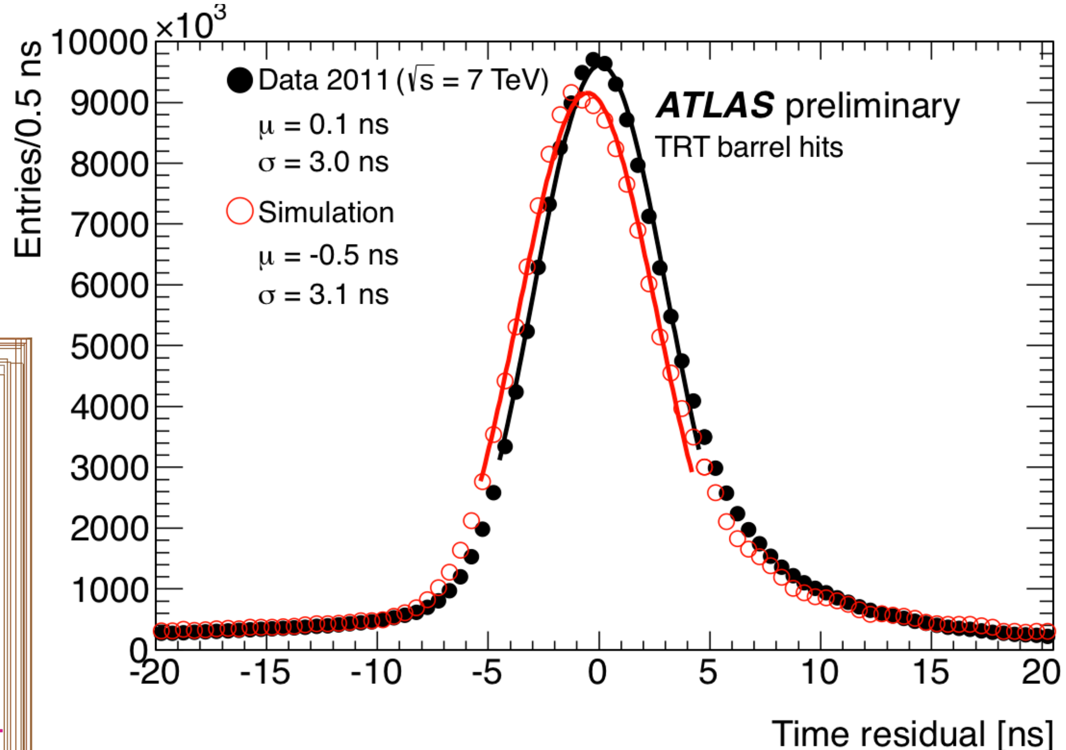
- Weighing hybrid solution
  - Few layers of straws inside vacuum
    - Track trigger + high precision points before wall
  - TPC outside





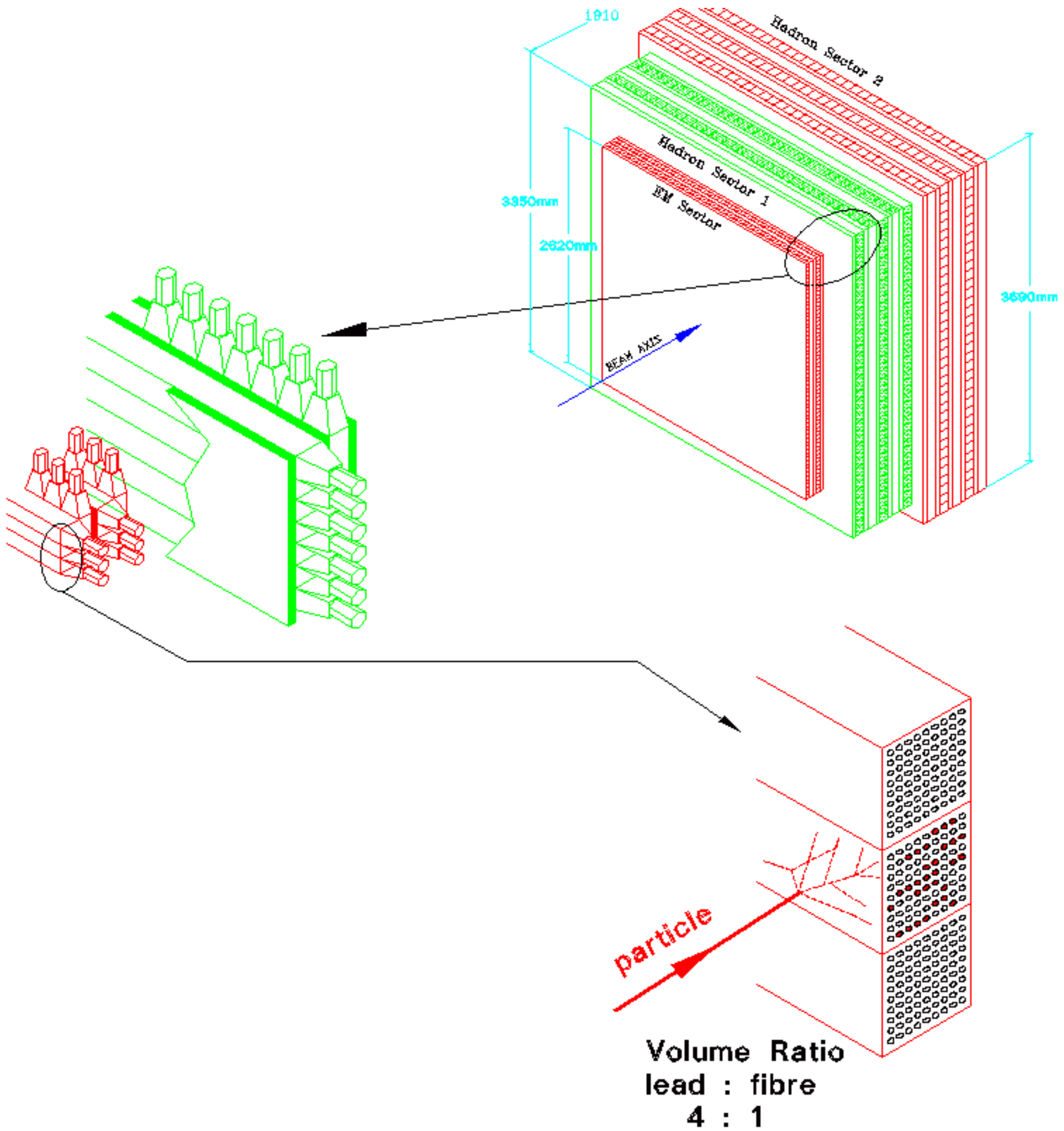
T2K TPC Box
Micromegas read-out



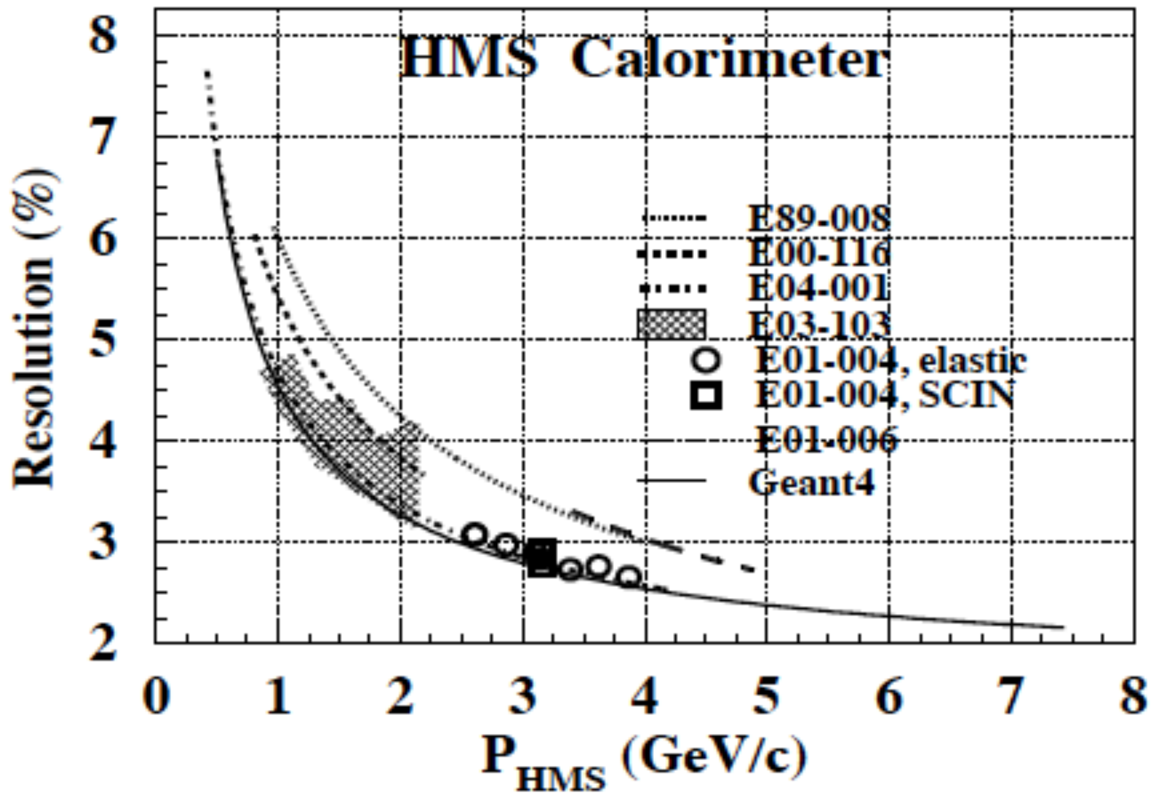


Calorimeter

- One possibility: spaghetti lead-scintillating fiber (as in CHORUS)
  - Good precision (achieved ~10%/√E in electromagnetic, compensating)
  - Fairly easy to build and operate
  - Cost-effective



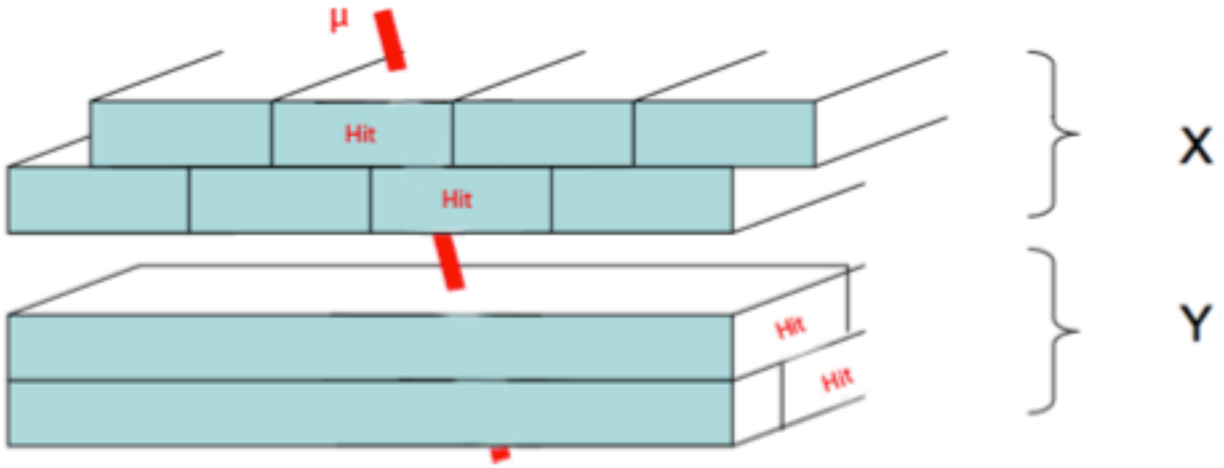
- Lead-glass?
  - Used for JLab calorimeters
    - Achieved 5-6%/√E in range 0.5-5 GeV for electrons

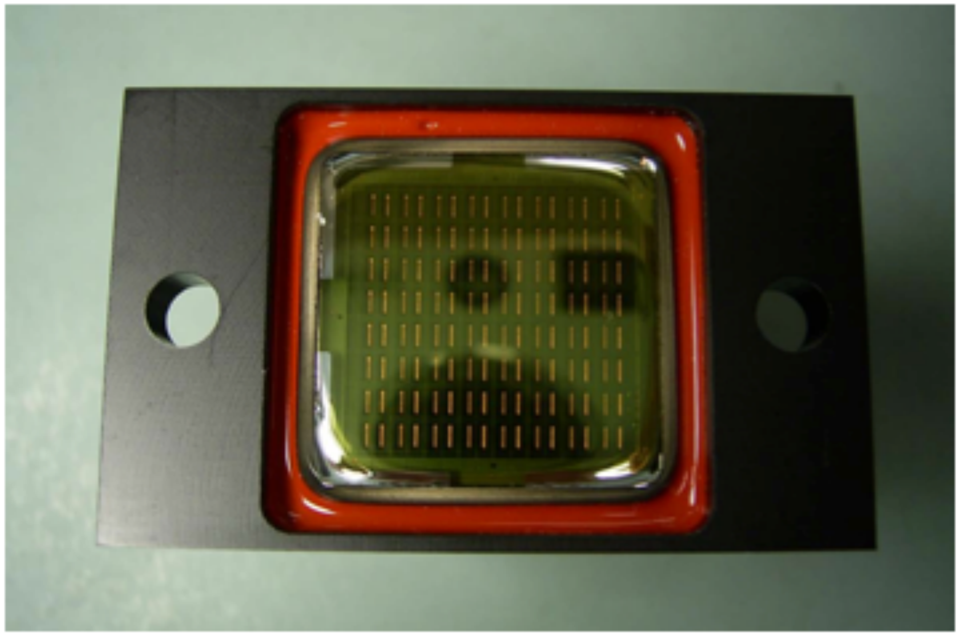


    - Radiation tolerance? Response drops by e after ~2 kRad
- BGO seems overkill

Cosmic Veto/TOF

- Simulation needed to see if necessary
- Potentially recyclable from Double Chooz or similar?
- In any case should be fairly cheap
    - Same readout as calorimeter?





64 pixel
Hamamatsu PMT

Trigger and DAQ

- High neutron flux likely to induce high single hit rates in individual detector elements
  - Multiple interested institutions have extensive experience in designing sophisticated hardware trigger systems
  - Number of channels will be relatively low by modern FPGA standards, so cost should be moderate
  - Algorithms fairly simple
- "Rate to tape"
  - Driven by offline computing resources
  - But events will be small, so not expected to affect physics

Expected Sensitivity

Potential Gains wrt ILL

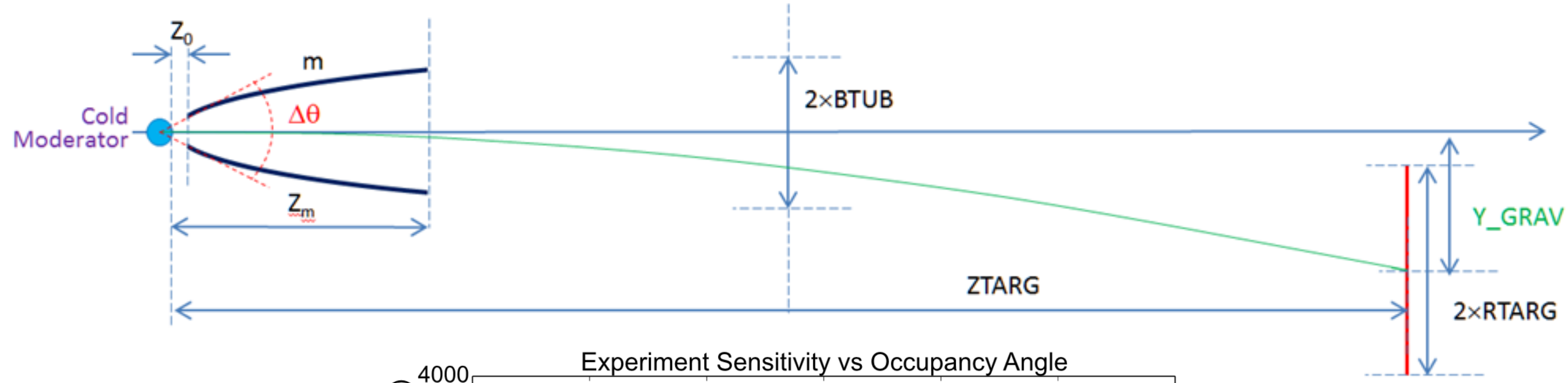
Brightness		≥ 1
Moderator Temperature	<TOF> driven by colder neutrons, ~quadratic (t^2)	≥ 1
Moderator Area	Needs large aperture	2
Angular Acceptance	2D, so quadratic sensitivity	40
Length	Scale with t^2, so L^2	5
Run Time	ILL run was 1 year	3
Total		≥ 1000

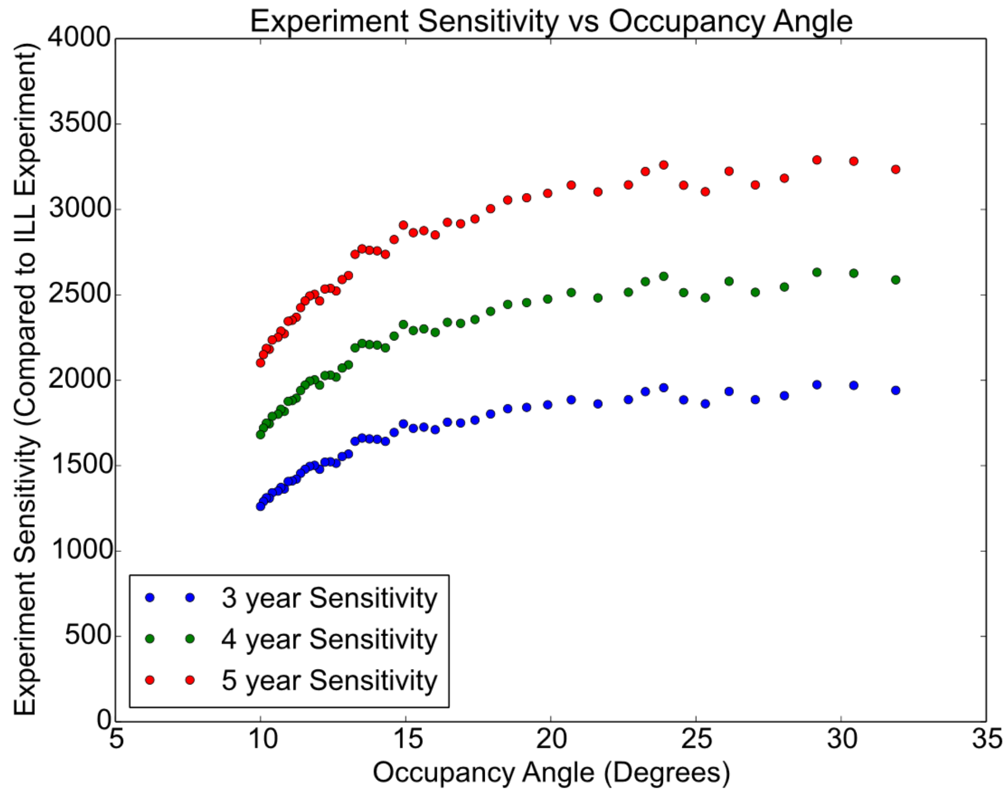
x 1000 in probability, reach $\tau \sim$ 2-3 x 10^9 s

(simulations with various moderator options underway)

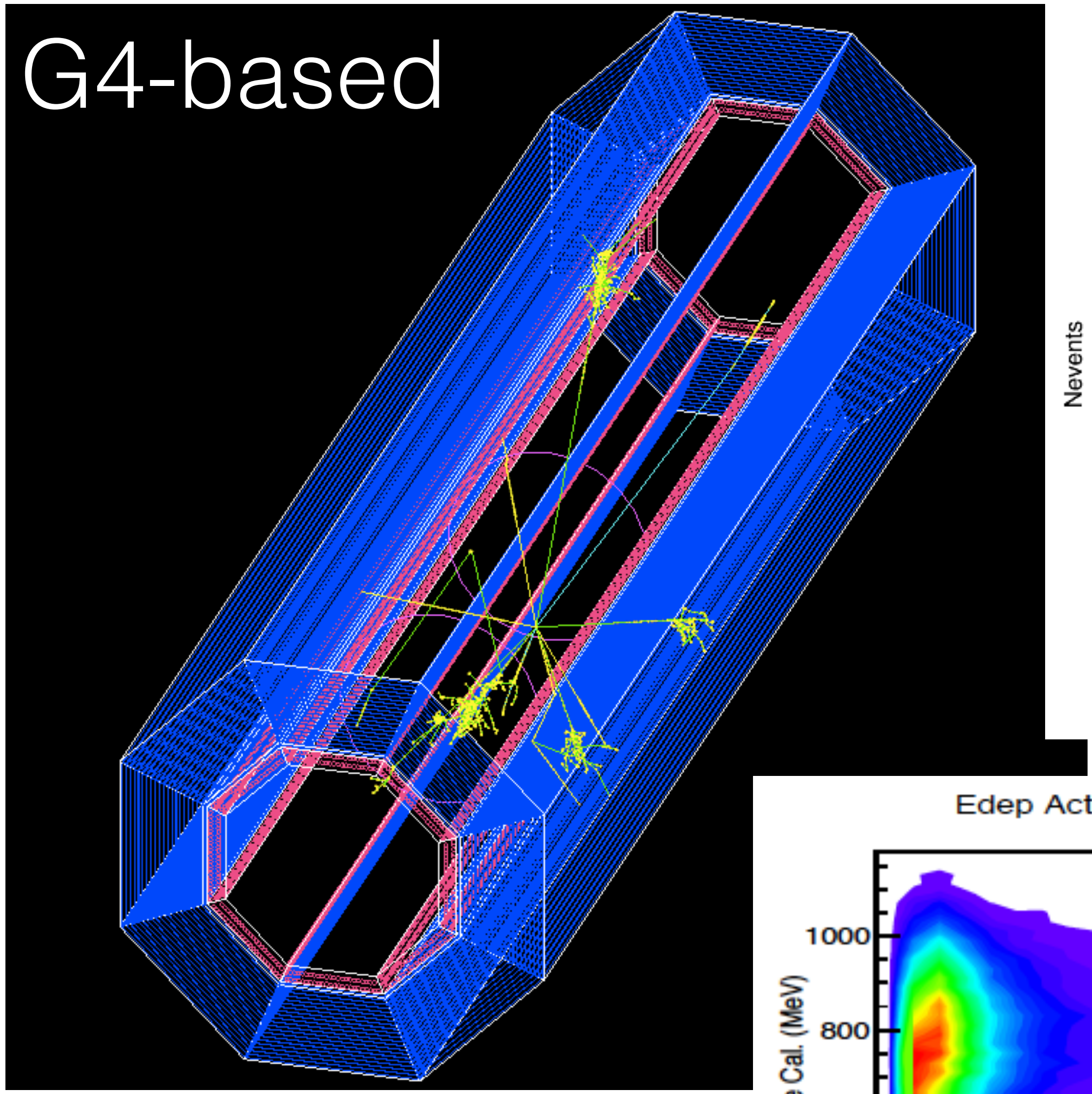
Early Simulations: Sensitivity

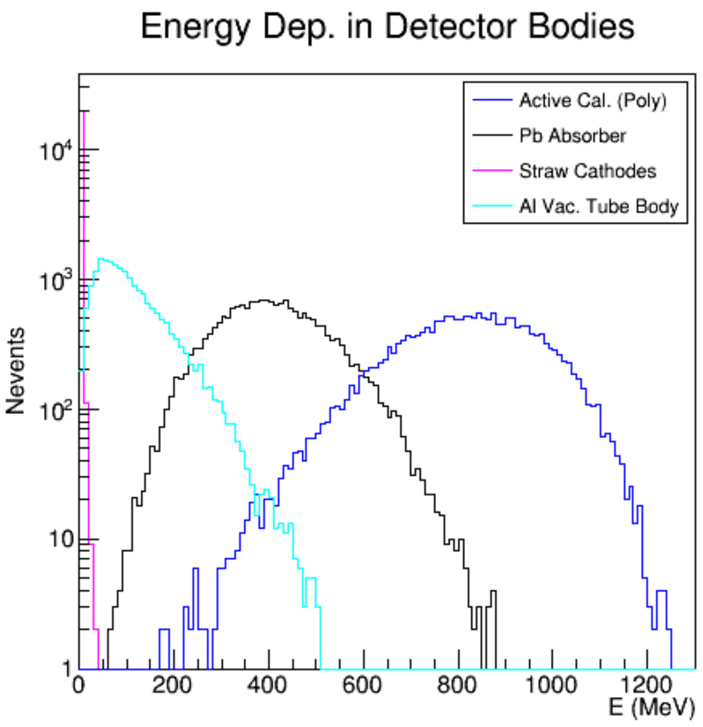
- Neutron spectrum files from ESS
- 50% detection efficiency (as for ILL)

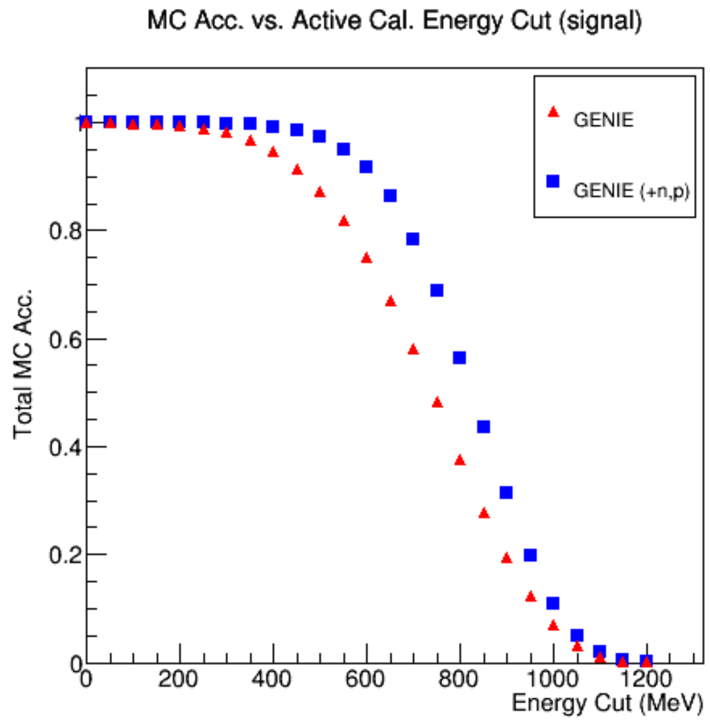


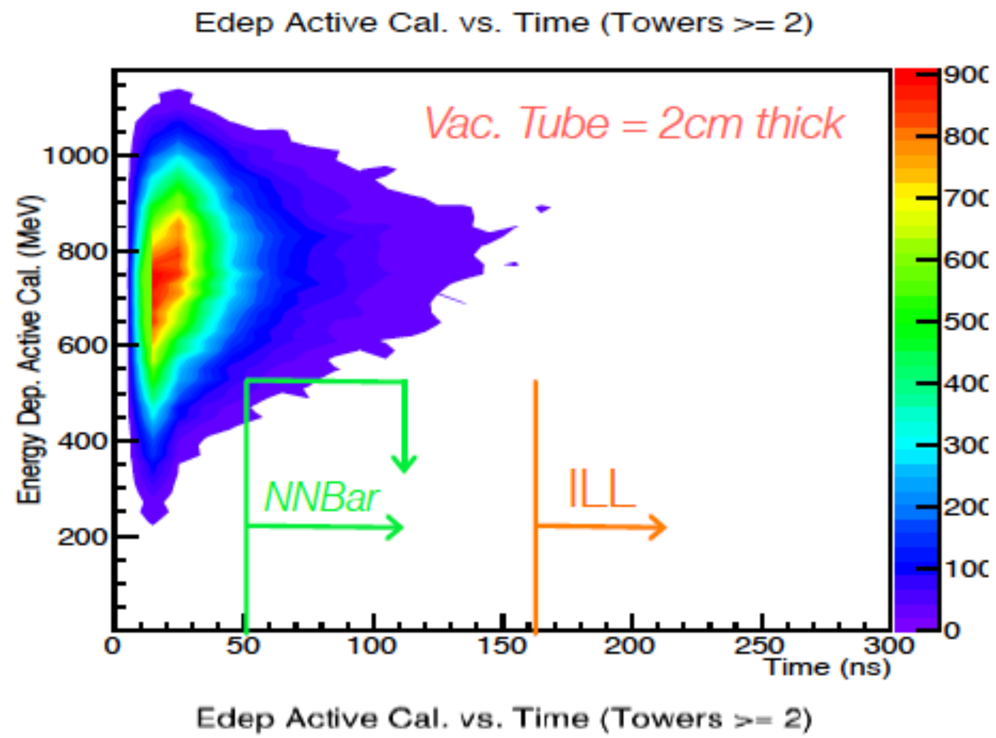


Early Simulations: Detector









Achieving acceptance ~90%

Collaboration

Neutron-Anti-Neutron Oscillations at ESS

12-13 June 2014, CERN, Geneva, Switzerland

Neutral particle oscillations have proven to be extremely valuable probes of fundamental physics. Kaon oscillations provided us with our first insight into CP-violation, fast Bs oscillations provided the first indication that the top quark is extremely heavy, B oscillations form the most fertile ground for the continued study of CP-violation, and neutrino oscillations suggest the existence of a new, important energy scale well below the GUT scale. Neutrons oscillating into antineutrons could offer a unique probe of baryon number violation.

The construction of the European Spallation Source in Lund, with first beam expected in 2019, together with modern neutron optical techniques, offers an opportunity to conduct an experiment with at least three orders of magnitude improvement in sensitivity to the neutron oscillation probability.

At this workshop the physics case for such an experiment will be discussed, together with the main experimental challenges and possible solutions. We hope the workshop will conclude with the first steps towards the formation of a collaboration to build and perform the experiment.

Organising committee:

G. Brooijmans (Columbia University)
S. Chattopadhyay (Cockroft Institute)
R. Hall-Wilton (European Spallation Source)
Y. Kamyshkov (University of Tennessee)
E. Klinkby (Technical University of Denmark and European Spallation Source)
M. Lindroos (European Spallation Source and Lund University)
L. Mapelli (CERN)
M. Mezzetto (INFN Padova)
H. M. Shimizu (Nagoya University)
W. M. Snow (Indiana University)
T. Soldner (Institut Laue Langevin)
C. Theroine (European Spallation Source)

Register before 19 May on www.nnbar-at-ess.org

EUROPEAN SPALLATION SOURCE

CERN

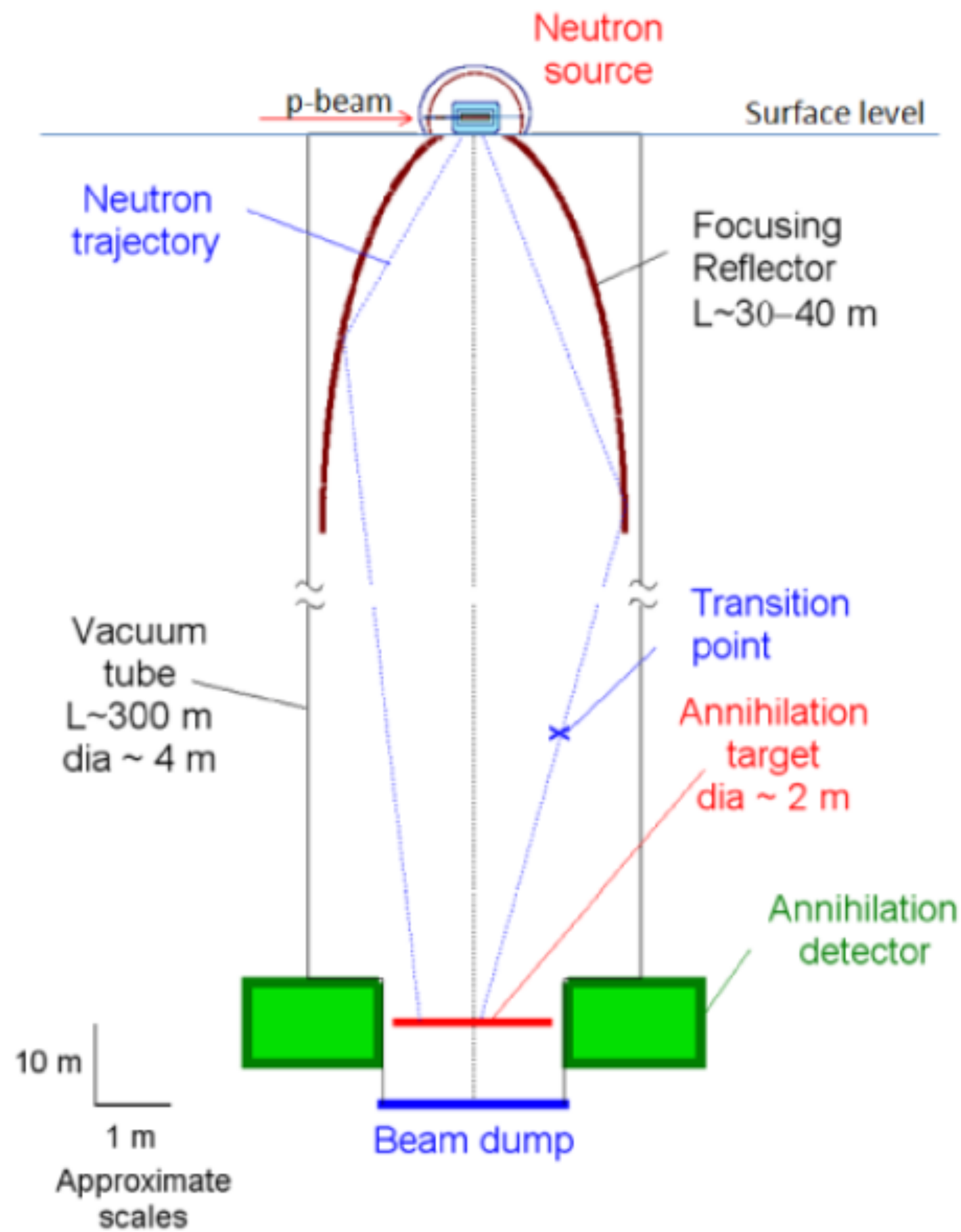
- Collaboration-building workshop held at CERN, June 12-13
  - Physics
  - Moderator & Beam Extraction
  - Vacuum Tube & Magnetic Shield
  - Detector
  - Software and Computing
  - Collaboration Formation

Timescales

- Agreed to target proposal in ~2 years
  - Work on-going to understand moderator optimization
  - ESS needs to freeze design in the next few months
- Working groups being put in place now
  - Physics
  - Neutronics
  - Magnetics
  - Detector
  - Software and computing
- Next meeting in Lund, February 19 and 20

Pushing Further

- Longer flight time with small beam divergence
  - Ultra cold neutrons Falling down?
    - Requires suitable site, some potential at Los Alamos
  - Shoot cold neutrons up?
    - Difficult radiological situation
- General agreement horizontal experiment prerequisite



Improve by 10^3

- Baryon Number Violation at the core of our existence
- Physics of Baryon Number Violation of utmost importance
  - Standard Model tells us about interactions
    - But *nothing* about nature of quarks and leptons
  - Standard Model is now complete
    - Understanding fermions is our biggest gap
    - Grand Unification our best hint
  - Baryon Number Violation excellent probe
    - We *know* it exists
    - Observation will tell us about mechanism, and Grand Unification, and maybe neutrinos
- Opportunities to gain a factor 1000 in sensitivity to processes at core of our existence and understanding of universe are rare
  - Should **not** be squandered

Concluding

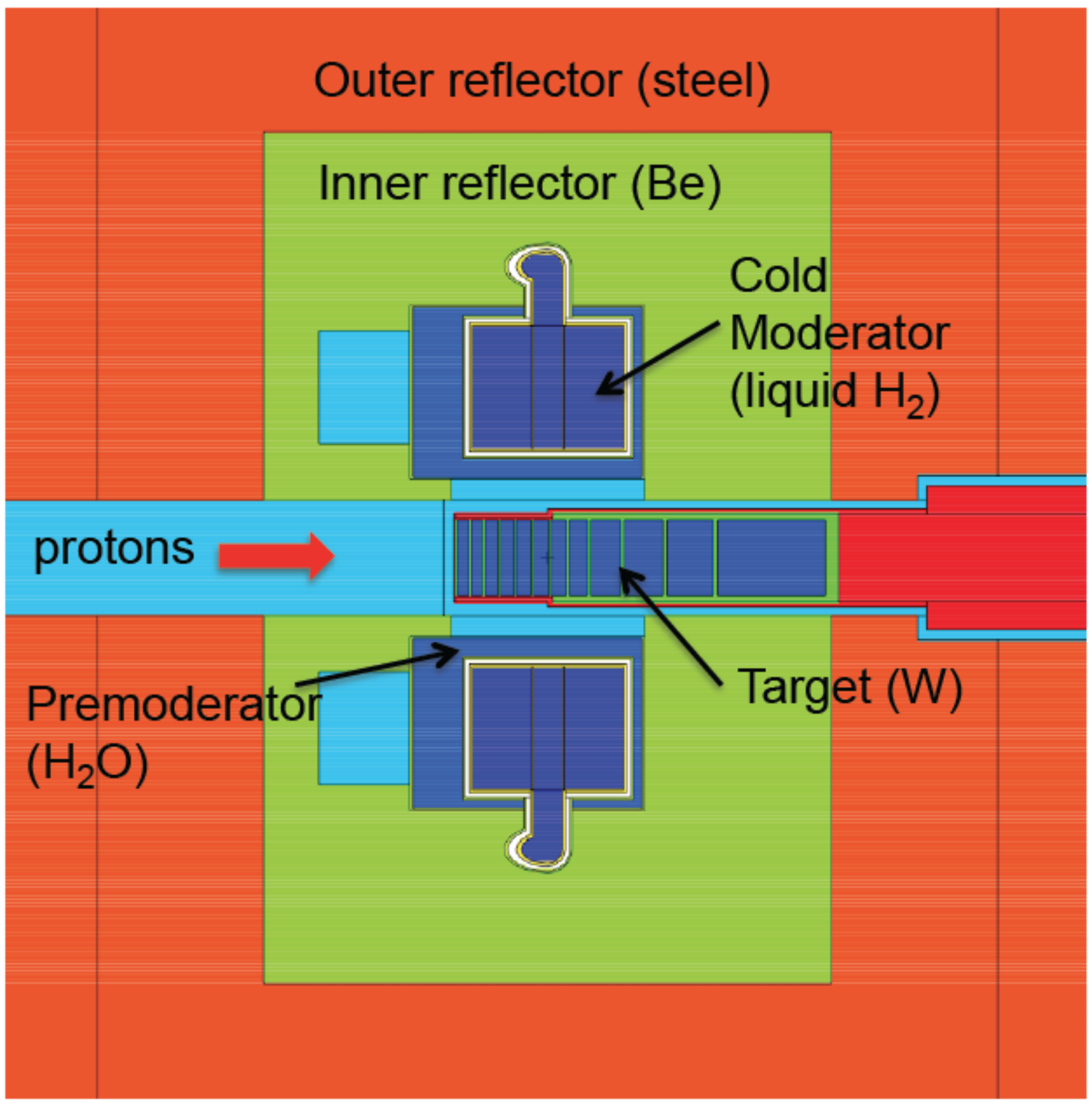
- Search for n-$\bar{n}$ oscillation strongly motivated:
  - $\Delta B=2$ baryon number violation appears in many models
  - Probe scales from 10^5 - 10^{12} GeV
  - Connection with baryogenesis, neutrino masses, …
- Experiment well within current capabilities
  - Very low technical risk
- Substantial community exists
  - Bridges particle and nuclear physics communities
  - Synergies with ESS neutron scattering community

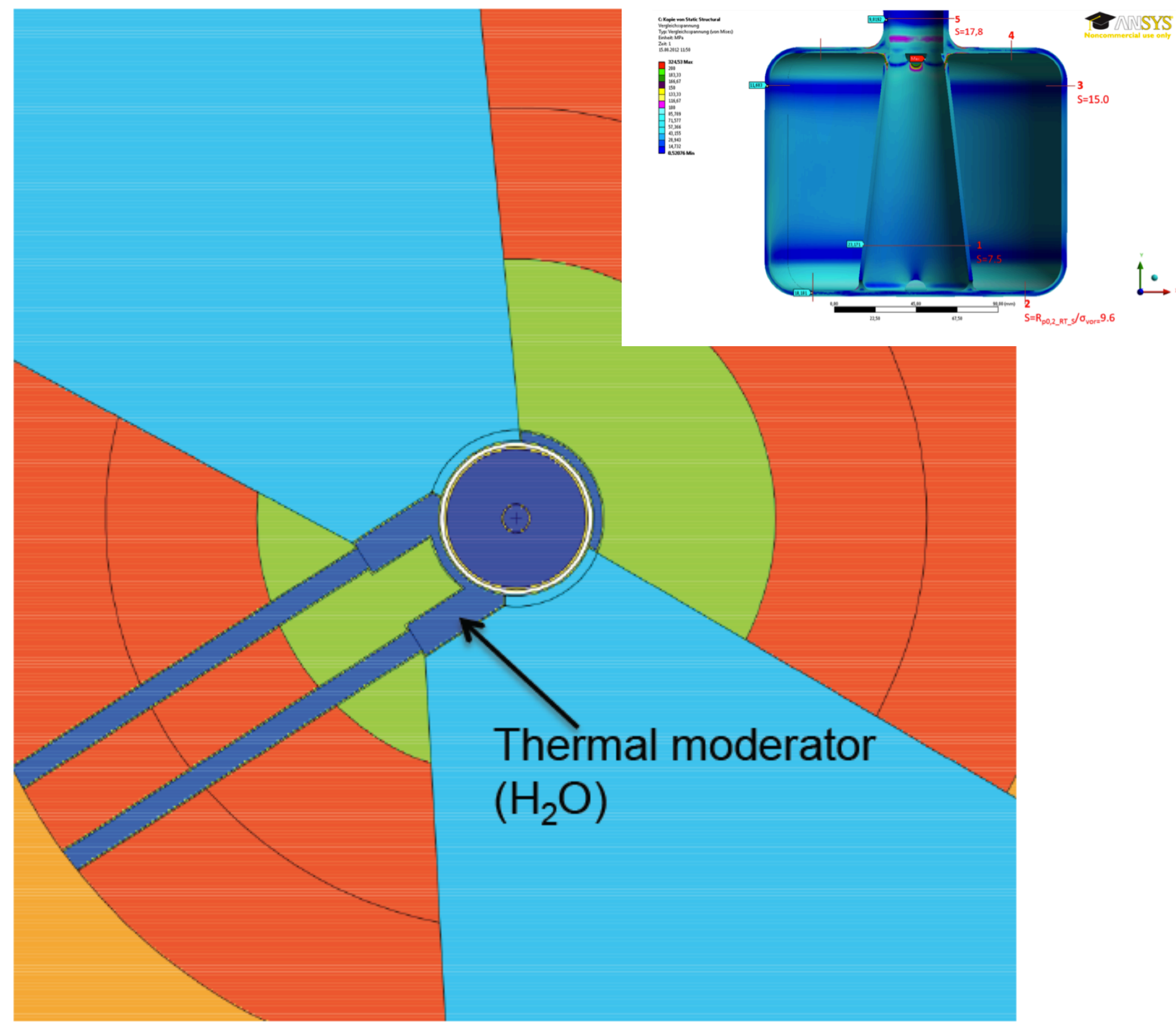
- Sensitivity mainly driven by neutron flux and time of flight
  - Moderator optimization
  - Large beam extraction port
    - Feeds super-mirror horn
- Collaboration in early stages of formation

http://www.nnbar-at-ess.org

Moderators

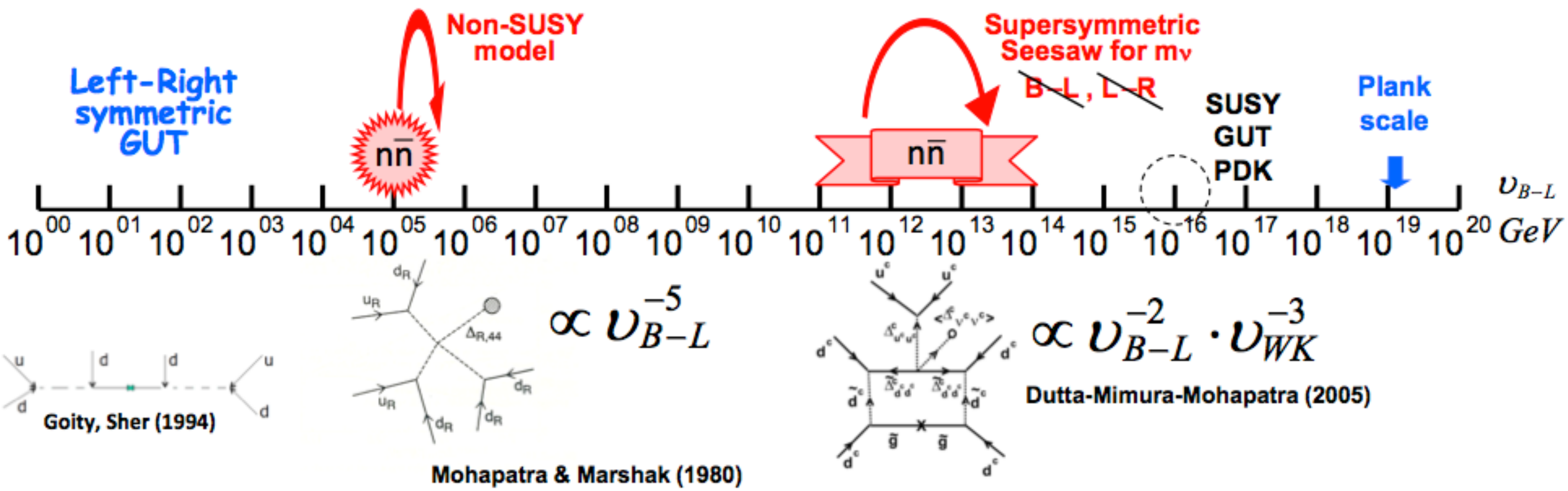
- Baseline has 13 cm high, 16 cm diameter para-hydrogen moderators
  - Very suitable for neutron oscillations: high integral flux
  - Tested at JPARC



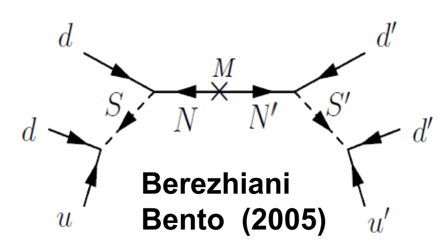


Scales in Neutron Oscillations

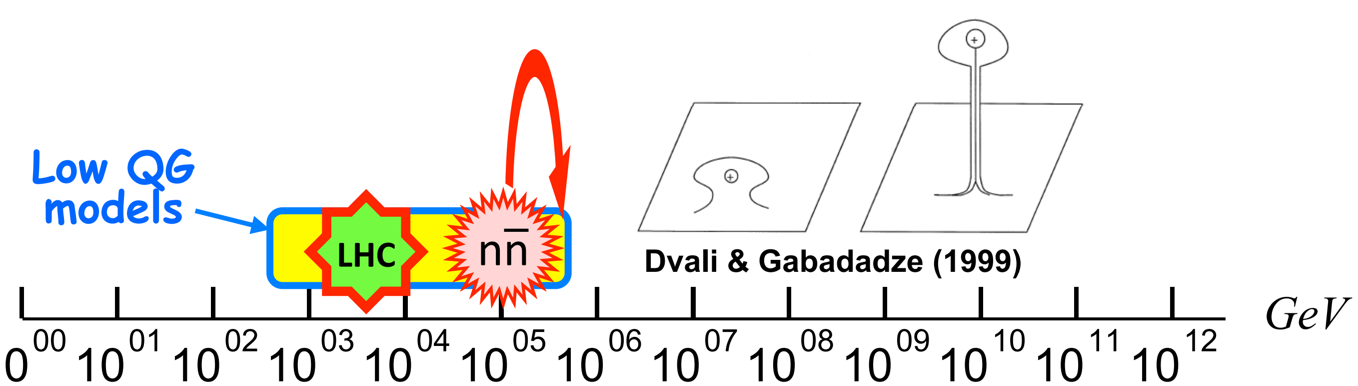
- Strongly dependent on mechanism, e.g.:



Post-Sphaleron Baryogenesis at TeV Scale



Anything is possible!



Review: Mohapatra arXiv:0902.0834

Particle Physics Strategy - US

- US: Snowmass concluded, Particle Physics Projects Prioritization Panel ("P5") underway
  - Charged with "developing a 10-year strategic plan under various budget scenarios"
  - As part of the process, many (Glashow, Arkani-Hamed, etc) have emphasized the complementarity of searches at energy frontier (hierarchy problem) and searches for breakdown of global symmetries
  - NNbarX has been presented to P5, with "ESS option"

ESS Budget

- Machine: 1.5 B€
- Instruments: 350 M€
  - Not meant to cover full cost of all instruments
  - In particular, bulk of cost for neutron oscillation experiment will need to come from other sources

Project # & Name	Total cost
15R Infrastructure	516 419 630
16R Energy	13 062 487
19R Licencing	13 326 667
20R Infrastructure Support	2 373 065
11R Accelerator Systems	510 213 237
12R Target Station 2014	155 250 000
14R Integrated Control Systems	72 817 028
18R Machine Administration	30 999 836
13R Neutron Scattering Systems Project	350 000 077
60R Admin & Line Management	112 995 342
Construction cost	**1 777 457 369**
CF additional scope	-93 000 000
Construction cost excl. CF additional scope	**1 684 457 369**
Contingency	158 542 631
	1 843 000 000

- In the US, an expression of interest to pursue this at Project X at Fermilab exists (endorsed by Fermilab PAC in Nov 2012)
  - Enthusiastic about joining an experiment at ESS

Expression of Interest

Search for Neutron-Antineutron Transformation at Fermilab

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