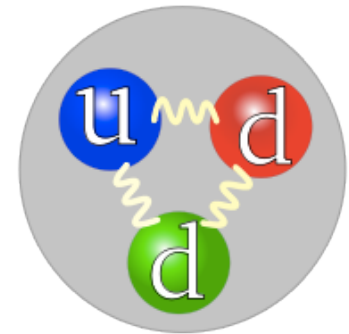


Fundamental Physics with Neutrons at ESS



David Silvermyr, Particle Physics



Outline

- “Big Picture” Introduction: nuclear & particle physics, European Spallation Source (ESS)
- Why fundamental physics with neutrons @ ESS ?
- Selected possible studies @ ESS
- Conclusions/Summary

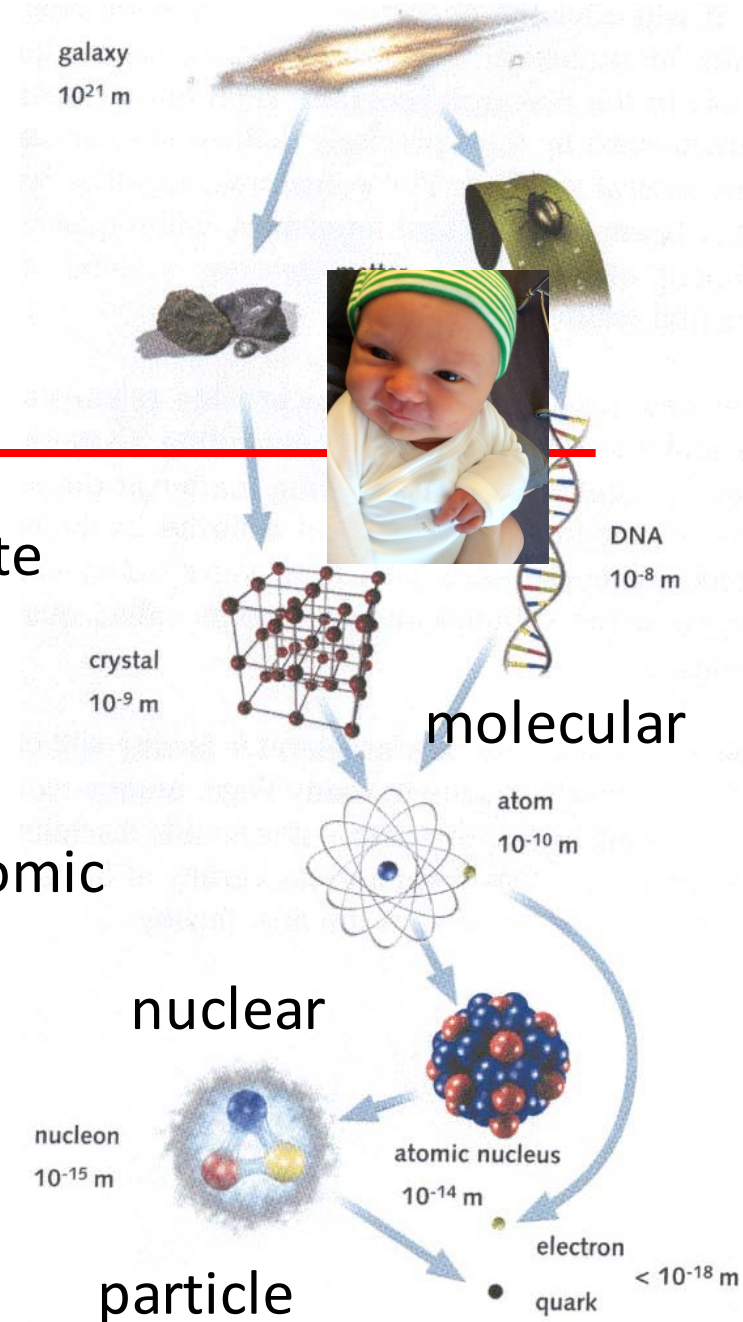
The Universe

Classical world

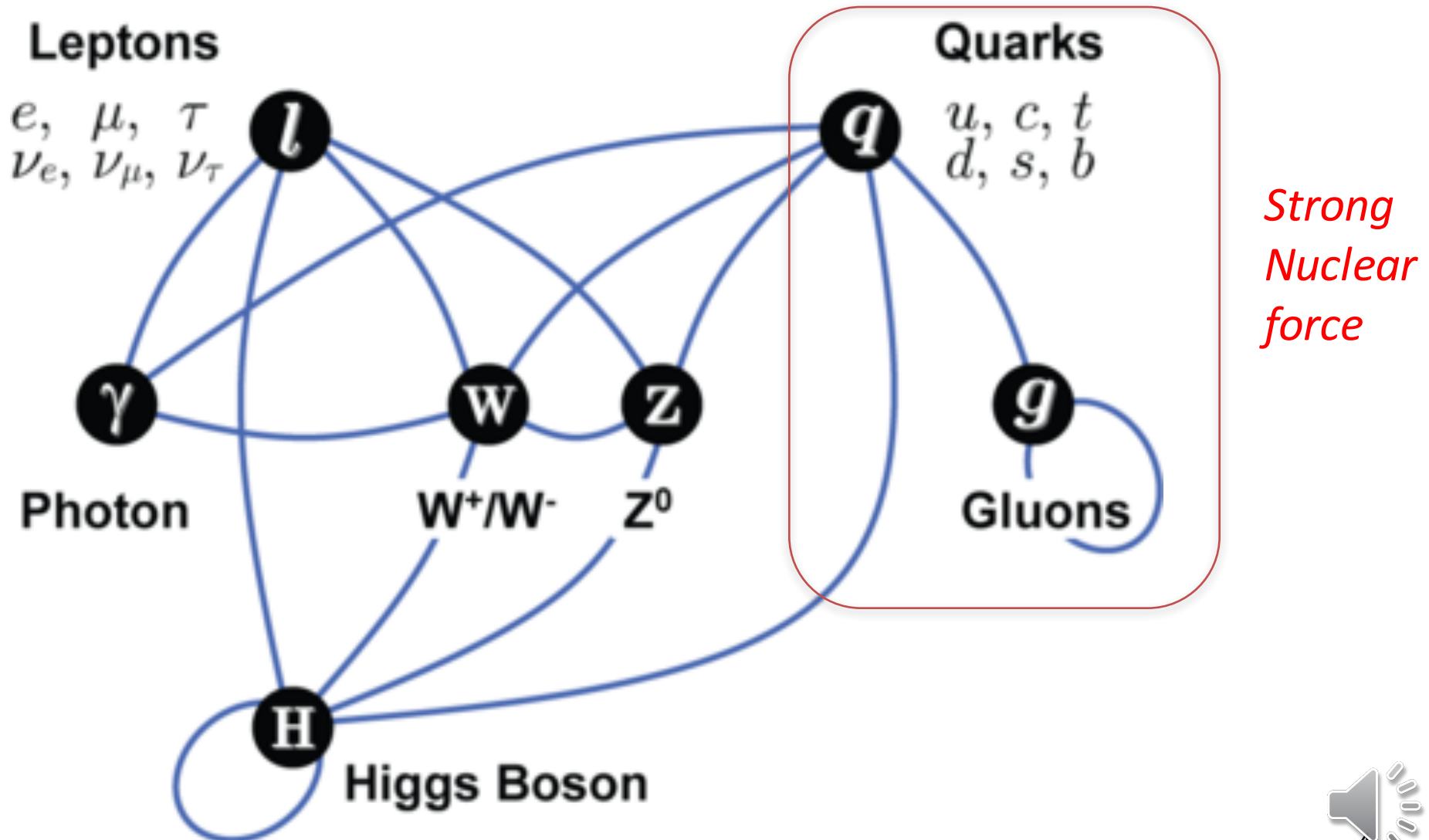
Quantum world

Fundamental:
Study the building blocks
of matter and the
forces between them

Solid state



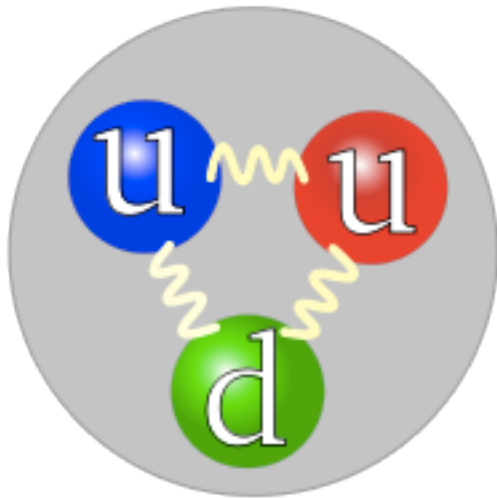
Known Elementary Particles ("Standard Model", X Nobel Prizes)



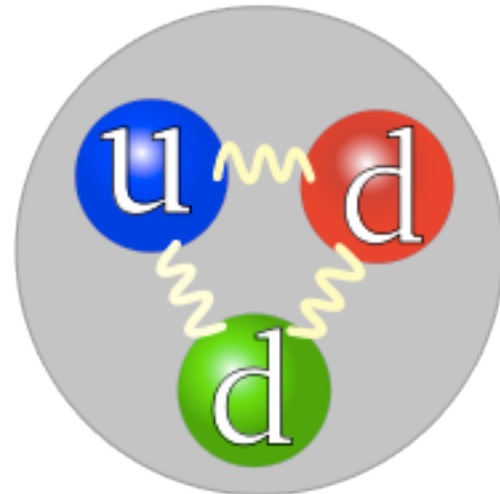
Nuclear Particles

Nucleons: composed of quarks and gluons

Proton



Neutron



Observations: quark – antiquark pairs (mesons), or sets of three quarks together (baryons)

No one has ever seen a “free quark”

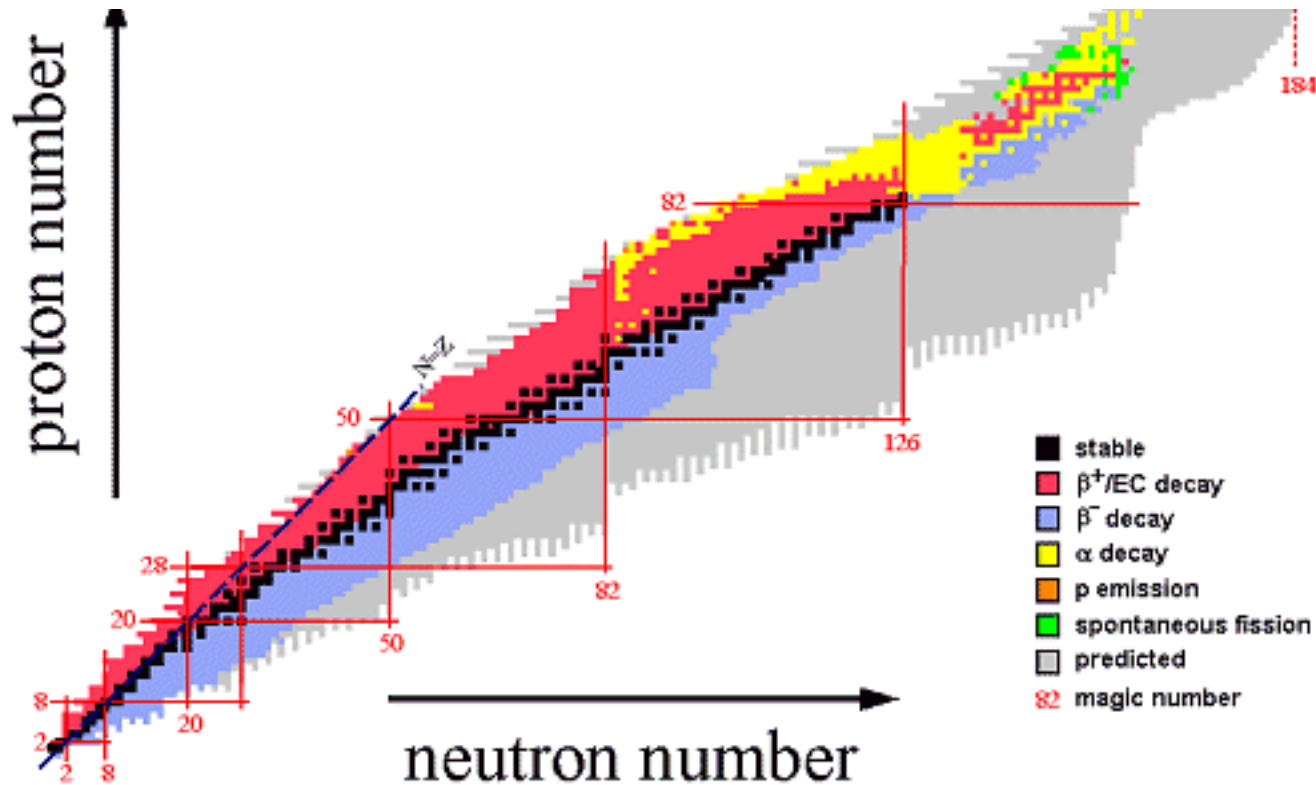
Nucleons (p, n) build up atomic nuclei

Periodic Table of the Elements																		18 VIII A 8A																			
<div>Atomic Number</div> <div>Melting Point</div> <div>Symbol</div> <div>Name</div> <div>Atomic Mass</div>																																					
1 1A 1A																	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	2 He Helium 4.003															
2 H Hydrogen 1.008																	5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180															
3 Li Lithium 6.941	4 Be Beryllium 9.012																	11 Na Sodium 22.990	12 Mg Magnesium 24.305	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948												
Normal melting points are in °C. TP = Triple Point Pressure is listed if not 1 atm. Allotrope is listed if more than one allotrope.																																					
11 Na Sodium 22.990	12 Mg Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948																				
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 84.80																				
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29																				
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine 209	86 Rn Radon 222.018																				
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium [289]	114 Fl Flerovium [289]	115 Uup Ununpentium [289]	116 Lv Livermorium [298]	117 Uus Ununseptium [298]	118 Uuo Ununoctium [298]																				
Lanthanide Series																																					
Actinide Series																																					
Alkali Metal																		Alkaline Earth		Transition Metal		Basic Metal		Semimetal		Nonmetal		Halogen		Noble Gas		Lanthanide		Actinide		© 2014 Todd Helmenstine sciencenotes.net	

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sciencenotes.org

Number of electrons (protons) determine chemical properties

Chart of the Nuclides



~300 in nature; ~254 stable, >3000 total – every nuclide has unique nuclear properties!

Neutrons stable in (some) nuclei, but free neutrons decay!

Neutron Decay Basics



Neutron



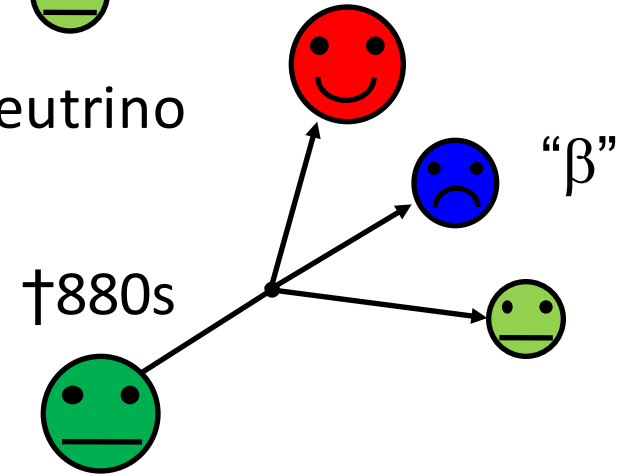
Proton



Electron




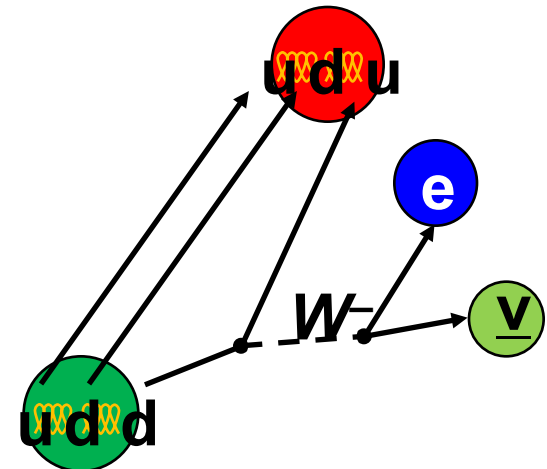
Neutrino



advanced:

$$\begin{array}{cc} +\frac{2}{3} & -\frac{1}{3} \\ \text{u} & \text{d} \end{array}$$

- Closer look: quarks 
- n: udd, p: uud, hold together by gluons
- Conversion by exchange of W^{\pm} boson



Neutron β decay – Brief History

1899: Beta decay separated from alpha decay (Rutherford)

...

1932: Neutron discovery (Chadwick)

1934: Theory of beta-decay (Fermi)

1956: Neutrino discovery (Cowan & Reines)

1967: Electroweak model theory (Weinberg & Salam)

1983: W & Z discovery (Rubbia, van der Meer)

Significant time period from first discovery to complete theory, and discovery of all involved particles

W is more than 80 times heavier than either a proton or a neutron: how can it play a role in the neutron decay?

The Heisenberg Uncertainty Principle

- Classical physics
 - Measurement uncertainty is due to limitations of the measurement apparatus
 - There is no limit in principle to how accurate a measurement can be made
- Quantum Mechanics
 - There is a small but fundamental limit to the accuracy of a measurement determined by the Heisenberg uncertainty principle
 - If a measurement of energy is made with precision ΔE and a simultaneous time measurement is made with precision Δt , then the product of the two uncertainties can never be less than $\hbar/2$ (10^{-34} Js or ~ 100 MeV fm/c):

$$\Delta E \Delta t \geq \frac{\hbar}{2}.$$

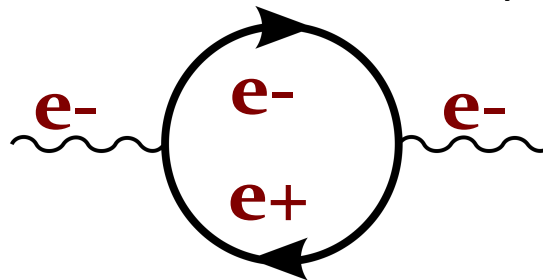
The Heisenberg Uncertainty Principle

- The time-energy uncertainty relation:

$$\Delta E \Delta t \geq \frac{\hbar}{2}.$$

W heavy => short time/range

- This equation has direct impact on the quantum vacuum: it means the vacuum can borrow energy for short periods
- The borrowed energy can be used to create particles $E=mc^2$

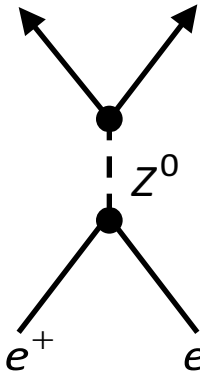


You cannot create only an electron because of charge conservation, but can create electron - antielectron pair

The quantum vacuum is a seeing particles appearing and disappearing constantly.... These particles are called virtual particles

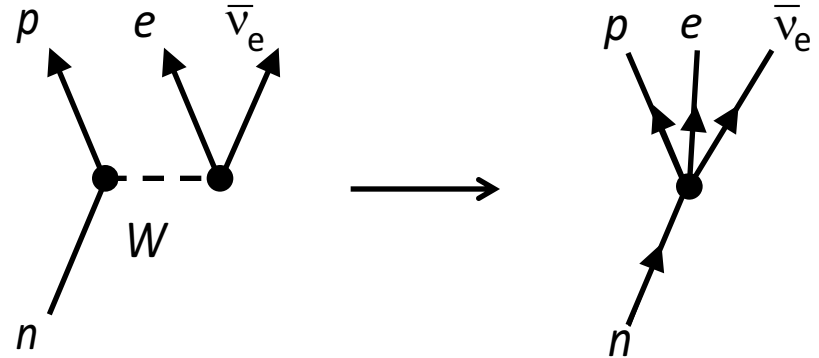
Particle Physics

HEP: Direct production



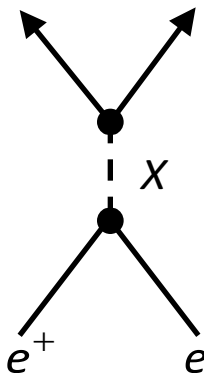
High energy frontier

Decay: Virtual Production



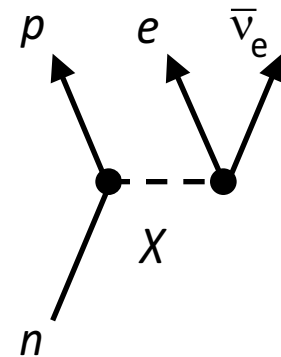
Precision frontier

If new particles above accelerator energy



$$m_X \gg E$$

→ *Precision frontier extra interesting*
(low probabilities => large statistics needed)



Searches Beyond the Standard Model

Why are we not satisfied with the Standard Model?

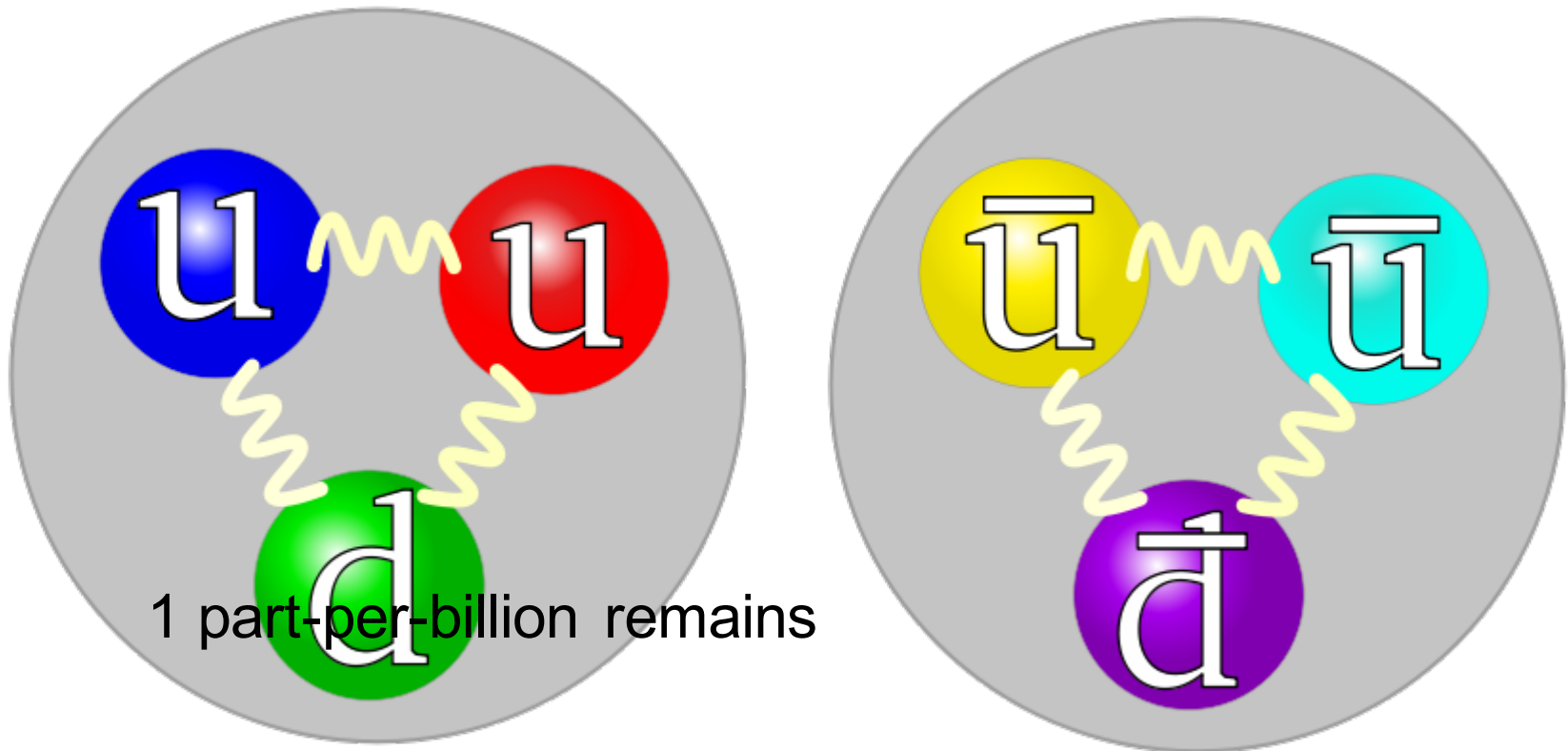
Explains a lot of data with fantastic precision, but astrophysics implies there is more...

- Why is there matter in the Universe? Should have been just as much antimatter as matter in the Big Bang?
- What is the dark matter and dark energy?

The neutrino should not have mass according to SM. But it has...

Is there a more fundamental level with fewer building blocks?
String theory? Supersymmetry?

There Is Matter In The Universe



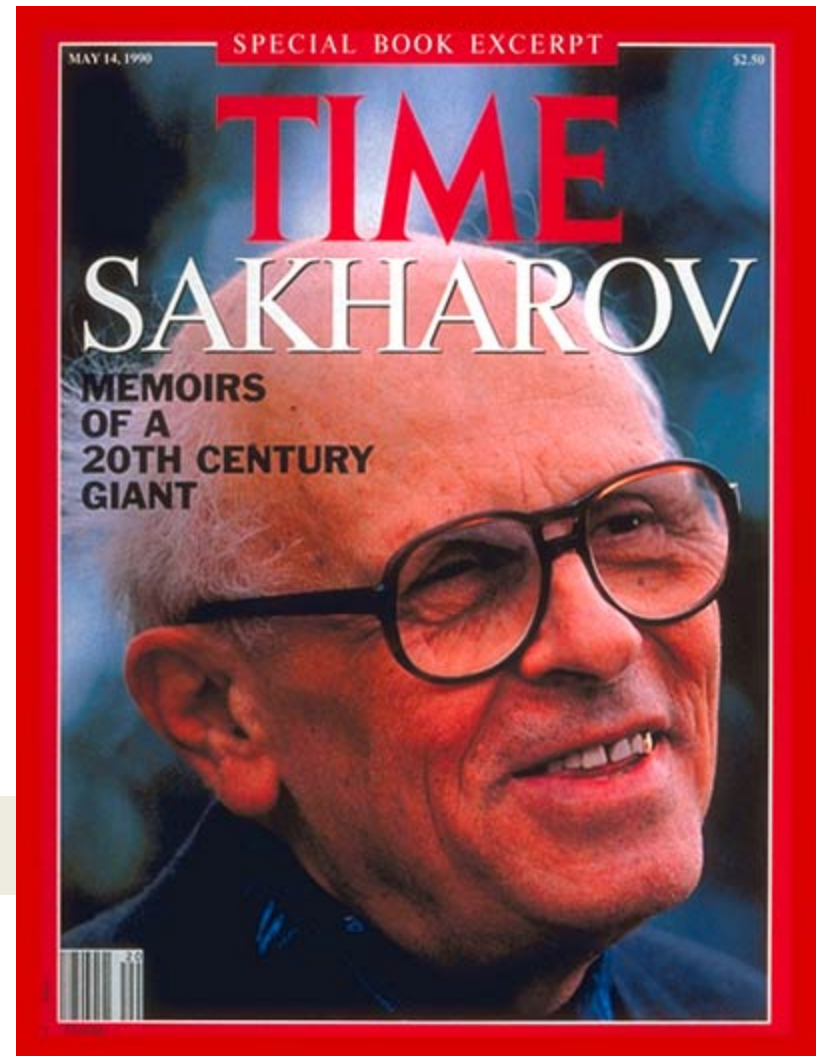
Big Bang: symmetry between matter (baryons) and anti-matter (anti-baryons)

Sakharov Criteria

Baryogenesis requires:

- Baryon-Number Violation
- C & CP violation
- Departure from thermal equilibrium

A.D. Sakharov, JETP **5** 24 (1967).



Fundamental Physics at ESS: Highlights

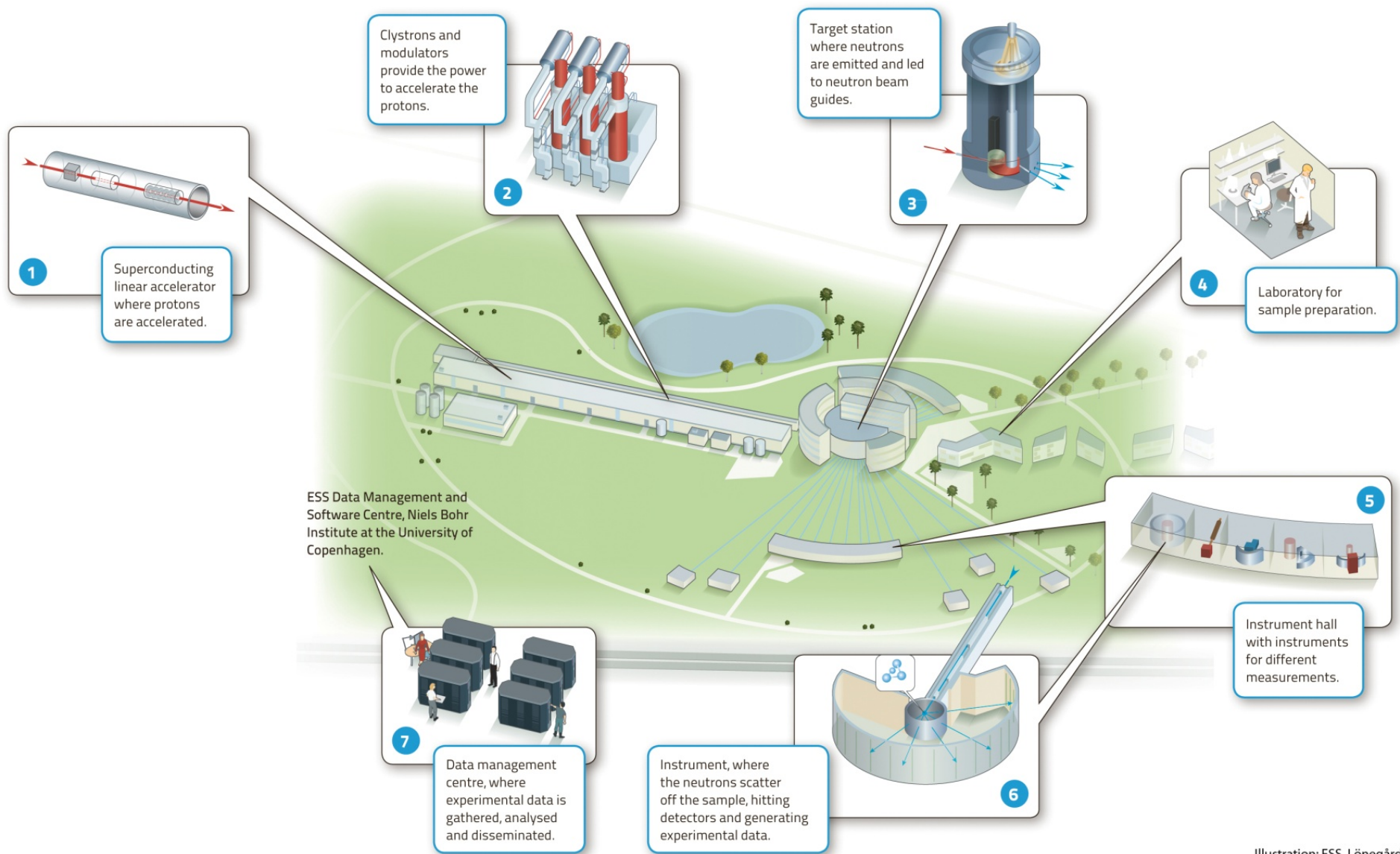
1. Neutron decay: improved Standard Model & Big Bang Nucleosynthesis (BBN) parameters, supersymmetry searches
2. Measurement of the neutron EDM, Beyond Standard Model search
3. Neutron anti-neutron oscillations: Baryon Number Violation (BNV), Beyond Standard Model search

(Neutrino physics not covered today)

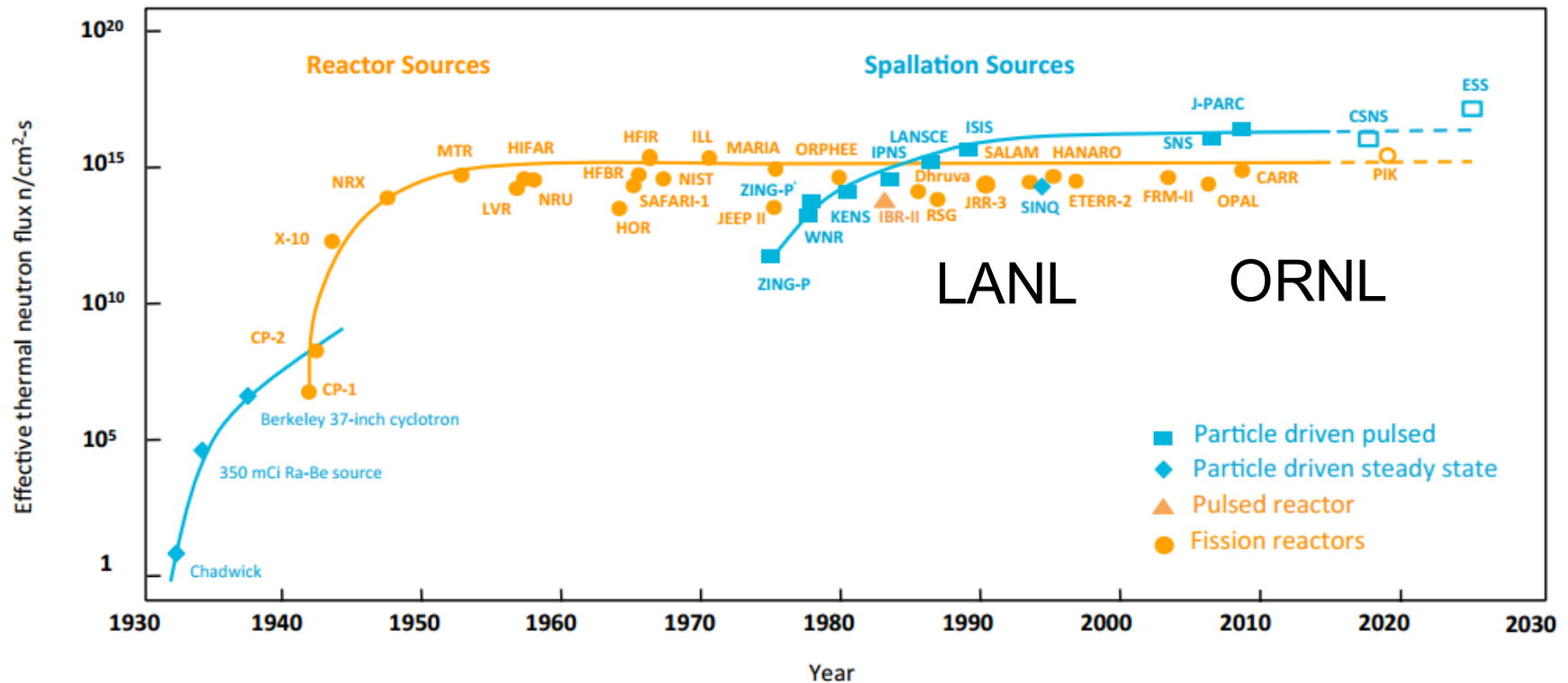
Two important points

- ESS fundamental physics measurements at precision frontier complementary with LHC measurements at the high energy frontier - in certain areas may reach far larger mass scales than reachable by accelerators
- Main ESS program use neutrons as probes of materials – for fundamental physics at ESS the neutron is “the patient, rather than the probe”

European Spallation Source



ESS will be the world's brightest neutron source for neutron scattering



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

Reminder: Since free neutrons decay, we need to generate neutrons. Since ESS will soon be the most powerful spallation neutron source in the world, it will be an ideal place for fundamental physics with neutrons...

Fundamental Physics @ ESS

- ✓ ANNI Cold beam Line (Full ESS proposal)
- ✓ A beam UCN source (Letter of Intent)
- ✓ The neutron –antineutron ($NN\bar{n}$) experiment (Letter of Intent)

Fundamental Physics at ESS: Highlights

1. Neutron decay: improved Standard Model & BBN parameters, supersymmetry searches
2. Measurement of the neutron EDM, Beyond Standard Model search

ANNI, UCN

3. Neutron anti-neutron oscillations: Baryon Number Violation (BNV), Beyond Standard Model search

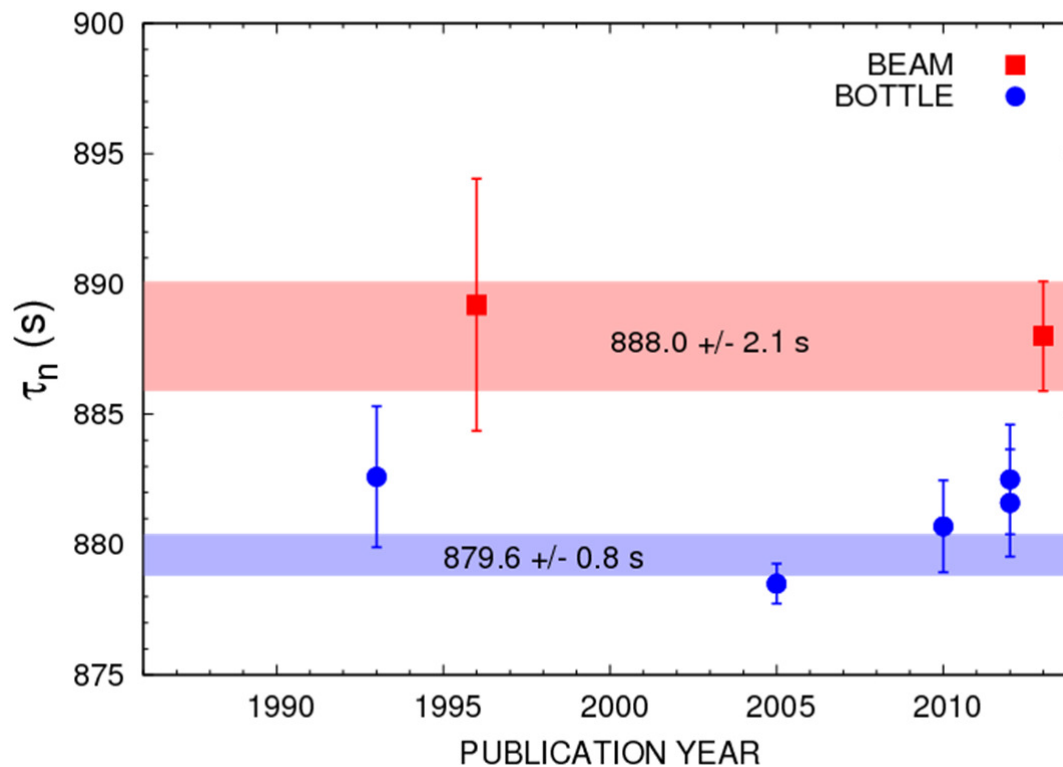
NNbar (HIBEAM)

Fundamental Physics at ESS: Highlights

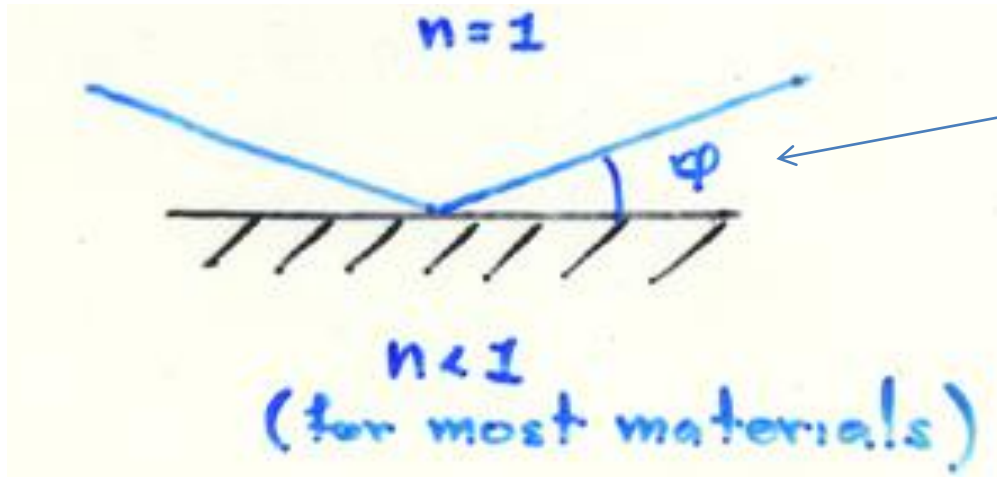
1. Neutron decay: improved Standard Model & BBN parameters, supersymmetry searches
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Neutron Decay Puzzle

- Different results in beam and bottle experiments... Why?



Ultra-Cold Neutrons



Energy-dependent; for low-enough energy, neutrons at any angle are reflected – behaves similar to an ideal gas

We can STORE them!

Kinetic Energy ≈ 100 neV

Velocity ≈ 5 m/s

Wavelength ≈ 500 Å

Beam vs Bottle

Bottle method: confine neutrons in a container for an hour or so and then count how many are left after a certain time = “count the survivors”

Beam method: count the decays by letting neutrons fly through a detector and looking for the particles into which they transform = “count the dead”

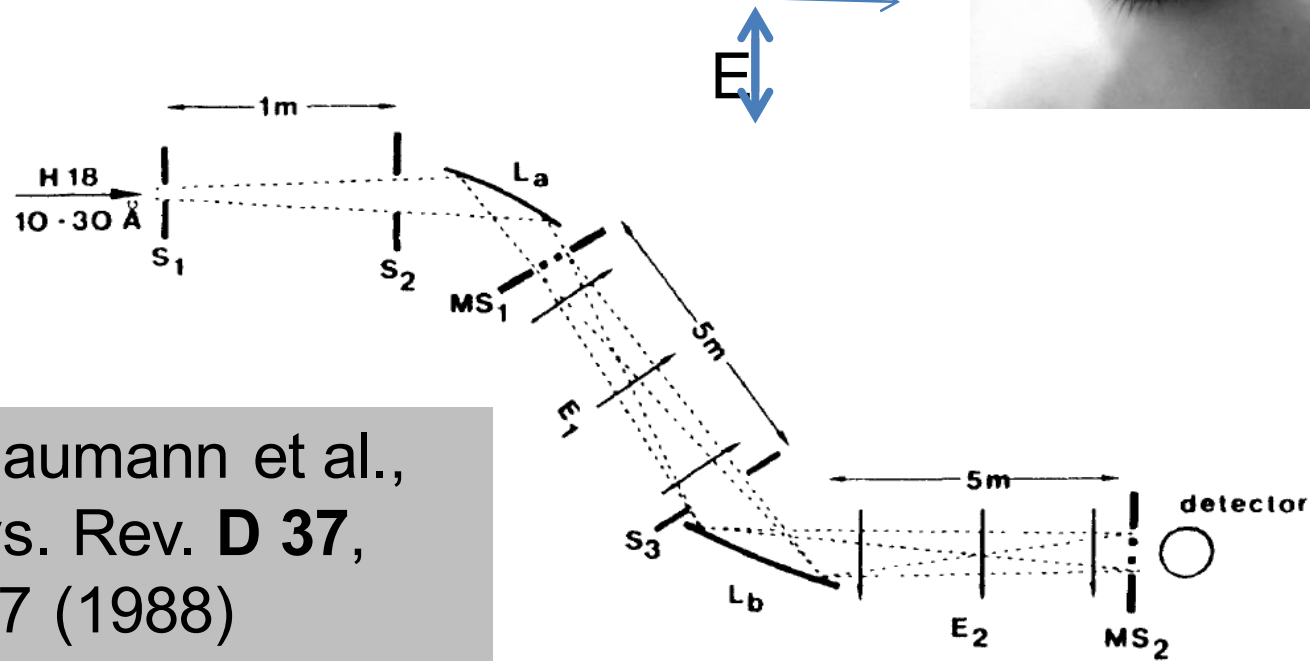
- Goal at ESS: improve beam method measurement uncertainty by factor 10
- Also: Improve measurements of correlation coefficients in neutron decay (backup slides...)

Fundamental Physics at ESS: Highlights

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The Neutron Appears To Be Neutral...

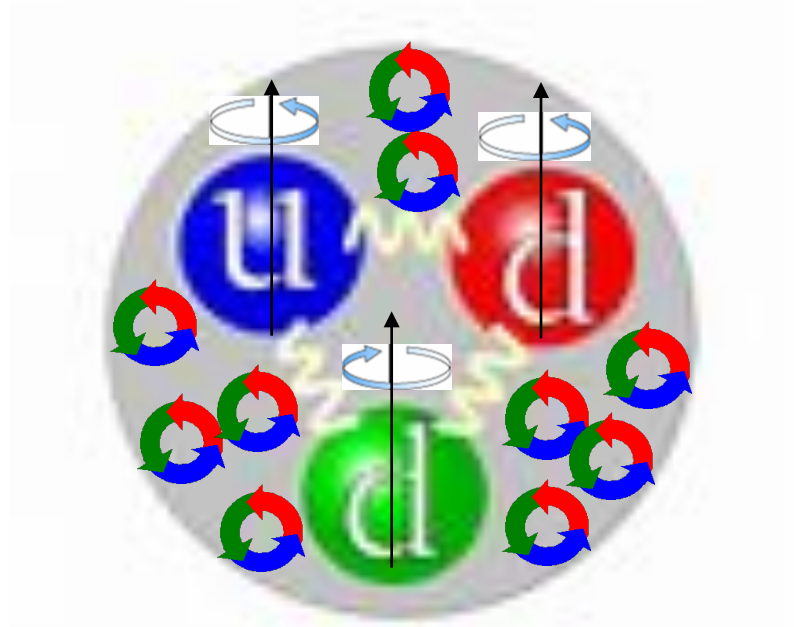
Neutron beam



J. Baumann et al.,
Phys. Rev. **D 37**,
3107 (1988)

$$Q_n = (-0.4 \pm 1.1) \times 10^{-21} e$$

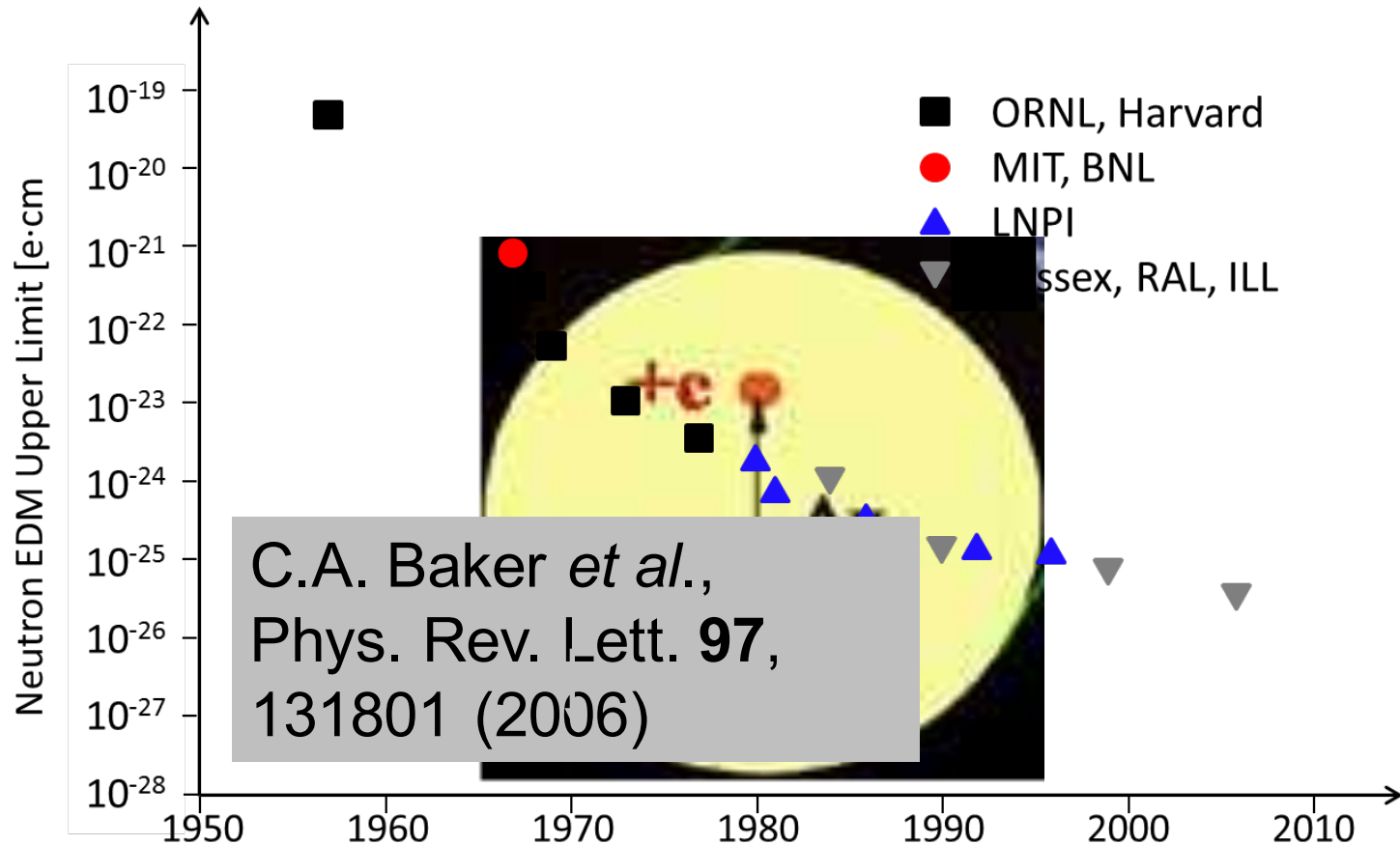
But Not Everywhere...



Has a magnetic dipole moment...

=> Does it also have an electric dipole moment?

Is The Neutron Round?



Current best limit: $|\mu_E| < 3 \times 10^{-26} \text{ e}\cdot\text{cm}$

Goal for next experiments: $|\mu_E| < 3 \times 10^{-28} \text{ e}\cdot\text{cm}$ (factor 100!)

SM prediction: $\sim 10^{-32} \text{ e}\cdot\text{cm}$ (clean signature for new physics)

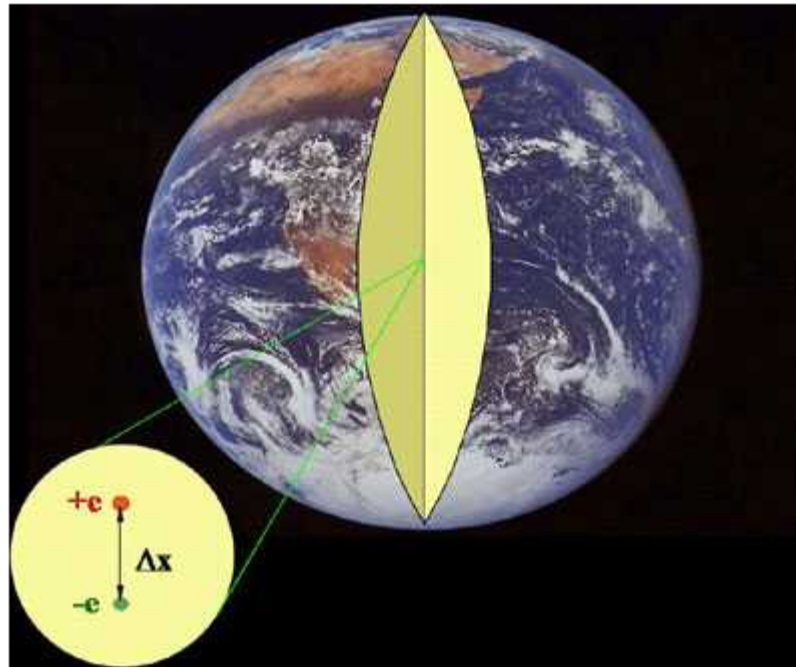
That's Pretty Round...

Relative unit charge separation :

$$x / d_n = 3 \cdot 10^{-28} \text{ cm} / 10^{-13} \text{ cm} = 3 \cdot 10^{-15}$$

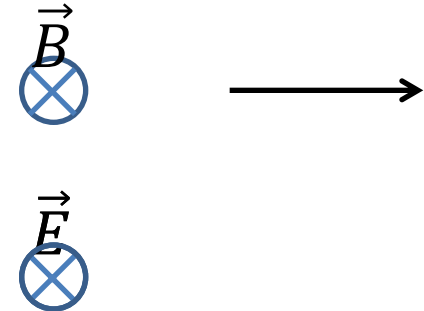
Unit charge separation for a neutron the size of the earth:

$$x = 3 \cdot 10^{-15} \cdot d_E = 40 \text{ nm}$$



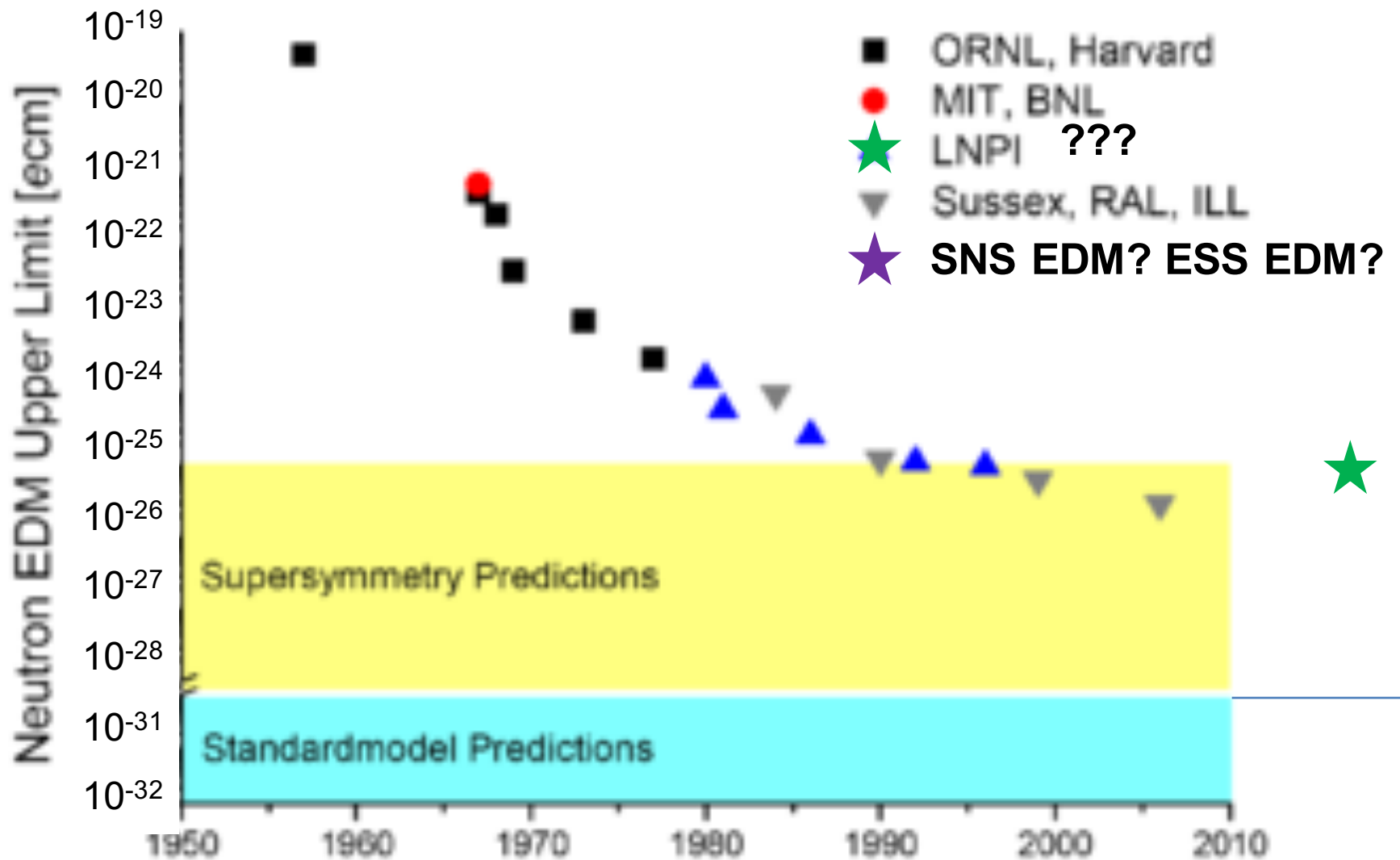
Details: How Does One Measure An EDM?

- Place your particle in a uniform magnetic field perpendicular to their spin.
 - Spins will precess at the Larmor frequency:
$$f = -\frac{2}{h}(\vec{\mu}_B \cdot \vec{B})$$
- Apply a strong electric field parallel to \vec{B} ...
- Flip the relative direction of \vec{B} and \vec{E} ...
- Look for a frequency shift proportional to E : $\Delta f = 4\mu_E E / h$
 - For $\mu_E = 10^{-28} \text{e}\cdot\text{cm}$ and $E = 75 \text{kV/cm}$,
$$\Delta f \sim 7.5 \text{ nHz}.$$



Repeat with many neutrons...

Many interesting experimental challenges

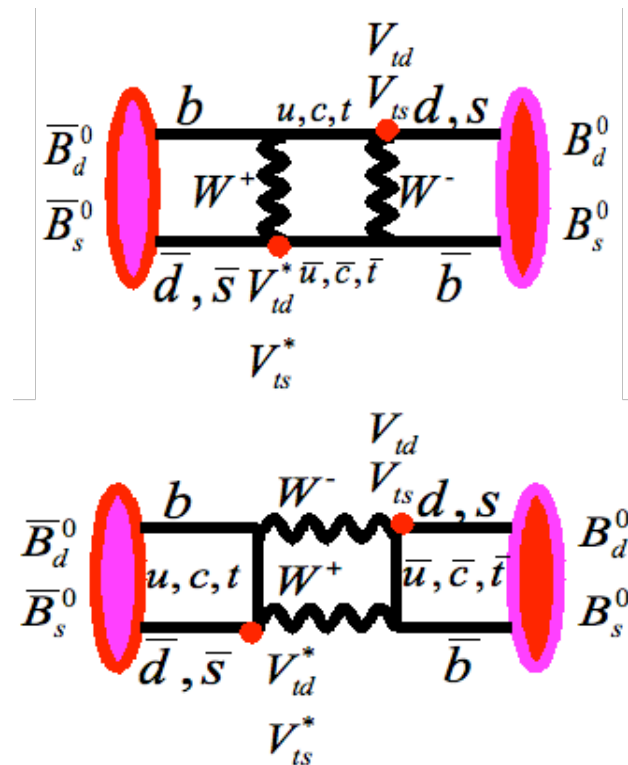


Fundamental Physics at ESS: Highlights

1. Neutron decay: improved Standard Model & BBN parameters, supersymmetry searches
2. Measurement of the neutron EDM, Beyond Standard Model search
3. Neutron anti-neutron oscillations: Baryon Number Violation (BNV), Beyond Standard Model search

Details: 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 (NP 1980)
 - B meson oscillations ($\Delta B_{\text{Beauty}} = 2$):
 - 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
- C.f. Neutrino oscillations (NP 2015)



Previous searches for BNV

Decay mode Partial mean life ($\times 10^{30}$ yrs)

(RPP)		
$N \rightarrow e^+ \pi$	> 2000 (n), > 8200 (p)	
$N \rightarrow \mu^+ \pi$	> 1000 (n), > 6600 (p)	
$N \rightarrow \nu \pi$	> 1100 (n), > 390 (p)	
$p \rightarrow e^+ \eta$	> 4200	
$p \rightarrow \mu^+ \eta$	> 1300	
$n \rightarrow \nu \eta$	> 158	
$N \rightarrow e^+ \rho$	> 217 (n), > 710 (p)	
$N \rightarrow \mu^+ \rho$	> 228 (n), > 160 (p)	
$N \rightarrow \nu \rho$	> 19 (n), > 162 (p)	
$p \rightarrow e^+ \omega$	> 320	
$p \rightarrow \mu^+ \omega$	> 780	
$n \rightarrow \nu \omega$	> 108	
$N \rightarrow e^+ K$	> 17 (n), > 1000 (p)	
$N \rightarrow \mu^+ K$	> 26 (n), > 1600 (p)	
$N \rightarrow \nu K$	> 86 (n), > 5900 (p)	
$n \rightarrow \nu K_S^0$	> 260	
$p \rightarrow e^+ K^*(892)^0$	> 84	
$N \rightarrow \nu K^*(892)$	> 78 (n), > 51 (p)	
$p \rightarrow e^+ \pi^+ \pi^-$	> 82	
$p \rightarrow e^+ \pi^0 \pi^0$	> 147	
$n \rightarrow e^+ \pi^- \pi^0$	> 52	
$p \rightarrow \mu^+ \pi^+ \pi^-$	> 133	
$p \rightarrow \mu^+ \pi^0 \pi^0$	> 101	
$n \rightarrow \mu^+ \pi^- \pi^0$	> 74	
$n \rightarrow e^+ K^0 \pi^-$	> 18	
$n \rightarrow e^- \pi^+$	> 65	
$n \rightarrow \mu^- \pi^+$	> 49	
$n \rightarrow e^- \rho^+$	> 62	
$n \rightarrow \mu^- \rho^+$	> 7	
$n \rightarrow e^- K^+$	> 32	
$n \rightarrow \mu^- K^+$	> 57	
$p \rightarrow e^- \pi^+ \pi^+$	> 30	
$n \rightarrow e^- \pi^+ \pi^0$	> 29	
$p \rightarrow \mu^- \pi^+ \pi^+$	> 17	
$n \rightarrow \mu^- \pi^+ \pi^0$	> 34	
$p \rightarrow e^- \pi^+ K^+$	> 75	
$p \rightarrow \mu^- \pi^+ K^+$	> 245	

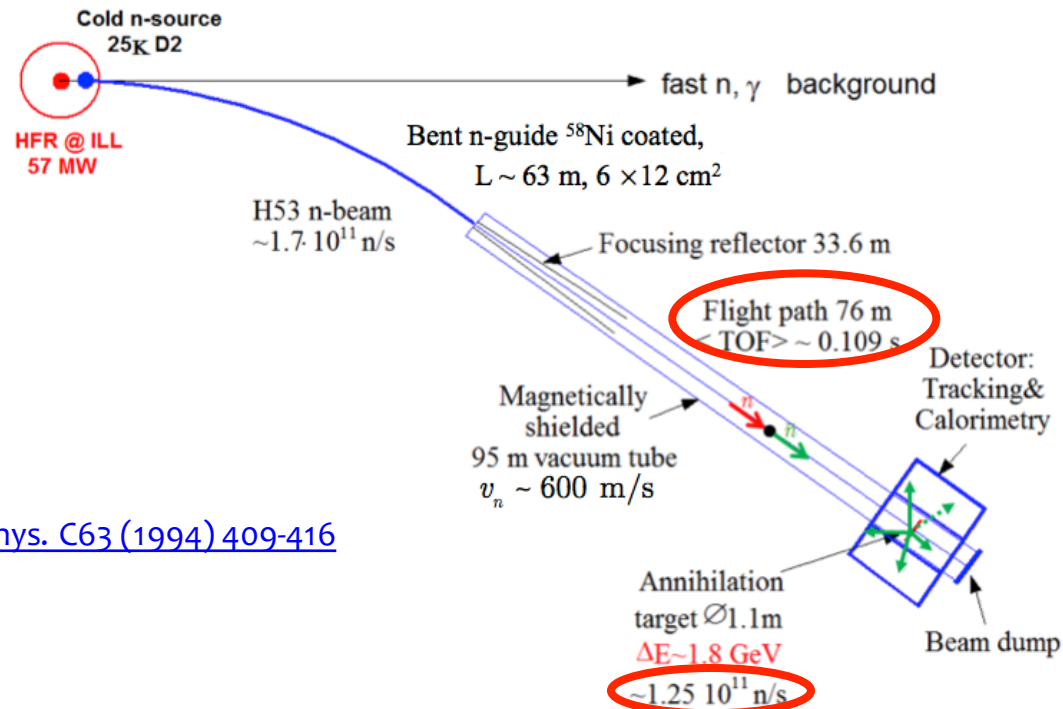
$p \rightarrow e^+ \gamma$	> 670
$p \rightarrow \mu^+ \gamma$	> 478
$n \rightarrow \nu \gamma$	> 28
$p \rightarrow e^+ \gamma \gamma$	> 100
$n \rightarrow \nu \gamma \gamma$	> 219
$p \rightarrow e^+ e^+ e^-$	> 793
$p \rightarrow e^+ \mu^+ \mu^-$	> 359
$p \rightarrow e^+ \nu \nu$	> 170
$n \rightarrow e^+ e^- \nu$	> 257
$n \rightarrow \mu^+ e^- \nu$	> 83
$n \rightarrow \mu^+ \mu^- \nu$	> 79
$p \rightarrow \mu^+ e^+ e^-$	> 529
$p \rightarrow \mu^+ \mu^+ \mu^-$	> 675
$p \rightarrow \mu^+ \nu \nu$	> 220
$p \rightarrow e^- \mu^+ \mu^+$	> 6
$n \rightarrow 3\nu$	> 0.0005
$N \rightarrow e^+ \text{anything}$	> 0.6 (n , p)
$N \rightarrow \mu^+ \text{anything}$	> 12 (n , p)
$N \rightarrow e^+ \pi^0 \text{anything}$	> 0.6 (n , p)
$pp \rightarrow \pi^+ \pi^+$	> 0.7
$pn \rightarrow \pi^+ \pi^0$	> 2
$nn \rightarrow \pi^+ \pi^-$	> 0.7
$nn \rightarrow \pi^0 \pi^0$	> 3.4
$pp \rightarrow K^+ K^+$	> 170
$pp \rightarrow e^- e^+$	> 5.8
$pp \rightarrow e^+ \mu^+$	> 3.6
$pp \rightarrow \mu^+ \mu^+$	> 1.7
$pn \rightarrow e^+ \bar{\nu}$	> 2.8
$pn \rightarrow \mu^+ \bar{\nu}$	> 1.6
$pn \rightarrow \tau^+ \bar{\nu}_\tau$	> 1.0
$nn \rightarrow \nu_e \bar{\nu}_e$	> 1.4
$nn \rightarrow \nu_\mu \bar{\nu}_\mu$	> 1.4

$$\Delta B \neq 0, \Delta L \neq 0$$

$$\Delta B \neq 0, \Delta L = 0$$

RPP/PDG : Few searches with $\Delta \text{Lepton} = 0$

Search for neutron antineutron oscillation @ ILL



Baldo-Ceolin et al, [Z.Phys. C63 \(1994\) 409-416](#)

- FOM: $Nt^2 = 1.5 \cdot 10^9 \text{ s}$; $P < 1.6 \cdot 10^{-18}$ (run lasted ~ 1 year) and $\tau > 0.86 \cdot 10^8 \text{ s}$

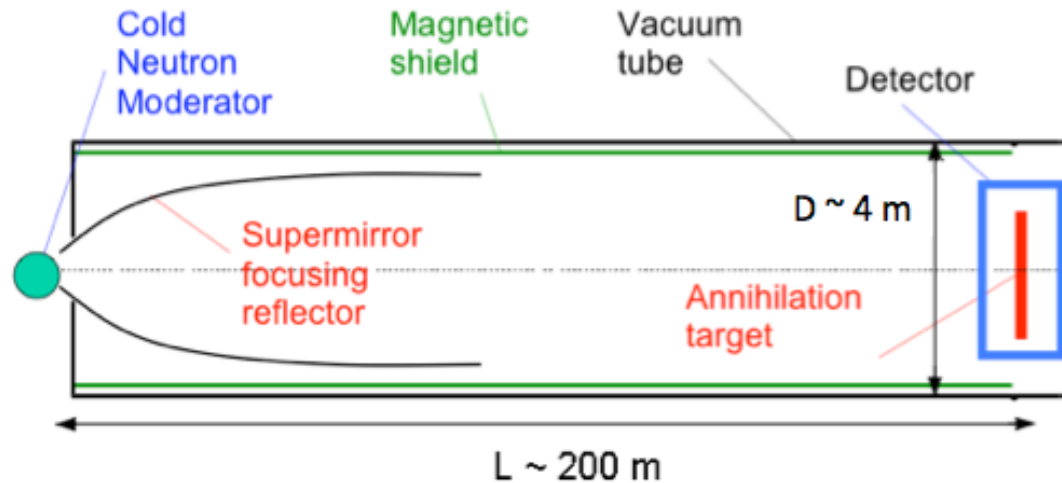
(N is the free neutron flux reaching the annihilation target per second and t is the neutron observation time.)

- Many subtle optimizations to minimize losses and backgrounds
- Experiment was background-free

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 ($\sim 50\%$), keep background at ~ 0
 - Exploit current, established hardware and software technologies
- Better B_{Earth} suppression
 - Improved passive (+ active?) shield

NNbar 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

Potential Gains wrt ILL

Brightness		≥ 1
Moderator Temperature	<TOF> driven by colder neutrons, \sim 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 $\tau \sim 3 \times 10^9$ s

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
 - Baryon Number Violation excellent probe
 - It should exist (at a value hopefully not too far away)...
 - Observation will tell us about Beyond Standard Model physics
- Opportunities to gain a factor 1000 in sensitivity to processes at core of our existence and understanding of universe are quite rare...

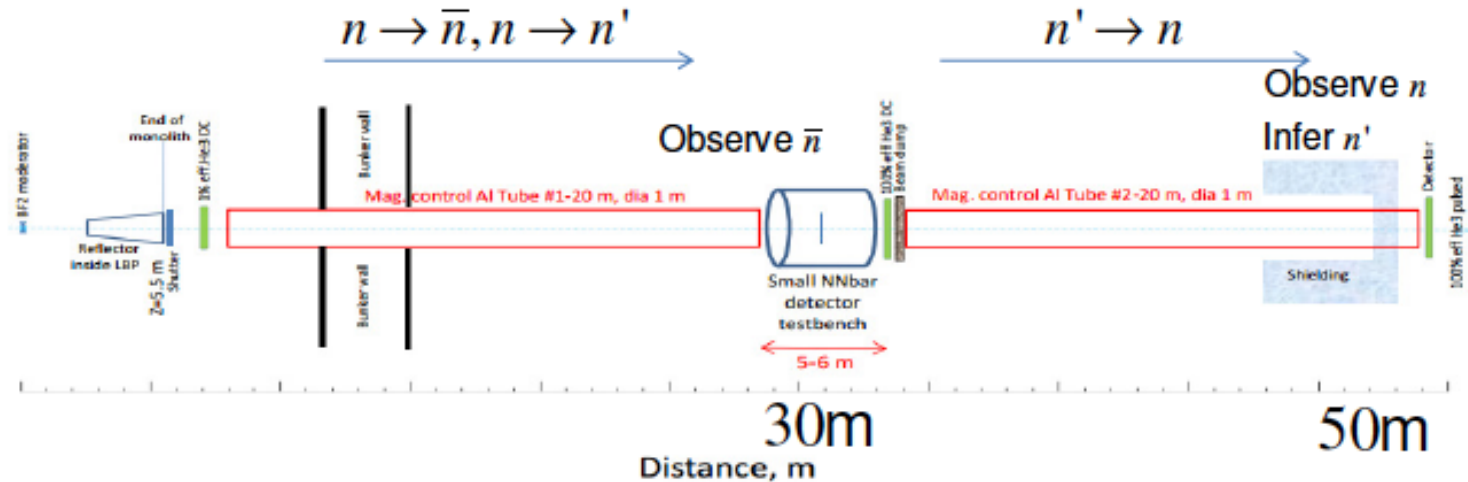
(almost) Summary

1. Neutron decay: improved Standard Model & BBN parameters, supersymmetry searches Factor 10^1 !

2. Measurement of the neutron EDM, Beyond Standard Model search Factor 10^2 !

3. Neutron anti-neutron oscillations: Baryon Number Violation (BNV), Beyond Standard Model search Factor 10^3 !

HIBEAM



Lower scale experiment including prototypes for full later experiment

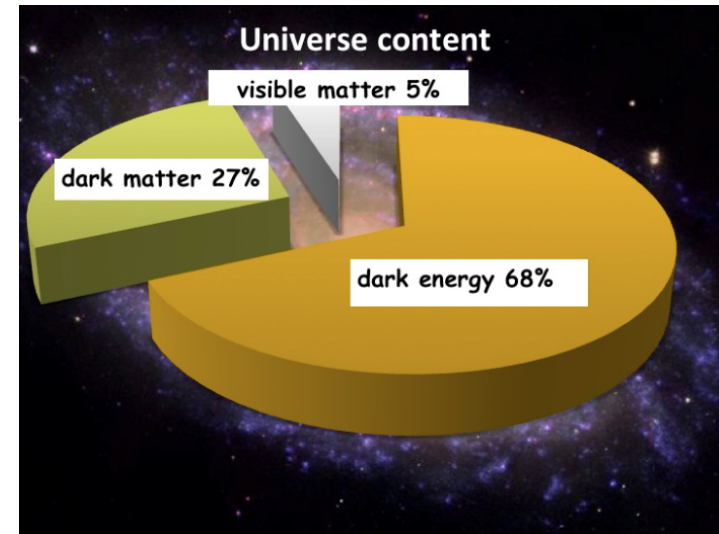
- High- m mirrors/focusing
- Magnetic shielding
- Neutron monitoring
- Detector
- BG

Physics

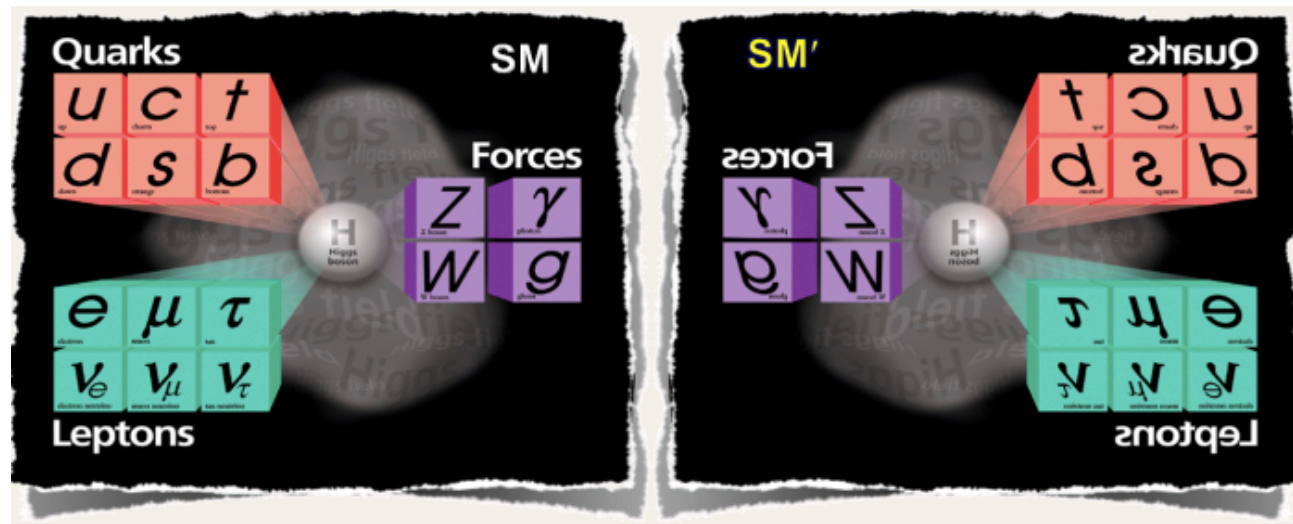
- Improve sensitivity wrt ILL
- Search for mirror neutron regeneration
- Other possible experiments (beam EDM, weak nucleon interactions, sensitivity to new long distance forces)

Mirror Matter

Mirror matter is one (of many) suggested Dark Matter candidates – has the same particle content and interactions described by SM and SM'. Ordinary matter makes up our world, while mirror matter might make up Dark matter...



Gravity is the only force we know of (so far) that communicates between the two worlds.



NNbar Summary

- Search for \bar{n} -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

Conclusion

- Fundamental Physics at ESS has a lot of possibilities
- Searches for fundamental physics at ESS complementary with LHC searches
- Could be a bright future ahead

Thanks

Thanks to Valentina Santoro, Torsten Soldner, Vince Cianiolo, Douglas di Julio, Hanno Perrey, David Milstead and Anders Oskarsson for material and discussions...

Backup

Big Bang



$$A_{B\bar{B}} \sim 0$$

Baryogenesis



$$A_{B\bar{B}} \sim 10^{-10}$$

Today



$$A_{B\bar{B}} \sim 1$$

$$A_{B\bar{B}} = \frac{B - \bar{B}}{B + \bar{B}}$$

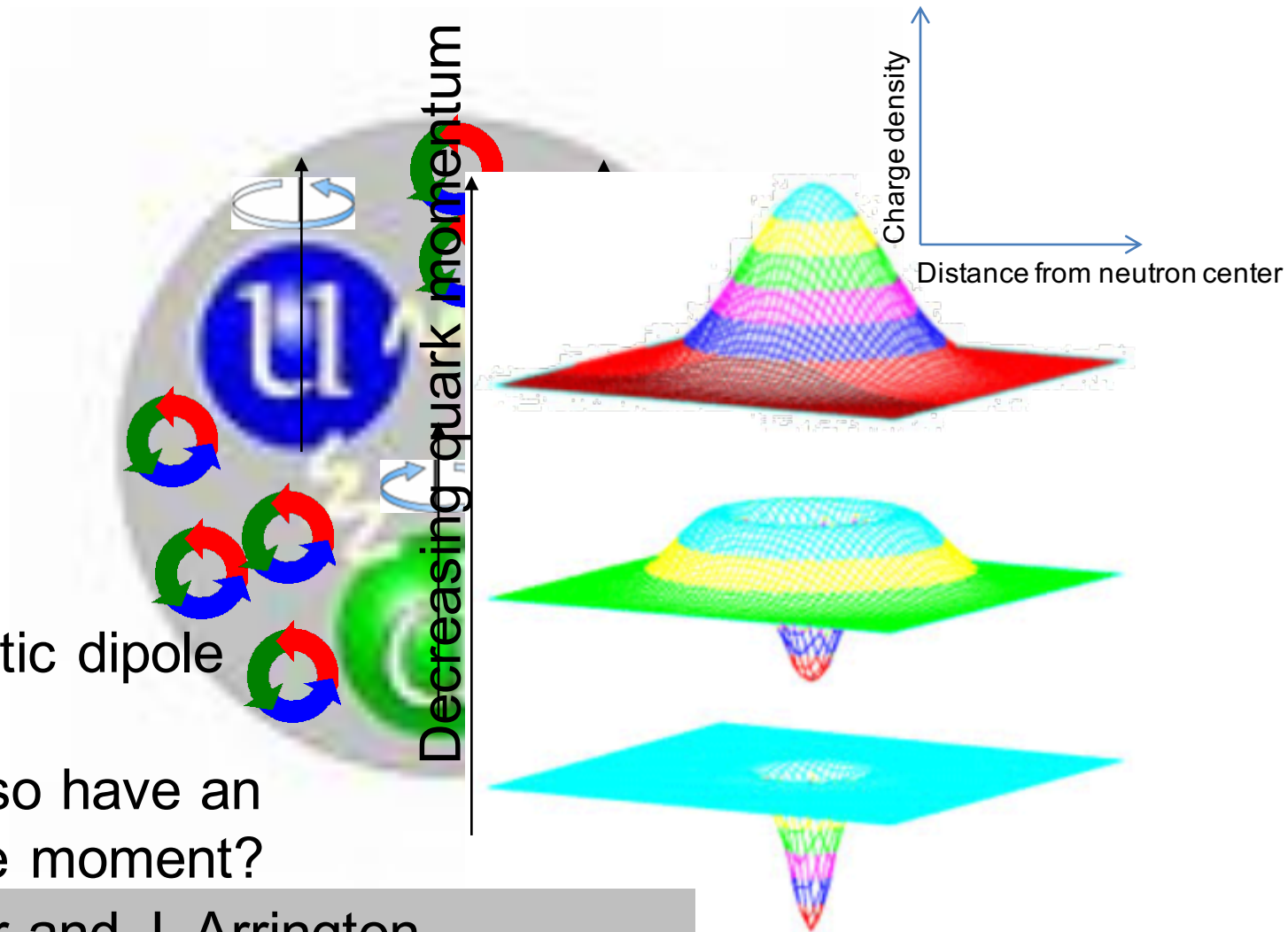
An aerial night-time photograph of the European Spallation Source (ESS) facility. The image shows a large circular building with a glowing interior, surrounded by various support structures and roads. A bright, glowing path of light extends from the circular building towards the top of the image, representing the particle beam's trajectory. The surrounding landscape is dark, with some trees and fields visible.

Indirect searches for New
Physics is the key of the
Fundamental and particle
physics at ESS

But Not Everywhere...

Has a magnetic dipole moment...
=> Does it also have an electric dipole moment?

G.A. Miller and J. Arrington
Phys. Rev. **C 78**, 032201 (2008)



The NNbar proposal @ ESS

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. Brojomans (Columbia University)
S. Choudhury (CERN)
R. Hall-Williams (European Spallation Source)
Y. Kamyshkov (University of Tennessee)
E. Kiskis (Technical University of Denmark and European Spallation Source)
M. Lindberg (European Spallation Source and Lund University)
L. Maepel (CERN)
M. Mozzeito (INFN Padova)
H. M. Shemshi (Rugby University)
W. M. Snow (Indiana University)
T. Soderer (Institut Laue-Langevin)
C. Thorne (European Spallation Source)

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



EUROPEAN
SPALLATION
SOURCE



A New Search for Neutron-Anti-Neutron Oscillations

Abstract

The observation of neutrons turning into antineutrons would constitute a discovery of fundamental importance for particle physics and cosmology. Observing the $n-\bar{n}$ transition would show that baryon number (B) is violated by two units and that matter containing neutrons is unstable. It would provide a clue to how the matter in our universe might have evolved from the $B=0$ early universe. If seen at rates observable in foreseeable next-generation experiments, it might well help us understand the observed baryon asymmetry of the universe. A demonstration of the violation of $B-L$ by 2 units would have a profound impact on our understanding of phenomena beyond the Standard Model of particle physics.

Neutron anti-neutron oscillation should not happen in the standard model ...

Details: Detector

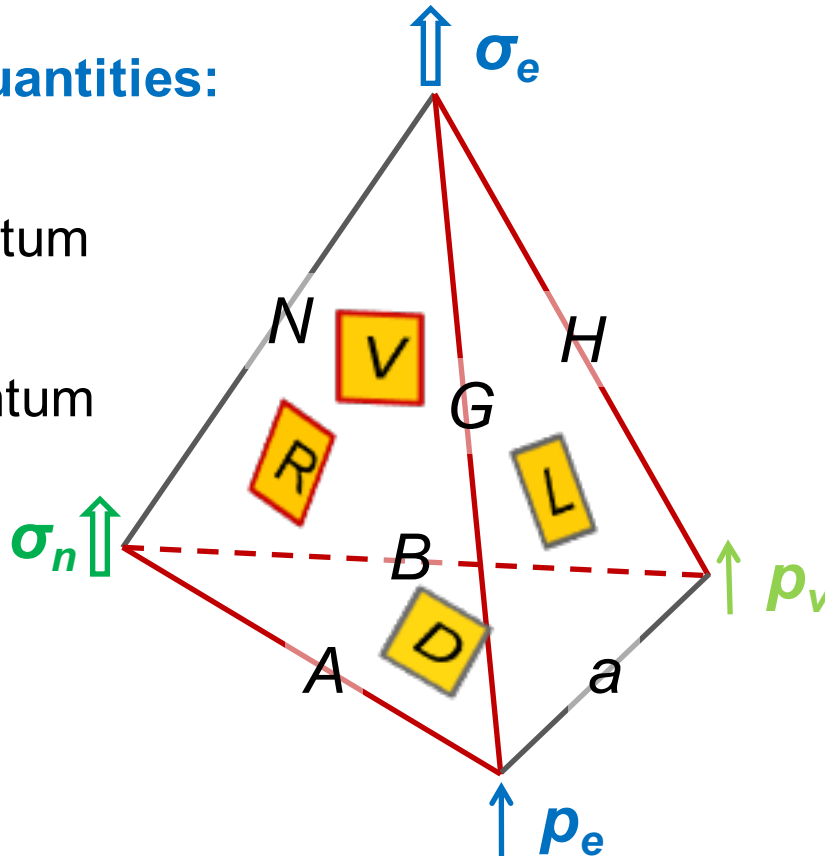
- Anti-neutron annihilation target
 - High annihilation probability, low Z , high transparency to neutrons
 - ILL experiment used a carbon foil, 130 μm thick
- Annihilation produces pions, $\langle n \rangle \sim 5$
- Background suppression:
 - Precise annihilation vertex identification
 - Good mass resolution
 - Beam time structure? (Mainly for background control samples)

Details: Observables in Neutron Decay



4 “detectable” quantities:

- ↑ Neutron spin
- ↑ Electron momentum
- ↑ Electron spin
- ↑ Neutrino momentum



- P conserving
- P violating
- T violating

Correlations:

6 twofold

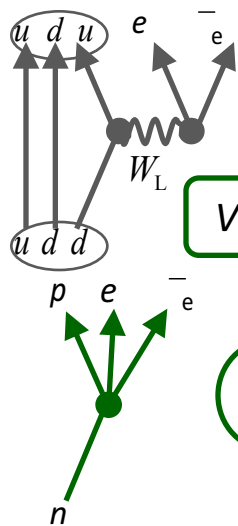
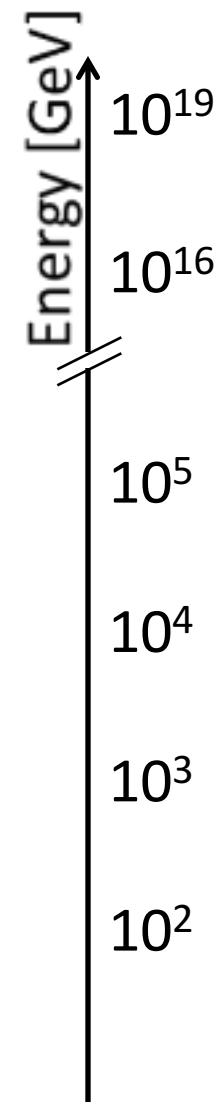
4 threefold

5 fourfold

1 fivefold

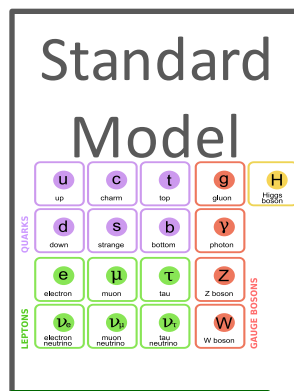
+ Fierz term (e-spectrum)

+ lifetime

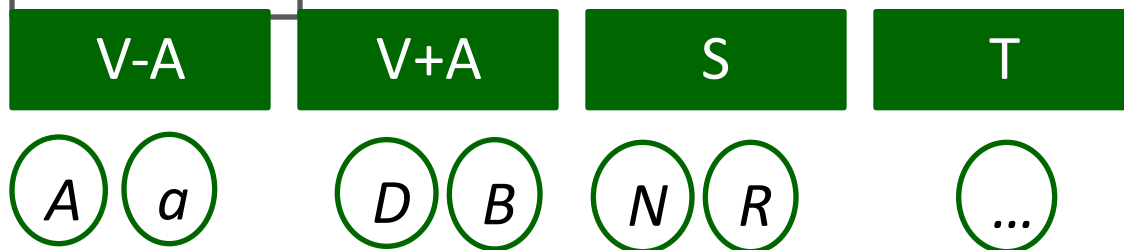


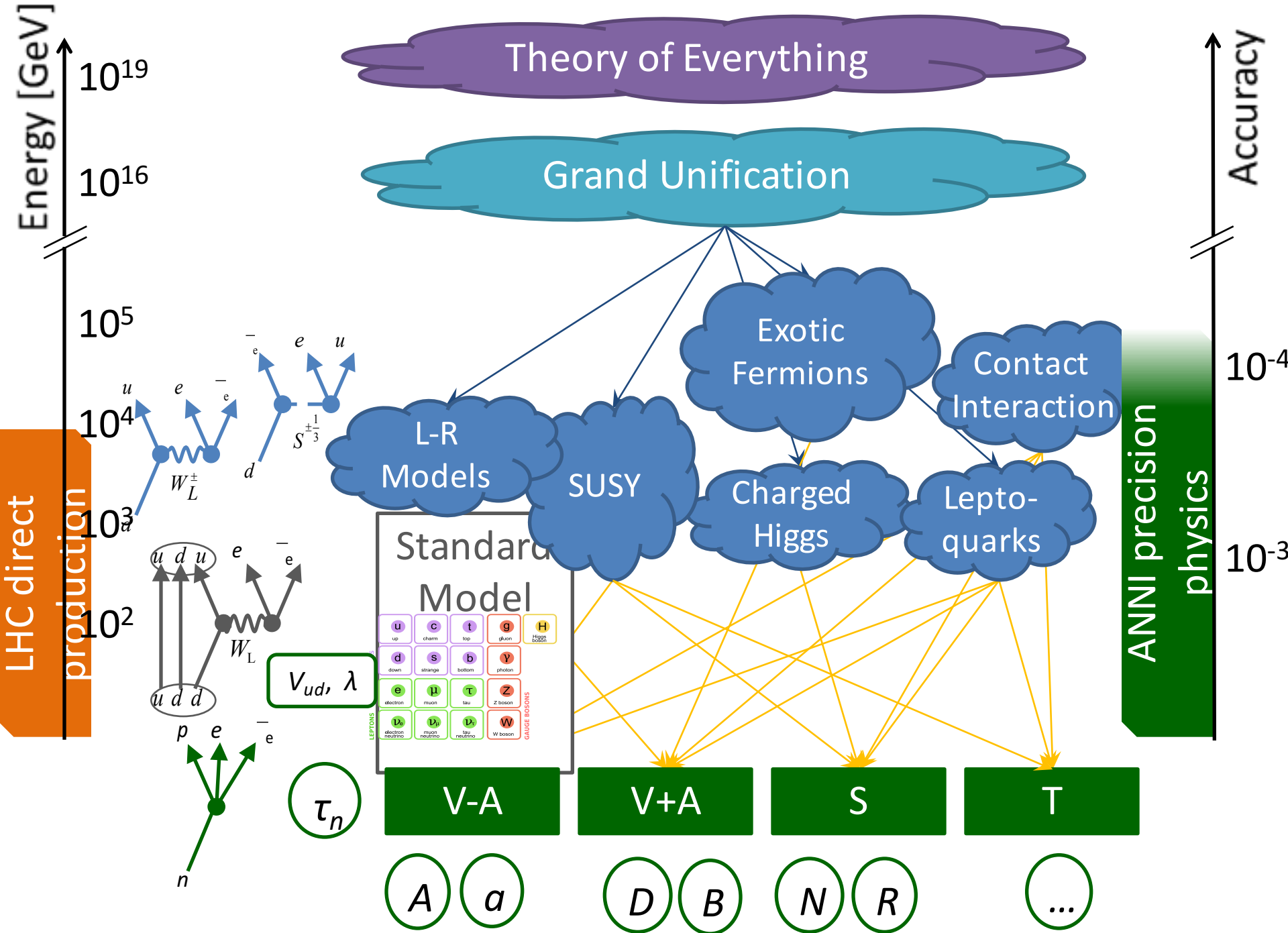
V_{ud}, λ

τ_n

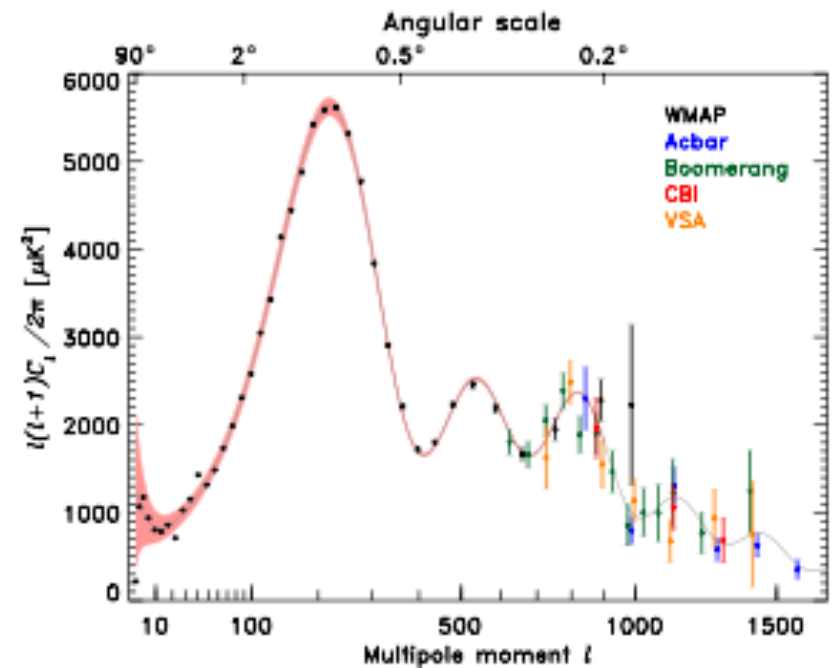
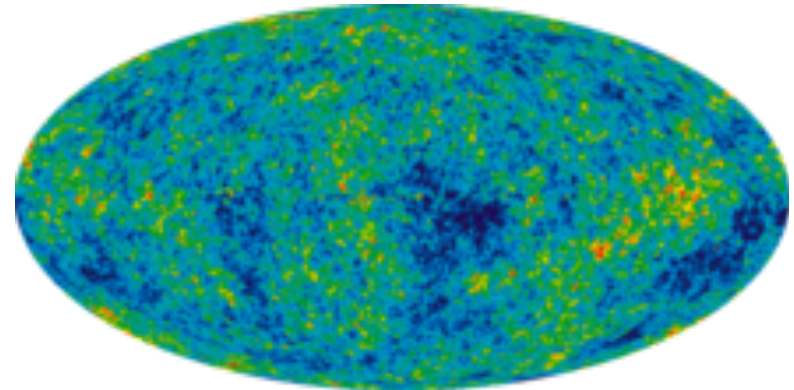
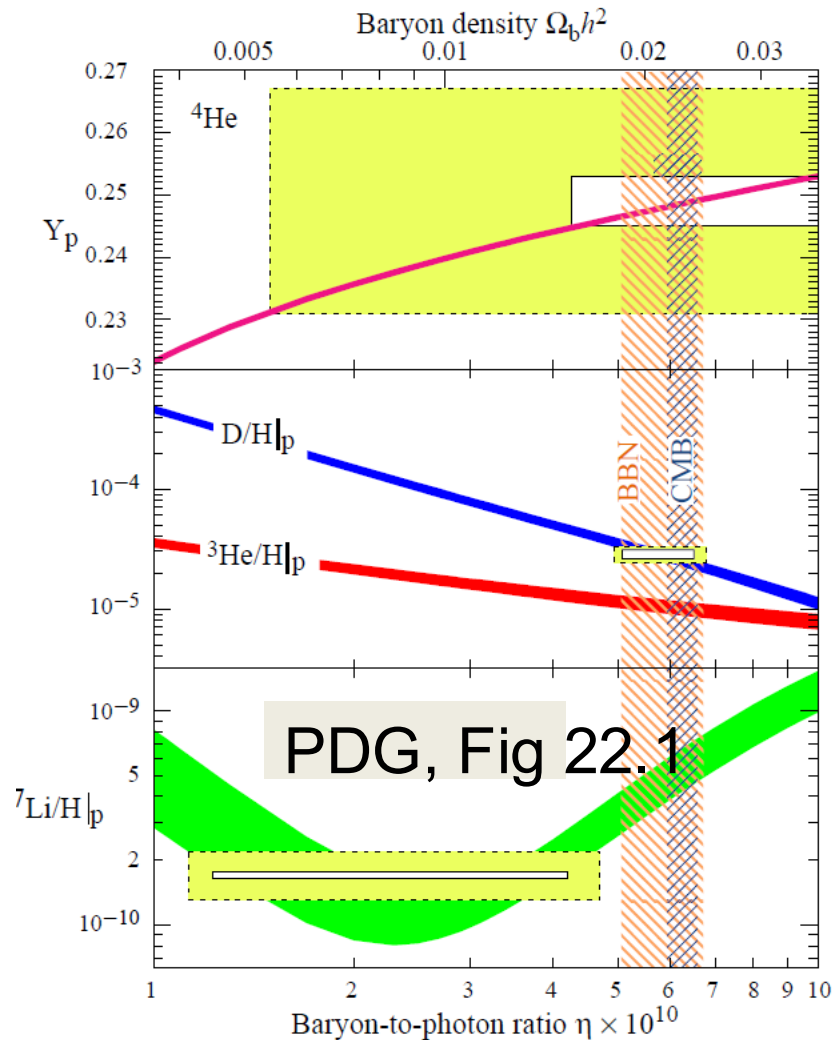


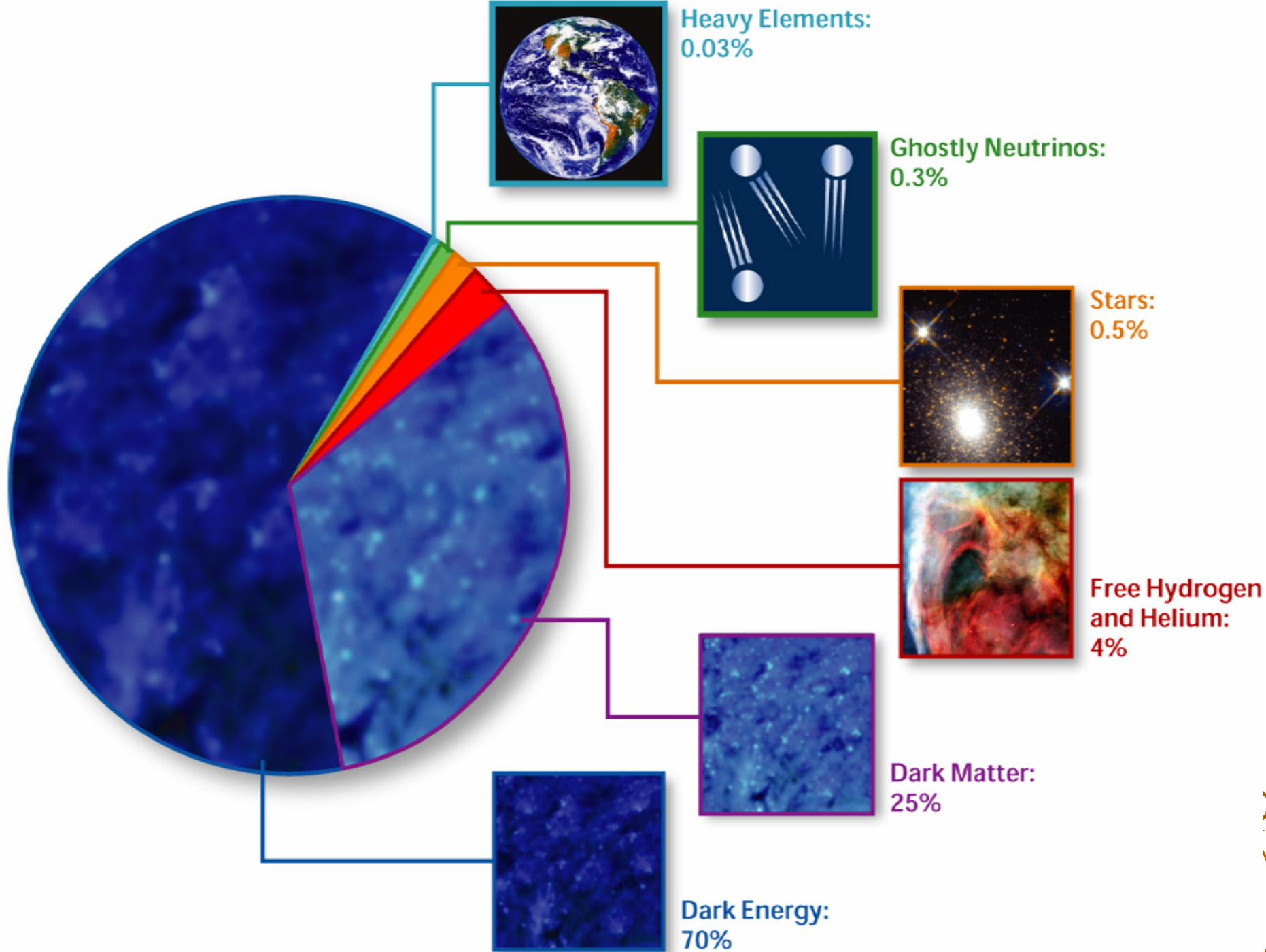
Vector, Axial, Scalar, Tensor





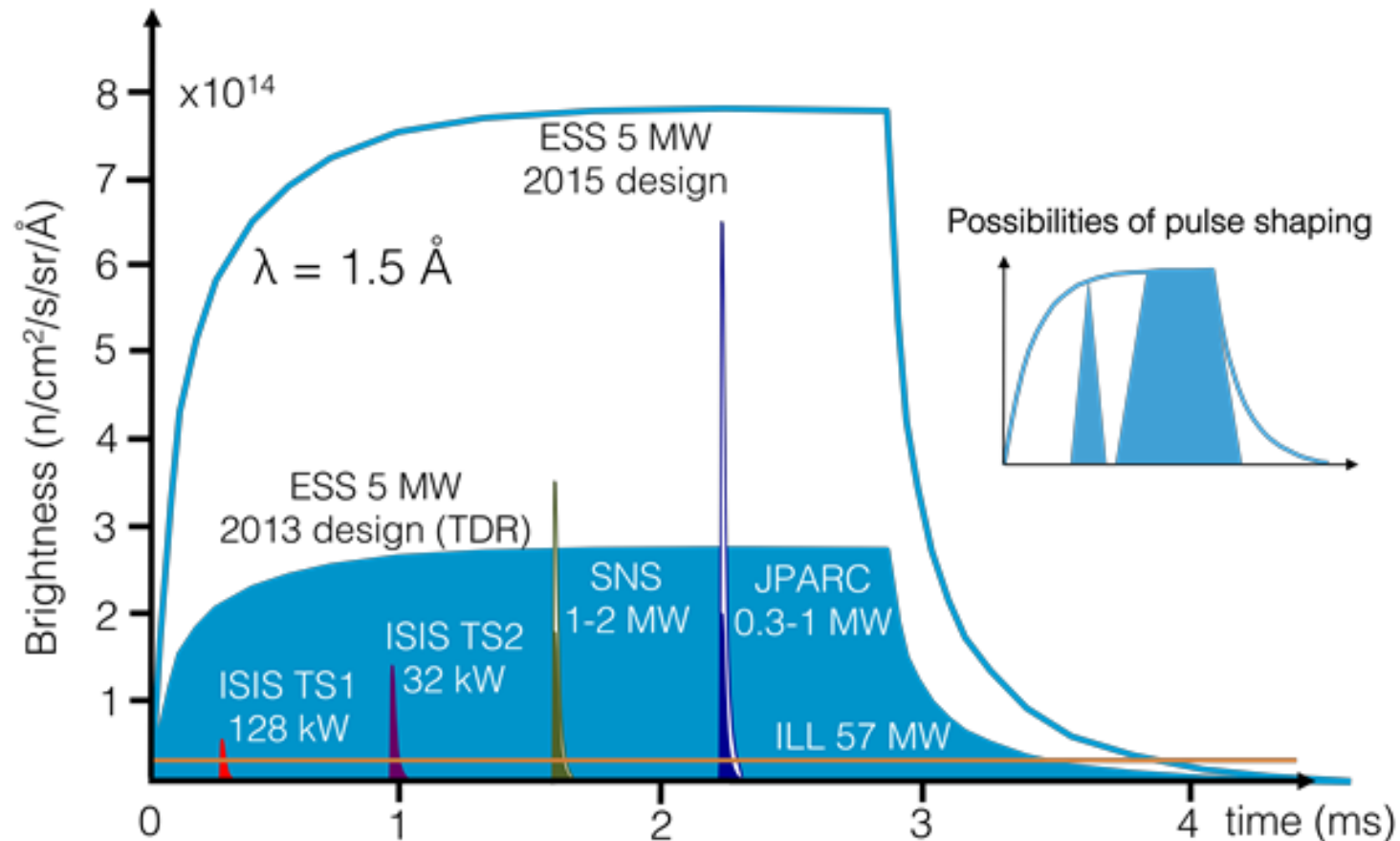
Most Matter Was DOA





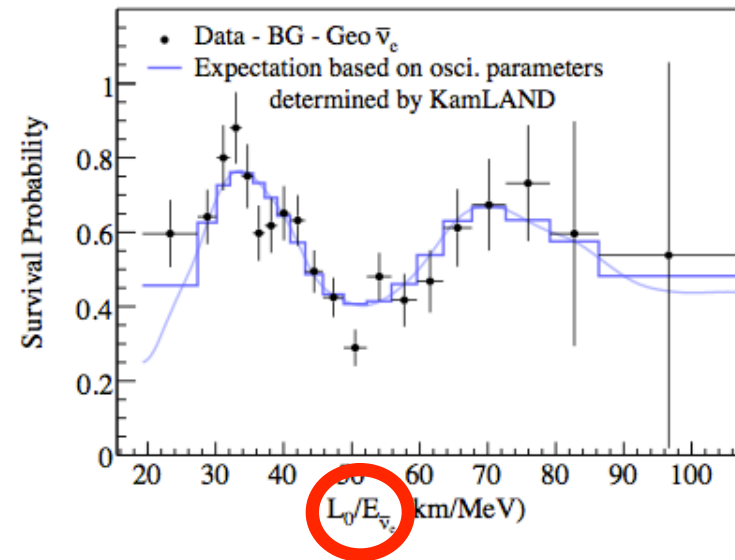
Sakharov Criteria Explained

ESS is a long-pulse spallation source



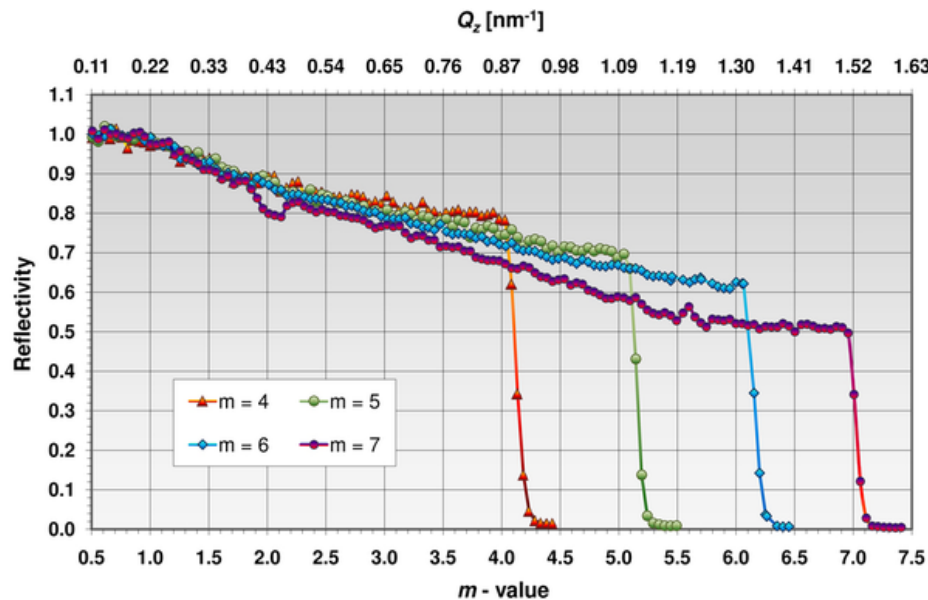
Neutrino Oscillations

- 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
 - $\Delta B = 2$ at a similar energy scale?



Supermirror

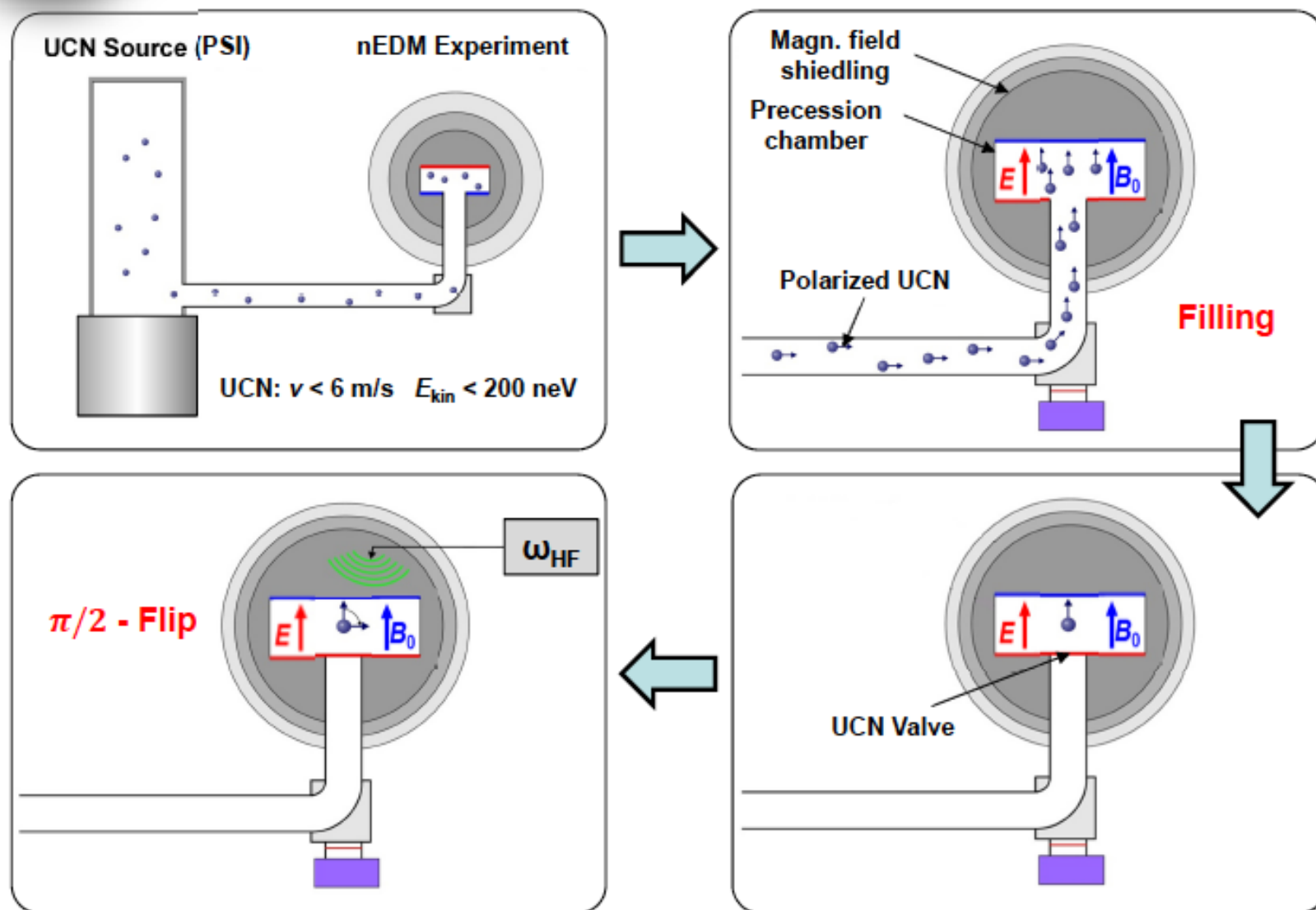
- Crucial in acceptance gain
 - 2D, so acceptance scales quadratically
 - Modern multi-layer supermirrors have good reflectivity at increasingly large momentum transfers

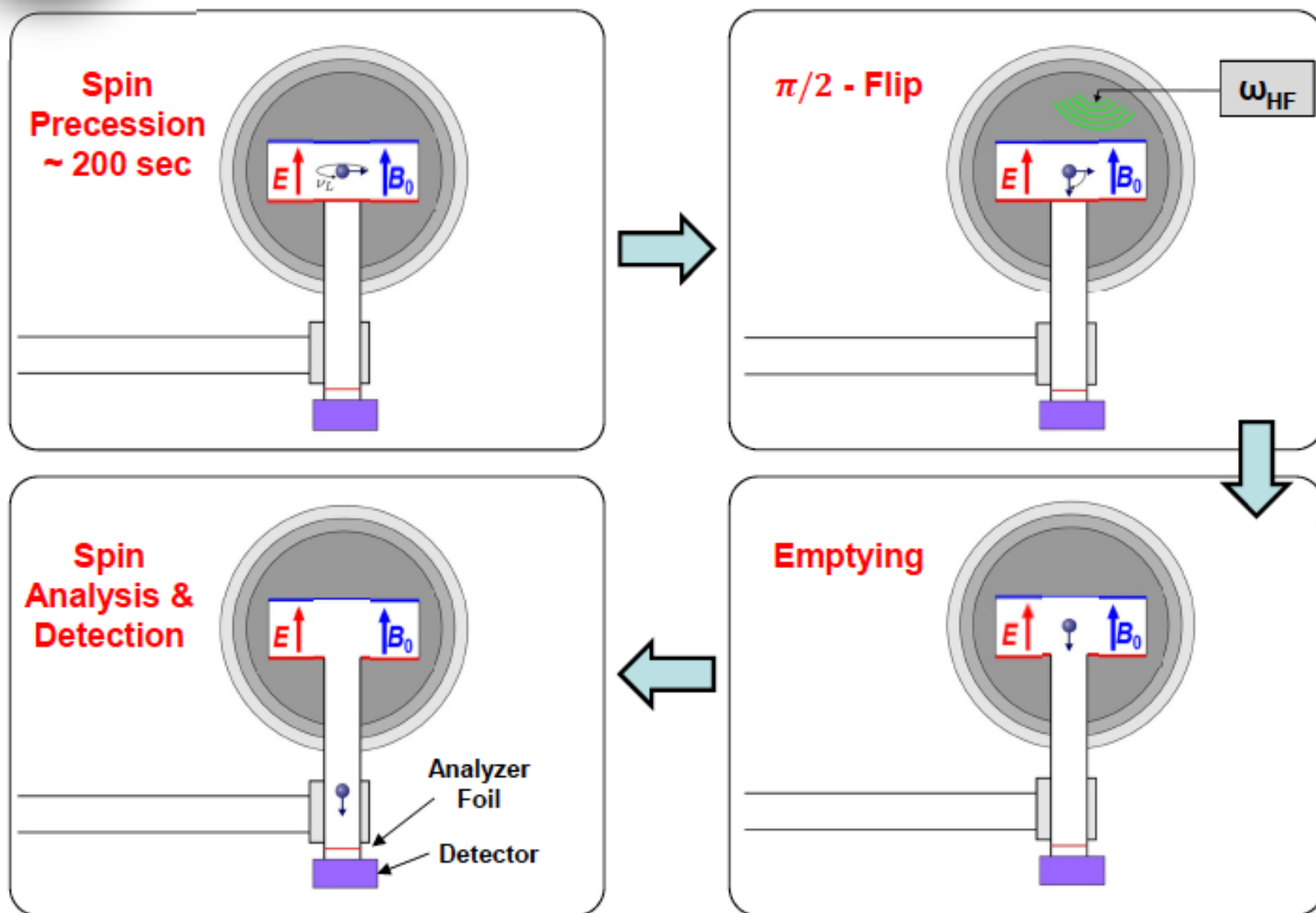


(Swiss Neutronics)

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

Ni reflectivity $\rightarrow 0$ defines $m=1$



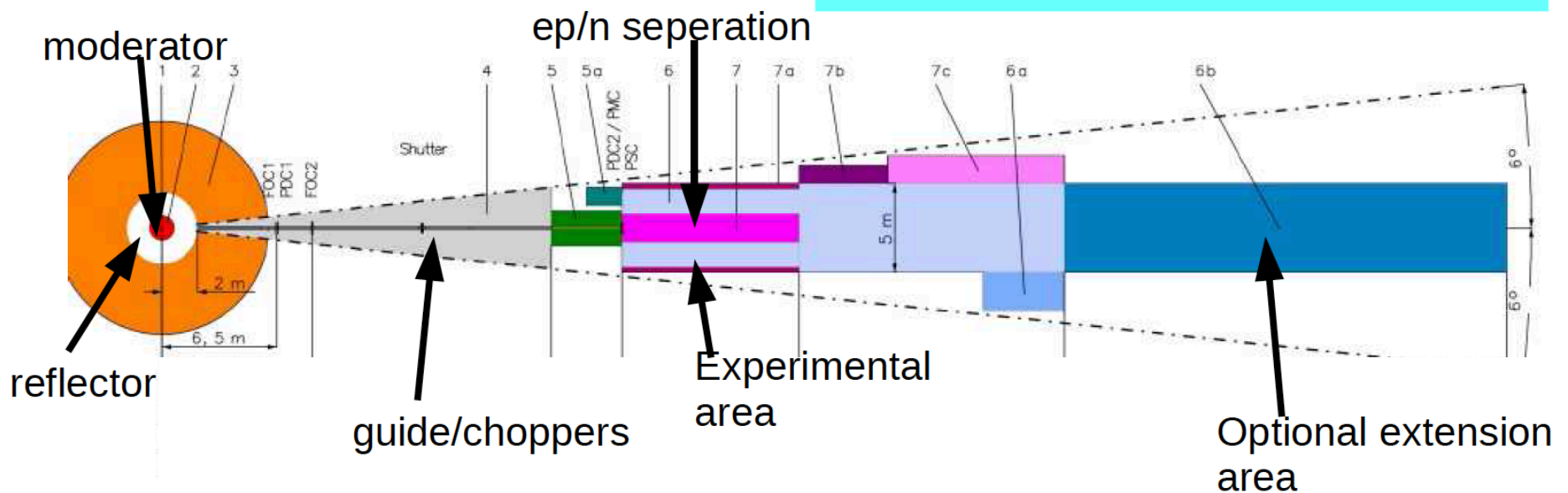


ANNI Beam Line

- Proposal for a fundamental physics beamline, using the neutron as patient rather than probe
- User community foreseen to install experiments for extended running periods: months-years

Envisioned measurements

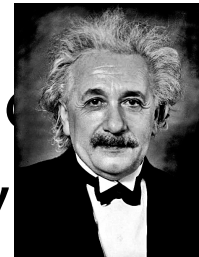
- Lifetime
- Decay correlation coefficients
- EDM and MDM
- charge





Fundamental Physics and curiosity (III)

The last century was fantastic
Special and General relativity
Discovery of electrons, neutrons, proton -
>STANDARD MODEL



Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

Leptons			Quarks		
Flavor	Mass GeV/c ²	Electric charge	Flavor	Approx. Mass GeV/c ²	Electric charge
ν_e electron neutrino	$<1 \times 10^{-8}$	0	u up	0.003	2/3
e electron	0.000511	-1	d down	0.006	-1/3
ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
μ muon	0.106	-1	s strange	0.1	-1/3
ν_τ tau neutrino	<0.02	0	t top	175	2/3
τ tau	1.7771	-1	b bottom	4.3	-1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of \hbar , which is the quantum unit of angular momentum, where $\hbar = 6.58 \times 10^{-25} \text{ GeV} \times \text{s} = 1.05 \times 10^{-34} \text{ J} \cdot \text{s}$.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is $1.60 \times 10^{-19} \text{ coulombs}$.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c² (remember $E = mc^2$), where $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \times 10^{-10} \text{ joule}$. The mass of the proton is $0.938 \text{ GeV}/c^2 \approx 1.67 \times 10^{-27} \text{ kg}$.

Baryons qqq and Antibaryons qqq

Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c ²	Spin
p	proton	uud	1	0.938	1/2
\bar{p}	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
n	neutron	udd	0	0.940	1/2
\bar{n}	anti-neutron	$\bar{u}\bar{d}\bar{d}$	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega minus	sss	-1	1.672	3/2

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., γ , Z^0 , and η , but not K^0 or D^0) are their own antiparticles.

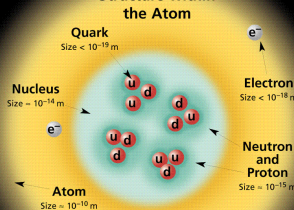
Figures

These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field and red lines the quark paths.

matter constituents

spin = 1/2, 3/2, 5/2, ...

Structure within the Atom



BOSONS

force carriers spin = 0, 1, 2, ...

Unified Electroweak			Strong (color)		
Name	Mass GeV/c ²	Electric charge	Name	Mass GeV/c ²	Electric charge
γ photon	0	0	g gluon	0	0
W^-	80.4	-1			
W^+	80.4	+1			
Z^0	91.187	0			

Color Charge Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

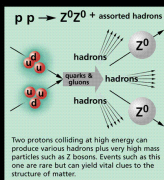
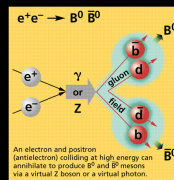
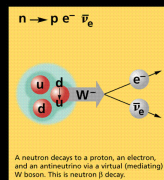
One cannot isolate quarks and gluons; they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: mesons (q \bar{q}) and baryons (qqq).

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property	Interaction	Gravitational	Weak		Electromagnetic	Strong	
			(Electroweak)			Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Quarks, Gluons	See residual strong interaction		
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons		
Particles mediating:	Graviton (not yet observed)	$W^+ \quad W^- \quad Z^0$	γ	Gluons	Mesons		
Strength relative to electromagnetism for two u quarks at:	10^{-41}	0.8	1	25	Not applicable to quarks		
	10^{-41}	10^{-4}	1	60			
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20		



The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at <http://ParticleAdventure.org>

This chart has been made possible by the generous support of:

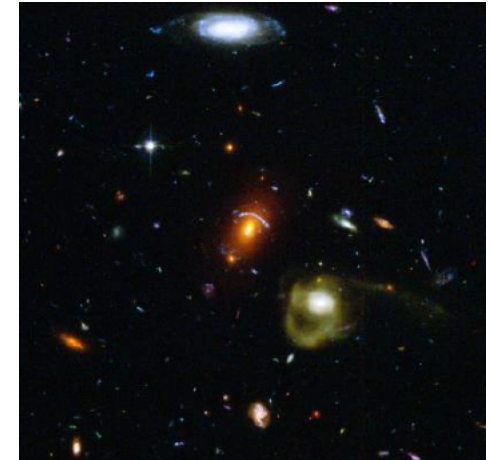
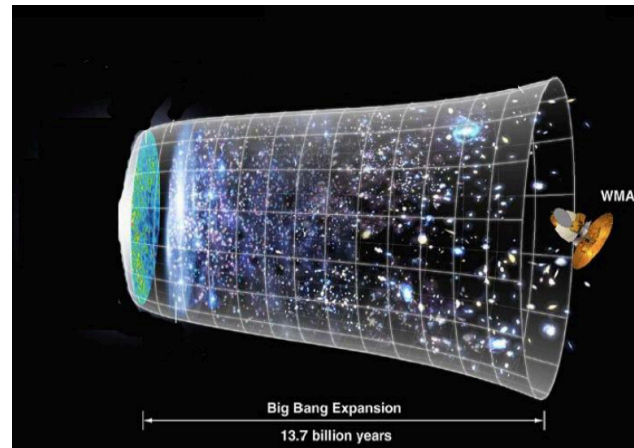
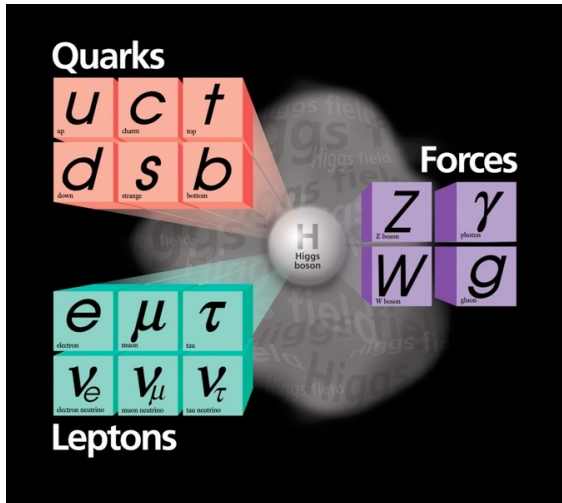
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BRIEF INDUSTRIES, INC.

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<http://CPEPweb.org>

Lacking in the Standard Model (I)

Standard Model + General Relativity = Universe



Less than 5% of the energy content of the universe are understood!

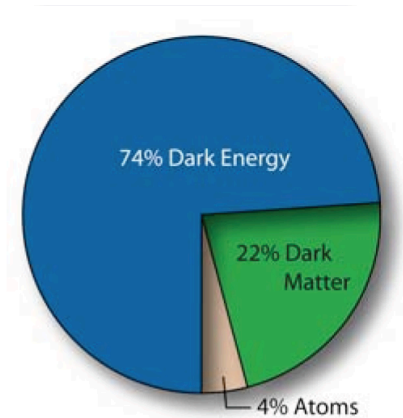
DARK MATTER ? DARK ENERGY?

Lacking in the Standard Model (II)

- What is the Universe REALLY made of?
- Particle physicist's answer: stable particles – protons, neutrons, electrons, neutrinos

(Why not antiprotons, positrons, etc.?)

(ANOTHER OPEN PROBLEM)



But astronomical observations

- indicate that the known particles make only about 4%
- of the stuff in the Universe!!!Made Of?

“The only true wisdom is in knowing you know nothing” Socrates

Masses and Energies



Neutron

939.565 MeV



Proton

938.272 MeV



Electron

0.511 MeV



Neutrino

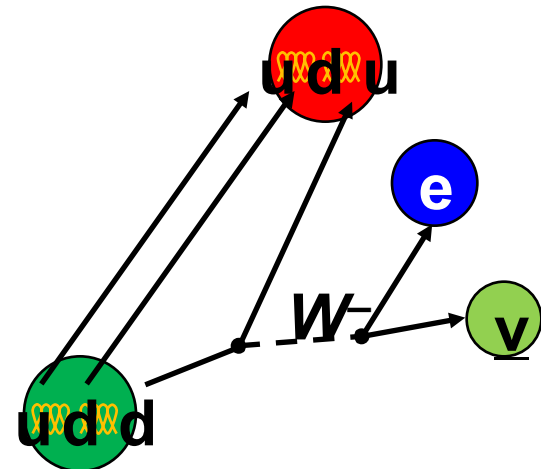
<2 eV

W boson

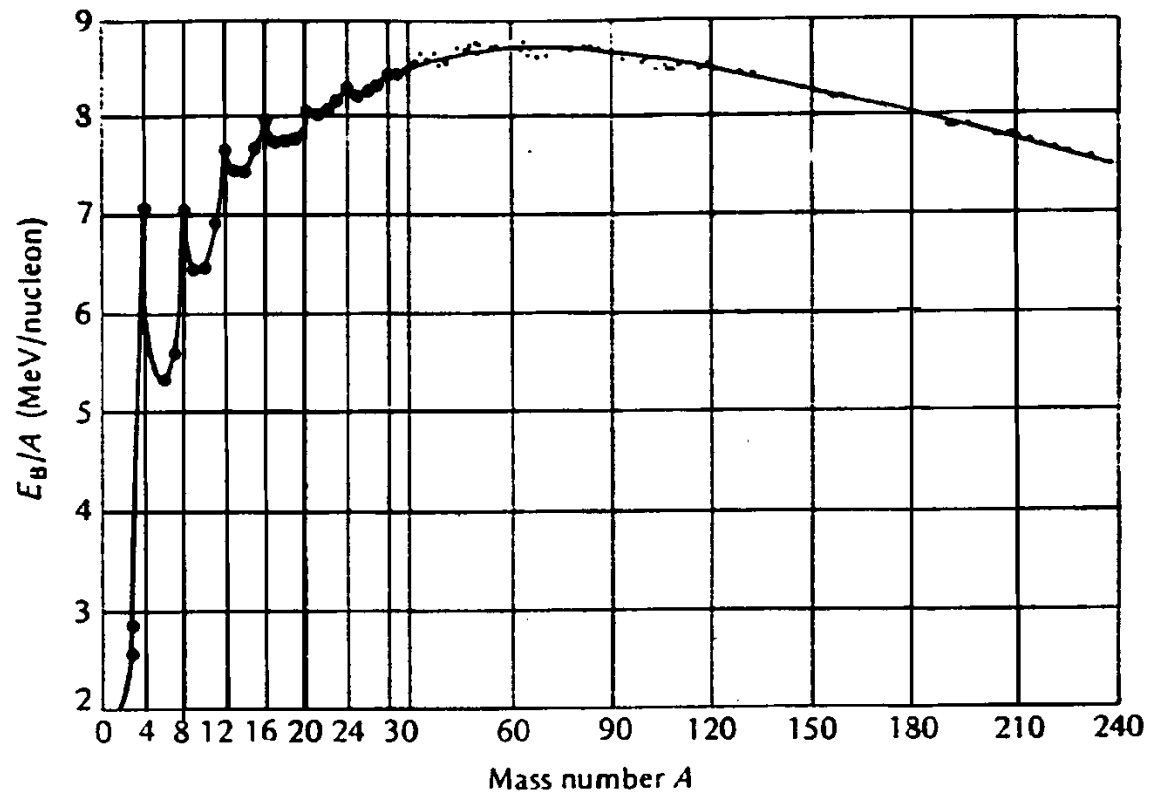
**80.385
GeV**

$Q = 0.781 \text{ MeV}$

- **Virtual** creation of W boson
- Heisenberg → Range 0.002 fm

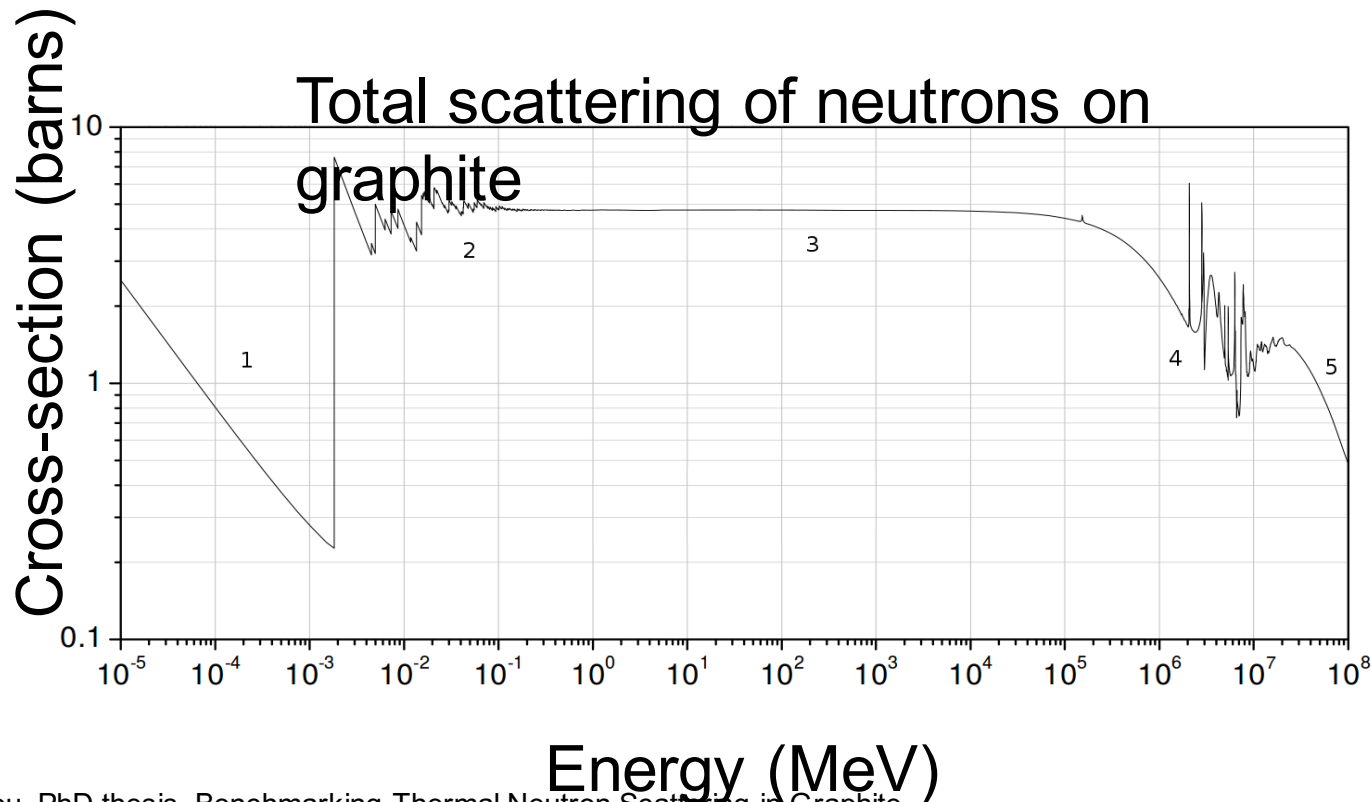


Most important diagram for our existence...

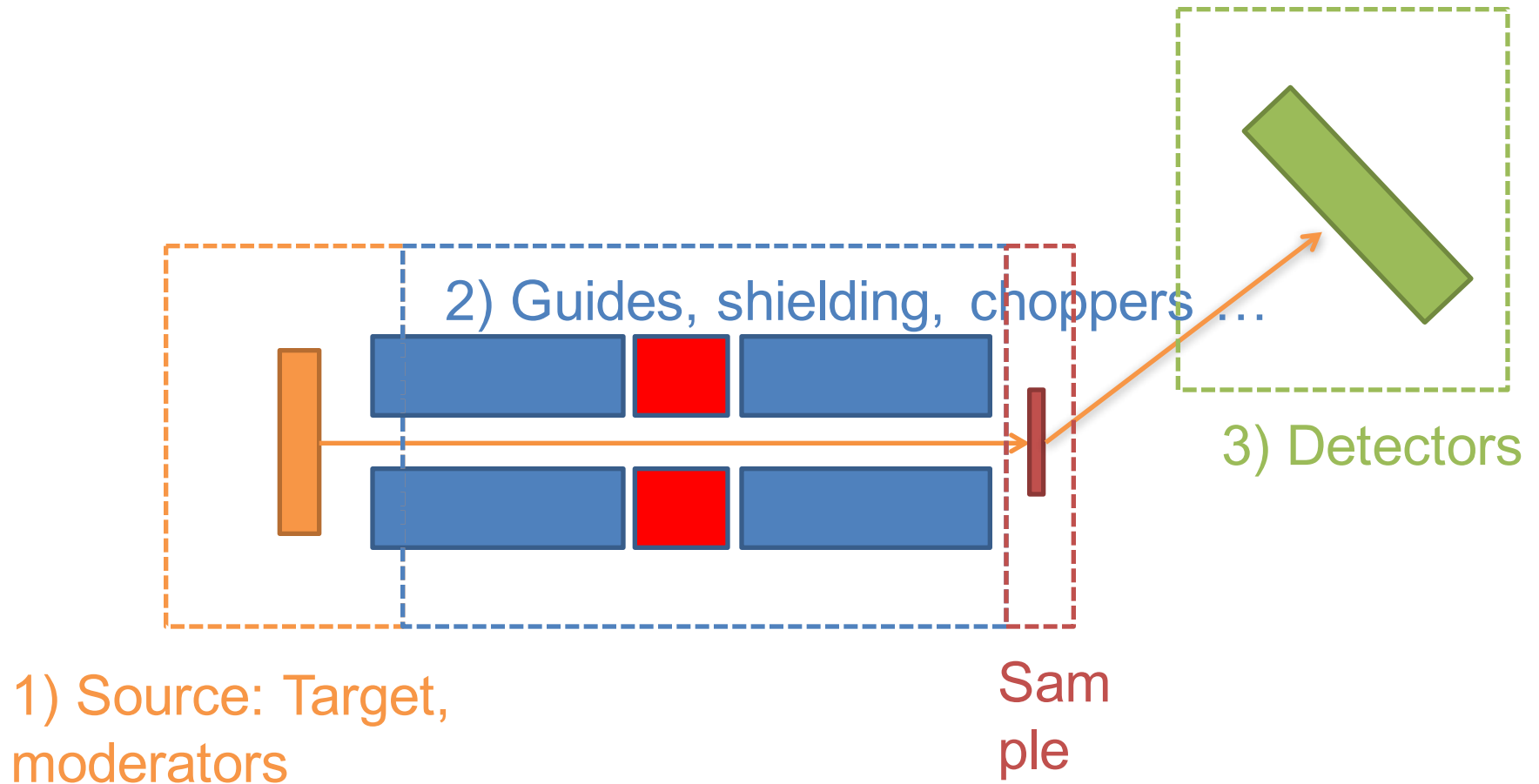


Spallation neutron physics

- Neutron energies range from \sim GeV down to \sim meV
- Wide range of interactions



A neutron scattering experiment

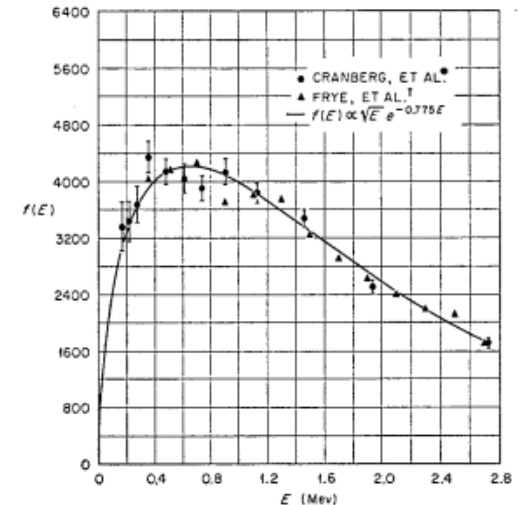


How a spallation source works

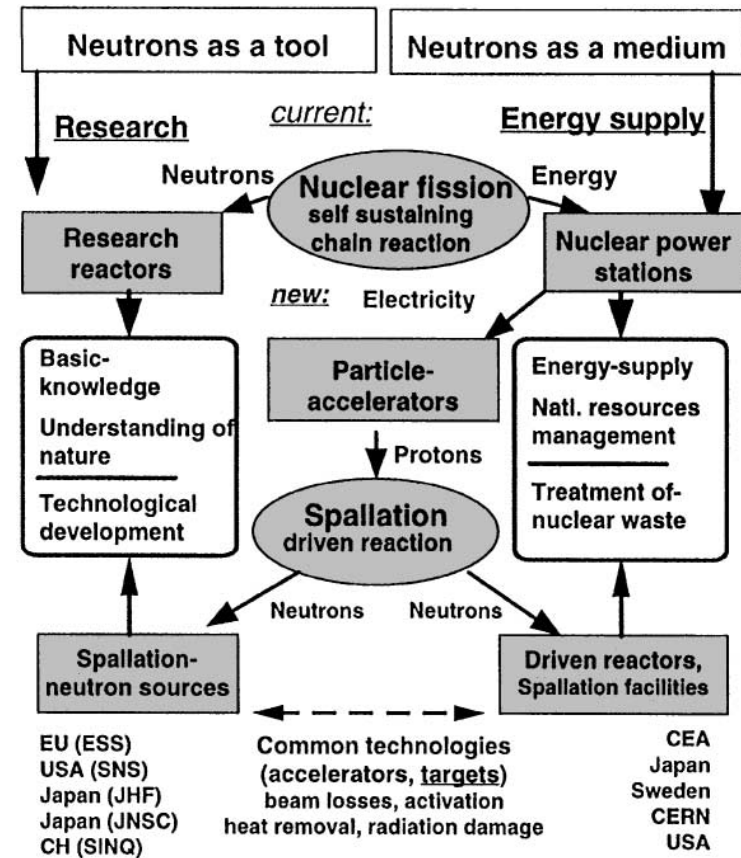
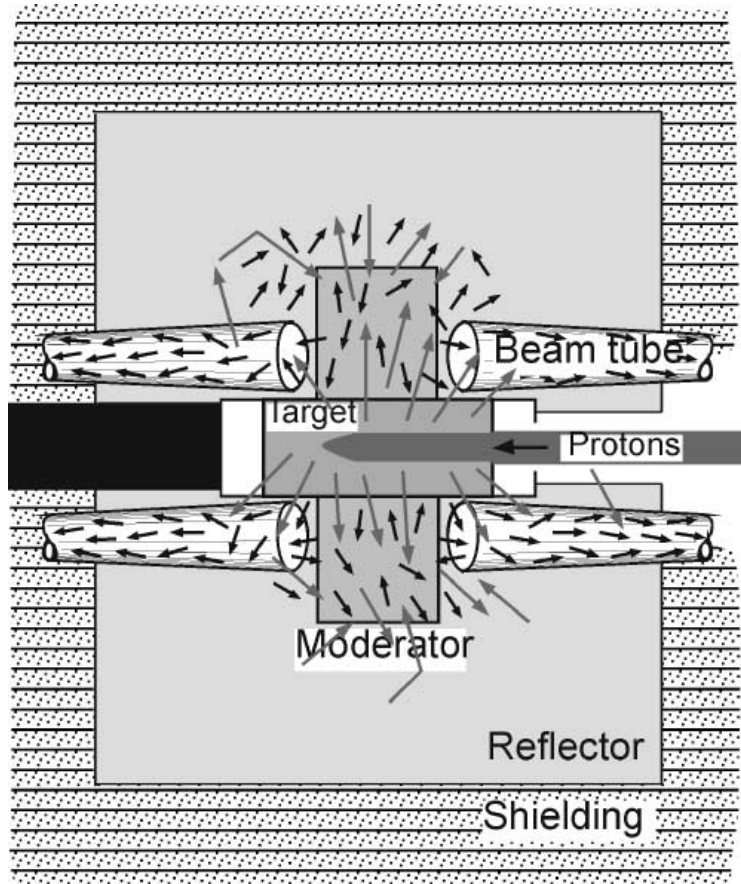
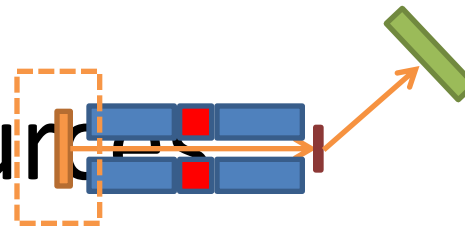
- Use a proton accelerator to generate neutrons via the spallation process (2 GeV, 2.86 ms pulse)
- Slow down the emitted neutrons with moderators placed close to the spallation target
- Direct the neutrons to instruments placed around the target position
- Neutrons interact with samples placed in the beam and reaction products are detected (not just materials science!)

Fission vs spallation

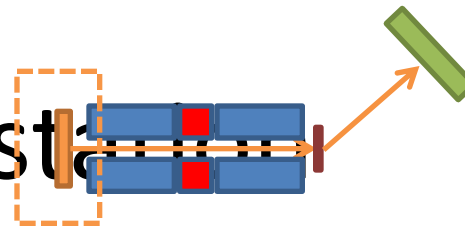
- Fission
 - 200 MeV/fission
 - Prompt neutrons evaporate from excited nuclei with energy ~ 2 MeV
 - ~ 2.5 neutrons / fission, but ~ 1 neutron from each fission is useful (1 neutron to continue to reaction, and about 0.5 is captured)
- Spallation
 - Produces around 20 neutrons per proton
 - 90% of the neutrons have energies around 2 MeV
 - 60% of beam energy (GeV) appears as heat in the target, albeit a short time and however, means dissipating ten times less heat energy per useful neutron than fission



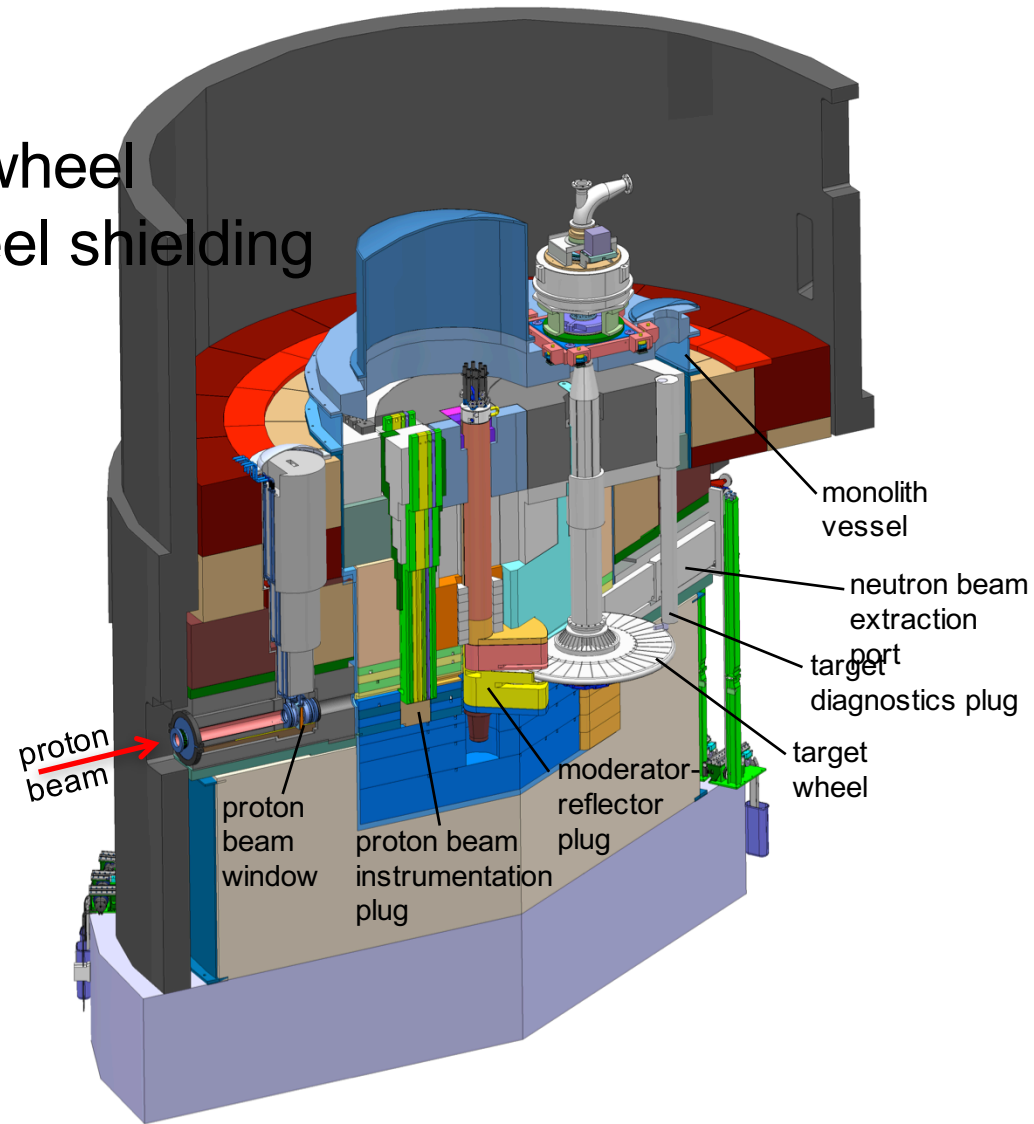
Spallation sources



ESS target station



- 4 tonnes target wheel
- 6,000 tonnes steel shielding



Spallation neutron physics

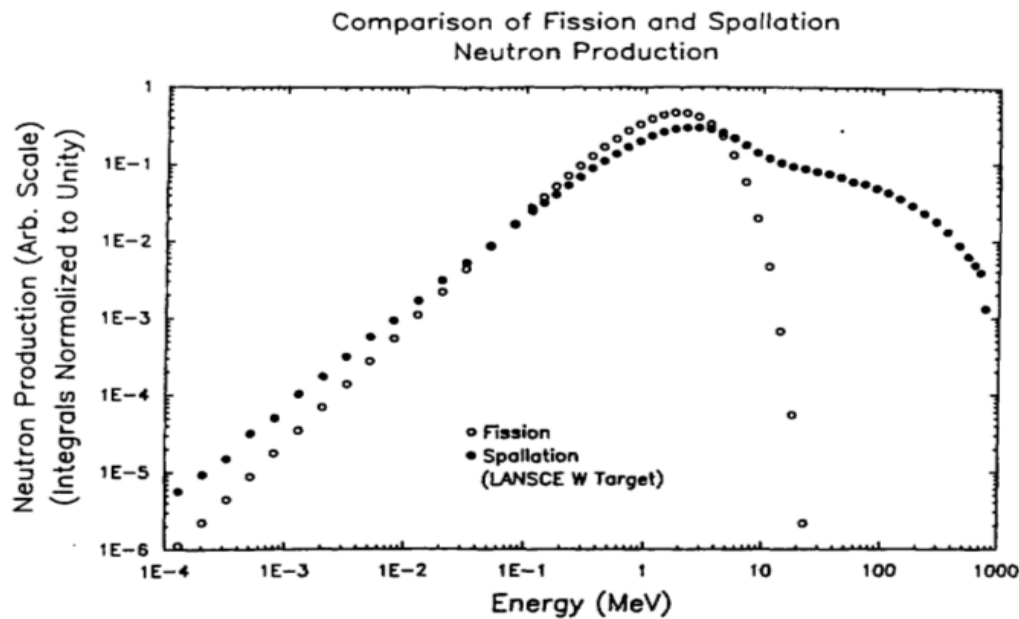
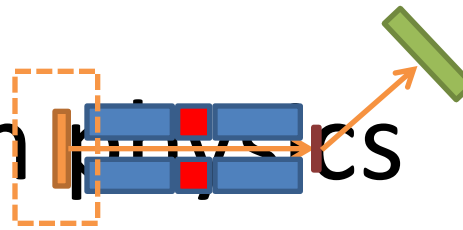
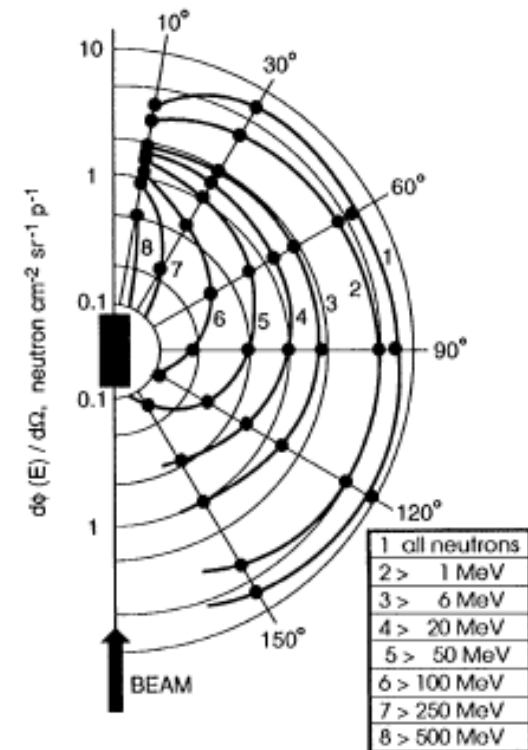


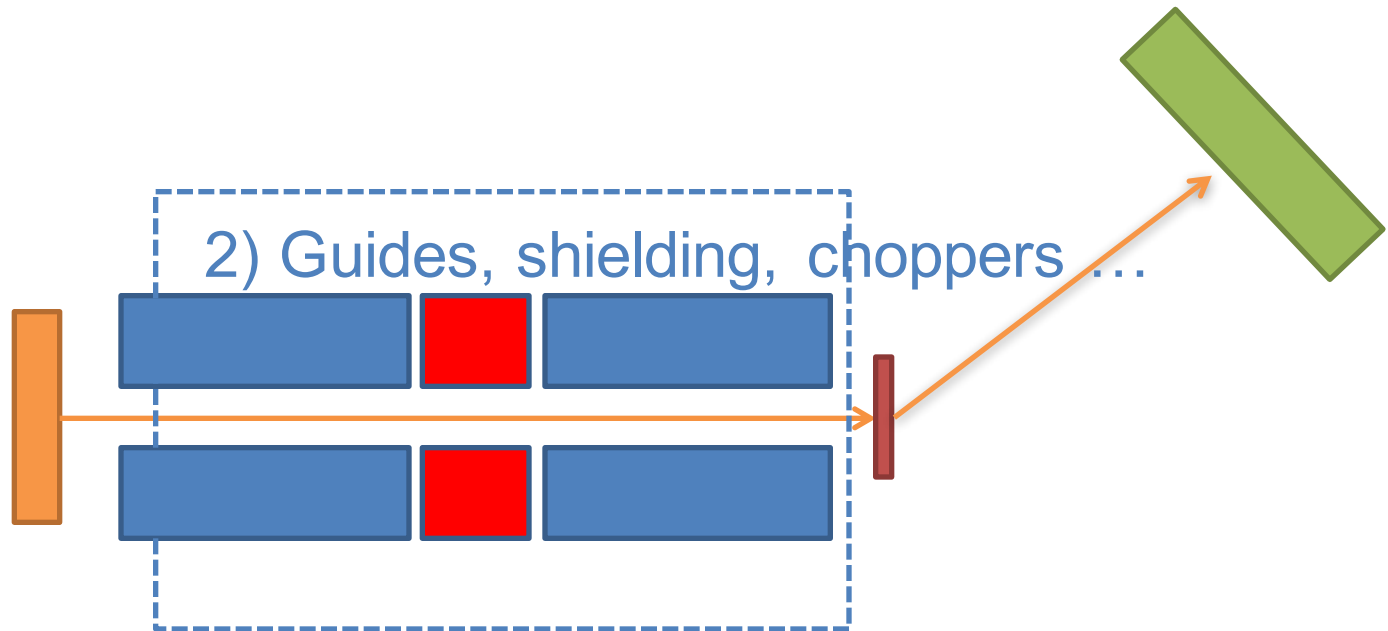
Figure 6. Neutron production from fission (○) and from spallation (●).



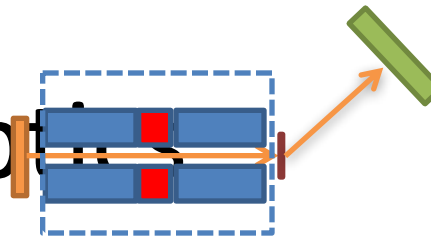
G. Russel, ICANS-XI proceedings, KEK, Tsukuba, Oct. 22-26 1990

G.S. Bauer / Nuclear Instruments and
Methods in Physics Research A 463 (2001)
505–543

Guides

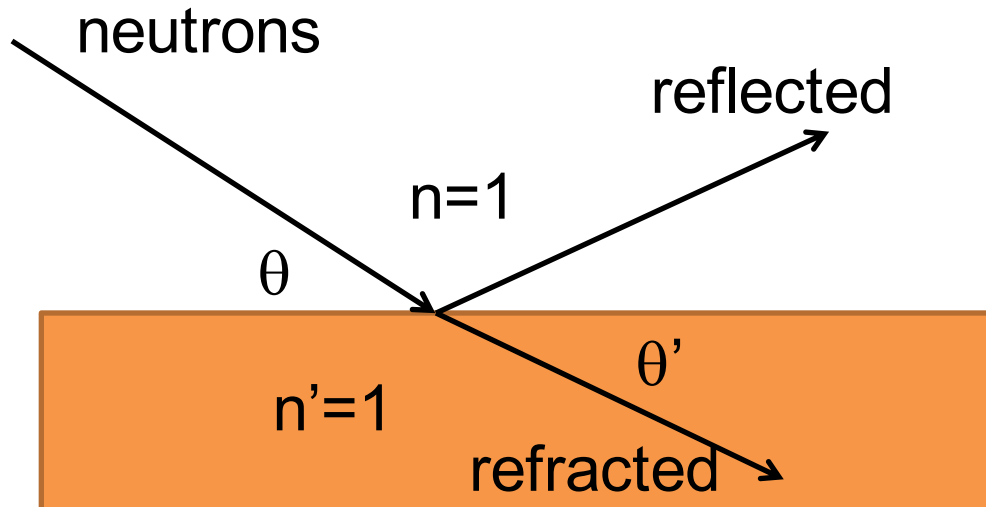


Neutron opt



- Transport of neutrons takes advantage of the wave-like nature of neutrons

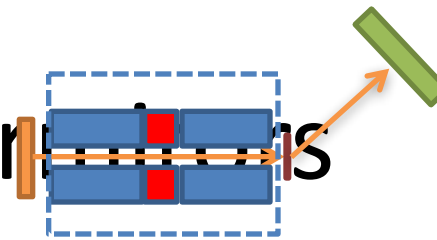
$$\frac{\cos \theta}{\cos \theta'} = \frac{n'}{n} = n'$$



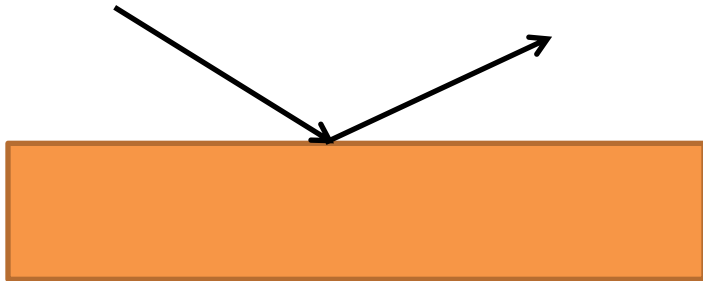
When $\theta'=0 \Rightarrow$ critical angle of reflection, can be shown that: $\frac{Nb}{c} \sqrt{\frac{Nb}{c}}$

Where N is the atomic density and b is the coherent scattering

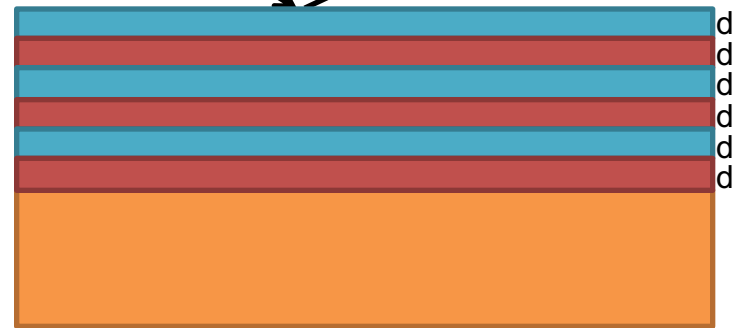
Neutron supermirrors



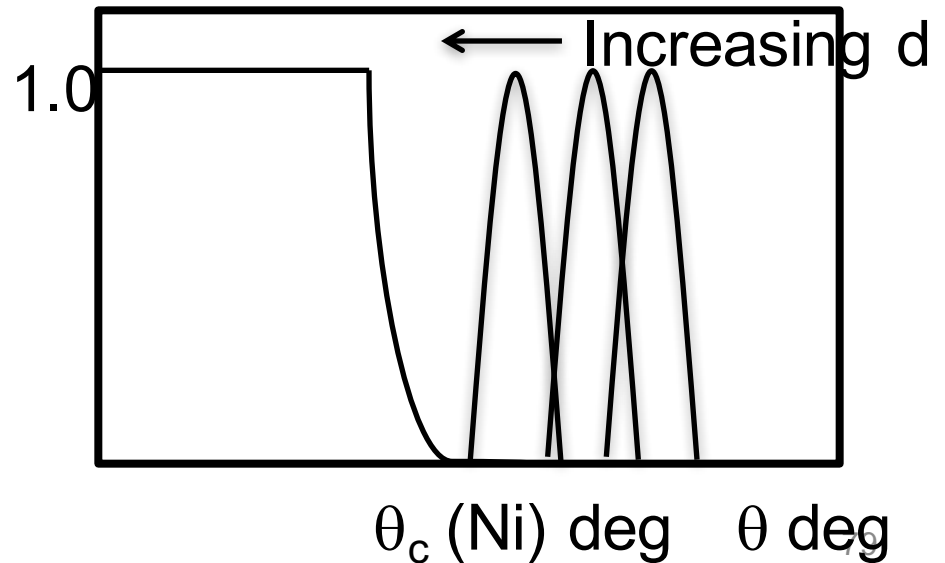
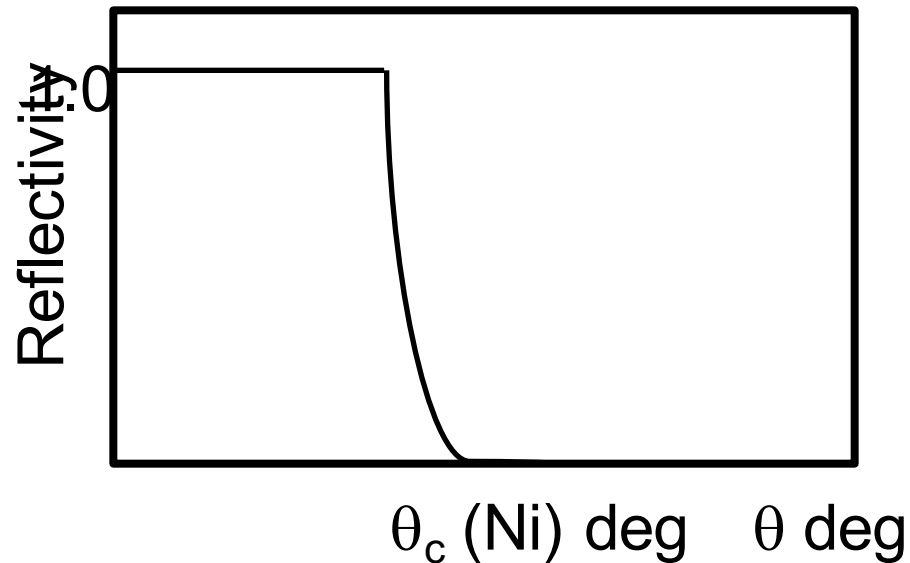
Single mirror



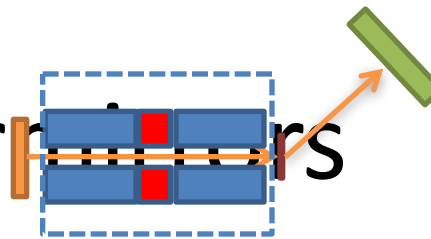
Multi-layer mirror



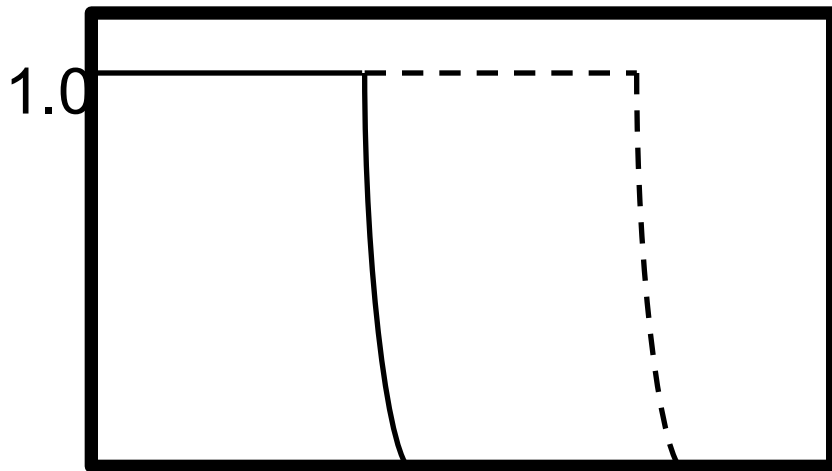
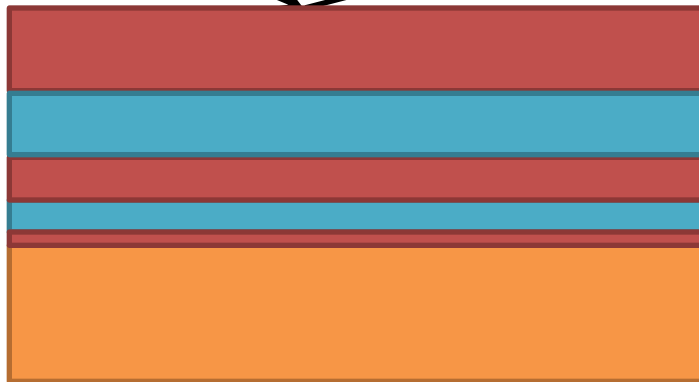
$$= 2d \sin$$



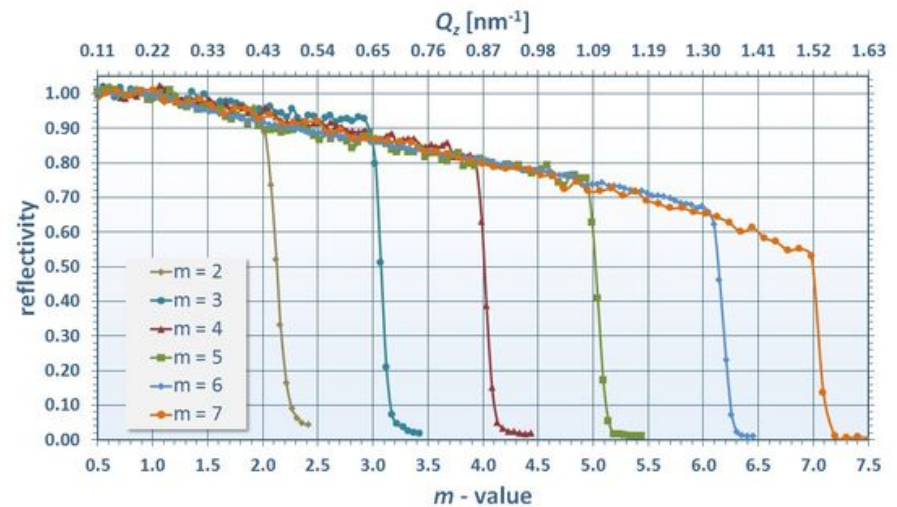
Neutron supermirrors



Supermirror

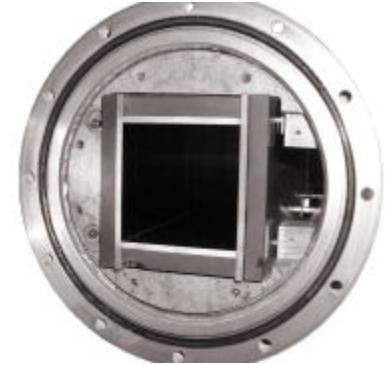
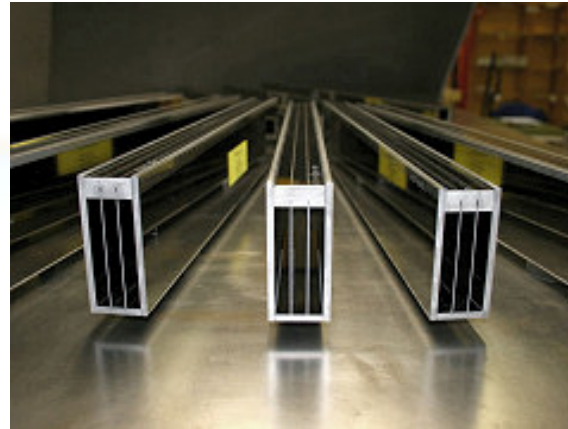
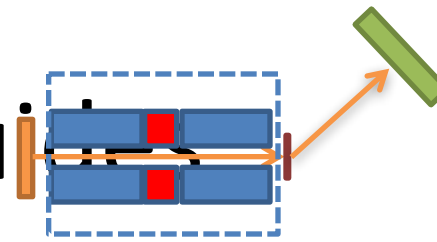


θ_c (Ni) deg $m\theta_c$ (Ni) deg θ deg

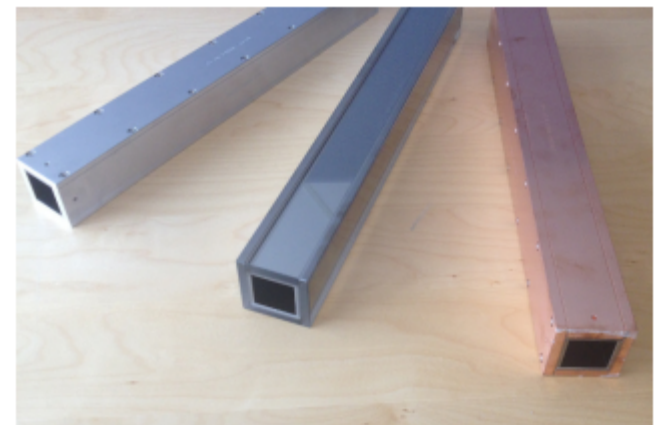


<http://www.swissneutronics.ch>

Neutron guide



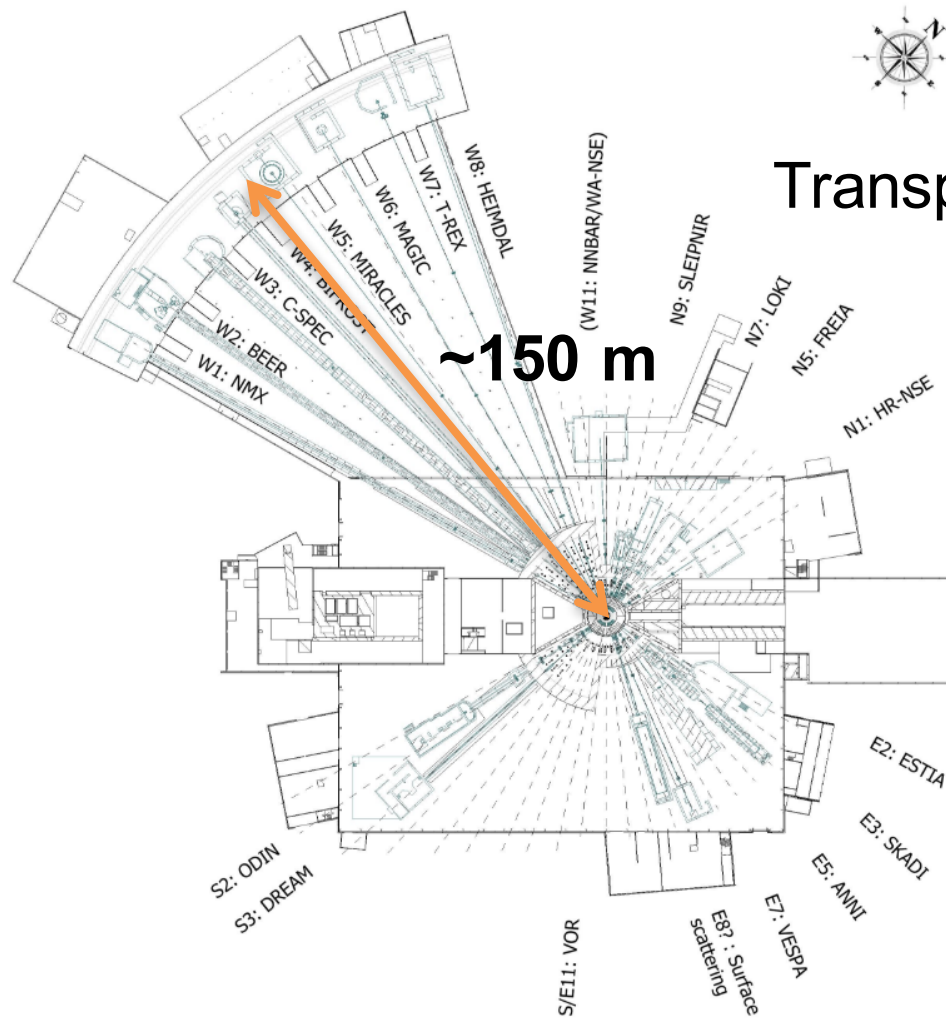
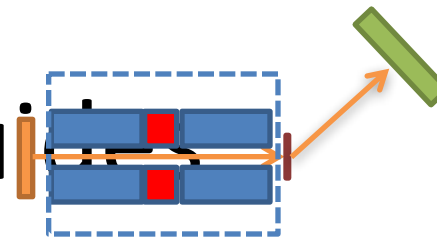
<http://www.mirrortron.kfkipark.h>



<http://www.swissneutronics.ch/>

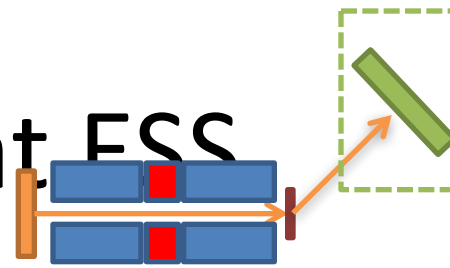
Different substrate materials

Neutron guide



Transport over long distance

Detectors at ESS



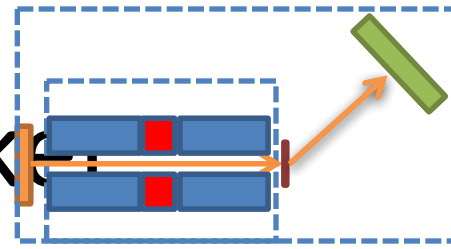
Instrument	Detector area [m ²]	Wavelength range [Å]	Time resolution [μs]	Spatial resolution [mm]
Multi-Purpose Imaging ^a (ODIN)	1	1 - 10	1	0.001 - 1
Broad-Band Small Sample SANS ^a (LOKI)	[8 - 16]	3 - 20	100	2 - 8
General Purpose Polarised SANS ^b (SKADI)	2.0674	2 - 18	100	5 - 10
Horizontal Reflectometer ^b (FREIA)	0.25	2 - 23	100	1×8
Vertical Reflectometer ^a (ESTIA)	0.16	5 - 9.4	100	0.5×2
Bi-Spectral Powder Diffractometer ^a (POWTEX)	11.69	0.5 - 20	< 10	2 × 2
Thermal Powder Diffractometer ^b (HEIMDAL)	15.002	1 - 13	100	3 × 3
Material Science & Engineering Diffractom. ^a (BEER)	6.4925	0.1 - 7	10	2 × 5
Macromolecular Diffractometer ^a (NMX)	1.08	1.8 - 3.5	1000	0.2
Cold Chopper Spectrometer ^a (C-SPEC)	47.47	1.5 - 20	10	25 × 25
Bi-Spectral Chopper Spectrometer ^a (VOR)	25.65	0.8 - 20	10	20 × 20
Inverse TOF Spectrometer ^b (CAMEA)	2.4	1 - 8	< 10	5 × 5
Total	[130 - 138]			

Table 1: Estimated detector requirements for the 22 reference instruments in terms of detector area, typical wavelength range of measurements and desired spatial and time resolution. The foot notes indicates the tranche in which the instruments is presently intended to be delivered.

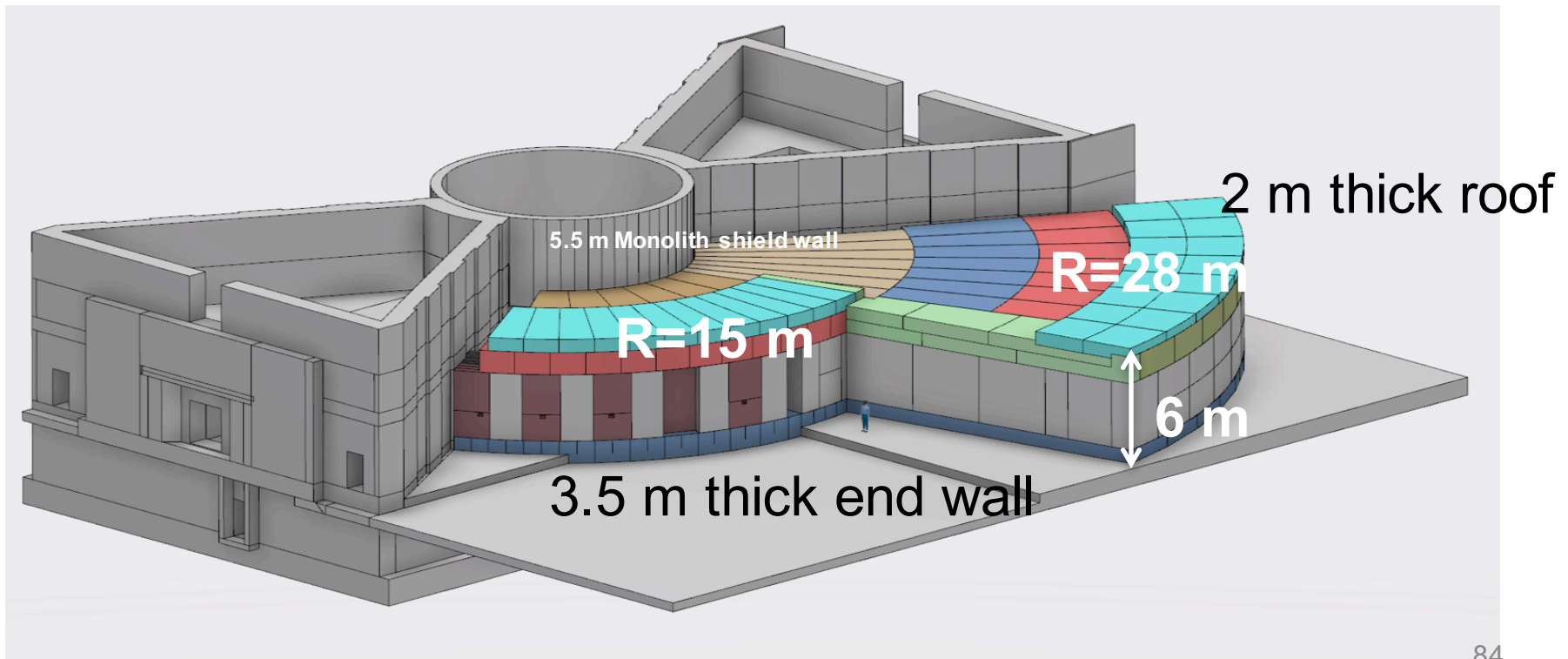
Instrument	Detector Technology						
	¹⁰ B Thin Films		Scintillators		³ He	Exotica	
	⊥		WLS	Anger		Gd	Other
ODIN	-	-	-	o	-	o	+
LOKI	o	+	-	o	-	-	-
SKADI	o	o	-	+	-	-	-
FREIA	-	+	o	o	+	-	-
ESTIA	-	+	o	o	+	-	-
HEIMDAL	o	o	+	-	-	-	-
DREAMS	o	+	o	-	-	-	-
BEER	+	+	o	-	-	-	-
NMX	o	o	o	o	-	+	o
C-SPEC	+	-	-	-	-	-	-
VOR	+	-	-	-	-	-	-
CAMEA	+	-	-	-	+	-	o

Table 3: Appropriate detector technology options for the recommended instruments. The detector technologies are grouped into perpendicular (⊥)- and inclined (||)- neutron incidence geometries for ¹⁰B thin film detectors, wavelength shifting fibers (WLS) and Anger/direct-coupled cameras for scintillator detectors, ³He detectors, Gd-based detectors and Other. In the matrix of options, '+' indicates that this technology is presently seen as a high possibility, '-' indicates that it is a disadvantageous technology for this instrument, and 'o' means that it is considered an option, though not the primary one.

Shielding bunker



- Massive shielding compared to reactor based sources
- Typical materials: Concrete, steel, plastics, boron-containing, and space!

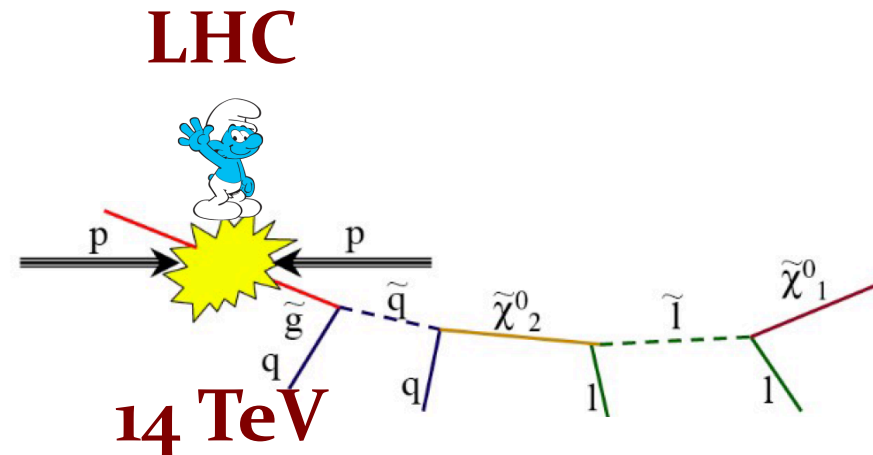
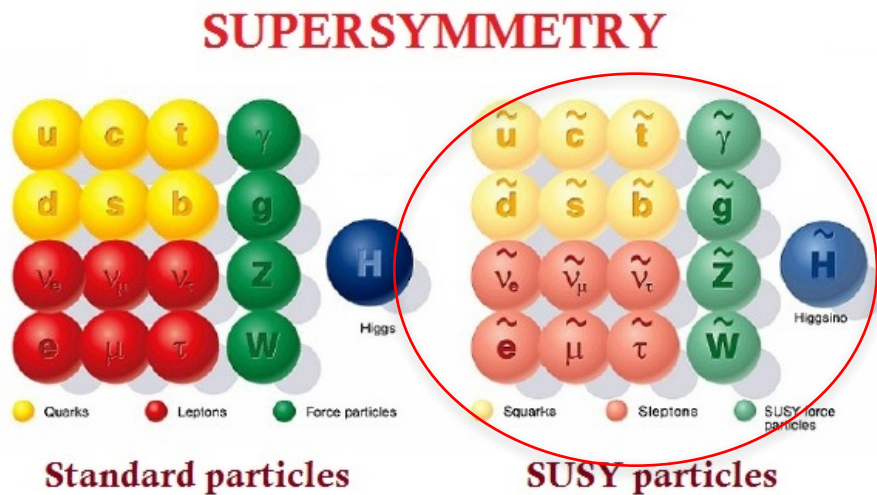


How do you want to look for new physics at LHC?

The matter we know account only for 5% of matter

We have to look for a new kind of matter

Many ideas from theoretical physicists



Possible candidate of new matter