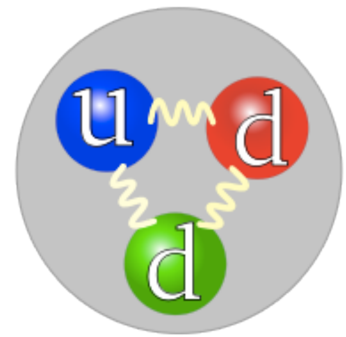
Fundamental Physics with Neutrons at ESS



David Silvermyr, Particle Physics

Outline

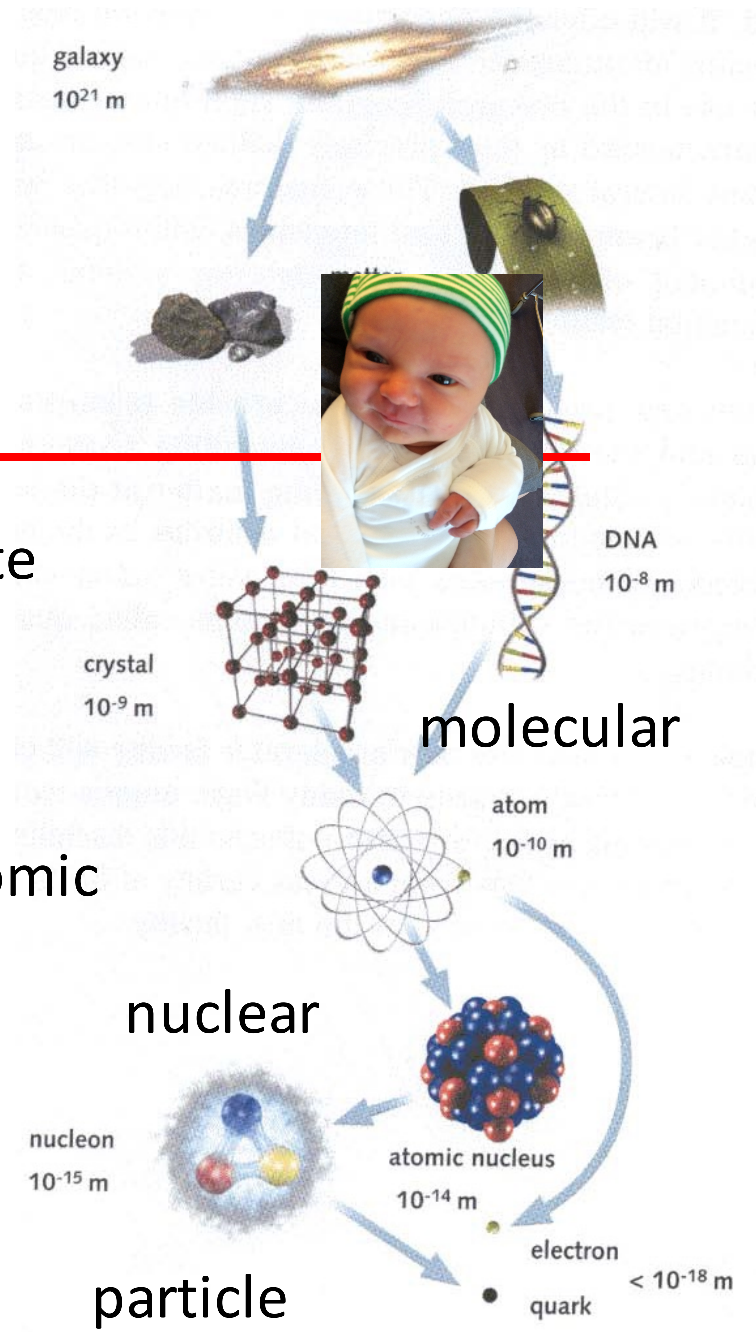
- "Big Picture" Introduction: nuclear & particle physics, European Spallation Source (ESS)
- Why fundamental physics with neutrons @ ESS ?
- Selected possible studies @ ESS
- Conclusions/Summary

The Universe

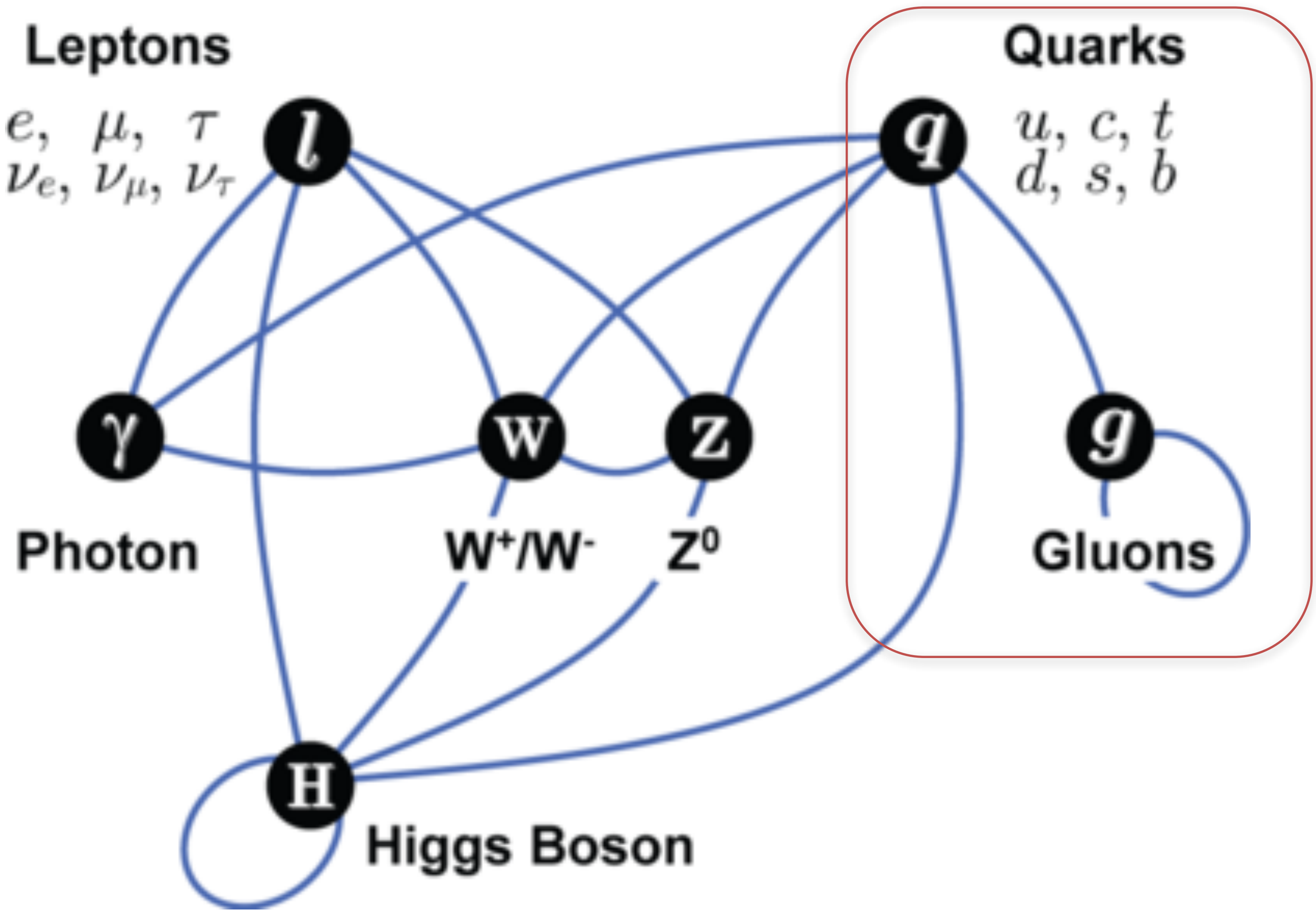
Classical world

Quantum world

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



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

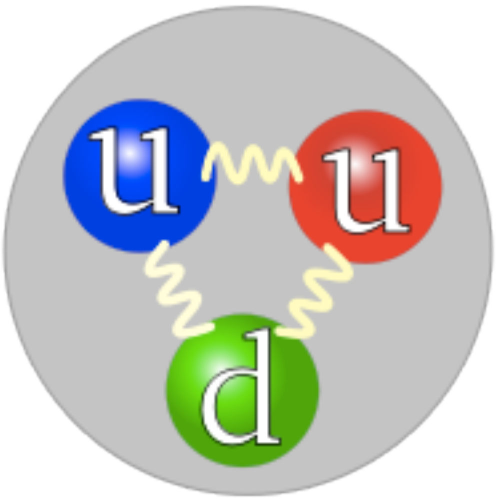


Strong Nuclear force

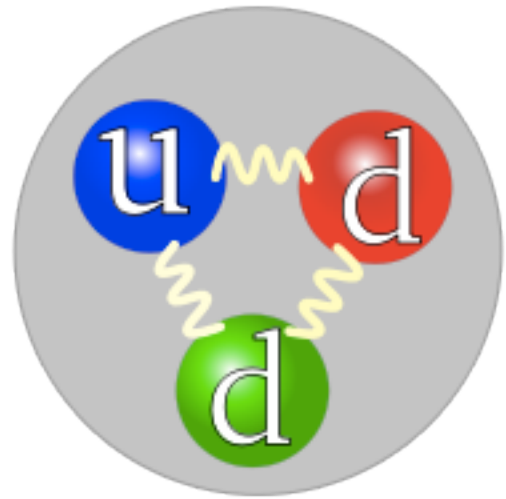
Nuclear Particles

Nucleons: composed of quarks and gluons

Proton



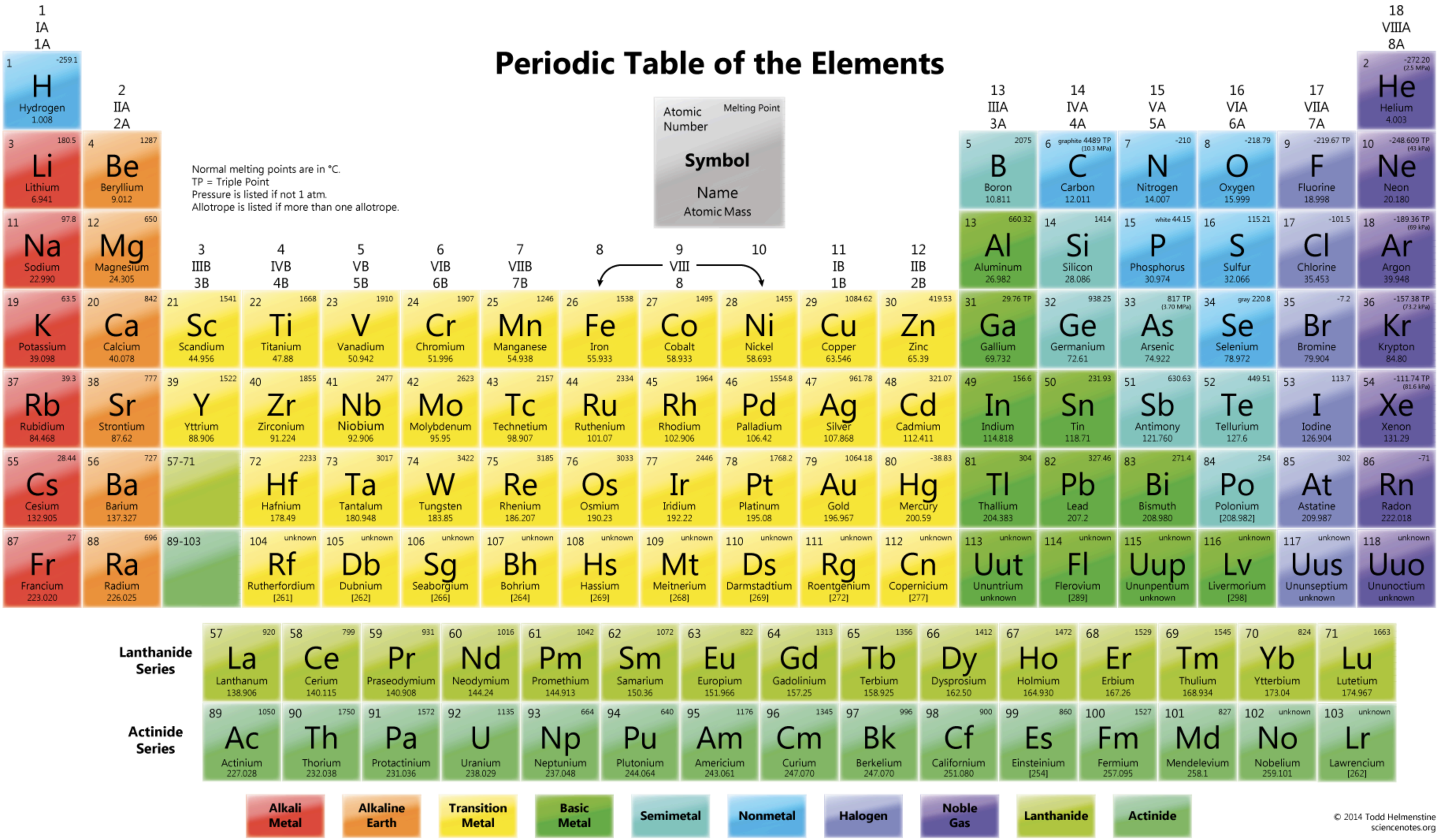
Neutron



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

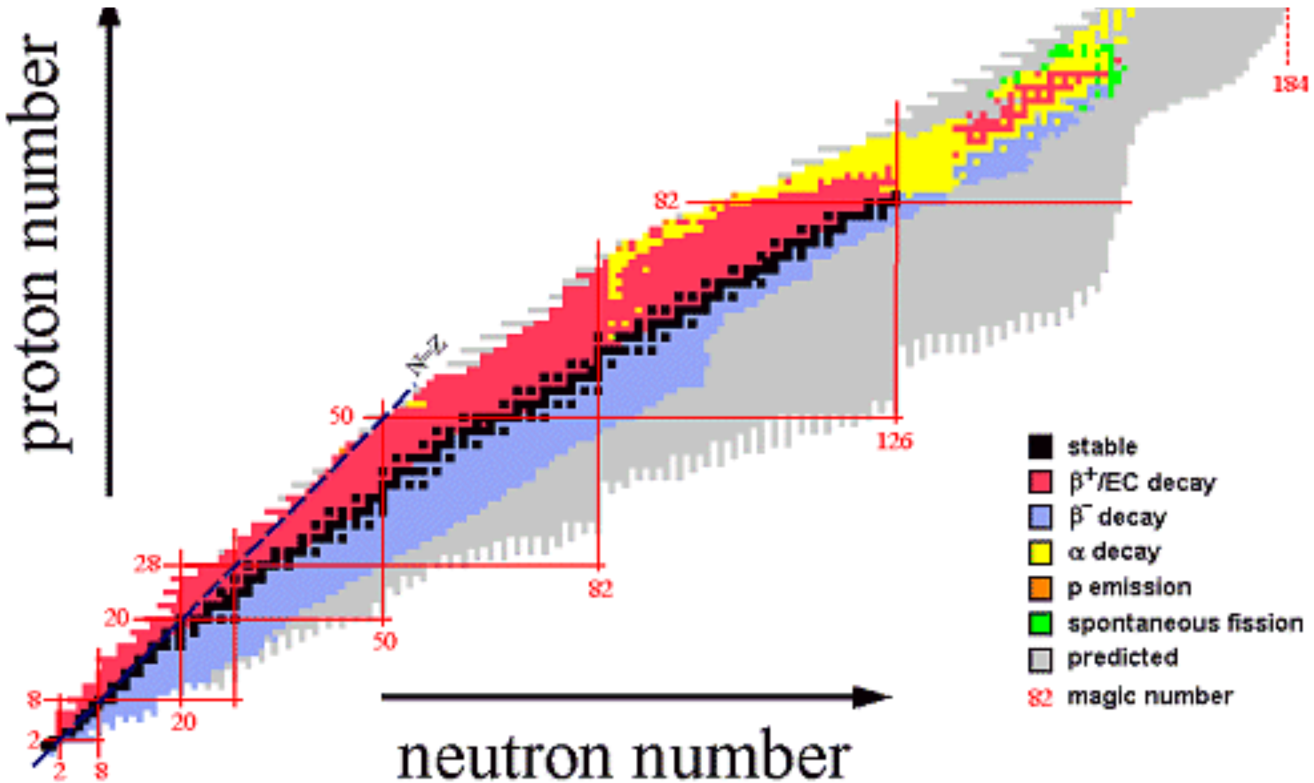
No one has ever seen a “free quark”

Nucleons (p, n) build up atomic nuclei



Number of electrons (protons) determine chemical properties

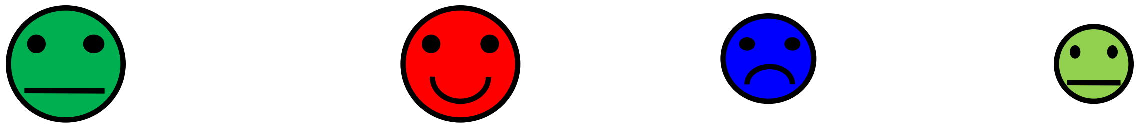
Chart of the Nuclides



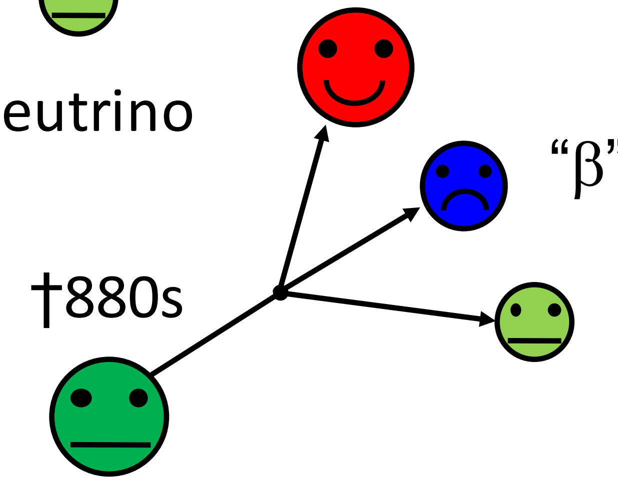
~300 in nature; ~254 stable, >3000 total – every nuclide has unique nuclear properties!

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

Neutron Decay Basics



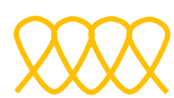
Neutron Proton Electron Neutrino

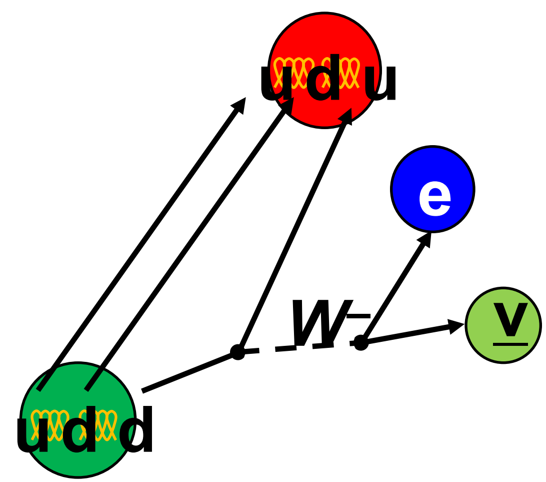


advanced:

$+\frac{2}{3}$ $-\frac{1}{3}$

u d





- 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):

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

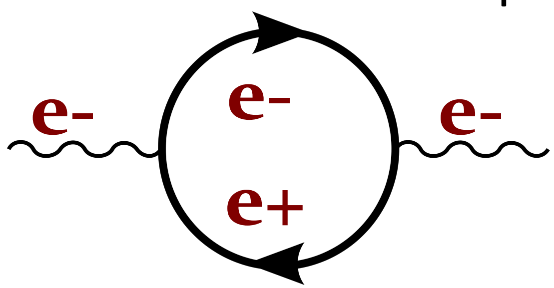
The Heisenberg Uncertainty Principle

– 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 $E=mc^2$

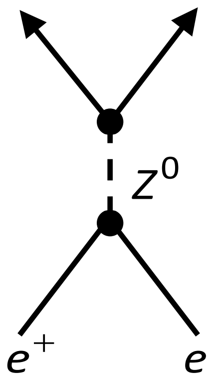


You cannot create only an electron because of charge conservation, but can create electron - antielectron pair

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

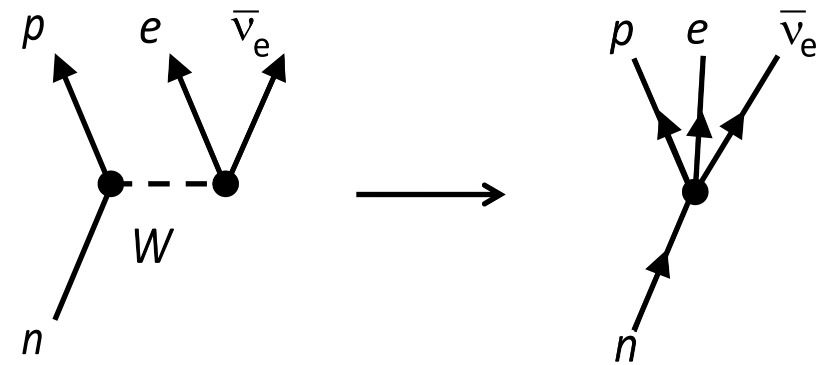
Particle Physics

HEP: Direct production



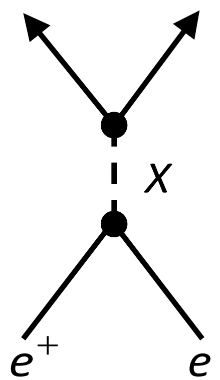
High energy frontier

Decay: Virtual Production



Precision frontier

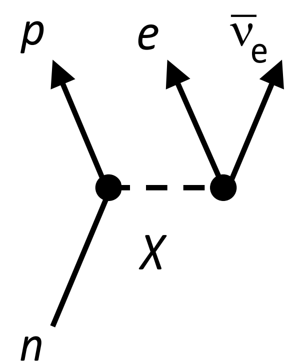
If new particles above accelerator energy



$$m_X \gg E$$

→ ***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…

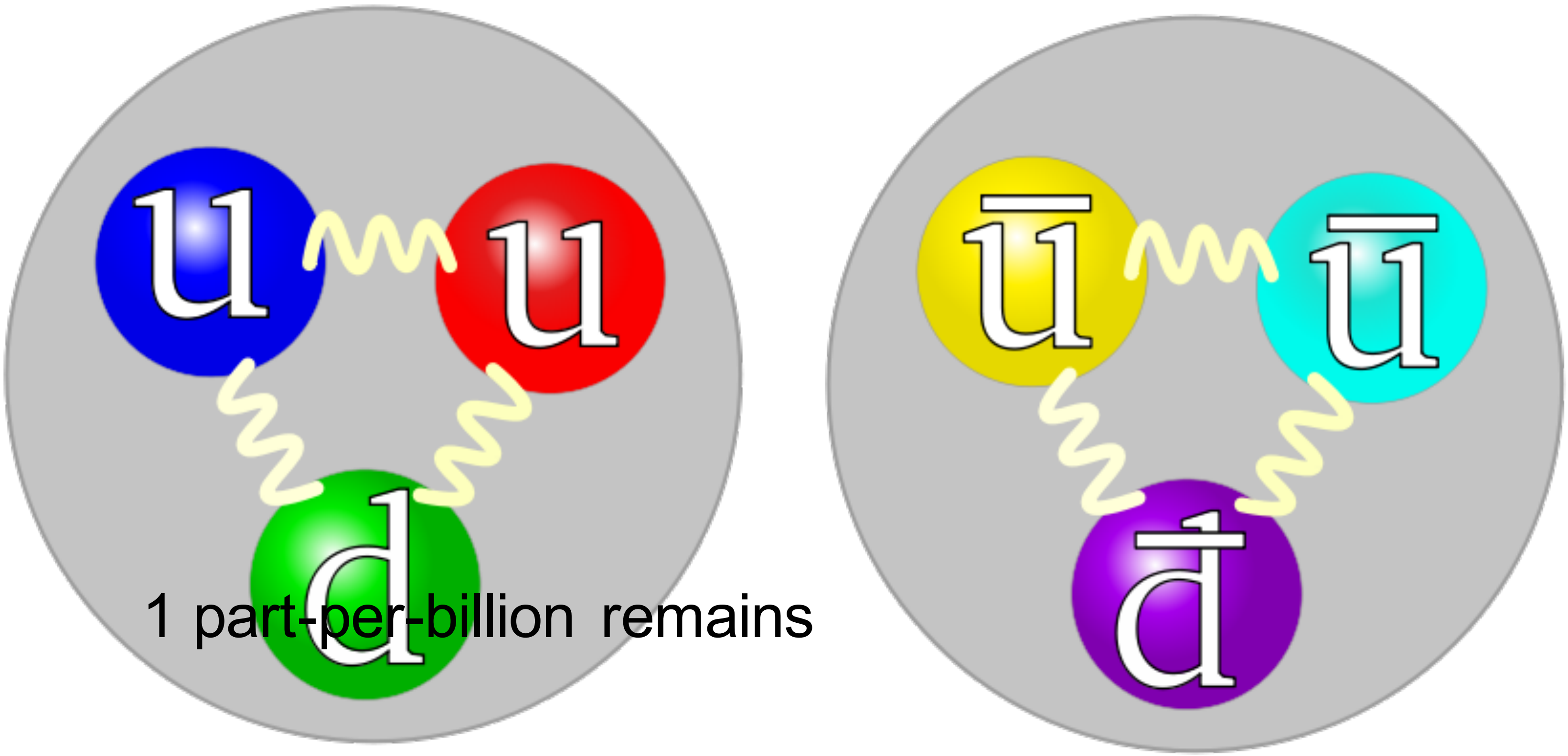
- Why is there matter in the Universe? Should have been just as much antimatter as matter in the Big Bang?
- What is the dark matter and dark energy?

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



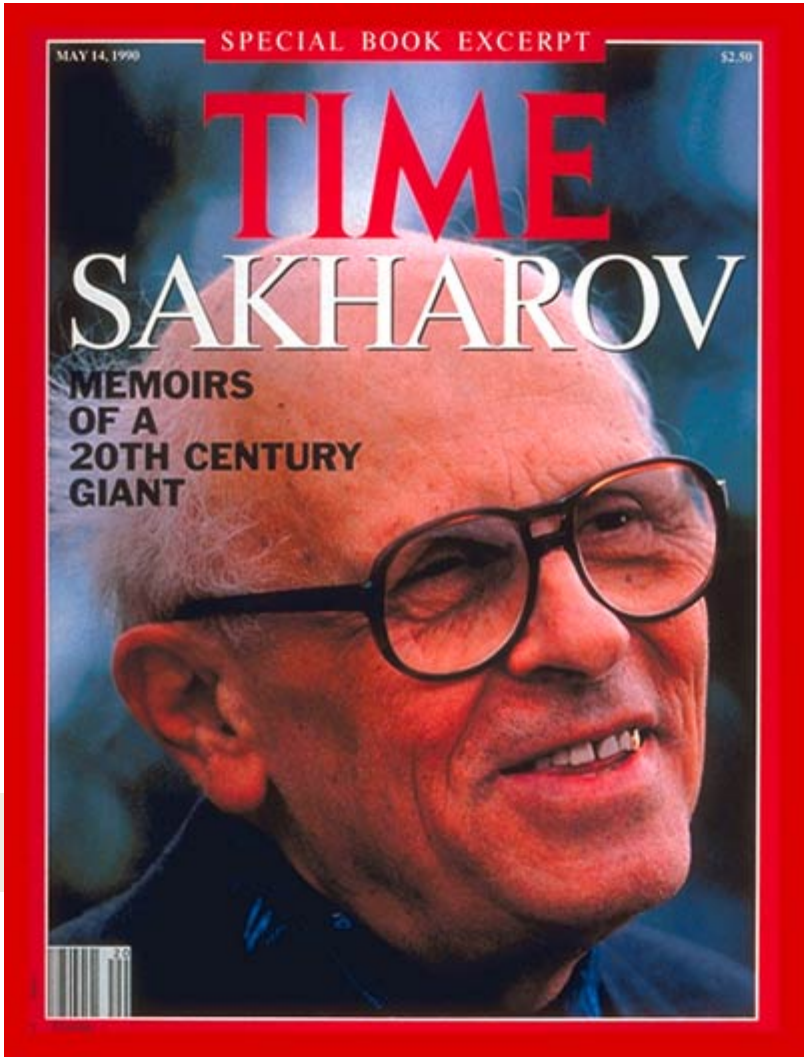
Big Bang: symmetry between matter (baryons) and anti-matter (anti-baryons)

Sakharov Criteria

<u>Baryogenesis requires:</u>

- 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

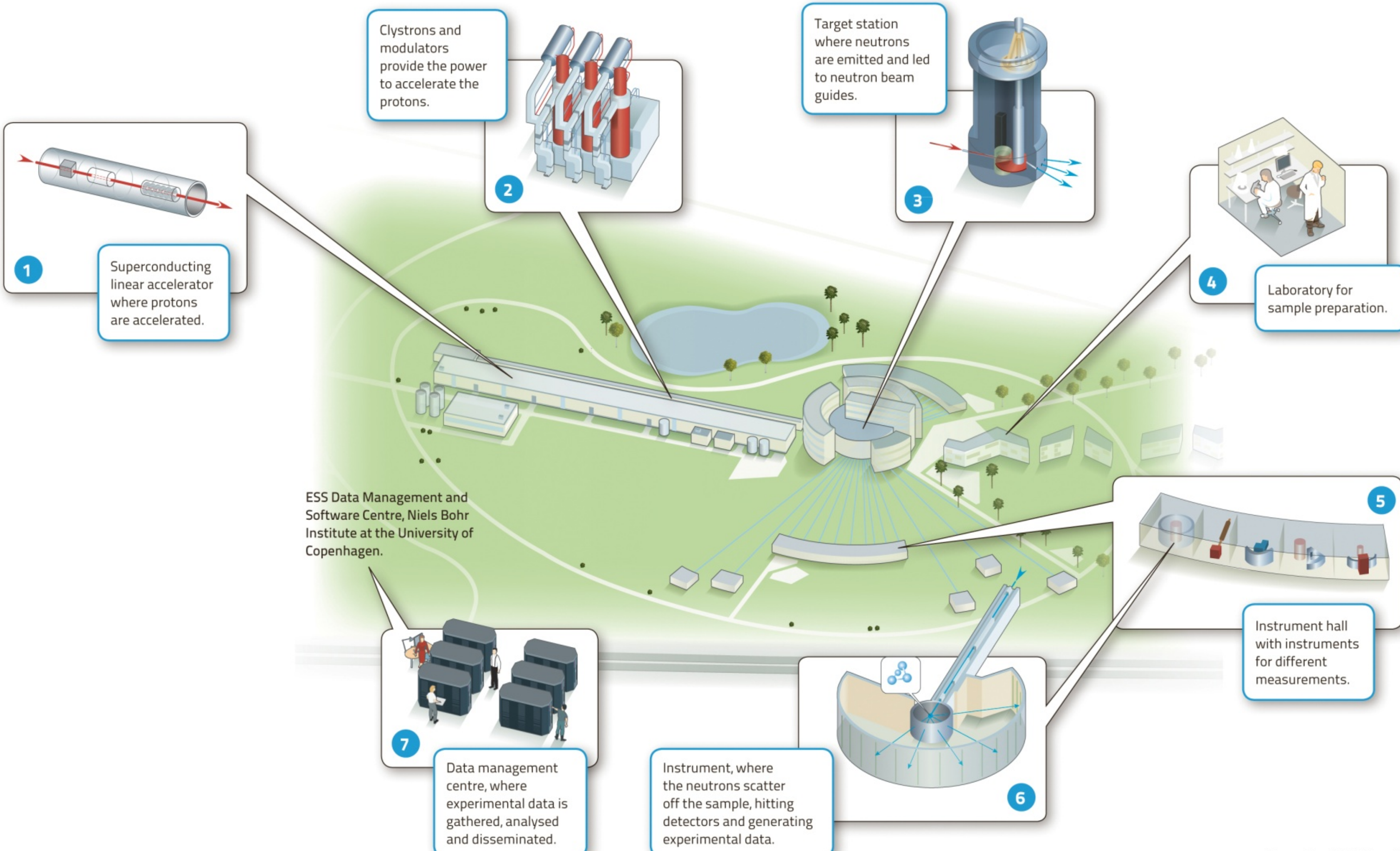
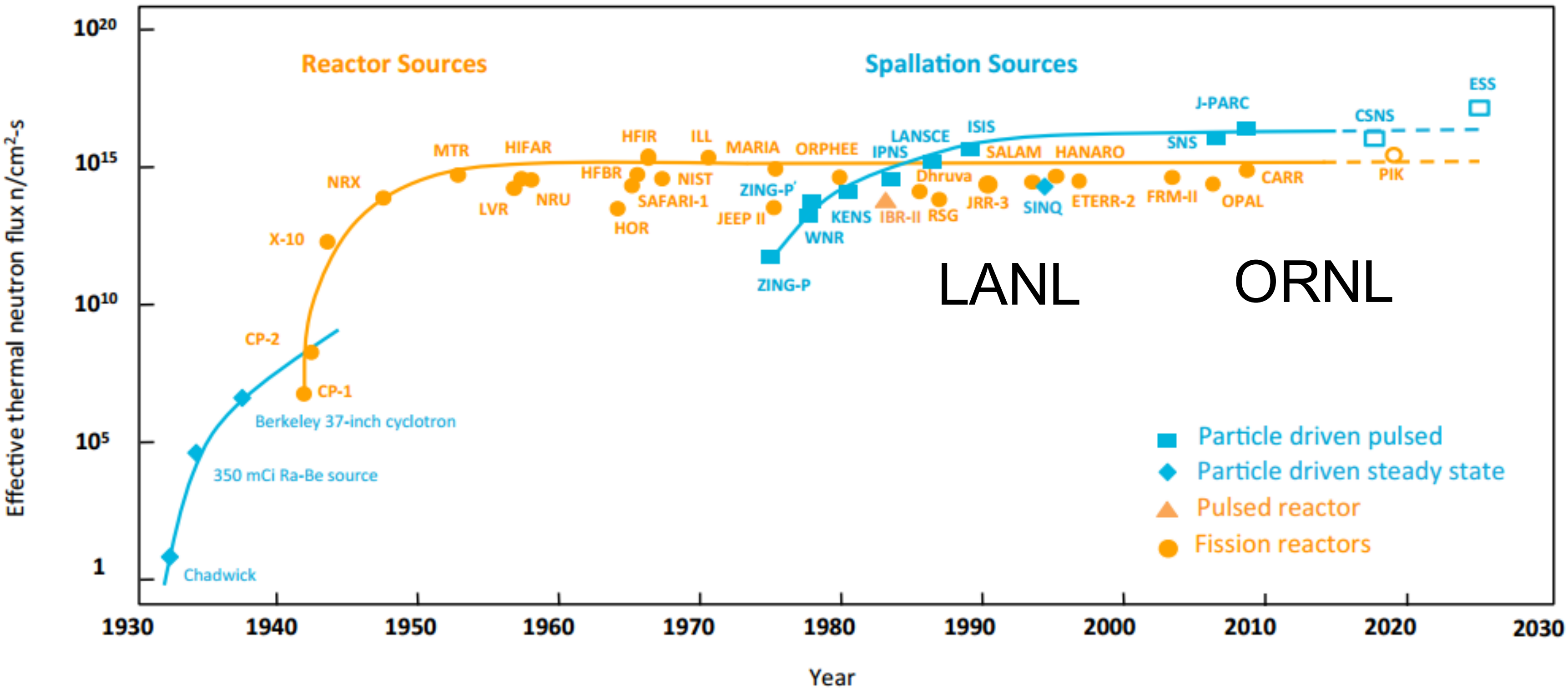


Illustration: ESS, Lönegård

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 (NNbar) 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

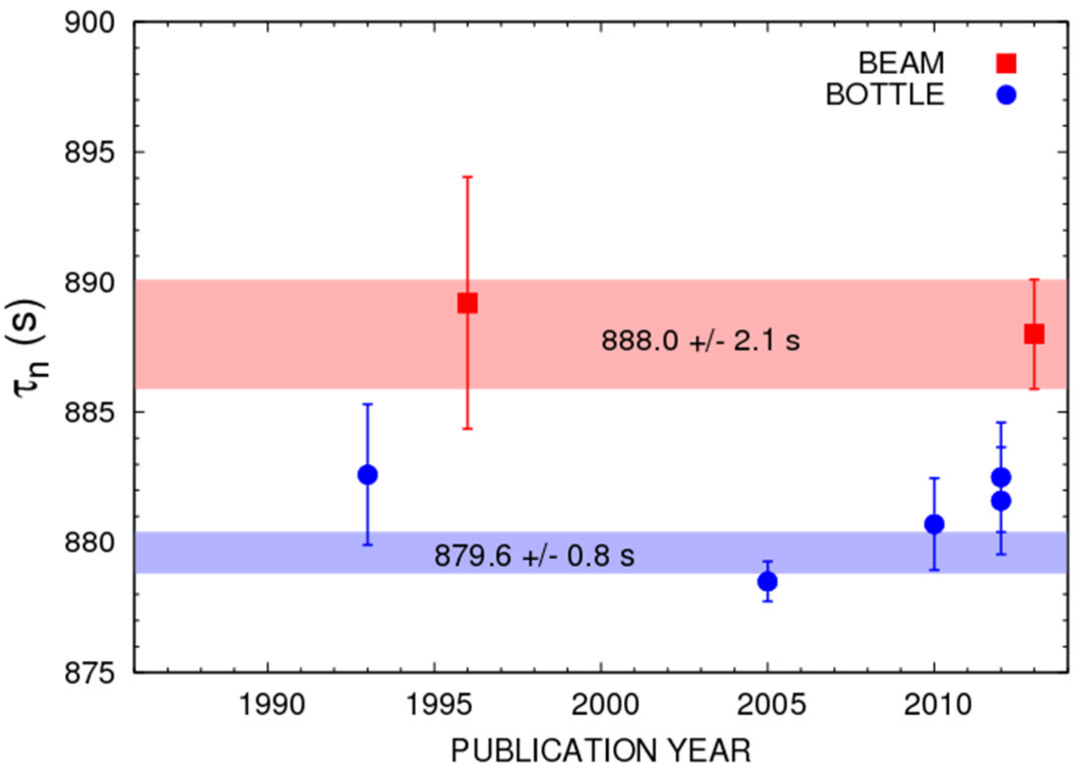
NNbar (HIBEAM)

Fundamental Physics at ESS: Highlights

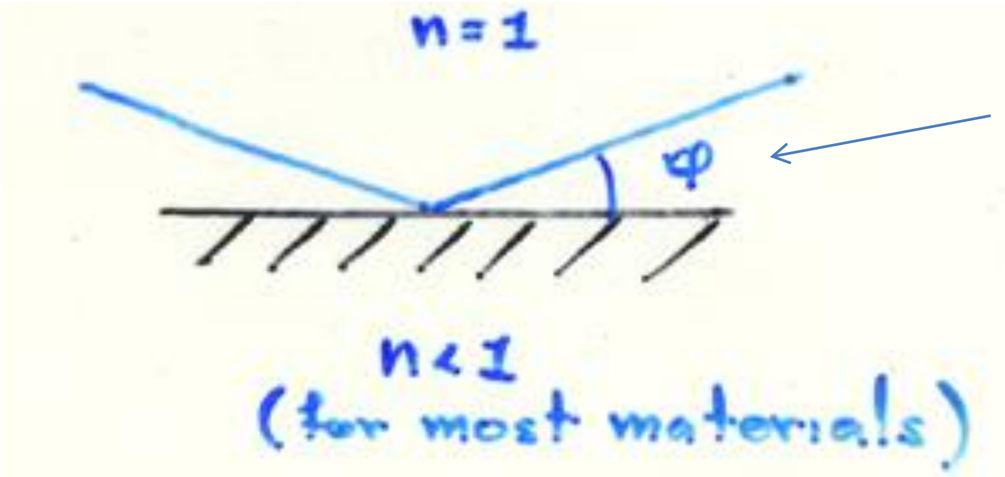
1. Neutron decay: improved Standard Model & BBN parameters, supersymmetry searches
2. Measurement of the neutron EDM, Beyond Standard Model search
3. Neutron anti-neutron oscillations: Baryon Number Violation (BNV), Beyond Standard Model search

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”

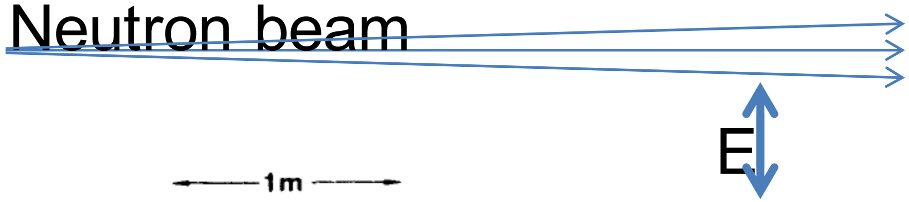
Beam method: count the decays by letting neutrons fly through a detector and looking for the particles into which they transform = “count the dead”

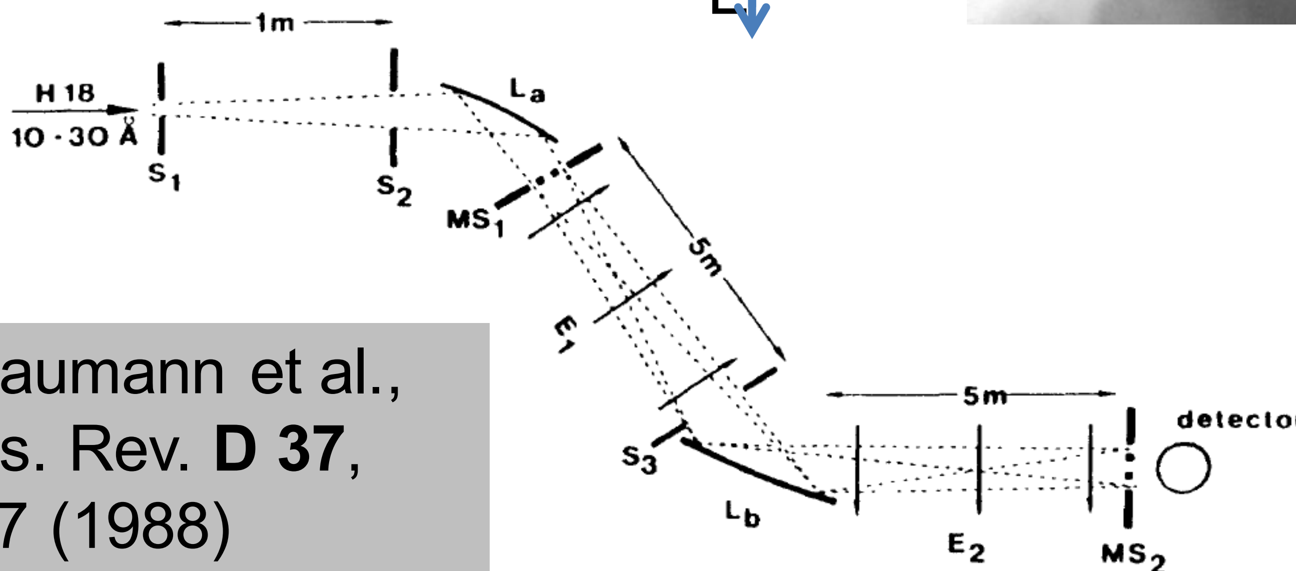
- Goal at ESS: improve beam method measurement uncertainty by factor 10
- Also: Improve measurements of correlation coefficients in neutron decay (backup slides…)

Fundamental Physics at ESS: Highlights

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

The Neutron Appears To Be Neutral…

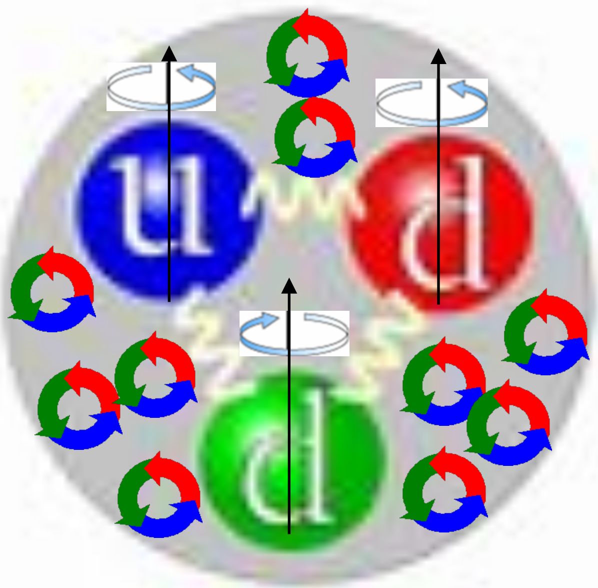




J. Baumann et al., Phys. Rev. **D 37**, 3107 (1988)

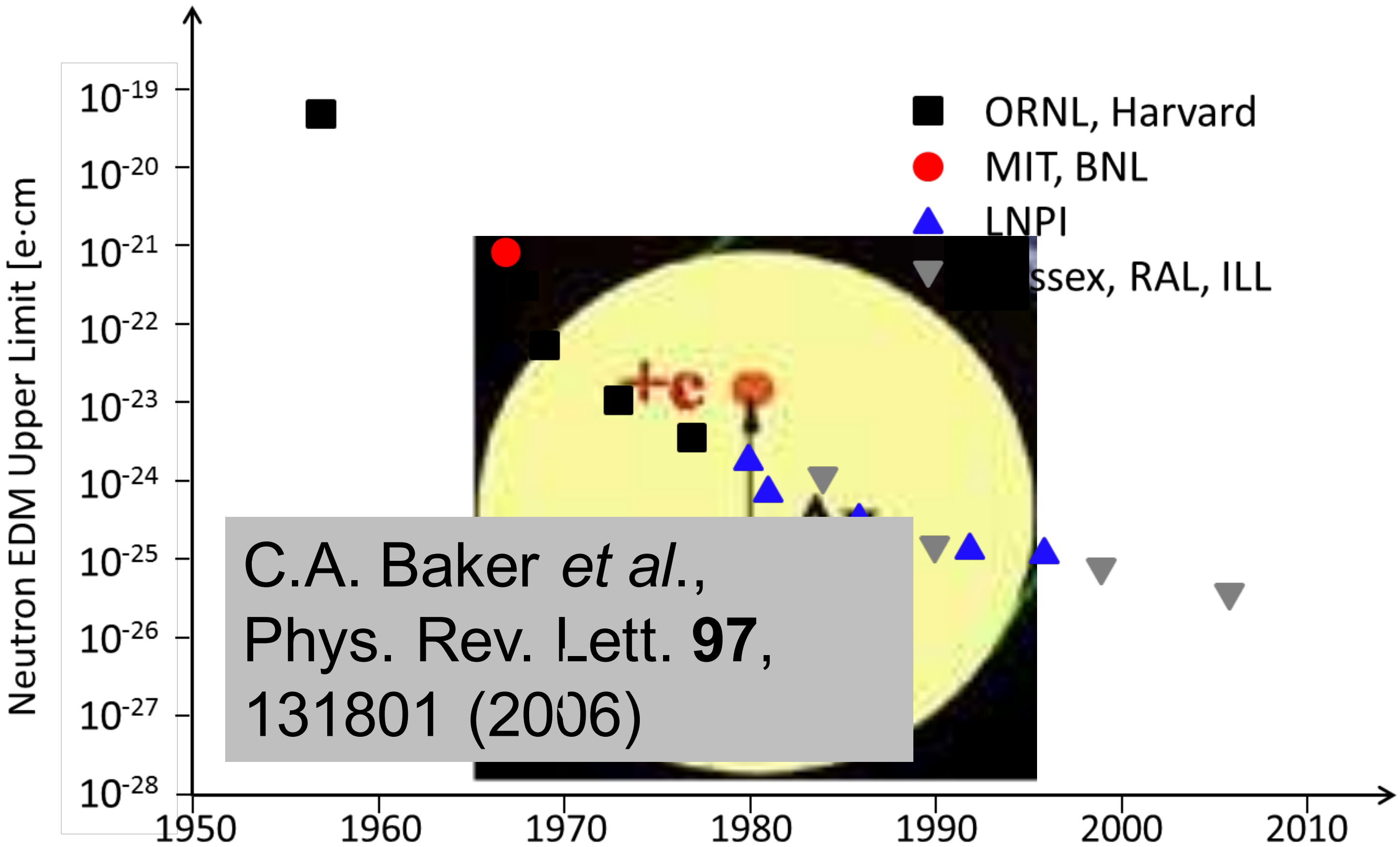
$$Q_n = (-0.4 +/- 1.1) \times 10^{-21}\, e$$

But Not Everywhere...



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

Is The Neutron Round?



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

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

SM prediction: ~ 10^{-32} e·cm (clean signature for new physics)

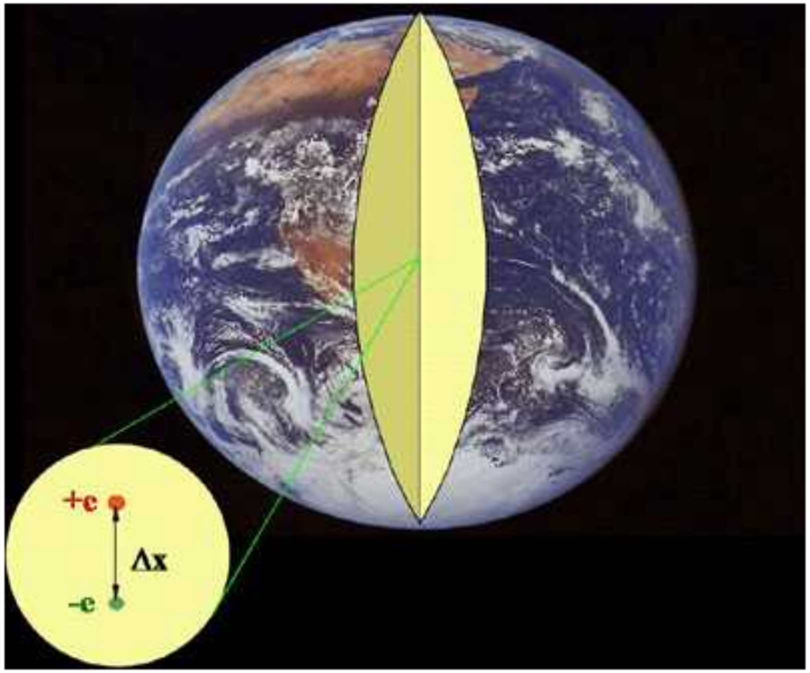
That's Pretty Round…

Relative unit charge separation :

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

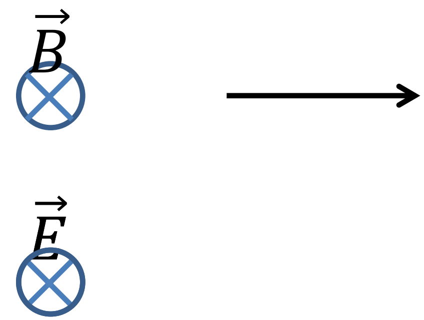
Unit charge separation for a neutron the size of the earth:

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



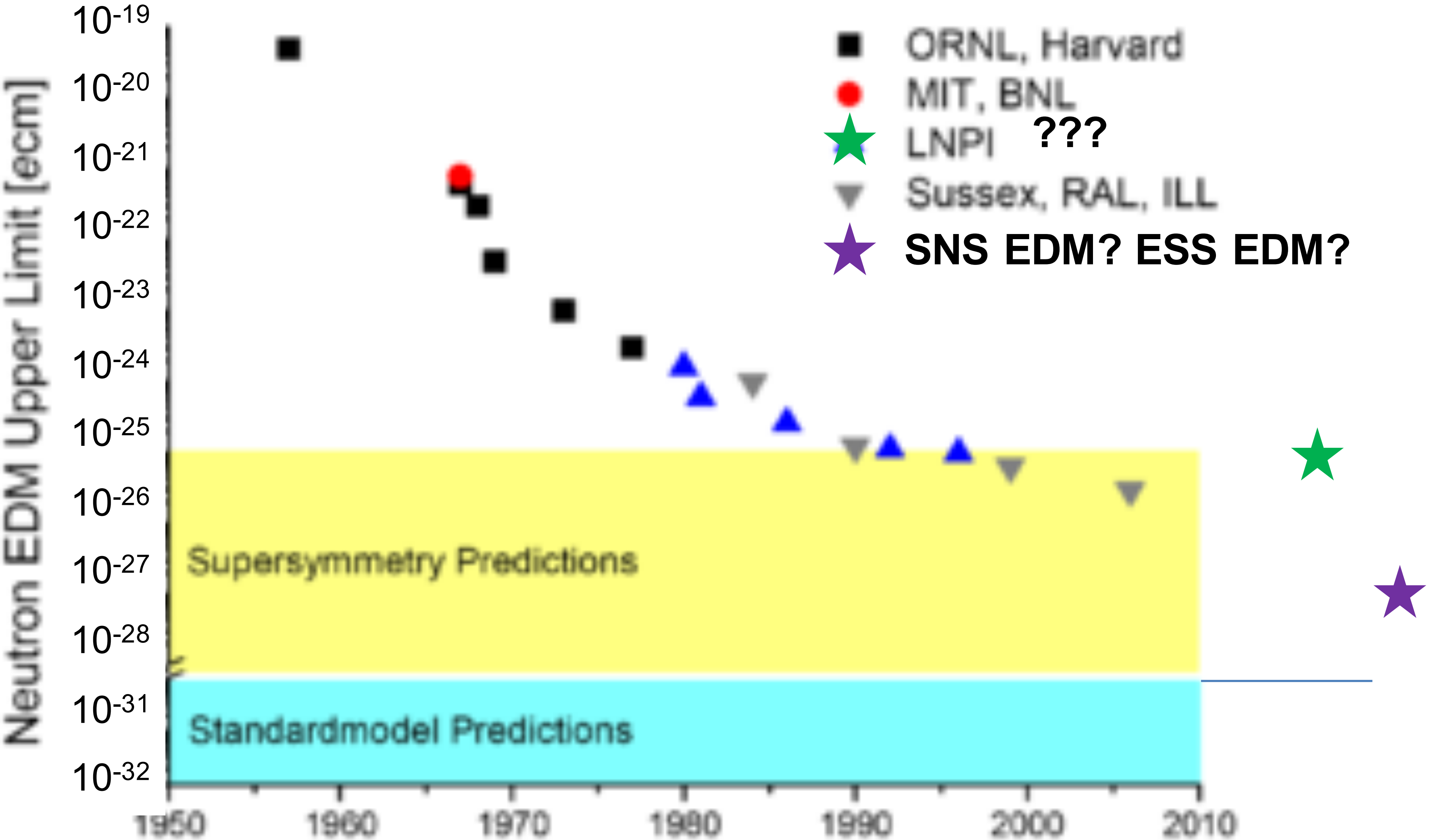
Details: How Does One Measure An EDM?

- Place your particle in a uniform magnetic field perpendicular to their spin.
  - Spins will precess at the Larmor frequency: $f = -\frac{2}{h}(\overrightarrow{\mu_B} \cdot \vec{B})$
- 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 $\mu_E = 10^{-28}$e·cm and $E = 75$kV/cm, $\Delta f \sim 7.5$ nHz.



Repeat with many neutrons…

Many interesting experimental challenges

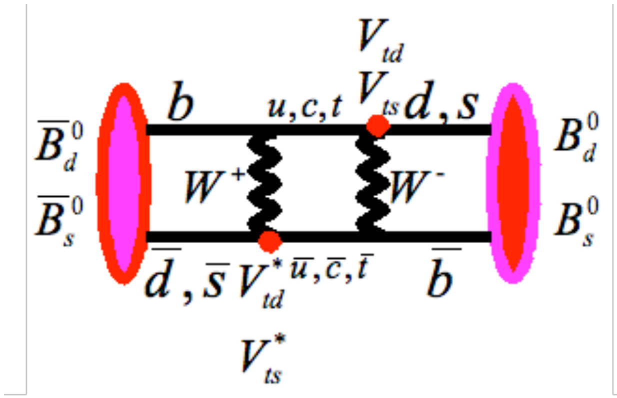

Neutron EDM Upper Limit [ecm]
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-31}
10^{-32}
1950
1960
1970
1980
1990
2000
2010
ORNL, Harvard
MIT, BNL
LNPI
???
Sussex, RAL, ILL
SNS EDM? ESS EDM?
Supersymmetry Predictions
Standardmodel Predictions

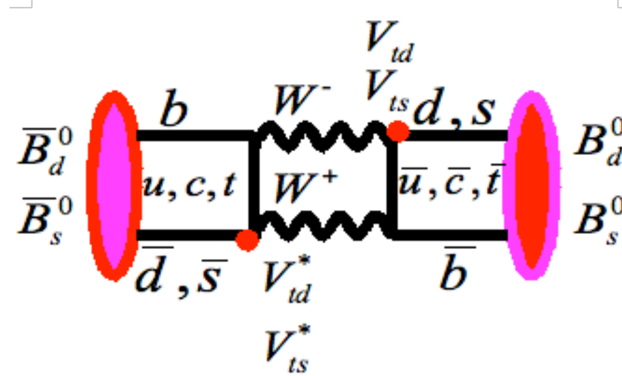
Fundamental Physics at ESS: Highlights

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-$\overline{K^0}$ oscillations (**ΔS = 2**) at the core of our initial understanding of CP-violation (NP 1980)
  - 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
- C.f. Neutrino oscillations (NP 2015)





Previous searches for *BNV*

(RPP)

Decay mode	Partial mean life ($\times 10^{30}$ yrs)
$N \to e^+\pi$	> 2000 (n), > 8200 (p)
$N \to \mu^+\pi$	> 1000 (n), > 6600 (p)
$N \to \nu\pi$	> 1100 (n), > 390 (p)
$p \to e^+\eta$	> 4200
$p \to \mu^+\eta$	> 1300
$n \to \nu\eta$	> 158
$N \to e^+\rho$	> 217 (n), > 710 (p)
$N \to \mu^+\rho$	> 228 (n), > 160 (p)
$N \to \nu\rho$	> 19 (n), > 162 (p)
$p \to e^+\omega$	> 320
$p \to \mu^+\omega$	> 780
$n \to \nu\omega$	> 108
$N \to e^+K$	> 17 (n), > 1000 (p)
$N \to \mu^+K$	> 26 (n), > 1600 (p)
$N \to \nu K$	> 86 (n), > 5900 (p)
$n \to \nu K^0_S$	> 260
$p \to e^+K^*(892)^0$	> 84
$N \to \nu K^*(892)$	> 78 (n), > 51 (p)
$p \to e^+\pi^+\pi^-$	> 82
$p \to e^+\pi^0\pi^0$	> 147
$n \to e^+\pi^-\pi^0$	> 52
$p \to \mu^+\pi^+\pi^-$	> 133
$p \to \mu^+\pi^0\pi^0$	> 101
$n \to \mu^+\pi^-\pi^0$	> 74
$n \to e^+K^0\pi^-$	> 18
$n \to e^-\pi^+$	> 65
$n \to \mu^-\pi^+$	> 49
$n \to e^-\rho^+$	> 62
$n \to \mu^-\rho^+$	> 7
$n \to e^-K^+$	> 32
$n \to \mu^-K^+$	> 57
$p \to e^-\pi^+\pi^+$	> 30
$n \to e^-\pi^+\pi^0$	> 29
$p \to \mu^-\pi^+\pi^+$	> 17
$n \to \mu^-\pi^+\pi^0$	> 34
$p \to e^-\pi^+K^+$	> 75
$p \to \mu^-\pi^+K^+$	> 245

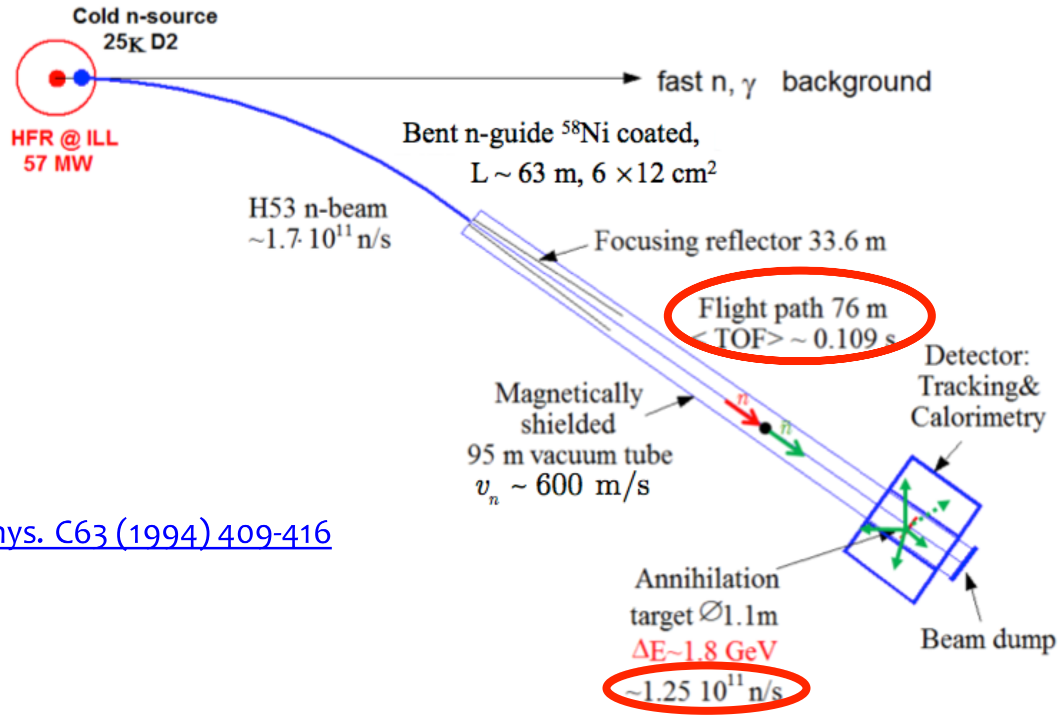
Decay mode	Partial mean life ($\times 10^{30}$ yrs)
$p \to e^+\gamma$	> 670
$p \to \mu^+\gamma$	> 478
$n \to \nu\gamma$	> 28
$p \to e^+\gamma\gamma$	> 100
$n \to \nu\gamma\gamma$	> 219
$p \to e^+e^+e^-$	> 793
$p \to e^+\mu^+\mu^-$	> 359
$p \to e^+\nu\nu$	> 170
$n \to e^+e^-\nu$	> 257
$n \to \mu^+e^-\nu$	> 83
$n \to \mu^+\mu^-\nu$	> 79
$p \to \mu^+e^+e^-$	> 529
$p \to \mu^+\mu^+\mu^-$	> 675
$p \to \mu^+\nu\nu$	> 220
$p \to e^-\mu^+\mu^+$	> 6
$n \to 3\nu$	> 0.0005
$N \to e^+$ anything	> 0.6 (n, p)
$N \to \mu^+$ anything	> 12 (n, p)
$N \to e^+\pi^0$ anything	> 0.6 (n, p)
$pp \to \pi^+\pi^+$	> 0.7
$pn \to \pi^+\pi^0$	> 2
$nn \to \pi^+\pi^-$	> 0.7
$nn \to \pi^0\pi^0$	> 3.4
$pp \to K^+K^+$	> 170
$pp \to e^+e^+$	> 5.8
$pp \to e^+\mu^+$	> 3.6
$pp \to \mu^+\mu^+$	> 1.7
$pn \to e^+\overline{\nu}$	> 2.8
$pn \to \mu^+\overline{\nu}$	> 1.6
$pn \to \tau^+\overline{\nu}_\tau$	> 1.0
$nn \to \nu_e\overline{\nu}_e$	> 1.4
$nn \to \nu_\mu\overline{\nu}_\mu$	> 1.4

$\Delta B \neq 0, \Delta L \neq 0$ (blue)

$\Delta B \neq 0, \Delta L = 0$ (yellow: $pp \to \pi^+\pi^+$ through $pp \to K^+K^+$)

RPP/PDG : Few searches with ΔLepton = 0

Search for neutron antineutron oscillation @ ILL



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

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

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

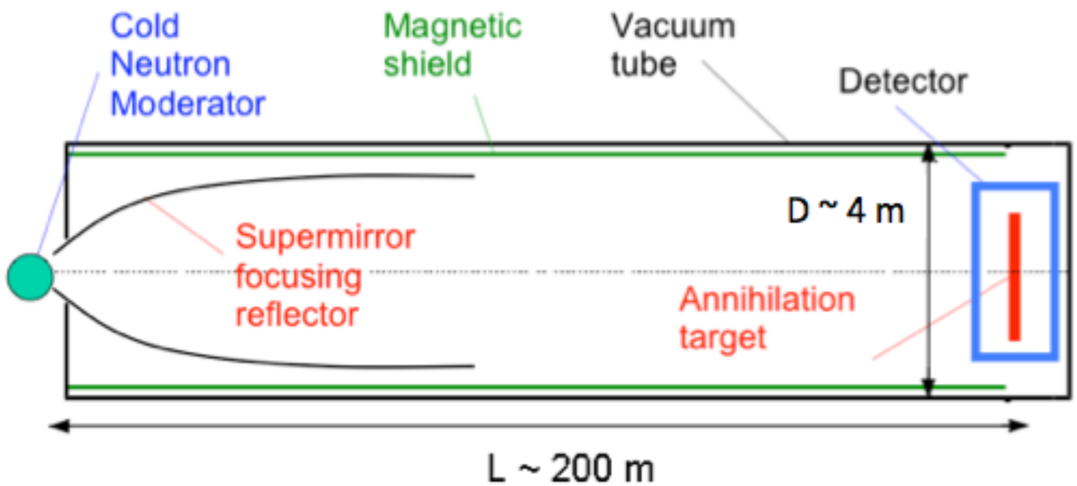
– Many subtle optimizations to minimize losses and backgrounds

– 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 (~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, ~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…

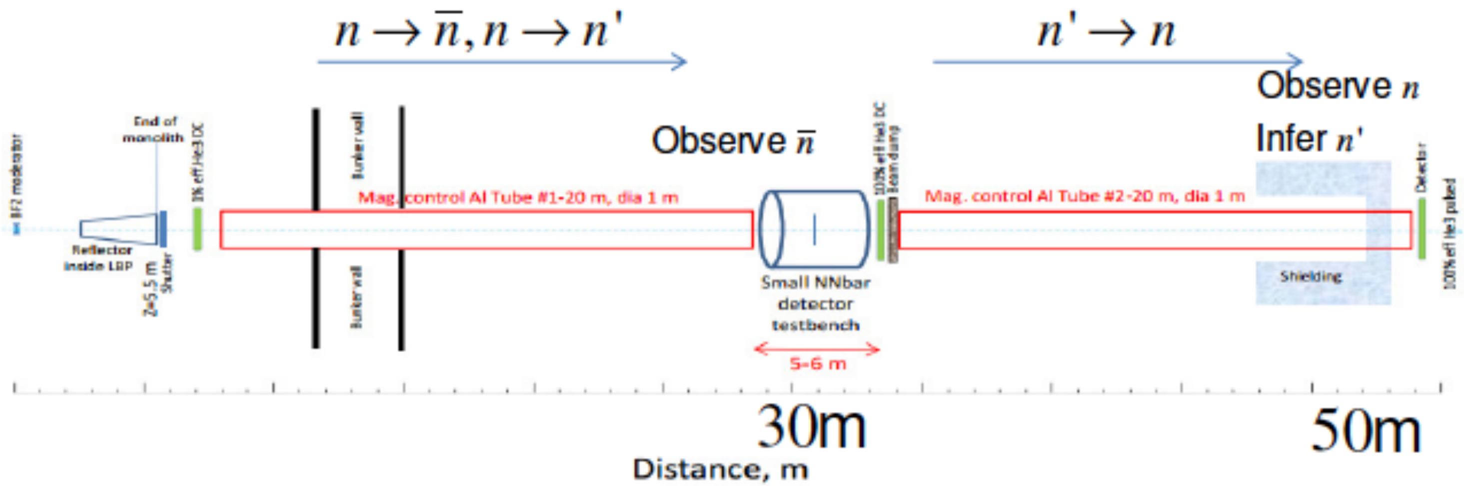
(almost) Summary

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

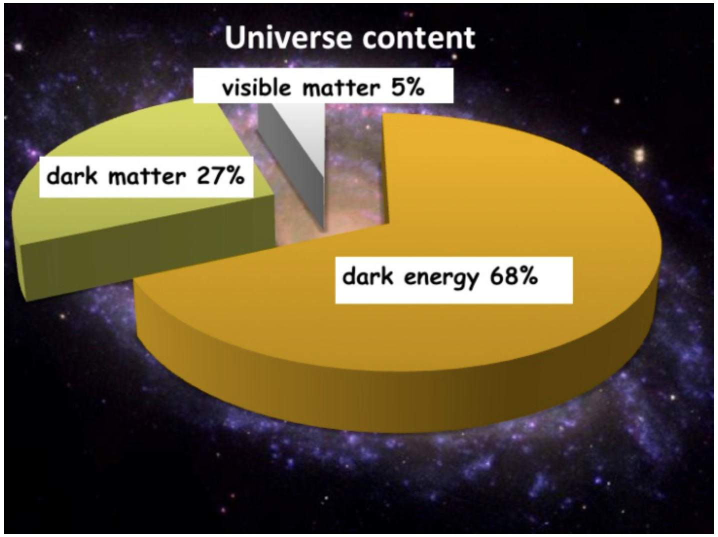
- High-m mirrors/focusing
- Magnetic shielding
- Neutron monitoring
- Detector
- BG

Physics

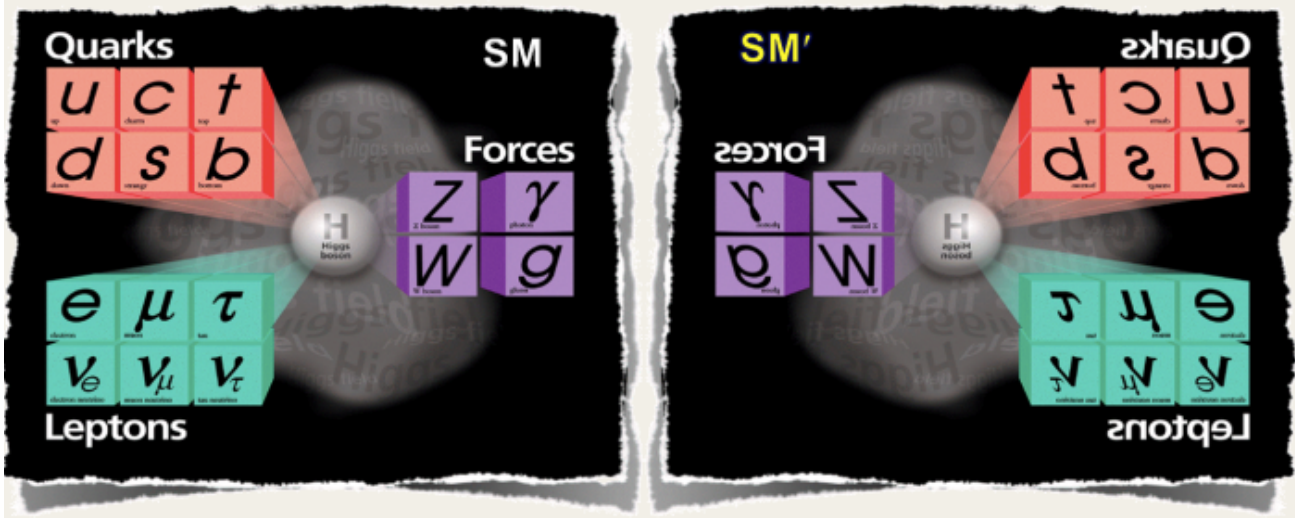
- Improve sensitivity wrt ILL
- Search for mirror neutron regeneration
- Other possible experiments (beam EDM, weak nucleon interactions, sensitivity to new long distance forces)

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

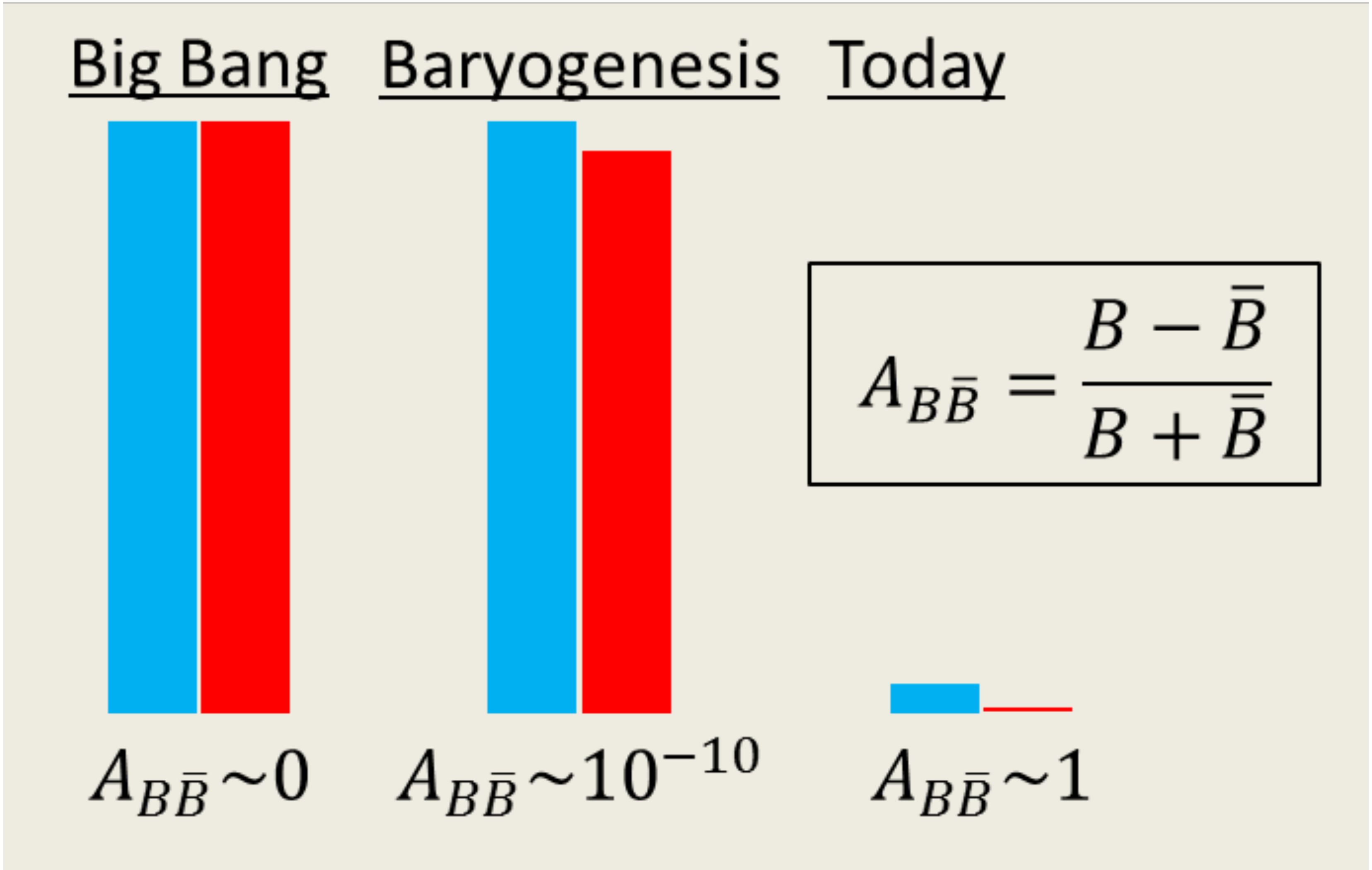
Conclusion

- 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 …..

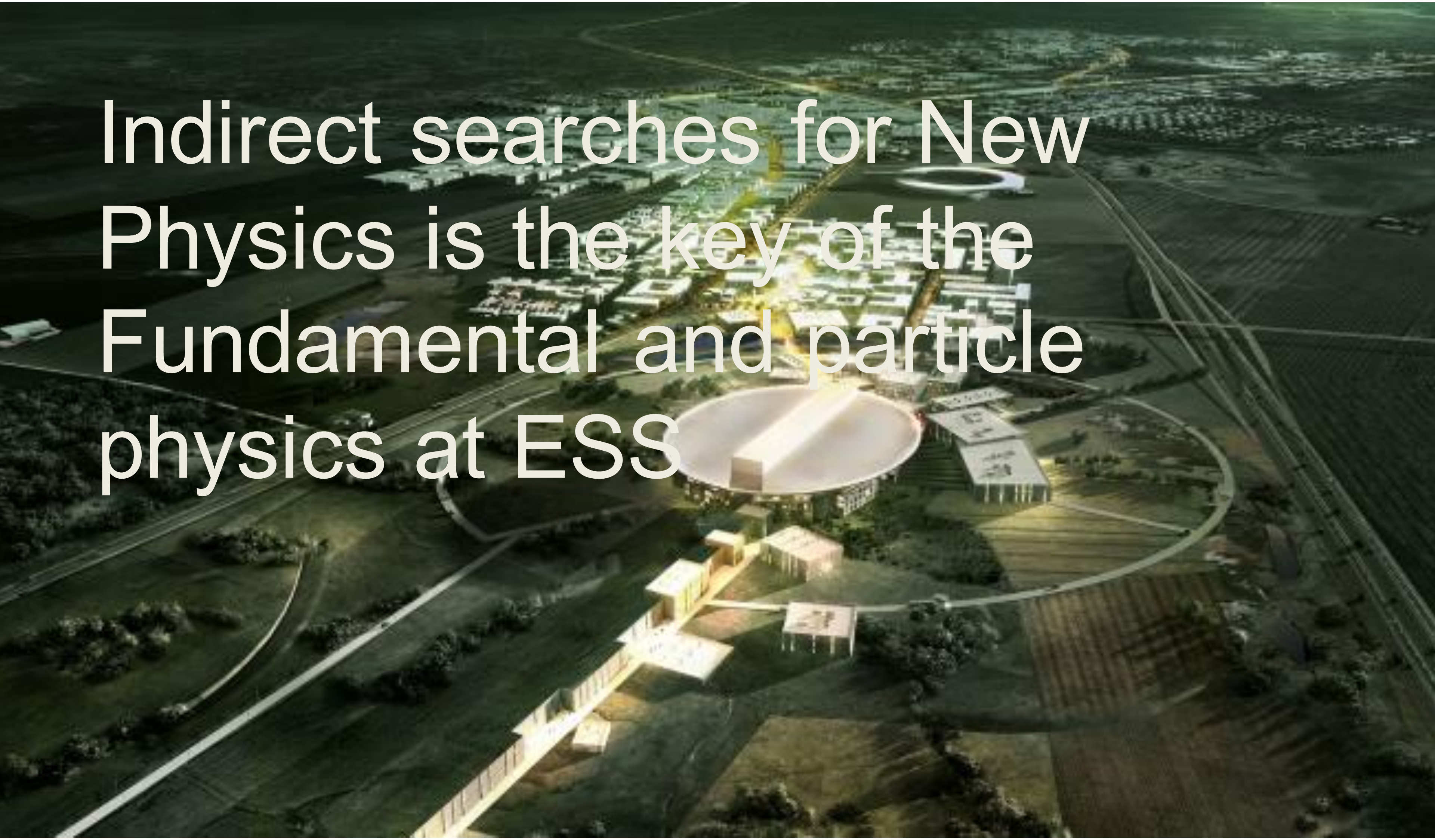
Thanks

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

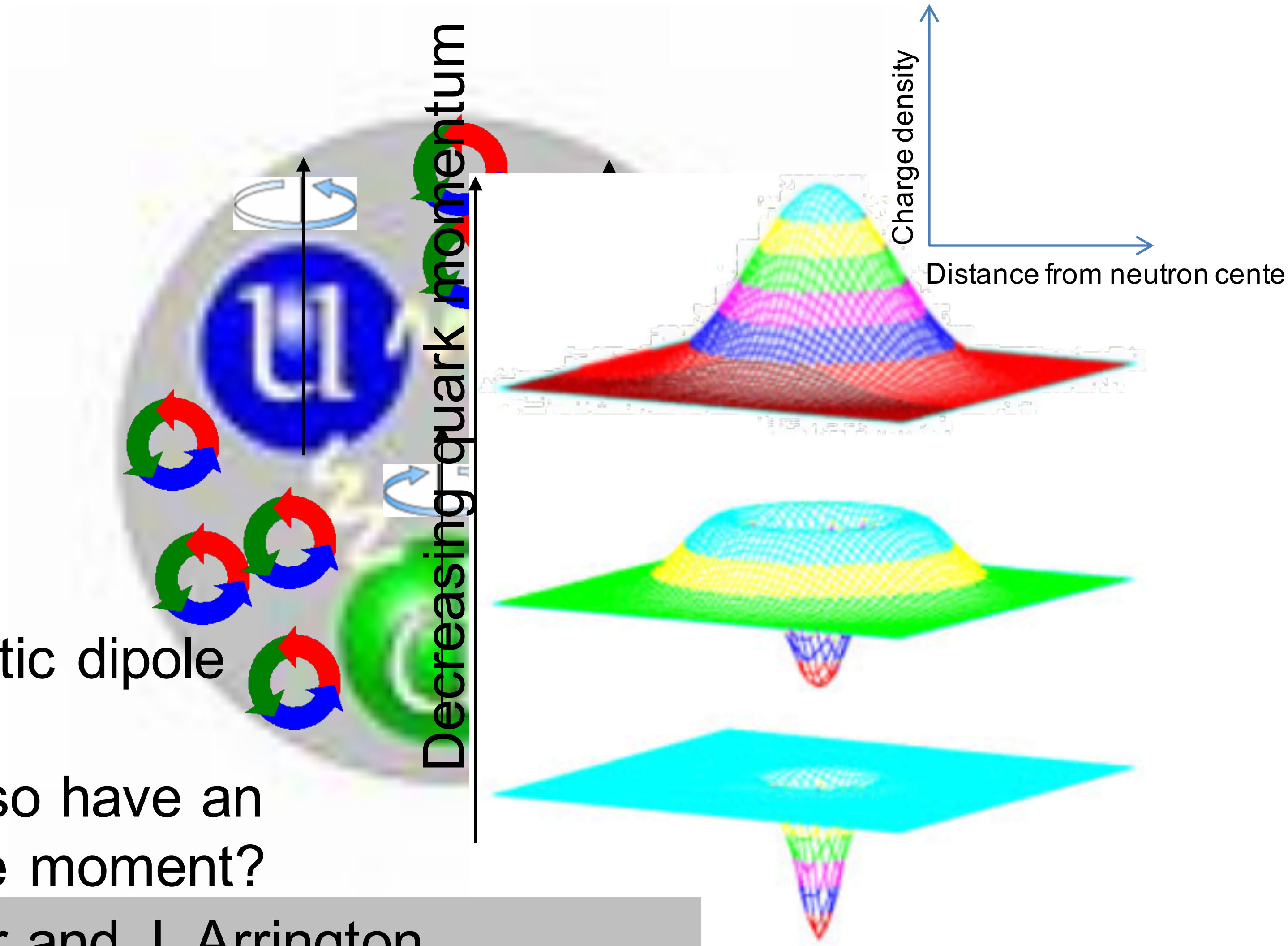
Backup


Big Bang
Baryogenesis
Today
$A_{B\bar{B}} = \frac{B - \bar{B}}{B + \bar{B}}$
$A_{B\bar{B}} \sim 0$
$A_{B\bar{B}} \sim 10^{-10}$
$A_{B\bar{B}} \sim 1$

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

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

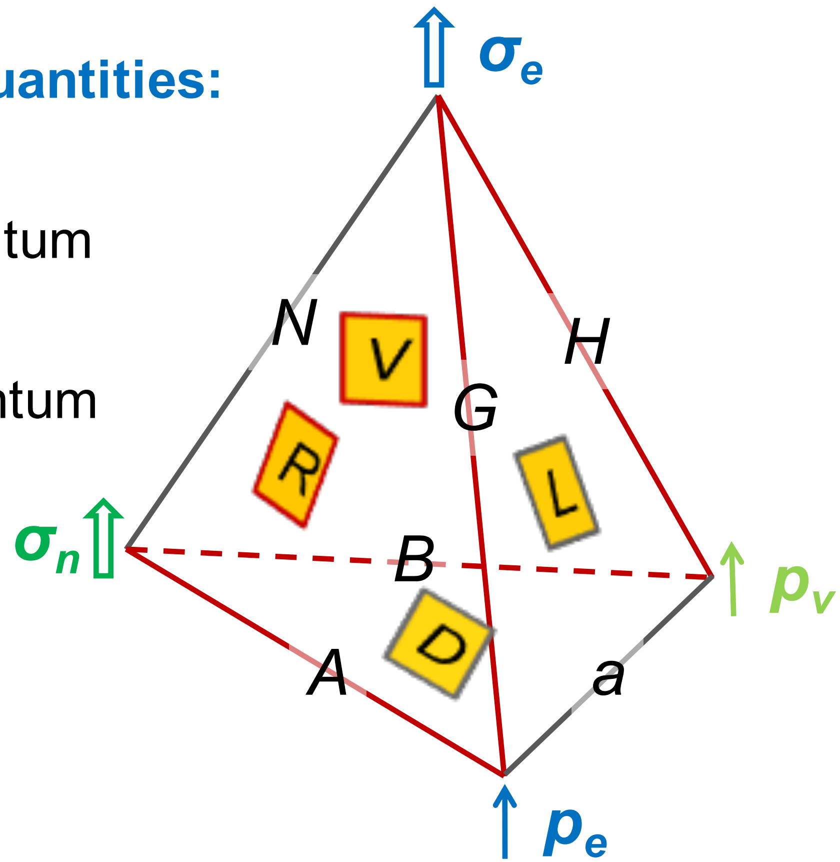
- Anti-neutron annihilation target
  - High annihilation probability, low Z, high transparency to neutrons
    - ILL experiment used a carbon foil, 130 μm thick
- Annihilation produces pions, <n> ~ 5
- Background suppression:
  - Precise annihilation vertex identification
  - Good mass resolution
  -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

Details: Observables in Neutron Decay

$n \rightarrow p\ e\ \underline{\nu}_e$

4 "detectable" quantities:

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



- P conserving
- P violating
- T violating

Correlations:

6 twofold

4 threefold

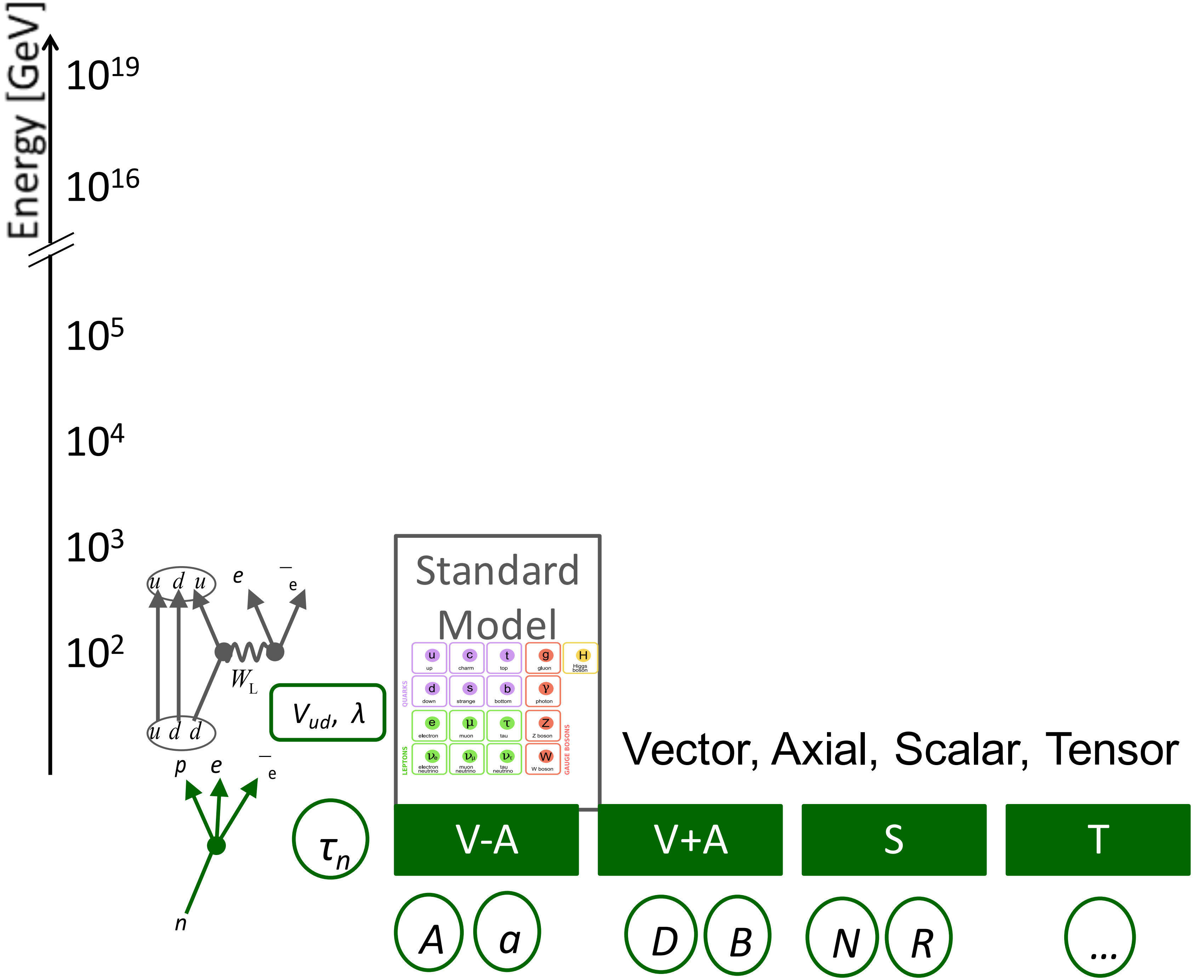
5 fourfold

1 fivefold

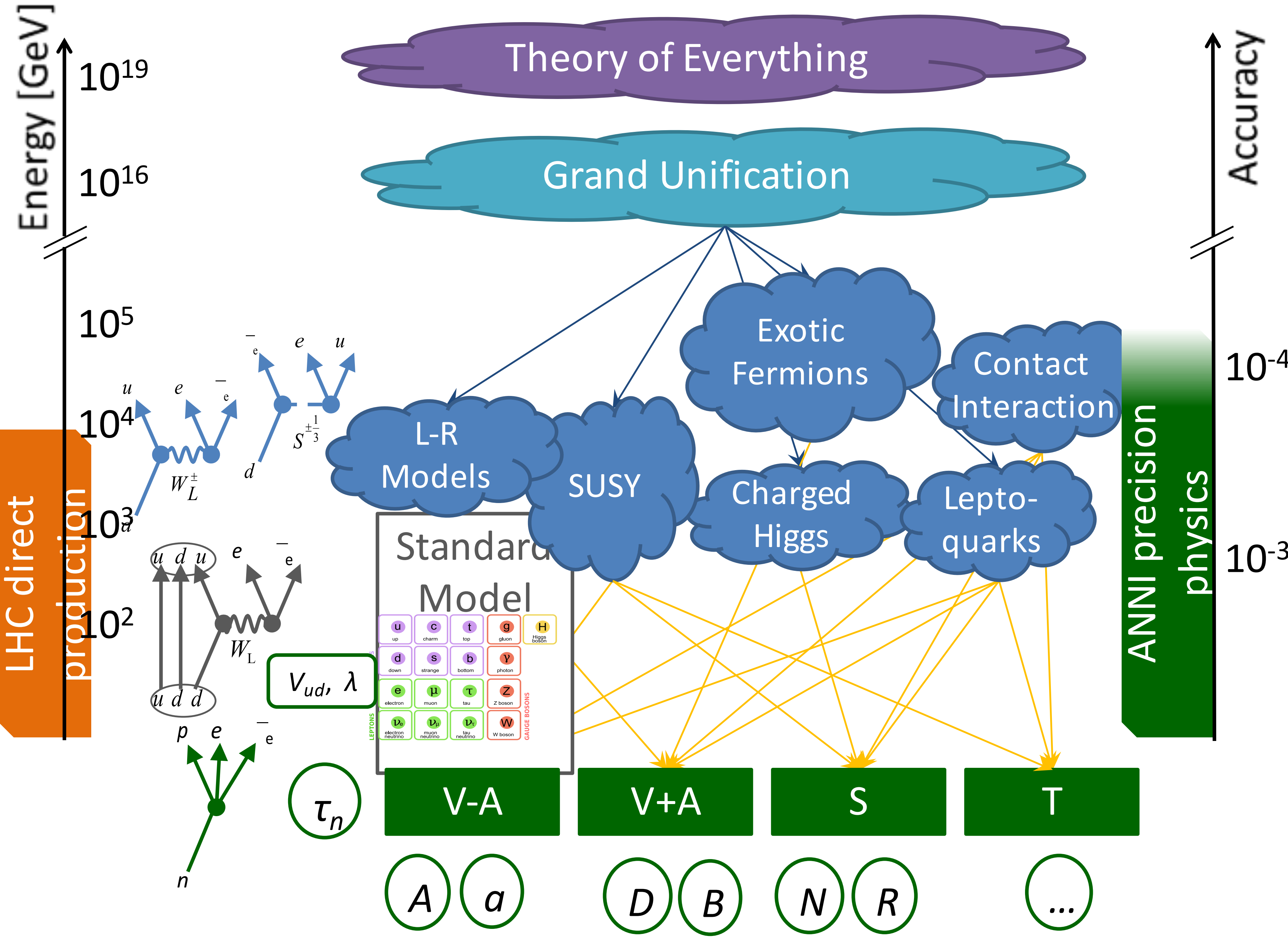
+ Fierz term (e-spectrum)

+ lifetime

From T. Soldner (2016) - Inspired by
Dubbers & Schmidt, Rev. Mod. Phys. 83 (2011) 1111

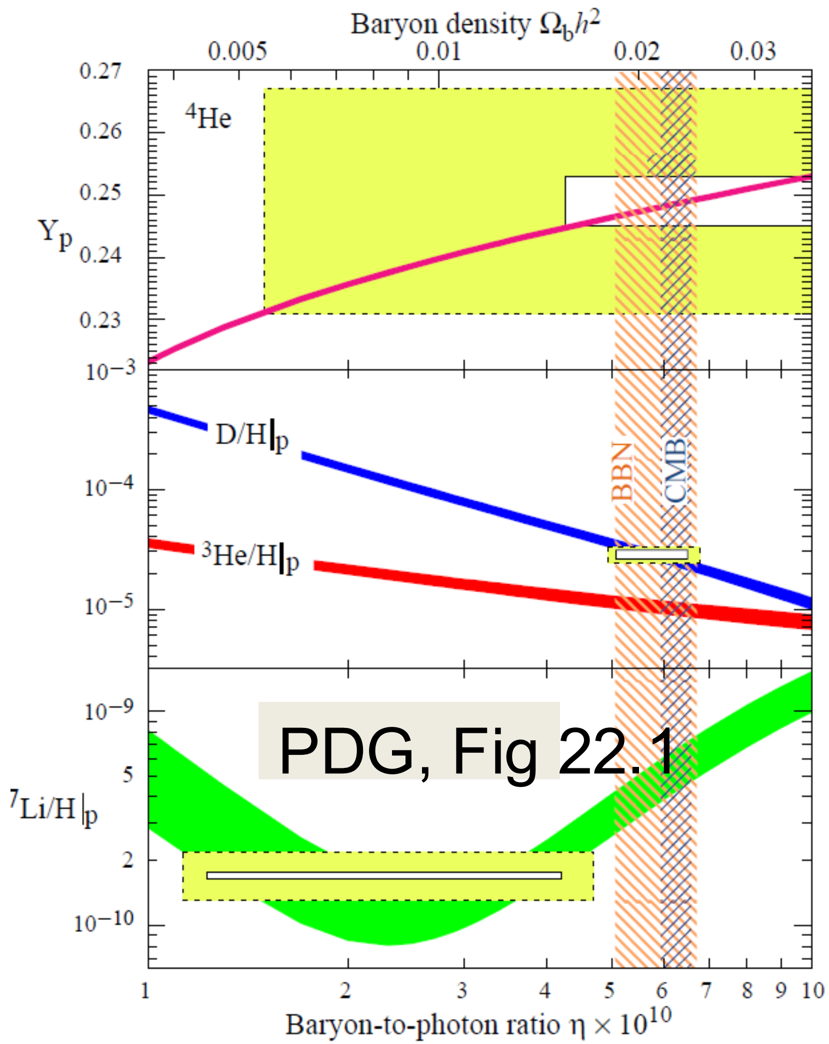


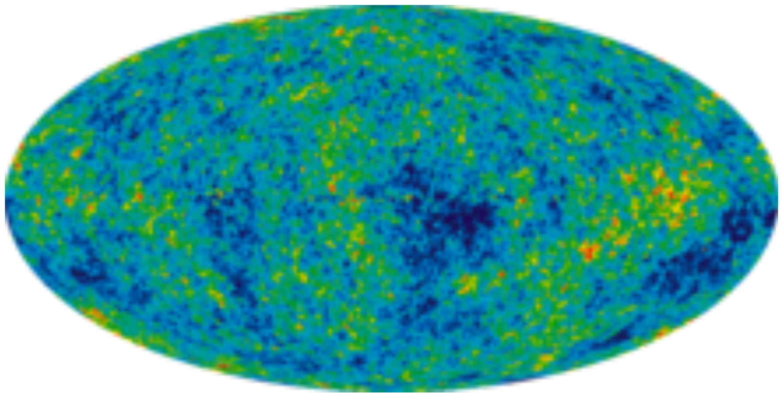
Energy [GeV]
10^19
10^16
10^5
10^4
10^3
10^2
u d u
e
e
W_L
u d d
p
e
e
n
V_ud, λ
τ_n
Standard Model
Vector, Axial, Scalar, Tensor
V-A
V+A
S
T
A
a
D
B
N
R
...

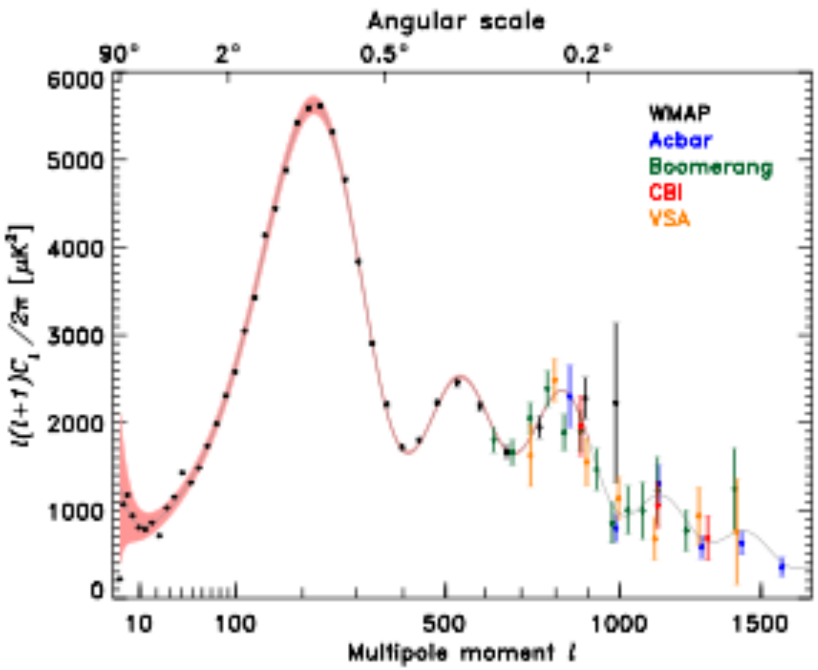


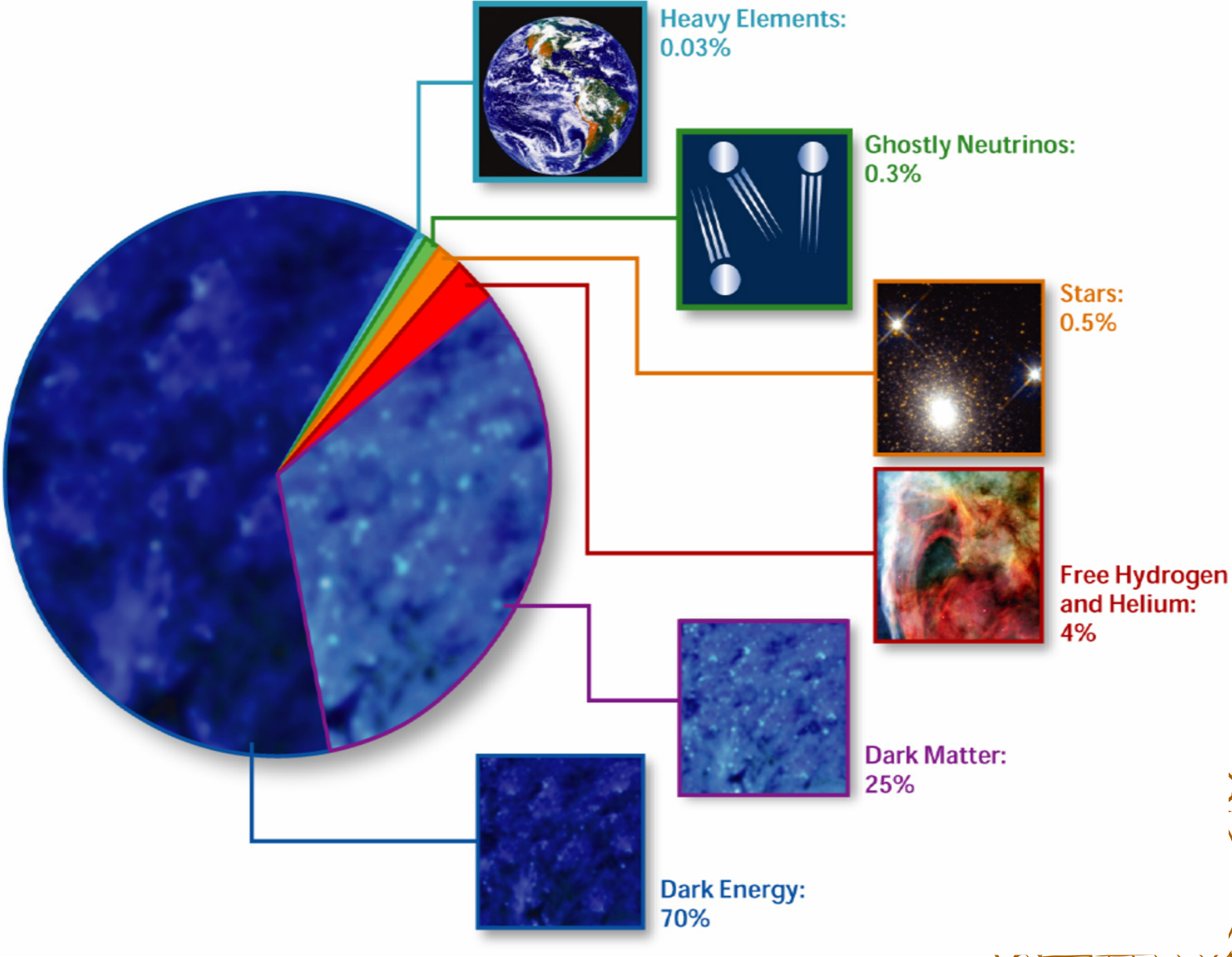
Theory of Everything
Grand Unification
Exotic Fermions
Contact Interaction
L-R Models
SUSY
Charged Higgs
Lepto-quarks
Standard Model
V-A
V+A
S
T
A
a
D
B
N
R
...
Energy [GeV]
10^19
10^16
10^5
10^4
10^3
10^2
LHC direct production
Accuracy
10^-4
10^-3
ANNI precision physics
V_ud, λ
τ_n
p e
n
W_L

Most Matter Was DOA



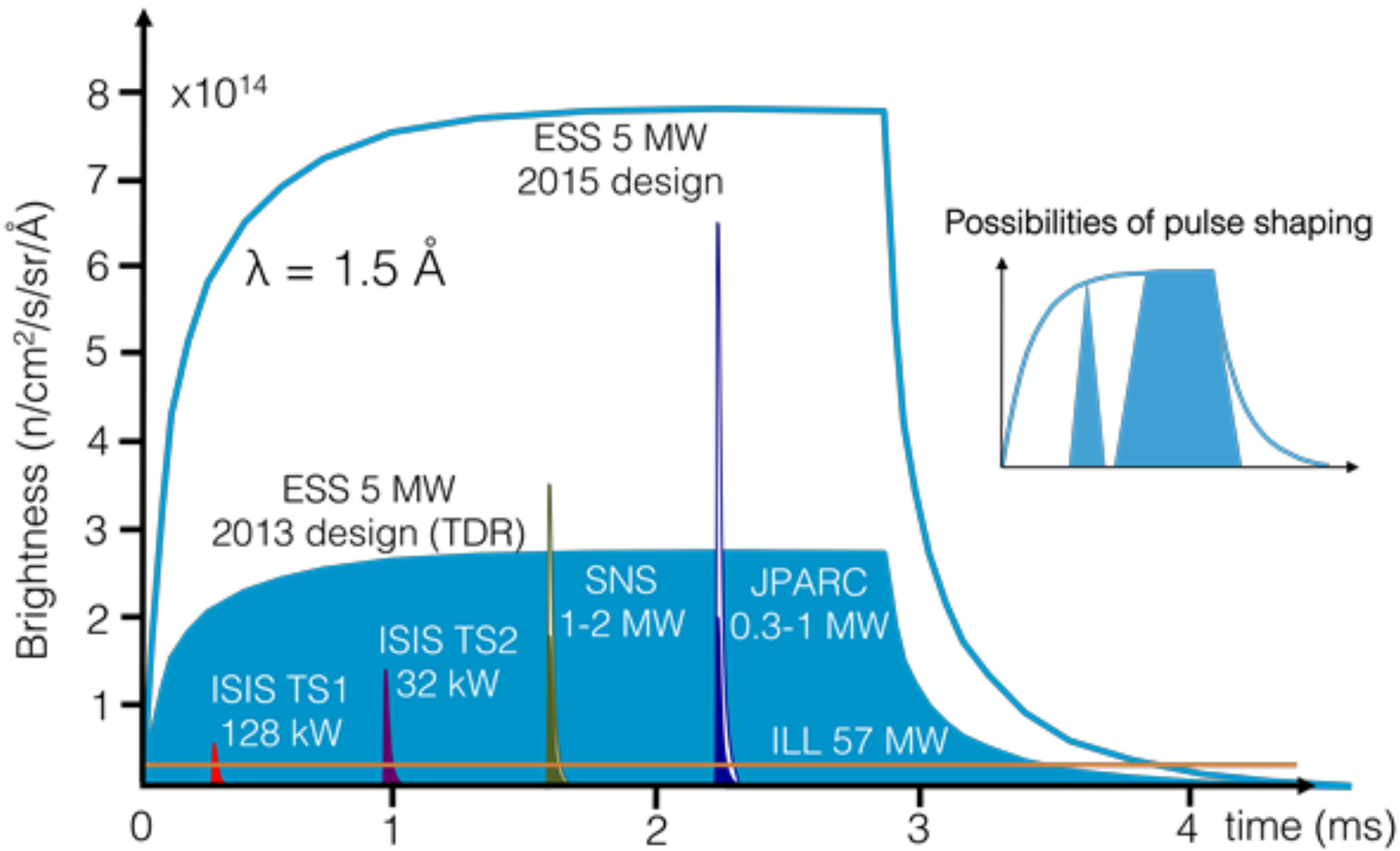





Heavy Elements:
0.03%
Ghostly Neutrinos:
0.3%
Stars:
0.5%
Free Hydrogen
and Helium:
4%
Dark Matter:
25%
Dark Energy:
70%

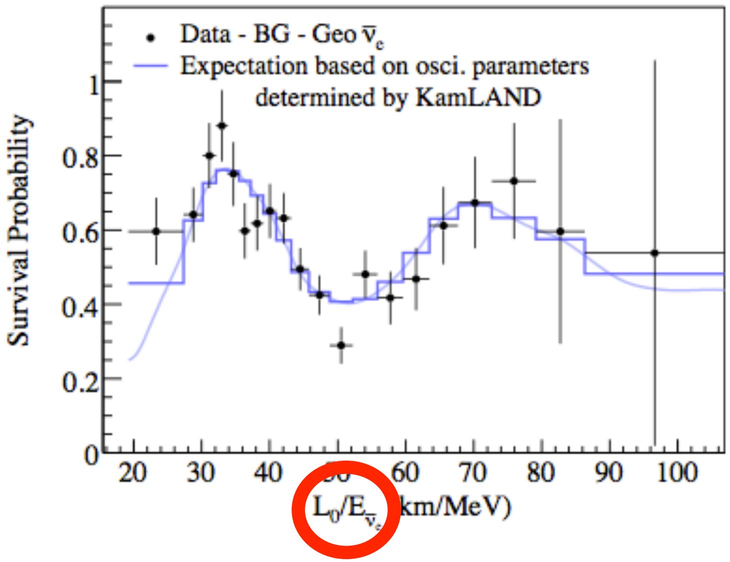
Sakharov Criteria Explained

ESS is a long-pulse spallation source



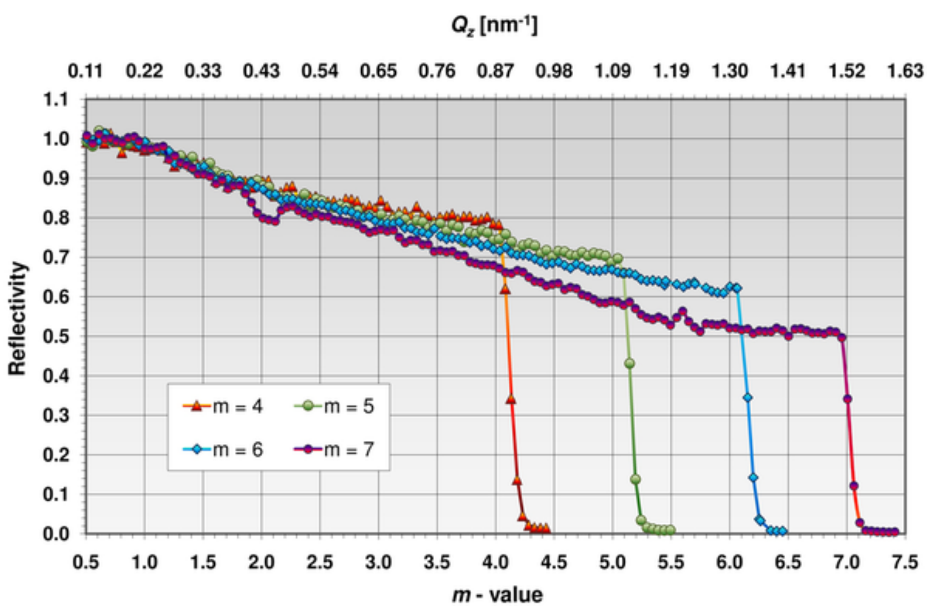
Neutrino Oscillations

- Neutrino oscillations unambiguously establish neutrinos are massive
  - Since neutral, **Majorana** mass term allowed
    - If exists, **ΔL = 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 (ΔL=2) scale 10^6 - 10^{10} GeV
  - **ΔB = 2** at a similar energy scale?



Supermirror

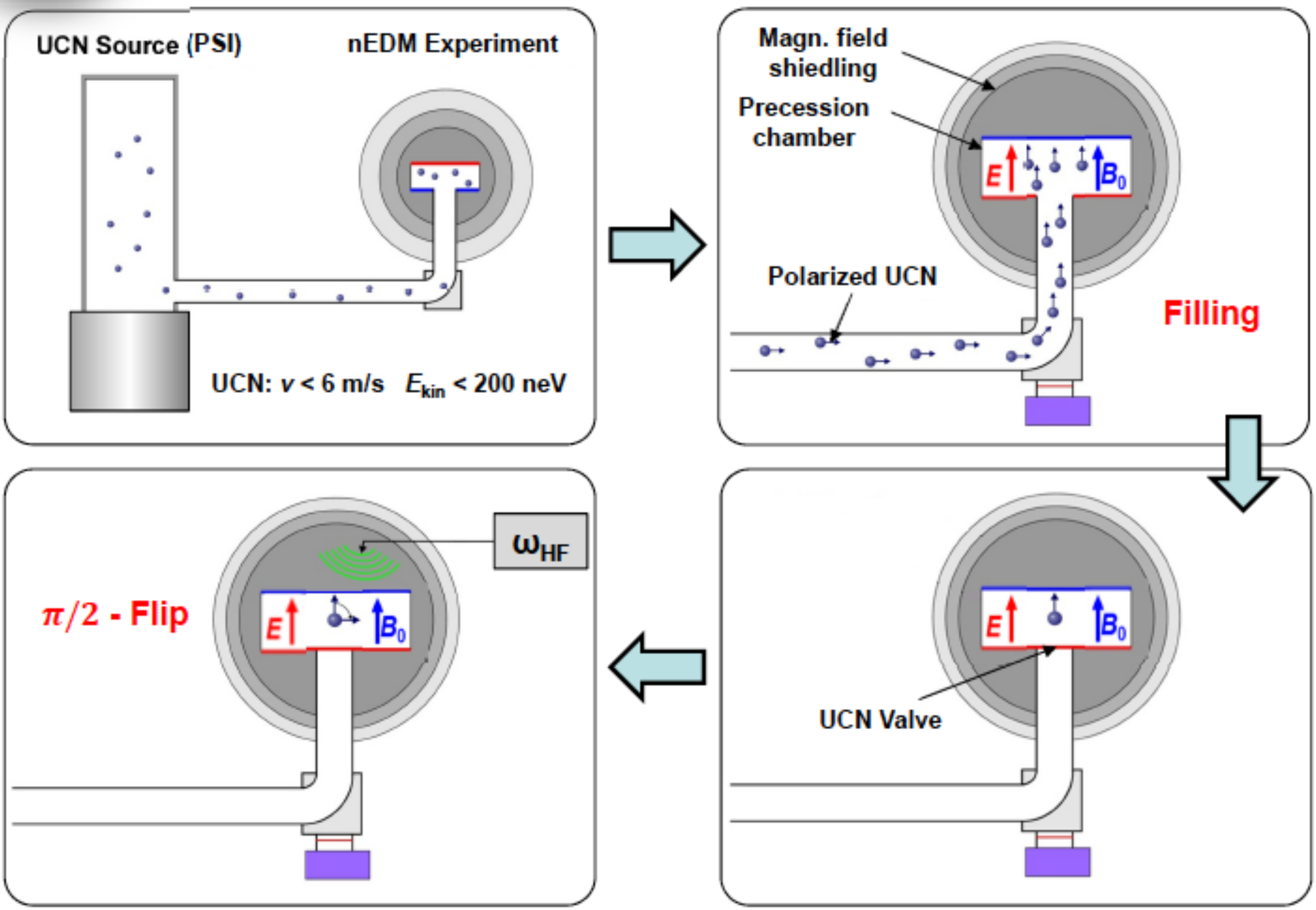
- Crucial in acceptance gain
  - 2D, so acceptance scales quadratically
  - Modern multi-layer supermirrors have good reflectivity at increasingly large momentum transfers

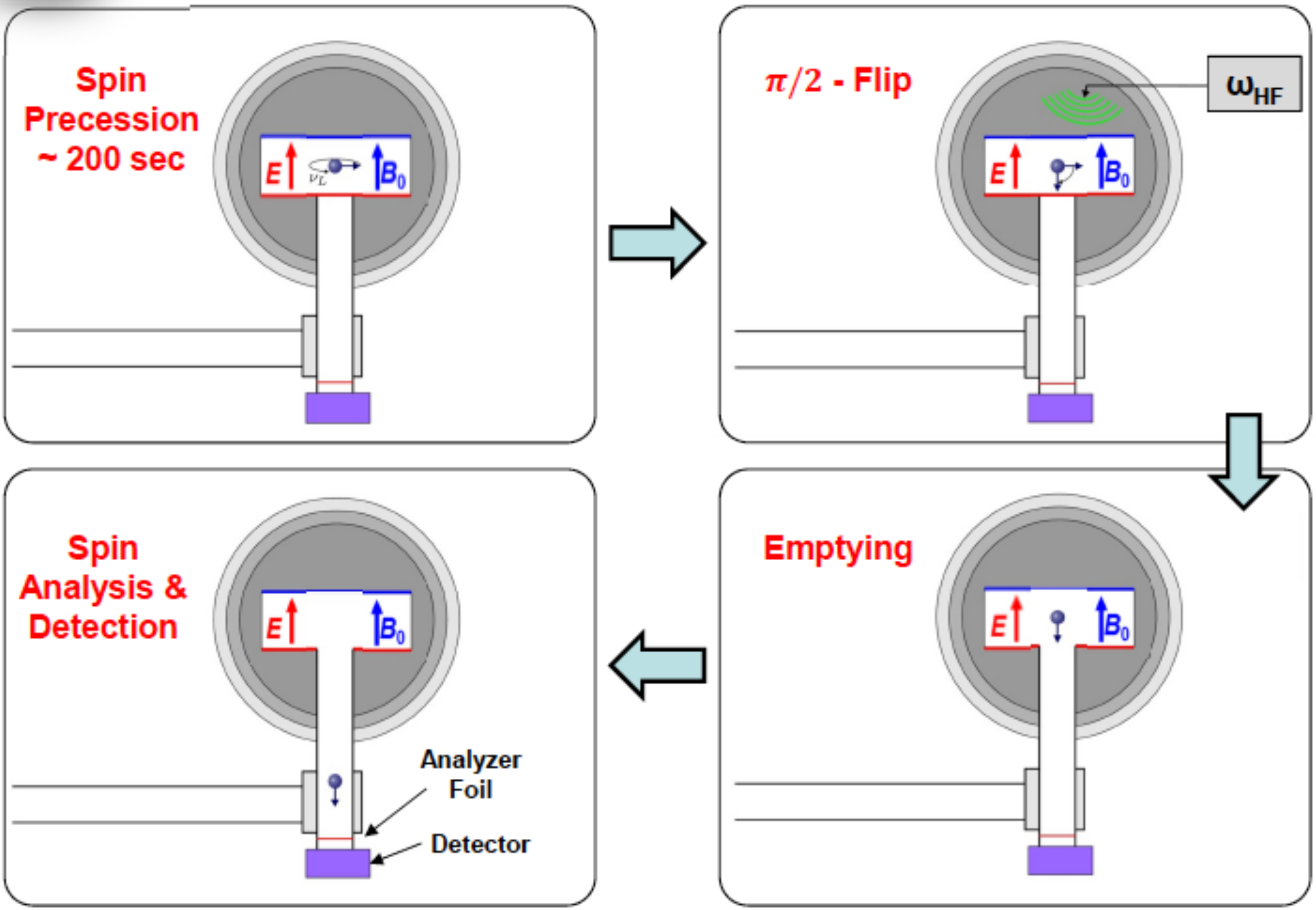


(Swiss Neutronics)

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

Ni reflectivity → 0 defines m=1


UCN Source (PSI)
nEDM Experiment
UCN: v < 6 m/s   E_kin < 200 neV
Magn. field shiedling
Precession chamber
Polarized UCN
Filling
E
B_0
UCN Valve
π/2 - Flip
ω_HF

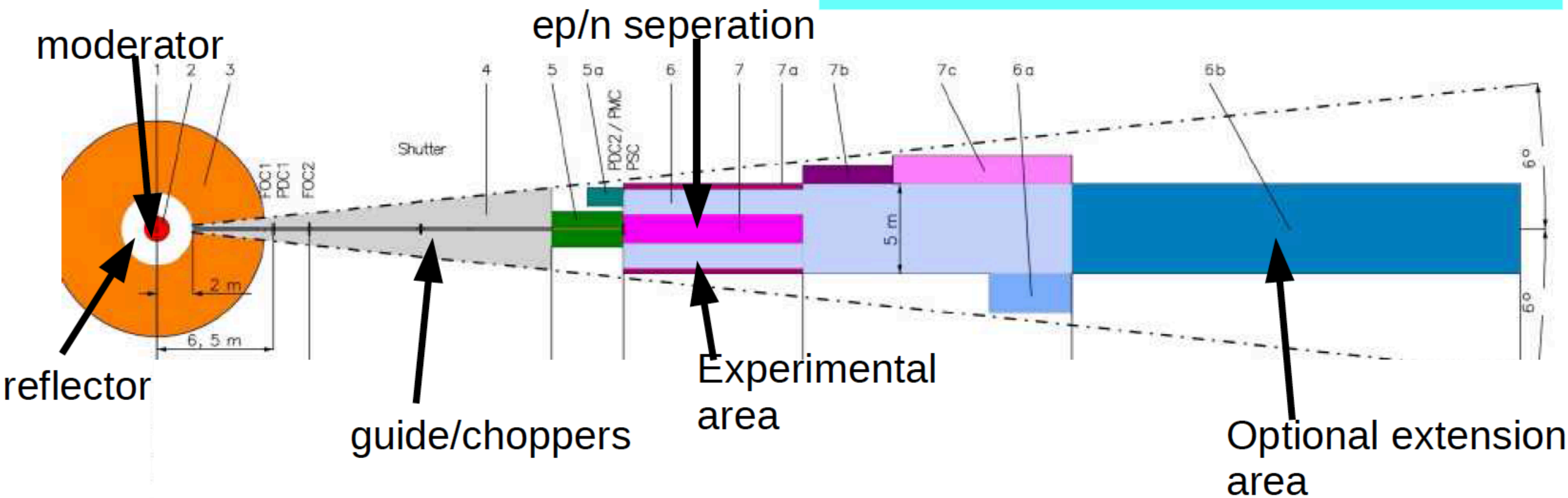

Spin
Precession
~ 200 sec
E
ν_L
B_0
$\pi/2$ - Flip
ω_{HF}
E
B_0
Emptying
E
B_0
Spin
Analysis &
Detection
E
B_0
Analyzer
Foil
Detector

ANNI Beam Line

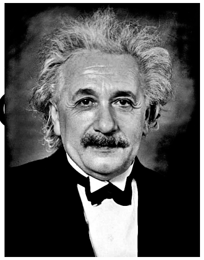
- Proposal for a fundamental physics beamline, using the neutron as patient rather than probe
- User community foreseen to install experiments for extended running periods: months-years

Envisioned measurements

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



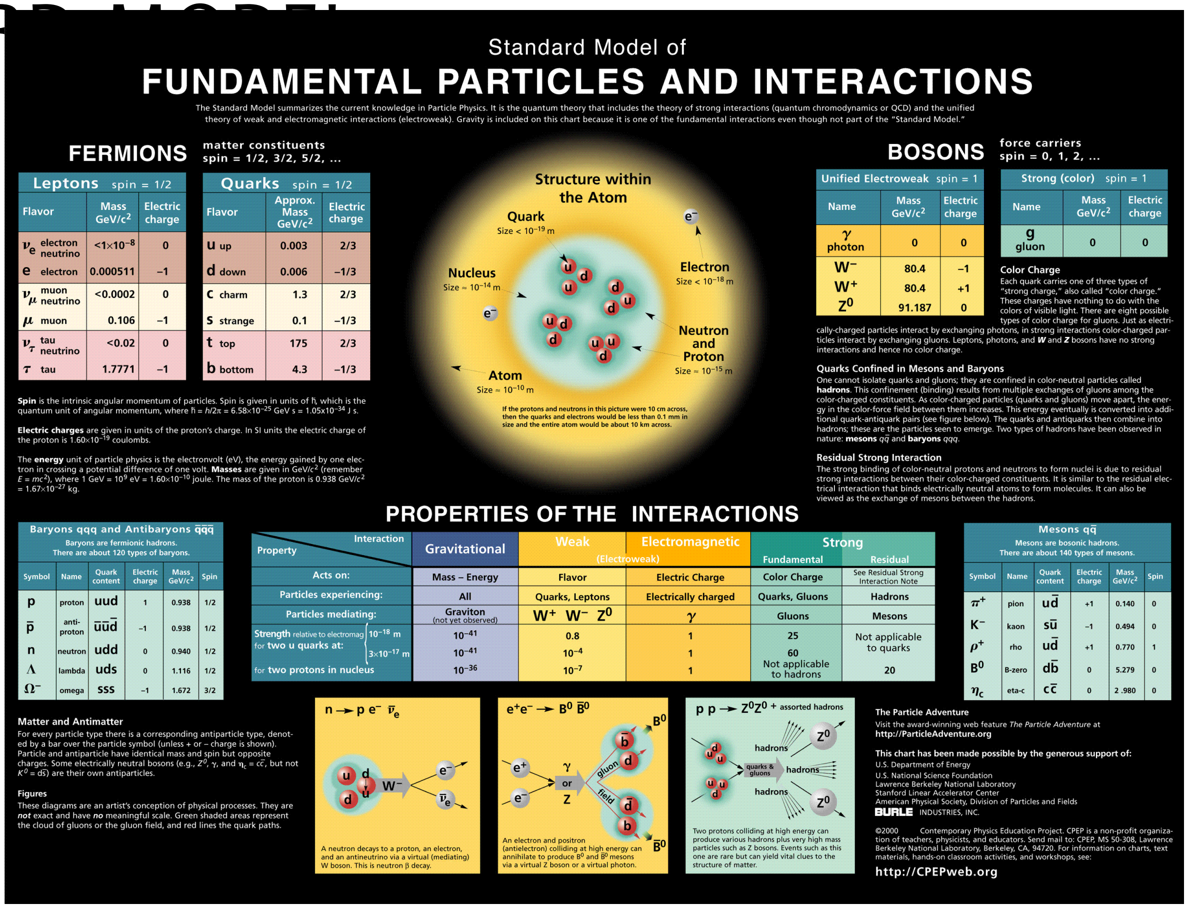
Fundamental Physics and curiosity (III)



The last century was fantastic

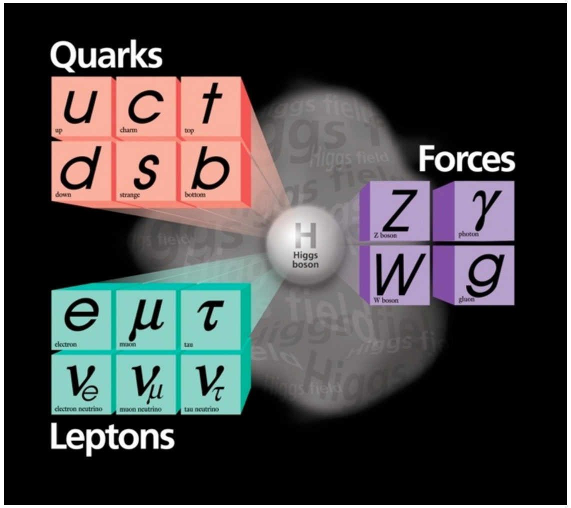
Special and General relativity

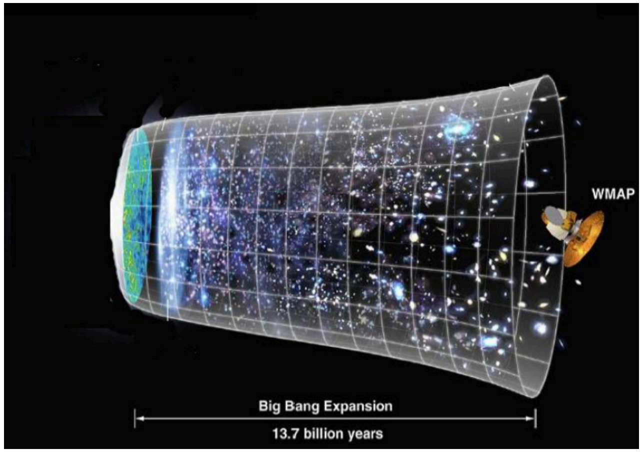
Discovery of electrons, neutrons, proton ->STANDAR

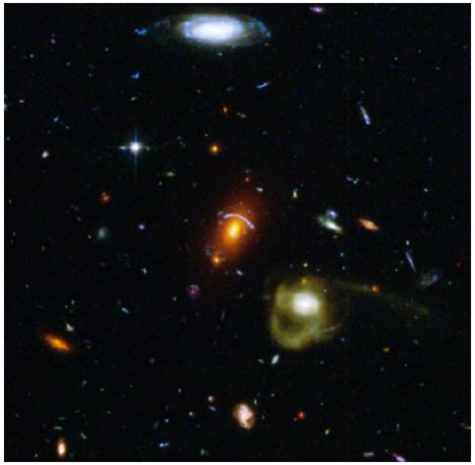


Lacking in the Standard Model(I)

Standard Model + General Relativity = Universe







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

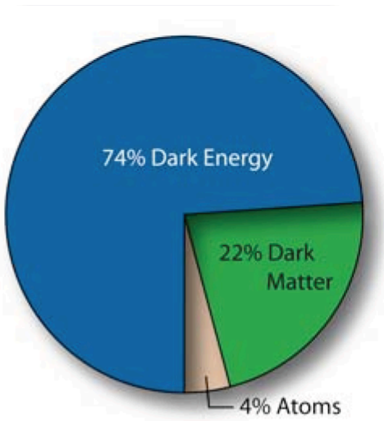
DARK MATTER ? DARK ENERGY?

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)

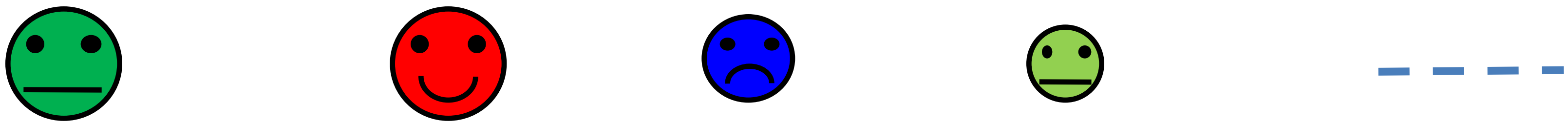


But astronomical observations

- 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

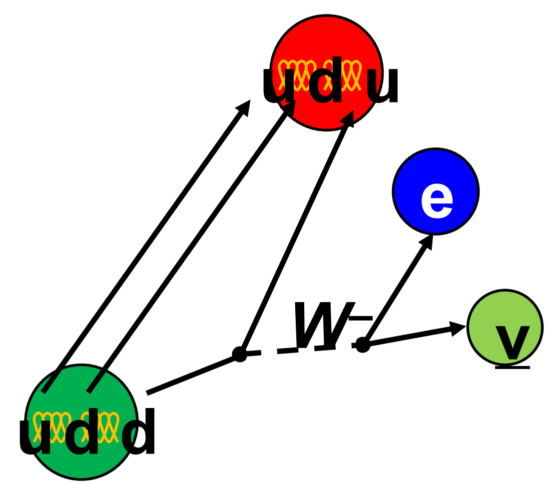
Masses and Energies



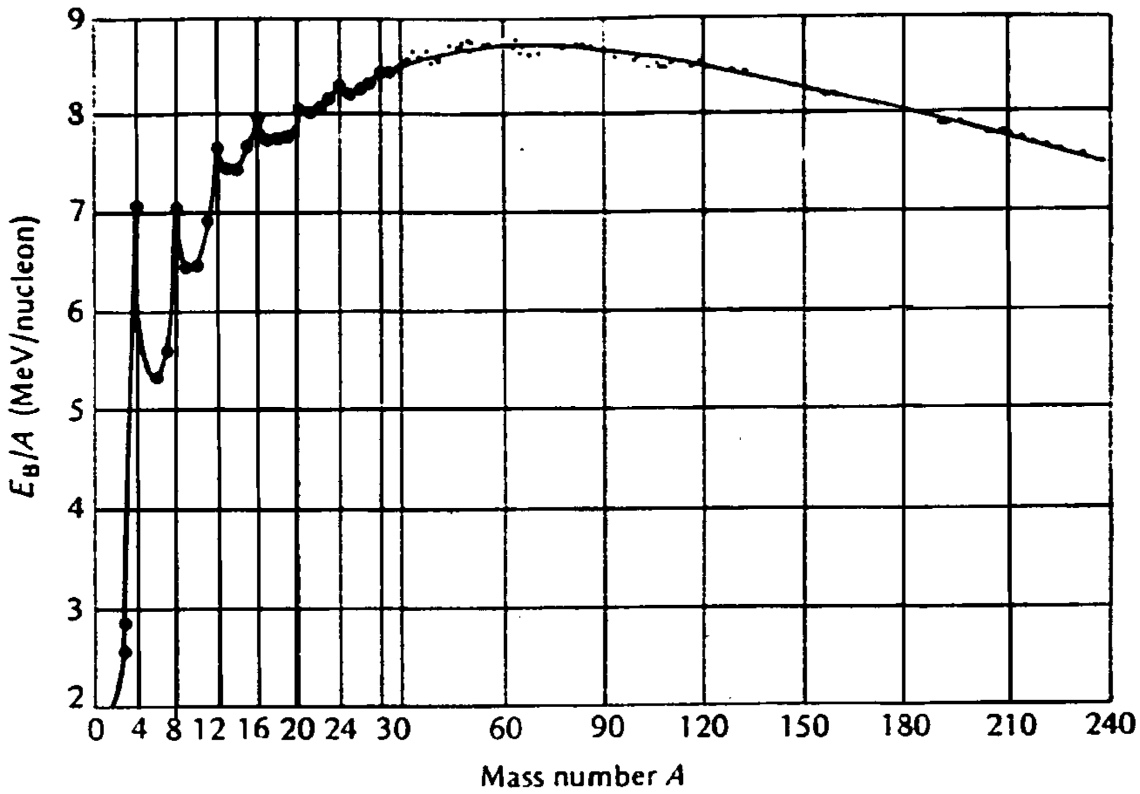
Neutron	Proton	Electron	Neutrino	**W boson**
939.565 MeV	938.272 MeV	0.511 MeV	<2 eV	**80.385 GeV**

***Q* = 0.781 MeV**

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

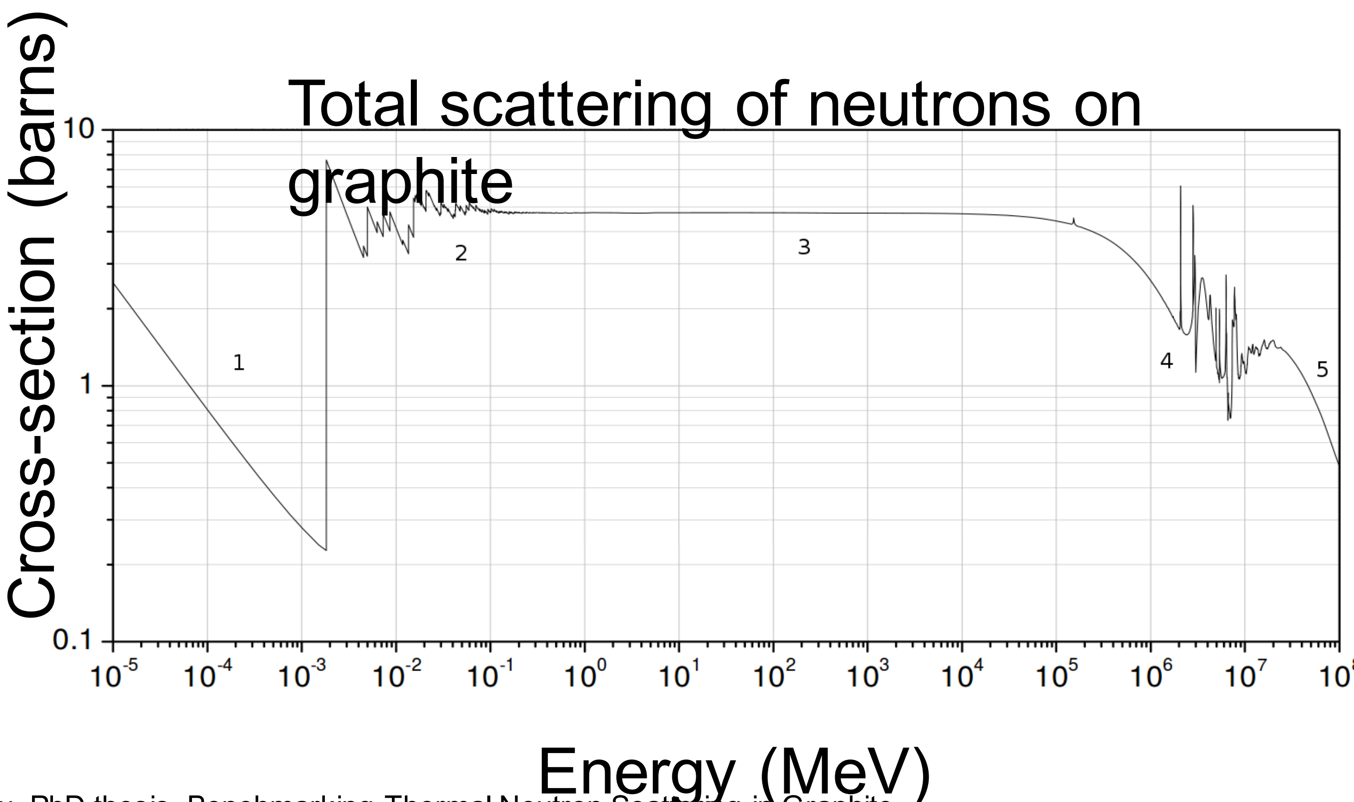


Most important diagram for our existence…



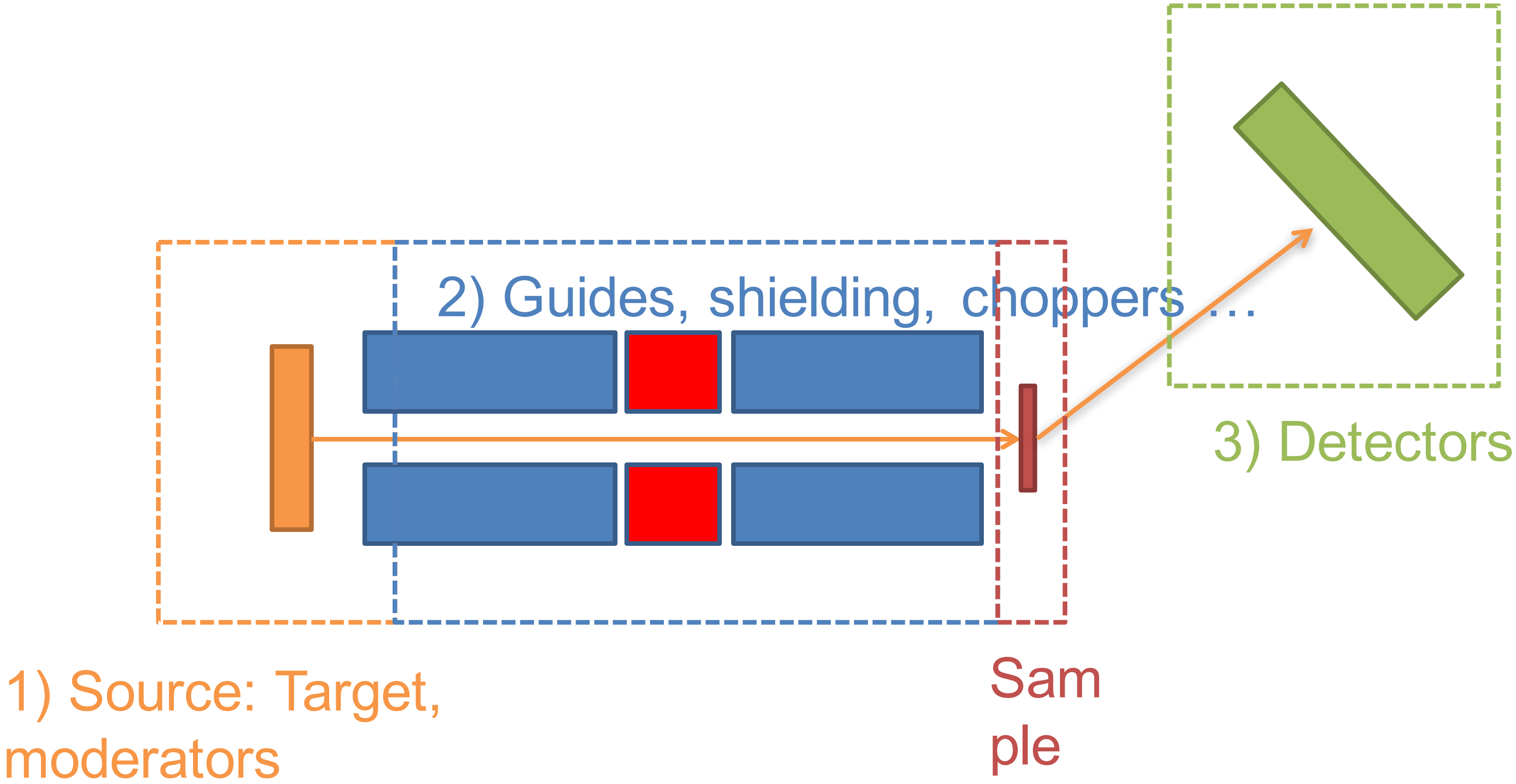
Spallation neutron physics

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



See: Tong Zhou, PhD thesis, Benchmarking Thermal Neutron Scattering in Graphite, http://www.lib.ncsu.edu/resolver/1840.16/3021

A neutron scattering experiment

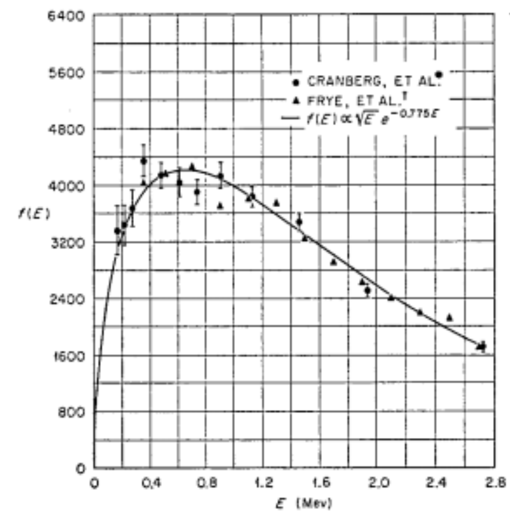


How a spallation source works

- 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!)

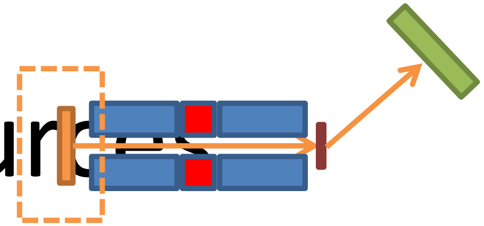
Fission vs spallation

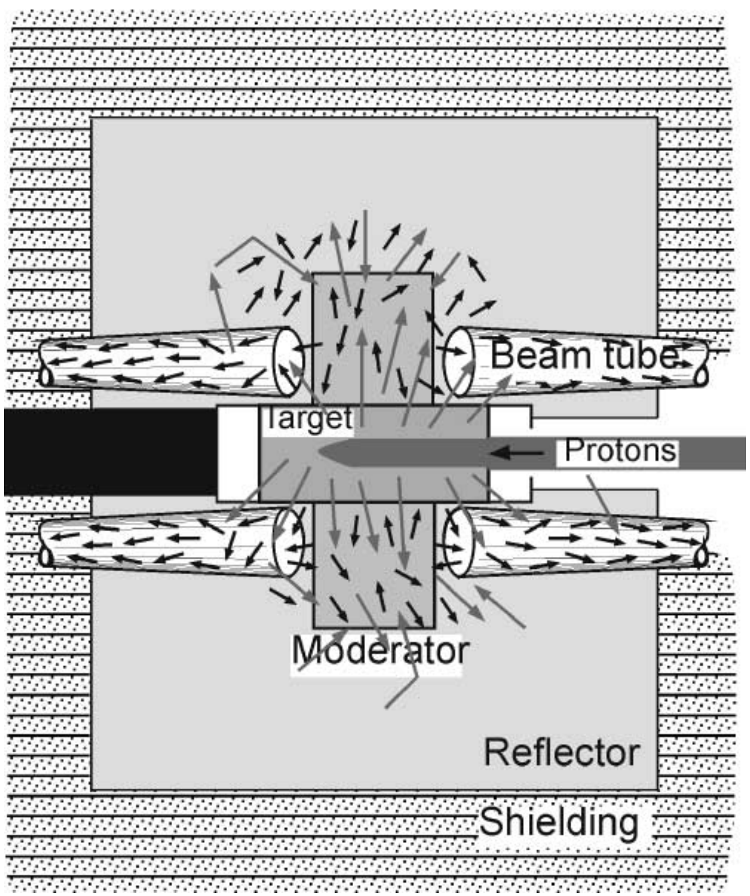
- Fission
  - 200 MeV/fission
  - Prompt neutrons evaporate from excited nuclei with energy ~2 MeV
  - ~2.5 neutrons / fission, but ~1 neutron from each fission is useful (1 neutron to continue to reaction, and about 0.5 is captured)
- Spallation
  - Produces around 20 neutrons per proton
  - 90% of 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 dissapating ten times less heat energy per useful neutron than fission

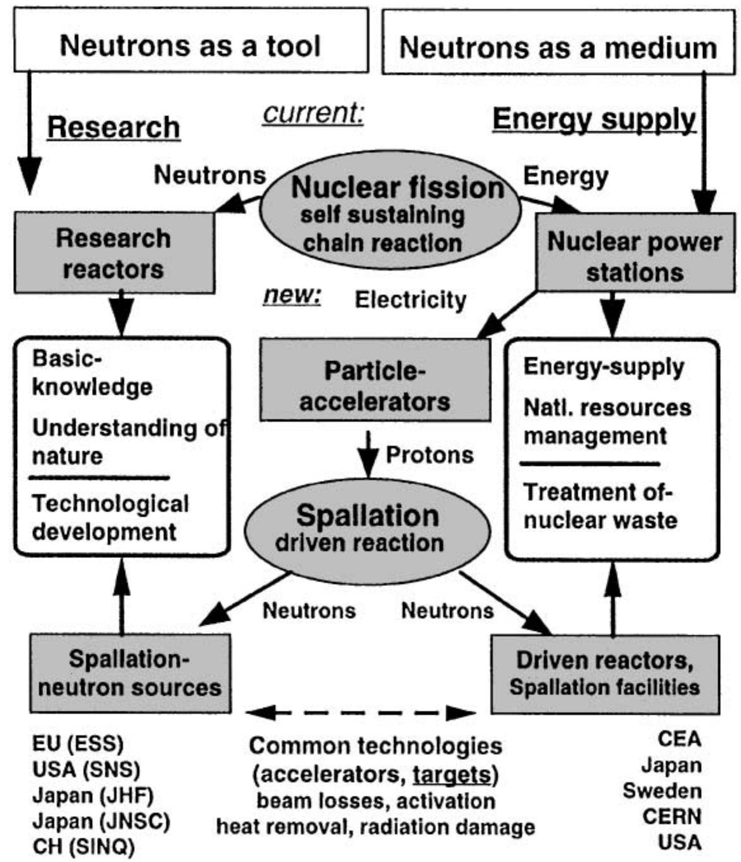


http://www.neutron.anl.gov/NeutronProduction.pdf

Spallation sources

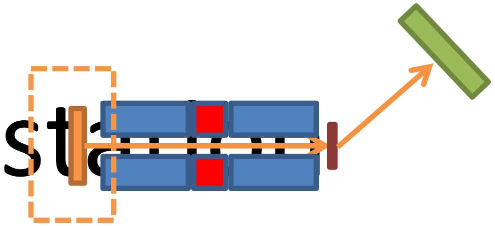




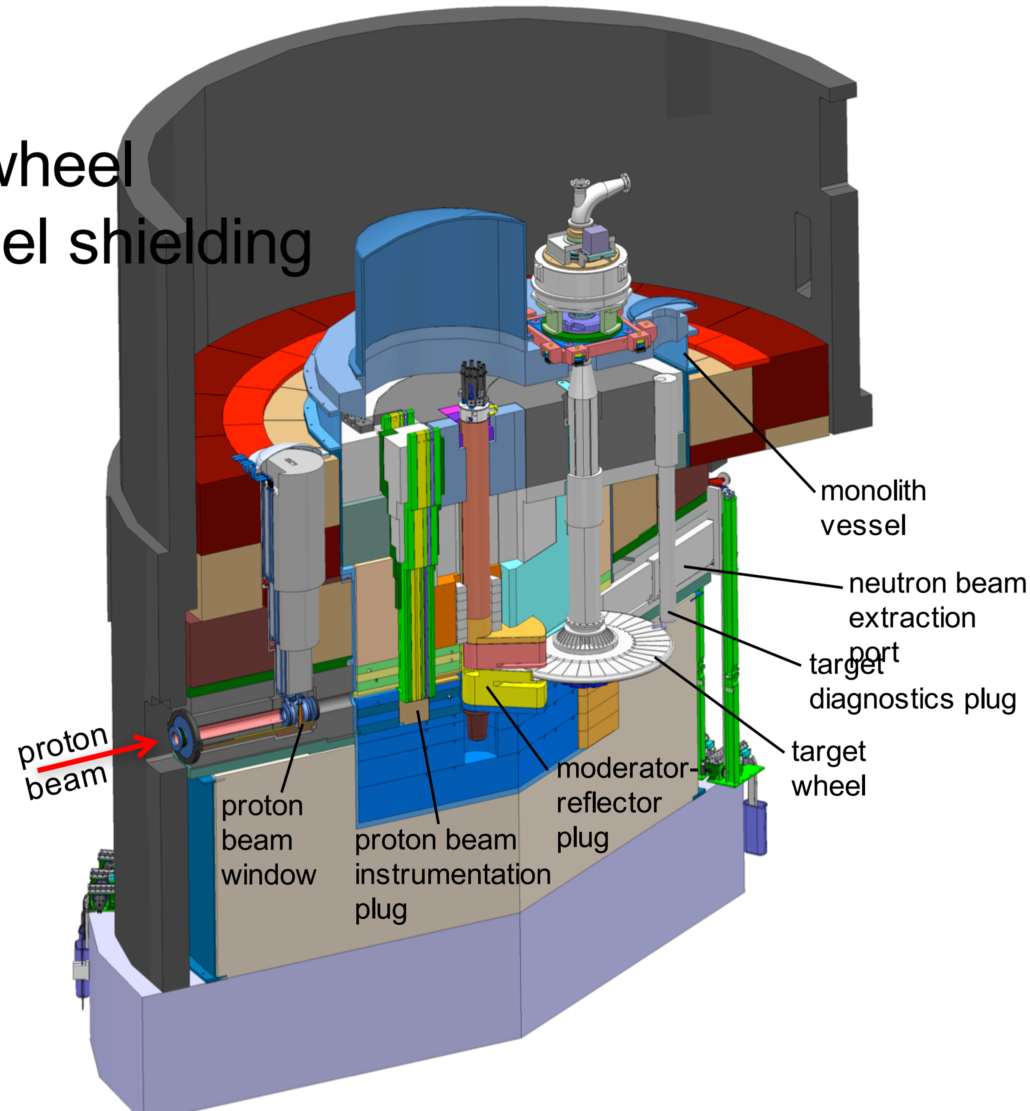


G.S. Bauer / Nuclear Instruments and Methods in Physics Research A 463 (2001) 505–543

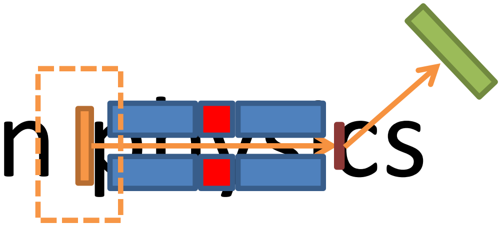
ESS target station



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



Spallation neutron physics



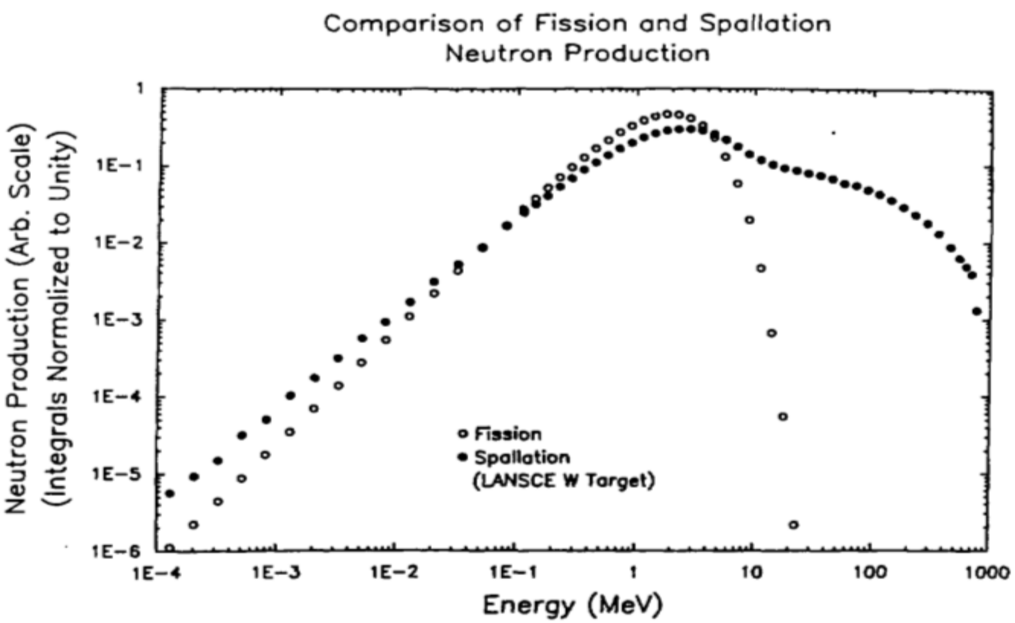
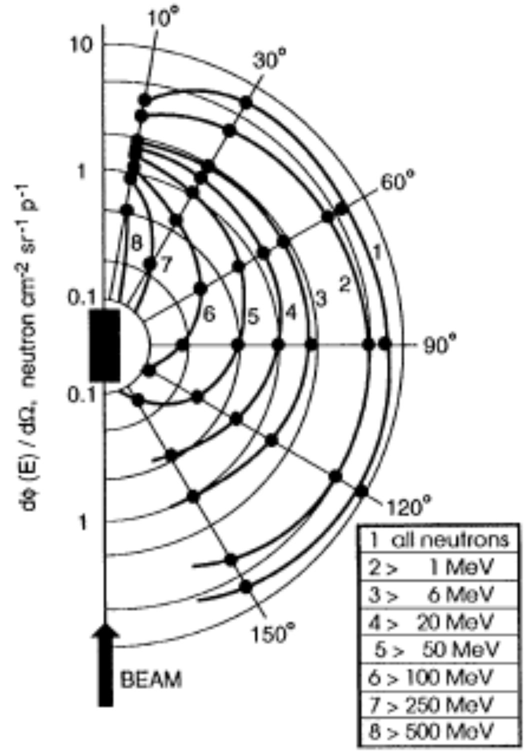


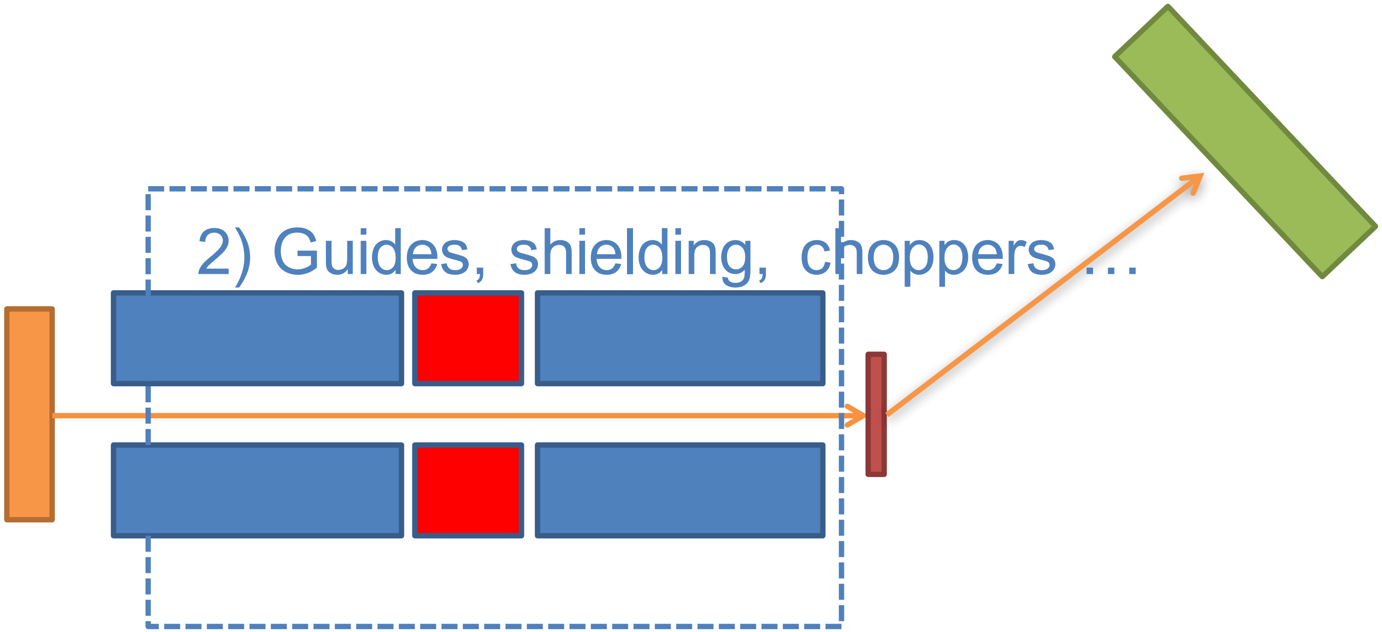
Figure 6. Neutron production from fission (o) and from spallation (•).

G. Russel, ICANS-XI proceedings, KEK, Tsukuba, Oct. 22-26 199(

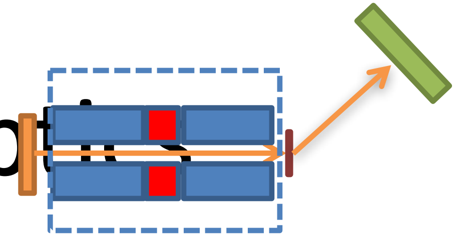


G.S. Bauer / Nuclear Instruments and Methods in Physics Research A 463 (2001) 505–543

Guides

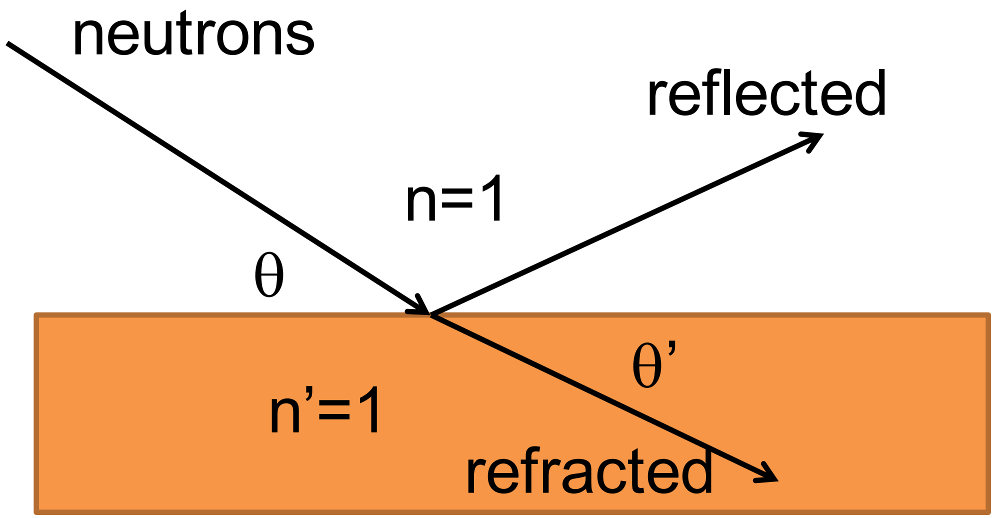


Neutron optics



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

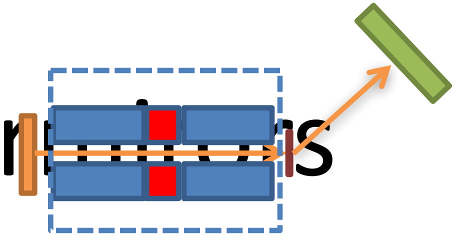
$$\frac{\cos}{\cos\ '} = \frac{n'}{n} = n'$$

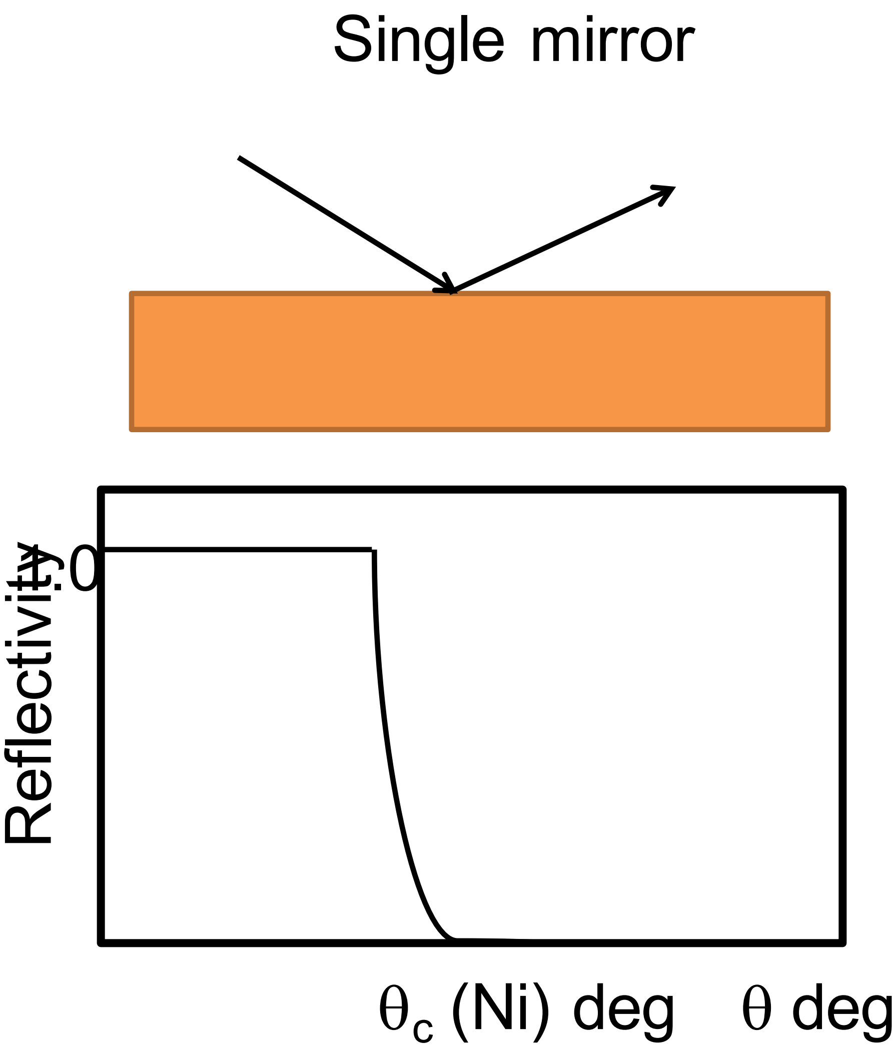


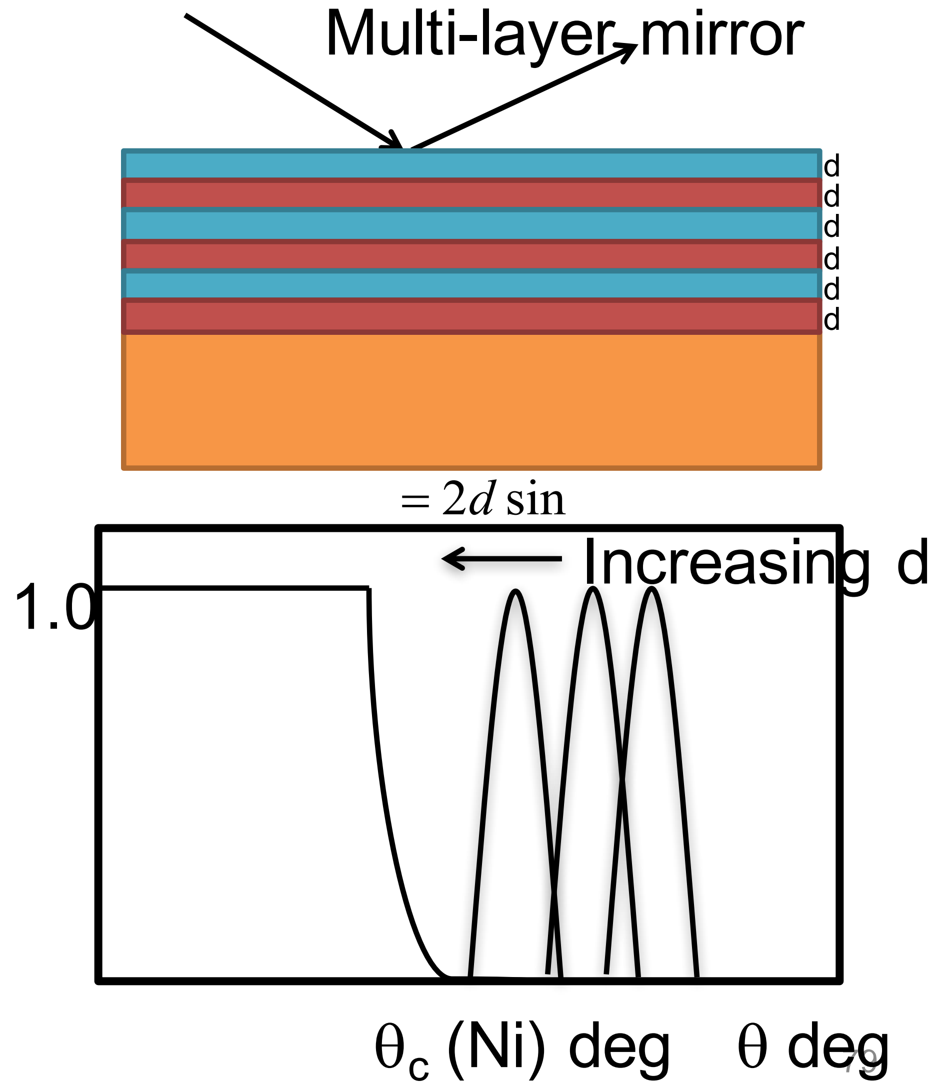
When θ'=0 => critical angle of reflection, can be shown that $\;_c = \;_c\sqrt{\frac{Nb}{\;}}$

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

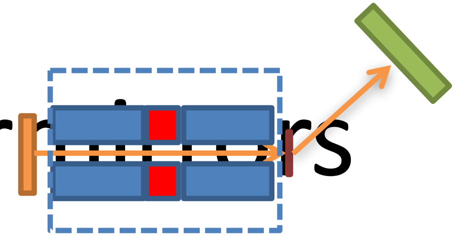
Neutron supermirrors

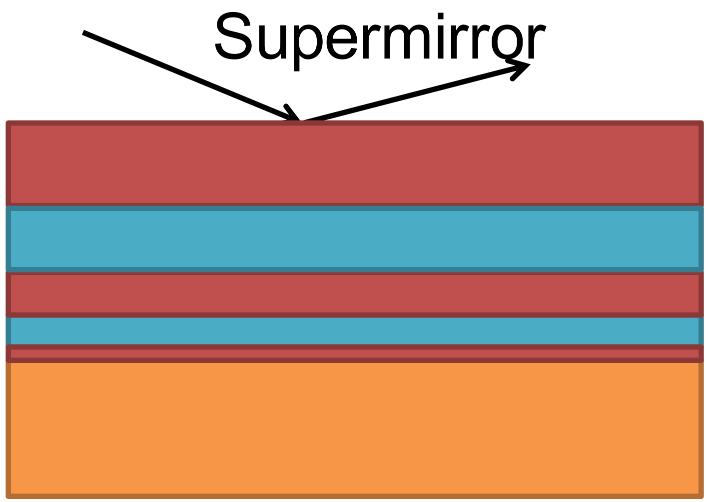


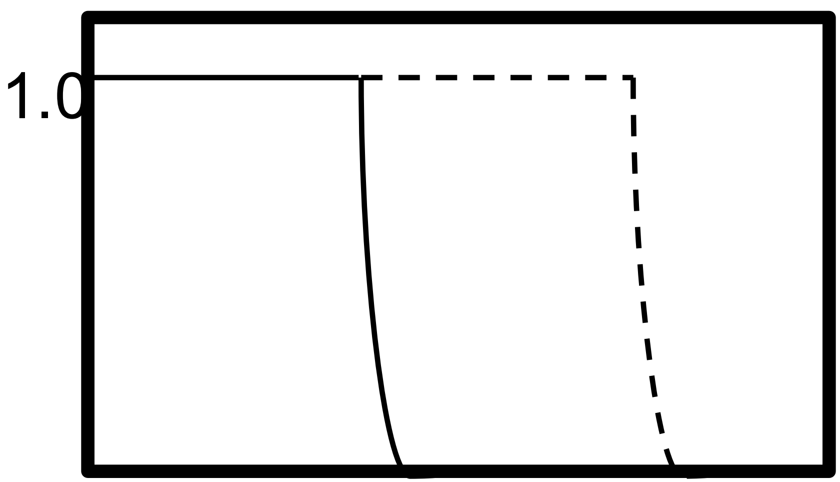


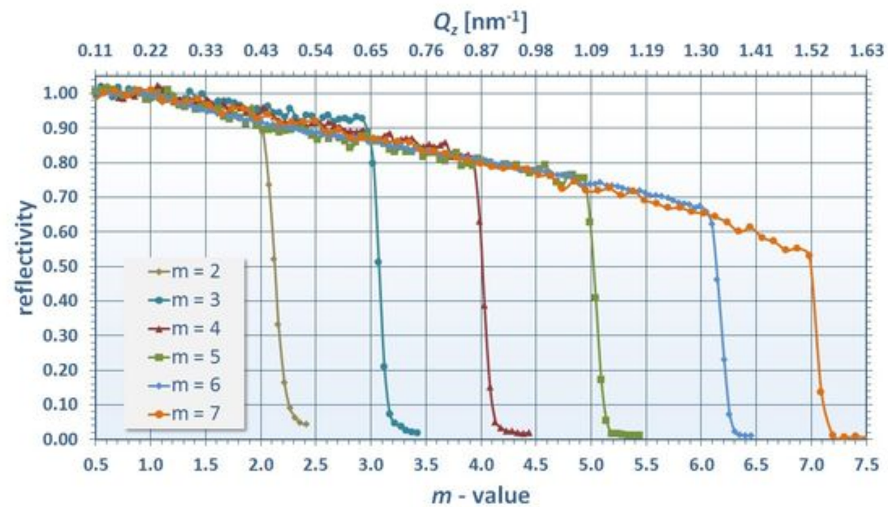


Neutron supermirrors





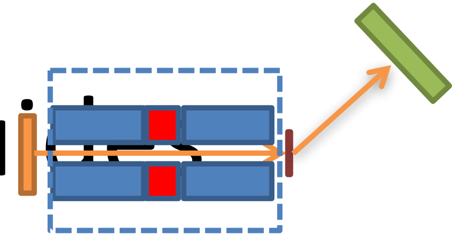


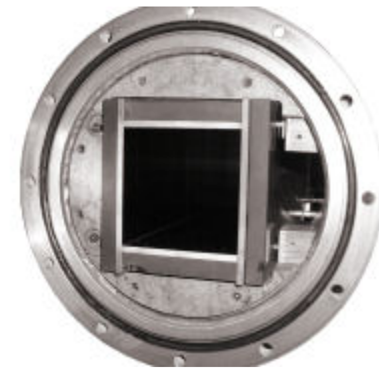


http://www.swissneutronics.ch

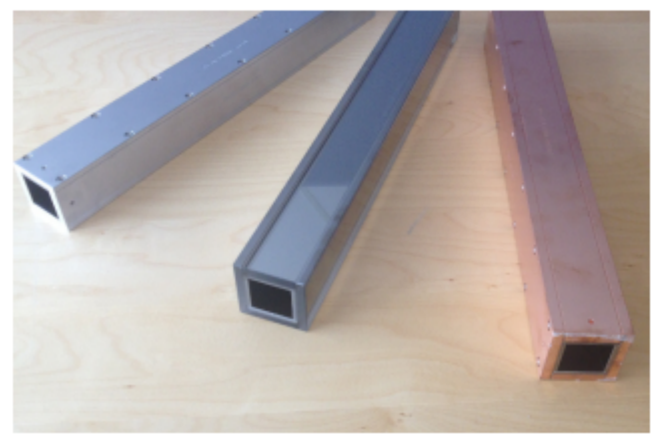
80

Neutron guides





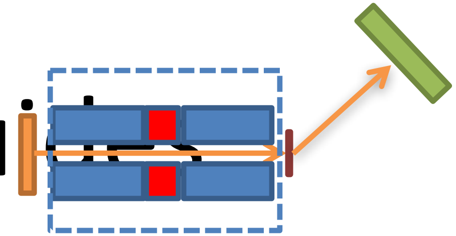
http://www.mirrotron.kfkipark.h

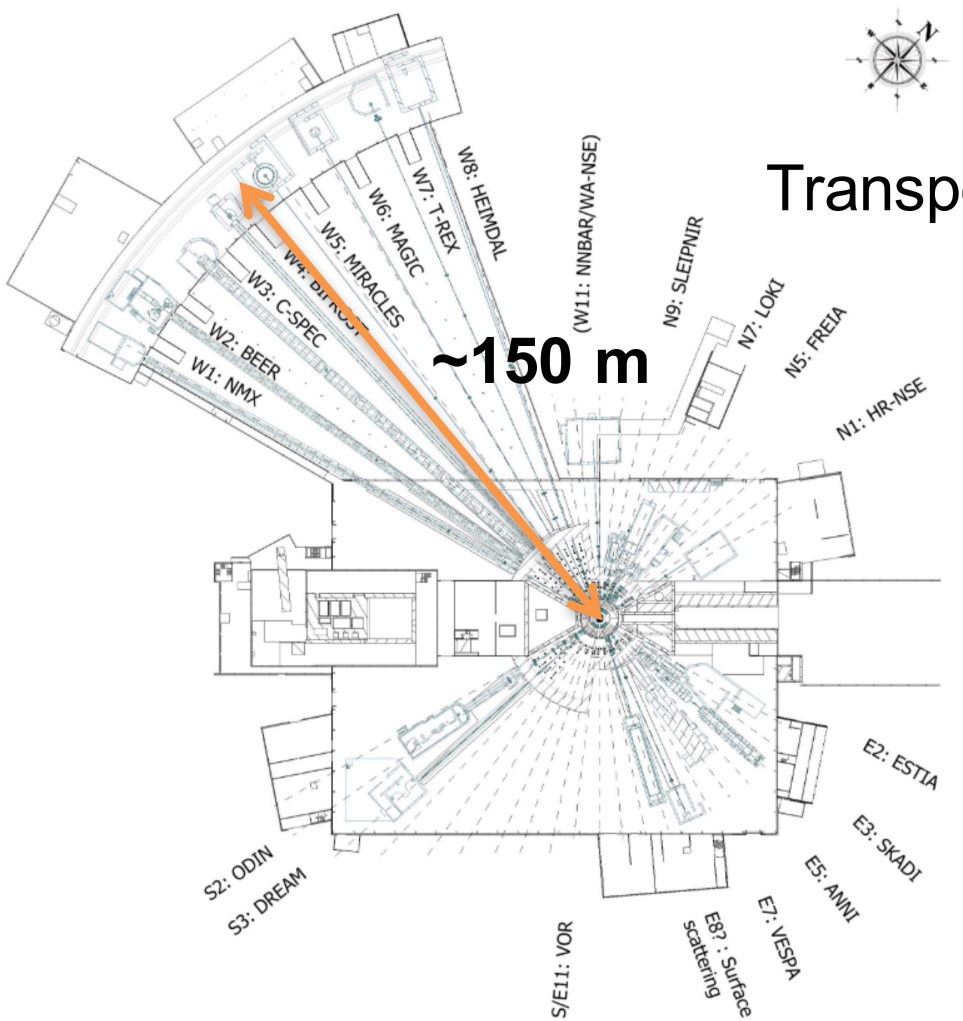


http://www.swissneutronics.ch/

Different substrate materials

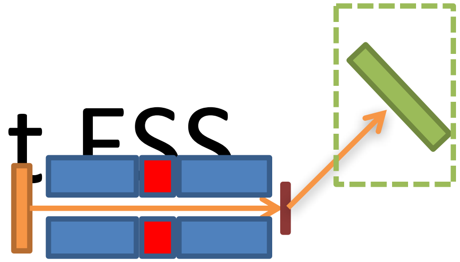
Neutron guides





Transport over long distar

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]**			

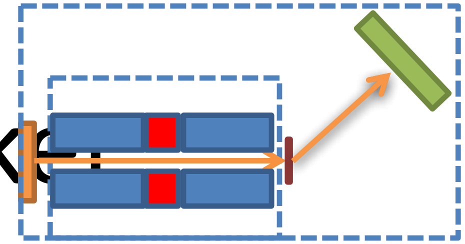
Table 1: Estimated detector requirements for the 22 reference instruments in terms of detector area, typical wavelength range of measurements and desired spatial and time resolution. The foot notes indicates the tranche in which the instruments is presently intended to be delivered.

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

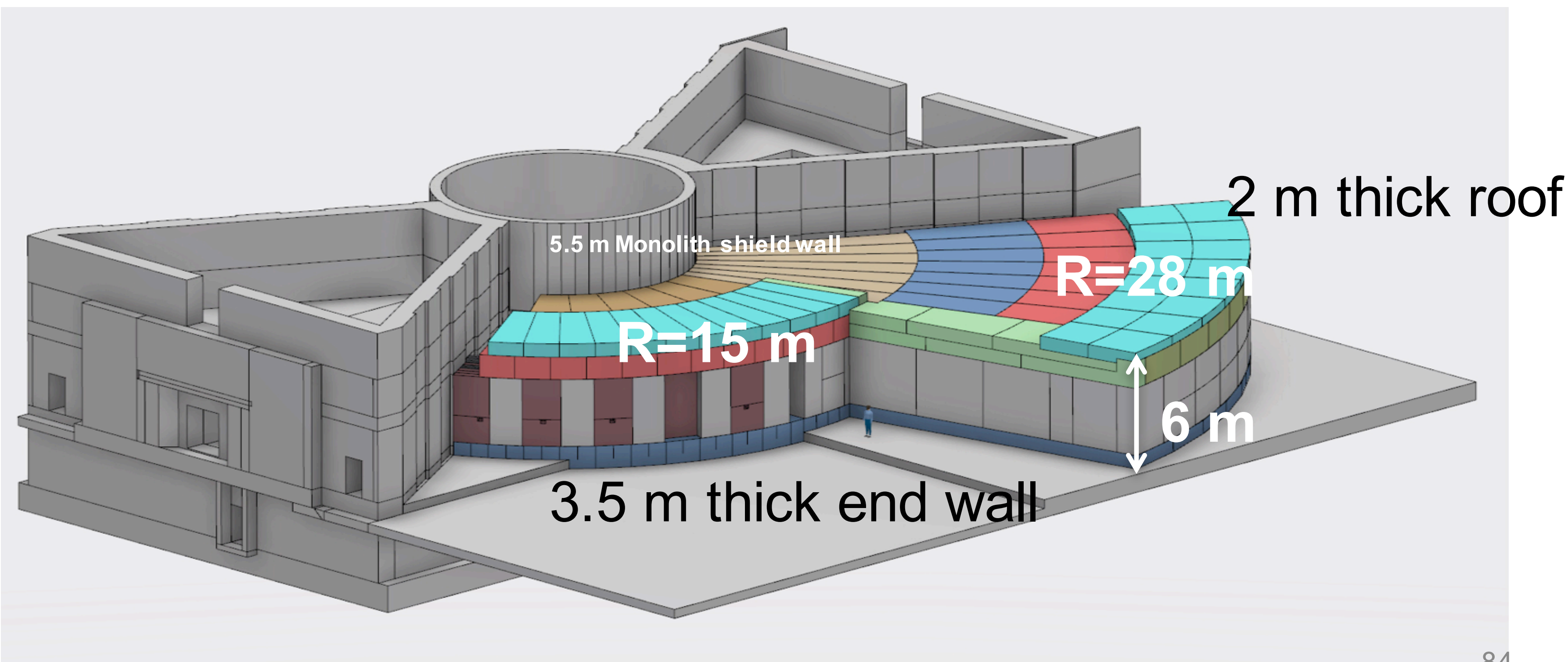
Table 3: Appropriate detector technology options for the recommended instruments. The detector technologies are grouped into perpendicular (⊥)- and inclined (∥)- neutron incidence geometries for ^{10}B thin film detectors, wavelength shifting fibers (WLS) and Anger/direct-coupled cameras for scintillator detectors, ^{3}He 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.

http://arxiv.org/pdf/1411.6194v1.pdf

Shielding bunker



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

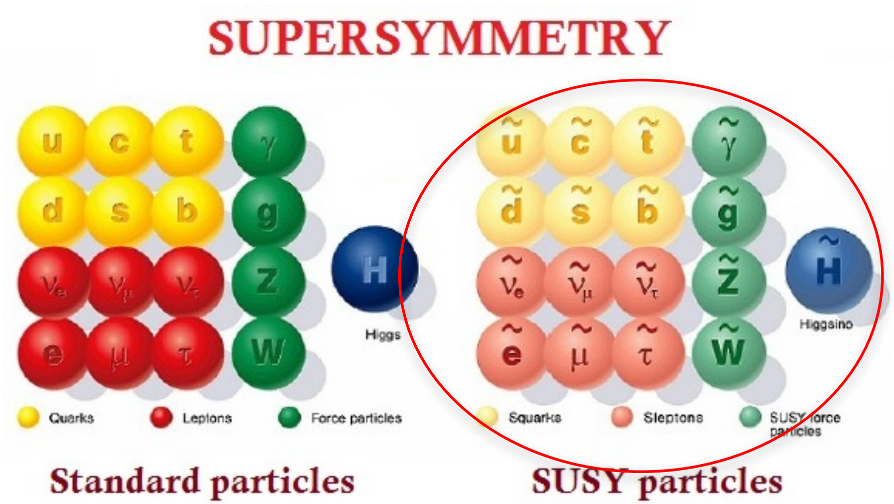


How do you want to look for new physics at LHC?

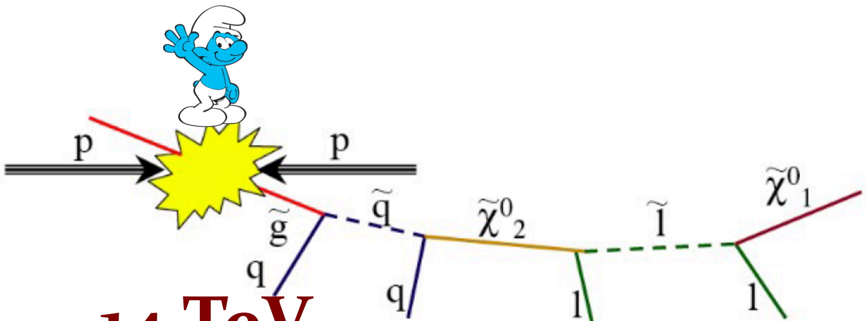
The matter we know account only for 5% of matter

We have to look for a new kind of matter

Many ideas from theoretical physicists



LHC



14 TeV

Possible candidate of new matter