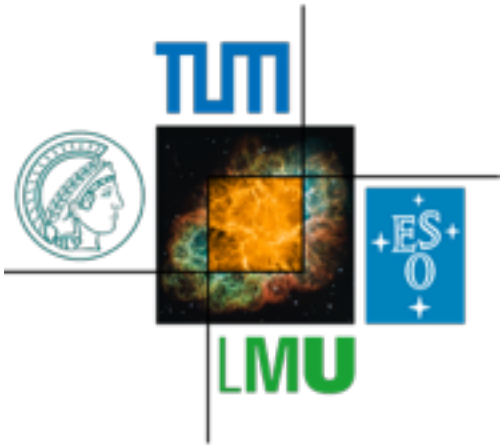
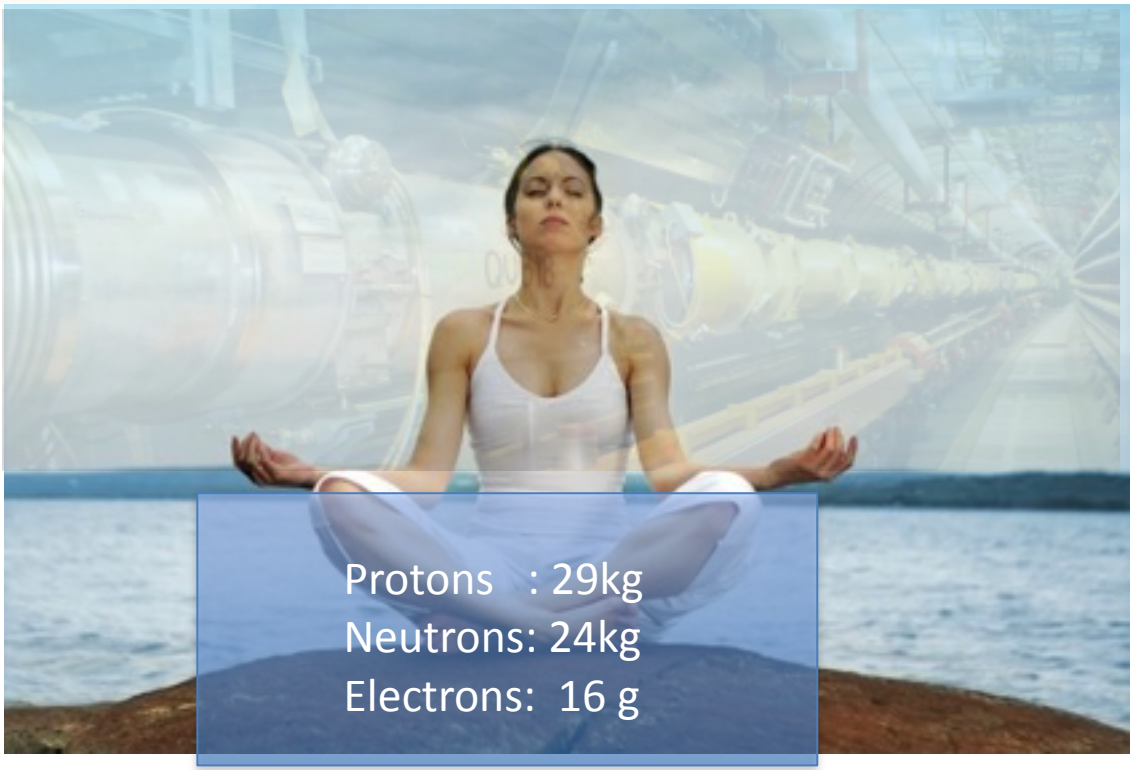
The neutron and the Universe
History of a Relationship



Stephan Paul
TU-München
and
Exzellenzcluster Universe
‚Origin and Structure of the Universe‘

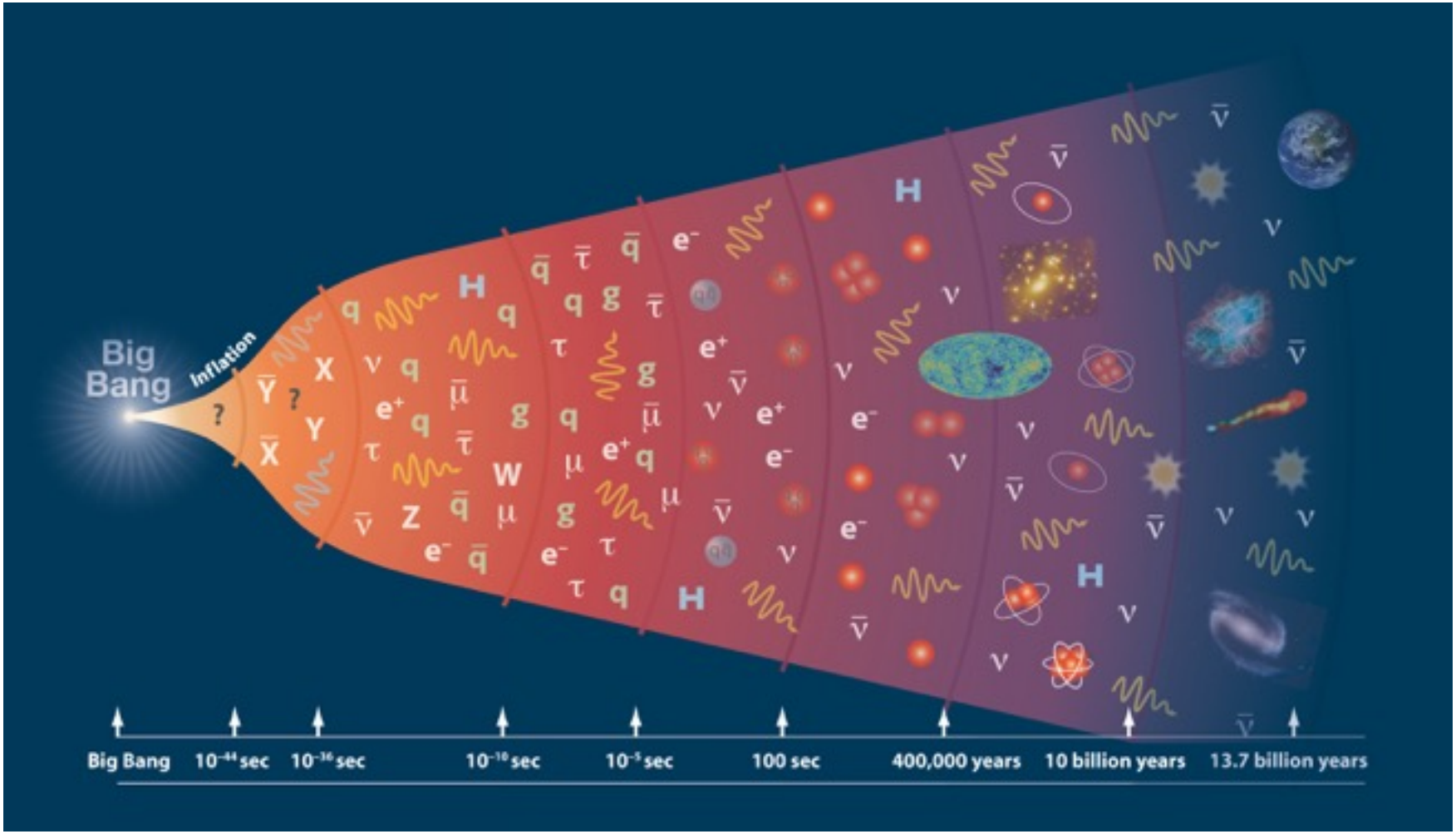
The Neutron

weight: 53 kg

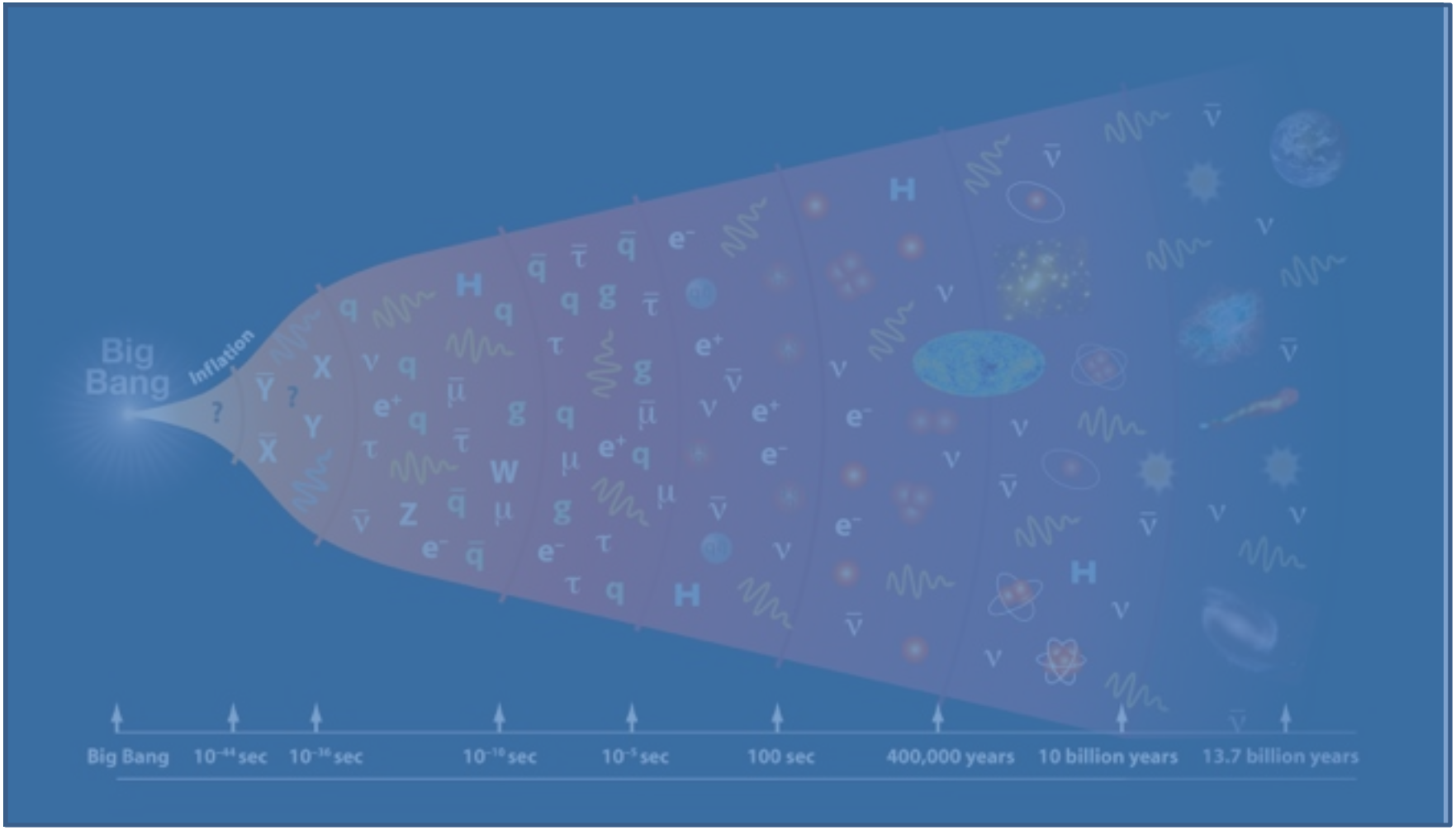


proton **neutron** **electron**

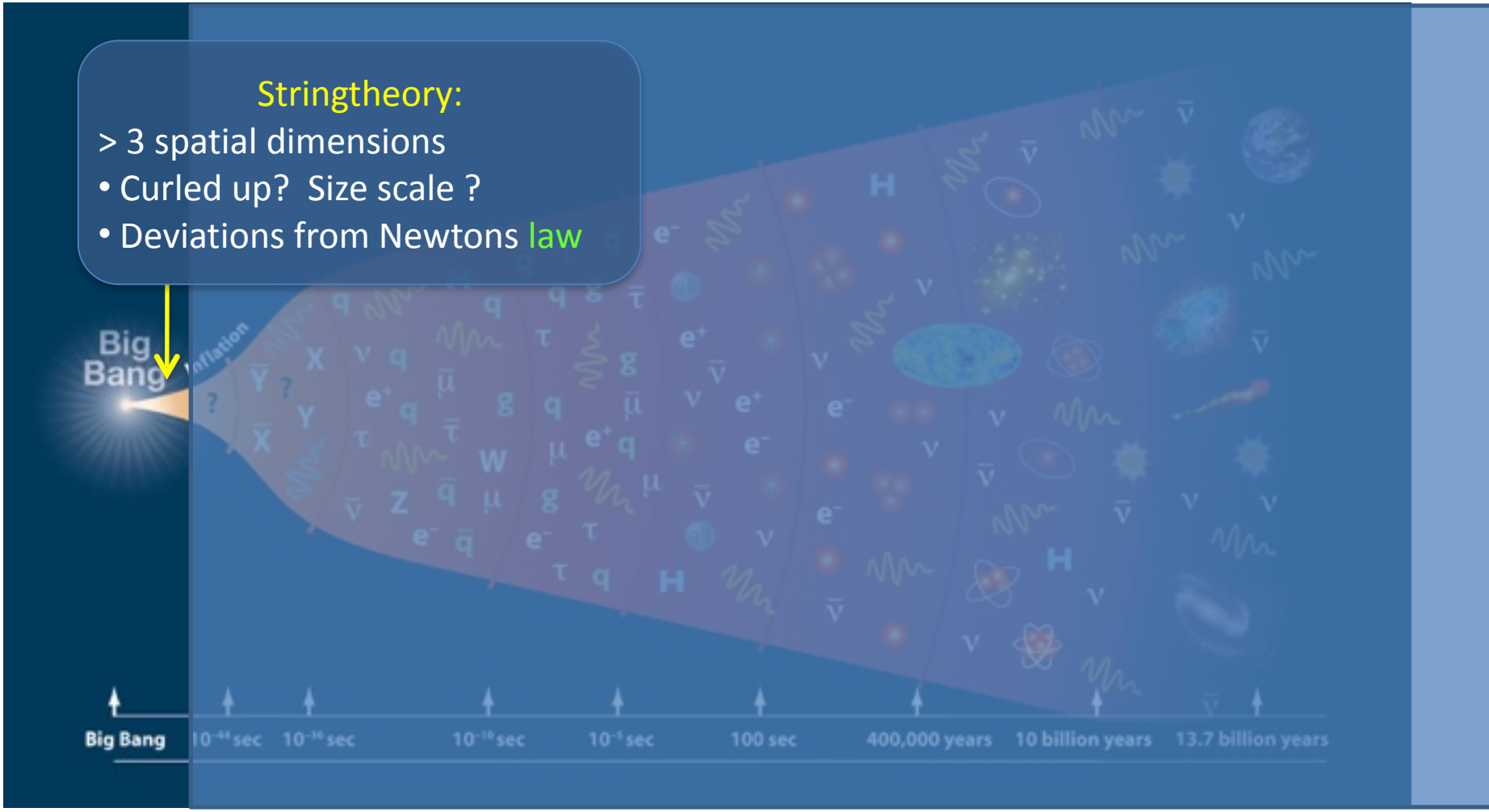
The Universe



The Neutron and the History of the Universe



The Neutron and the History of the Universe



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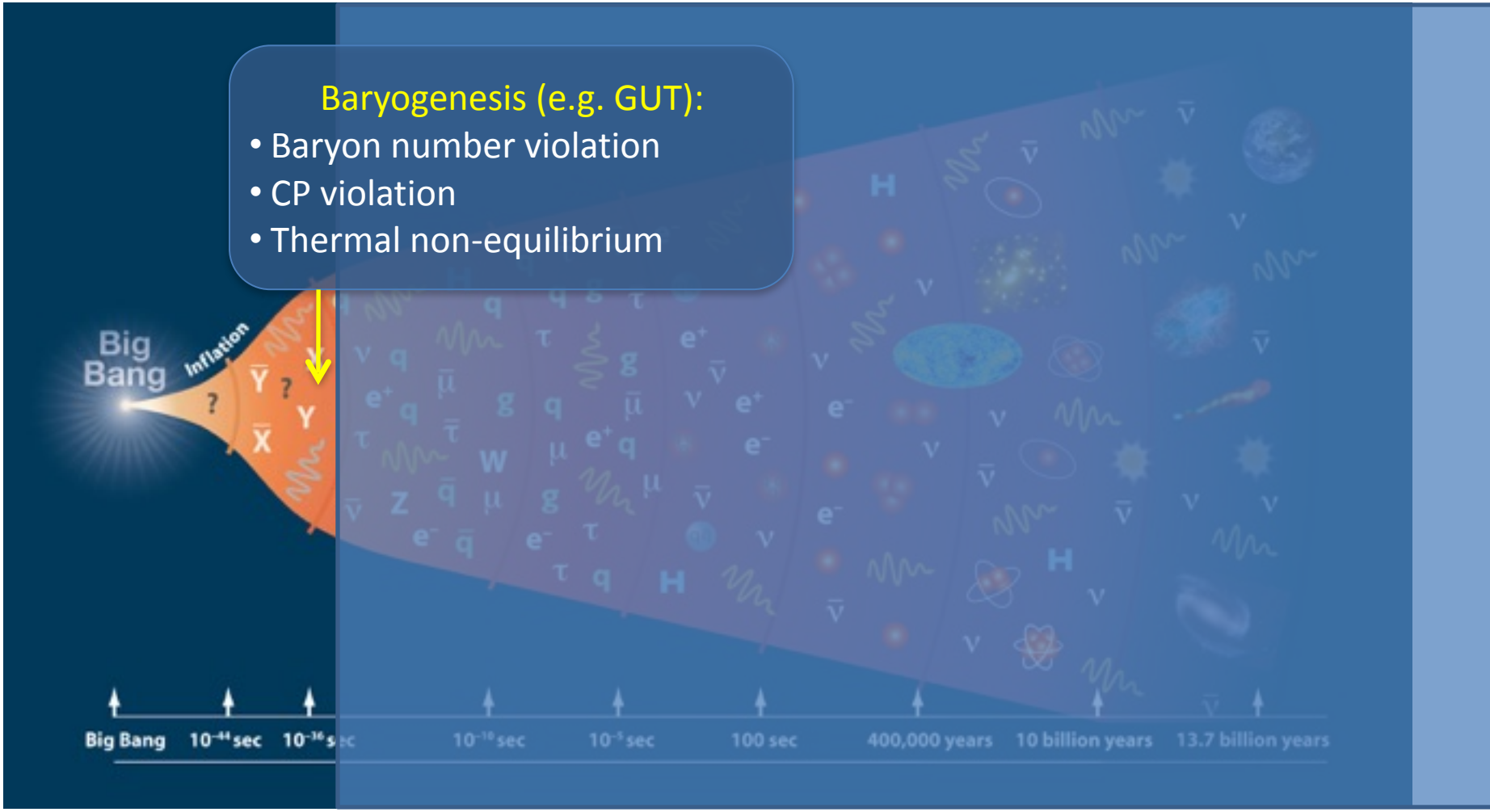

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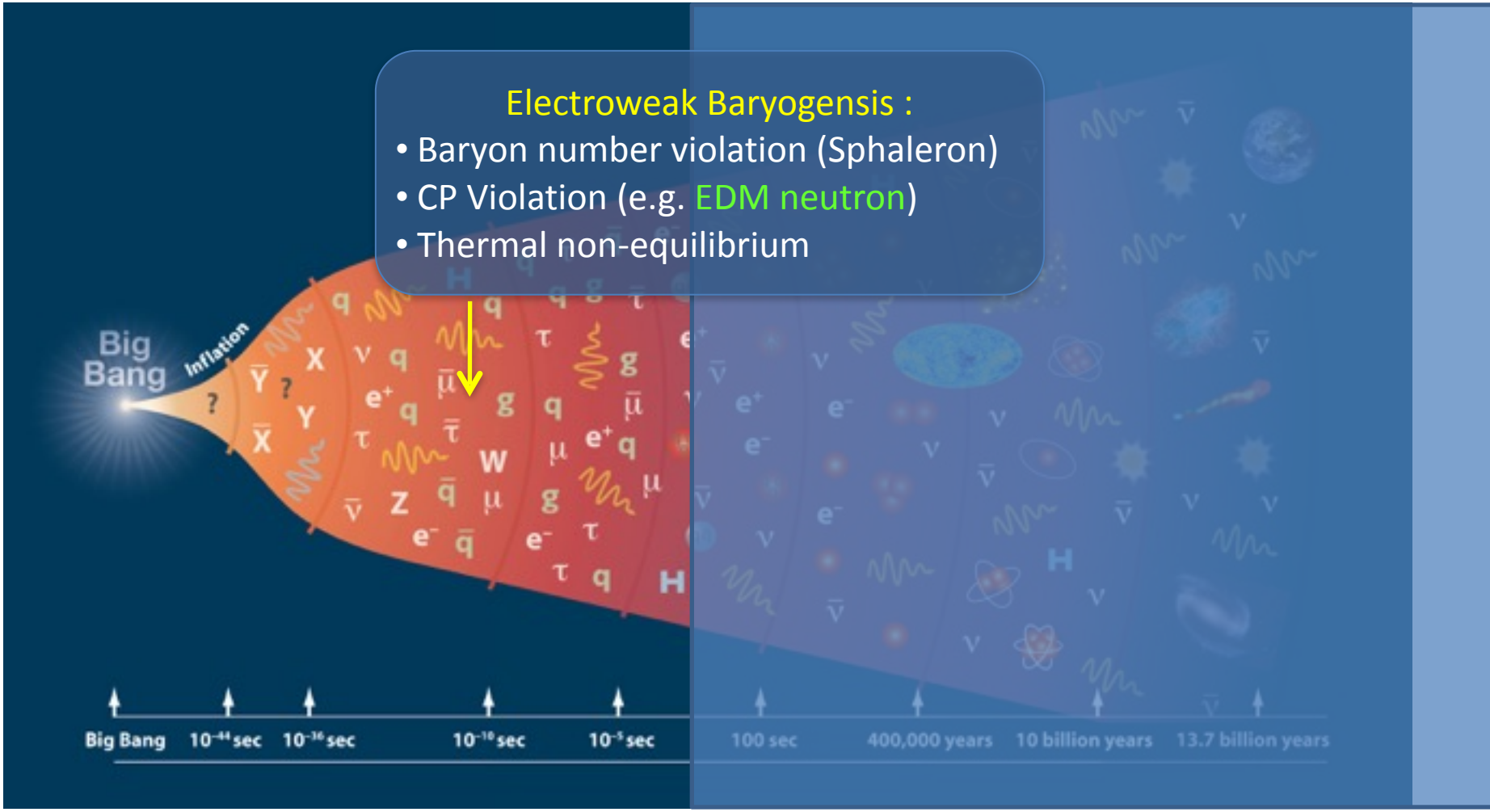

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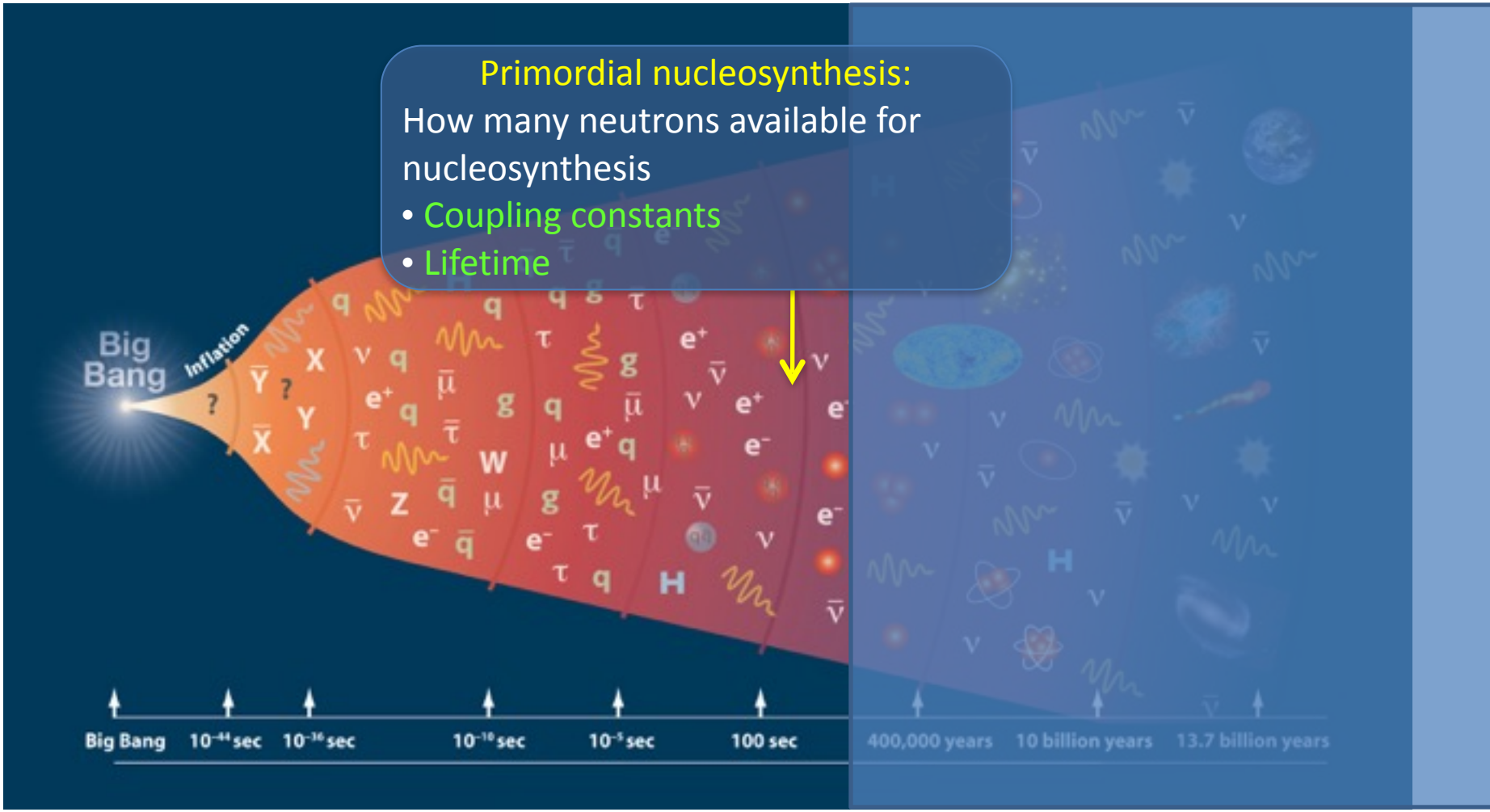

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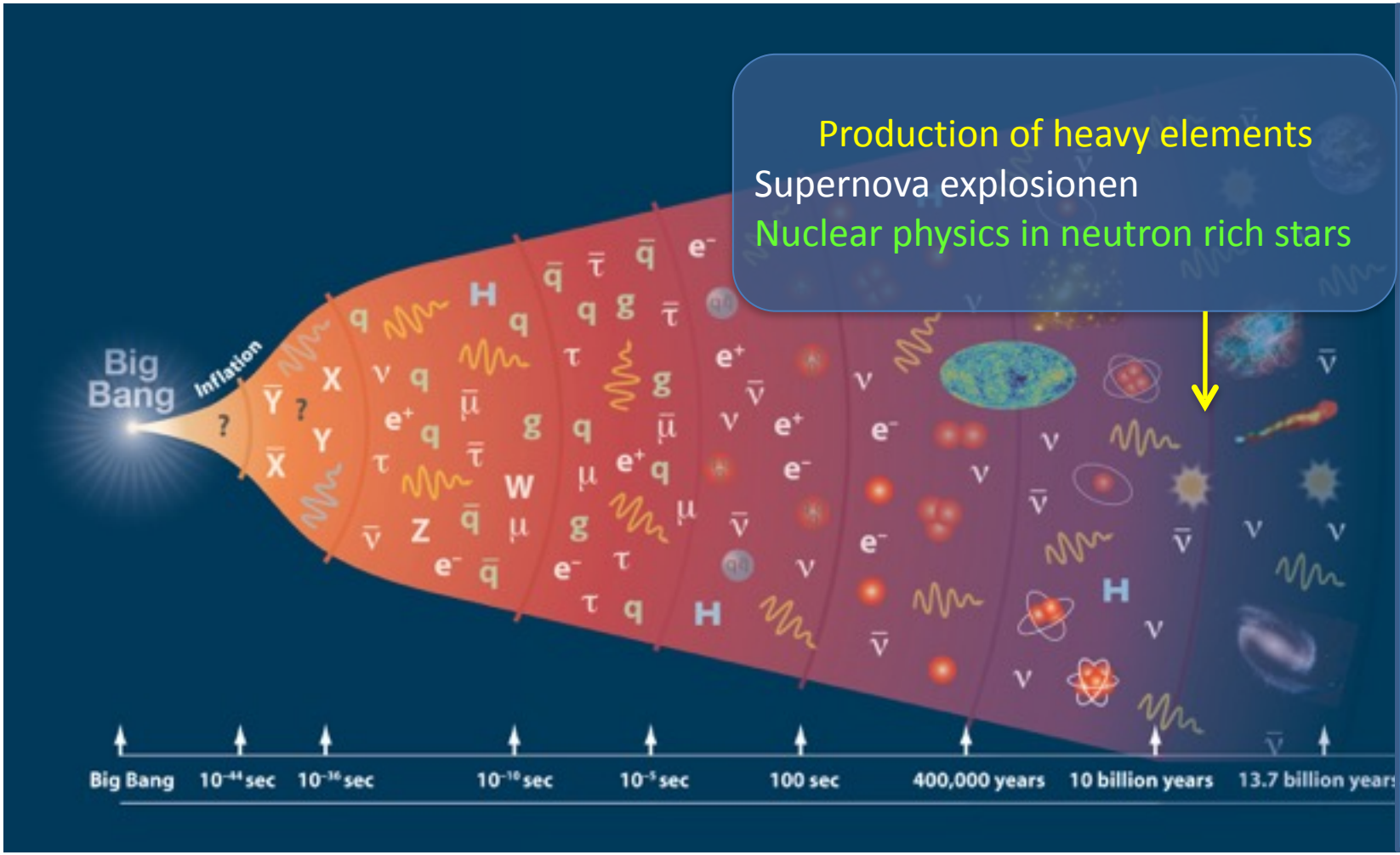

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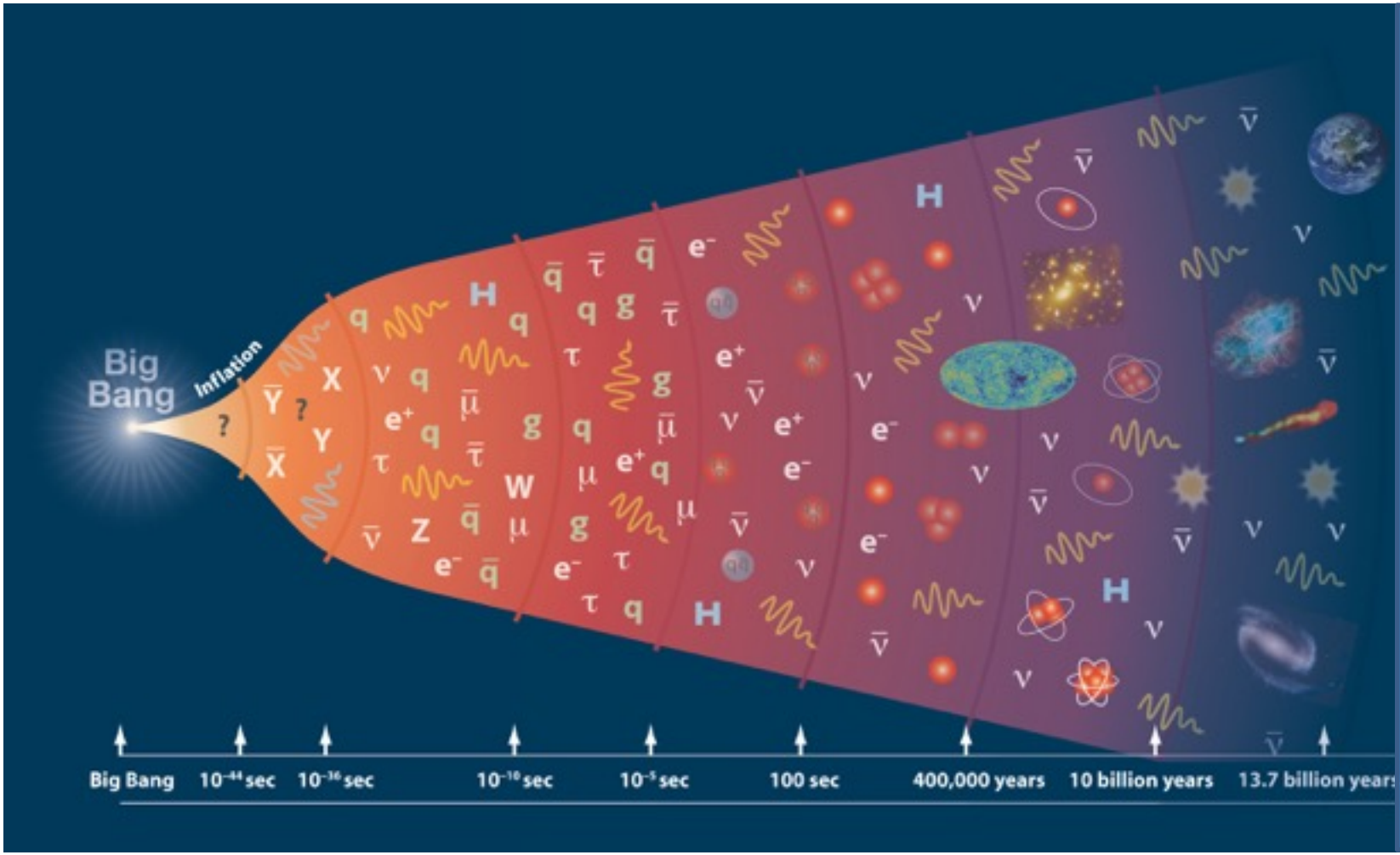
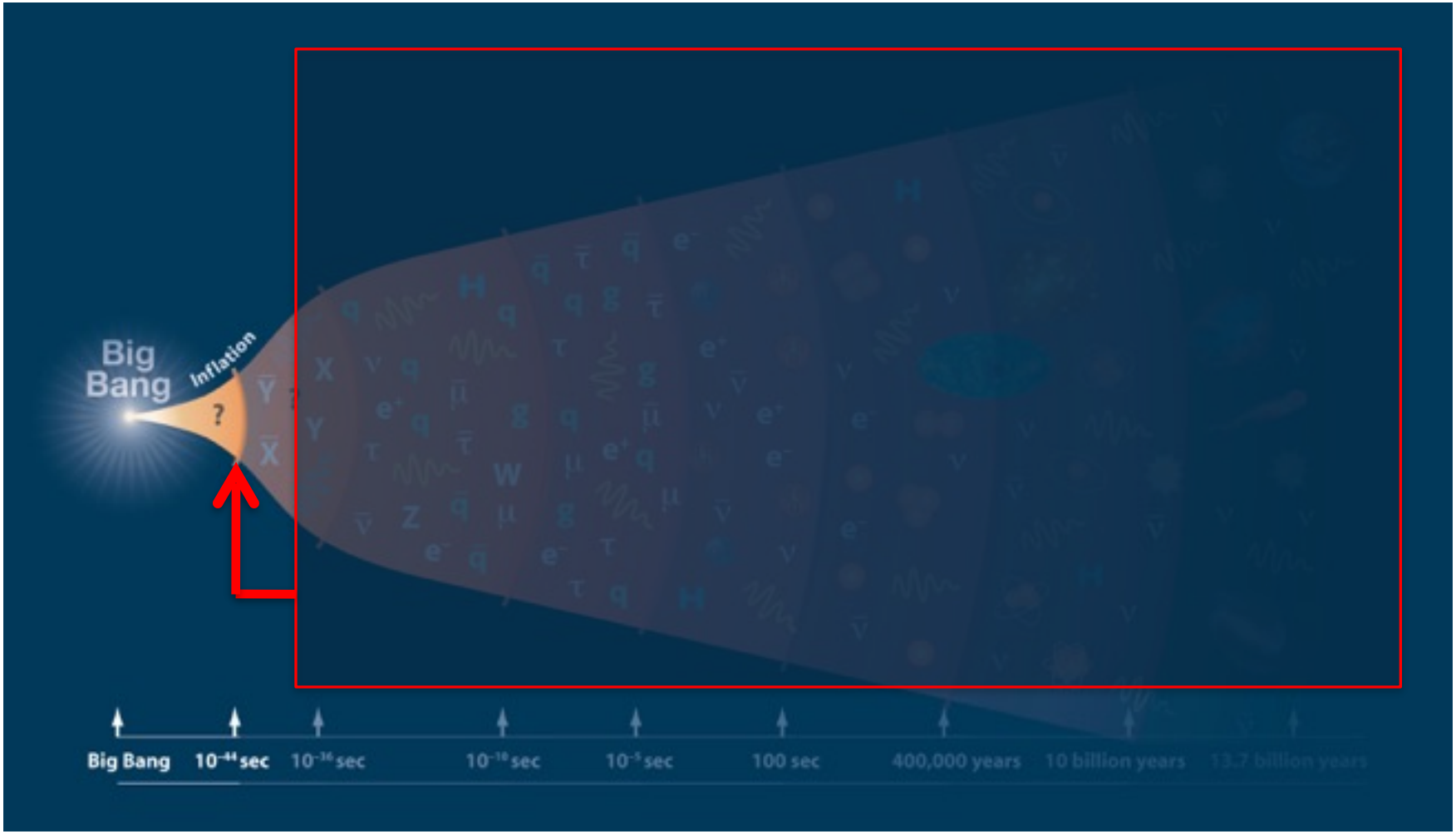


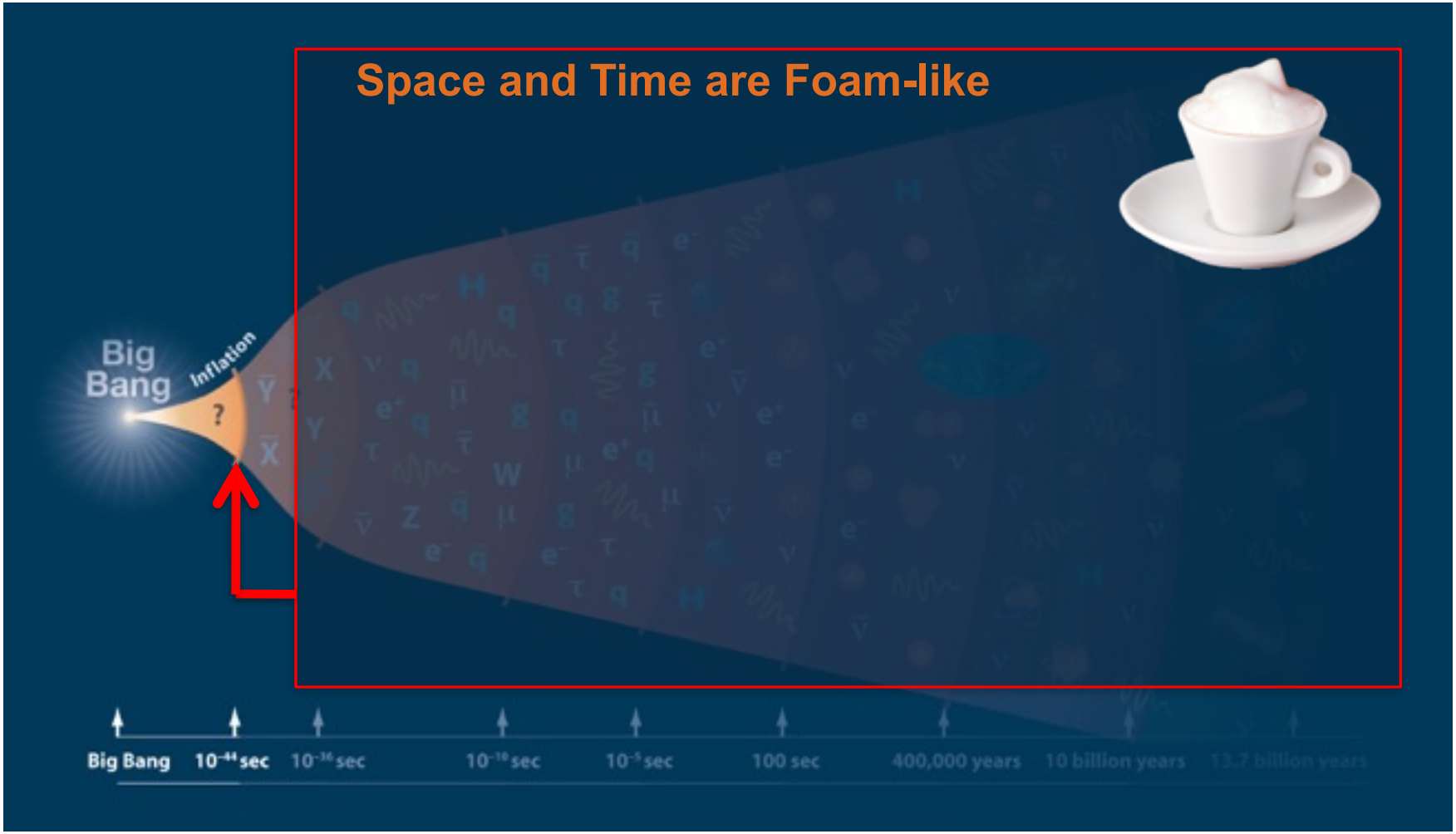
Neutrons and Particle Physics

- Symmetries
  - Violation of CP-symmetry (EDM)
  - Hints for new symmetries (SUSY) (EDM, n-decay)
  - θ-term in QCD (EDM)
  - L/R symmetries of SM (P-violation) (n-decay)
- Quark-mixing
  - Unitarity and the size of V_{ud} (n-decay)
- Nucleon-coupling
  - G_V, G_A (n-decay)
- Properties of neutrinos
  - Right handed contributions (neutron 2-body decay)
- Structure of gauge theories
  - Charge quantization (n-charge)
- Neutrons and gravitation

10^{-43} Sec. past Big-Bang: How it all began



10^{-43} Sec. past Big-Bang: How it all began



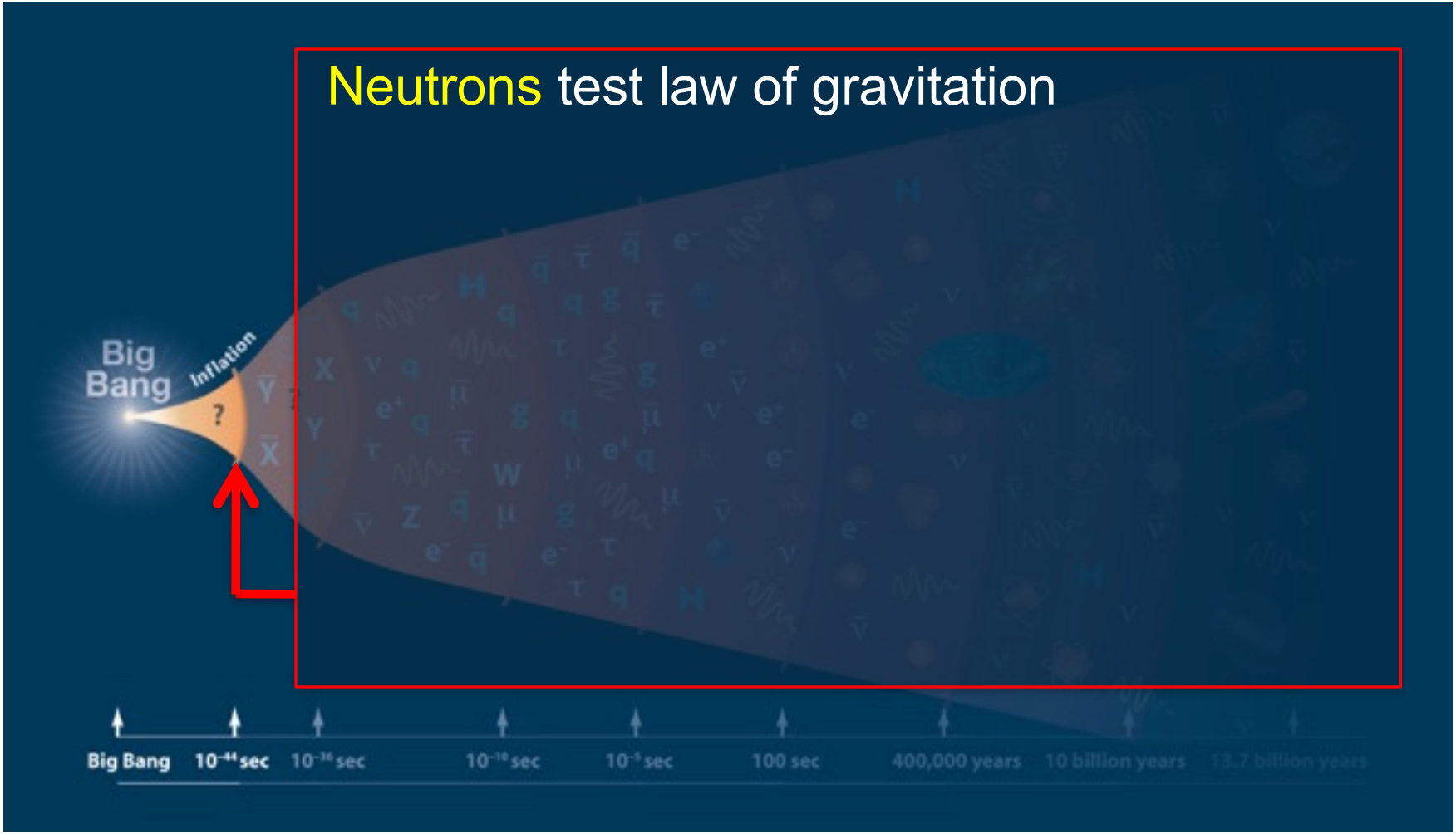
10^{-43} Sec. past Big-Bang: How it all began

Space and Time are Foam-like

Superstrings: a '**Weltformel**' ?

- Forces unified
- The world is 10+1-dimensional
- Only 4 dimensions participate in inflationary expansion
- All other Dimensions are curled up

10^{-43} Sek. nach Big Bang: Neutronen testen den Raum



10^{-43} Sek. nach Big Bang: Neutronen testen den Raum

Neutrons test law of gravitation

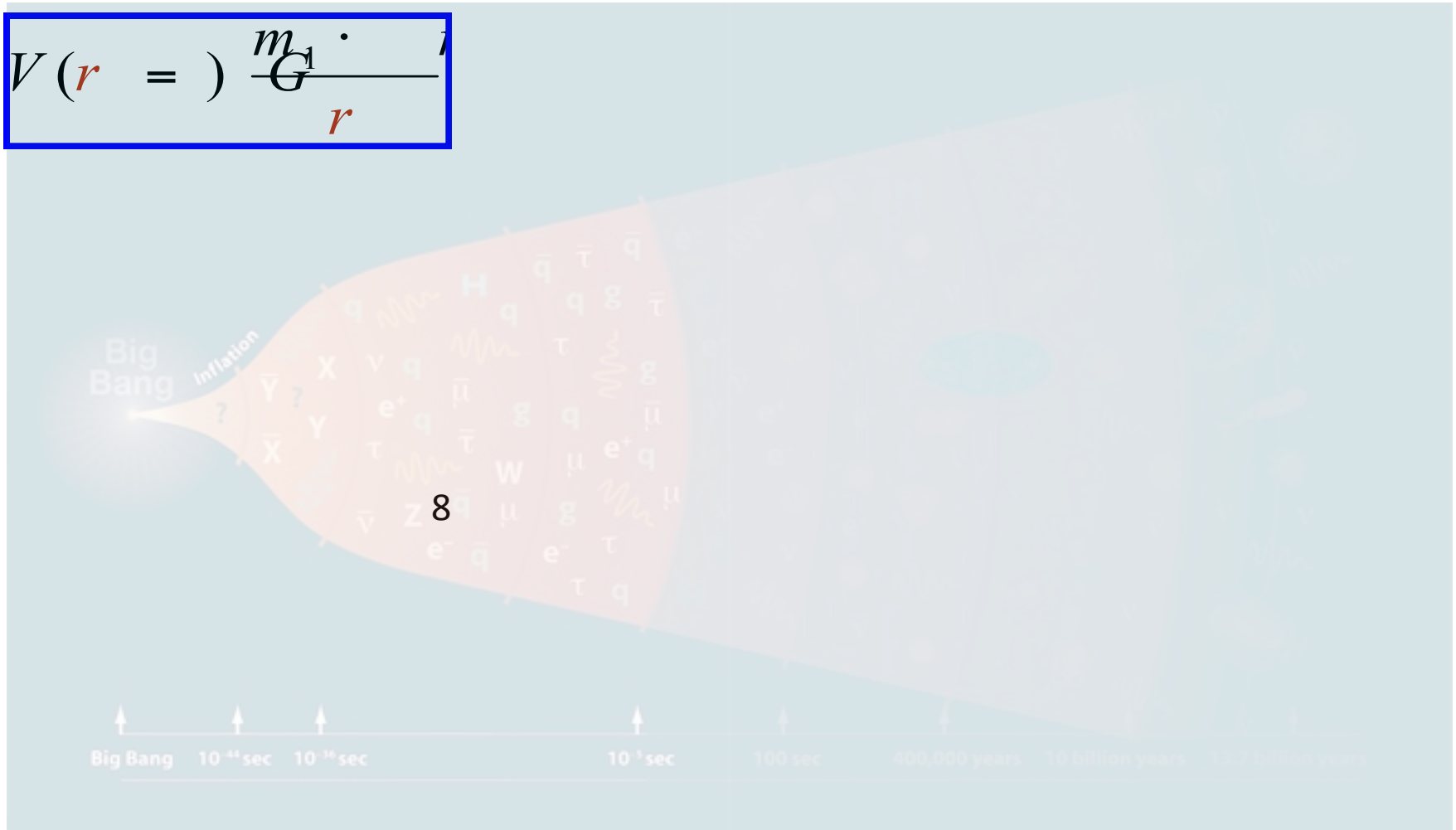
Is Newtons law correct ?

- Deviations at small distances could hint to higher dimensions
- Neutrons sensitive to distances < 50 μm
- Quantum states in earth gravitational field

Gravitation – Quantisation in Earth Gravitational field

Gravitation – Quantisation in Earth Gravitational field

$$V(r) = -G\frac{m_1 \cdot m_2}{r}$$

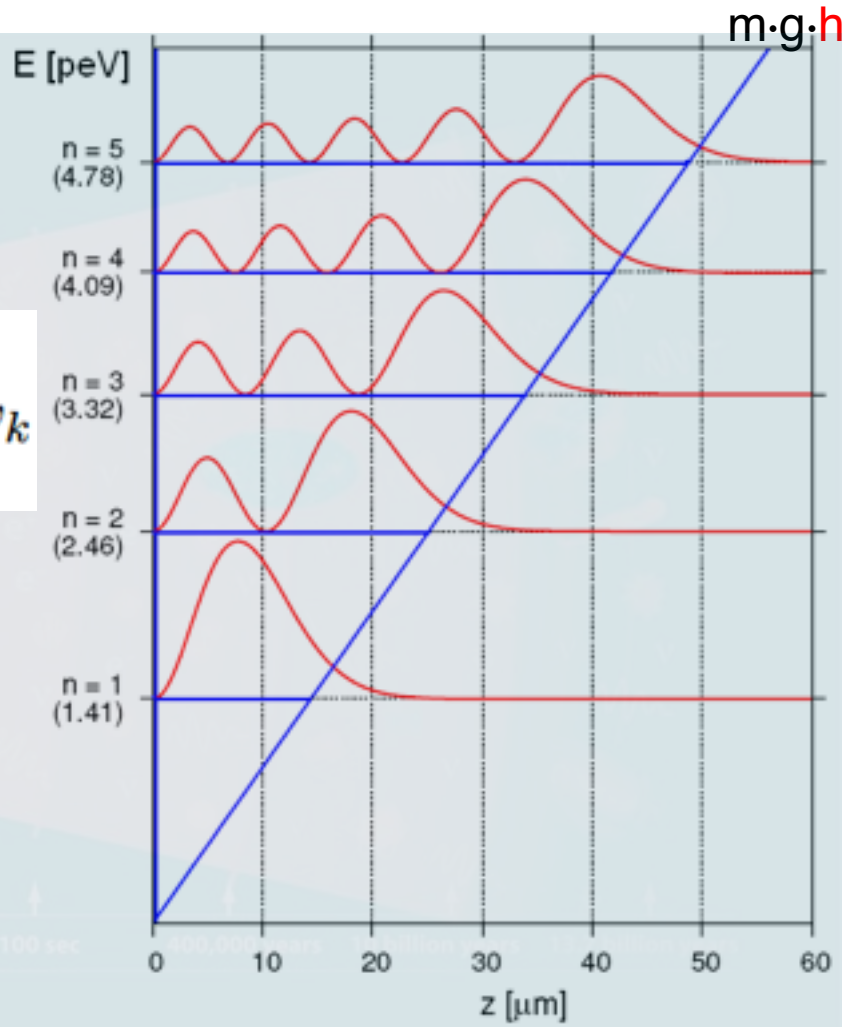


Gravitation – Quantisation in Earth Gravitational field

$$V(r) = -G\frac{m_1 \cdot m_2}{r}$$

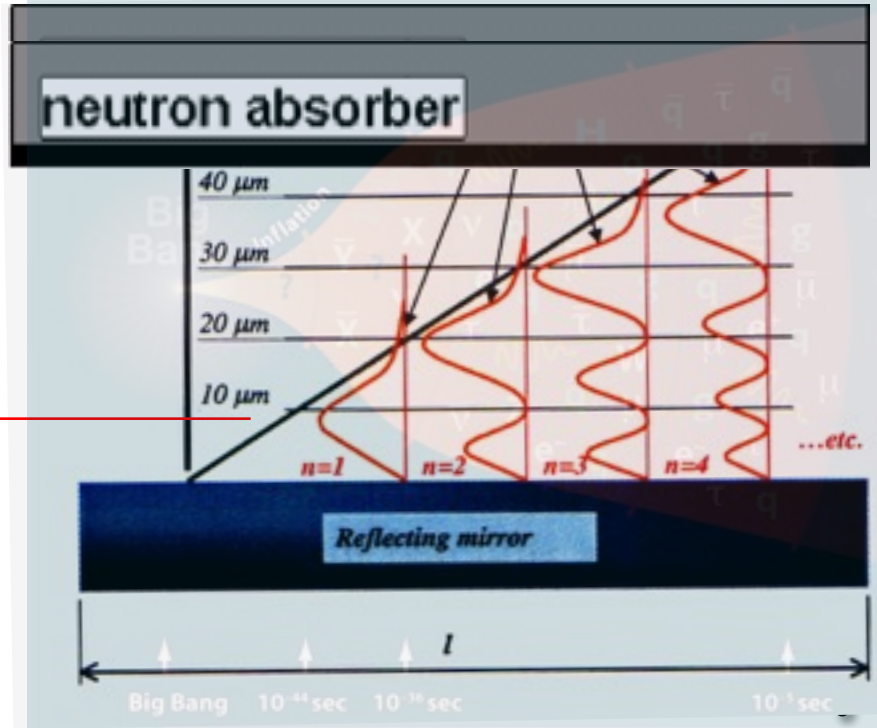
$$\left(-\frac{\hbar^2}{2m_i}\frac{\partial^2}{\partial z^2} + m_g g z\right)\psi_k = i\hbar\frac{\partial}{\partial t}\psi_k$$

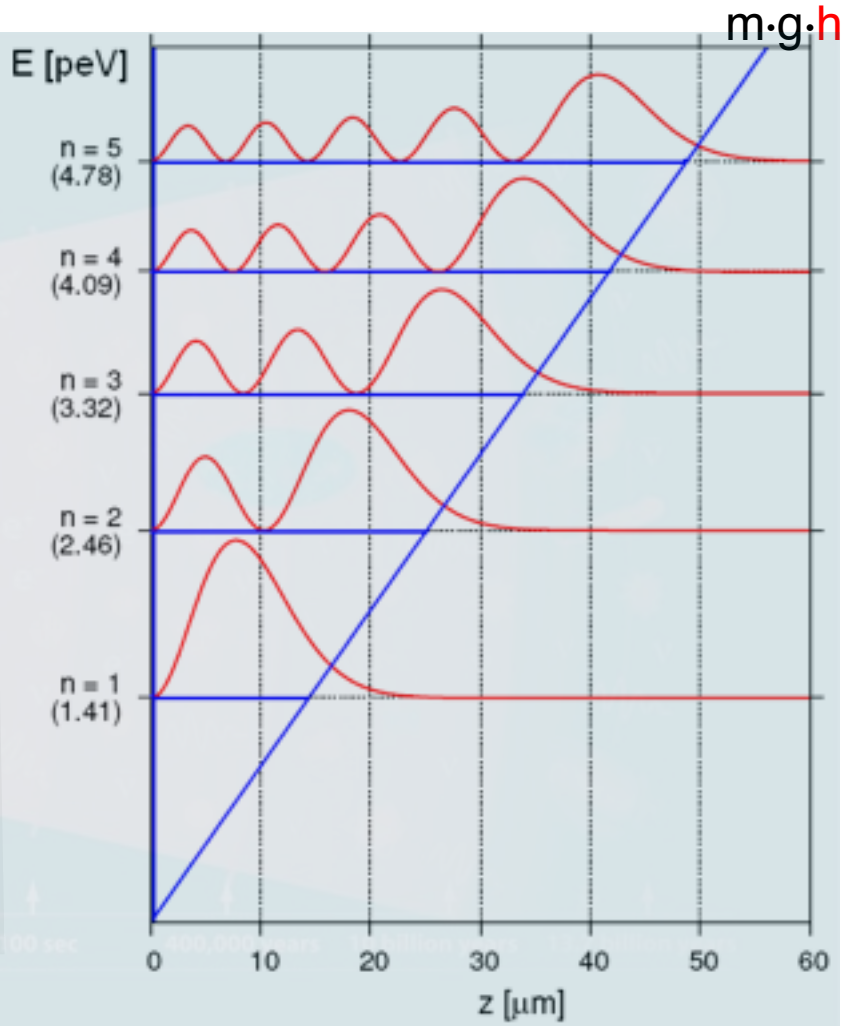
8



Gravitation – Quantisation in Earth Gravitational field

$$V(r) = -\frac{m_1 \cdot m_2 \cdot G}{r}$$



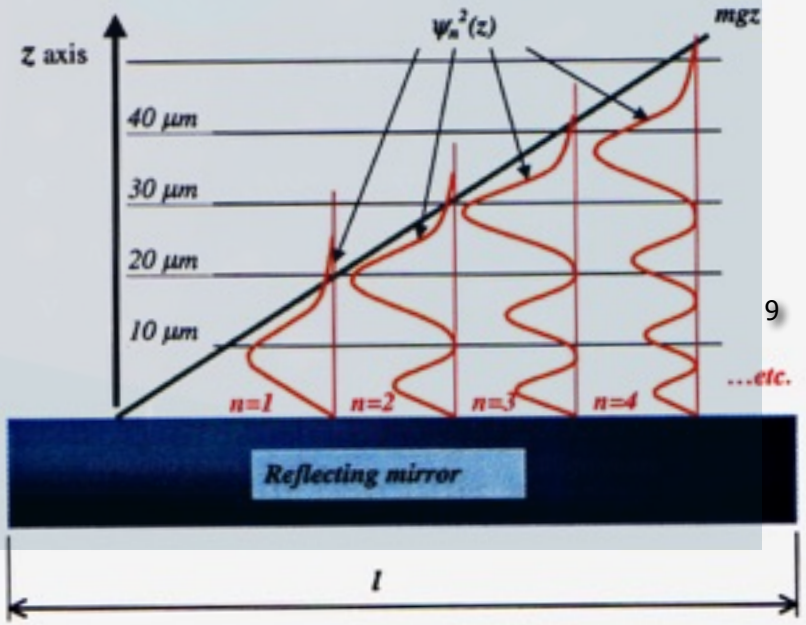


Gravitation – Bound states in Earth‘s field

Sensitivity: peV

Distance scales : <10μm

Nature 415 299 (2002)



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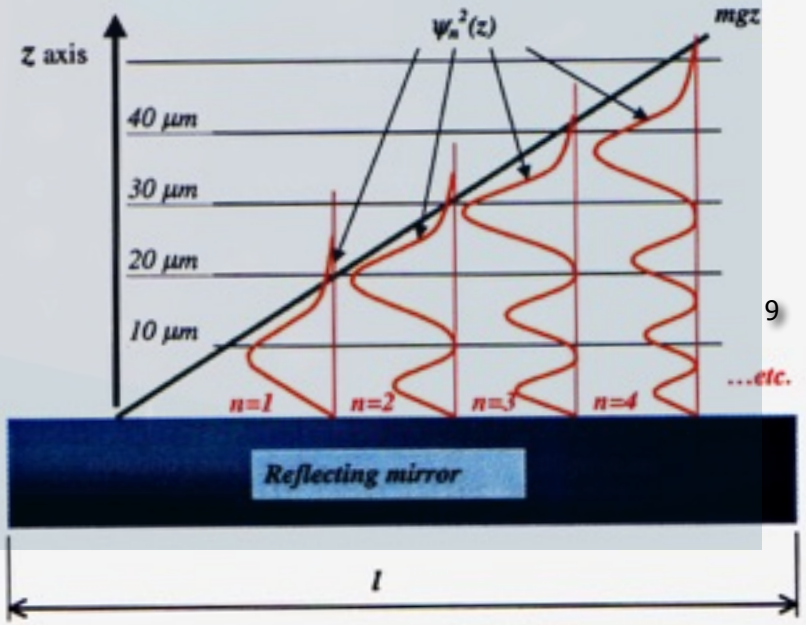

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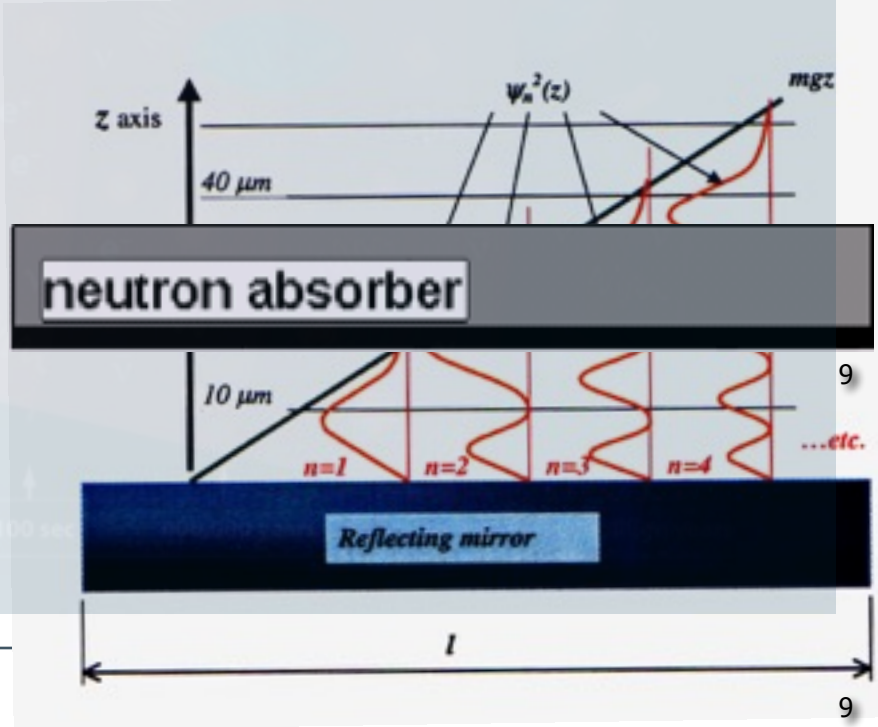

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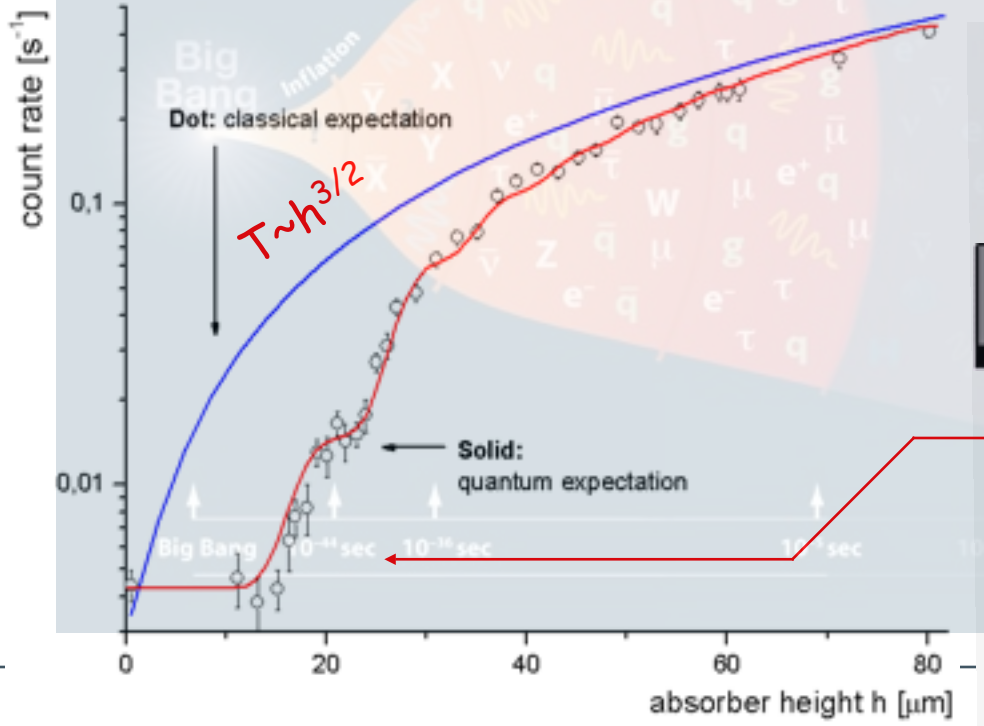

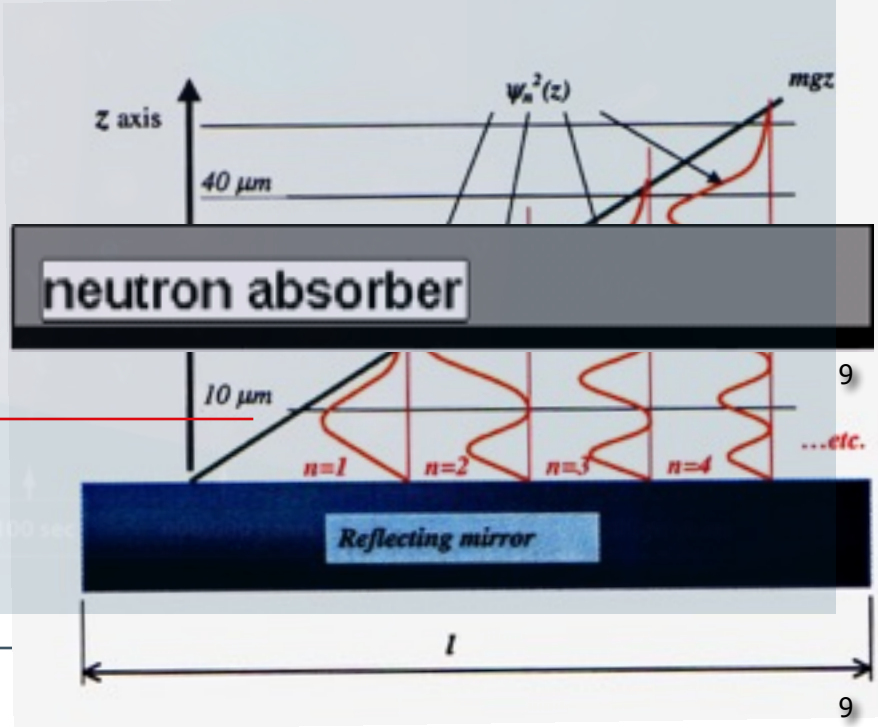

9

Gravitation – Bound states in Earth's field

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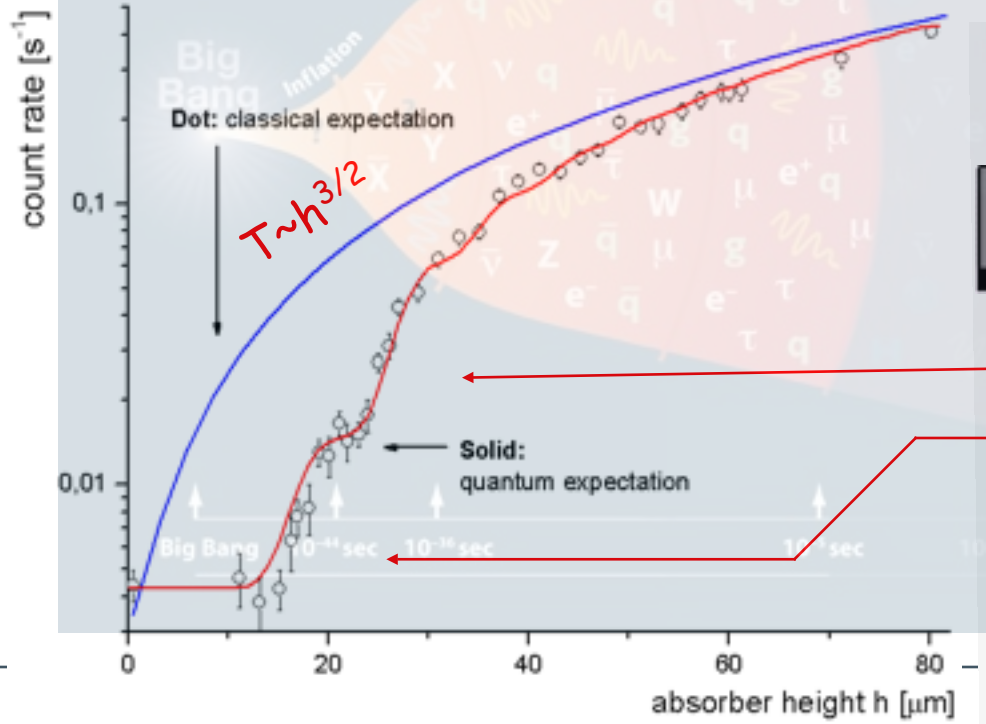
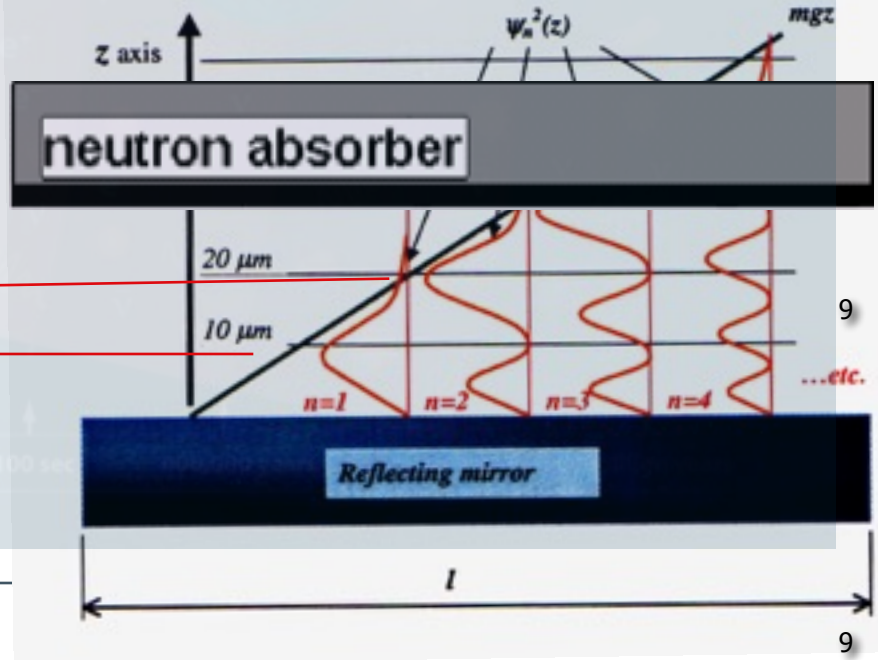
Distance scales : <10μm

Nature 415 299 (2002)





9

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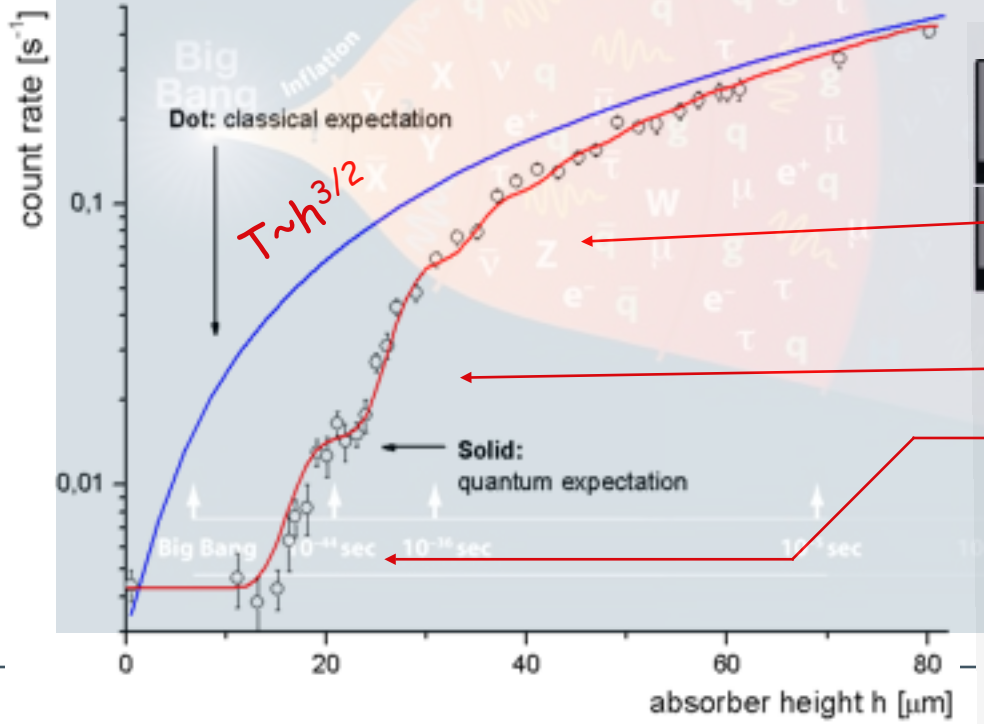
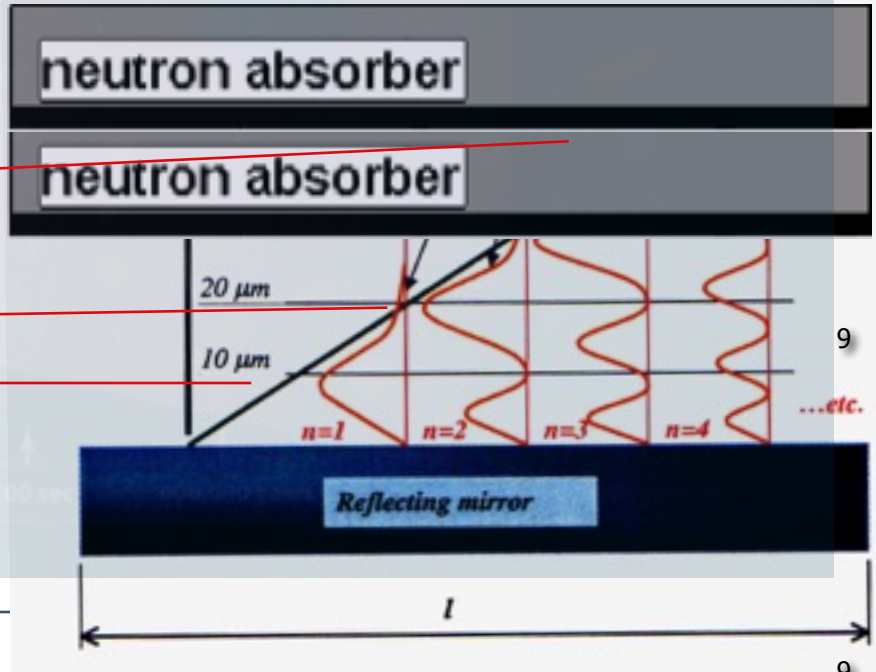




9

Gravitation – Quantization in Earth Field II

$$V(r) = -\frac{m_1 \cdot G \cdot m_2}{r}\left(1 + \alpha \cdot e^{-r/\lambda}\right)$$

Yukawa coupling:

- strength α
- range λ

Until now:

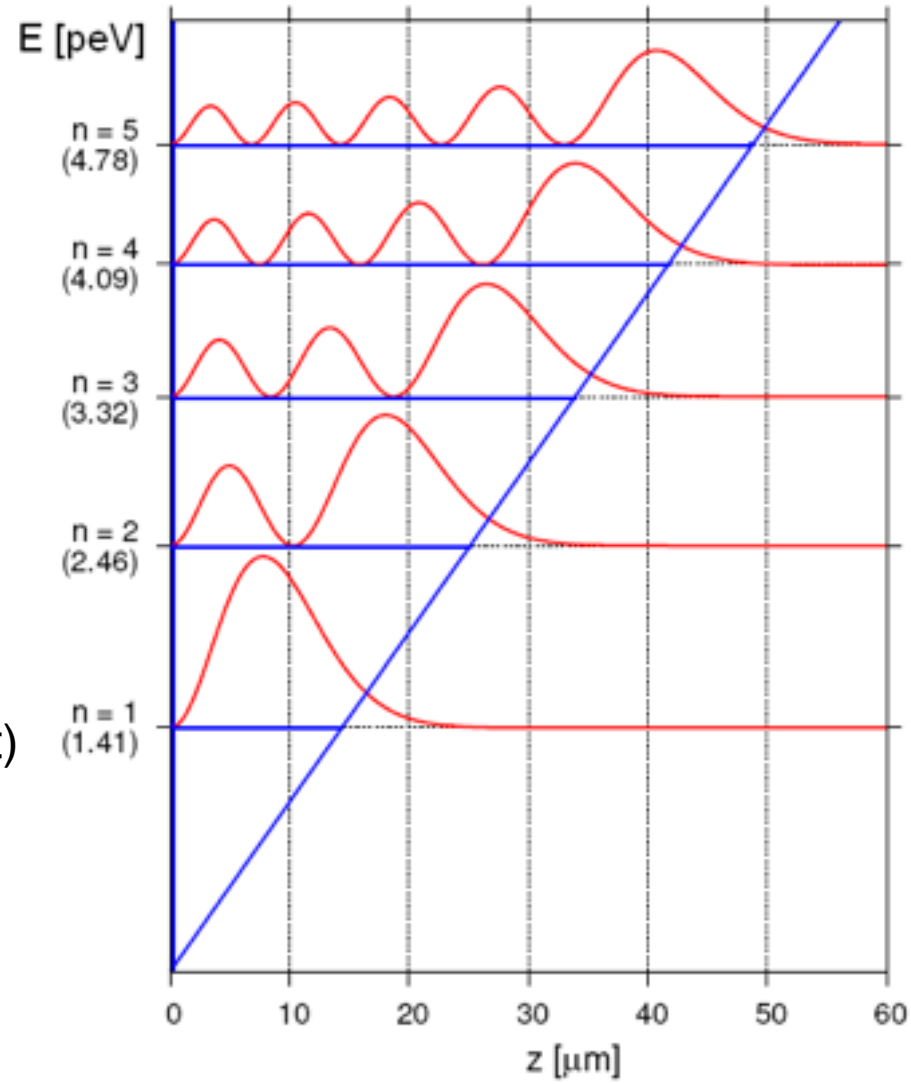
Atomic force microscope:

- Newton r > 10μm

Problem: Casimir effect („falsch“-effect)

Neutrons:

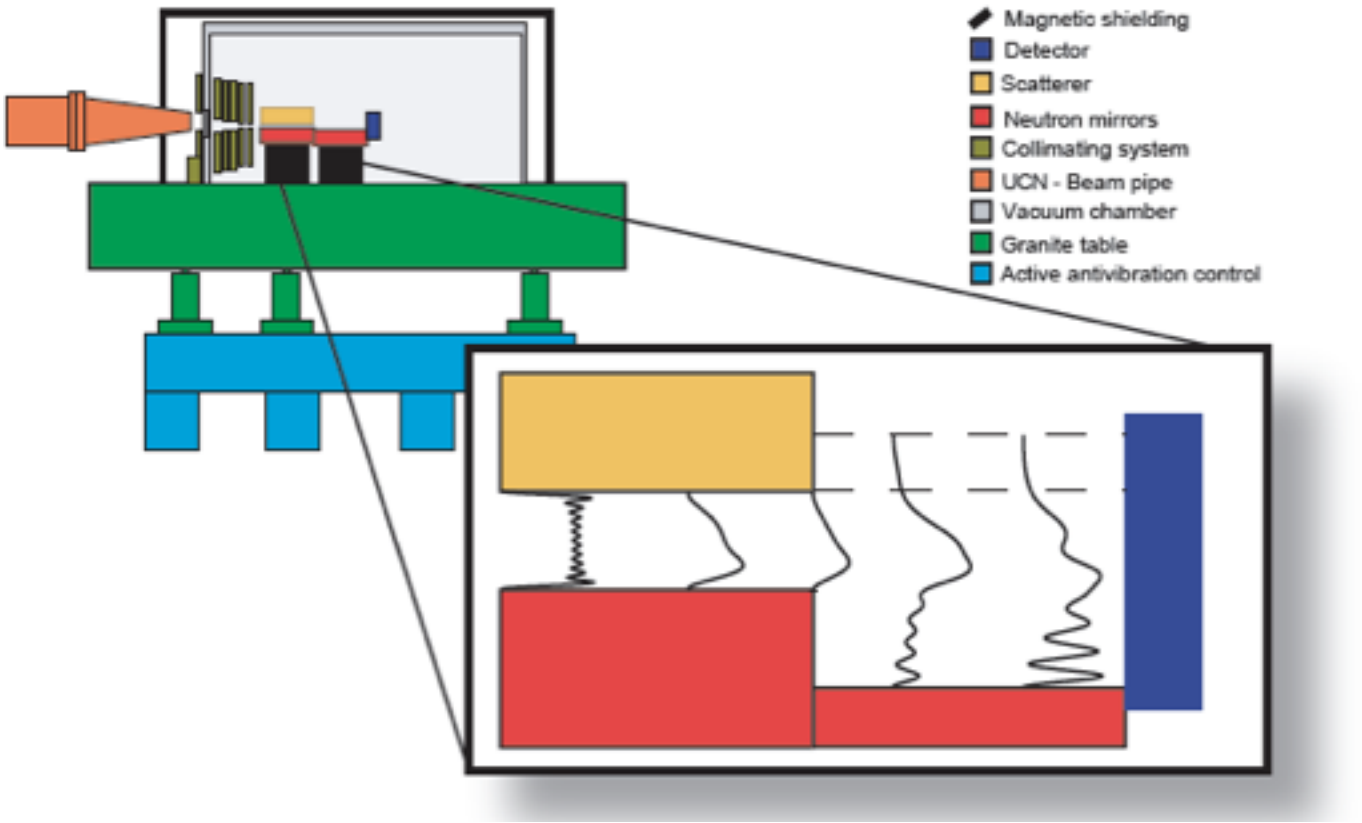
- limits for Newton: r < 10μm
- range: 1 nm < λ < 100 μm
- strength: $\alpha \sim 10^8$



Gravitation: Q-Bounce

Abele et al.: arXiv:1510.03078v1

H. Abele et al.



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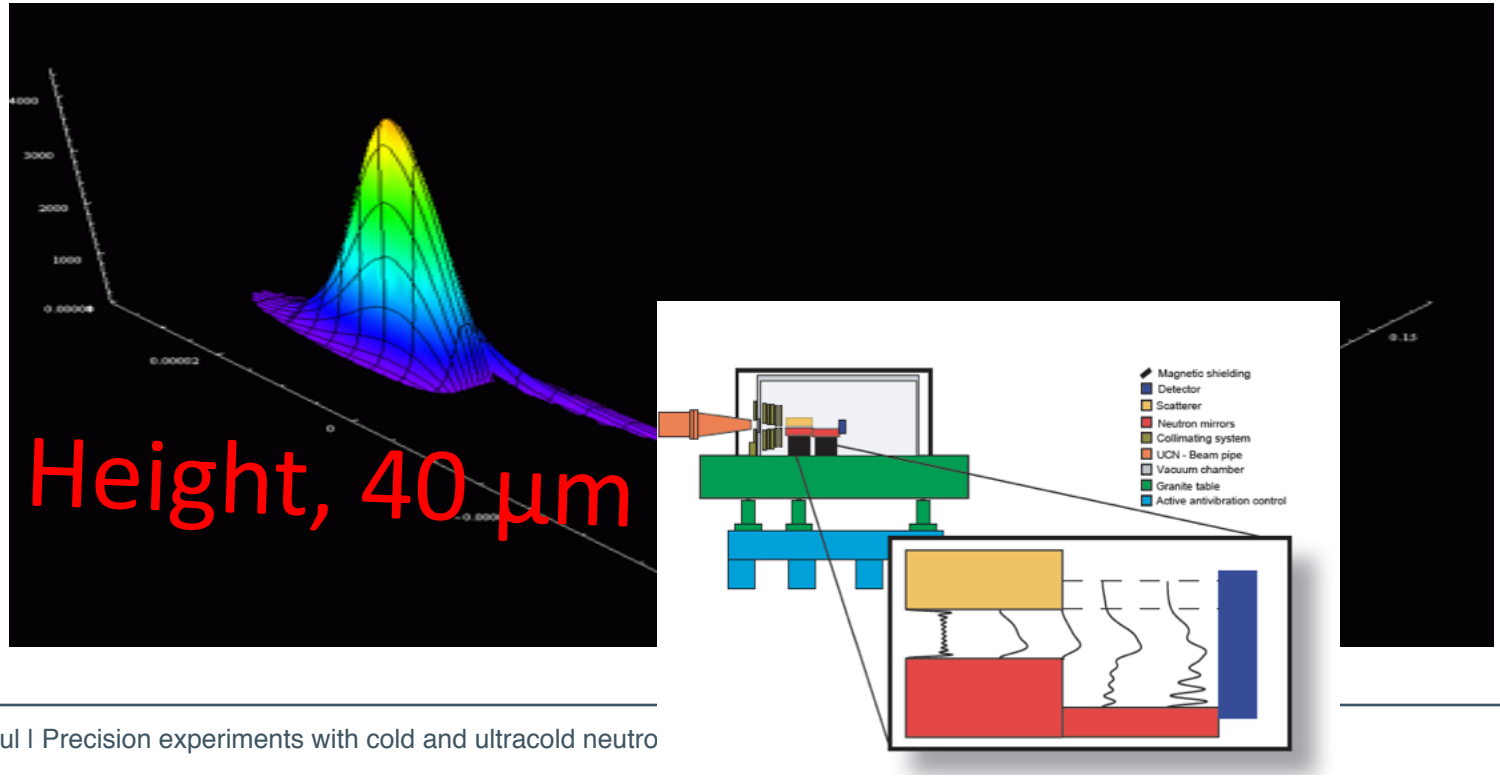

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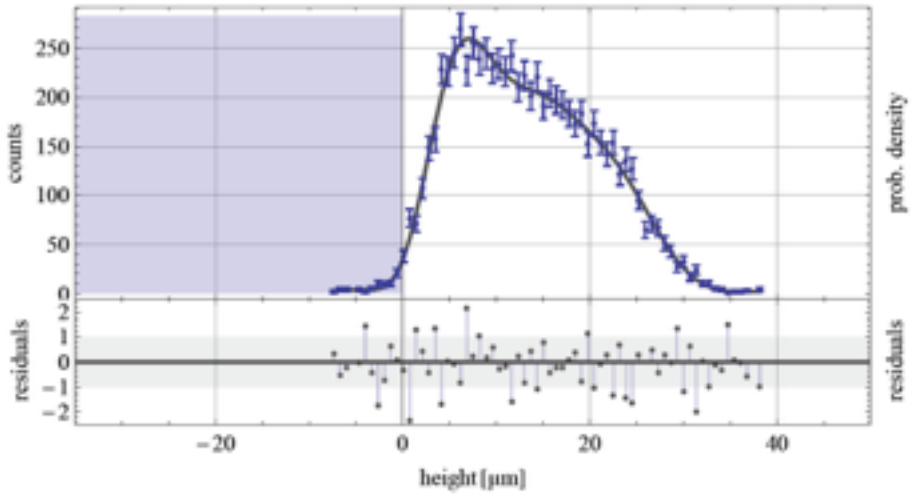
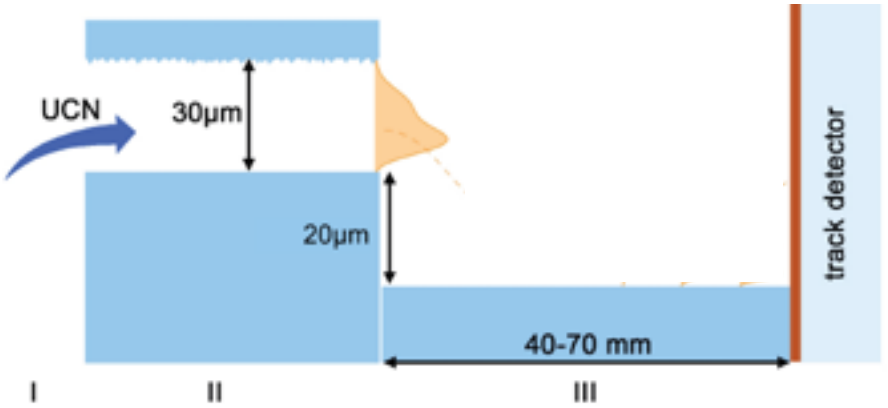
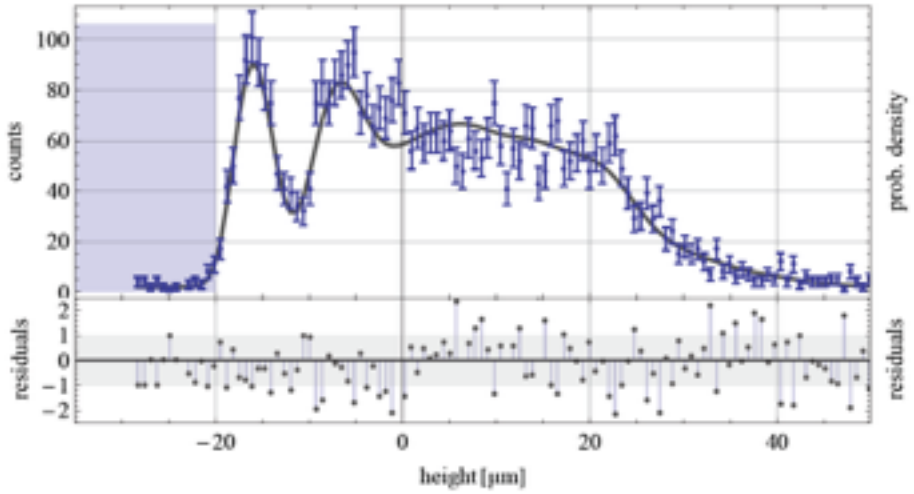
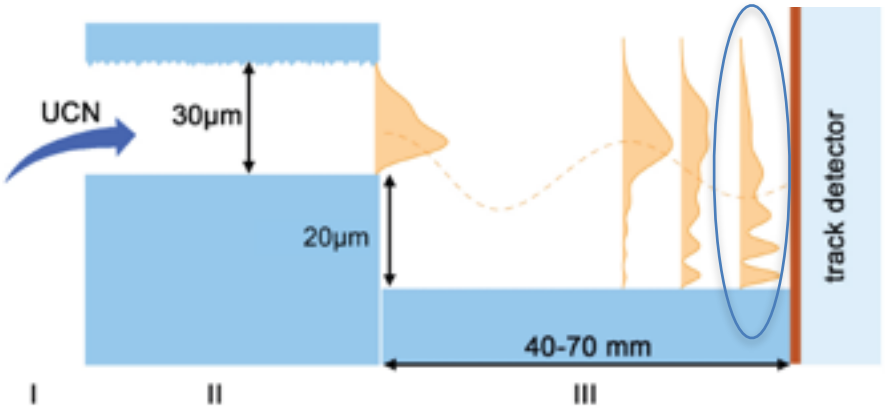






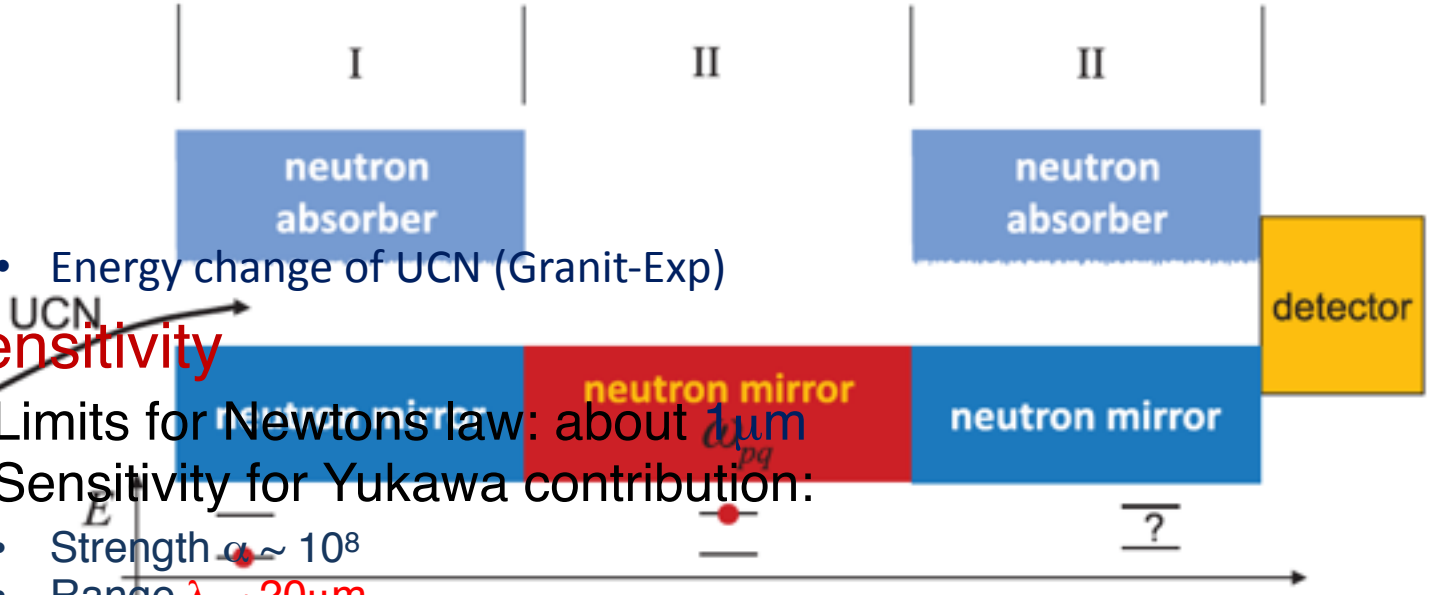


Gravitation: New Generation Measurements

- Level scale
  - Determine level distance via induction of transitions
    - Mechanical excitation
    - Magnetic excitations(Granit)-Exp
  - Energy resolution
    - Rabi method
      - use 2-level system with transition frequency– „ω_{Lamor}“
      - Induce mechanical transitions (replace RF field)
      - Phase comparison with external mechanical oscillator (kHz)
    - Energy change of UCN (Granit-Exp)
- Sensitivity
  - Limits for Newtons law: about 1μm
  - Sensitivity for Yukawa contribution:
    - Strength $\alpha \sim 10^8$
    - Range $\lambda \sim 20\mu m$

Gravitation: New Generation Measurements

H. Abele et al.



- Energy change of UCN (Granit-Exp)

- **Sensitivity**
  - Limits for Newtons law: about 1μm
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Gravitation: New Generation Measurements

H. Abele et al.

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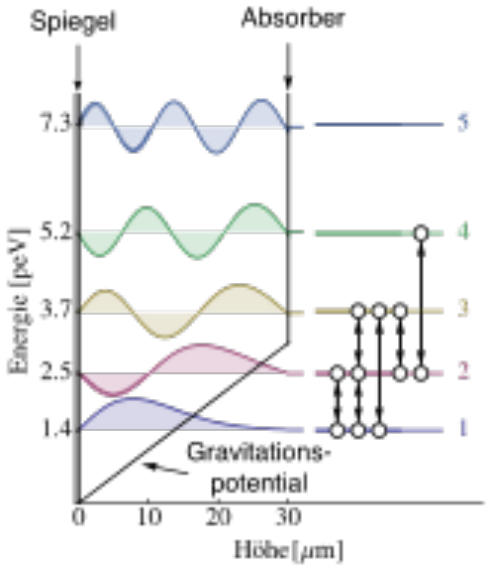
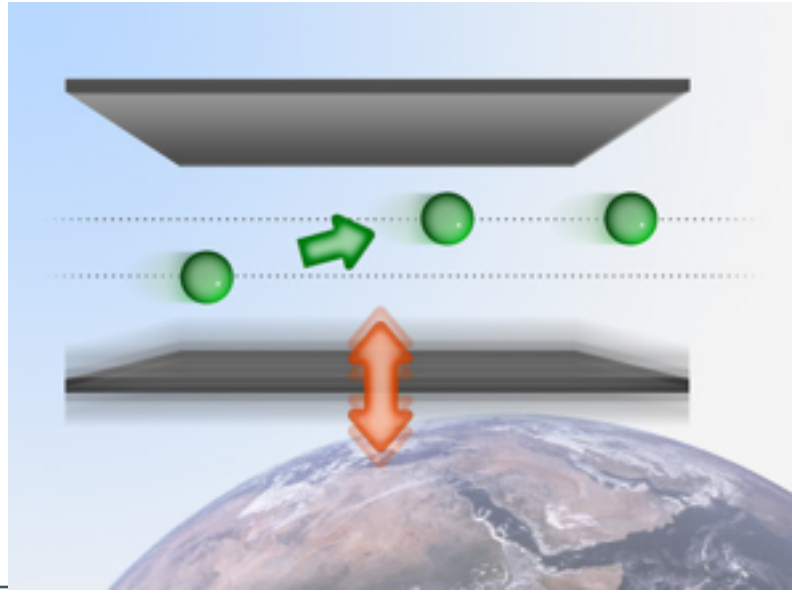
Gravitational Resonance Spectroscopy

Simplified experiment

- Just one mirror
- Shape of potential
- State selection – resonance transition

	2	3	4	5	6
1	292,7	542,1	918,5	1405,3	2003,4
2		279,4	655,4	1142,6	1740,7
3			376,0	863,2	1461,3
4				487,3	1085,3
5					598,1





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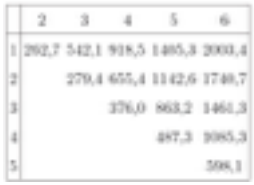

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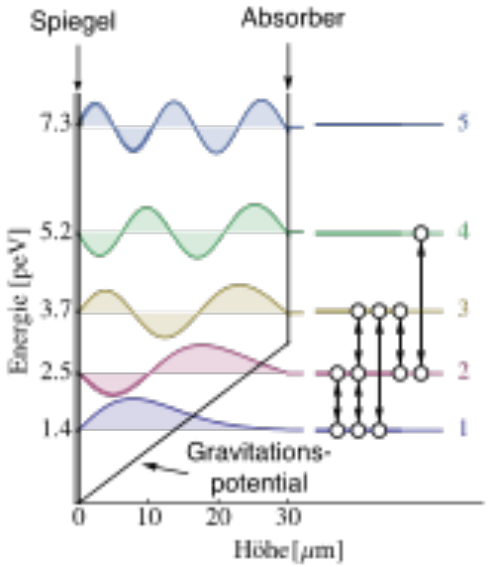

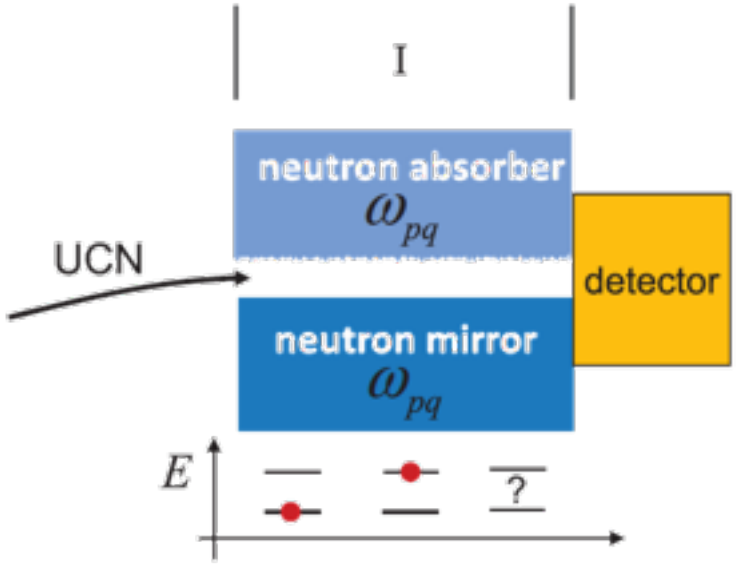

Gravitational Resonance Spectroscopy

Simplified experiment

- Just one mirror
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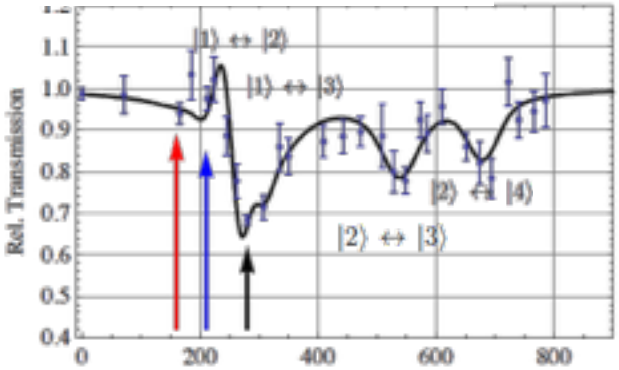
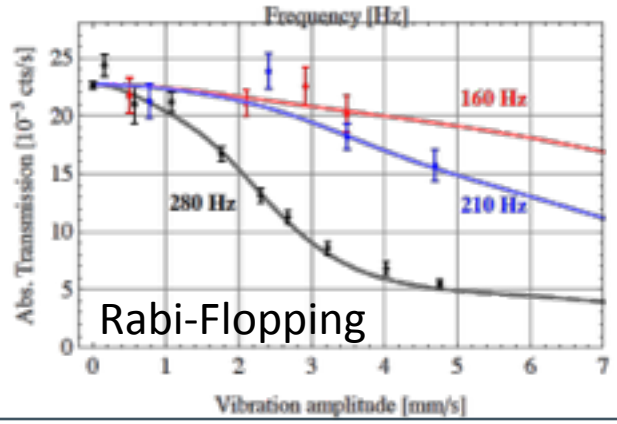
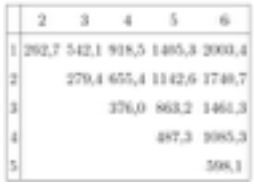
- State selection – resonance transition

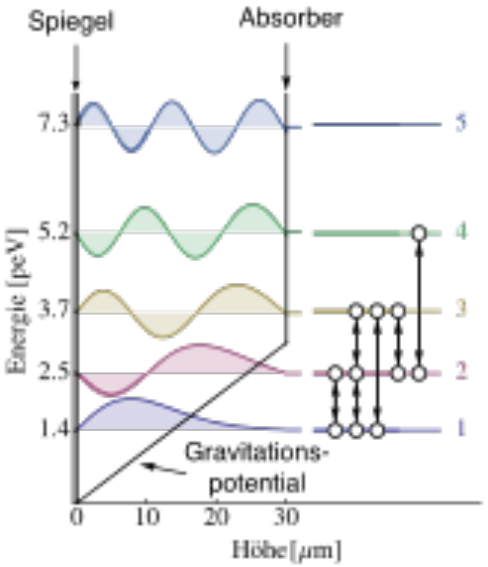
$$5.7\,\mathrm{m\,s^{-1}} < v < 7\,\mathrm{m\,s^{-1}}$$

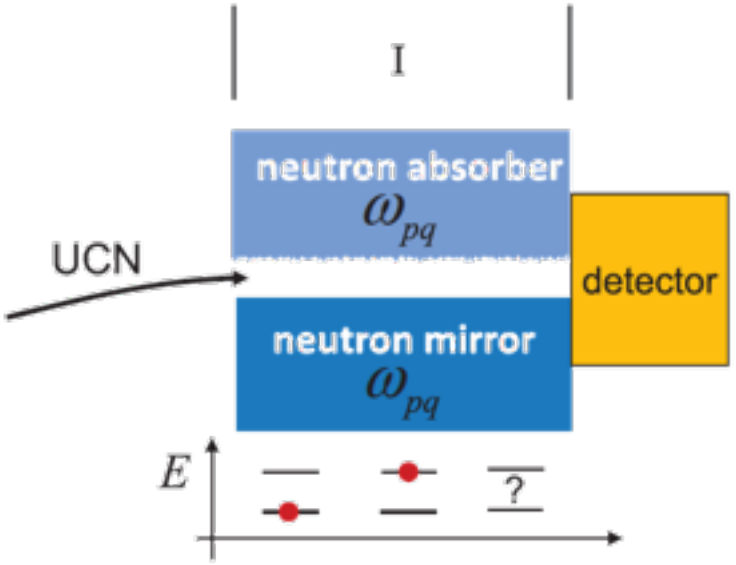




$$\frac{\Delta E}{E} \approx 10^{-14}$$







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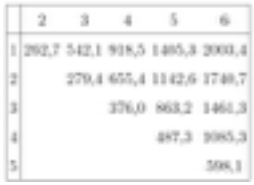
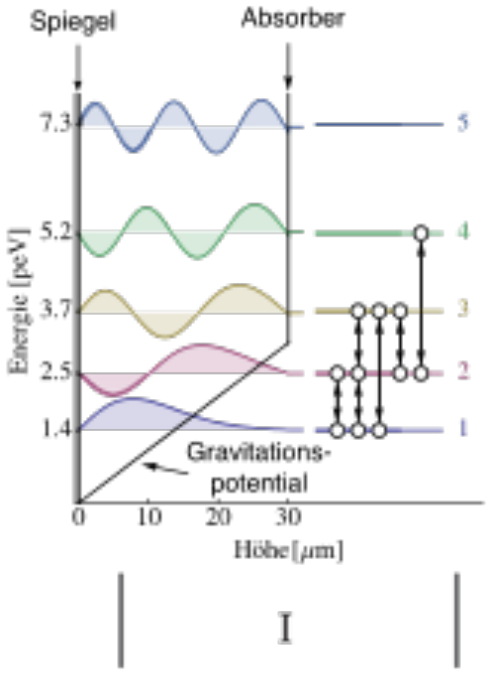


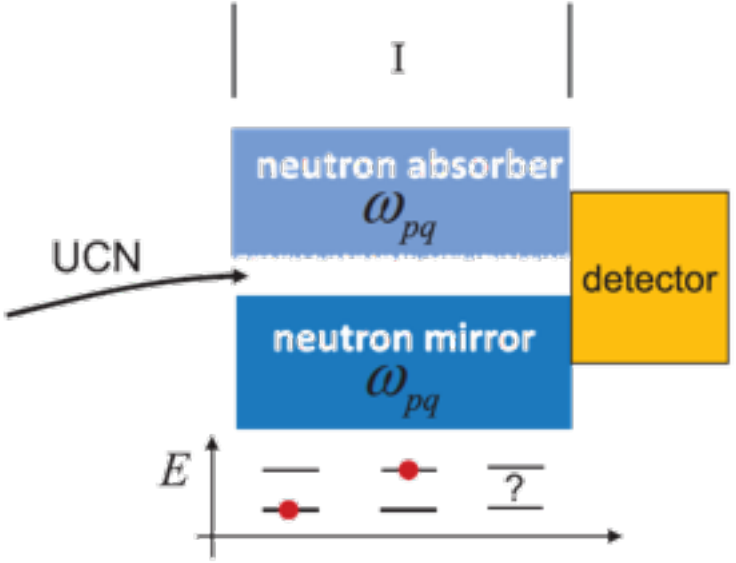


Gain sensitivity to short range forces

Level dependent modification of level spacing

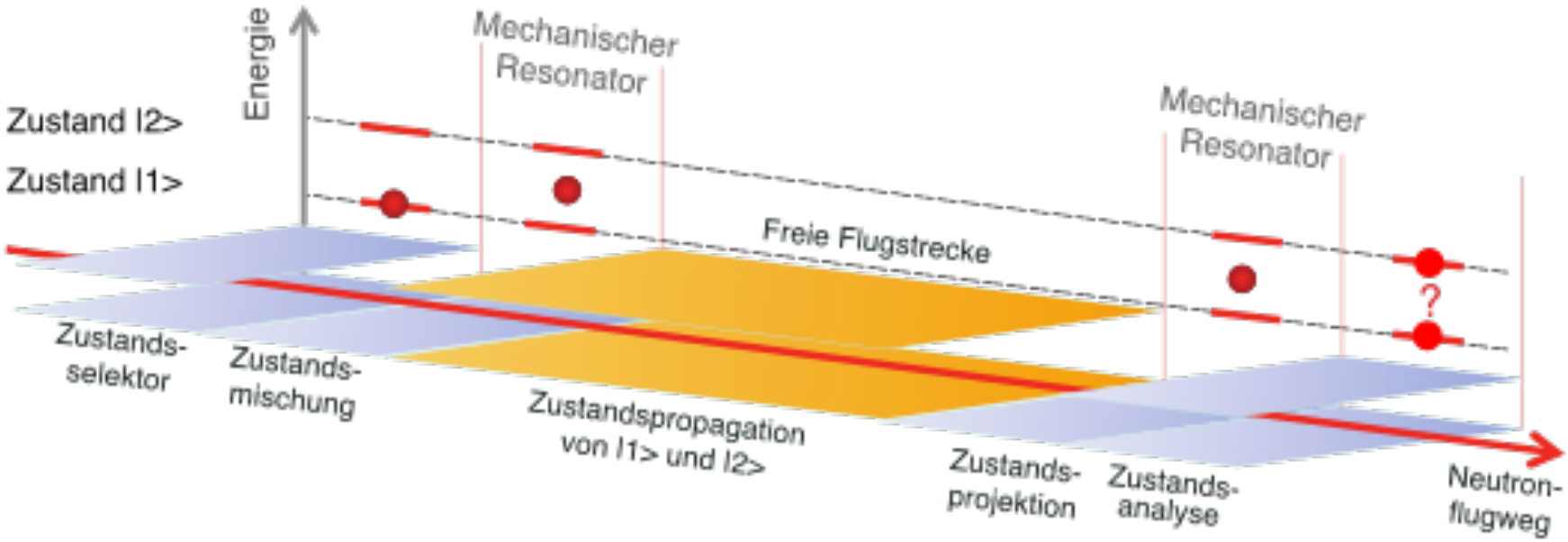
- Scalar fields (Chamaeleon – Quintessence)
- Axion fields (spin dependent effects)

Already now: excellent limits

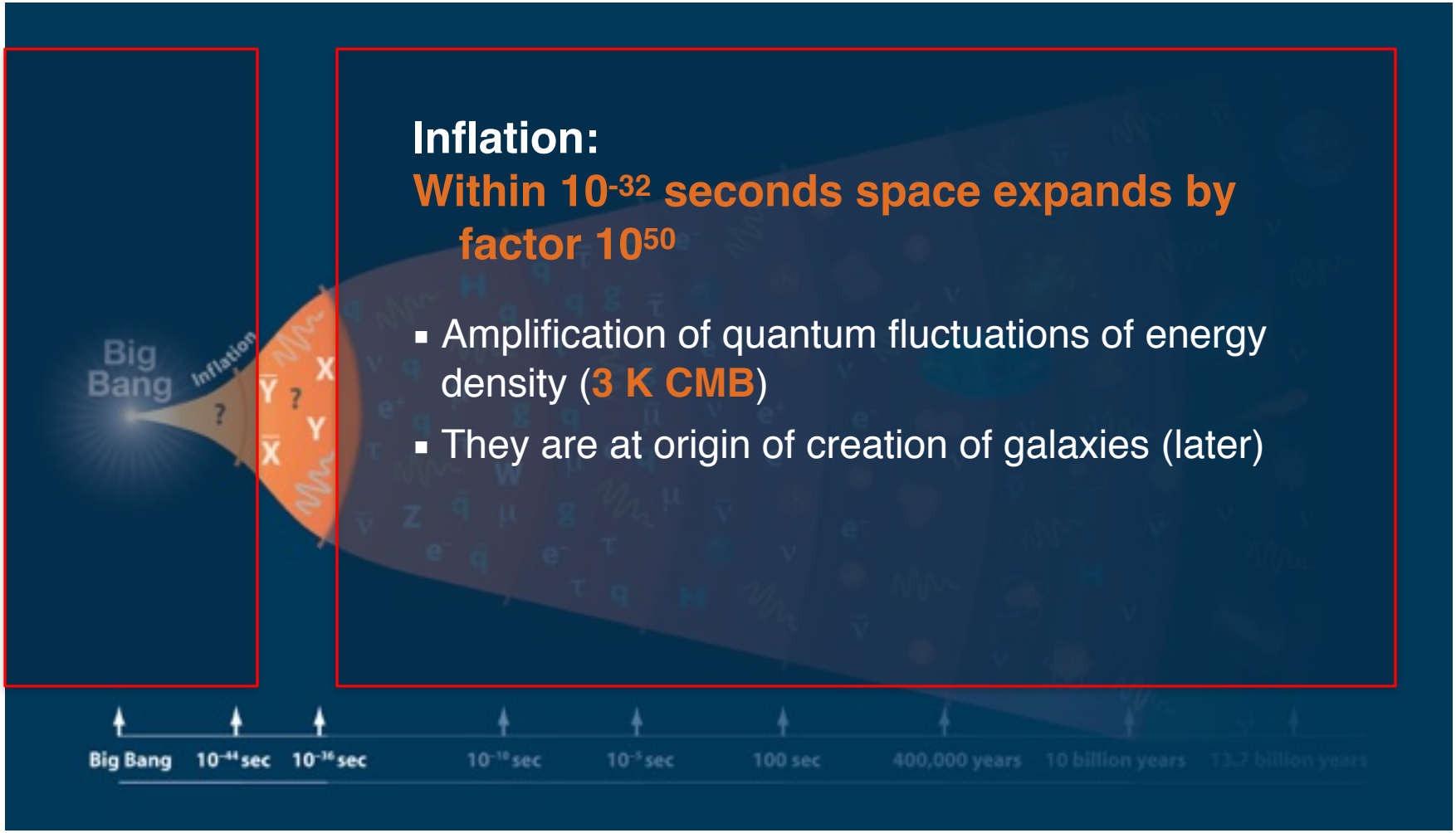


Gravitation: Future Measurements

- Sensitivity
  - Limits for Newtons law: about 1μm
  - Sensitivity toYukawa contributon:
    - Strength $\alpha \sim 10^4$
    - Range $\lambda \sim 5\mu m$



10^{-35} bis 10^{-32} sec. Past Big Bang

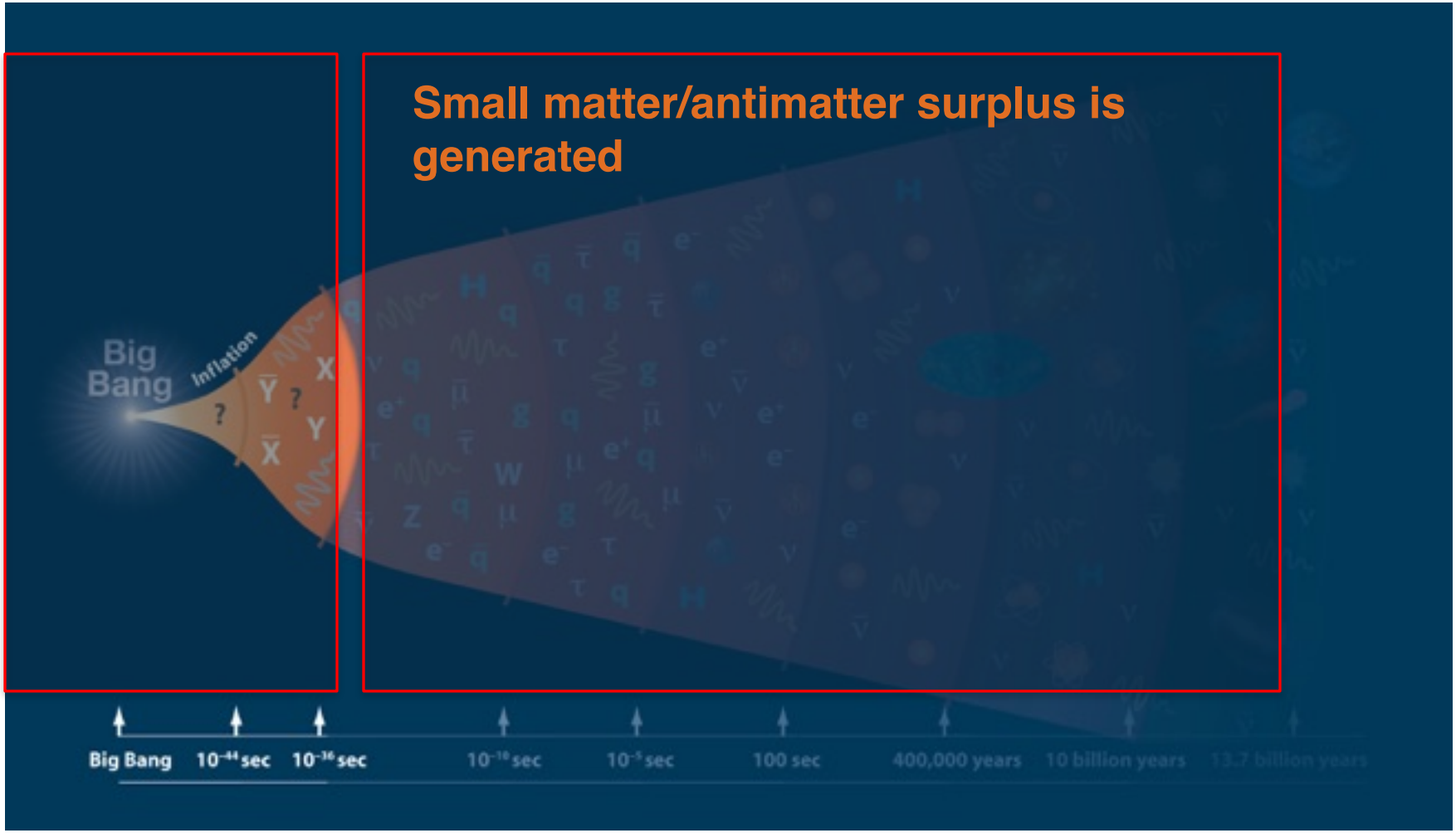


Inflation:

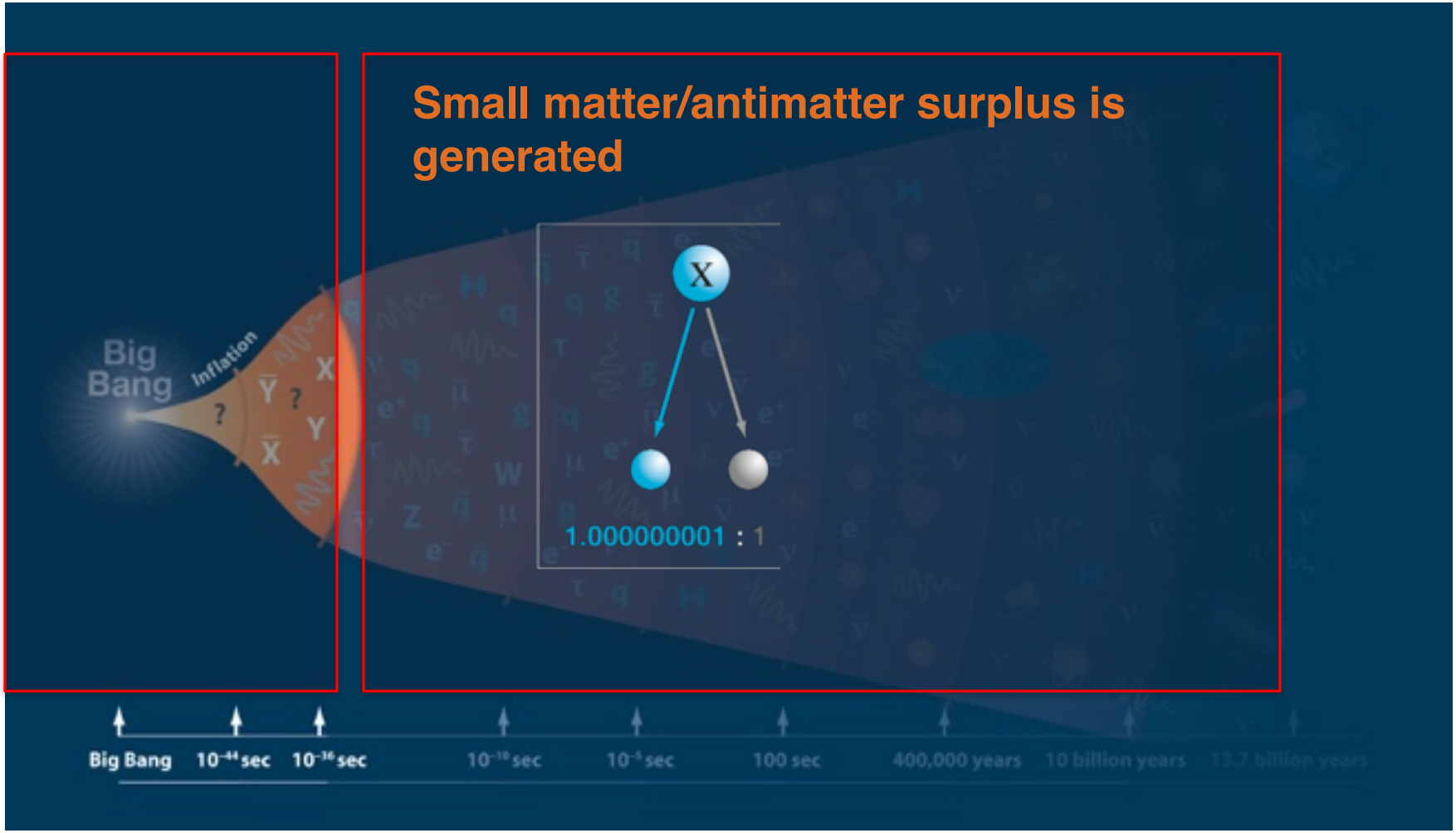
Within 10^{-32} seconds space expands by factor 10^{50}

- Amplification of quantum fluctuations of energy density (**3 K CMB**)
- They are at origin of creation of galaxies (later)

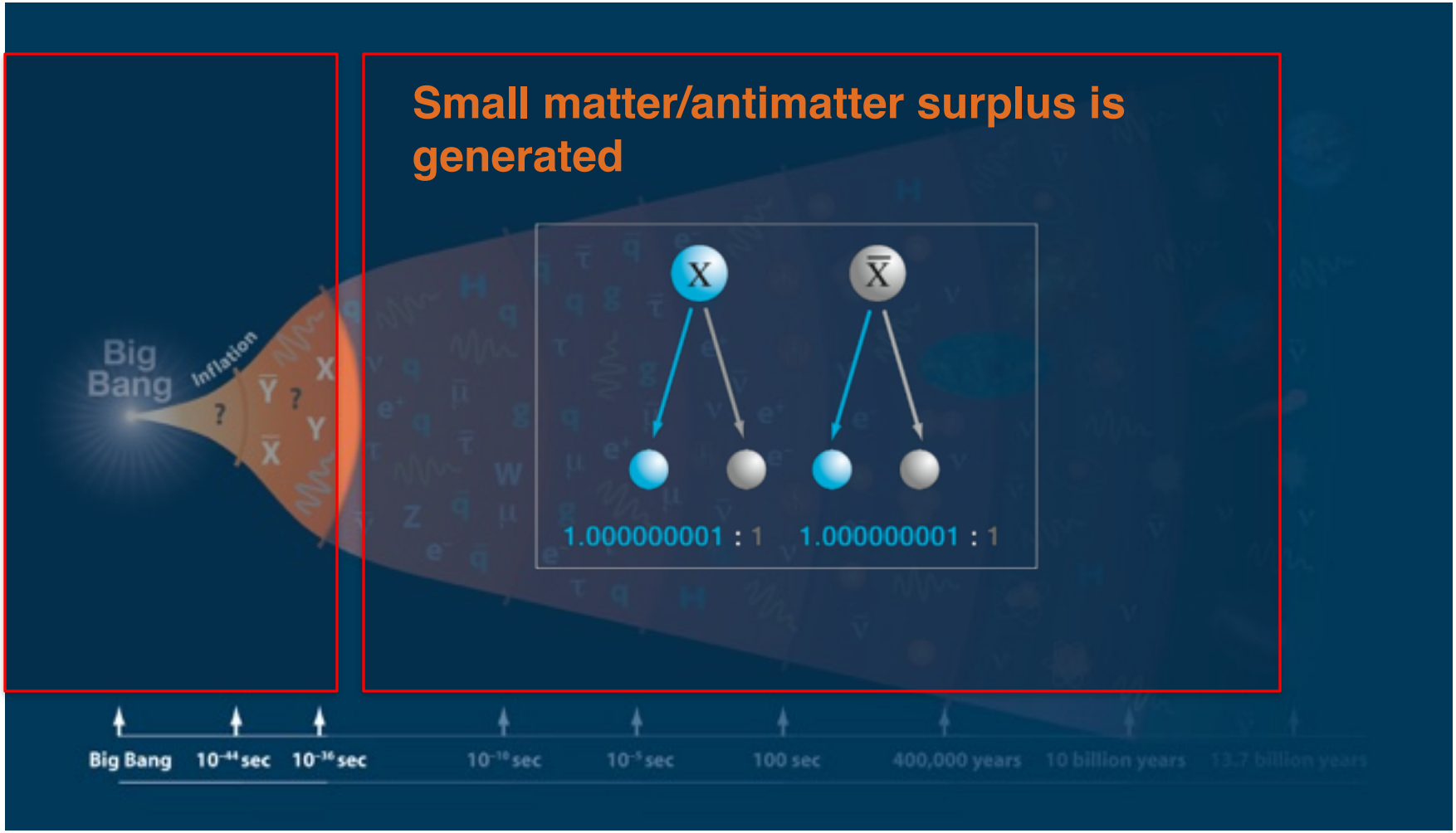
10^{-34} bis 10^{-33} Seconds after Big Bang



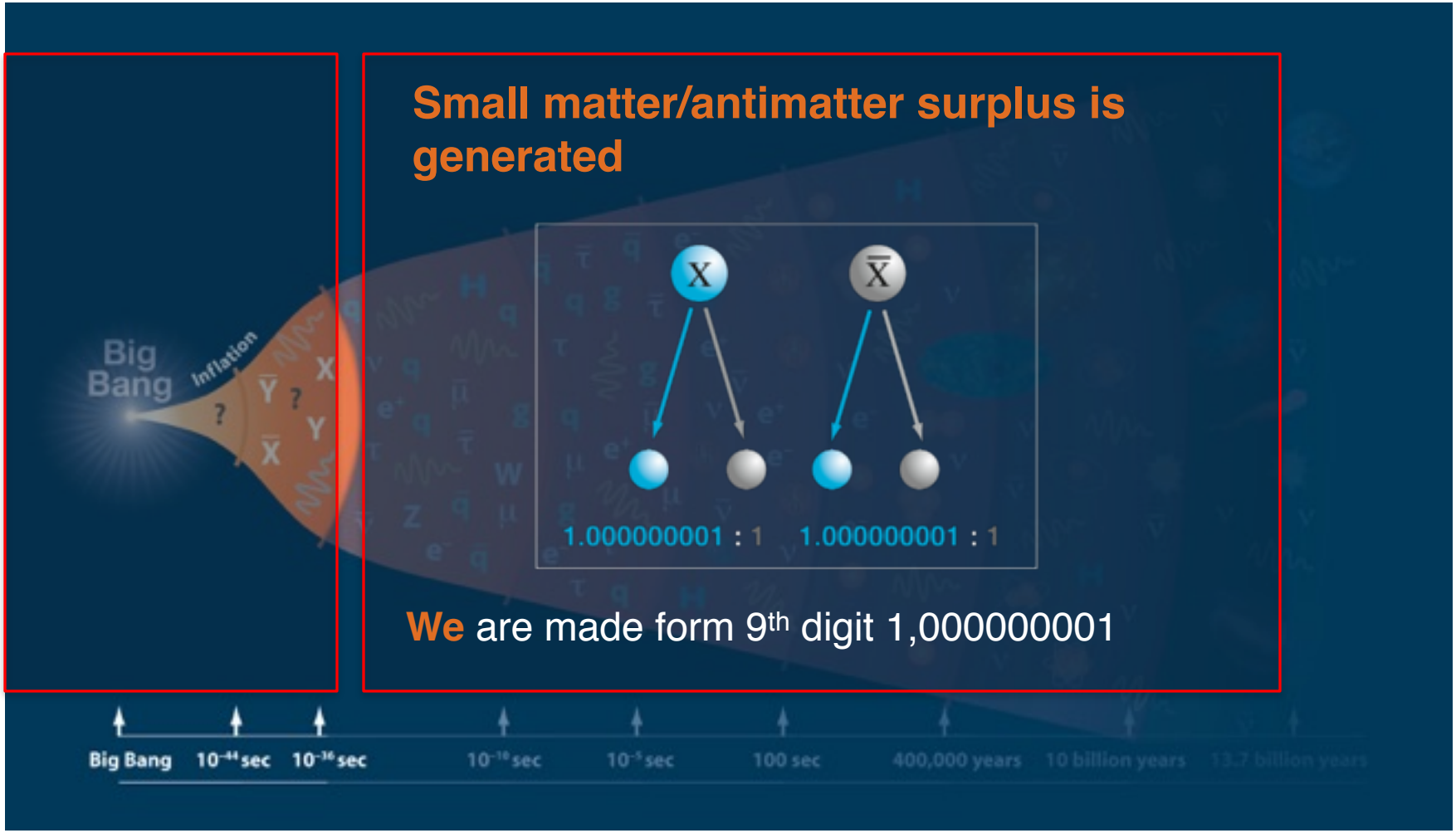
10^{-34} bis 10^{-33} Seconds after Big Bang



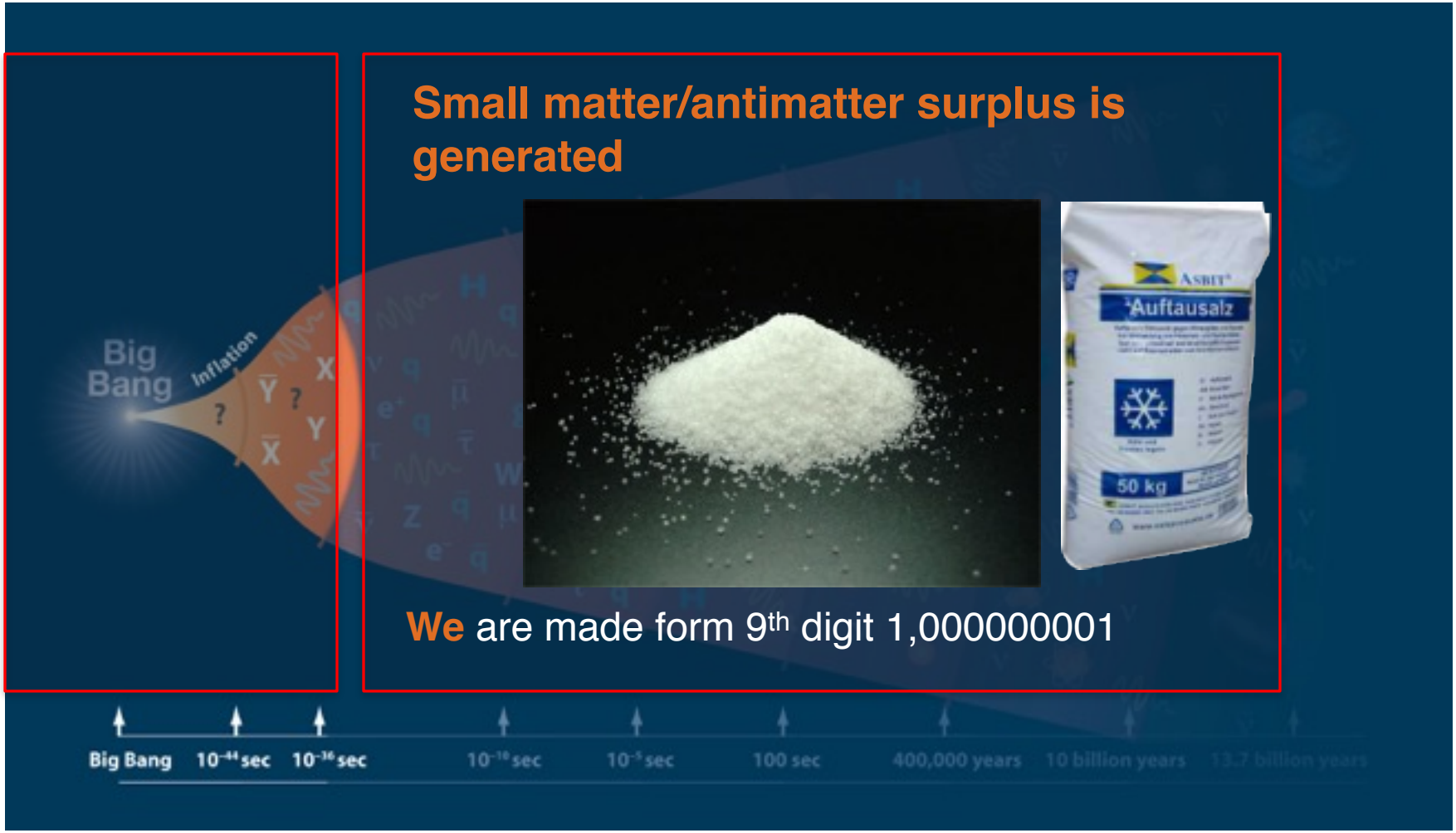
10^{-34} bis 10^{-33} Seconds after Big Bang



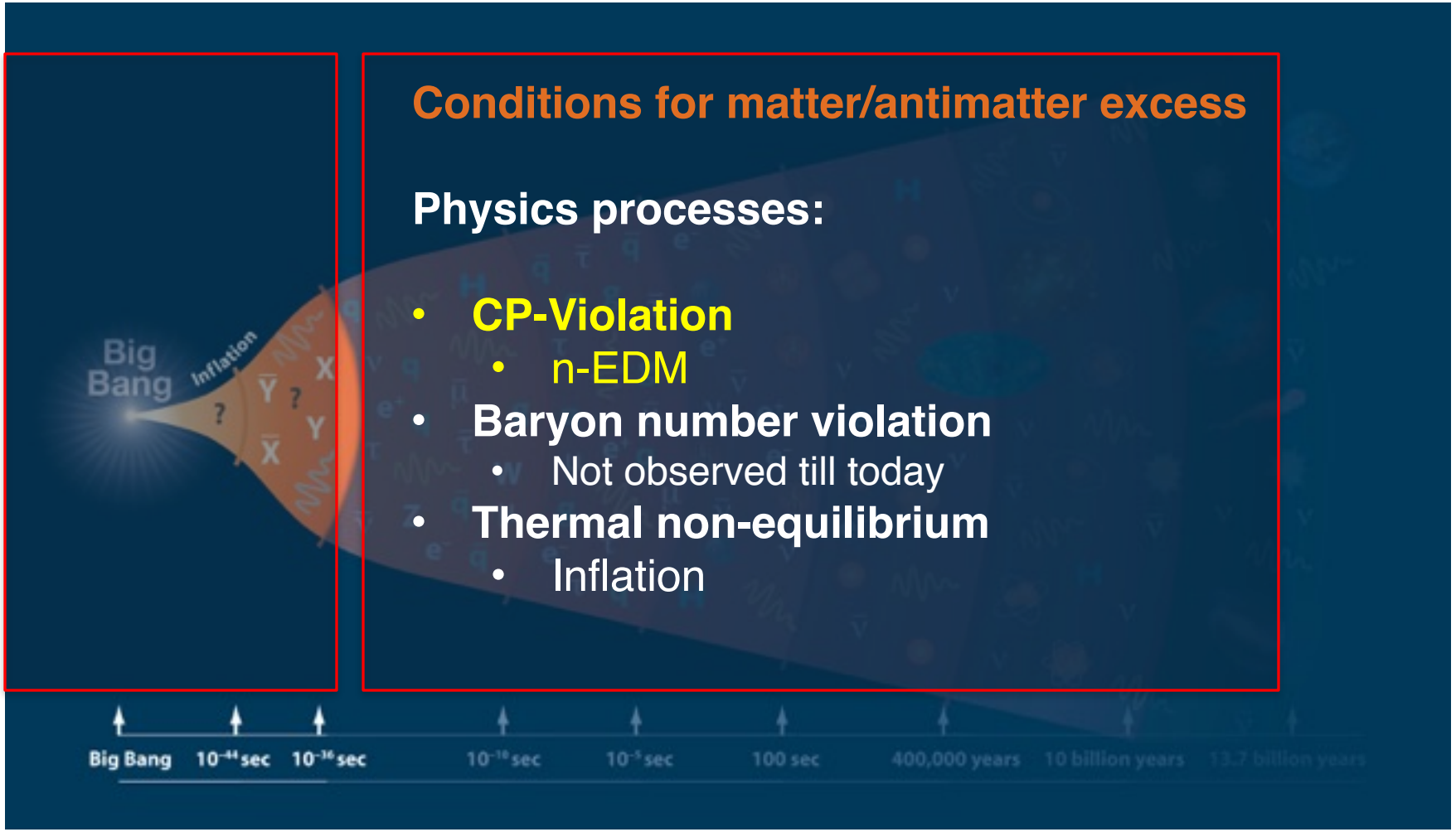
10^{-34} bis 10^{-33} Seconds after Big Bang



10^{-34} bis 10^{-33} Seconds after Big Bang



10^{-34} bis 10^{-33} Sekunden nach dem Big Bang



Conditions for matter/antimatter excess

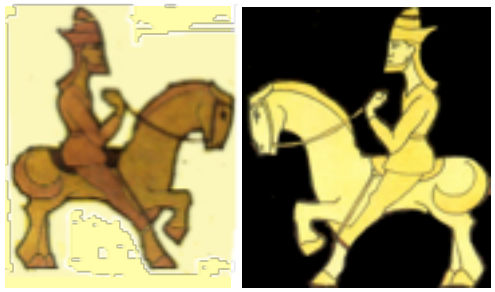
Physics processes:

- **CP-Violation**
  - n-EDM
- **Baryon number violation**
  - Not observed till today
- **Thermal non-equilibrium**
  - Inflation

Symmetries

Exzellenzcluster Universe

Discrete Symmetries



anti-particle e^+ particle e^-

following Escher ©

© idea taken from H.W. Wilschut

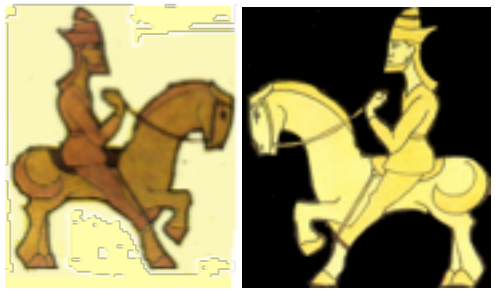
Exzellenzcluster Universe

Discrete Symmetries

Matter

mirror image

P



anti-particle **particle**

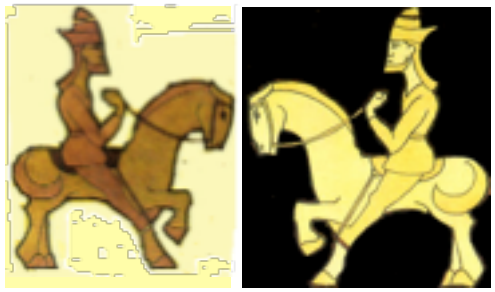
e^+ e^-

following Escher ©

© idea taken from H.W. Wilschut

Exzellenzcluster Universe

Discrete Symmetries



anti-particle e^+ **particle** e^-

following Escher ©

© idea taken from H.W. Wilschut

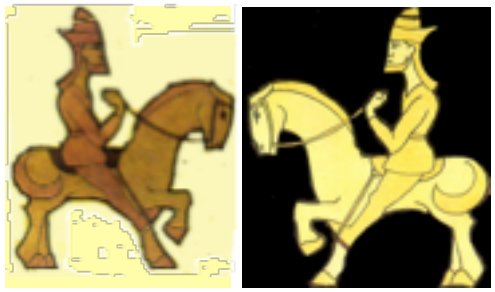
Exzellenzcluster Universe

Discrete Symmetries

mirror image
P

time →
C

← time
T



anti-particle **particle**

e^+ e^-

The world is invariant under CPT

following Escher ©

© idea taken from H.W. Wilschut

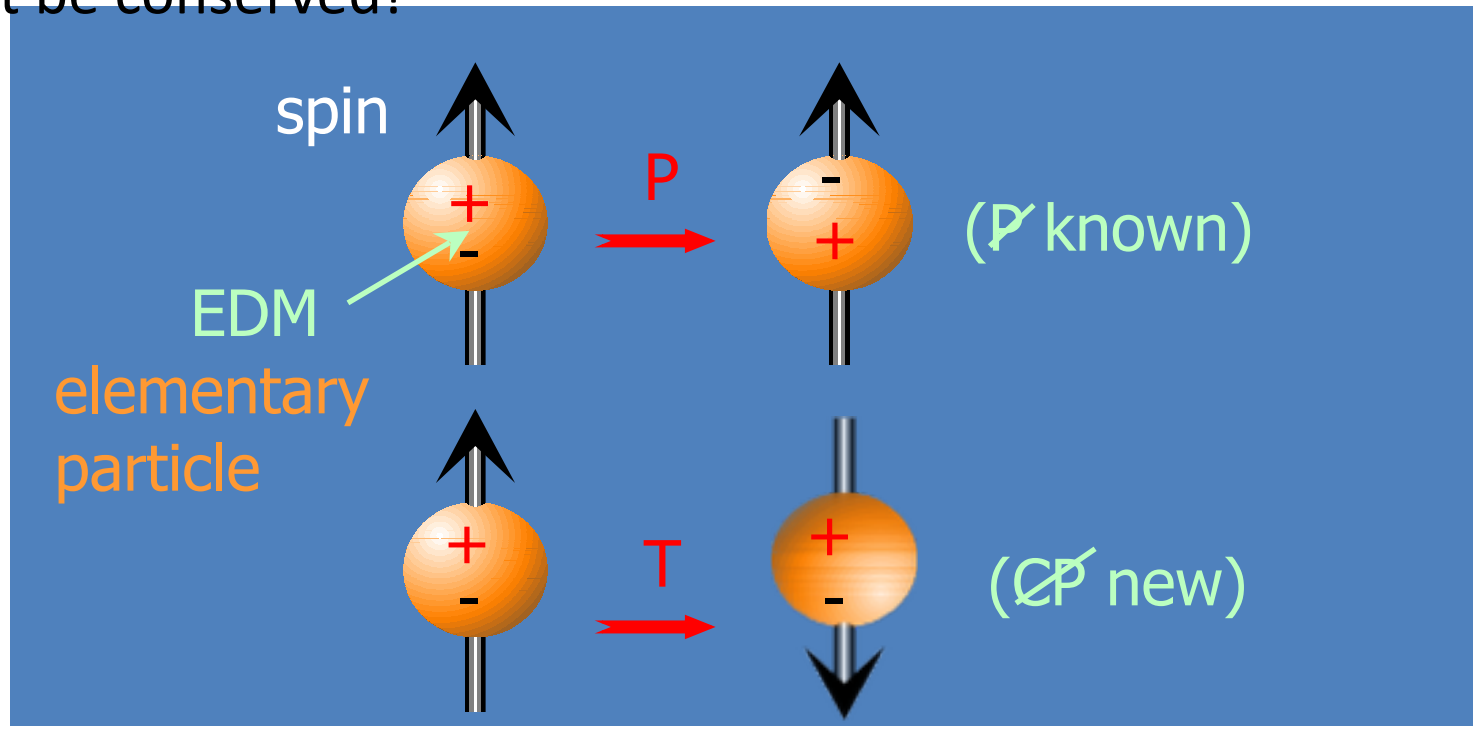
EDM and CP-Violation

- P – mirror operation (x → - x)
- C – charge conjugation (q → - q)
- T – time reversal (t → - t) .....

$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\mathbf{E} \cdot \frac{\mathbf{S}}{S}$$

$P = +1$ $\quad$ $P = -1$

CPT must be conserved!



The role of an n-EDM

EDM is test for flavour diagonal ~~CP~~

- Test of vacuum structure at small distances
- Background free probe for 'new physics' (on contrast to CKM ind.. ~~CP~~)

CP violation in nucleon (neutron) needed for

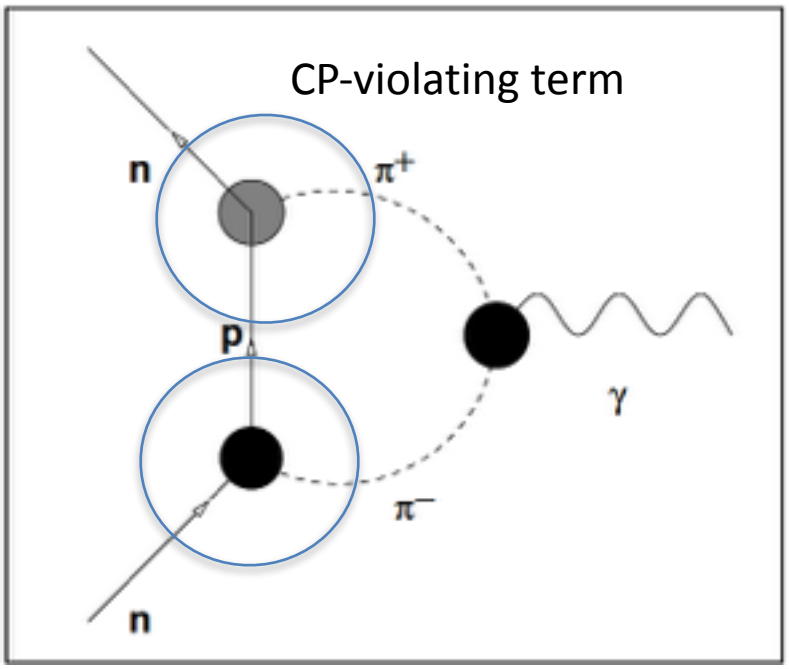
- Baryogenesis Problem (matter vs antimatter in universe)
  cosmological necessity (Sakharov criteria)
- Test CP violating part in QCD (θ-term)
  Magic fine tuning to zero ($\theta < 10^{-9}$)

EDM is studied in

- Diamagnetic atoms (strong CP problem)
- Paramagnetic atoms, molecules, (~~CP~~ inducing electron-EDM d_e)
- Neutron (~~CP~~ in quark-sector)

Neutron EDM

strong interaction

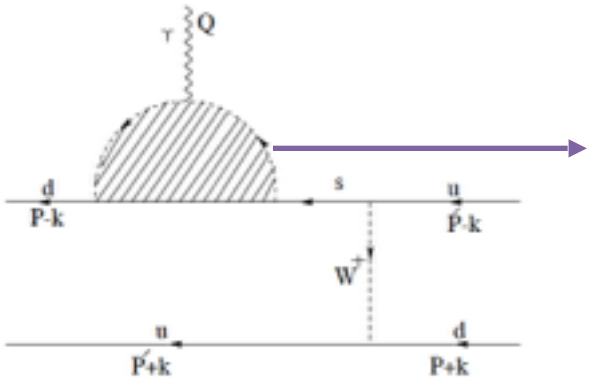


1fm

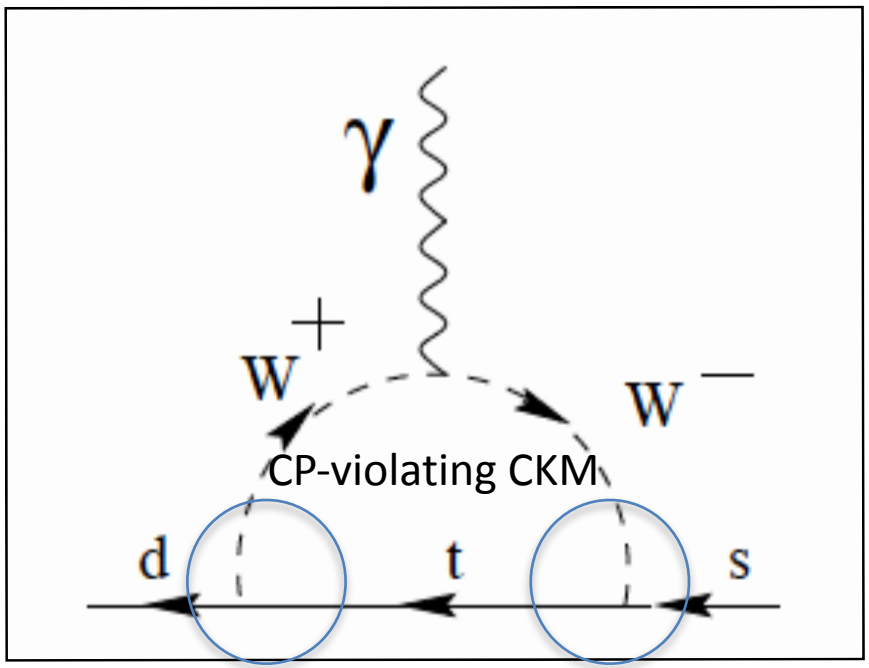
$$d_n \equiv D_n(k^2 = 0) = \frac{g_{\pi NN}\overline{g_{\pi NN}}}{4\pi^2 M_N} \ln\left(\frac{M_N}{m_\pi}\right)$$
$$\sim \bar{\theta} \times 2 \times 10^{-16} \mathrm{e-cm}$$

Neutron EDM

Exzellenzcluster Universe

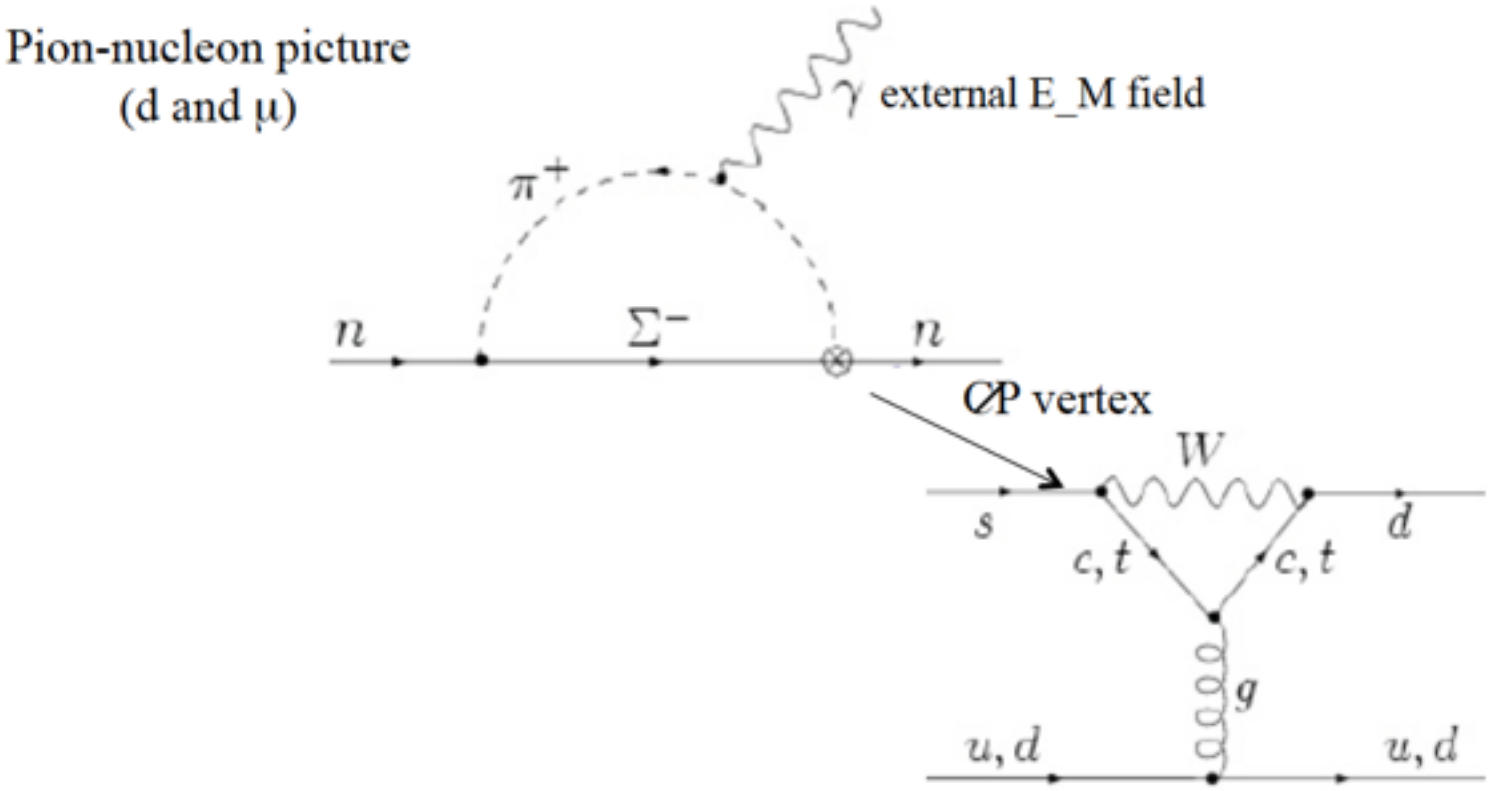


electroweak interaction



0.001fm

Standard Model EDM



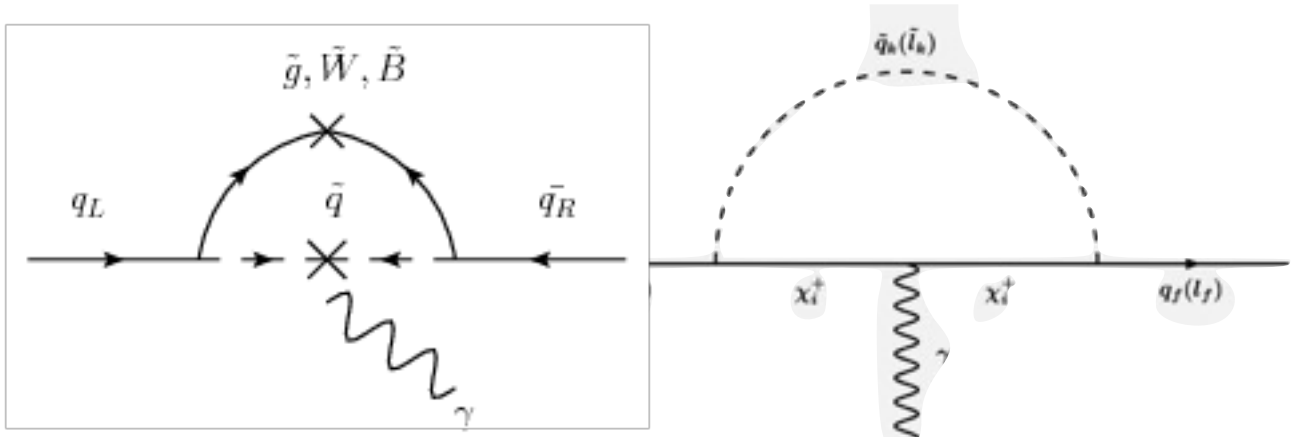
$$d_n^{SM} \approx 10^{-32} \text{ e cm}$$

Neutron EDM

Exzellenzcluster Universe

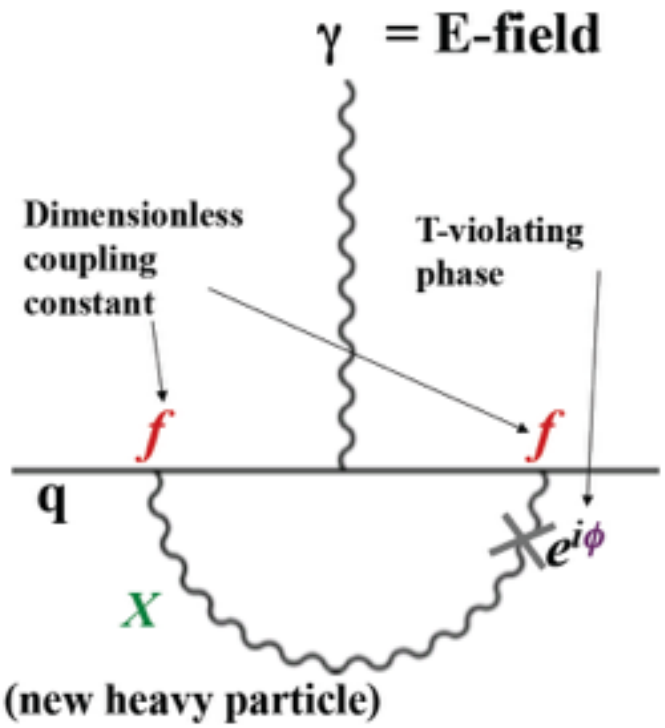
Supersymmetry creates many CP violating phases

quark EDM



$0.2/M_{new}$ fm
10 TeV:
$2\ 10^{-5}$ fm

New Physics at the TEV scale



$$d_n < 10^{-26}\ e\cdot cm$$

$$f = \sqrt{\alpha}$$

$$\frac{d}{e} \approx \hbar c \alpha^N \frac{m_q}{\Lambda_x^2} \sin\phi \qquad m_q \approx 1\ MeV$$

$$\Big| \approx 10^{-13}\ fm$$

$$\Lambda_x \approx 10^7\ MeV = 10\ TeV$$

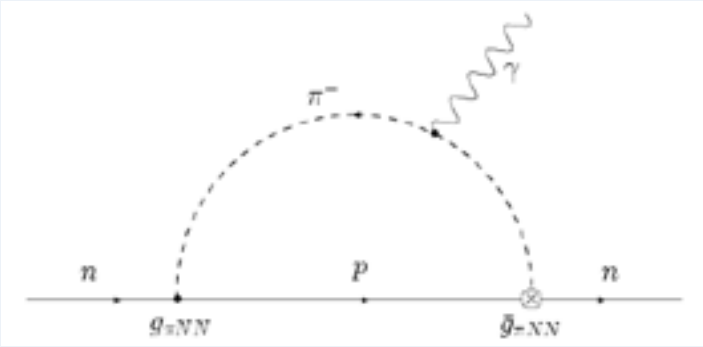
$$\sin\varphi \sim 1$$

EDM – particle physics

Strong interaction – ‘strong CP‘-Problem in QCD

$$d_n \propto \bar{\theta}\,\frac{1}{\Lambda_{QCD}} \approx 10^{-16}\,\bar{\theta}\; e\cdot cm$$

$$\bar{\theta} < 1.2\cdot 10^{-10} \text{ (95\% C.L.) via } {}^{199}\text{Hg}$$

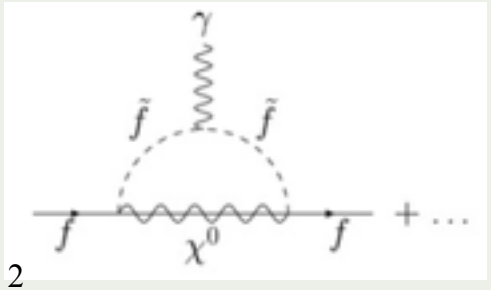


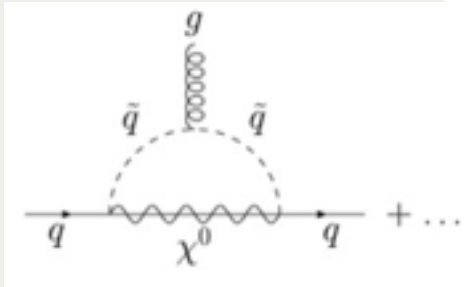
Supersymmetry

generate quark EDM d_q

$$d_n^{SUSY} \sim \frac{1}{M_{SUSY}^2}\cdot \sin\theta_{CPV}^{SUSY}$$

Existing Data: $\theta_{CPV}^{SUSY}\cdot\left(\frac{1\ TeV}{M_{SUSY}}\right)^2 < 1$





Example: 1-loop SUSY

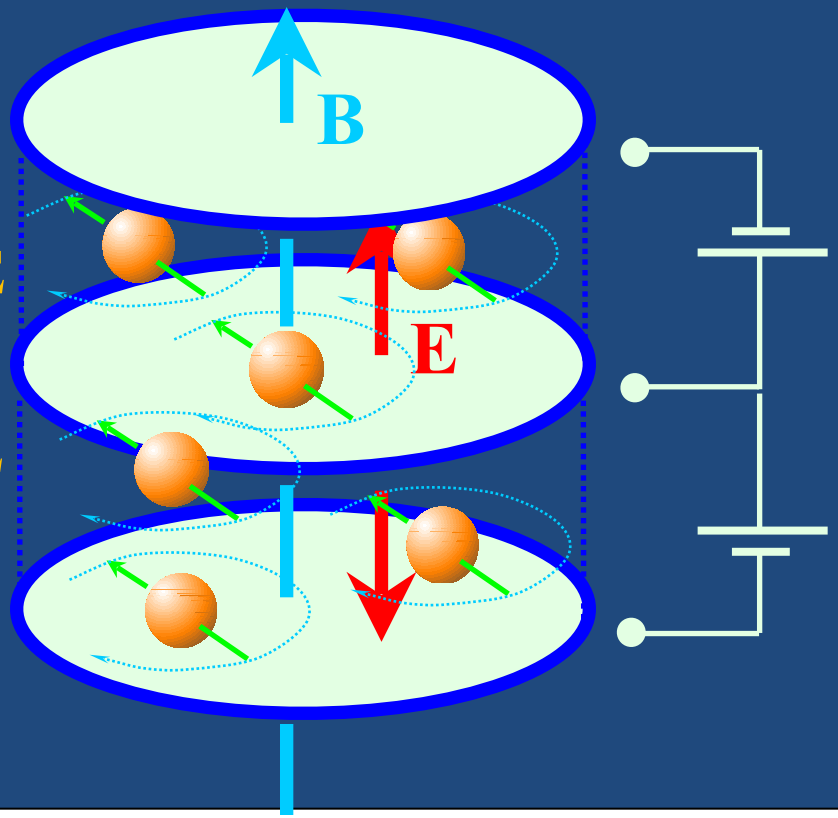
How to measure an EDM ?

Ramsey method

e.g. double chamber System

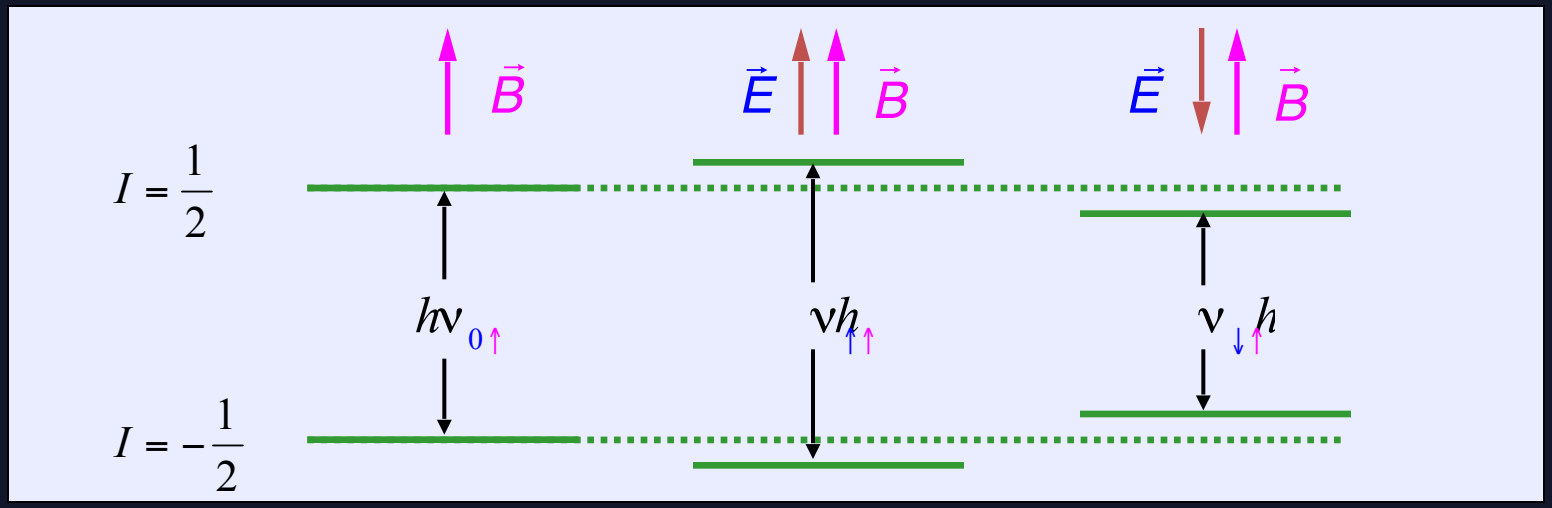
$$\Delta\omega = \omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow} = 4 \cdot d_n \cdot E/\hbar$$

$$h\omega = \pm \mu B$$



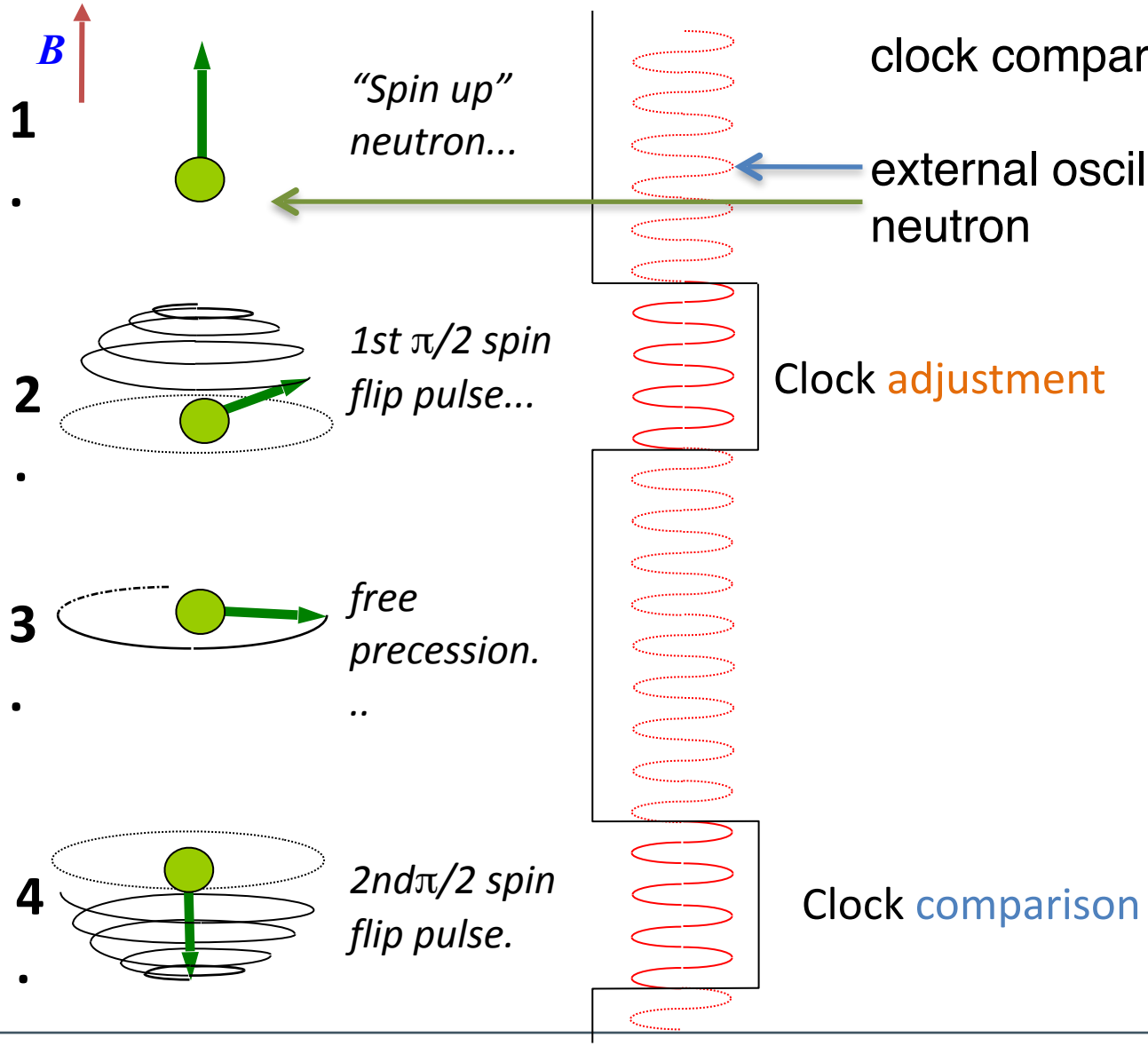
EDM-Measurement

Neutron
Larmor frequency



HF normal

Measure: neutron EDM – Ramsey method



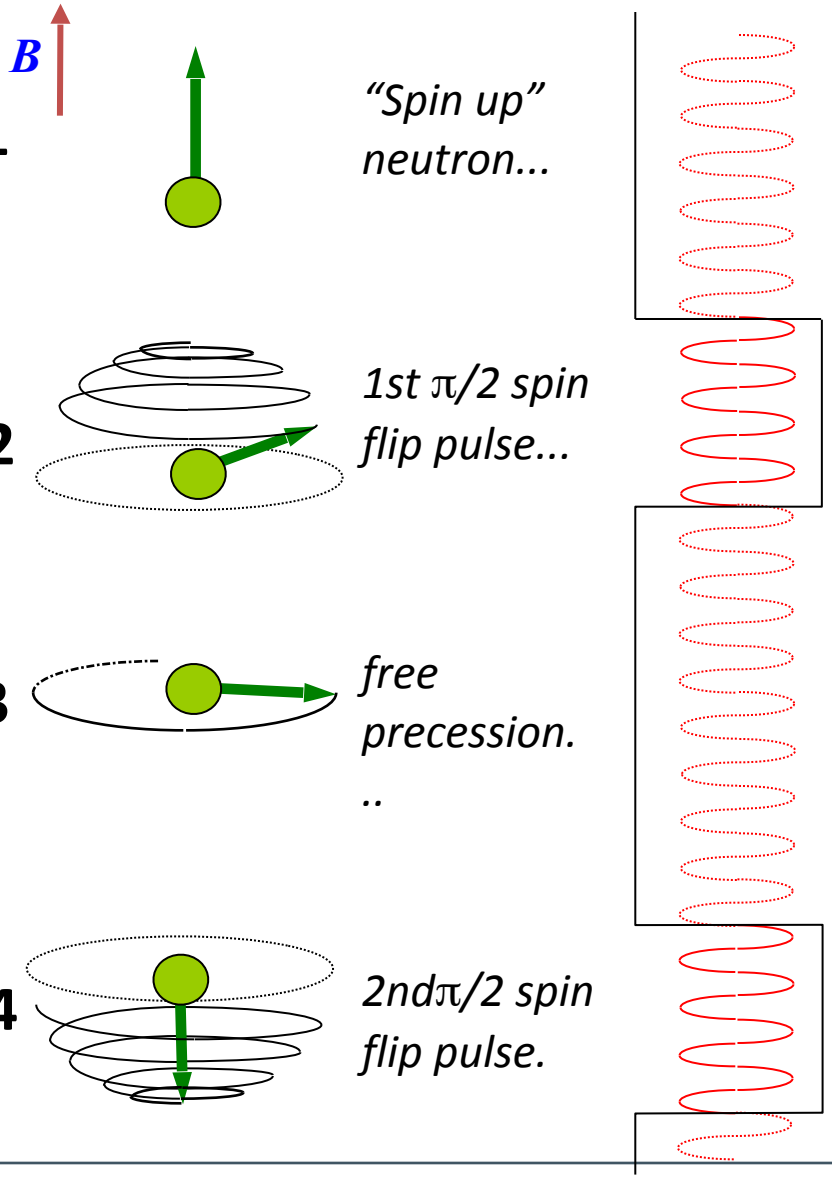
clock comparison:

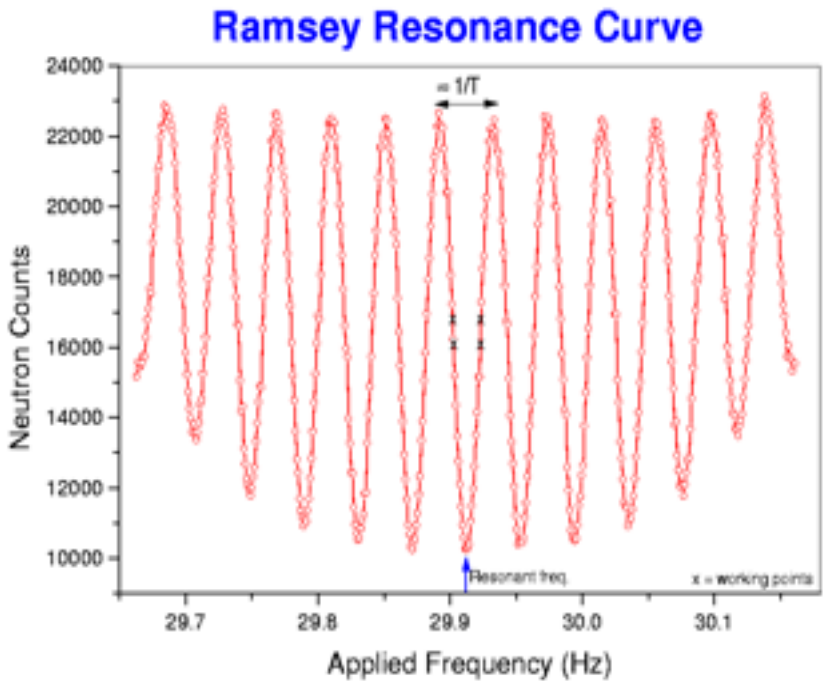
external oscillator neutron

Clock adjustment

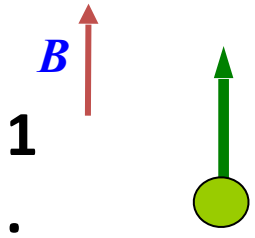
Clock comparison

Measure: neutron EDM – Ramsey method

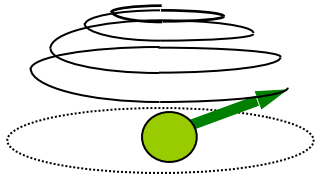




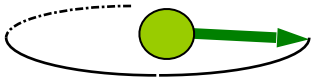
Measure: neutron EDM – Ramsey method



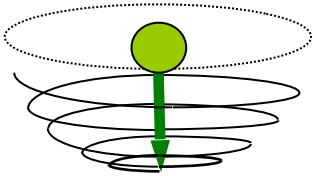
1. *"Spin up" neutron...*



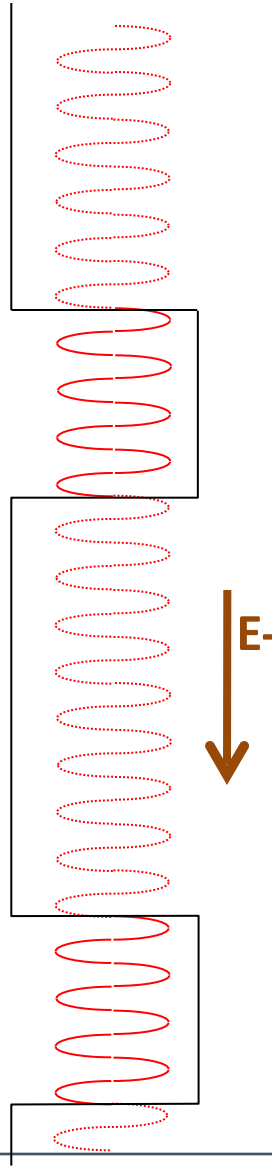
2. *1st π/2 spin flip pulse...*

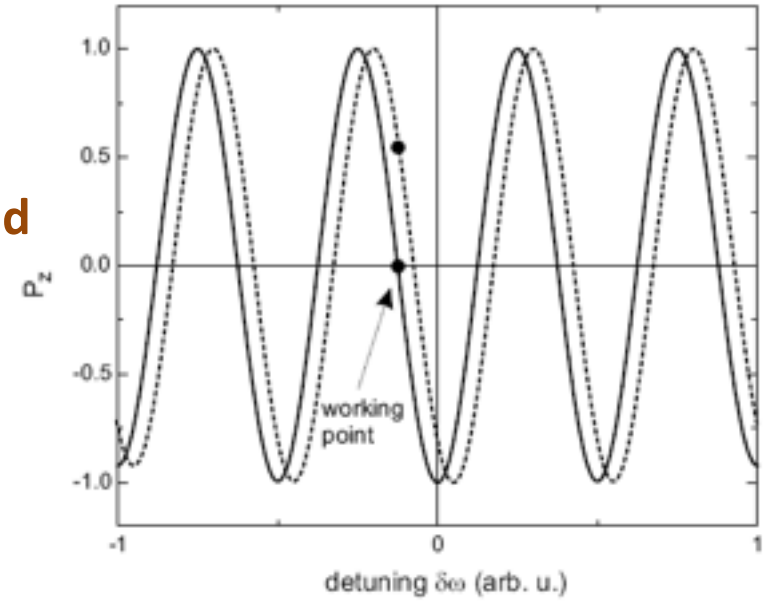


3. *free precession. ..*



4. *2ndπ/2 spin flip pulse.*





Measure: neutron EDM – Ramsey method

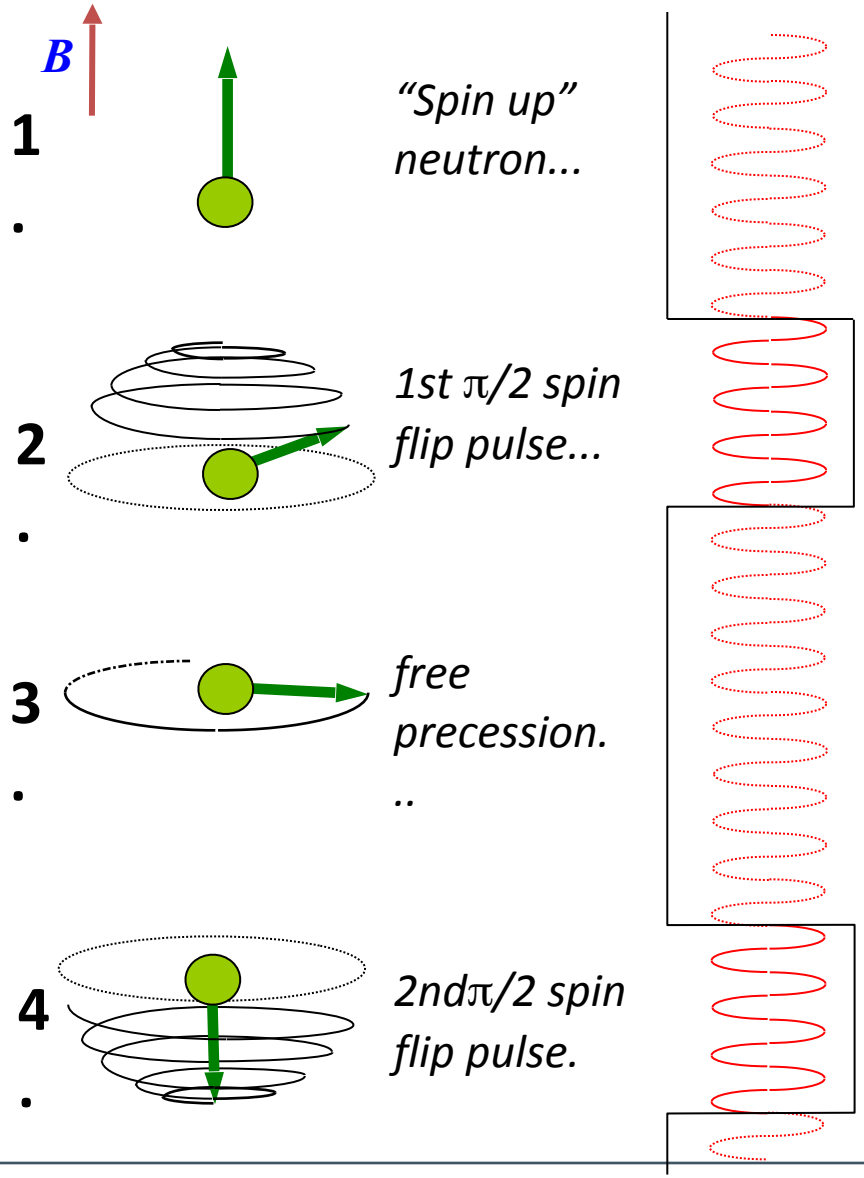
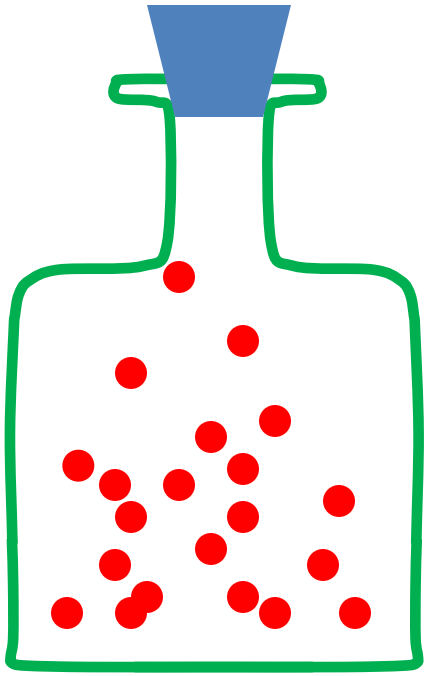


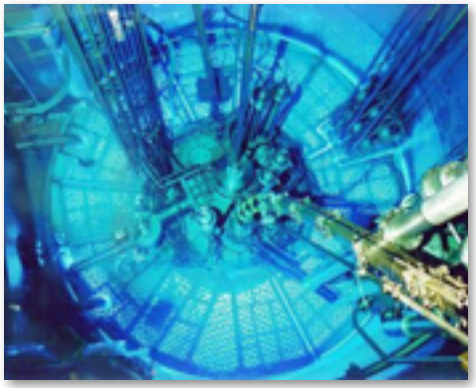
Figure of Merit

$$\mathcal{M} = \alpha E T \sqrt{N}$$

α	visibility of Ramsey pattern
E	electric field strength
T	time of free precession
N	number of neutrons observed

Ultra cold Neutrons (UCN)





Source @ ILL Grenoble

- Kinetic energy < 250 neV (< 7 m/s velocity)
- Gravitational potential 100 neV/m (< 2.5m against gravity)
- magnetic level splitting ~ 60 neV/T
- Strong interaction: n reflect from many surfaces
  Fermi-potential < 340 neV

UCN storage for ~ 885 s (β-decay time)

How accurately do we have to measure ?

Exzellenzcluster Universe

Neutron(spin) precession of 30 Hz

Present sensitivity:

one spin-rotation in 180 days

energy resolution: $E_{EDM} = 3 \cdot 10^{-22}$ eV

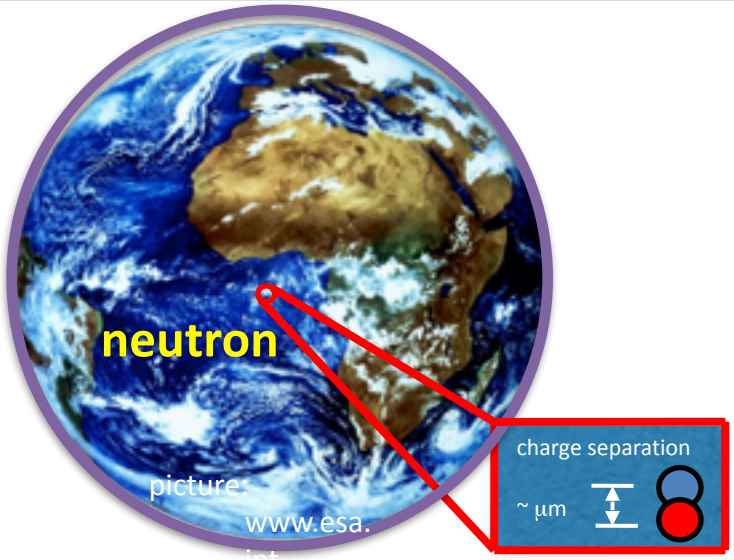
$$| d_n | < 3 \cdot 10^{-26}\ e \cdot cm$$

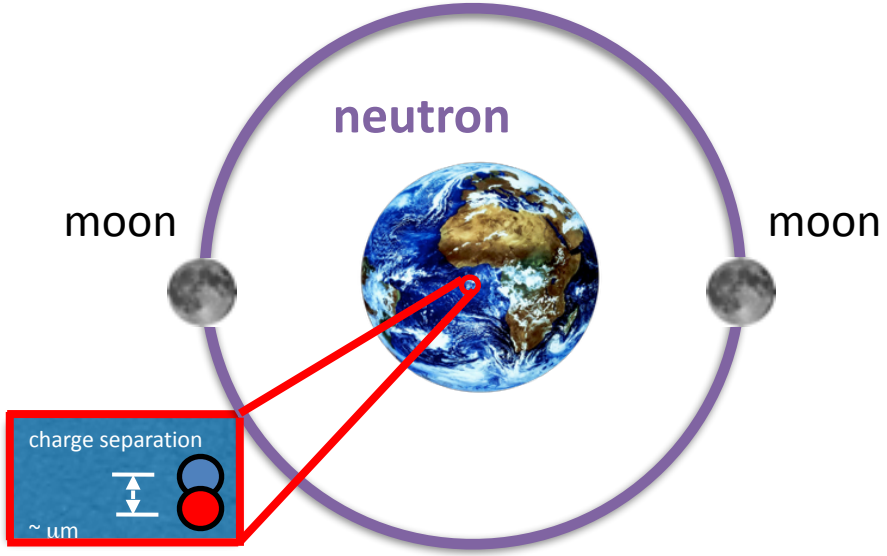
planned sensitivity (FRMII):

one spin rotation in 50 years

energy resolution: $E_{EDM} = 3 \cdot 10^{-24}$ eV

$$| d_n | < 3 \cdot 10^{-28}\ e \cdot cm$$

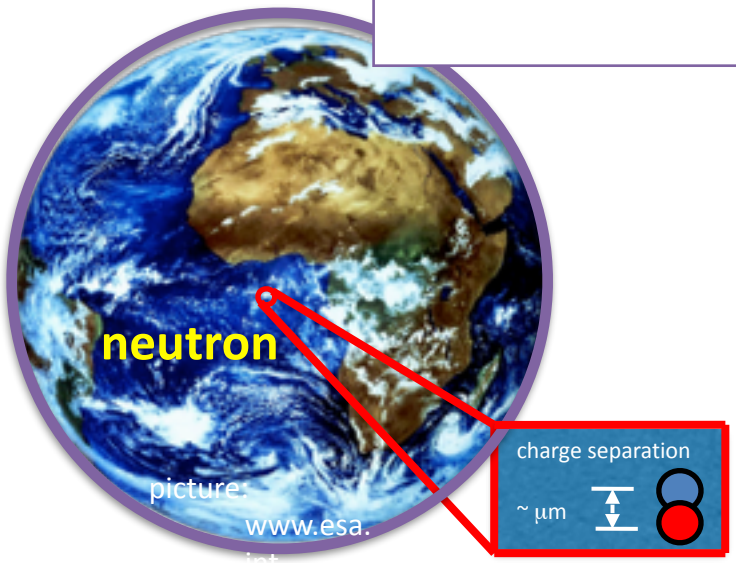


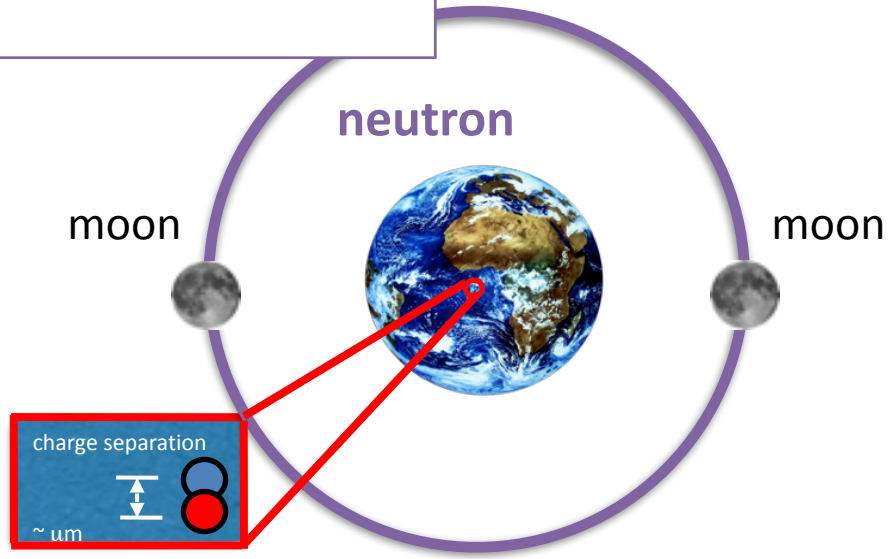


How accurately do we have to measure ?

Exzellenzcluster Universe

Measurement will exclude many „false“ theories and „hypotheses“



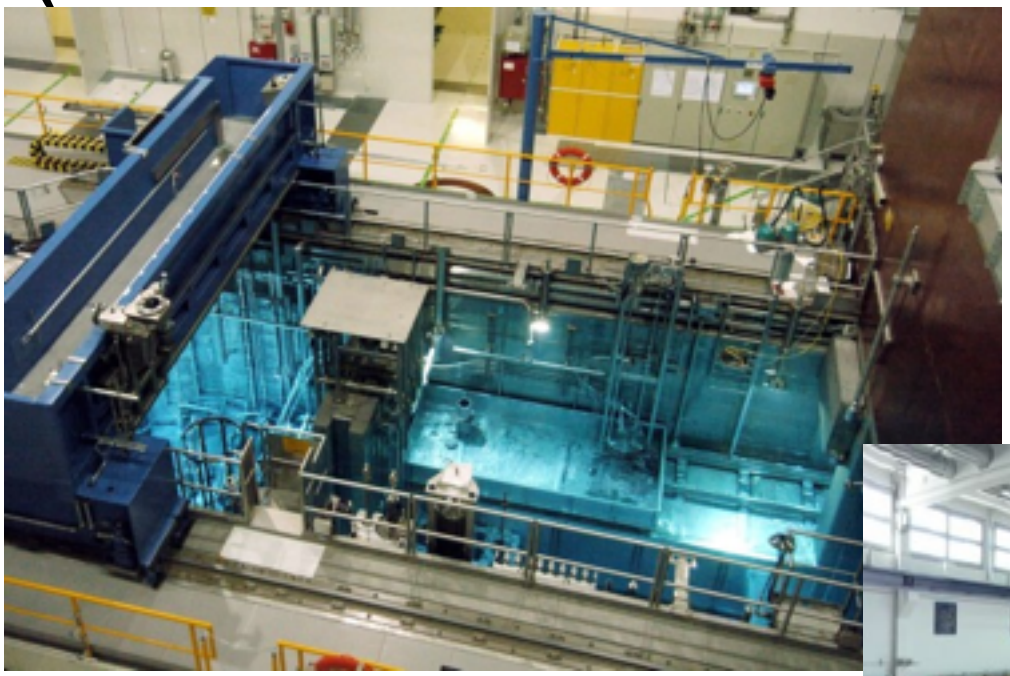


Exzellenzcluster Universe

Science with Neutrons
(Fission neutron source in München/Garching)

Exzellenzcluster Universe

Science with Neutrons
(Fission neutron source in München/Garching)



The Real Setup

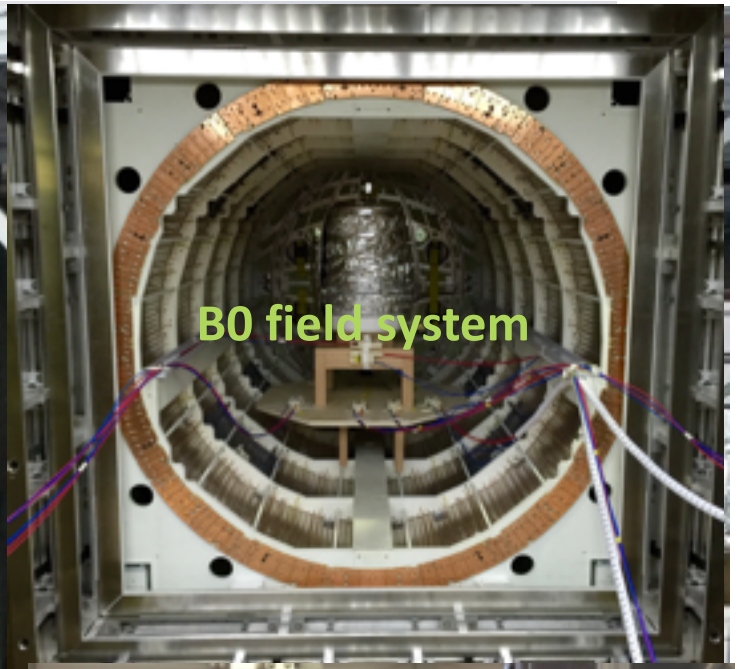
Fierlinger et al.

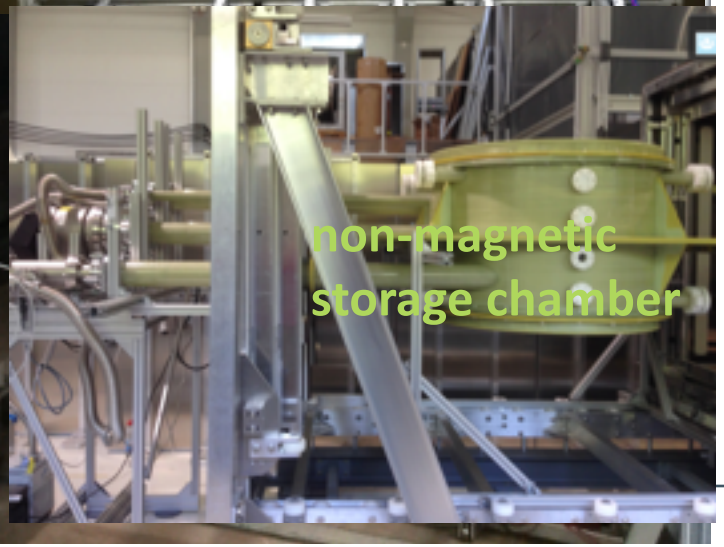
Exzellenzcluster Universe

The Real Setup

Fierlinger et al.

Exzellenzcluster Universe





The Real Setup

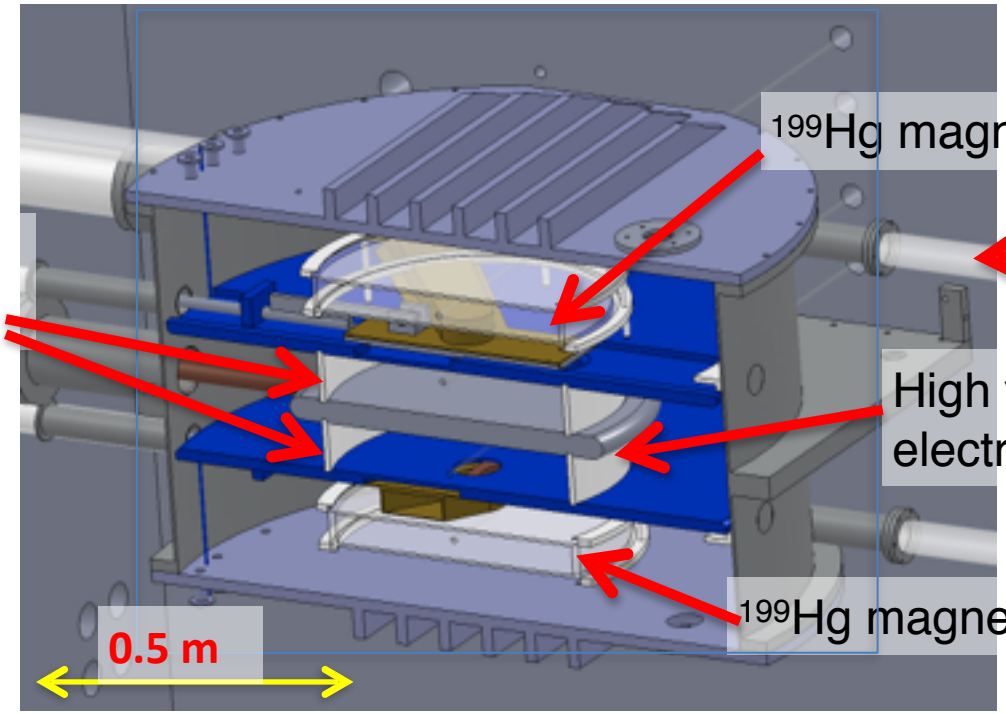
Fierlinger et al.

Exzellenzcluster Universe

Key: avoid magnetic false effects

- „perfect“ magnetic shielding - best room worldwide (remaining field few fT)
- „Perfect“ control over non-magnetic material
- Frequent and rapid demagnetization
- Co-magnetometry (^{199}Hg)
- nEDM < 10^{-28} e cm in reach
- missing : UCN !!

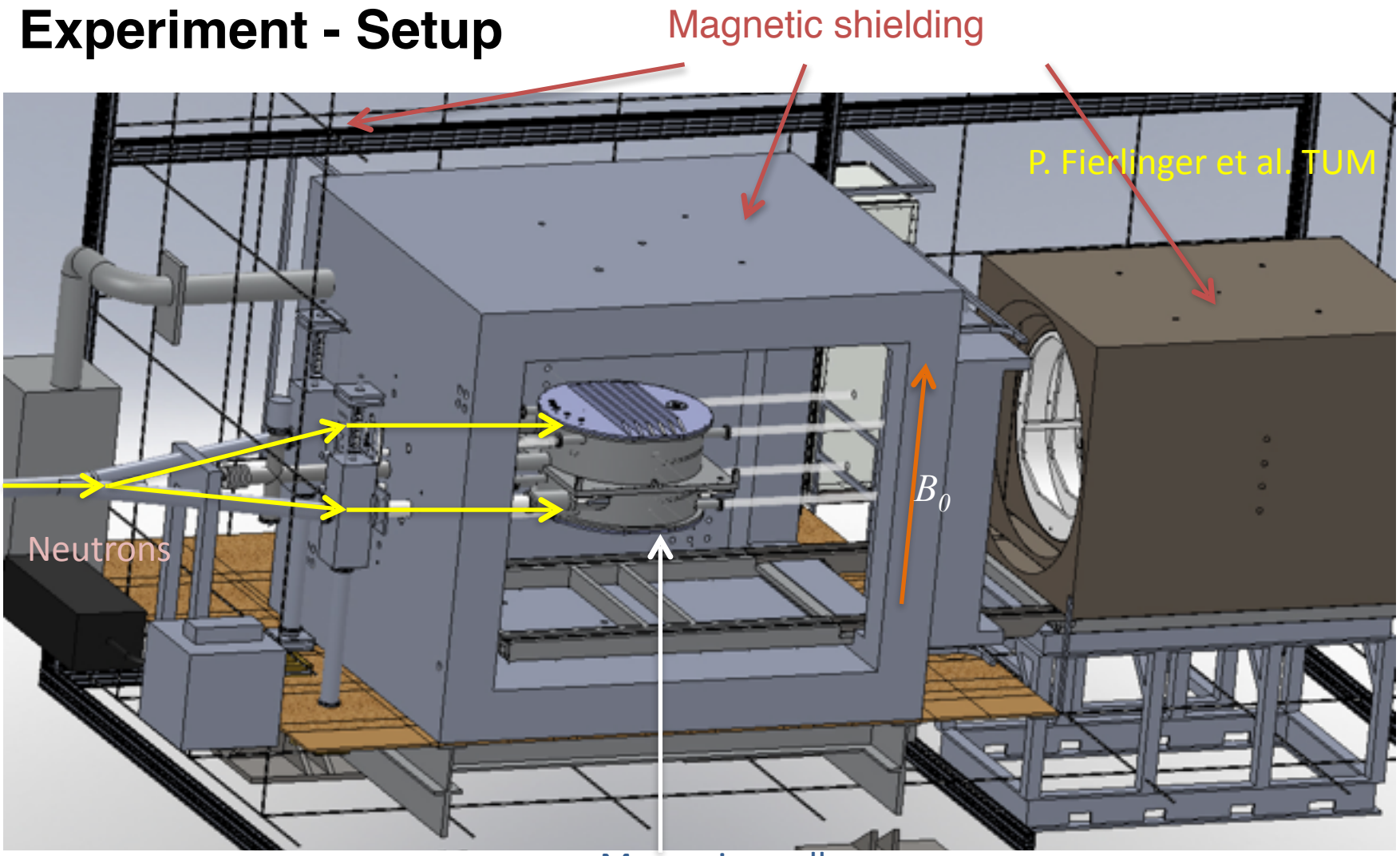
The new EDM apparatus at FRM2



Goal: $\sigma(d_n) < 5.10^{-28}$ ecm (3σ) with 200 days data, stat.+syst.

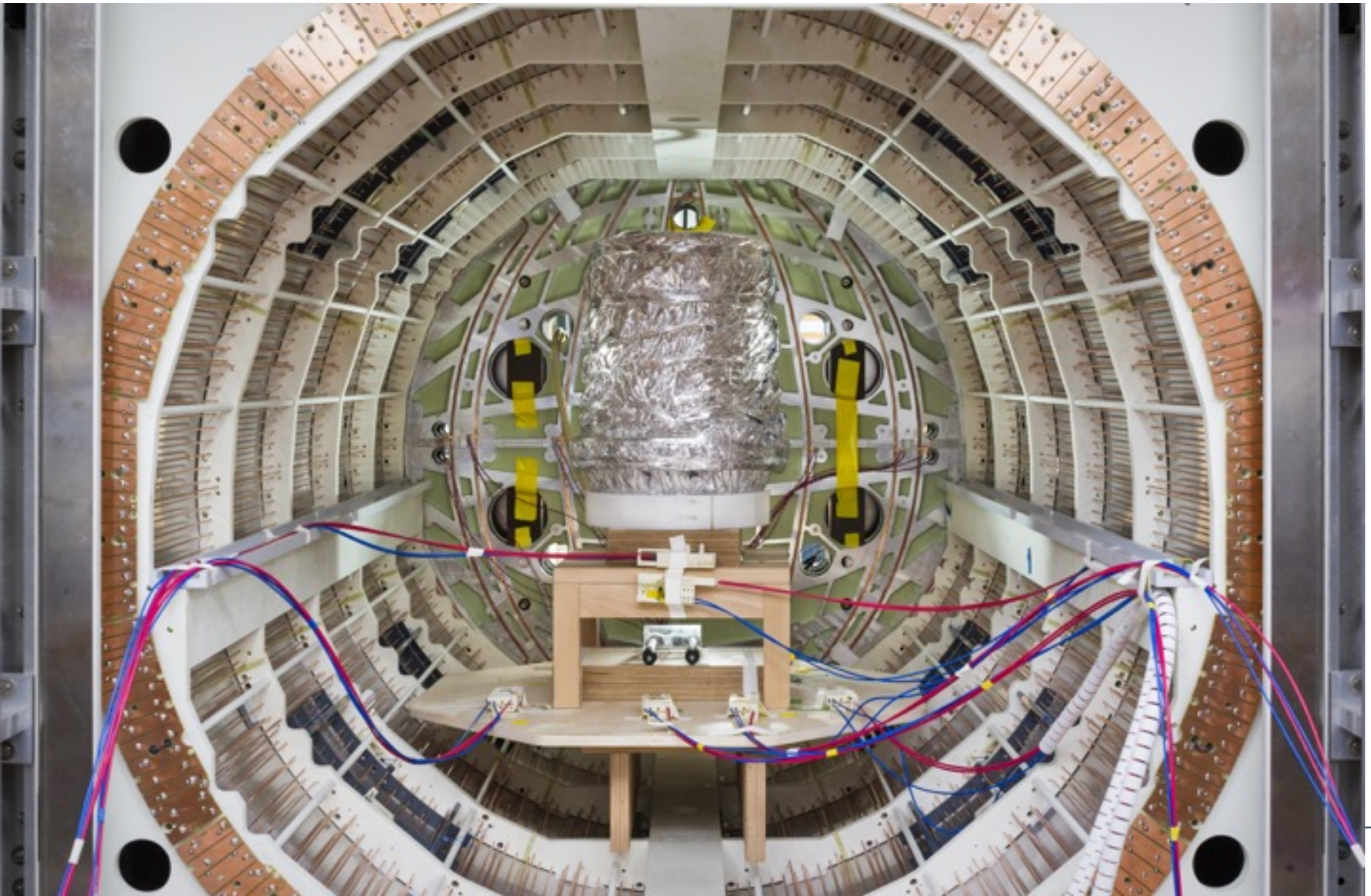
The new EDM apparatus at FRM2

Experiment - Setup



External Magnetic Shielding

Fierlinger et al.



External Magnetic Shielding

Fierlinger et al.

- The ‘best performing’ shield
  - SF 10^6 @ 1mHz (w/o ext. comp. coil)
- Degaussing in 30 s
- Technology understood and available
- Further improvements possible

- Measured field in outer shield:
  < 3 nT in 5 cm distance from shield walls
  < 0.5 nT in 1 m^3 volume
  < 150 pT in EDM cell volume
  < 1 pT/cm gradient in
  0.5 m diameter

Key issue: magnetometry
- Cs magnetometers and Hg co-magnetometer

Dominant Systematic Effects

Leakage current of electrodes

produced additional magnetic field:

precession - small for $I_{Leak} < 1\ nA$

Motional fields

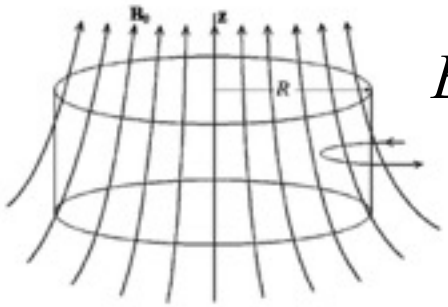
B-field in rest system of neutron

owing to is motion

< 10^{-26} e·cm

$$\vec{B}_{\upsilon} = \frac{\vec{E} \times \vec{\upsilon}}{c^2}$$

Vertical gradient



$$B_z \rightarrow B_r \propto r$$

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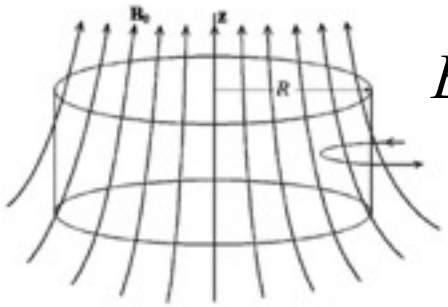

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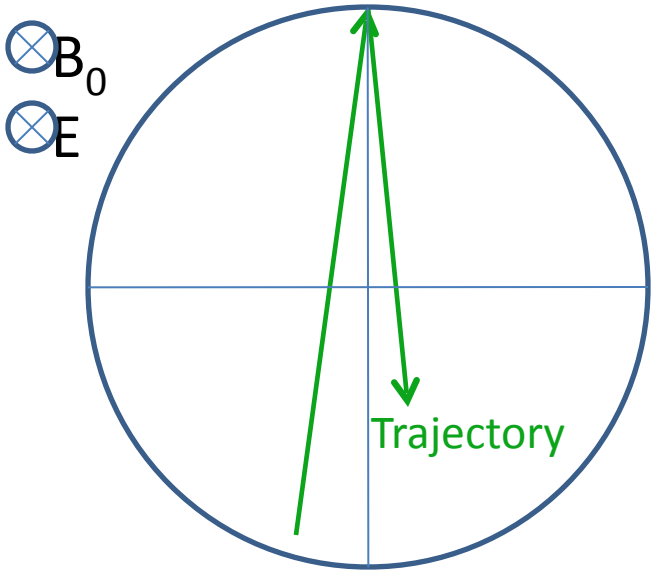
Motional fields and gradient cause 'geometrical' phase effect



(view from above into neutron storage chamber B, E are vertical)

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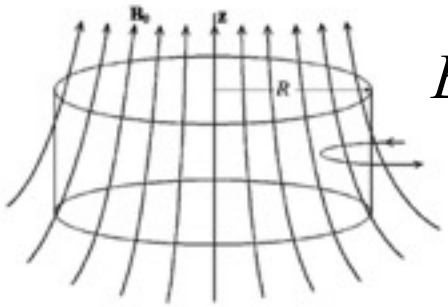

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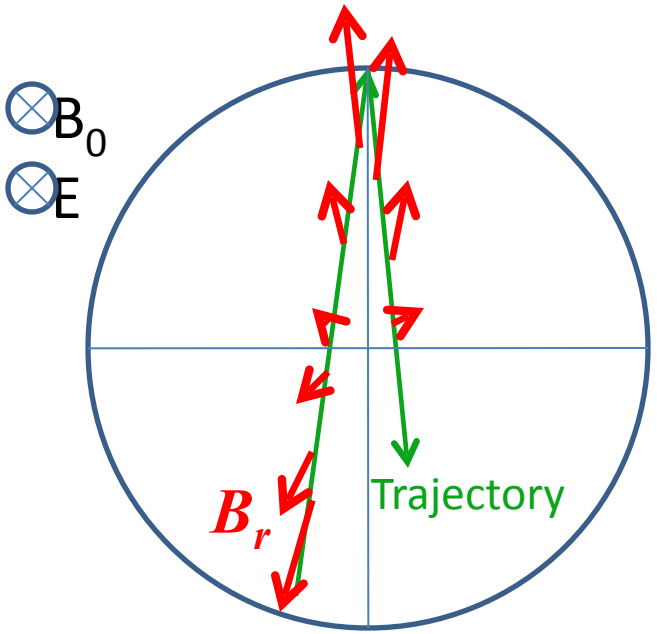

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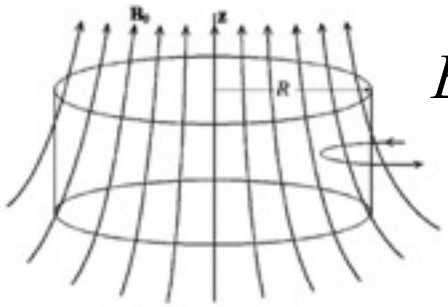

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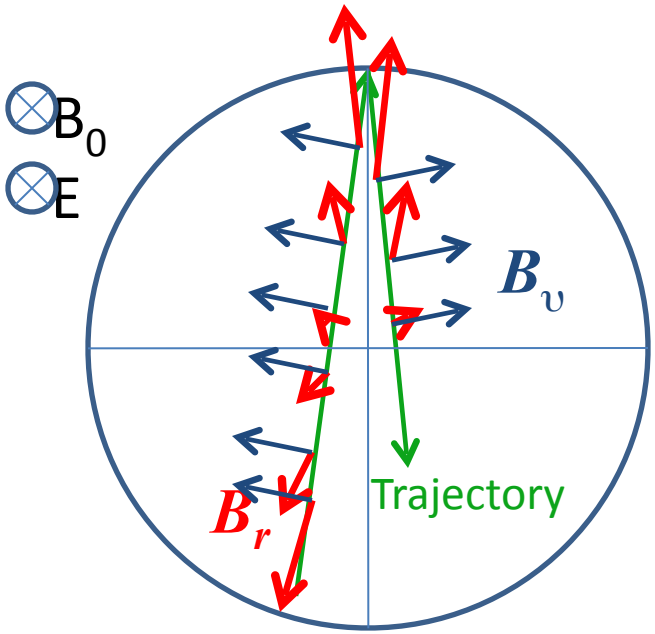

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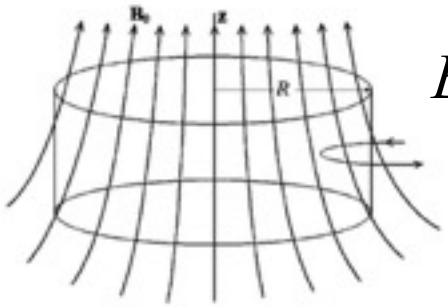

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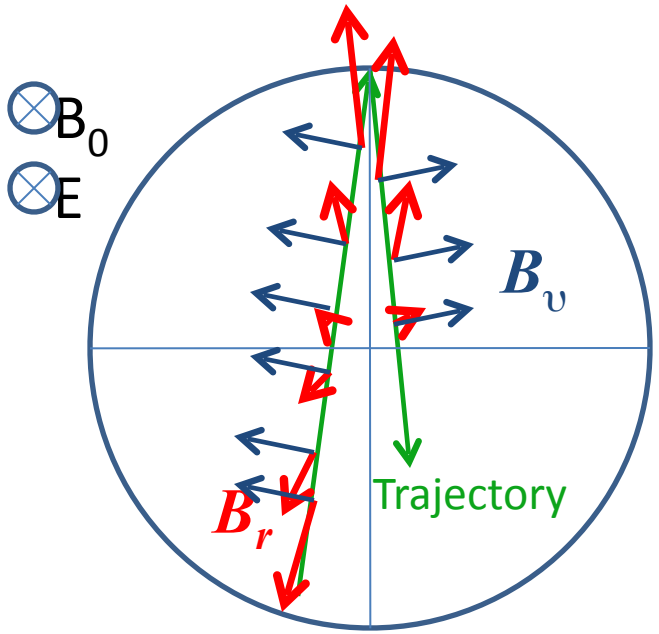
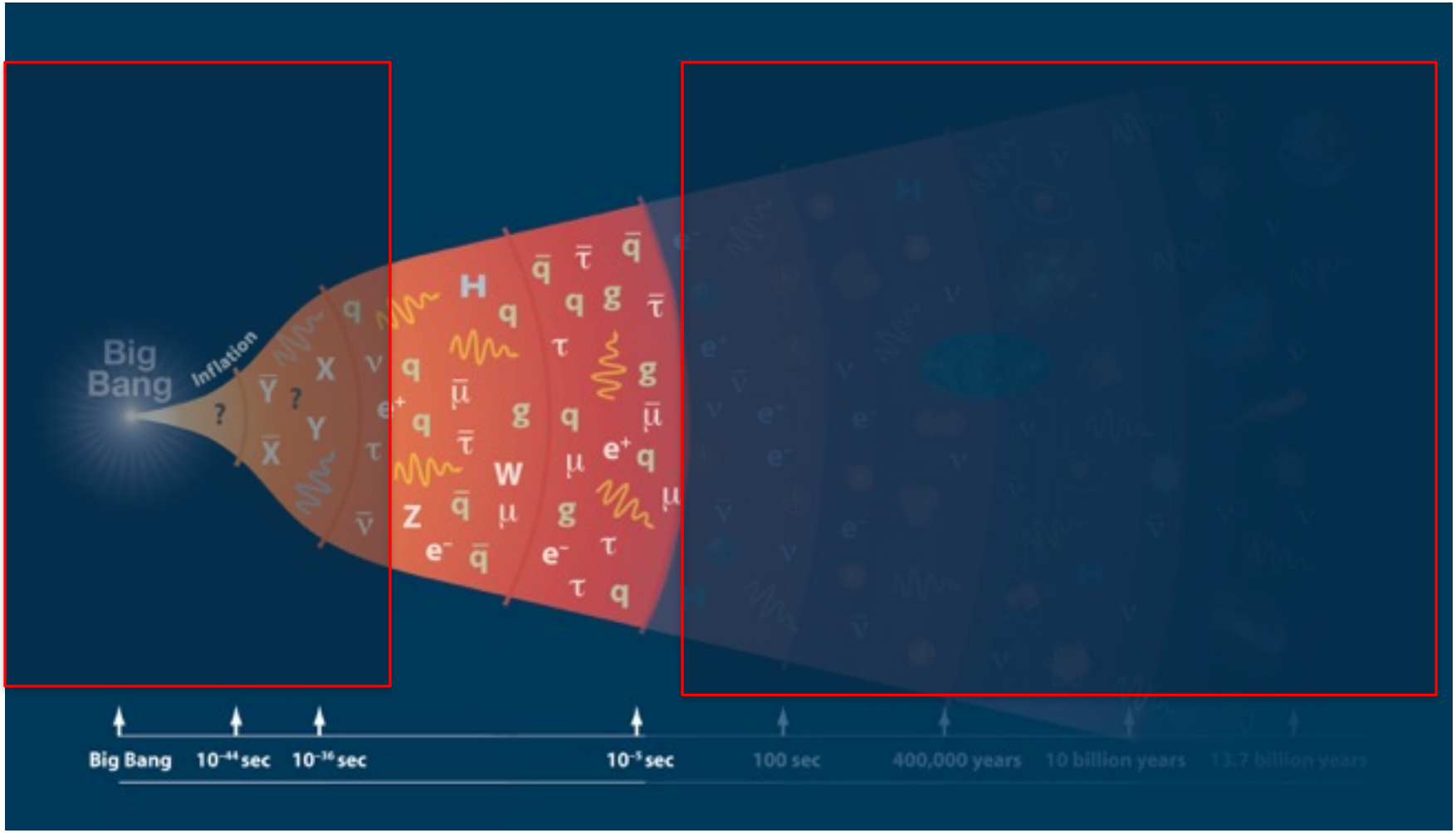


(view from above into neutron storage chamber B, E are vertical)

Different for UCN and comagnetometer:

10^{-26} e·cm level

Until 10^{-6} Seconds past Big Bang



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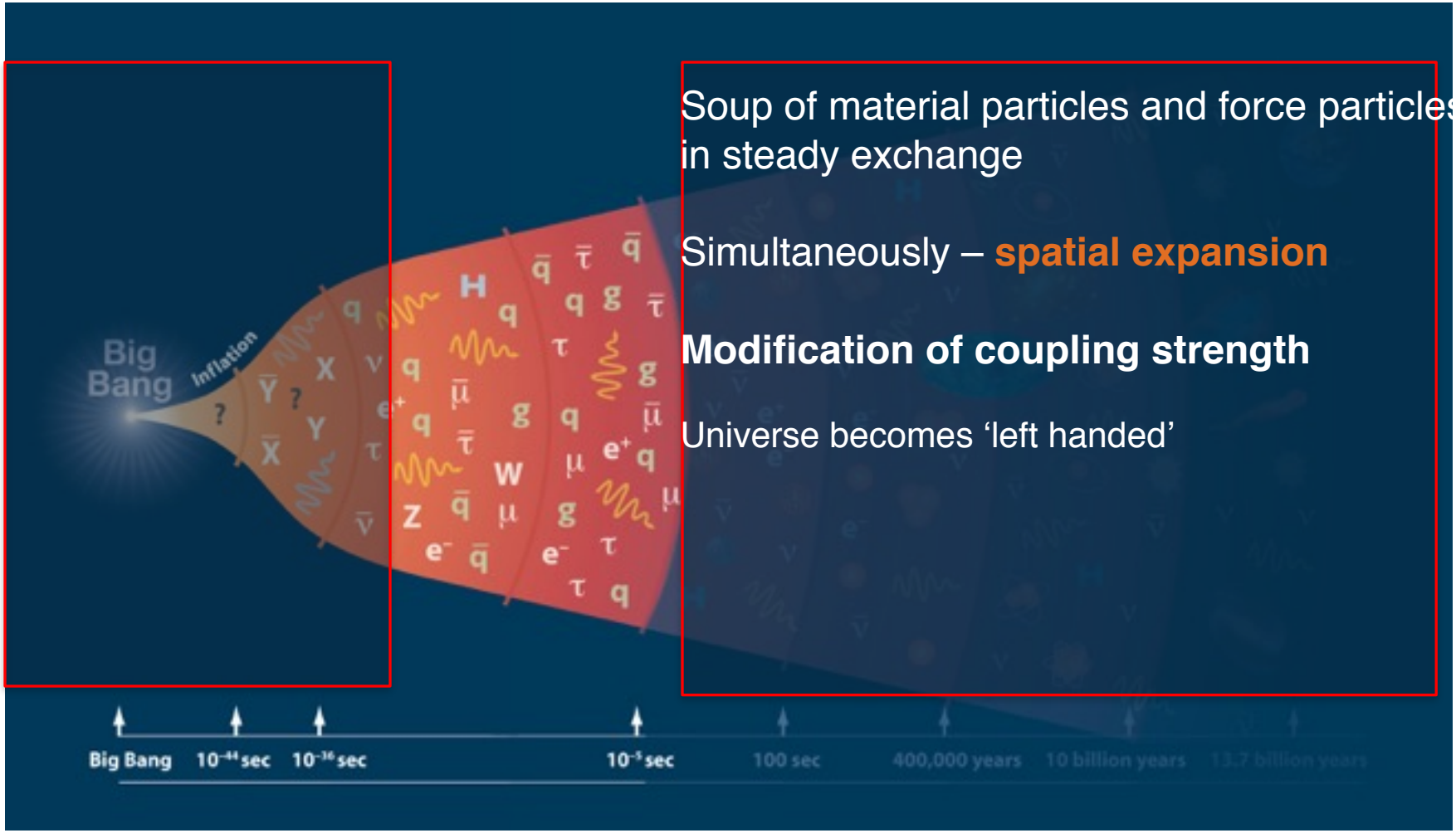

Soup of material particles and force particles in steady exchange

Simultaneously – **spatial expansion**

Modification of coupling strength

Universe becomes ‘left handed’

β-Decay

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

β-decay rate:

$$w \propto 1 + a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \frac{\langle \vec{J}_A \rangle}{j_A} \left[A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right] + c[..]$$

$$\frac{C_S}{C_V} < 7\%, \quad \frac{C_T}{C_A} < 9\%$$

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- a, b, c, A, B, D.. Depend on 10 Coupling constants C_i , C'_i
- sensitive to S, V, A, T, P type interaction
- sensitive to symmetries
  - P-violating: A, B , C, R
  - T-violating: D, R

- in standard model: a, A, B and C connected to $\lambda = \frac{g_A}{g_V}$

SM Parameter and Observables

Parameter

Strength: G_F

Quark mixing: V_{ud}

Ratio: $\lambda = g_A/g_V$

$$\tau^{-1} = V_{ud}^2 G_F^2 (1 + 3\lambda^2) \frac{f^R m_e^5 c^4}{2\pi^3 \hbar^7}$$

SM Parameter and Observables

Parameter

Strength: G_F

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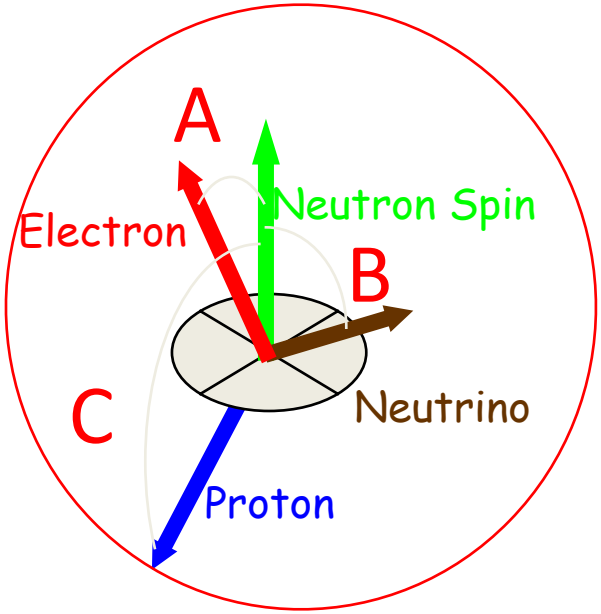
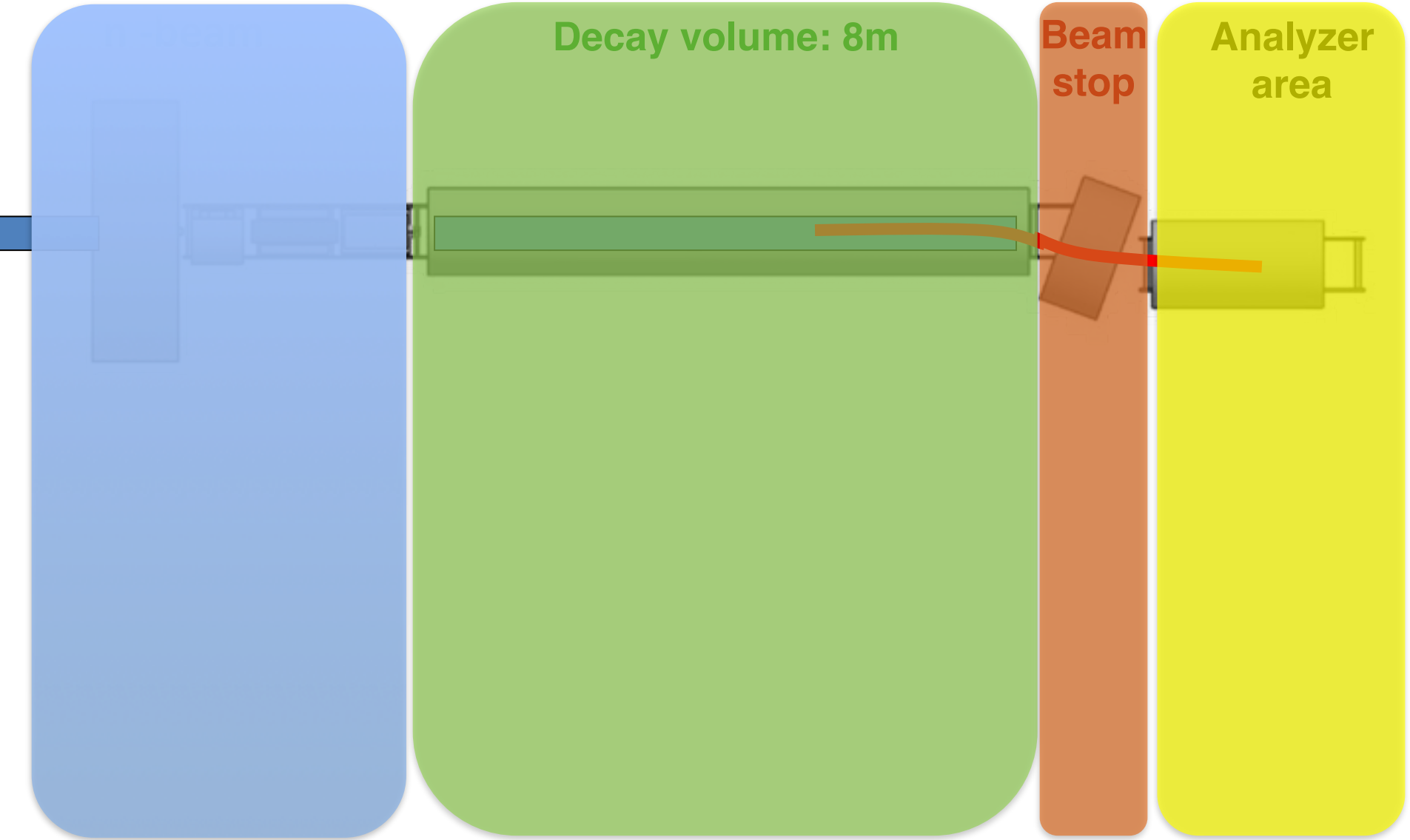
Ratio: $\lambda = g_A/g_V$



A: electron asymmetry
C: proton asymmetry
B: electron spectrum
a: proton spectrum
D: triple product

PERC:
Precision experiments for decay asymmetries



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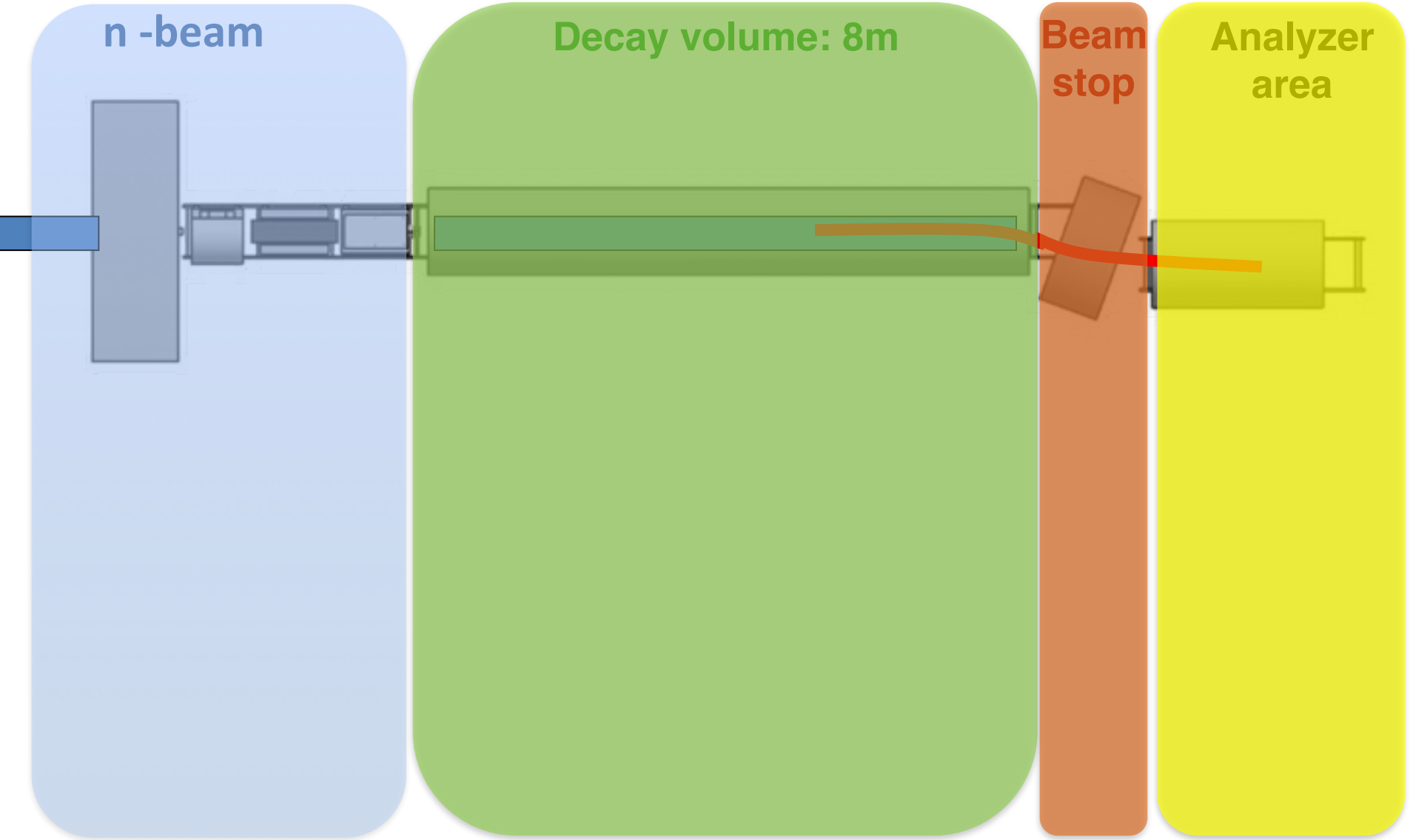

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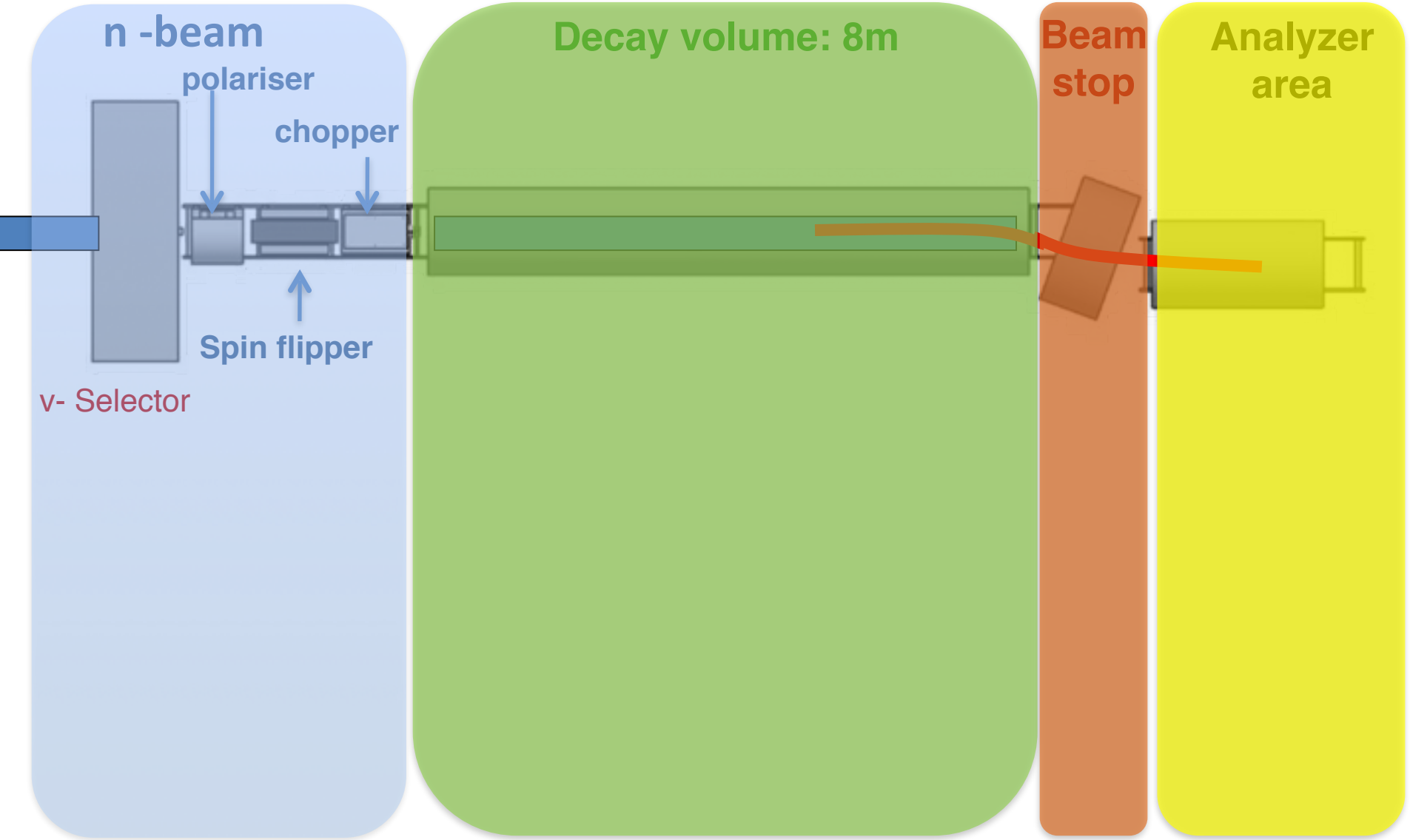

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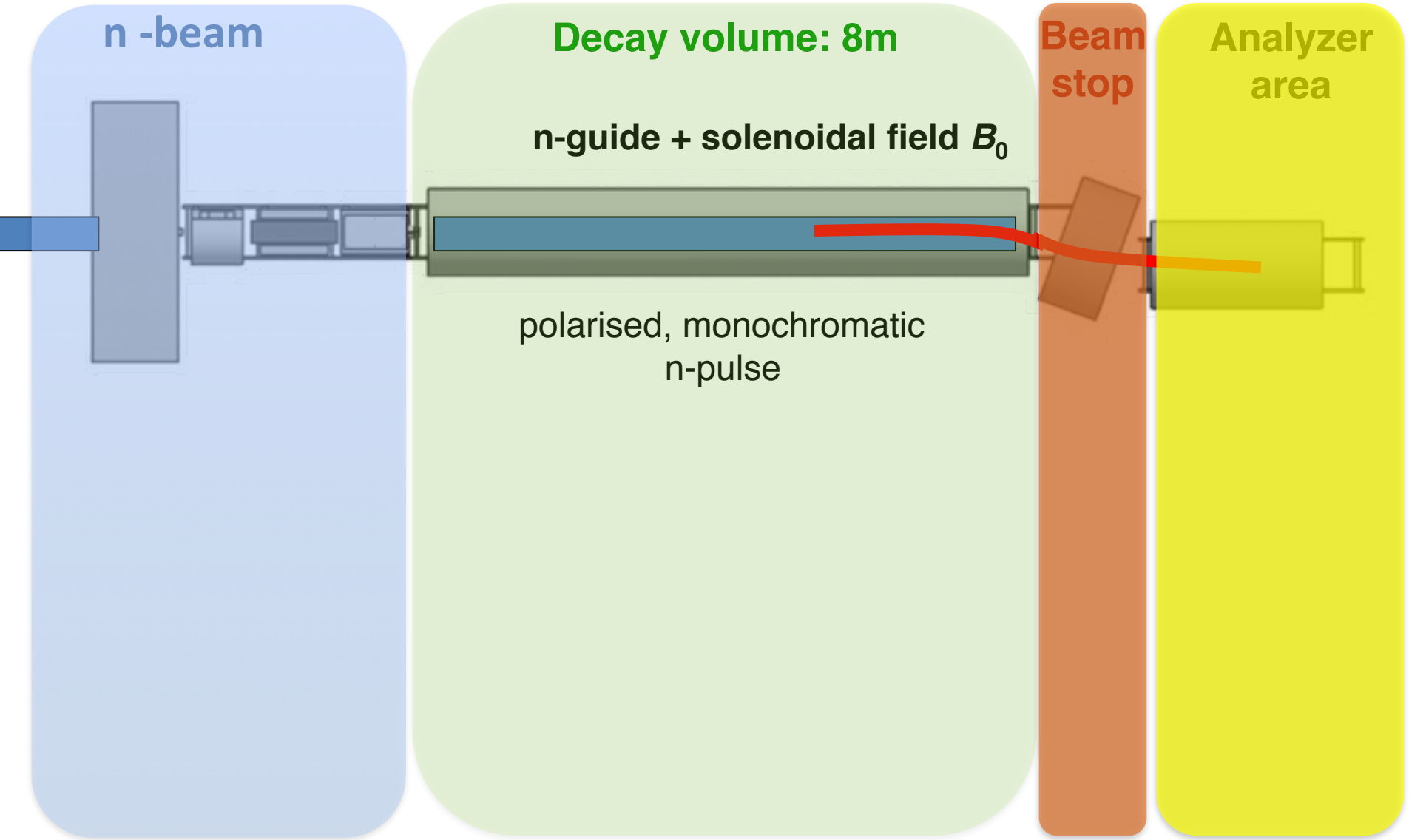

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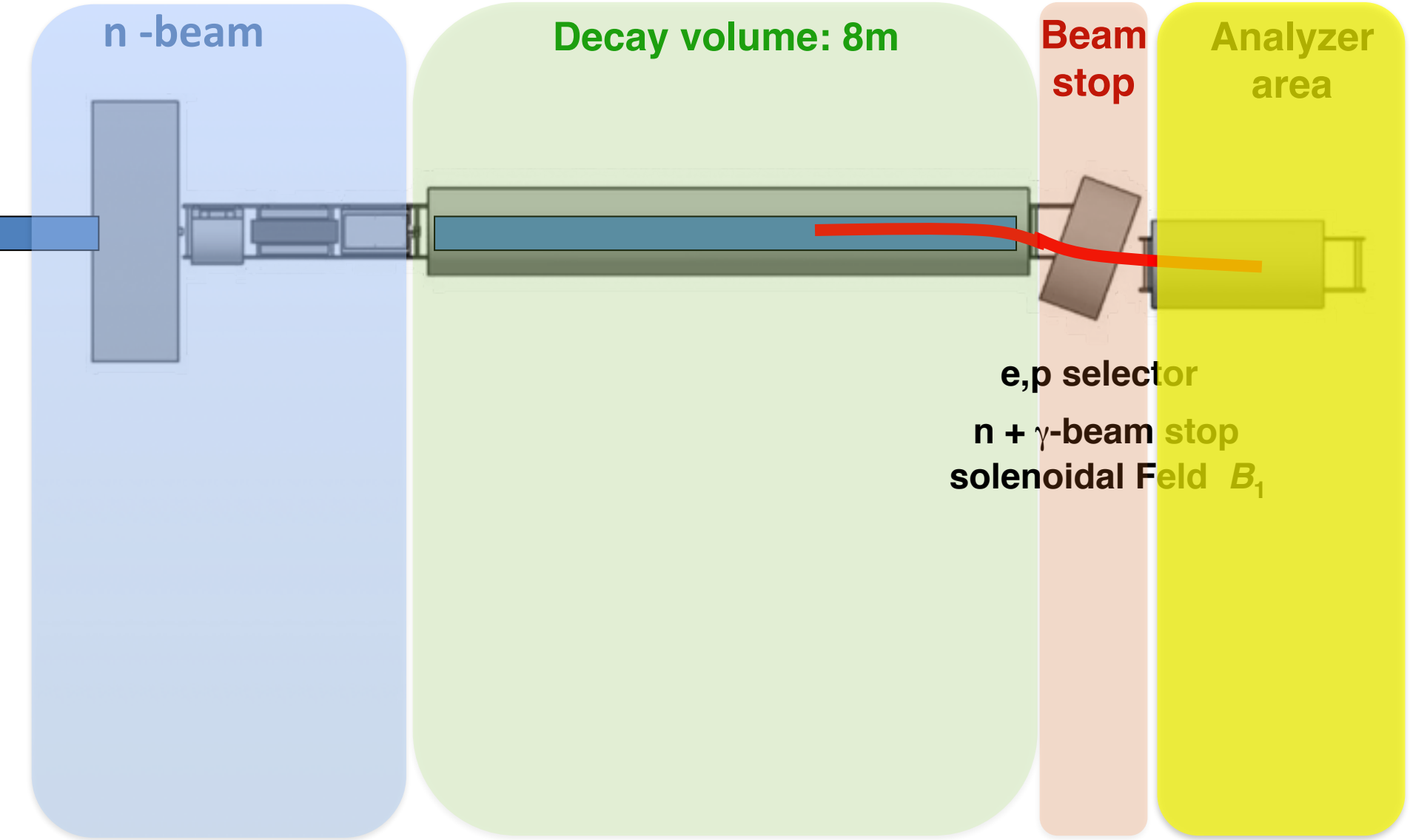

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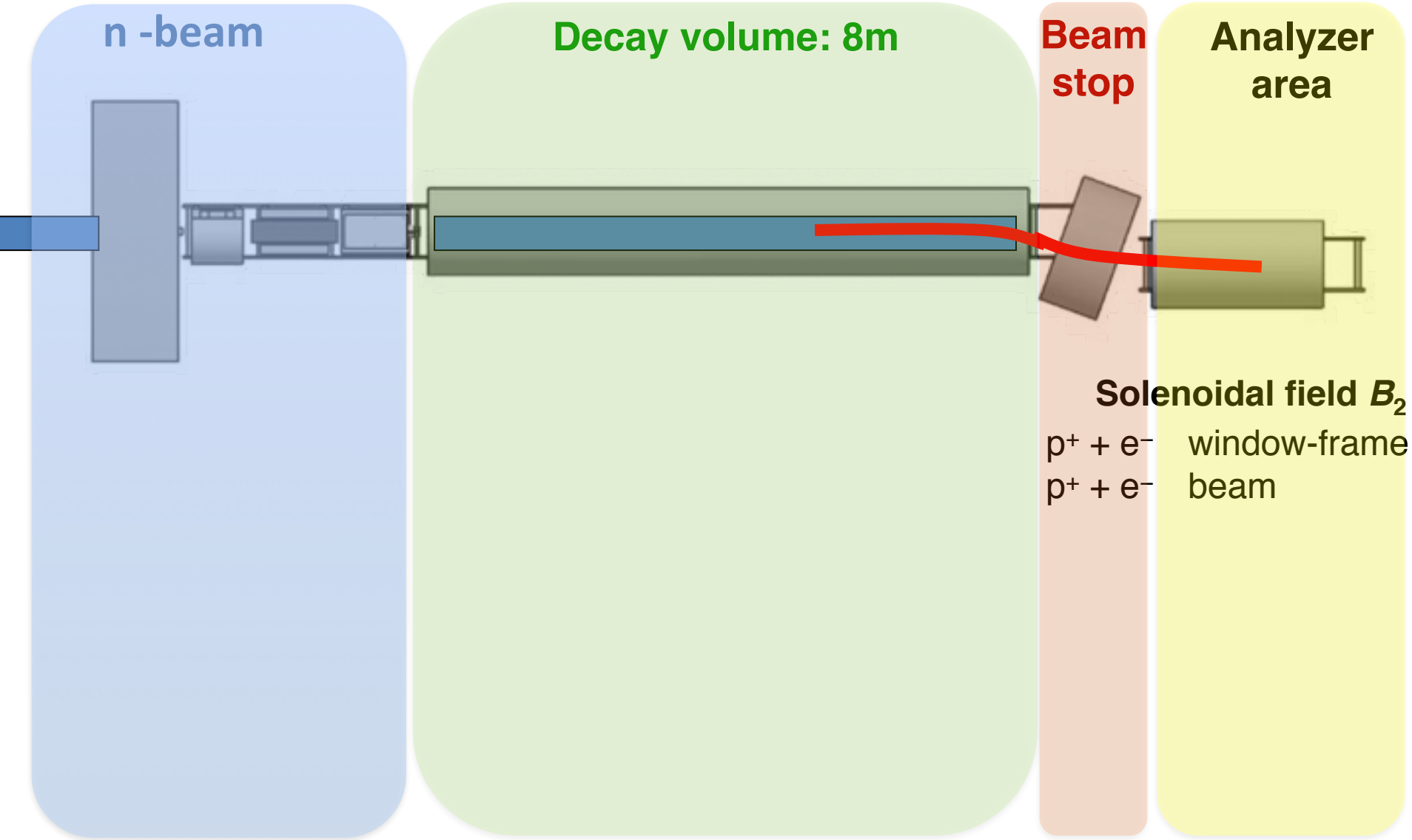

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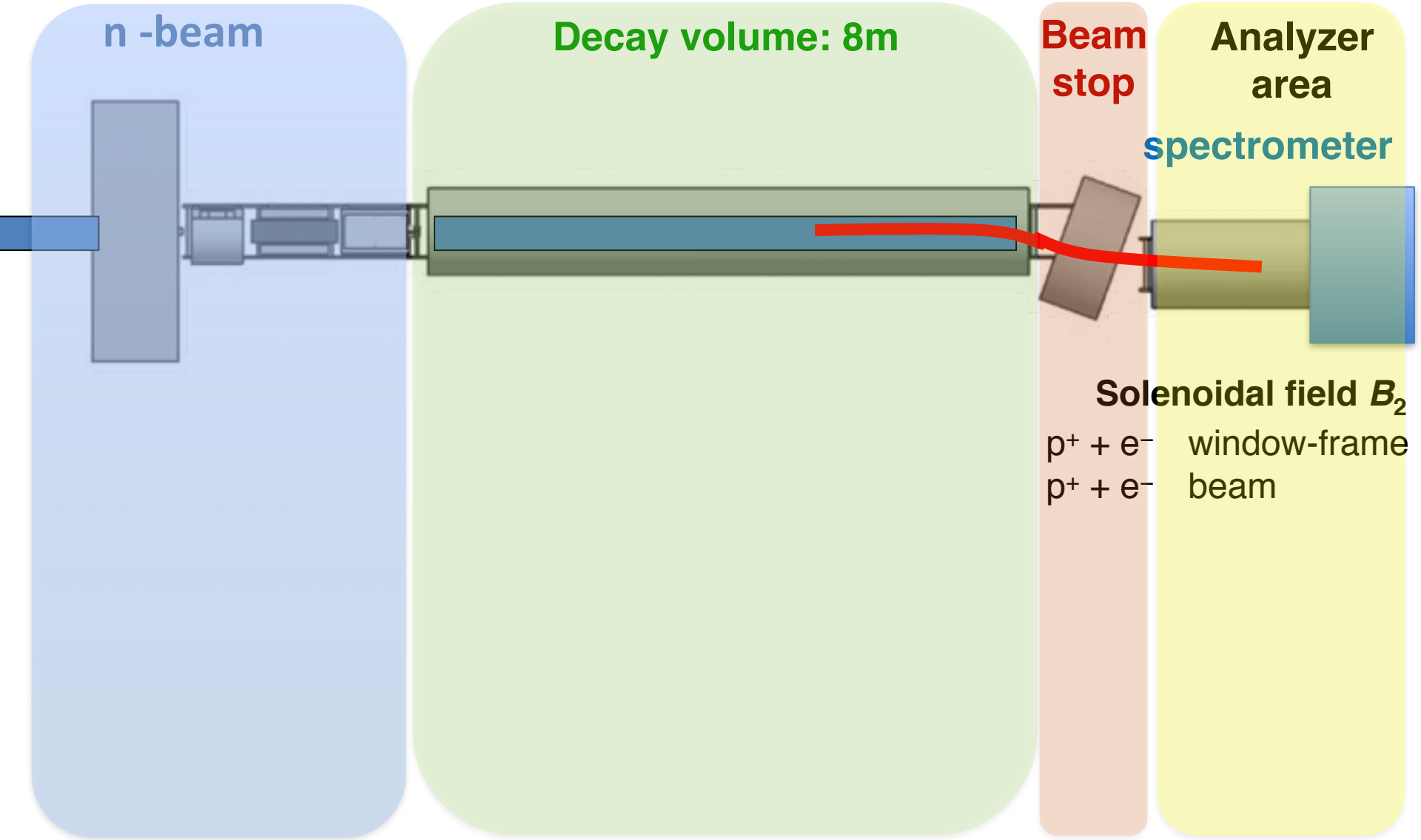

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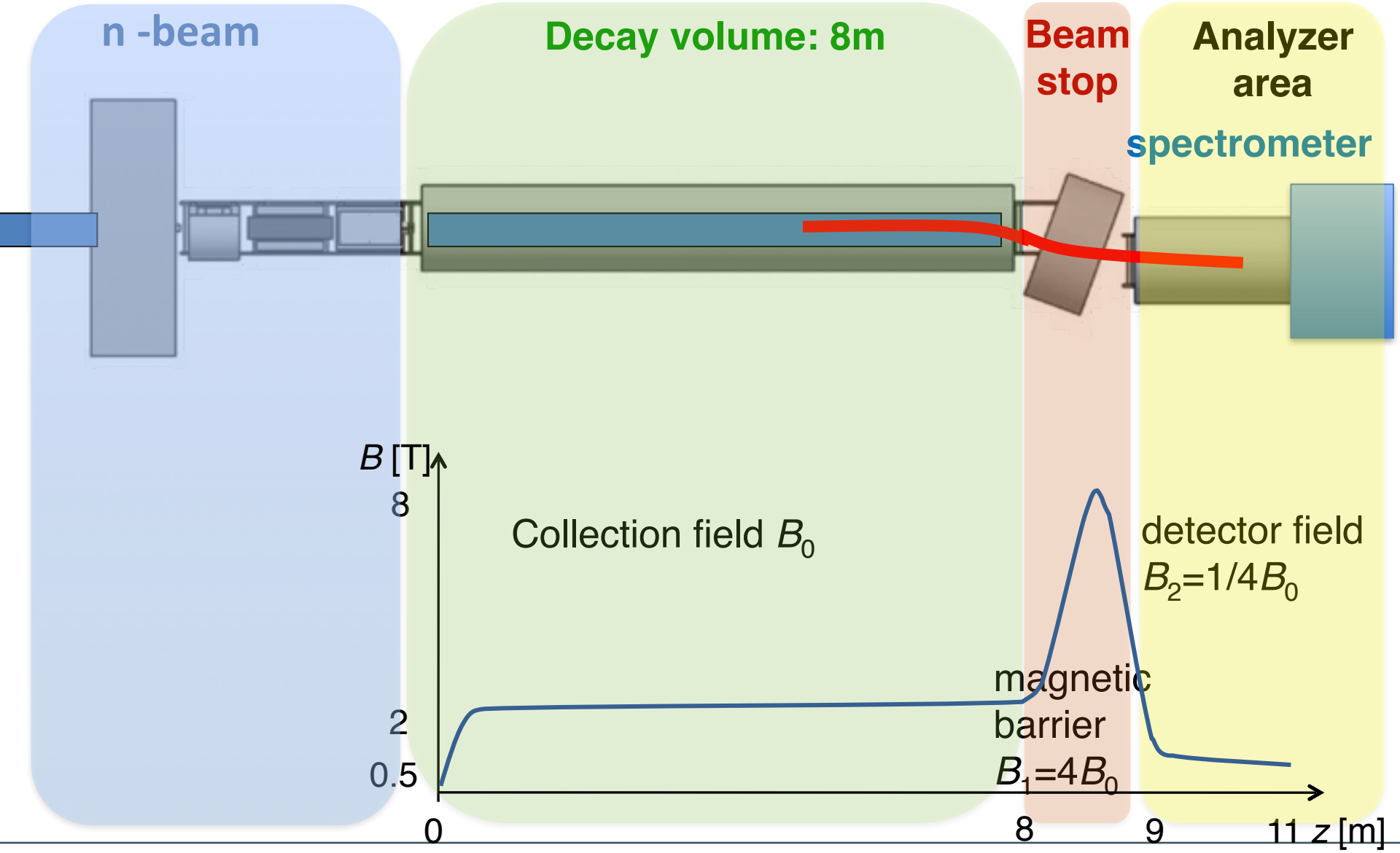


PERC

Properties:

- High flux: $\Phi = 2 \times 10^{10}$ cm^{-2}s^{-1} → decay rate : 1 MHz / meter
- Polarizer: > 99.7 ± 0.01 %
- Spin Flipper: 100 % ± 0.1 %
- Analyzer: 100 % ^{3}He-cells
- Spectrometer free choice

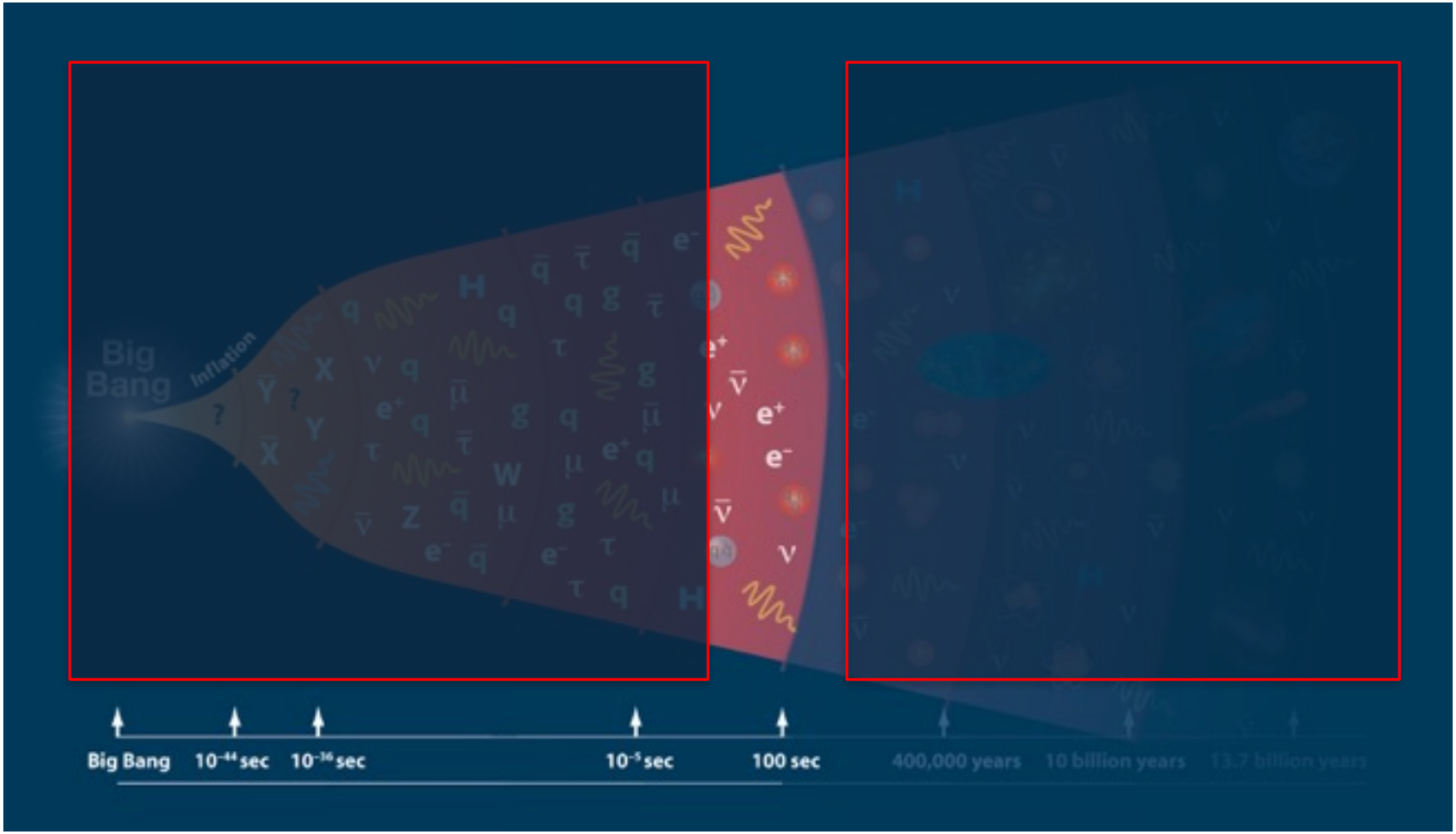
Goal: Improve precision on asymmetries by

1-2 orders of magnitude in both, statistical and systematic uncertainties

Magnet delivery: 2017

Start: 2018

10^{-2} – 10^{3} Seconds after Big Bang



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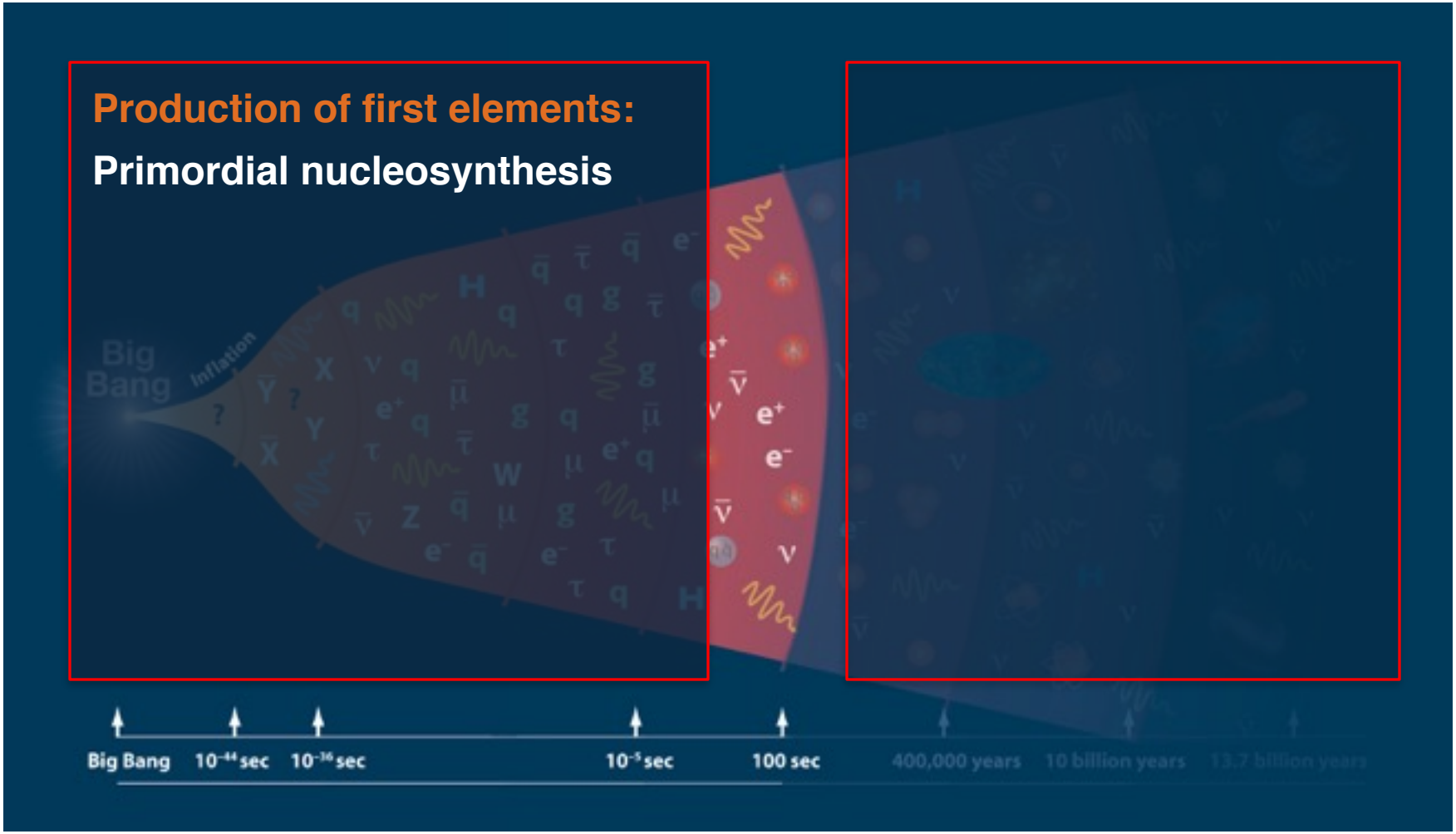
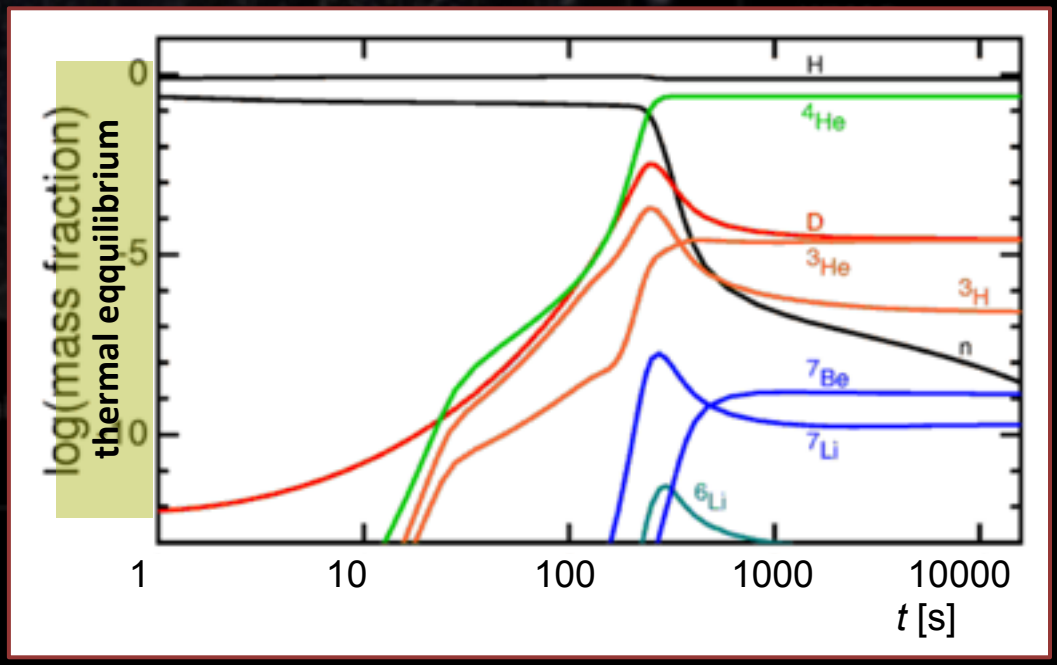


Primordial Nucleosynthesis

t < *1* s, *kT* > *1.3* MeV (15 billion °C)*
thermal equilibrium

$$p + e^- \rightleftharpoons n + \nu$$
$$n + e^+ \rightleftharpoons p + \bar{\nu}$$



T in sun 6000°C at surface to 15 Mio°C in the core

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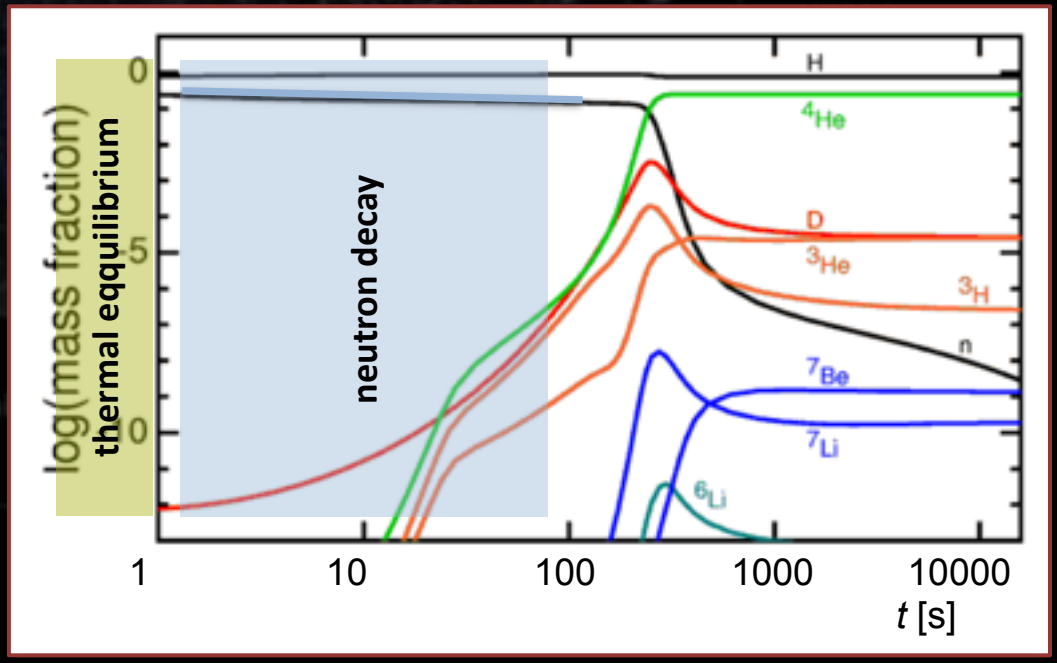
1 s < t < 100 s, 0.1 MeV < *kT* < *1.3* MeV
neutron decay

$$n \rightarrow p + e^- + \bar{\nu}$$

n/p: 1/6 ➢ 1/7



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Primordial Nucleosynthesis

Exzellenzcluster Universe

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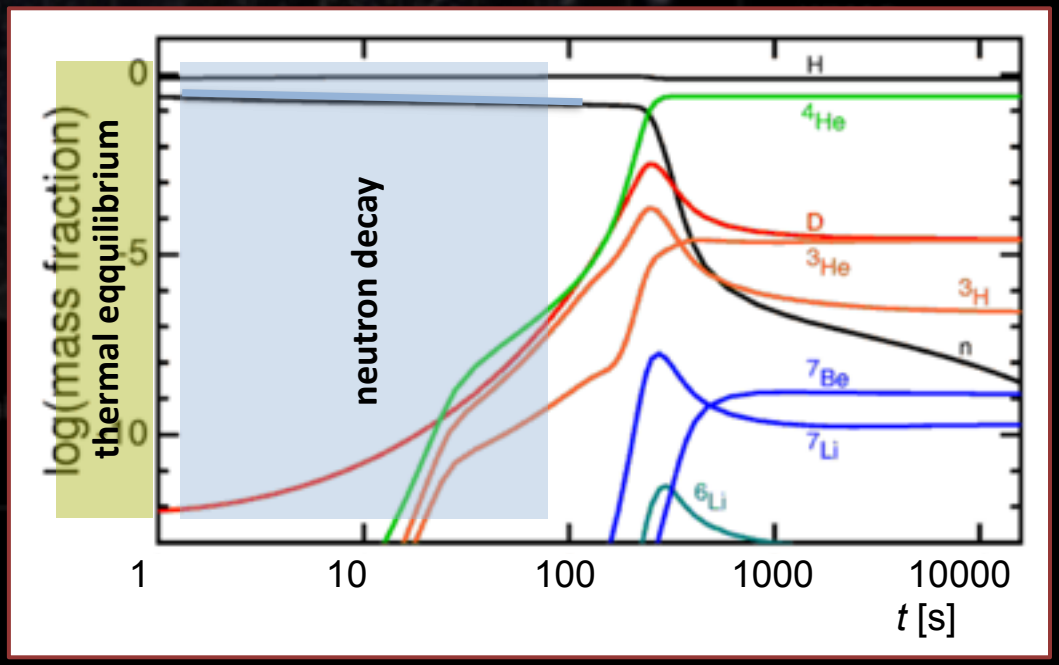
t > *100* s, *kT* < *0.1* MeV, bec. of γ/B

deuterium fusion

$$n + p \rightarrow d + \gamma$$



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Primordial Nucleosynthesis

t < 1 s, *kT > 1.3* MeV (15 billion °C)*

thermal equilibrium

$$p + e^- \rightleftharpoons n + \nu$$

$$n + e^+ \rightleftharpoons p + \bar{\nu}$$

t > 100 s, *kT < 0.1* MeV (1.2 billion °C)

nucleosynthesis

$$d + p \rightarrow {}^3\mathrm{He} + \gamma \qquad {}^3\mathrm{He} + n \rightarrow {}^3\mathrm{H} + p$$

$$d + d \rightarrow {}^3\mathrm{H} + p \qquad {}^7\mathrm{Li} + p \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$$

$$d + d \rightarrow {}^3\mathrm{He} + n \qquad {}^7\mathrm{Be} + n \rightarrow {}^7\mathrm{Li} + p$$

$${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma \qquad {}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$$

$${}^3\mathrm{He} + d \rightarrow {}^4\mathrm{He} + p$$

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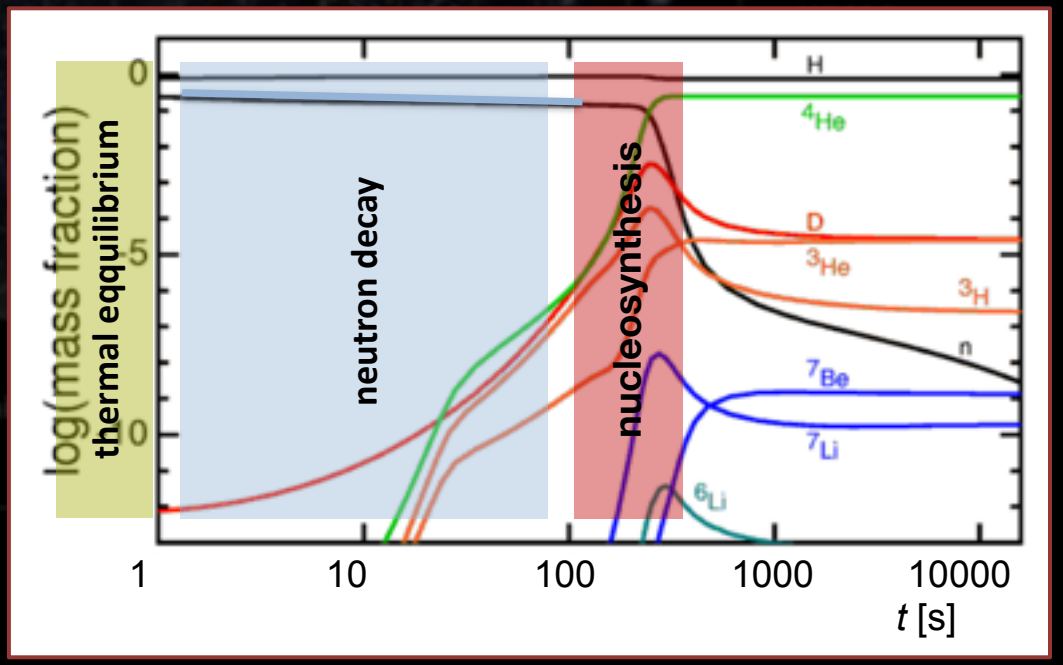

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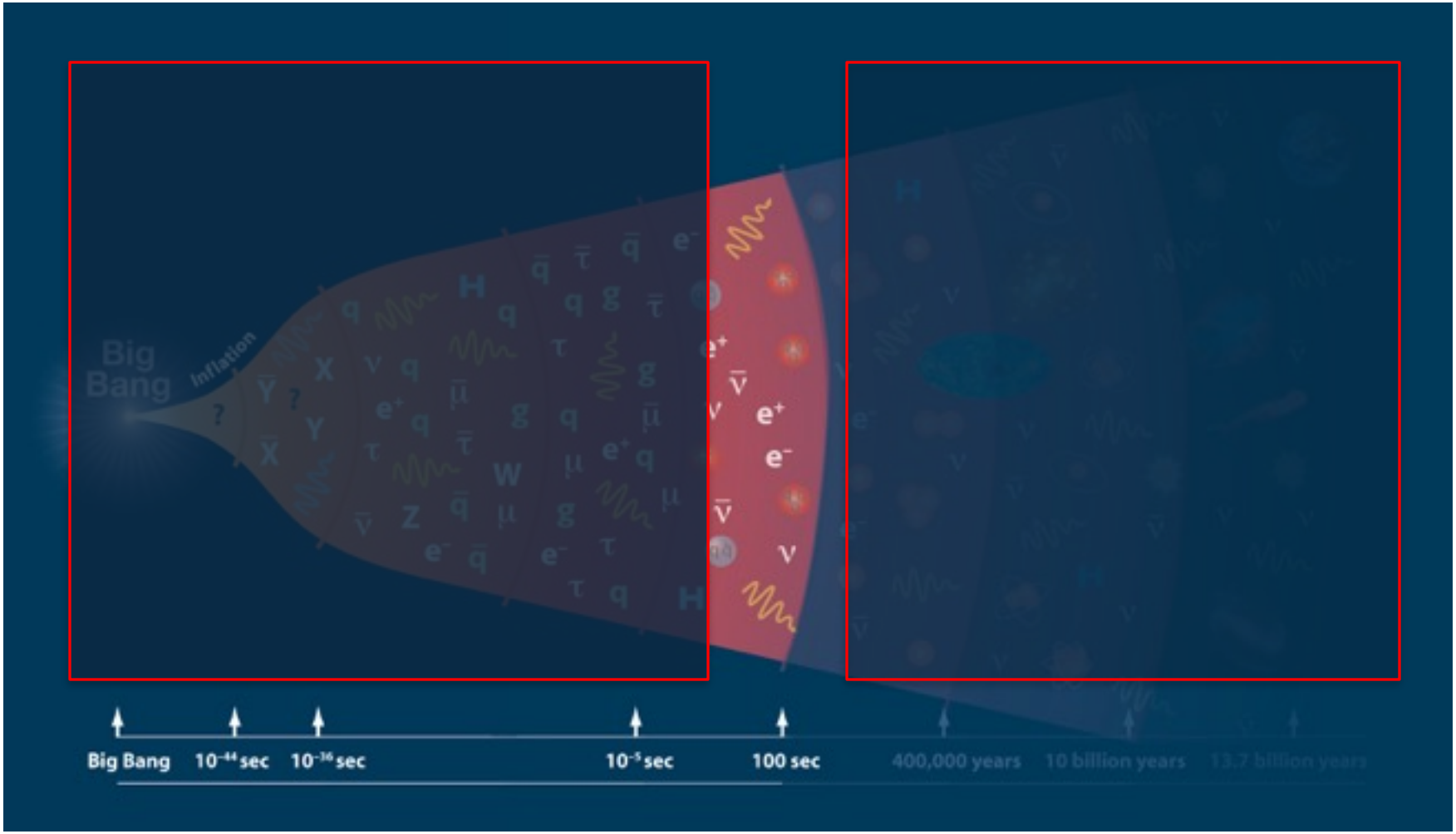
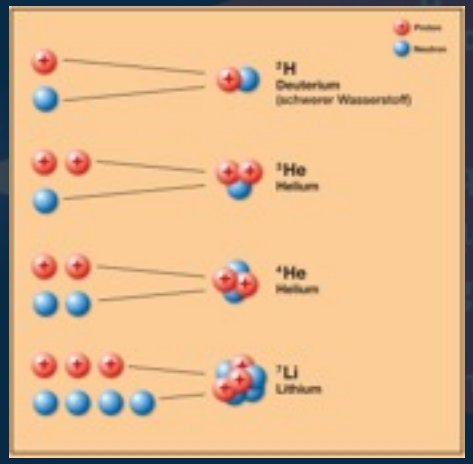
10^{-2} – 10^{3} Seconds past Big Bang



10^{-2} – 10^{3} Seconds past Big Bang

Production of first elements:

Primordial nucleosynthesis



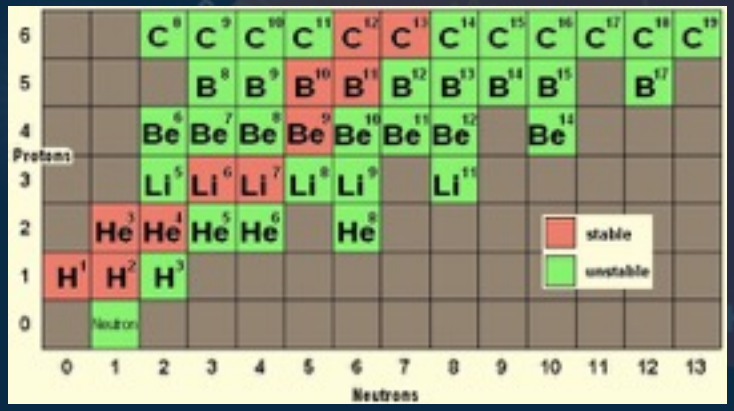
Big Bang

Big Bang | 10^{-44} sec | 10^{-36} sec | 10^{-5} sec | 100 sec | 400,000 years | 10 billion years | 13.7 billion years

10^{-2} – 10^{3} Seconds past Big Bang

Production of first elements:

Primordial nucleosynthesis



No stable element with A = 5 and A = 8

^{4}He is final product

relevant quantity:
neutron lifetime
and couplings

10^{-2} – 10^{3} Seconds past Big Bang

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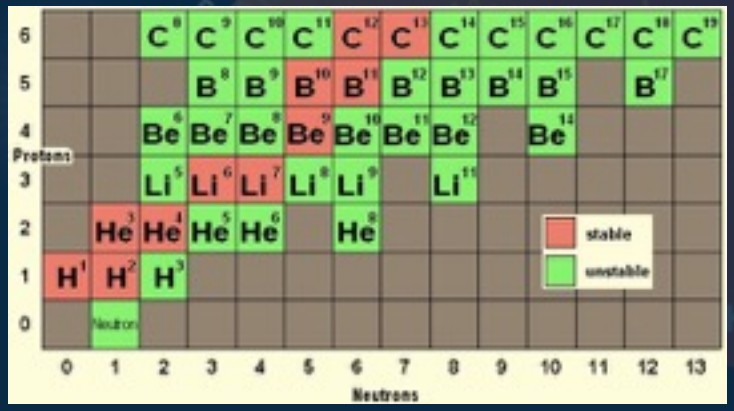
Primordial nucleosynthesis



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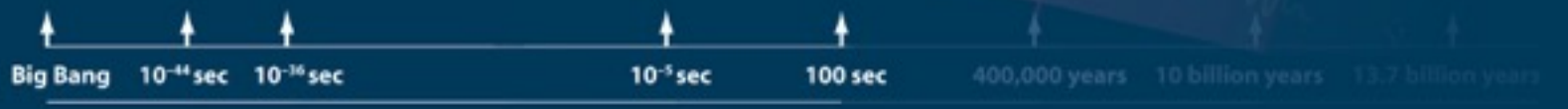
first 3 Minutes are over



Neutron Lifetime and Nucleosynthesis

Three parameters:

$\eta_{10} = (n_B / n_\gamma) * 10^{10}$

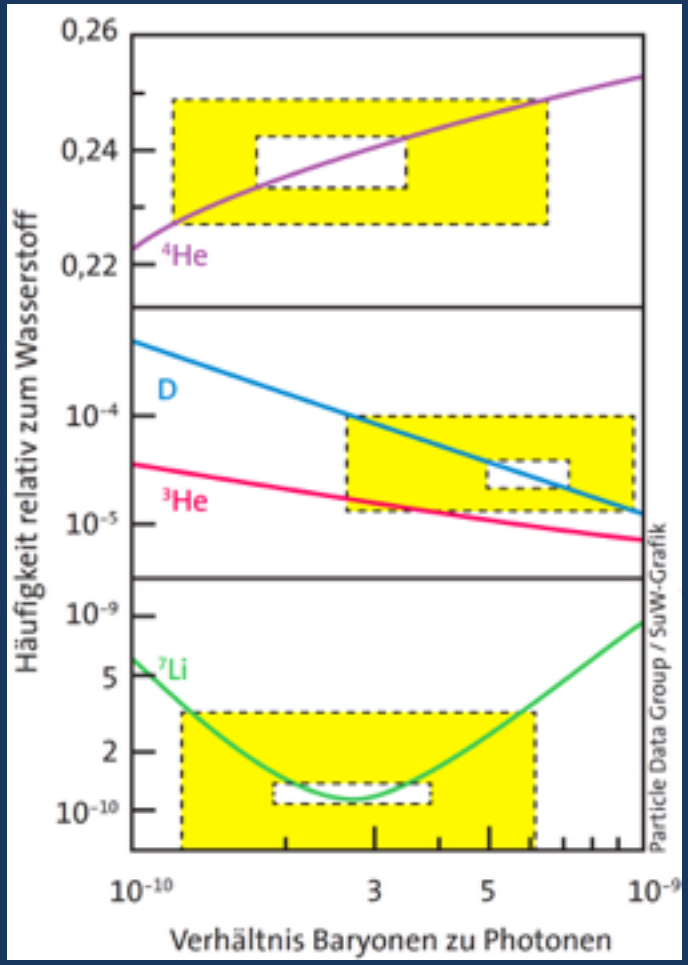
- CMB (WMAP-Satellit)

$Y_p = 4\,He / (p + 4\,He)$

- Low metallicity (early) stars/galaxies

τ_n

- Experiments



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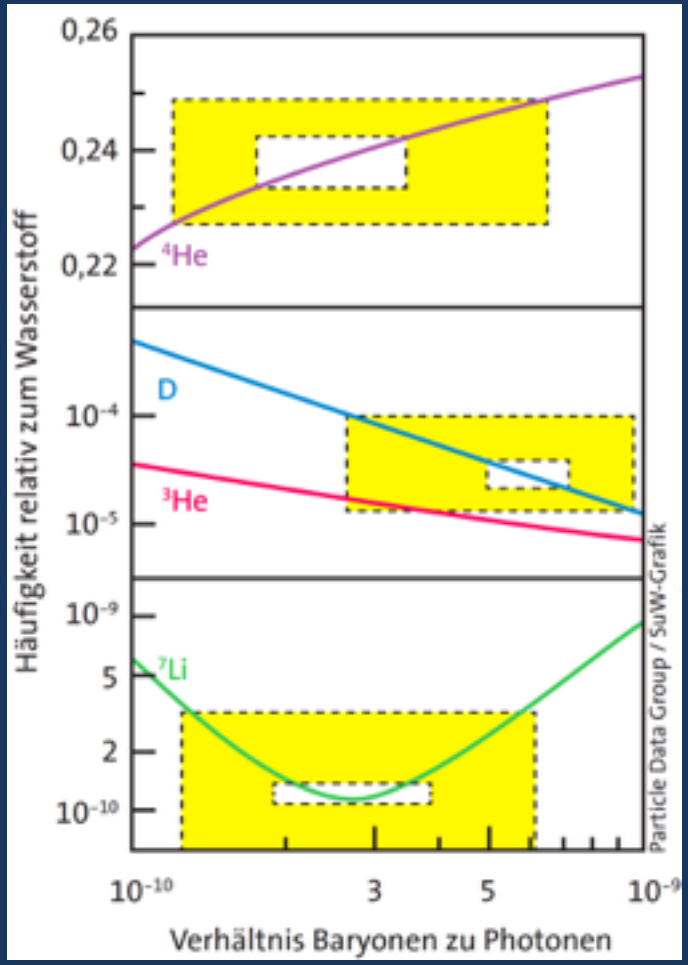
Knowledge of weak and nuclear force:

- Helium abundance*
- Deuteron abundance(small)**
- Lithium abundance(small)**



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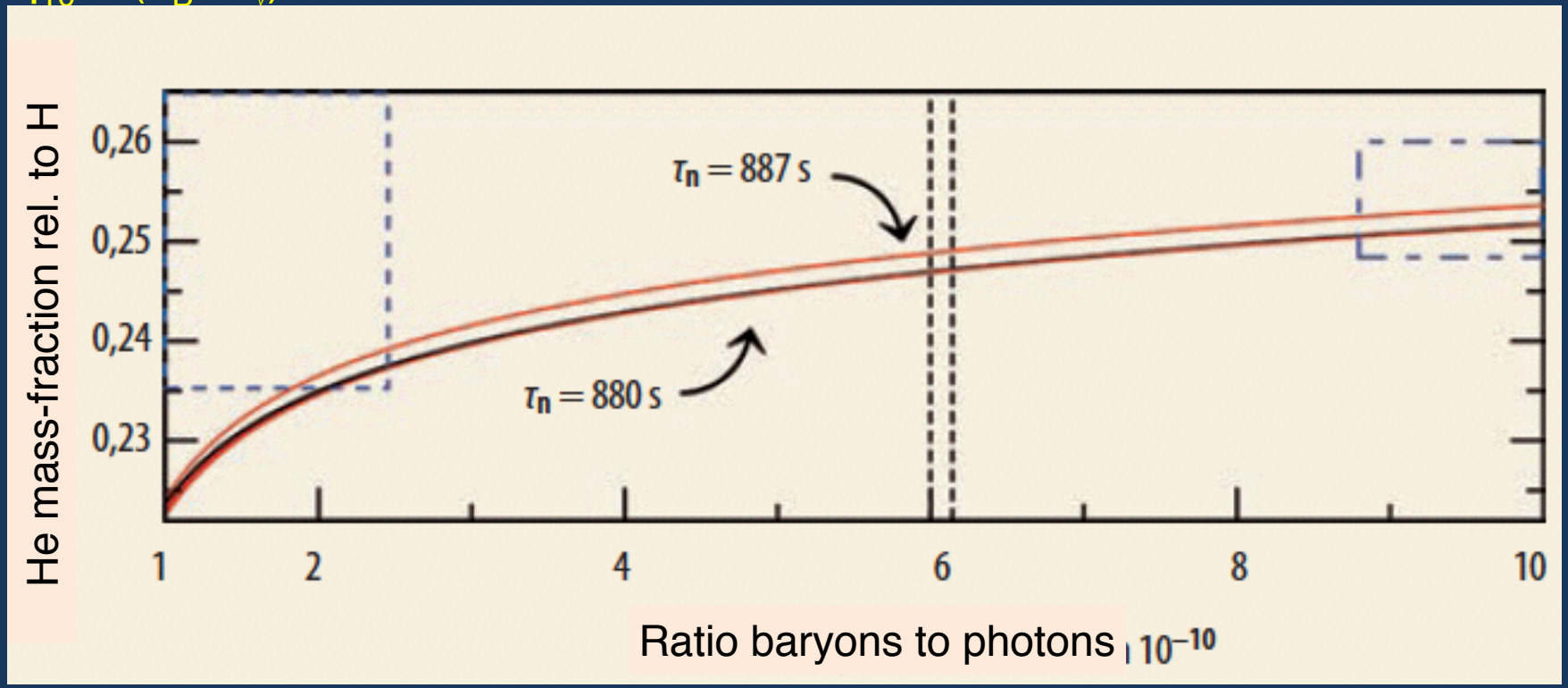

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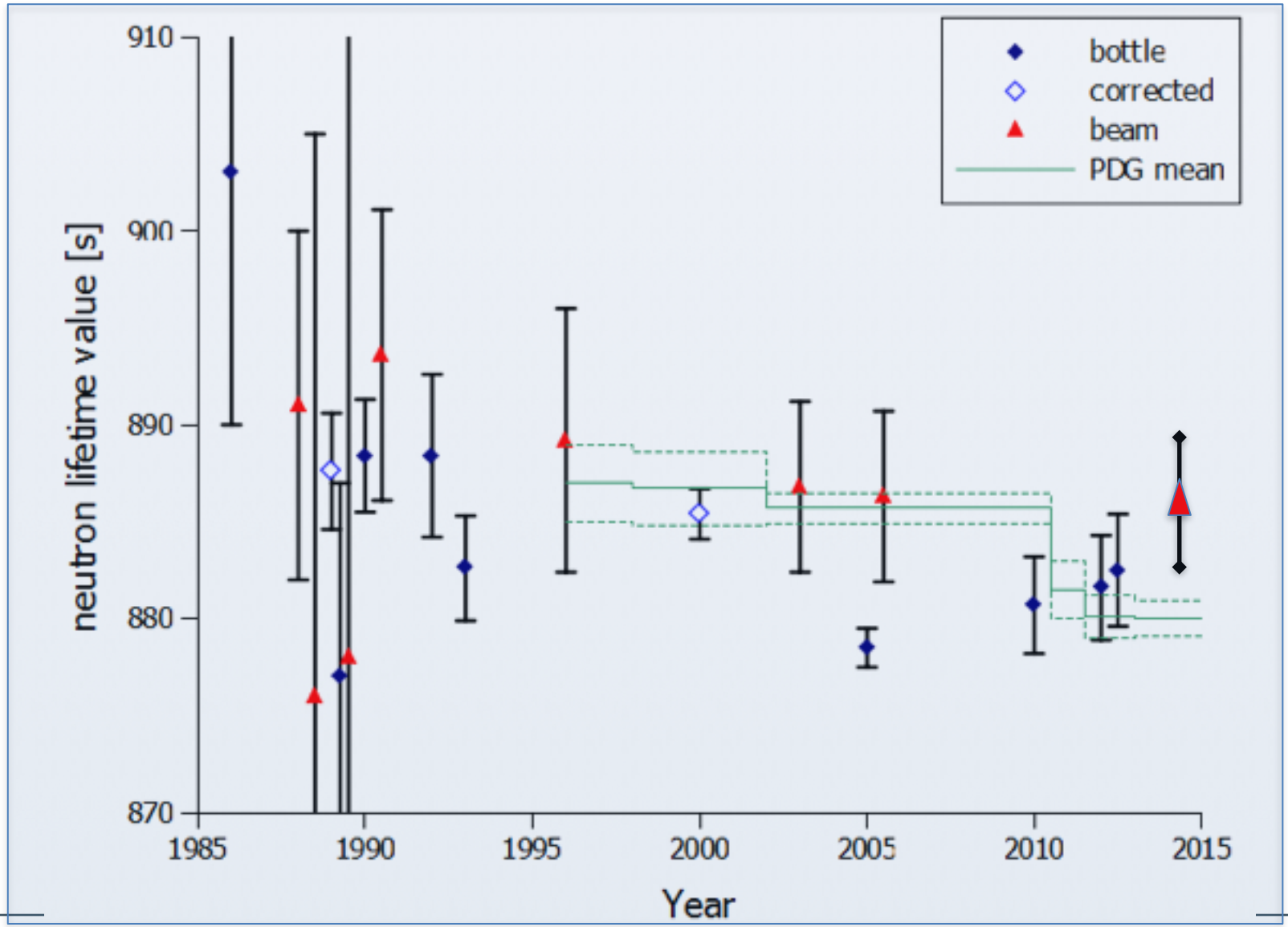
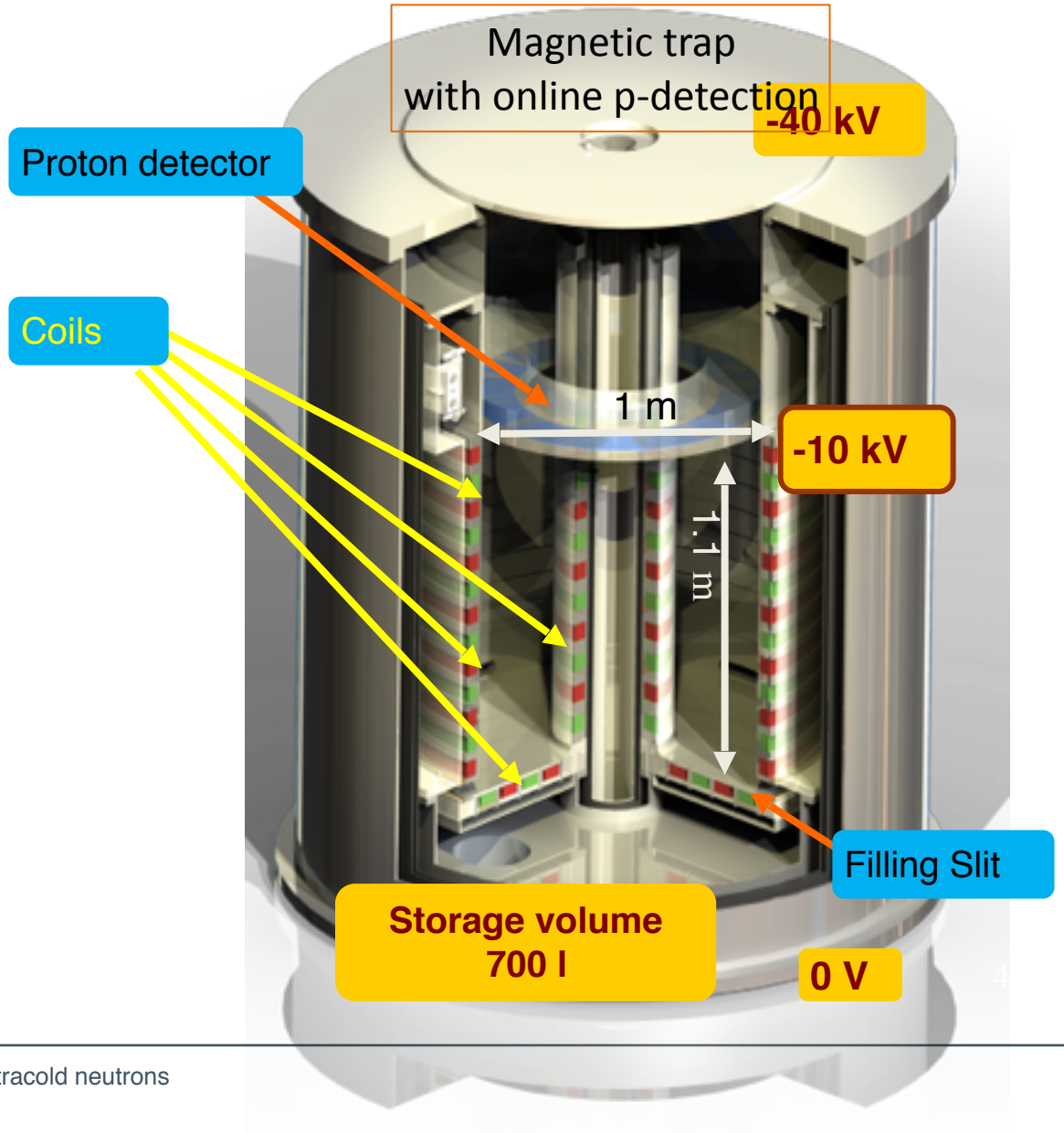
Lifetime - Overview



Lifetime - Overview

Measurement of n-Lifetime with PENeLOPE

Exzellenzcluster Universe



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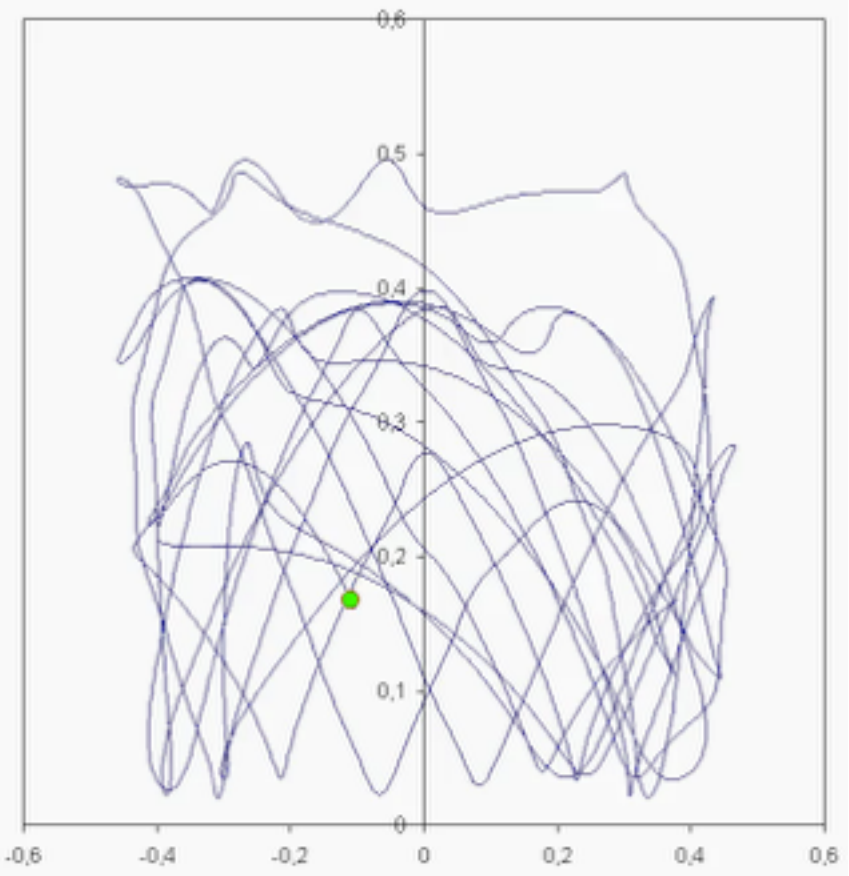
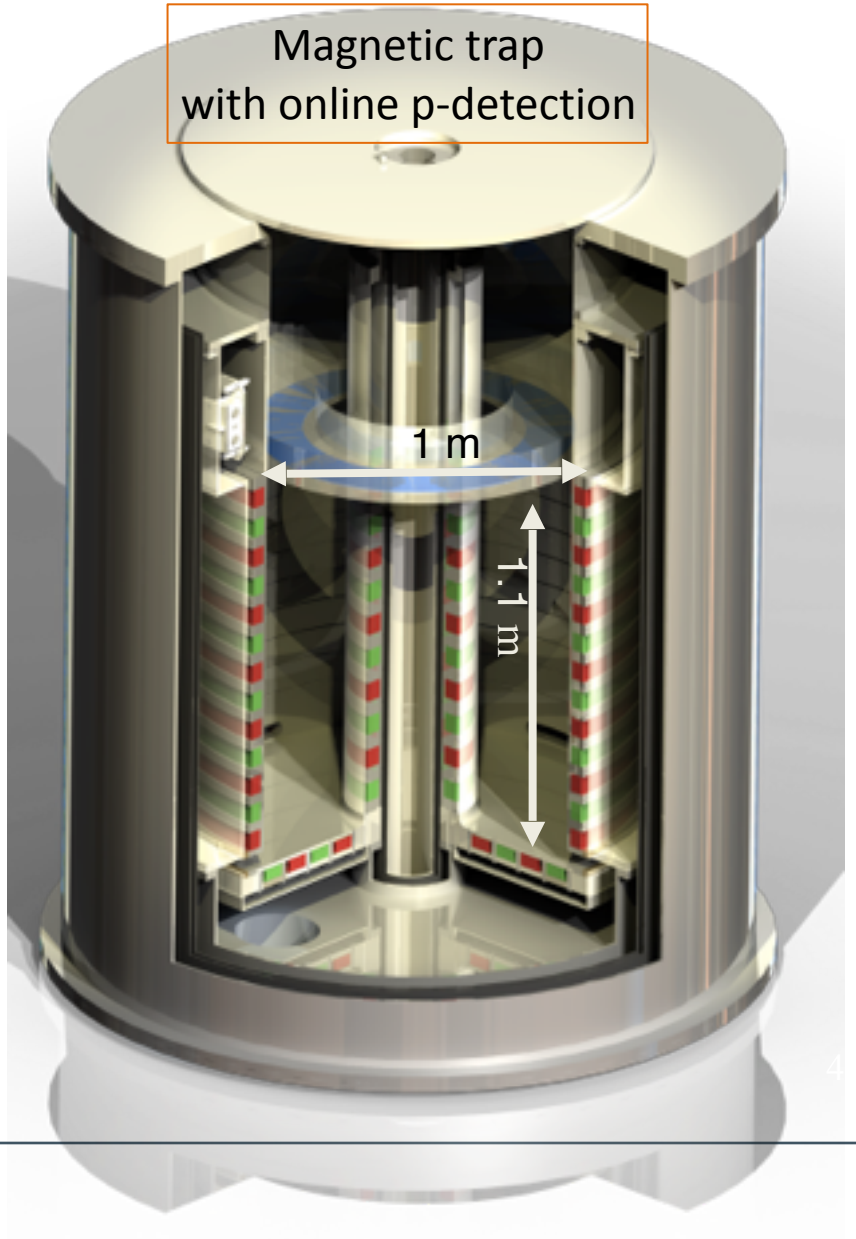




Measurement of n-Lifetime with PENeLOPE

Detect protons online

- Each measuring cycle gives expontential
- Post accelerate protons onto detector

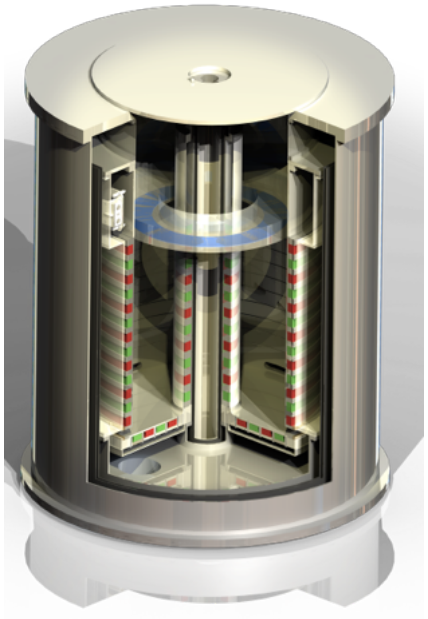
Detect neutrons past storage time t

- Many cycles to get exponential

Assumption:

- new intense UCN source(FRMII, PSI)
- UCN (gas-) density: $\rho = 10^3$-10^4 cm^{-3}
- B_{max}= 2 T B_{min}= 10^{-3} T
- Volume: 700 l
- $N_{storage}$= 10^7 -10^8
- Real time detection of p,e

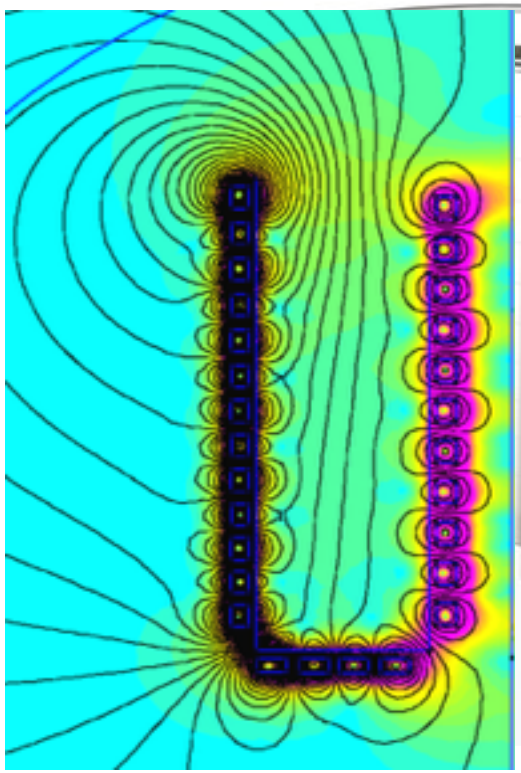
Magnetic trap
with online p-detection

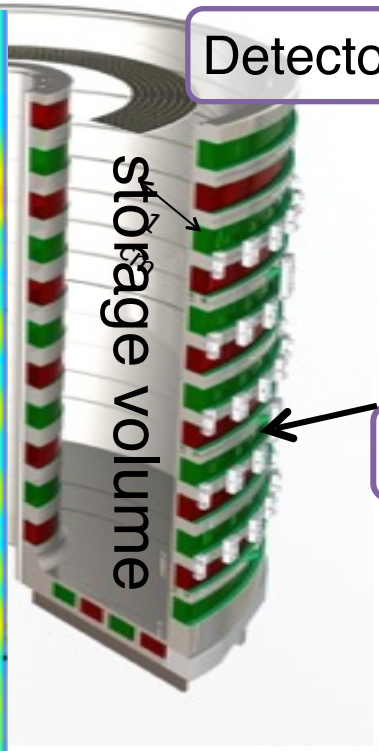


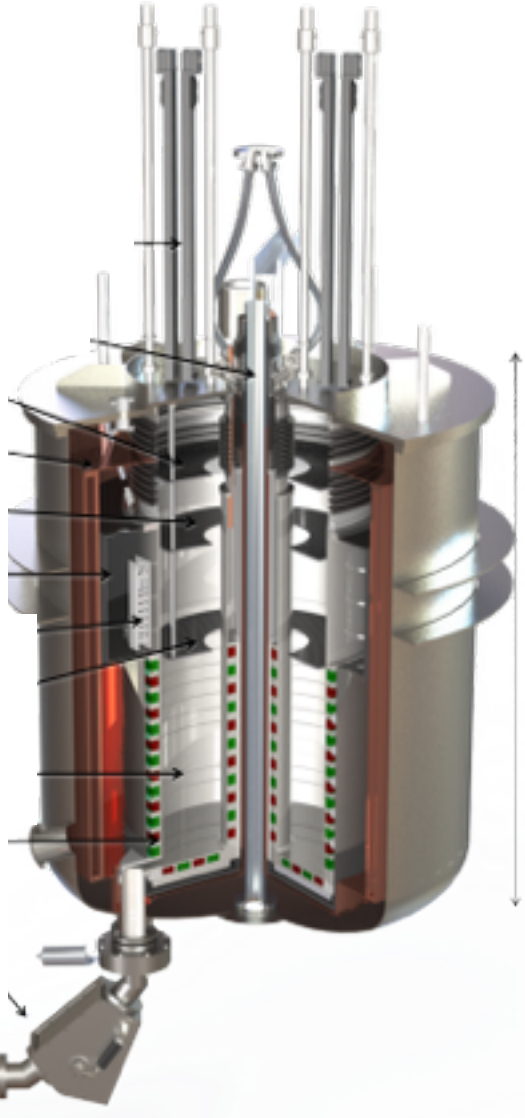
Statistical accuracy:

- $\Delta t \sim 1s$ per measuring cycle (30 min):
- $\Delta t \sim 0.1s$ in 2-4 days

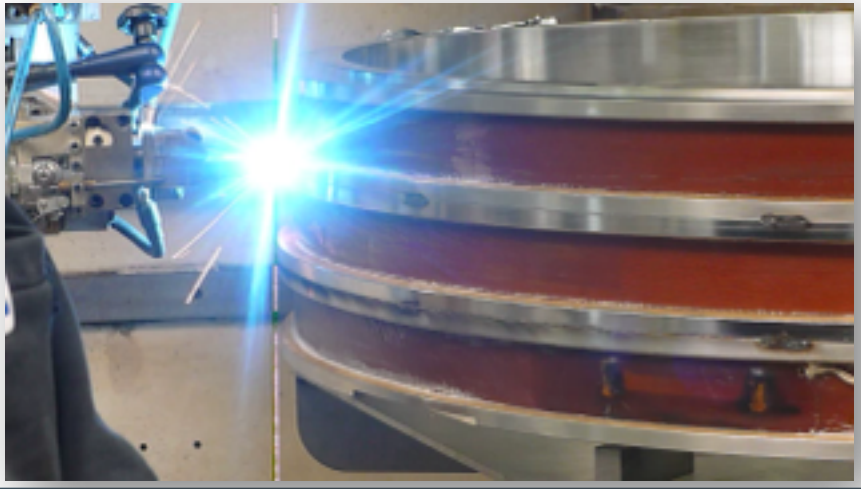
Configuration of PENeLOPE







Magnet/Coil Design and Test



First-of-series coils in CoTEx 2.0

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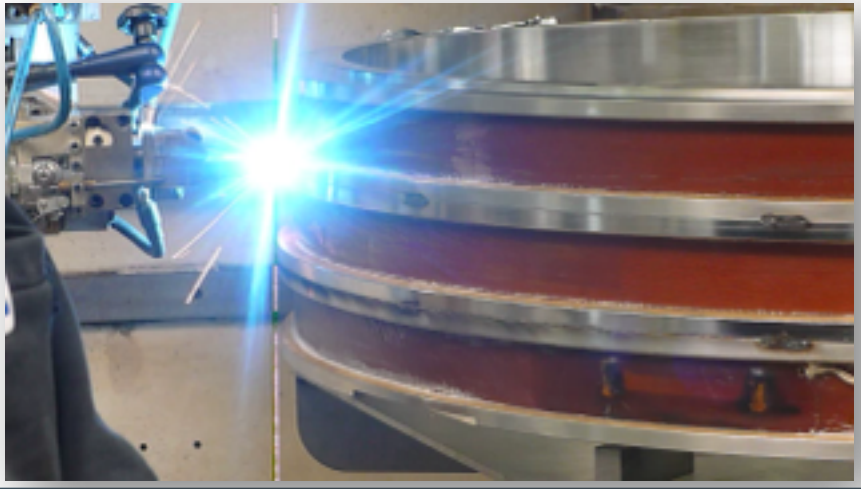


Source for ultra cold Neutrons

FRM II of TUM

Source for ultra cold Neutrons

Production of Ultracold Neutrons

Reactor neutrons : $E_0 = \sim 2$ MeV

from nuclear fission of ^{235}U

↓

Moderator (heavy water) T = 300K

thermal neutrons $E_0 = 25$ meV 2.2 km/s

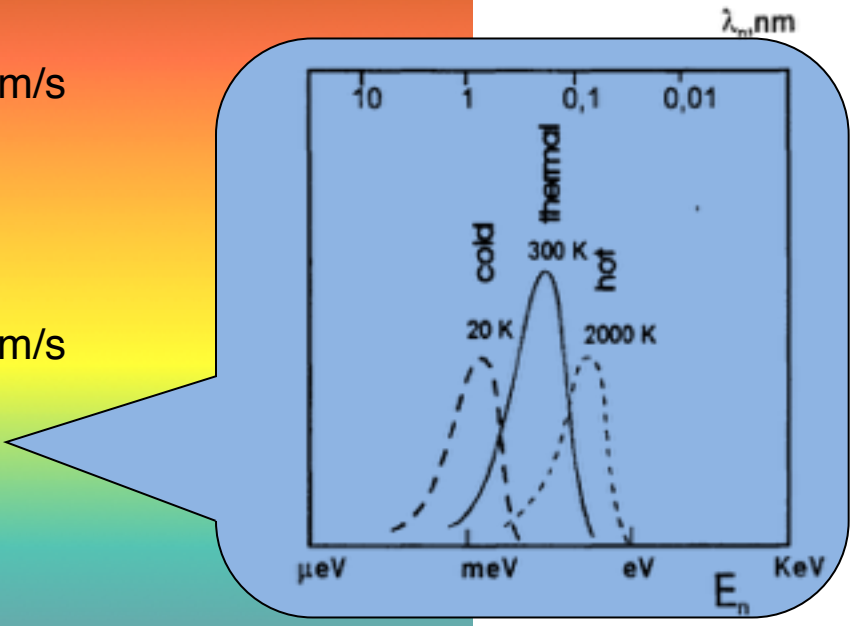
↓

Near reactor core:

Cold moderator (Deuterium) T = 20 K

Cold neutrons $E_0 = 4$ meV 1.1 km/s

Velocity distribution



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Velocity distribution

↓

Selection or further cooling ?

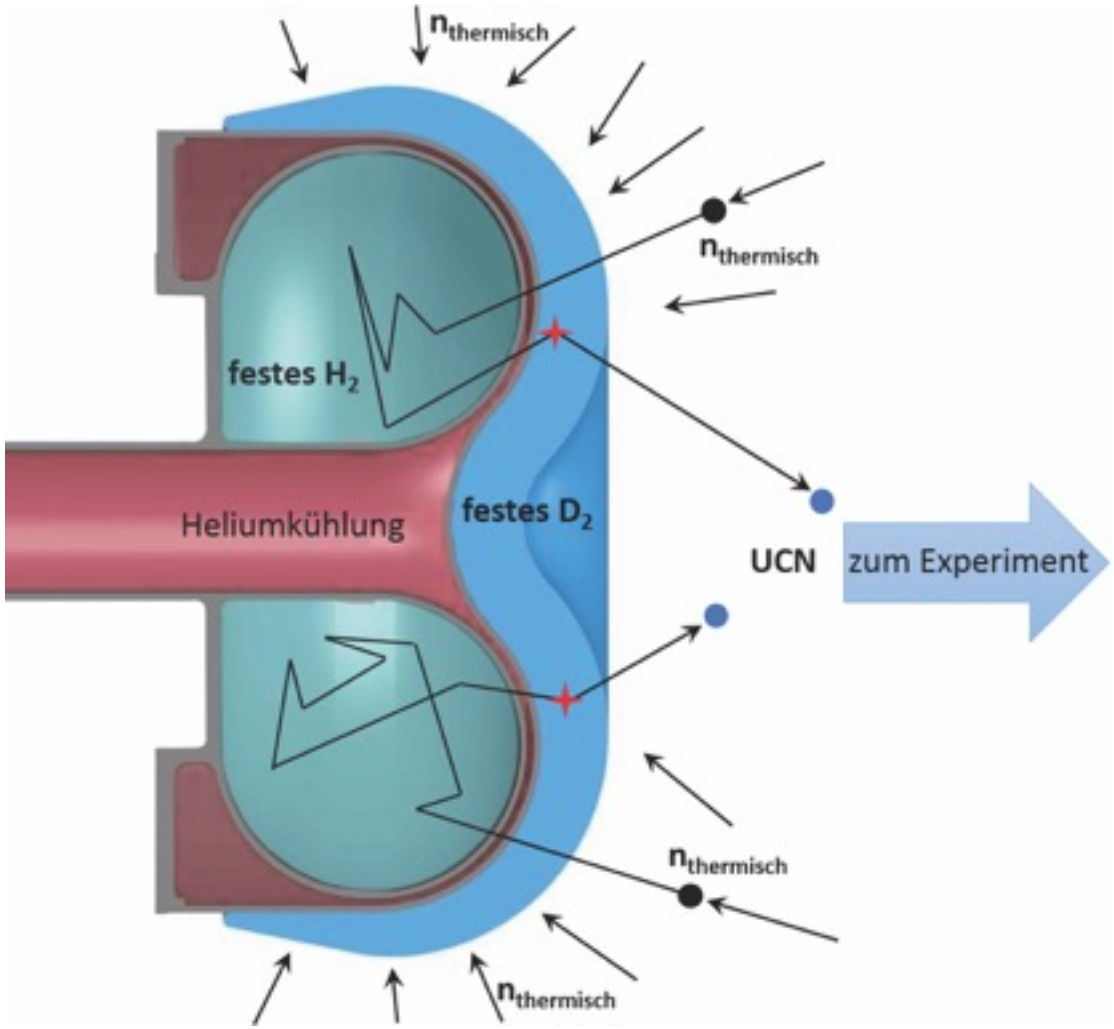
Very cold (VCN) $E_0 = 10^{-5}$ - 10^{-6} eV 50-15 m/s

↓

Selection or further moderation ?

Ultracold (UCN) $E_0 = 10^{-7}$ eV 5 m/s

UCN Source: Generating Ultra Cold Neutrons



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strong new UCN source :
superthermal D_2-source at FRM-II

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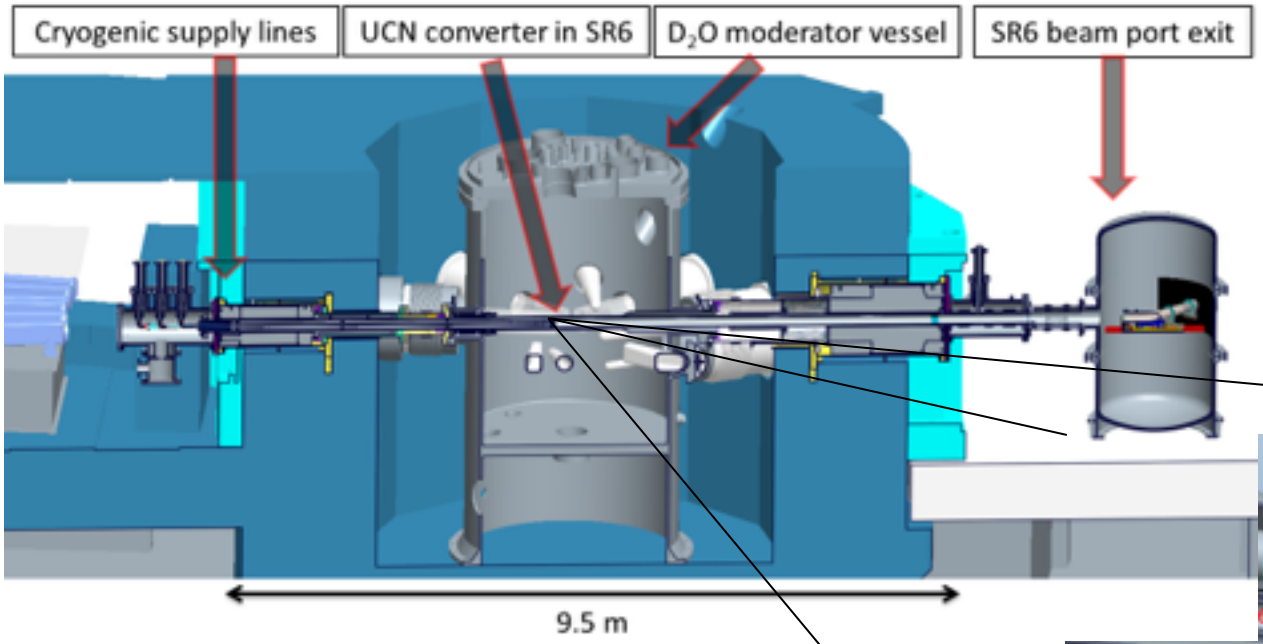
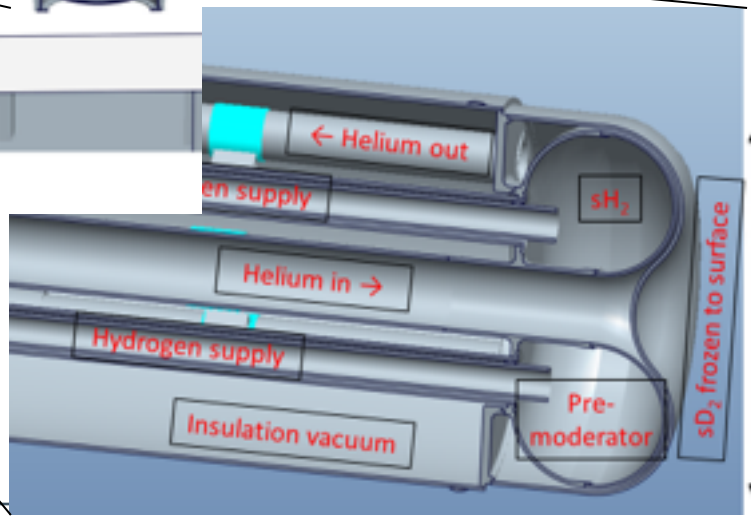
FRM II
Forschungs-Neutronenquelle
Heinz Maier-Leibnitz





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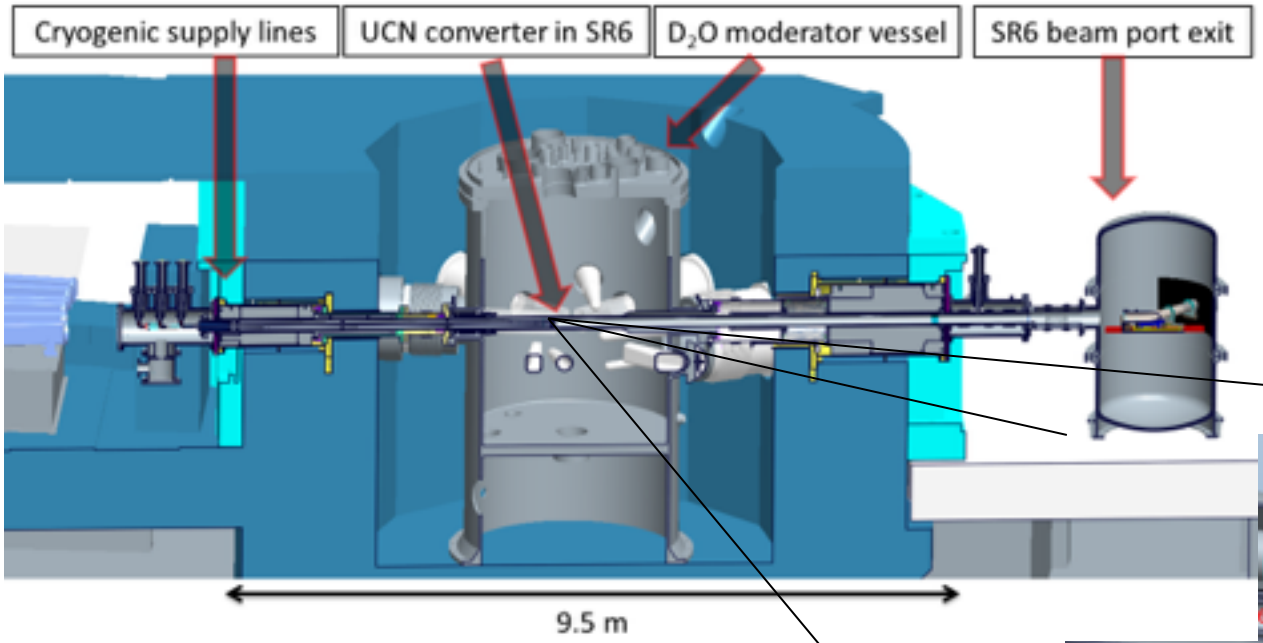

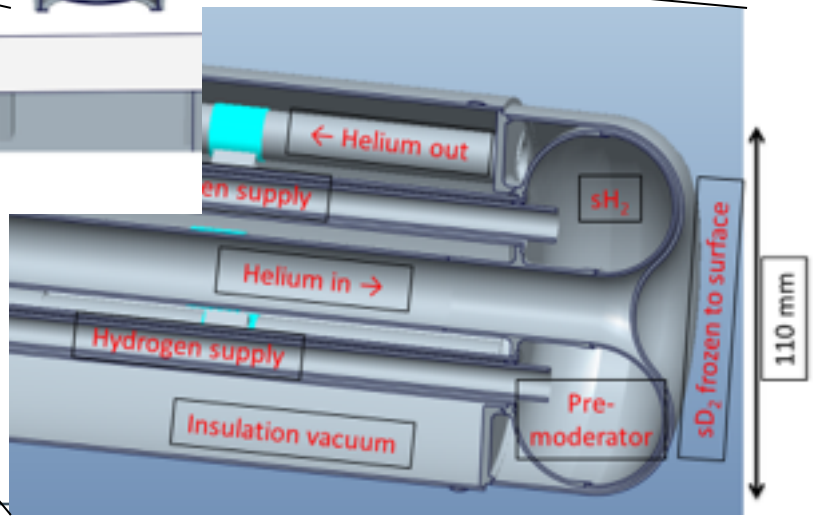

Status:

- UCN production tested
- components ordered
- installation 2018

Setting up the test facility.

freezing deuterium

Example for UCN sources

Solid (Ortho)D_2- source:

LANL

TRIGA (Mainz)

- using TUM geometry/prototype: 10^5 UCN per ‘shot’ detected
- set-up improvements

PSI FRMII - Tech. Univ. München (2018)

Superfluid helium

NIST source (built-in lifetime-experiment)

ILL: Cryo-EDM (built-in EDM-Experiment)

Small ‘portable’ test source at FRMII/ILL – extraction possible

Summary

- Particle physics with neutrons is adresses early Universe
- Precision experiments test model of particle physics
  - Sensitivity beyond TeV scale
    - Limit for mass scales given by precision alone
    - No limit by particle energies
  - Interpretation of deviations not unique
    - need several complementary measurements
- Precision experiments test gravitation
  - Complementary to ‚classical methods'
  - No principle limit (background free measurement)
- New neutron sources (UCN-source, cold beams) in construction (FRMII)
- Internationally active field of science

Some items not coverred

- Neutrality of the neutron
  - Improve present status by few orders of magnitude

- Neutrino helicity

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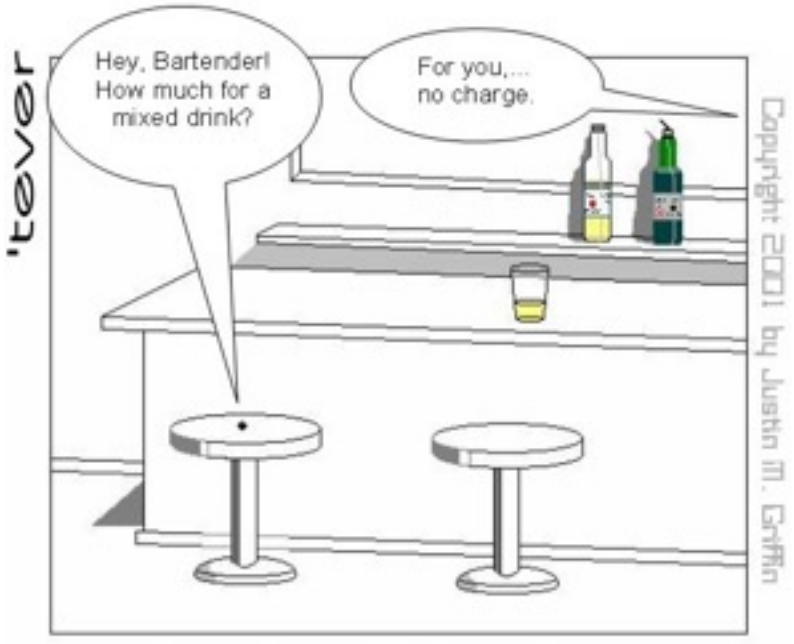

A neutron walks into a bar...

- Neutrino helicity

$$n \rightarrow pe\bar{\nu}_e \rightarrow H\bar{\nu}_e$$