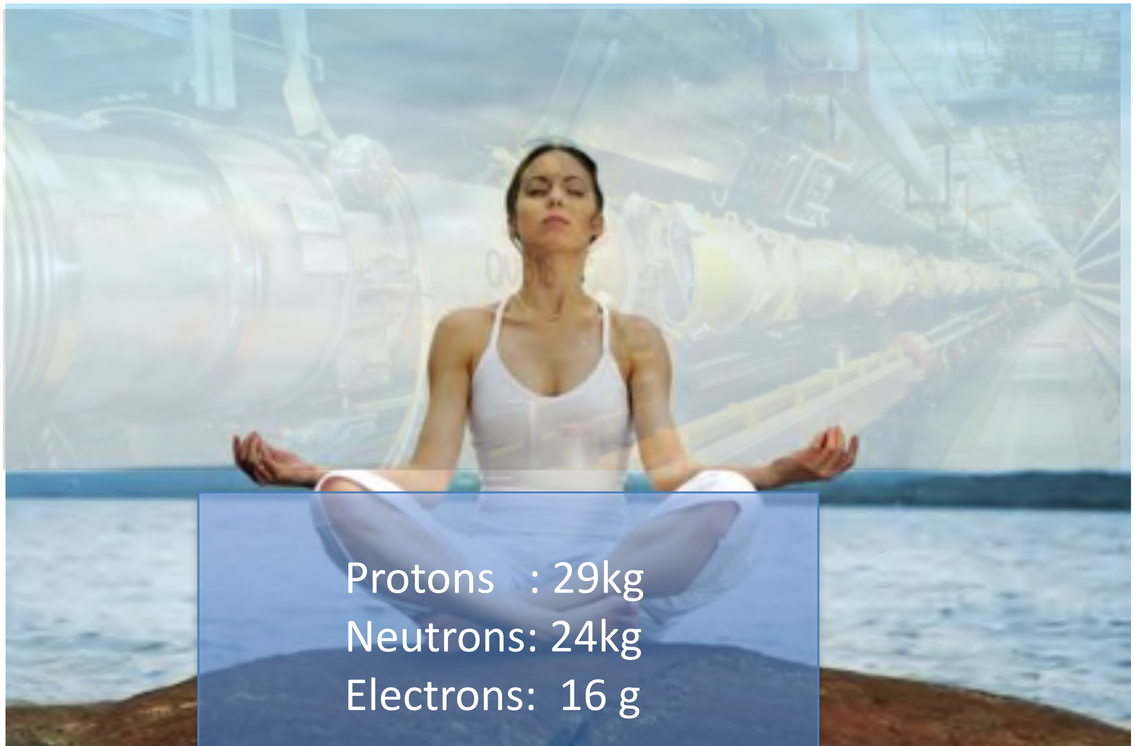
The neutron and the Universe
History of a Relationship

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

The Neutron

weight: 53 kg



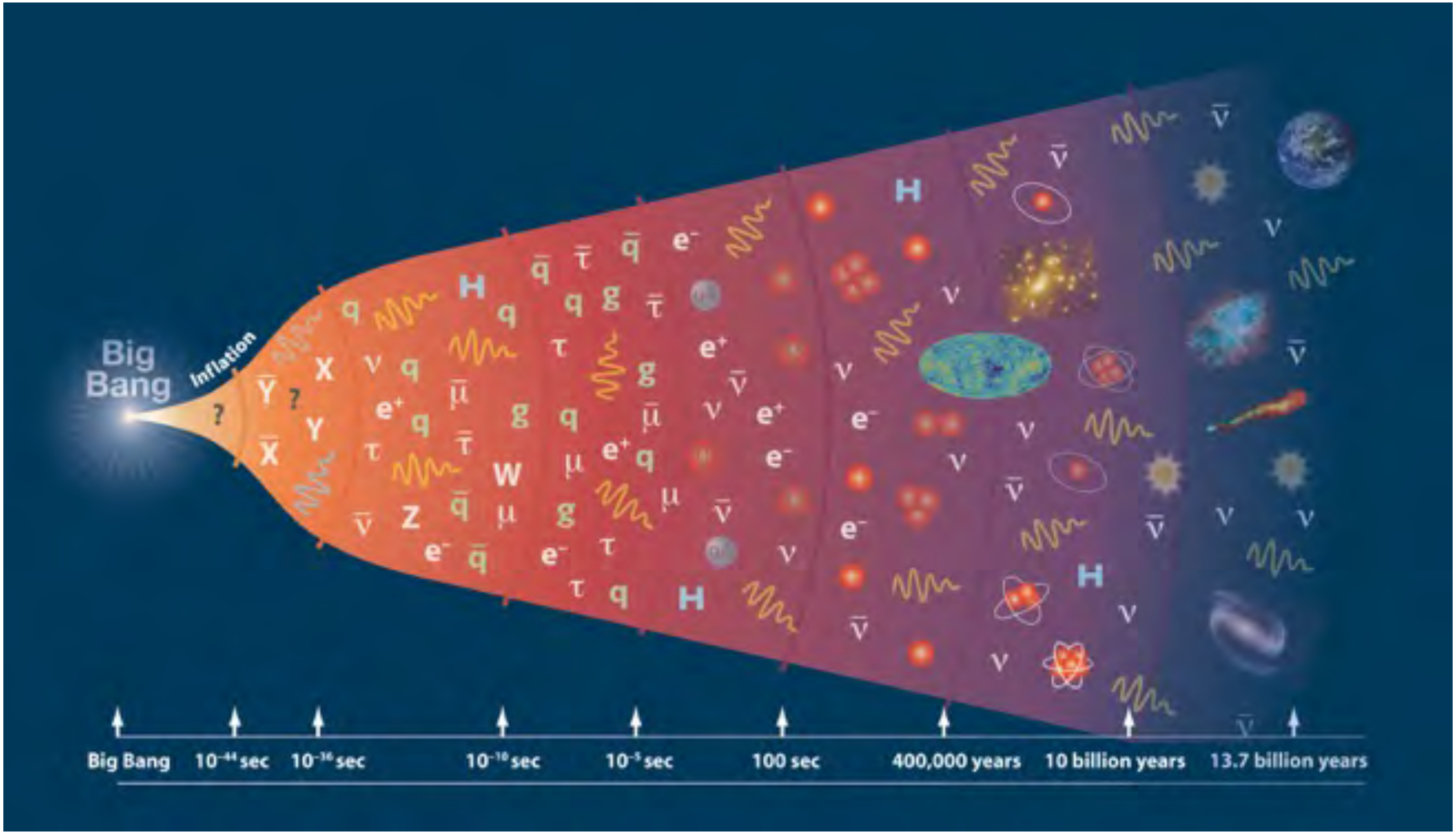
Protons : 29kg
Neutrons: 24kg
Electrons: 16 g

proton

neutron

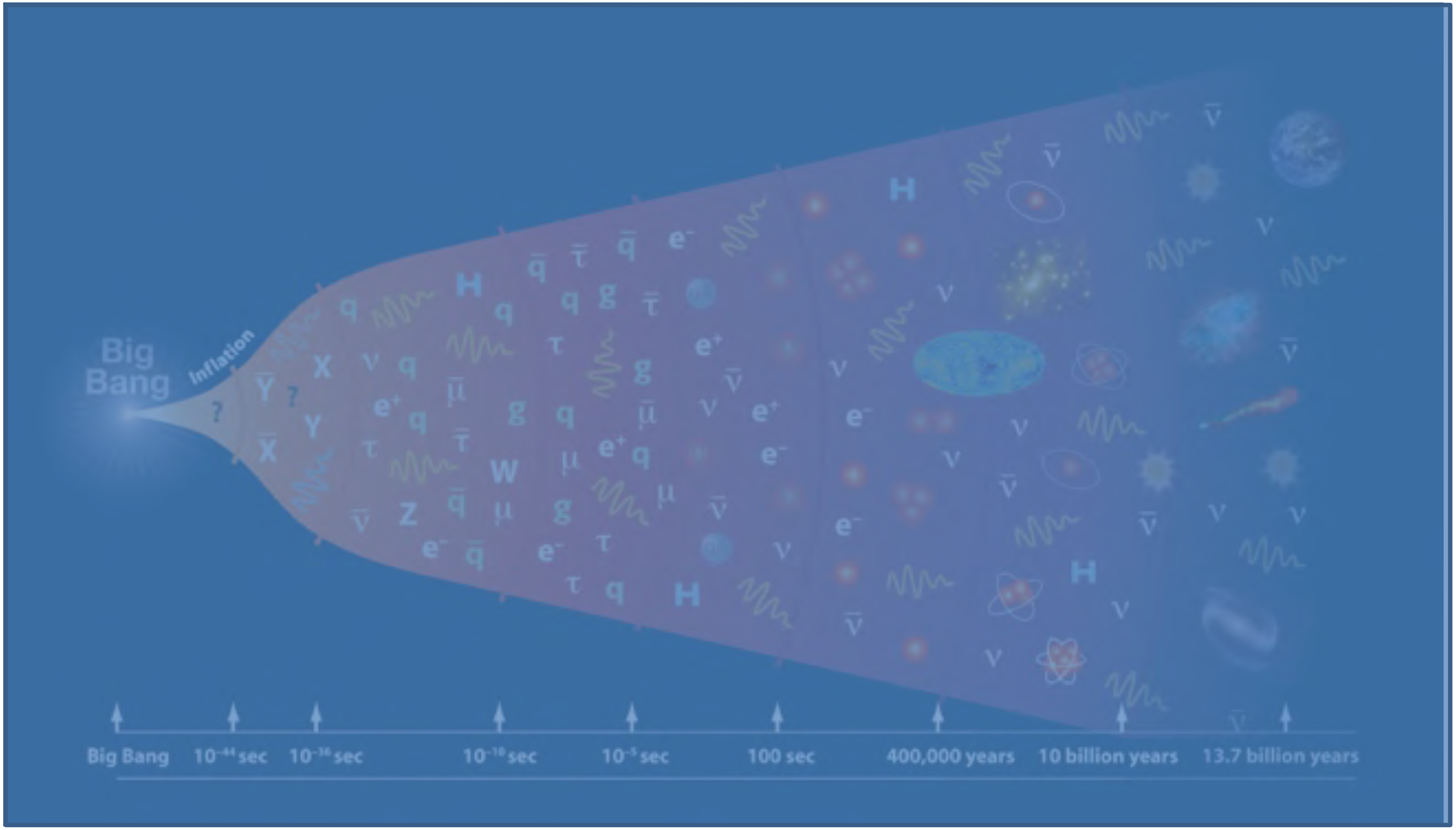
electron

The Universe



The Neutron and the History of the Universe

Exzellenzcluster Universe

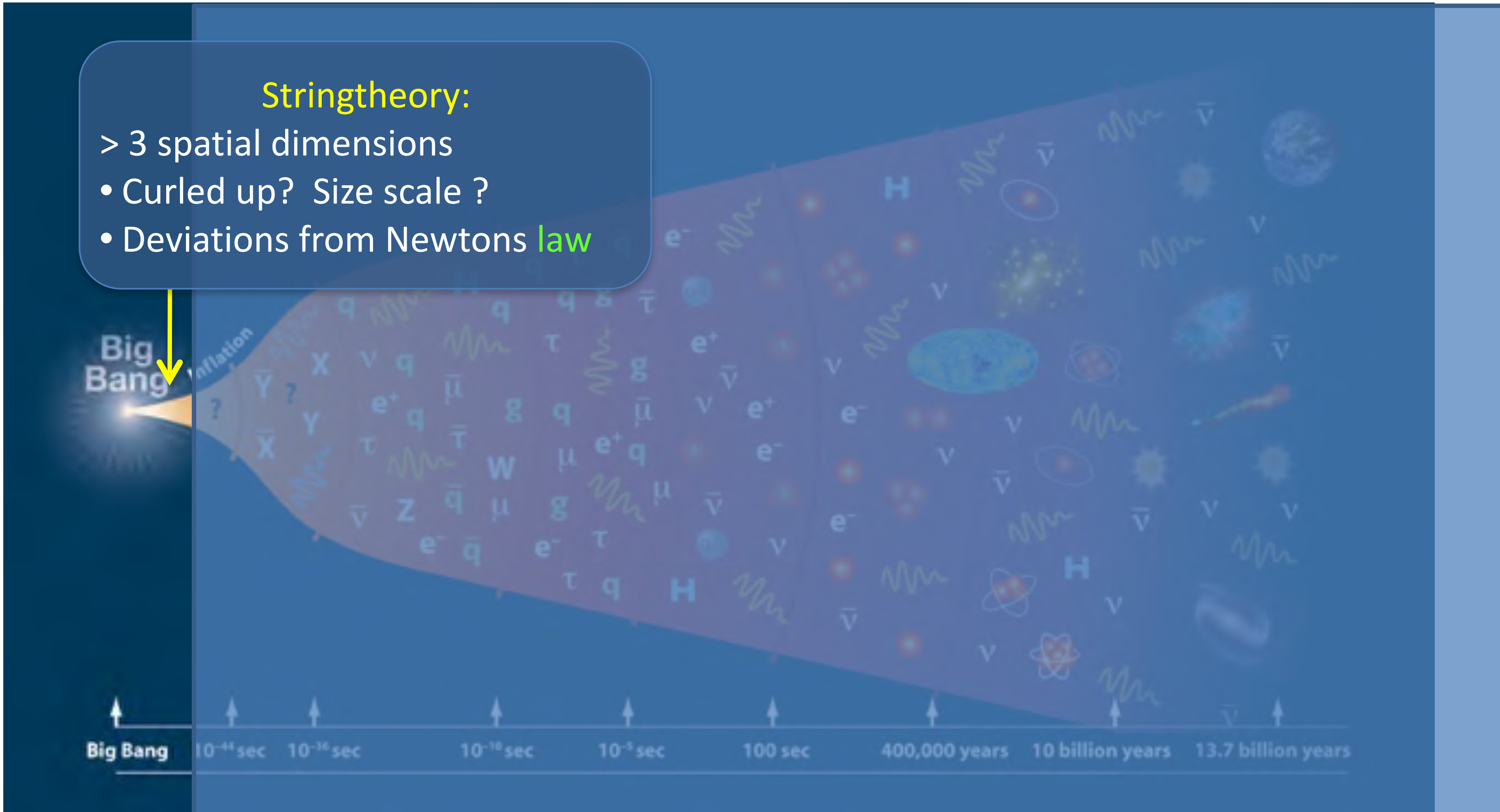


The Neutron and the History of the Universe

Stringtheory:

> 3 spatial dimensions

- Curled up? Size scale ?
- Deviations from Newtons law



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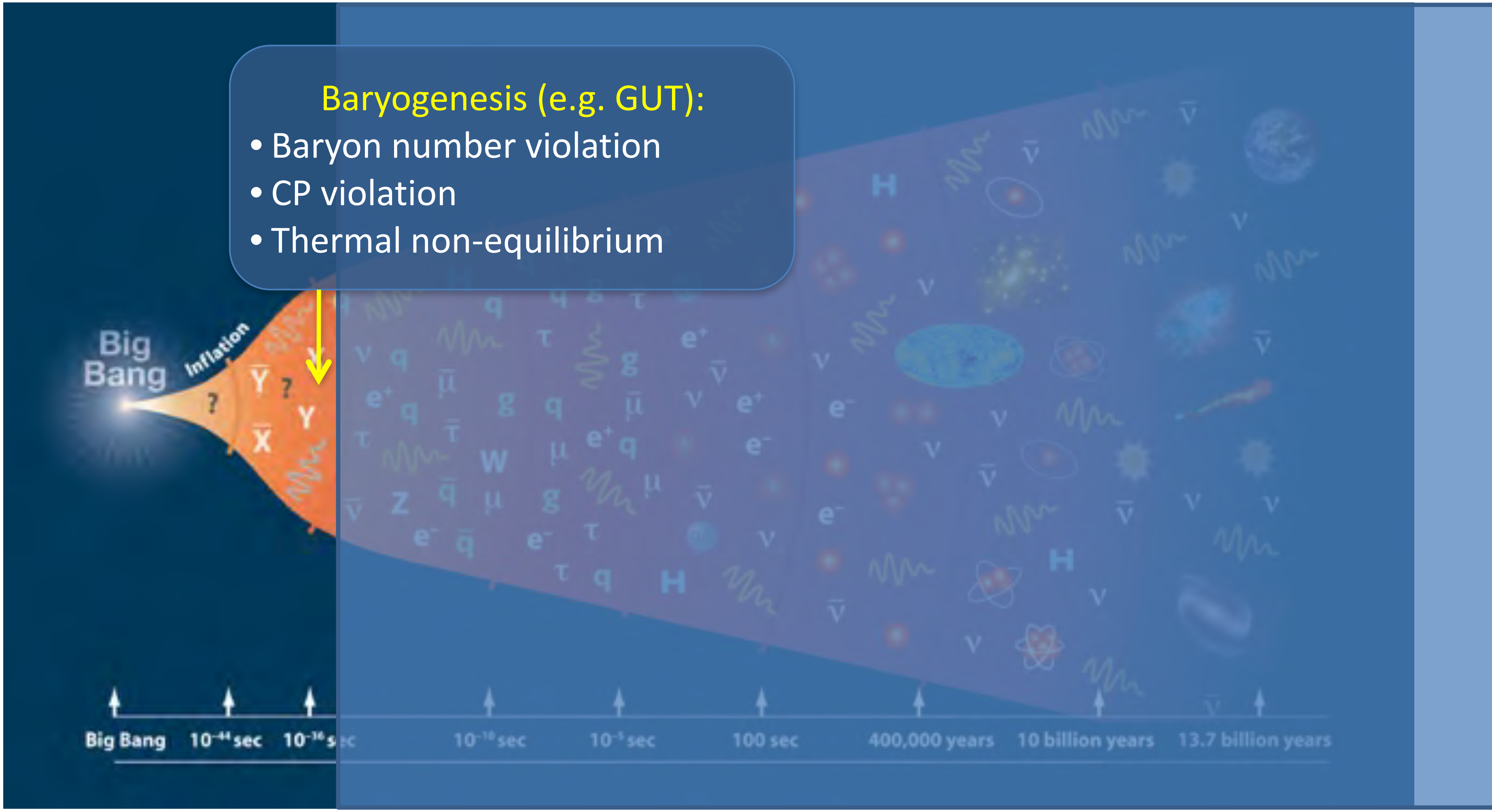
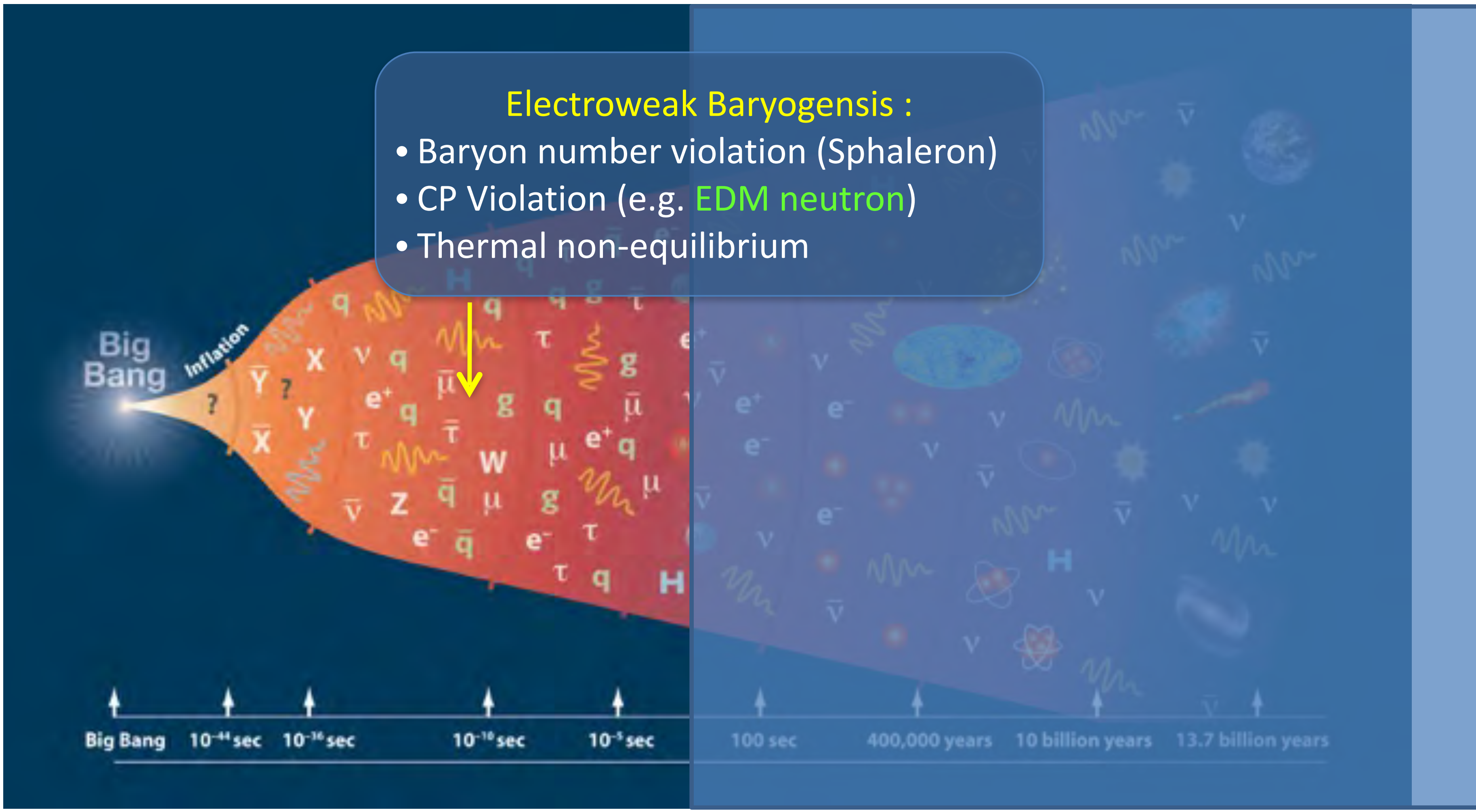


The Neutron and the History of the Universe

Electroweak Baryogensis :

- Baryon number violation (Sphaleron)
- CP Violation (e.g. EDM neutron)
- Thermal non-equilibrium

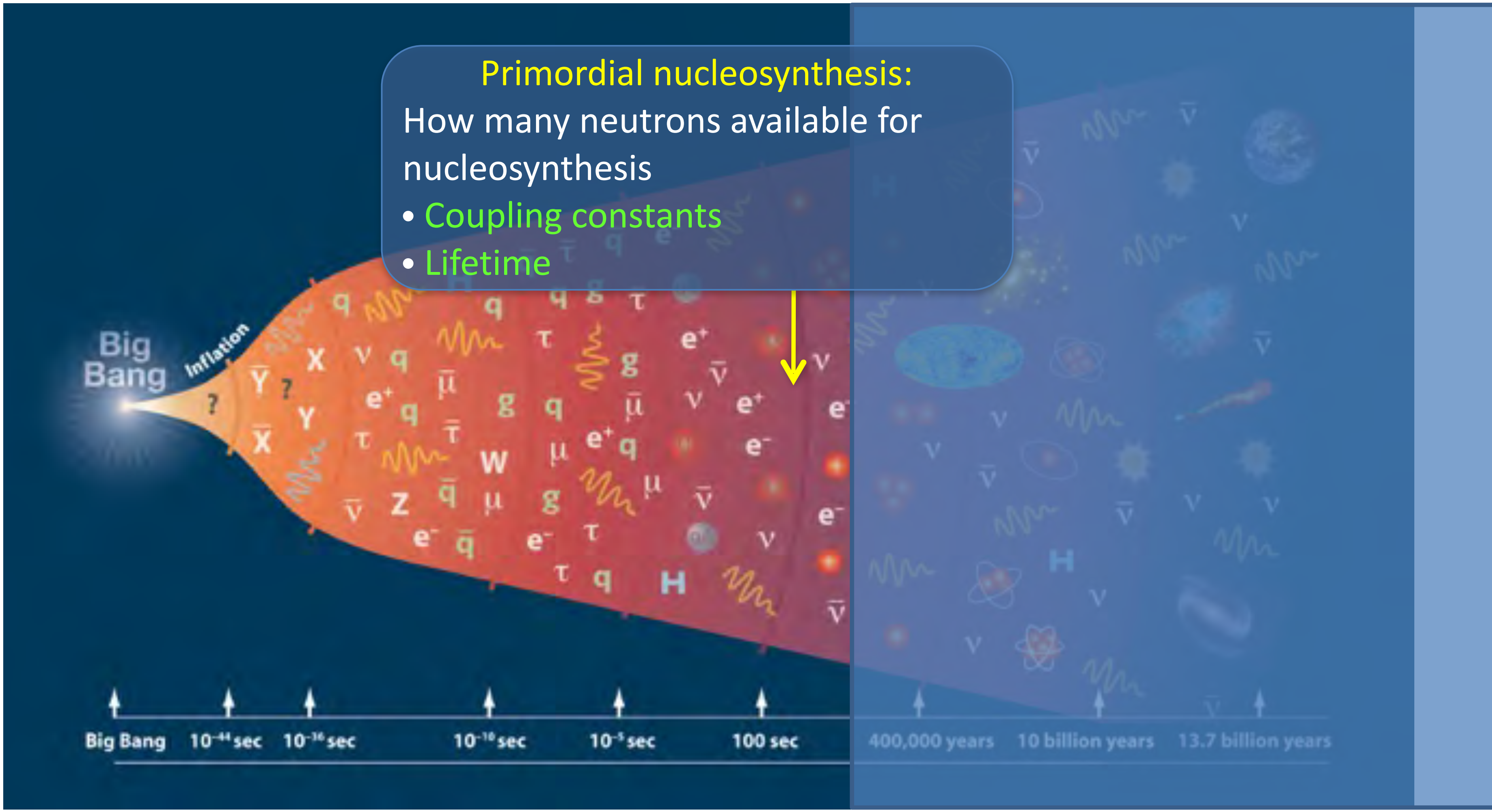


The Neutron and the History of the Universe

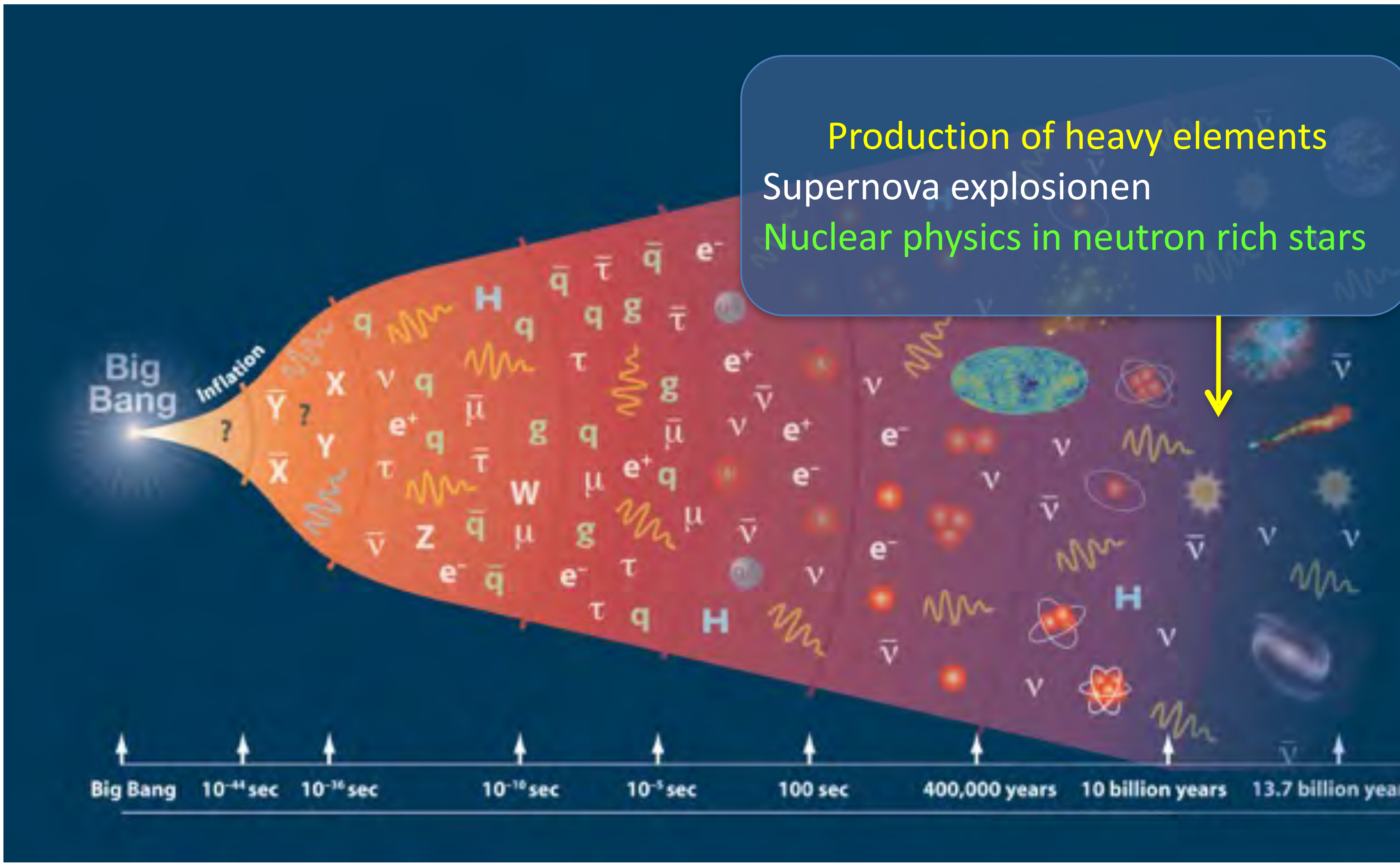
Primordial nucleosynthesis:

How many neutrons available for nucleosynthesis

- Coupling constants
- Lifetime



The Neutron and the History of the Universe

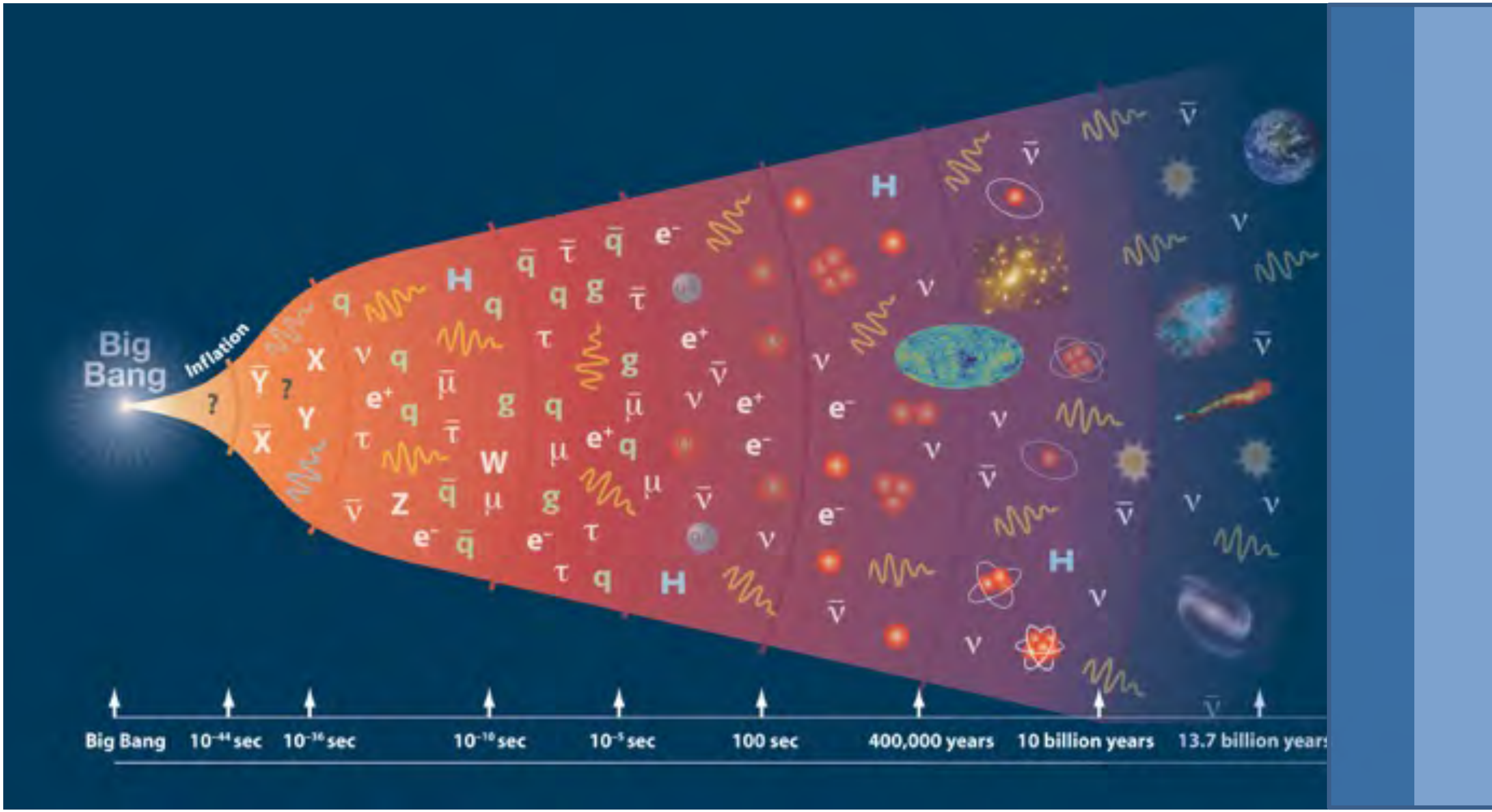


Production of heavy elements

Supernova explosionen

Nuclear physics in neutron rich stars

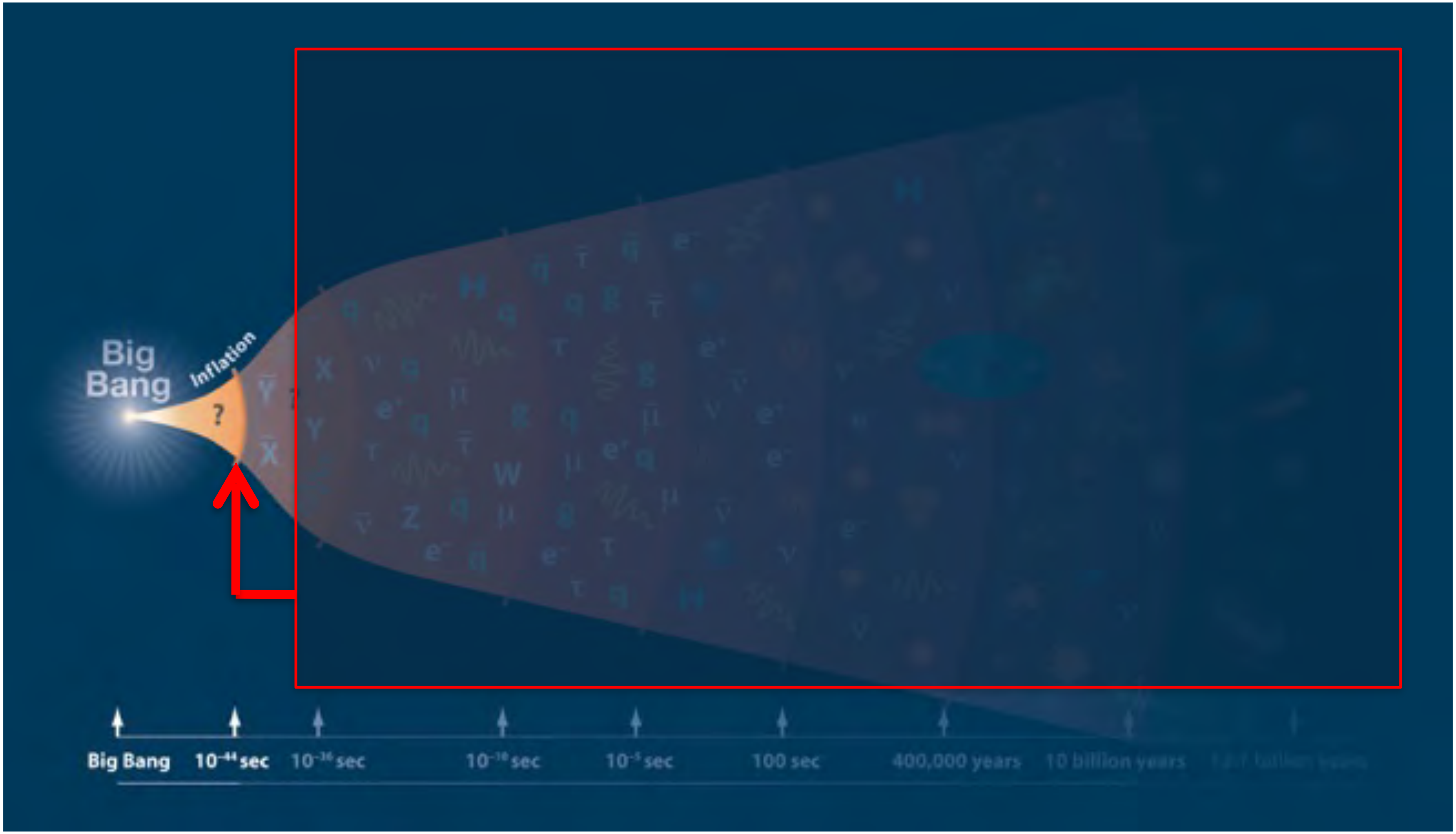
The Neutron and the History of the Universe



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



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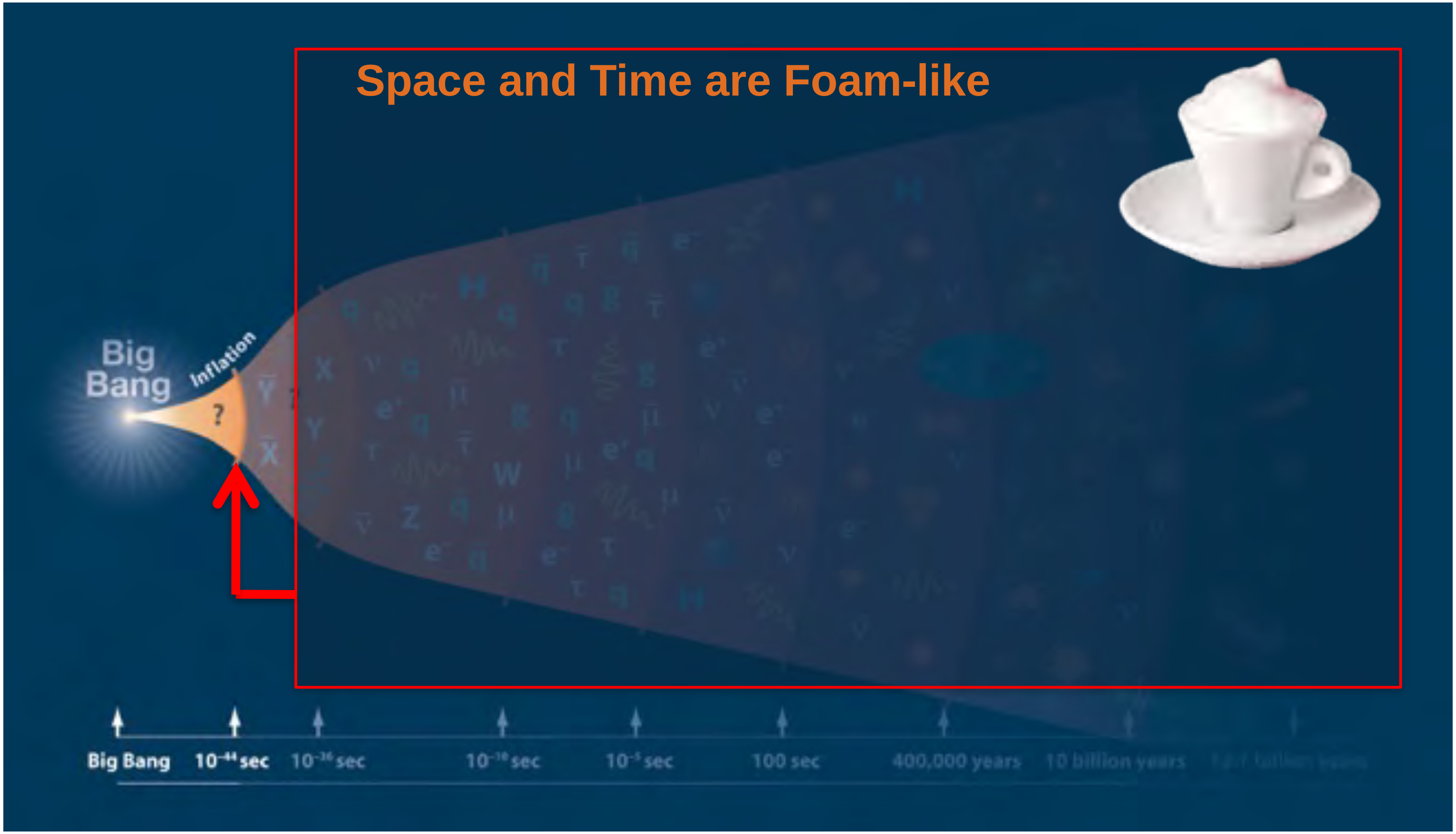

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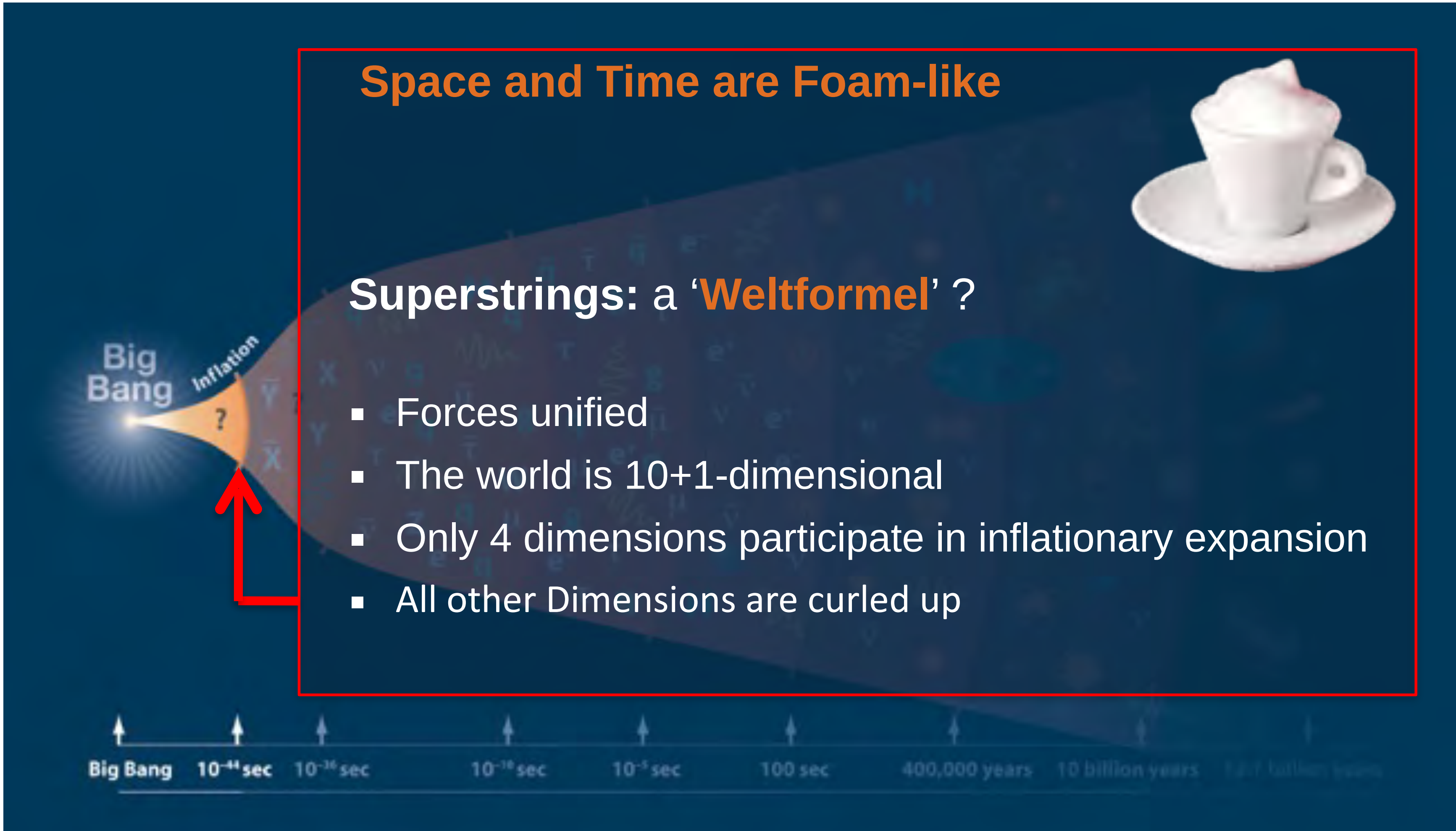
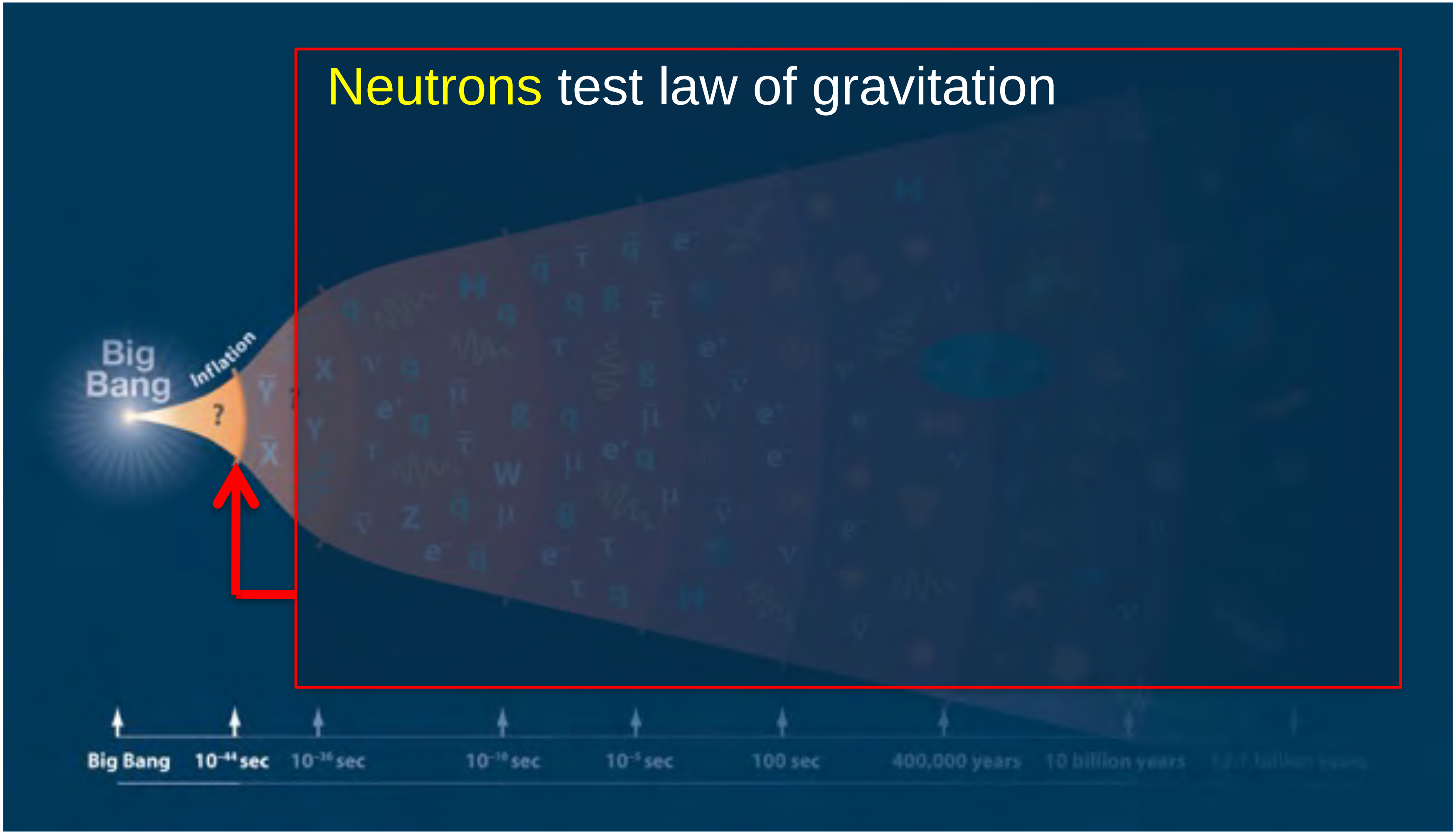


Space and Time are Foam-like

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



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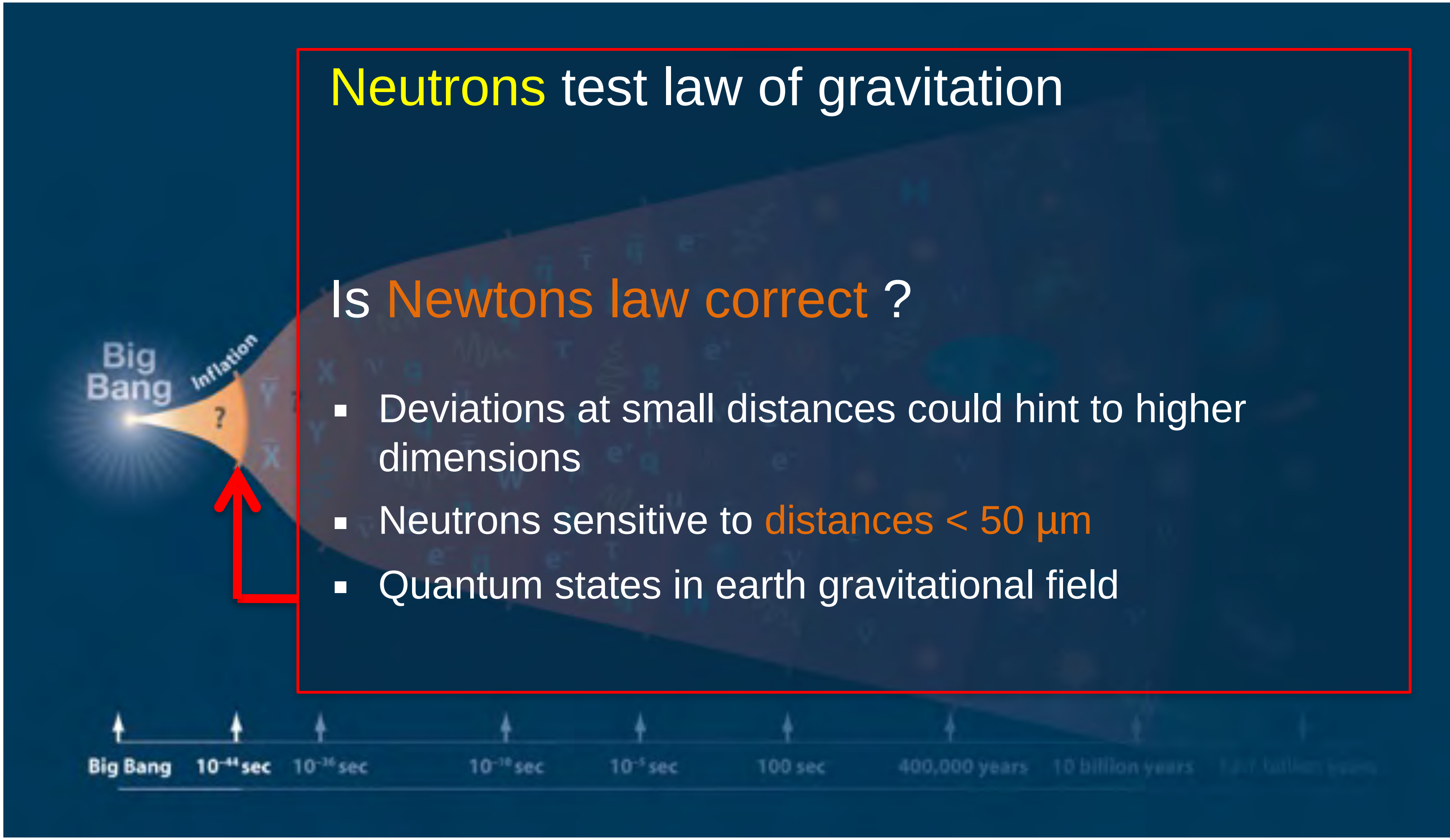


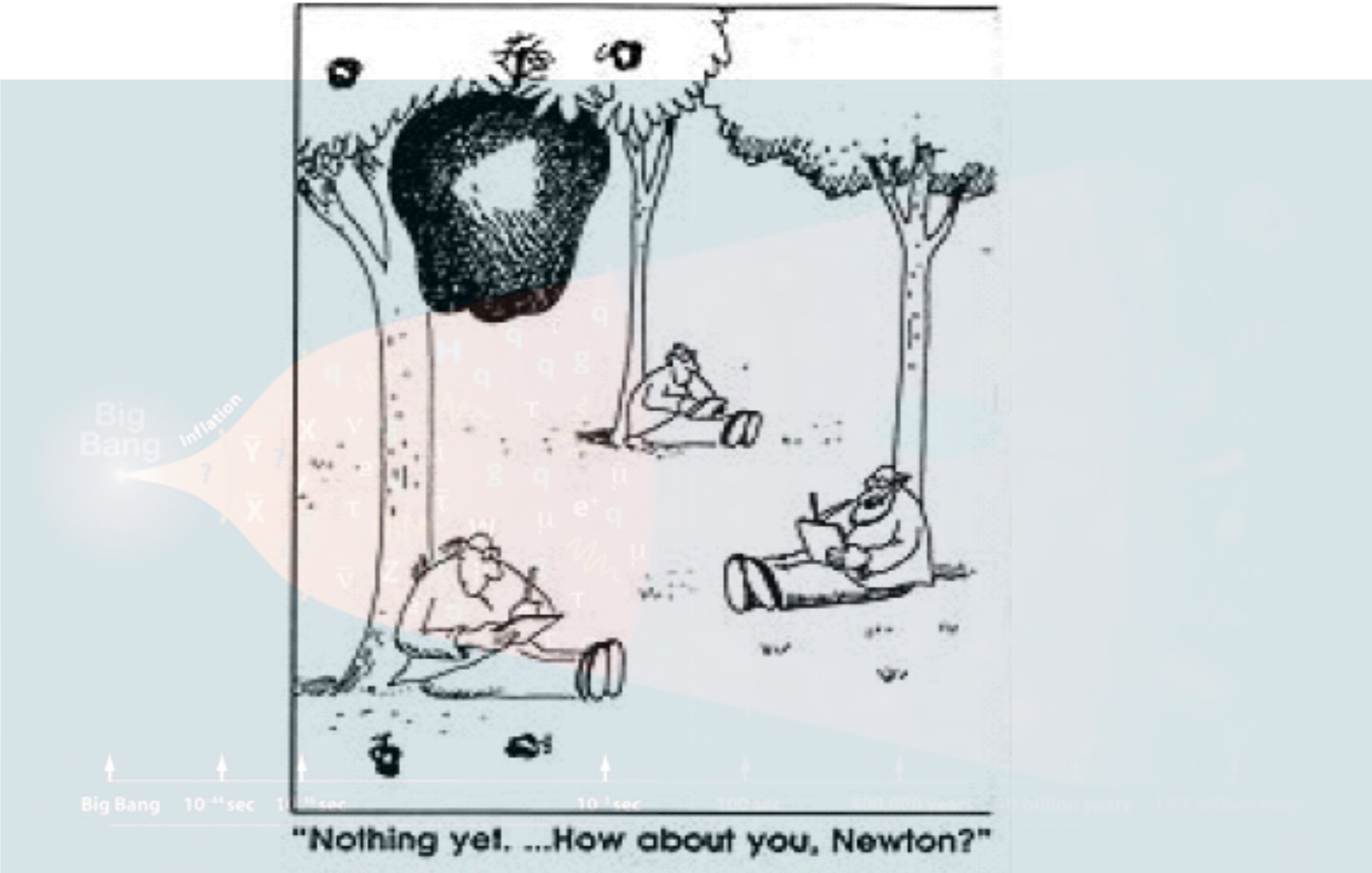
Neutrons test law of gravitation

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

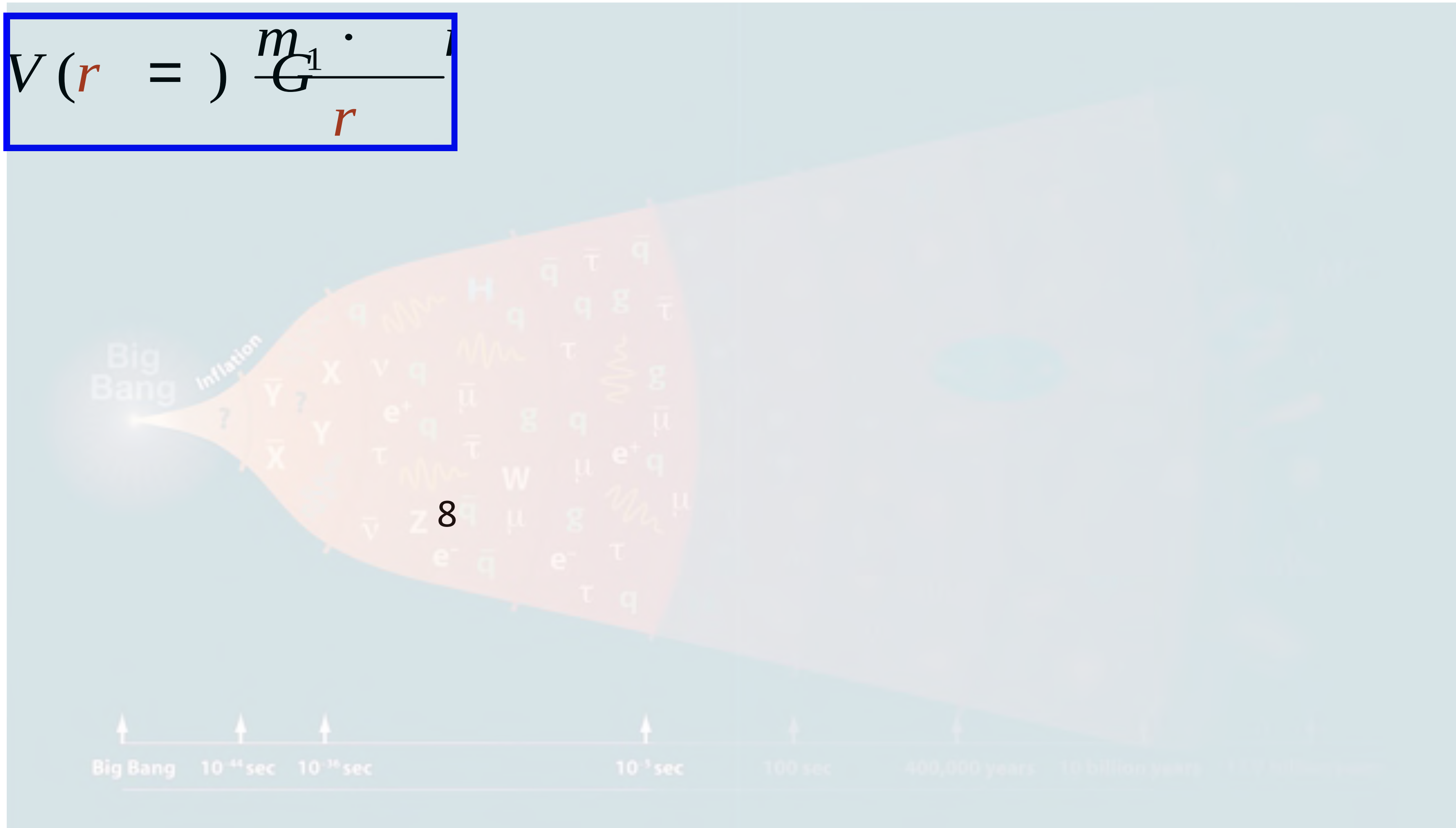
Gravitation – Quantisation in Earth Gravitational field

Exzellenzcluster Universe



Gravitation – Quantisation in Earth Gravitational field

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



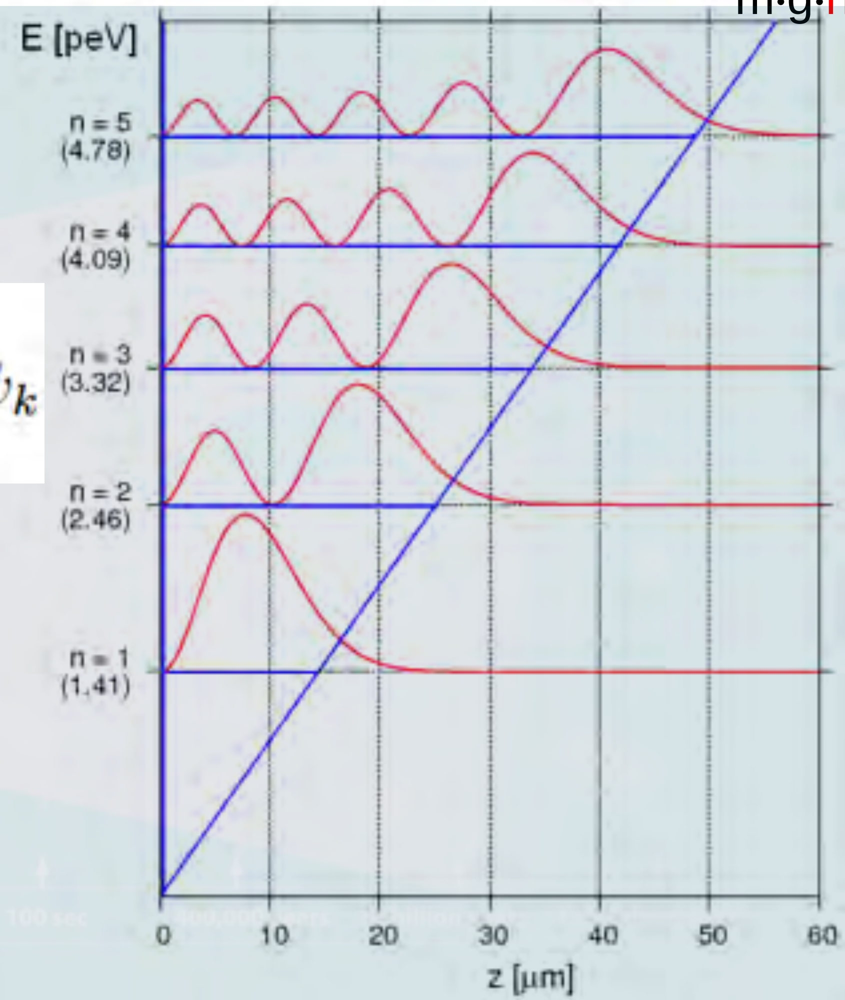
Gravitation – Quantisation in Earth Gravitational field

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

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

8

m·g·h



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Exzellenzcluster Universe

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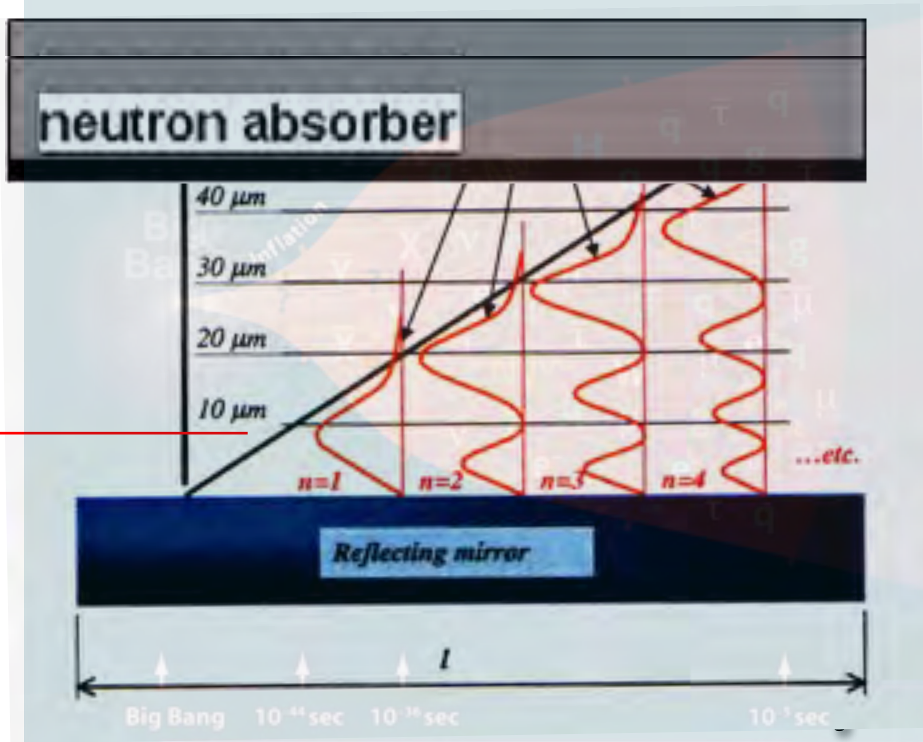
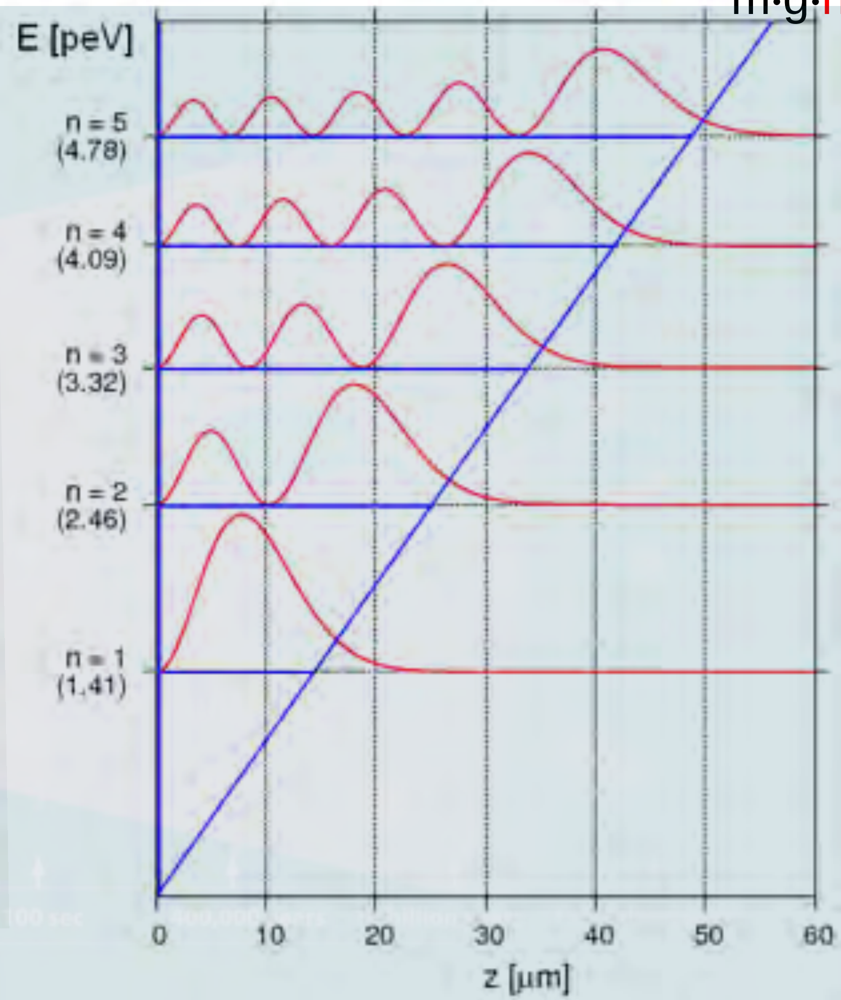


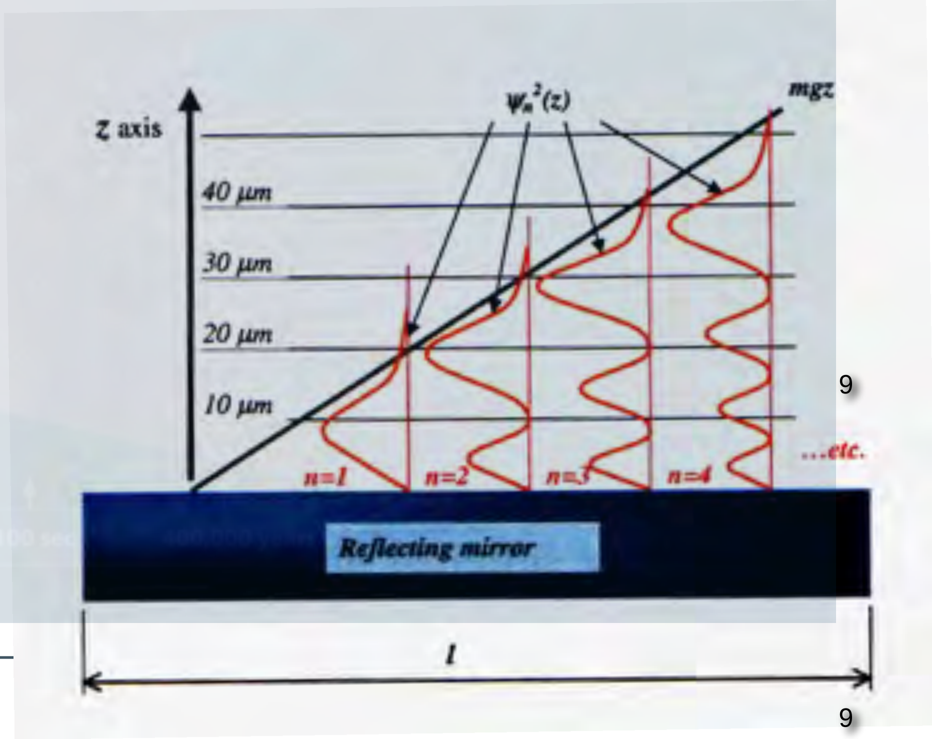


Gravitation – Bound states in Earth‘s field

Sensitivity: peV

Distance scales : <10µm

Nature 415 299 (2002)



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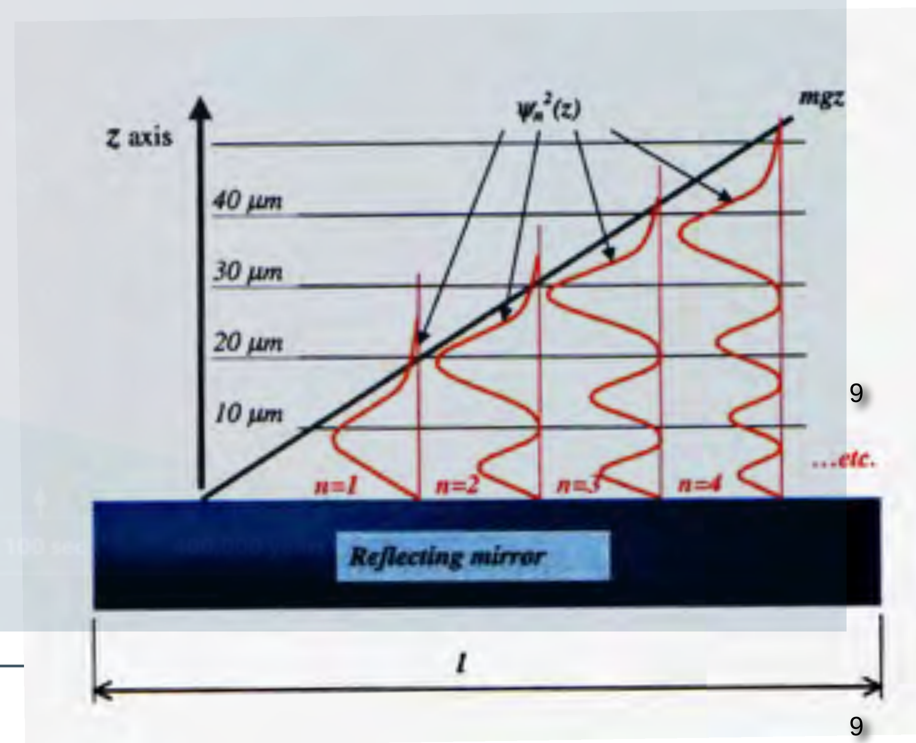

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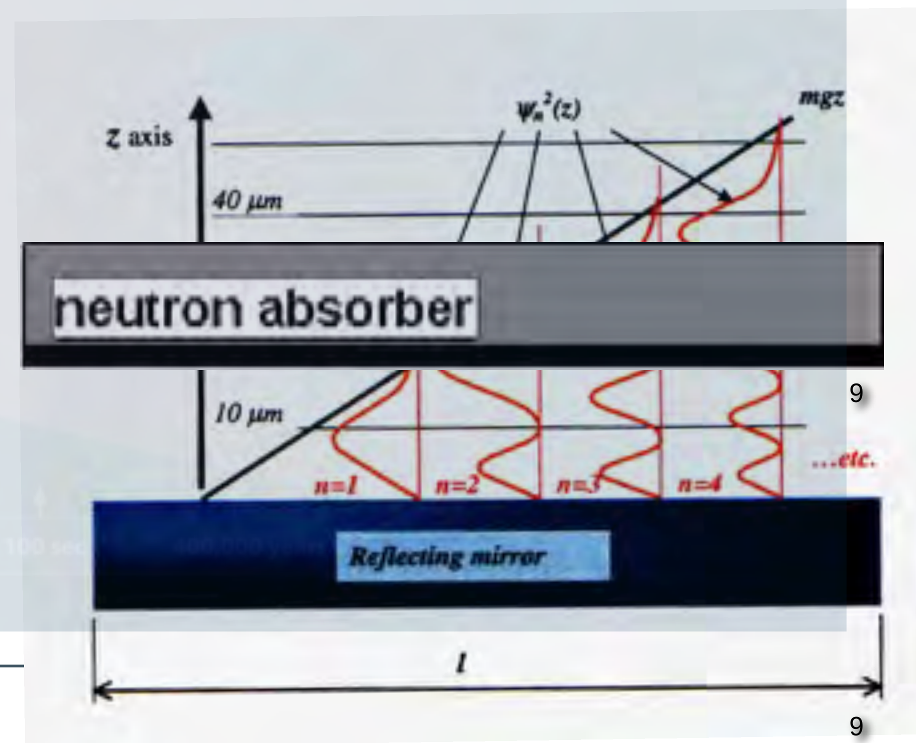

9

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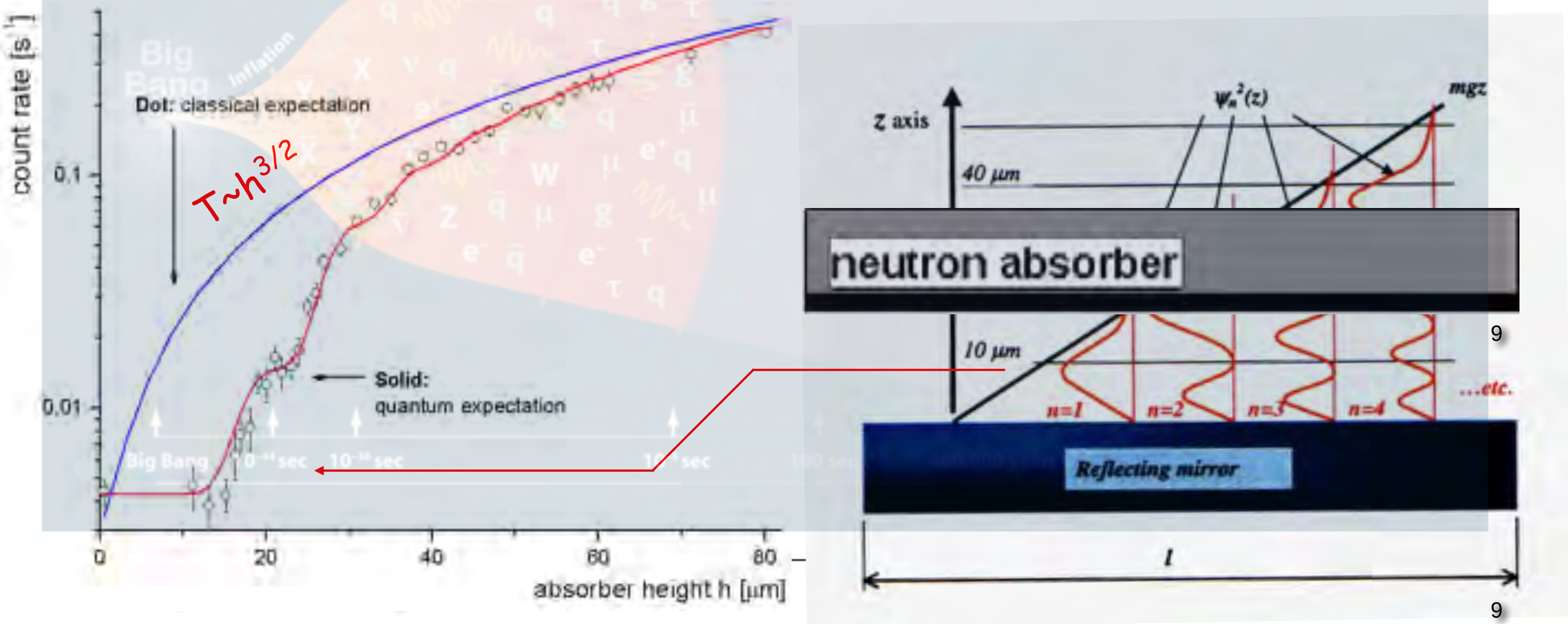
Nature 415 299 (2002)



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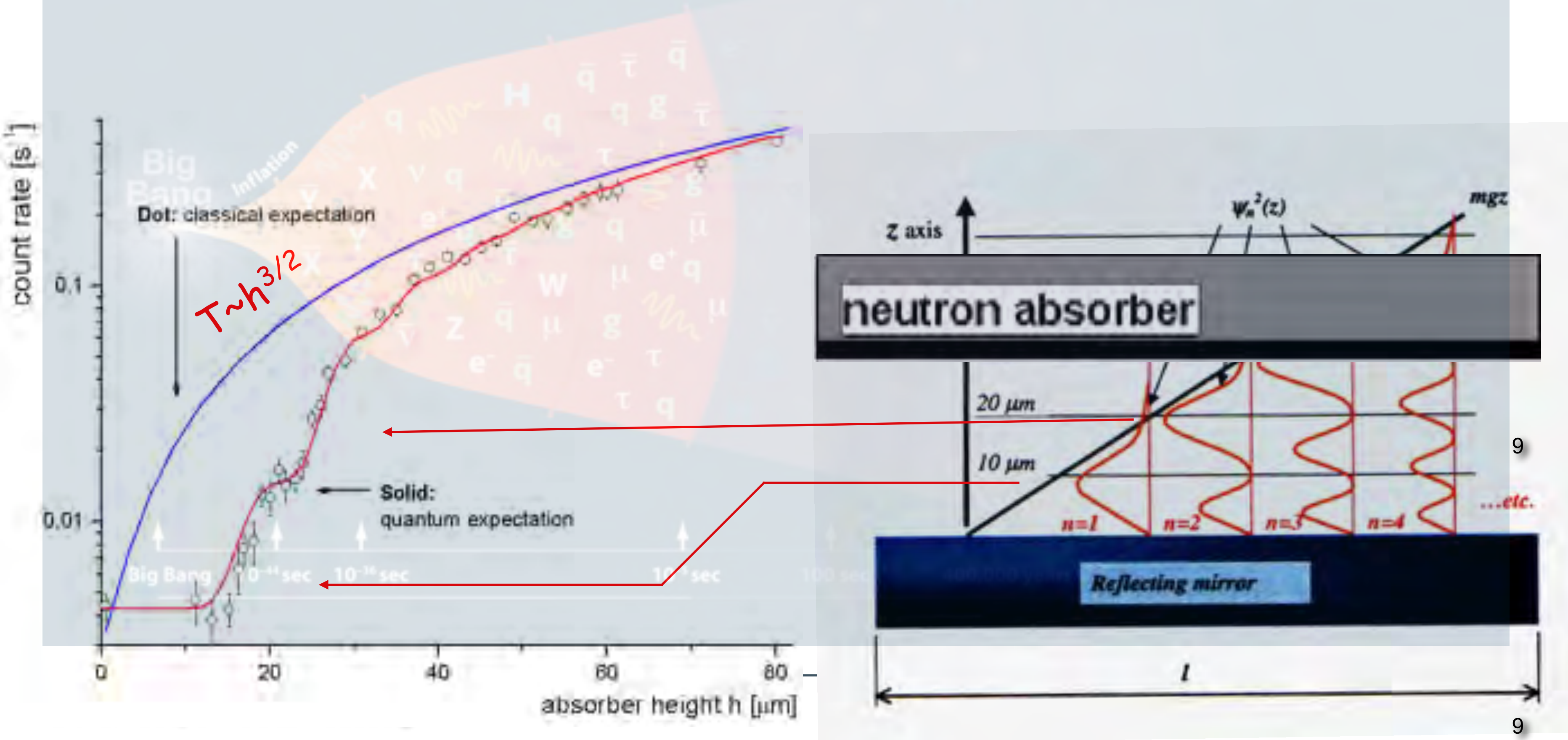

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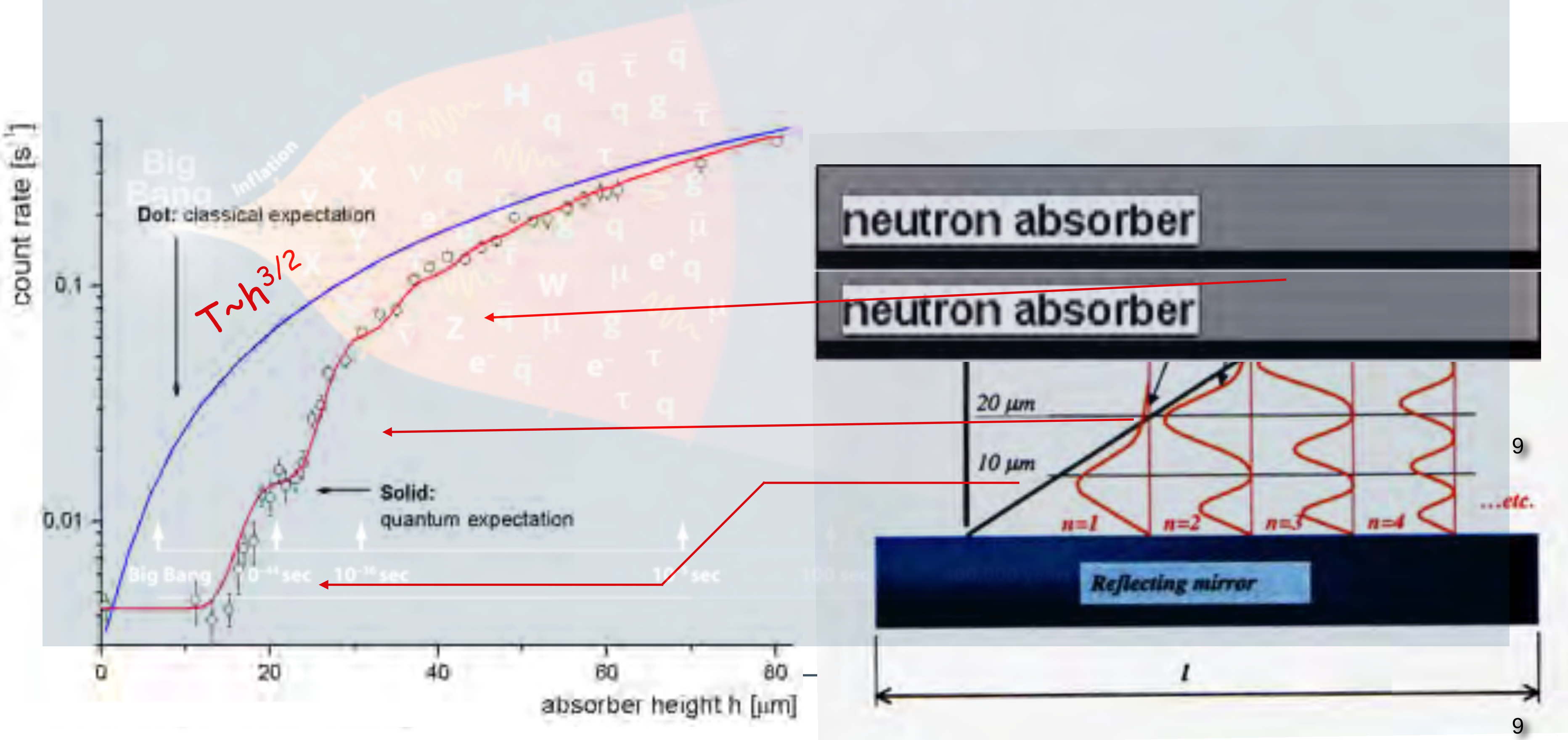


Gravitation – Quantization in Earth Field II

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

Yukawa coupling:

- strength α
- range λ

Until now:

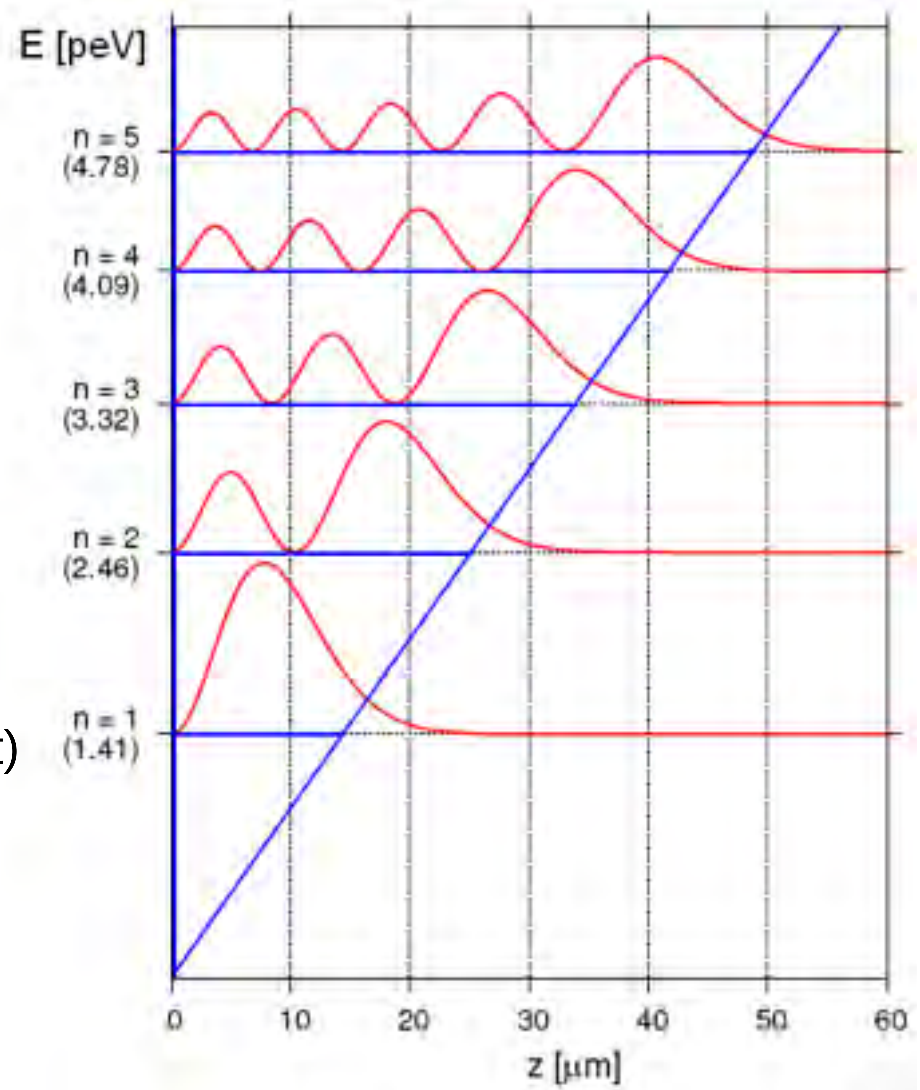
Atomic force microscope:

- Newton r > 10µm

Problem: Casimir effect („falsch“-effect)

Neutrons:

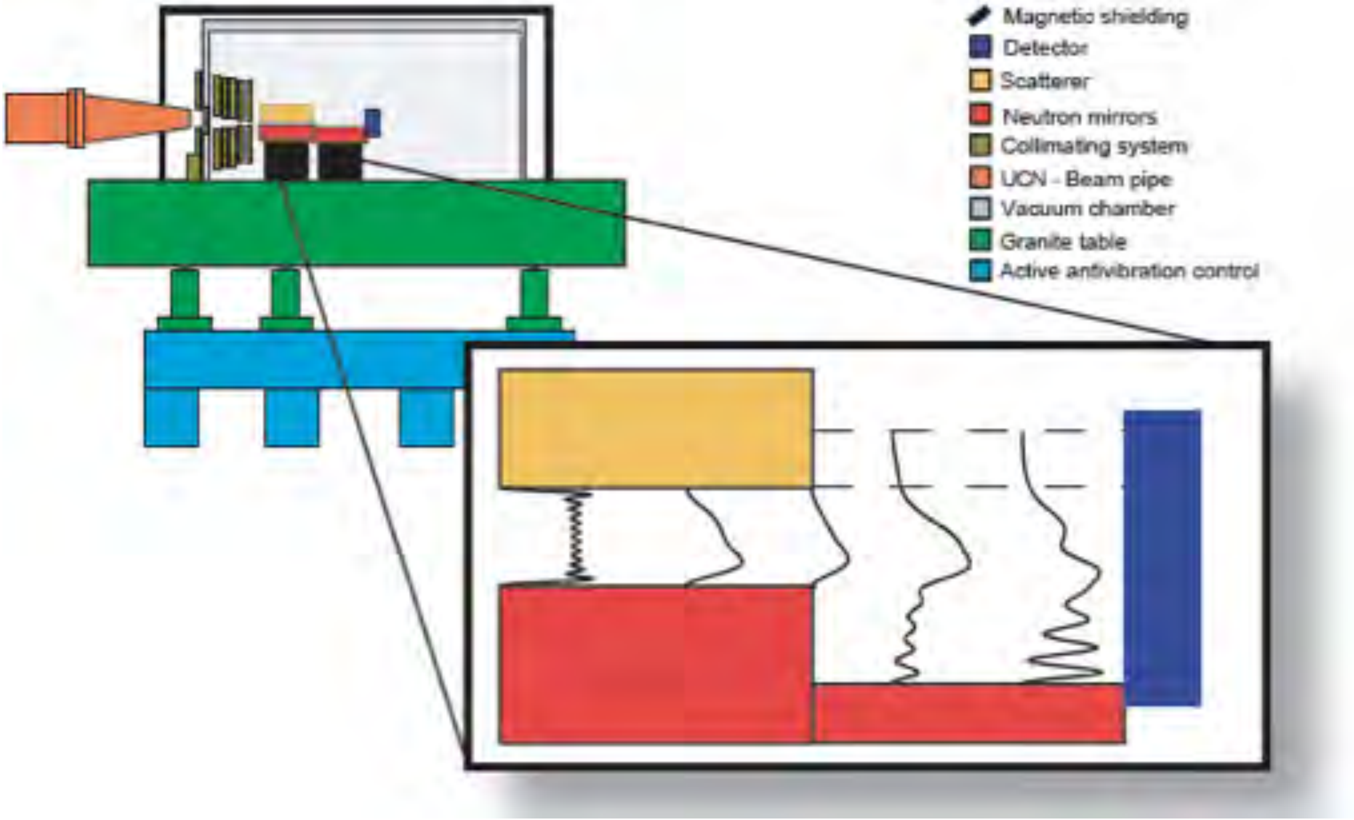
- limits for Newton: r < 10µm
- range: 1 nm < λ < 100 µm
- strength: $\alpha \sim 10^8$



Gravitation: Q-Bounce

Abele et al.: arXiv:1510.03078v1

H. Abele et al.



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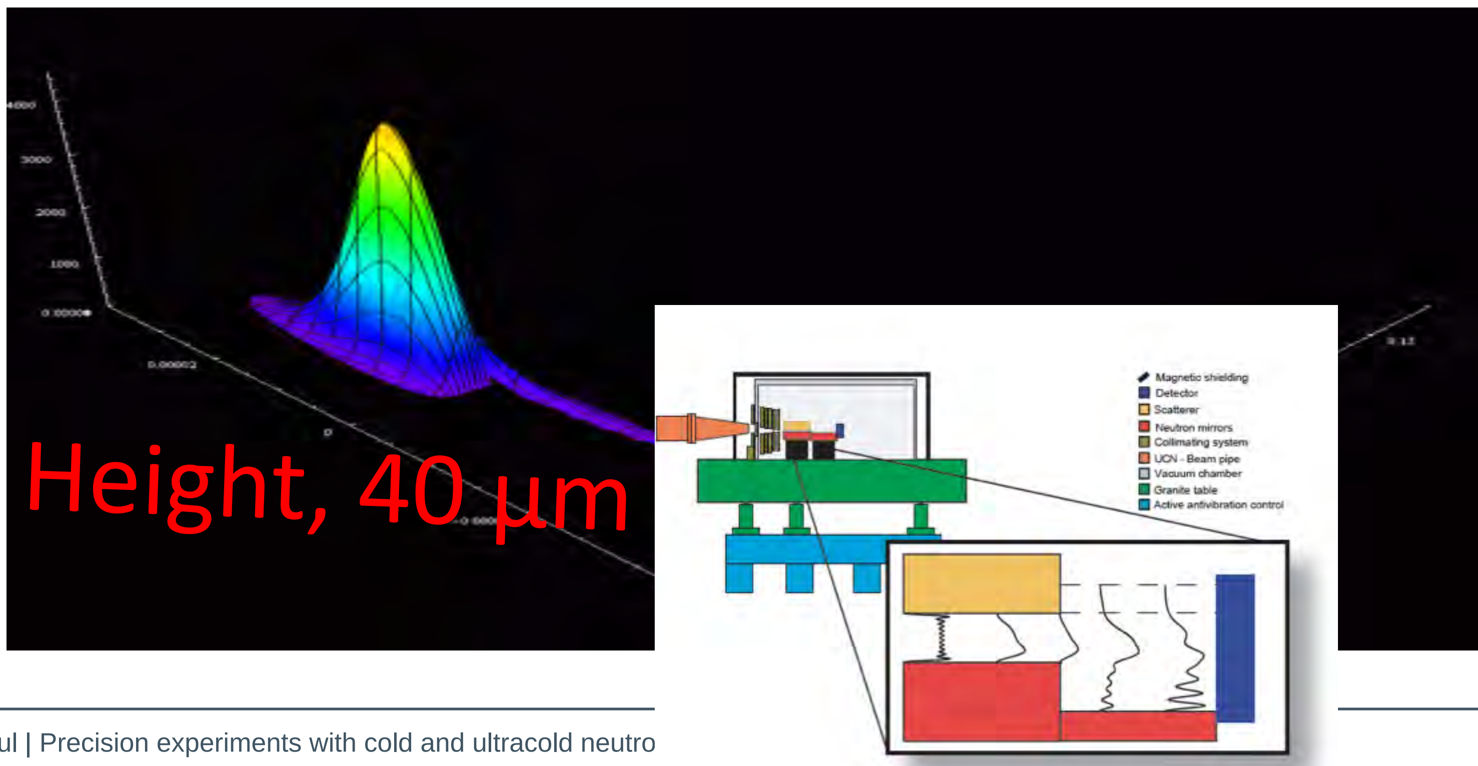
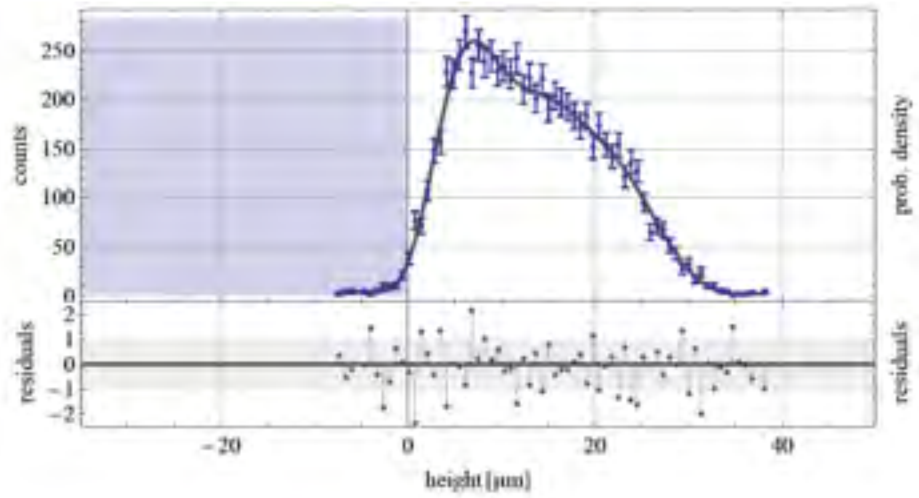
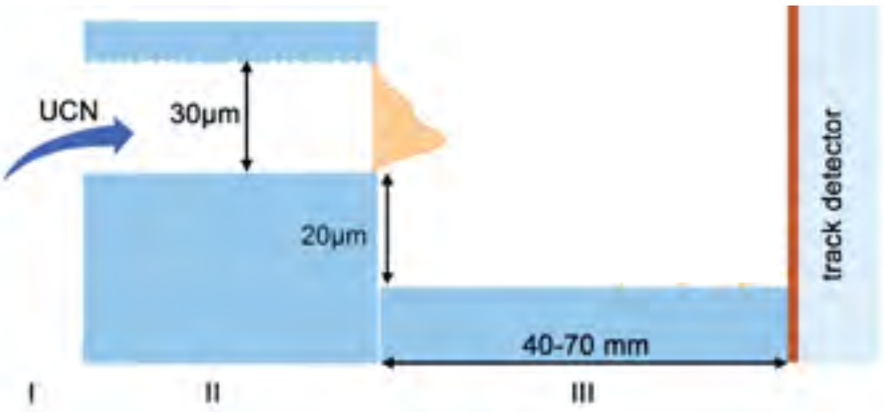
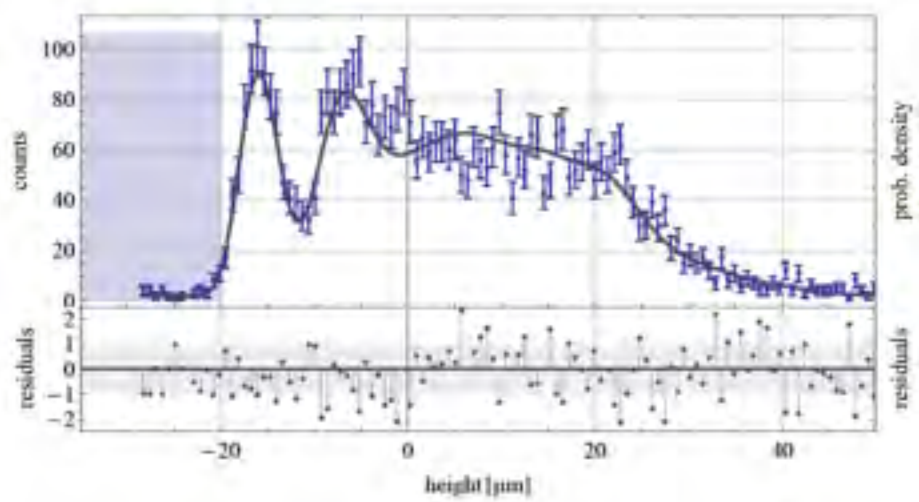
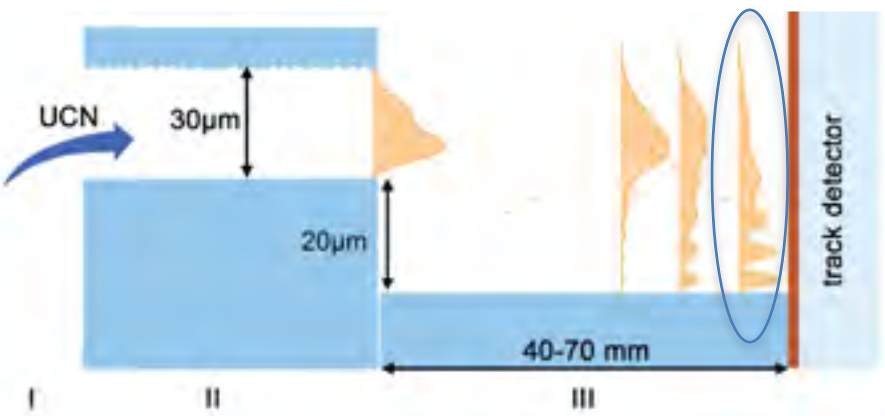

Height, 40 µm
Magnetic shielding
Detector
Scatterer
Neutron mirrors
Collimating system
UCN - Beam pipe
Vacuum chamber
Granite table
Active antivibration control

Gravitation: Q-Bounce Abele et al.: arXiv:1510.03078v1







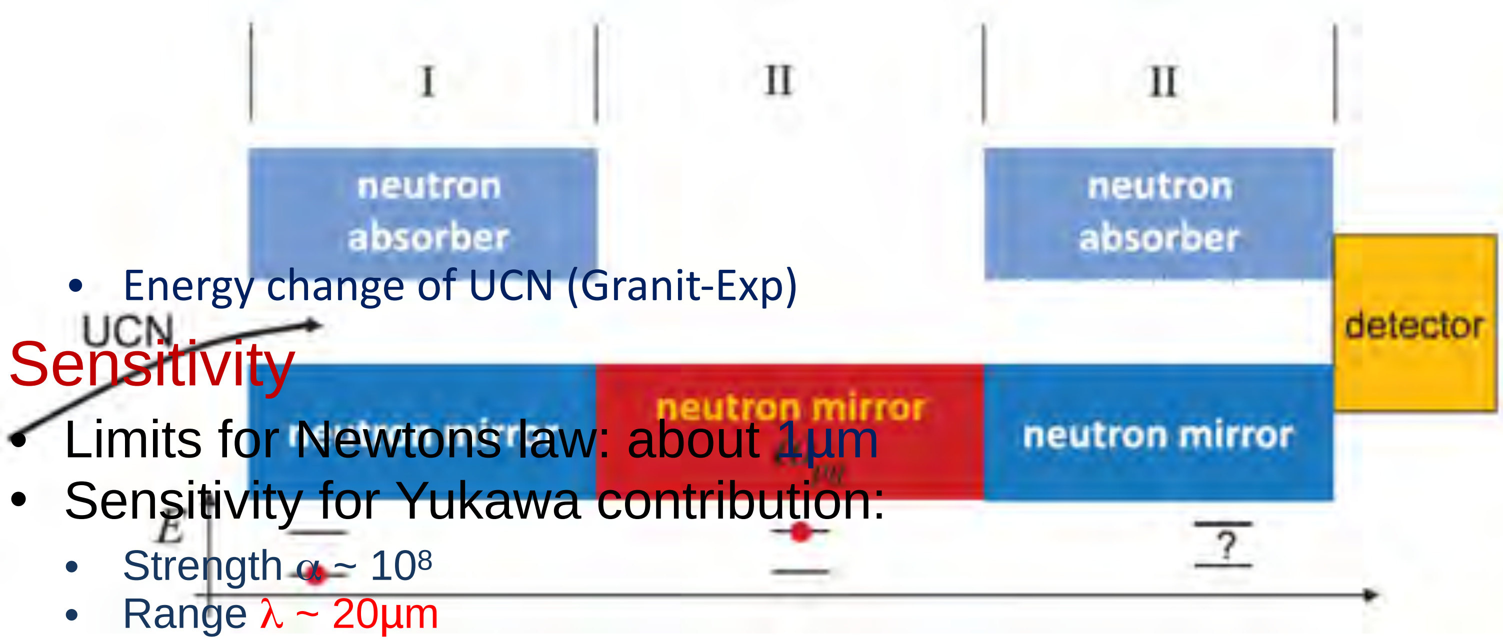


Gravitation: New Generation Measurements

- 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
  - Sensitivity for Yukawa contribution:
    - Strength α ~ 10^8
    - Range λ ~ 20µm

Gravitation: New Generation Measurements

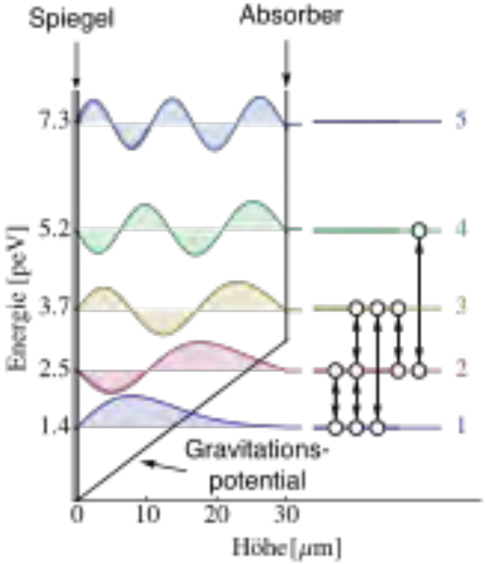
H. Abele et al.

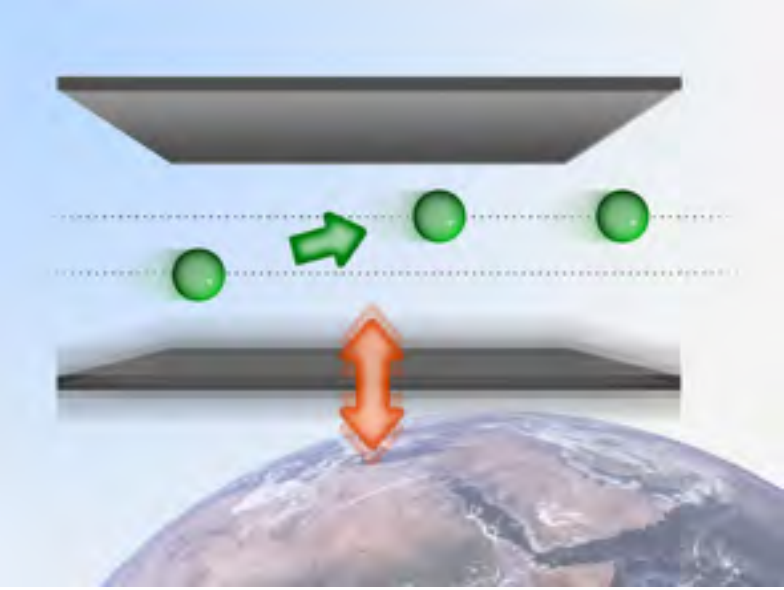
- Sensitivity
  - Limits for Newtons law: about 1µm
  - Sensitivity for Yukawa contribution:
    - Strength $\alpha \sim 10^8$
    - Range $\lambda \sim 20\mu m$

Gravitational Resonance Spectroscopy

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

	2	3	4	5	6
1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2		[illegible]	[illegible]	[illegible]	[illegible]
3			[illegible]	[illegible]	[illegible]
4				[illegible]	[illegible]
5					[illegible]





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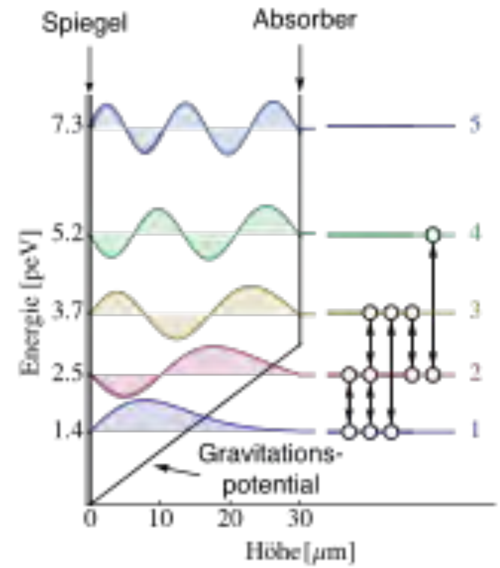

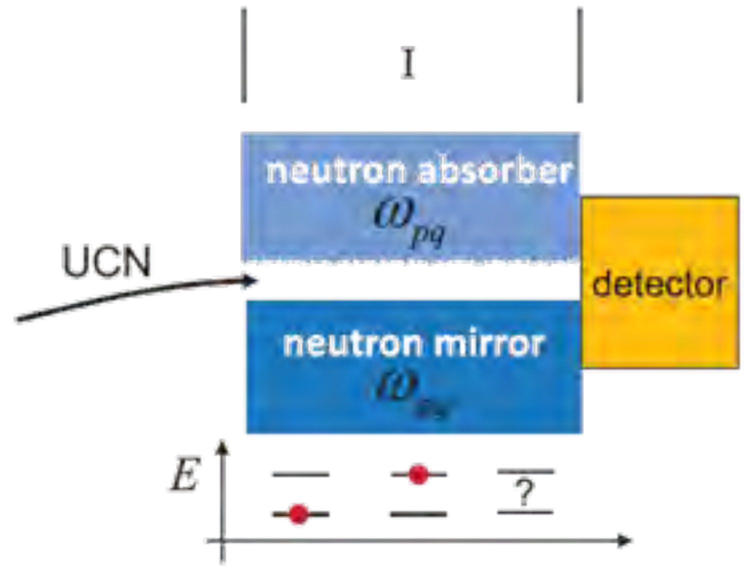

Gravitational Resonance Spectroscopy

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

	2	3	4	5	6
1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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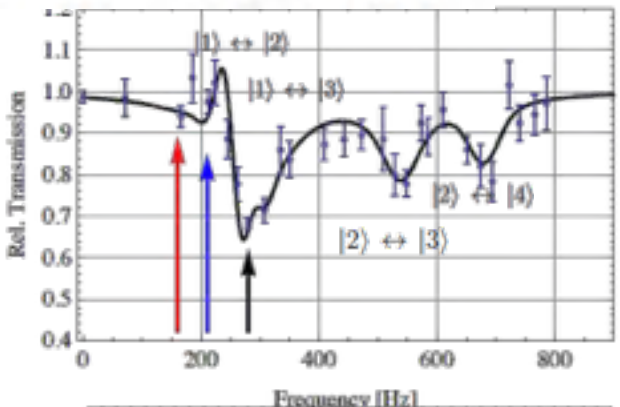
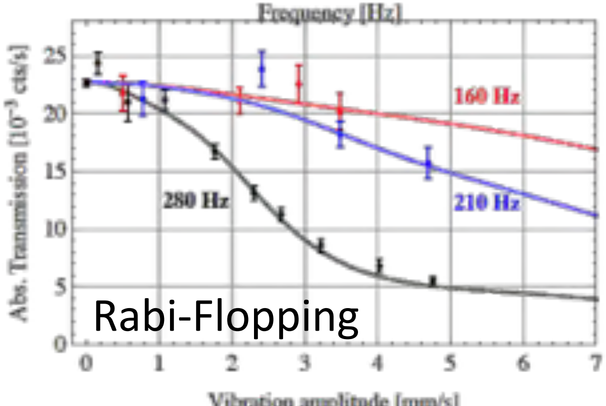
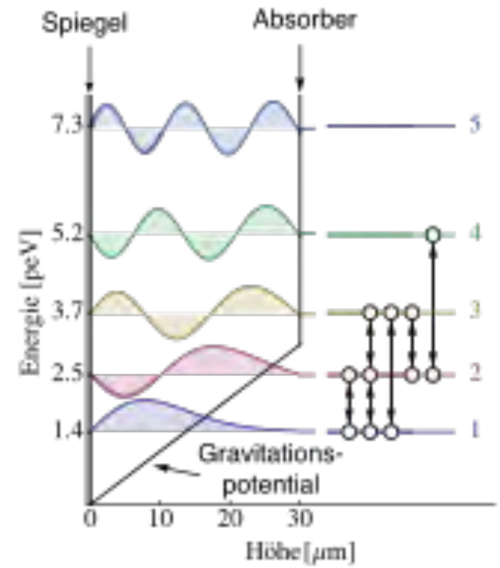
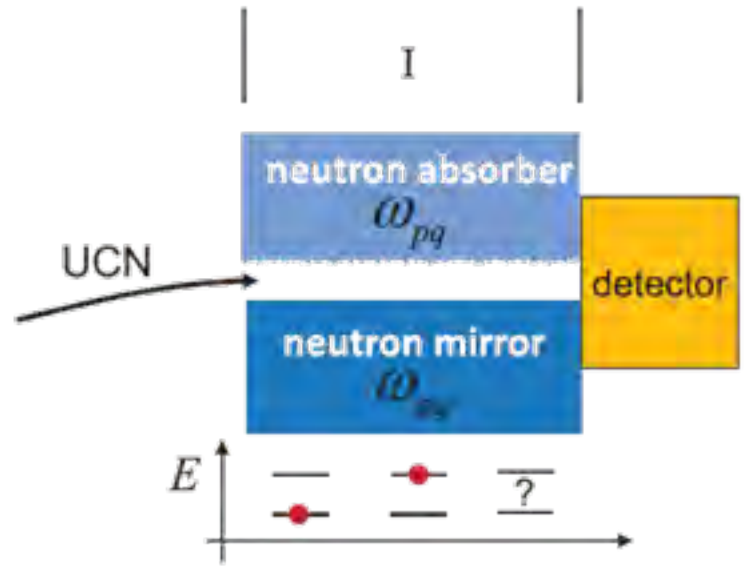




$$\frac{\Delta E}{E} \approx 10^{-14}$$





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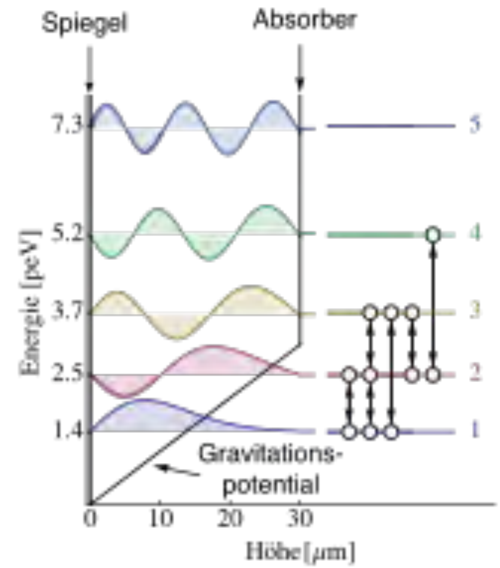
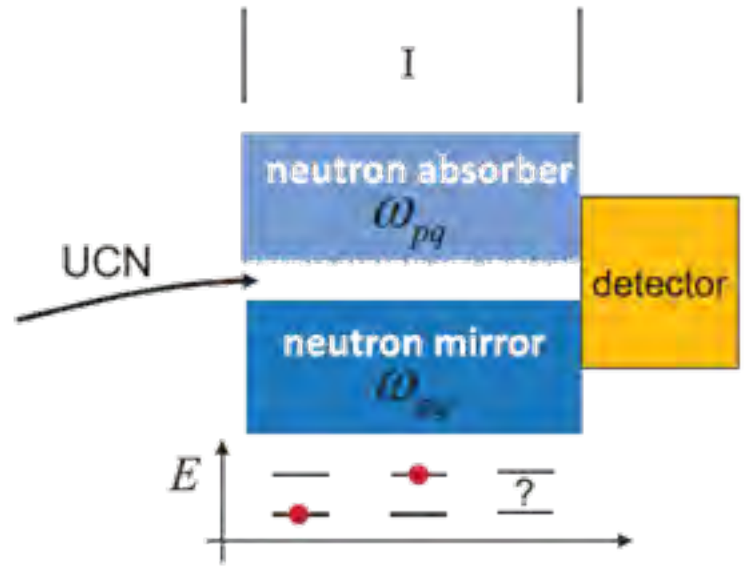




Gain sensitivity to short range forces

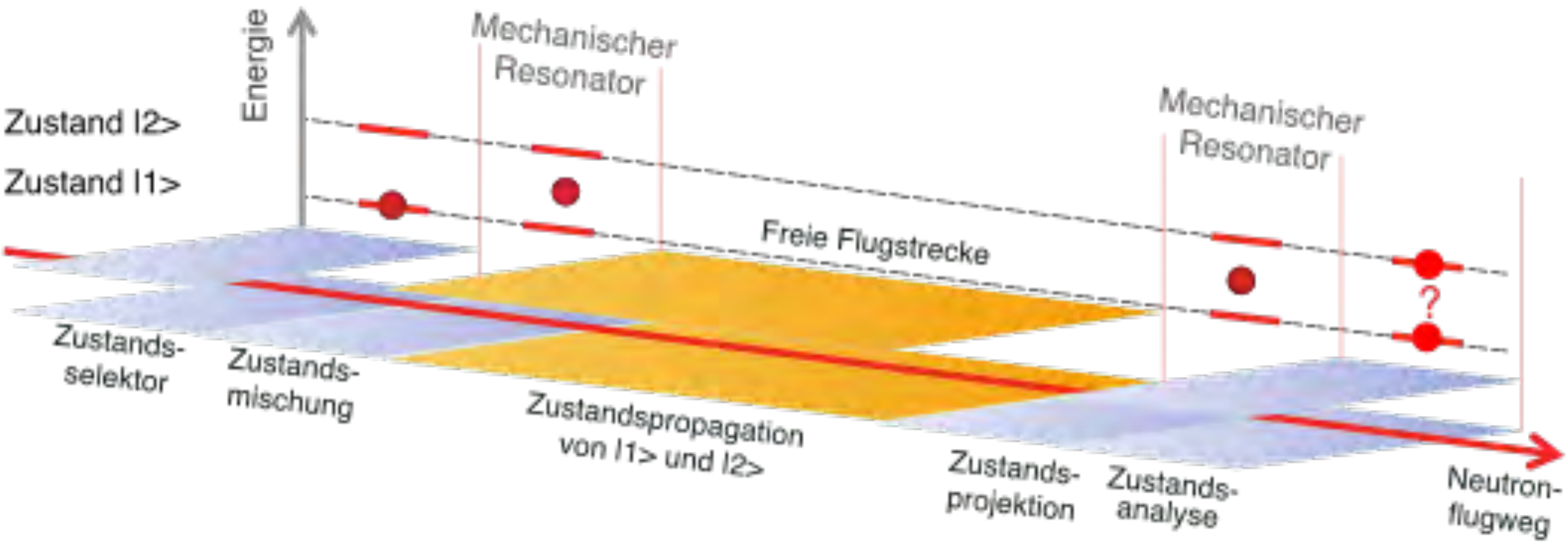
Level dependent modification of level spacing

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

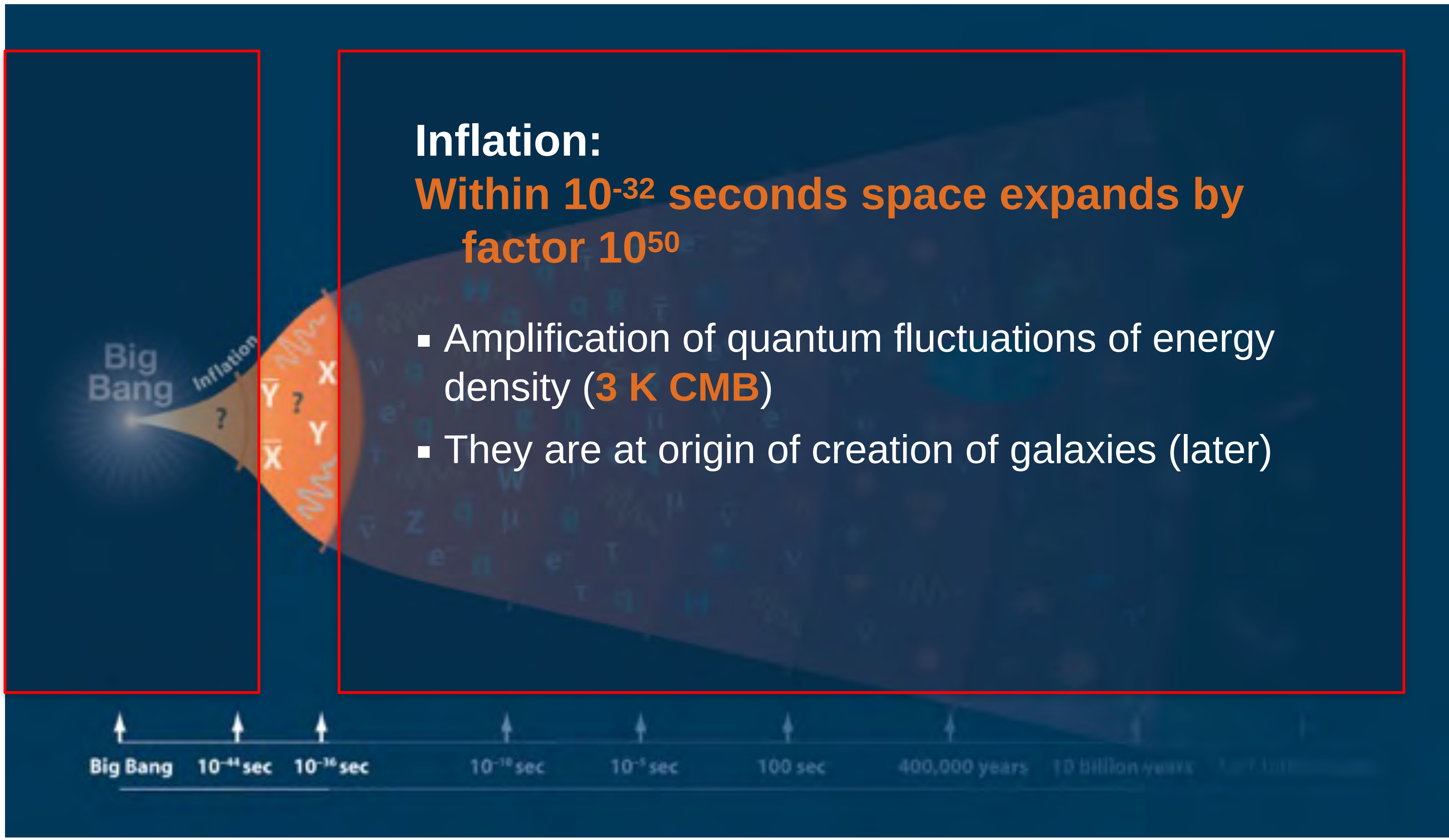
Already now: excellent limits

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



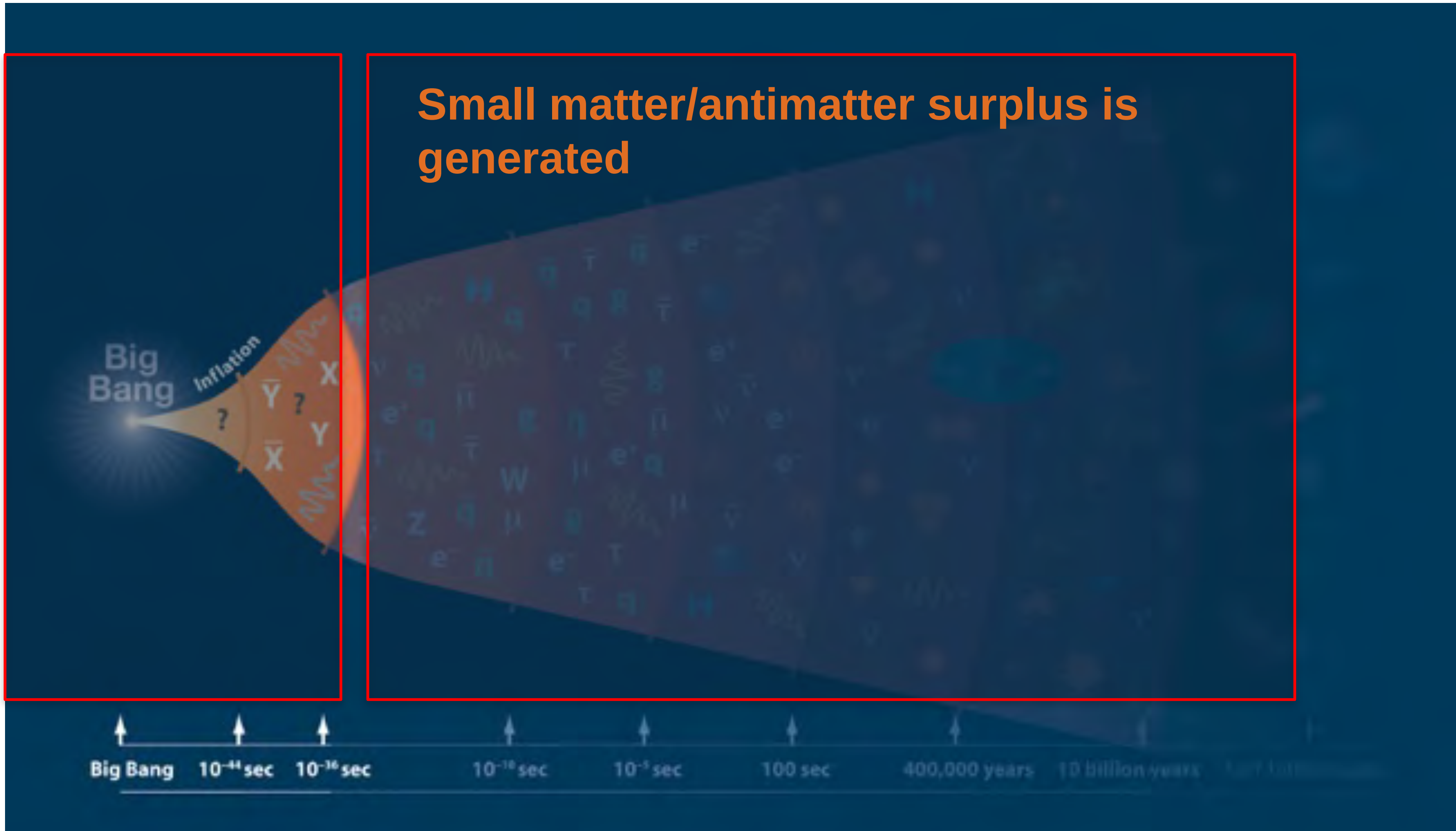
Inflation:

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

Small matter/antimatter surplus is generated



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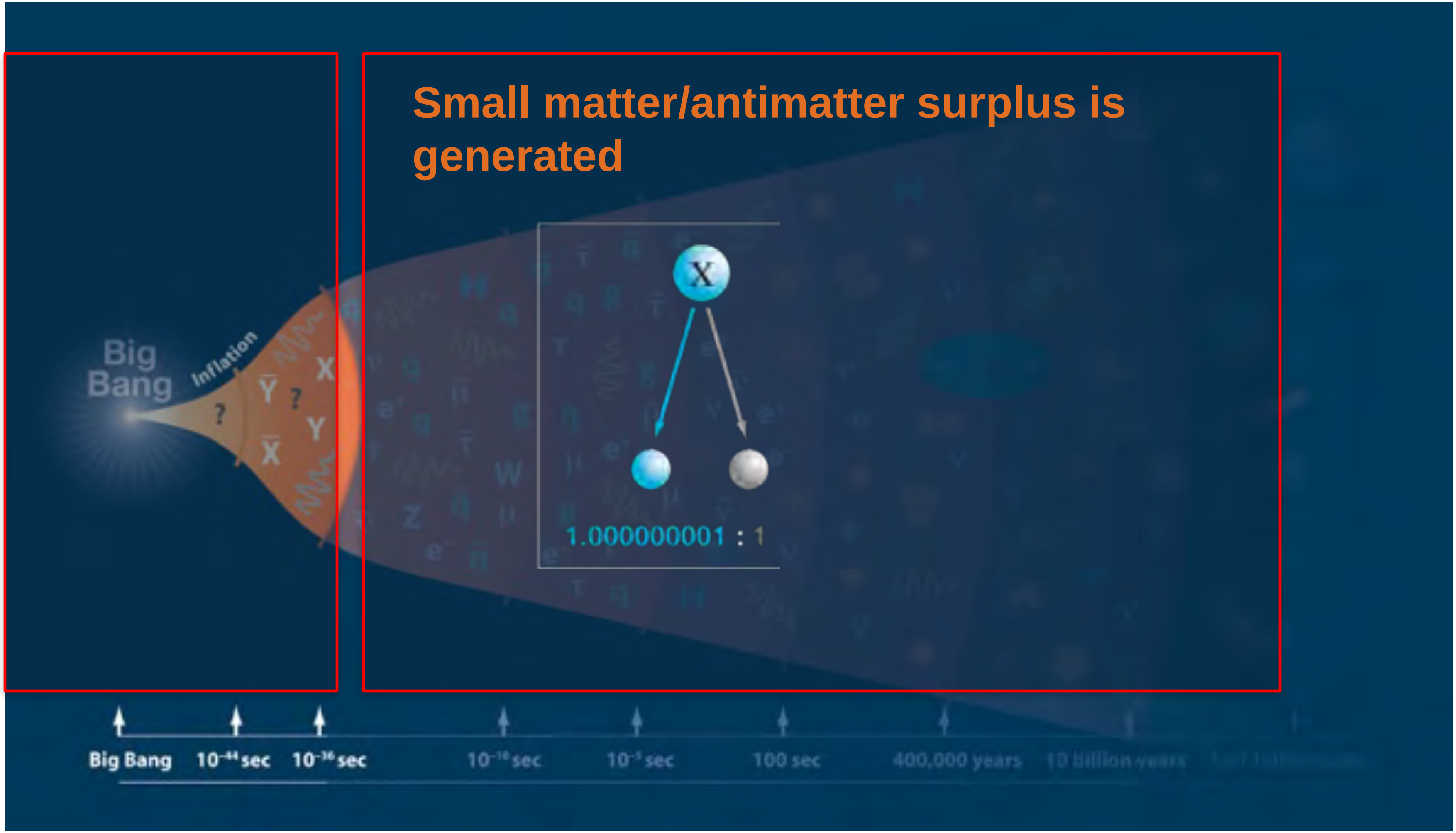

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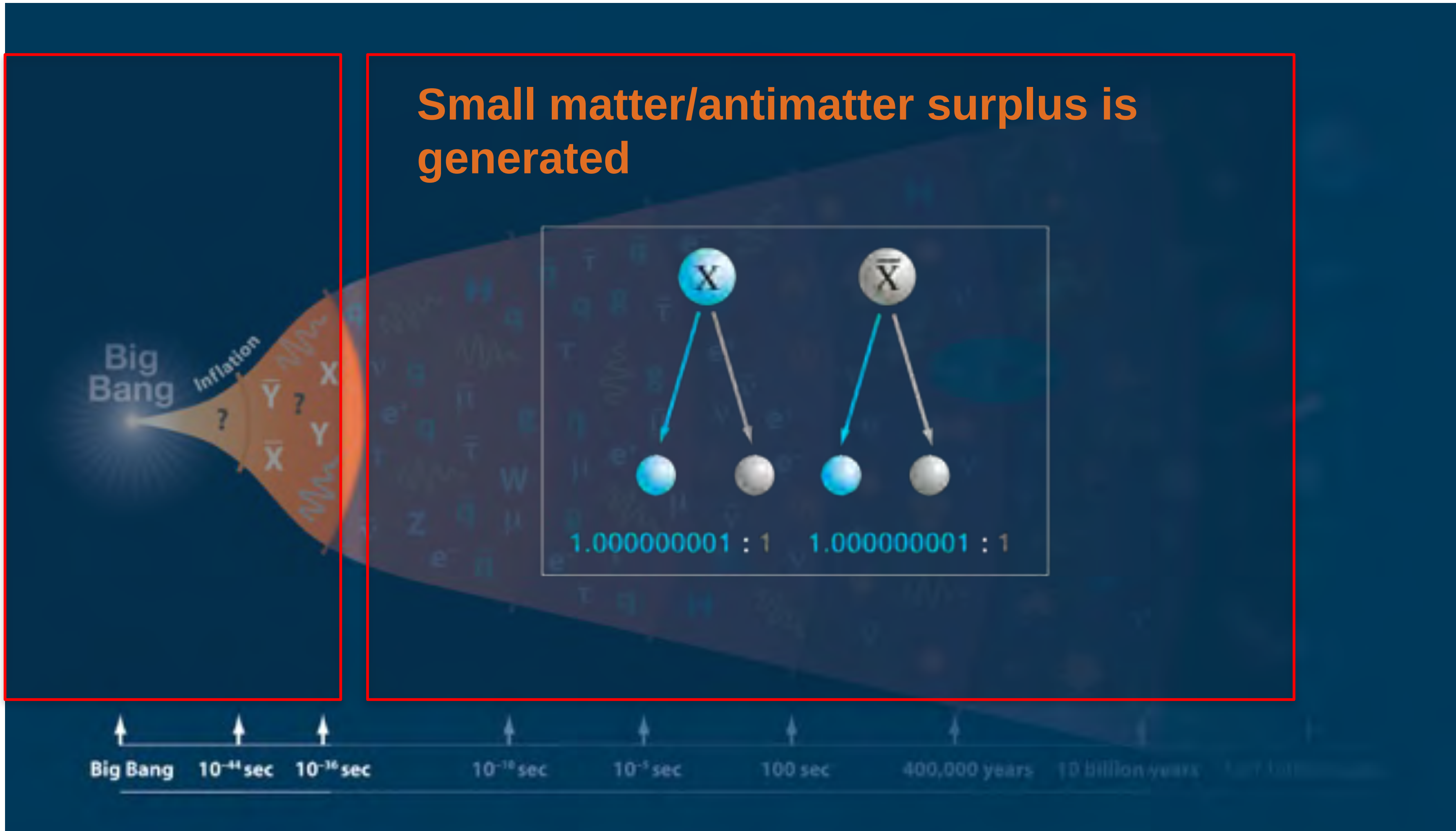
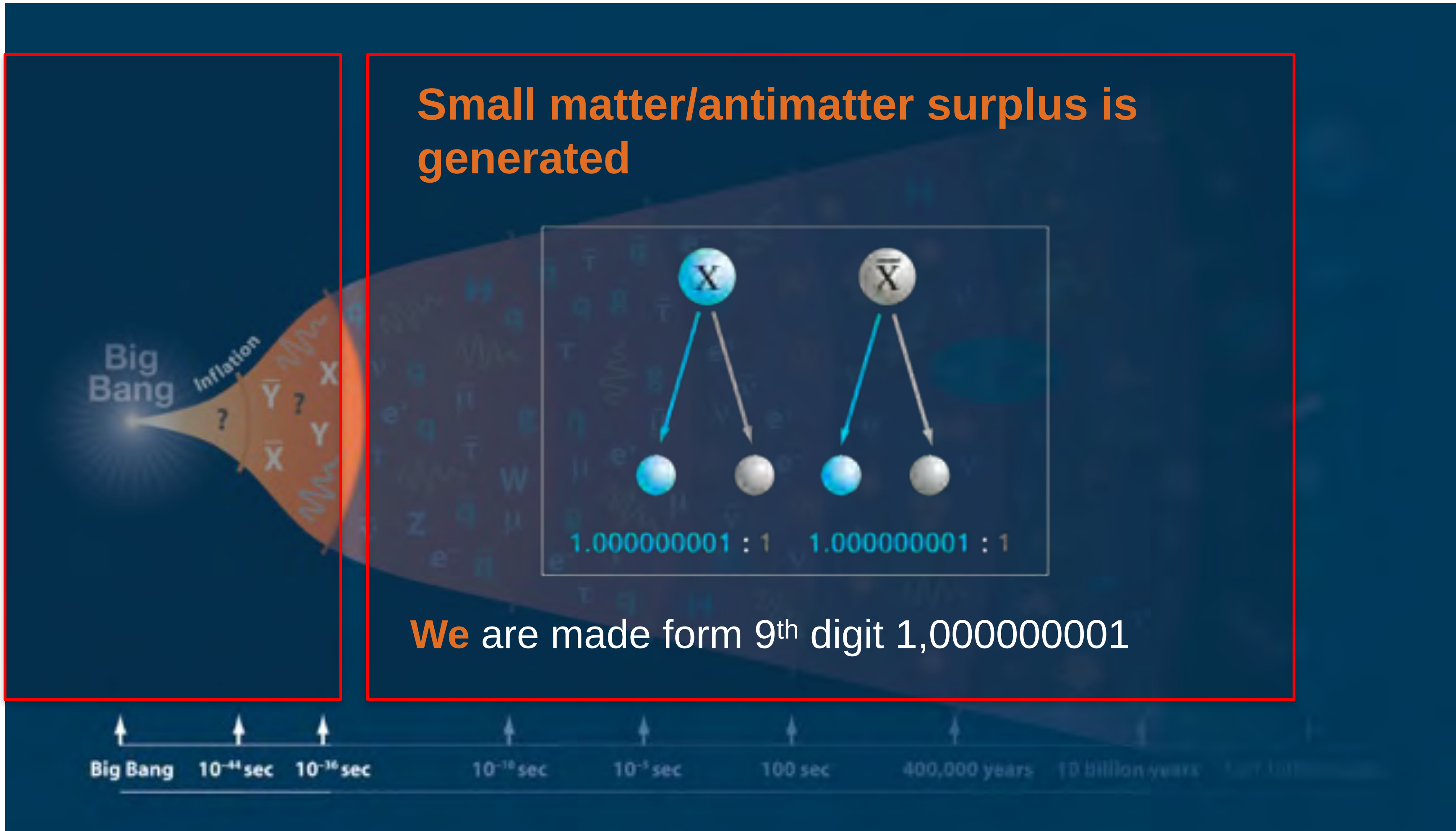


10^{-34} bis 10^{-33} Seconds after Big Bang



Small matter/antimatter surplus is generated

We are made form 9th digit 1,000000001

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

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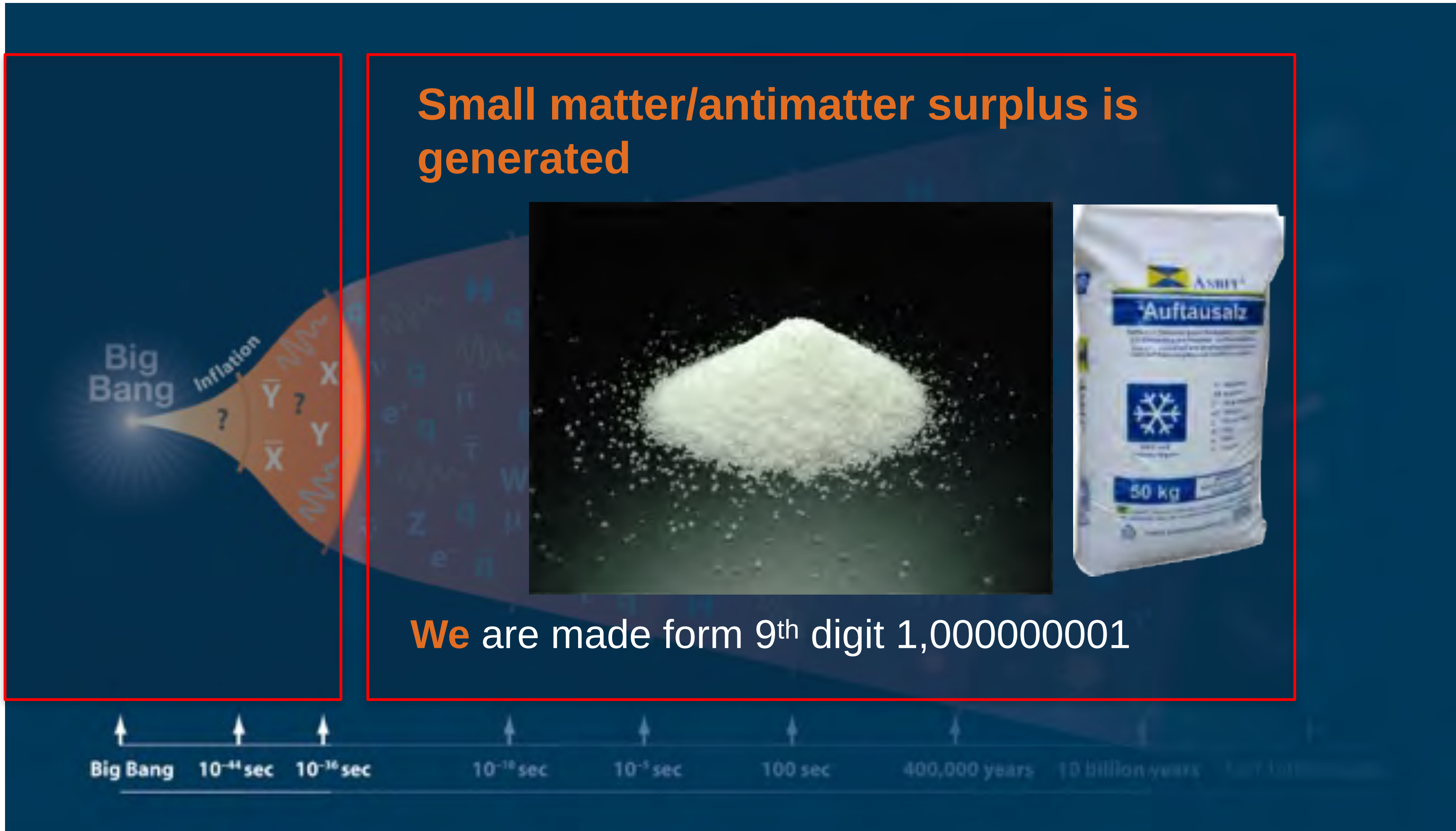
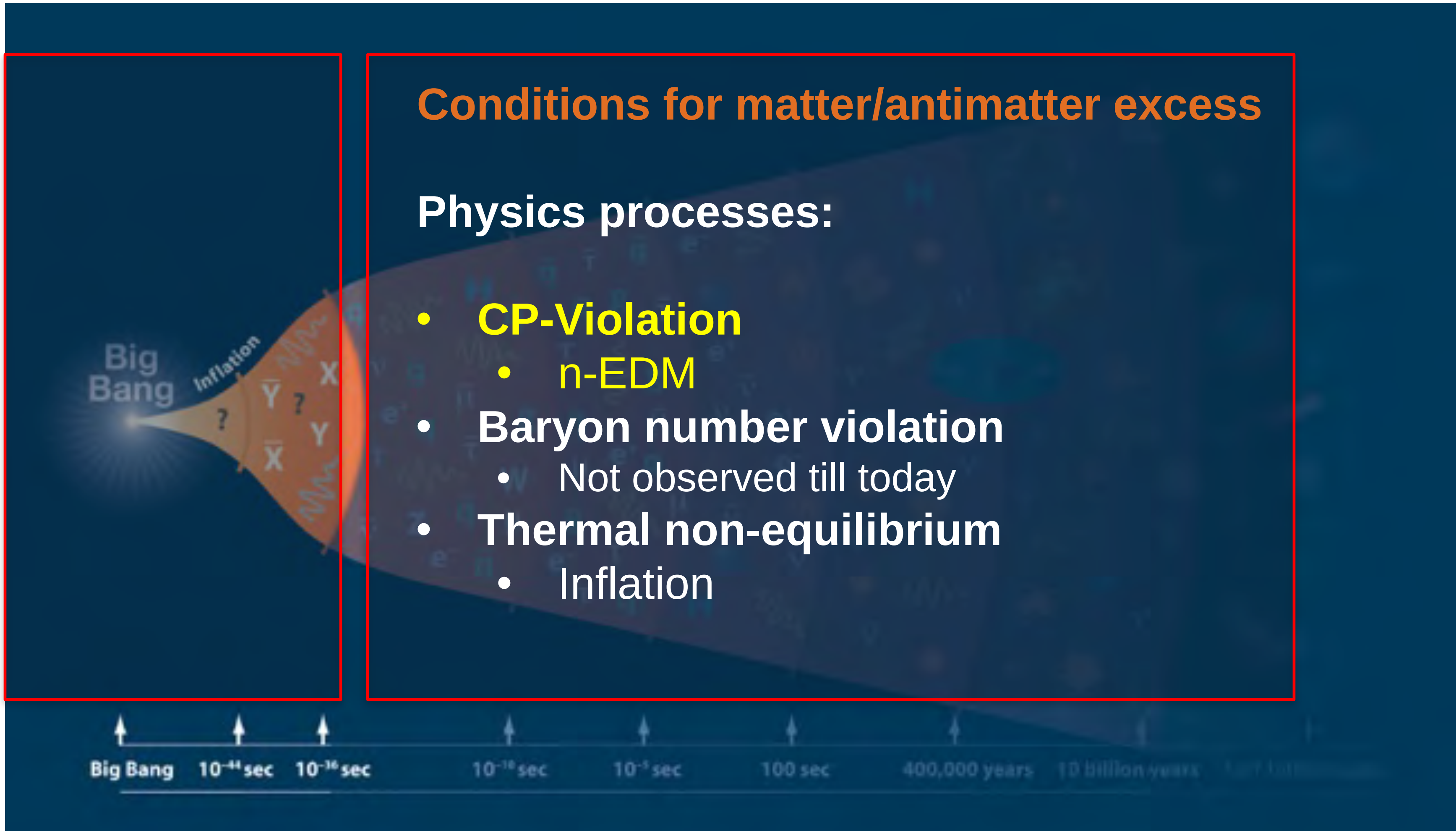


We are made form 9th digit 1,000000001

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

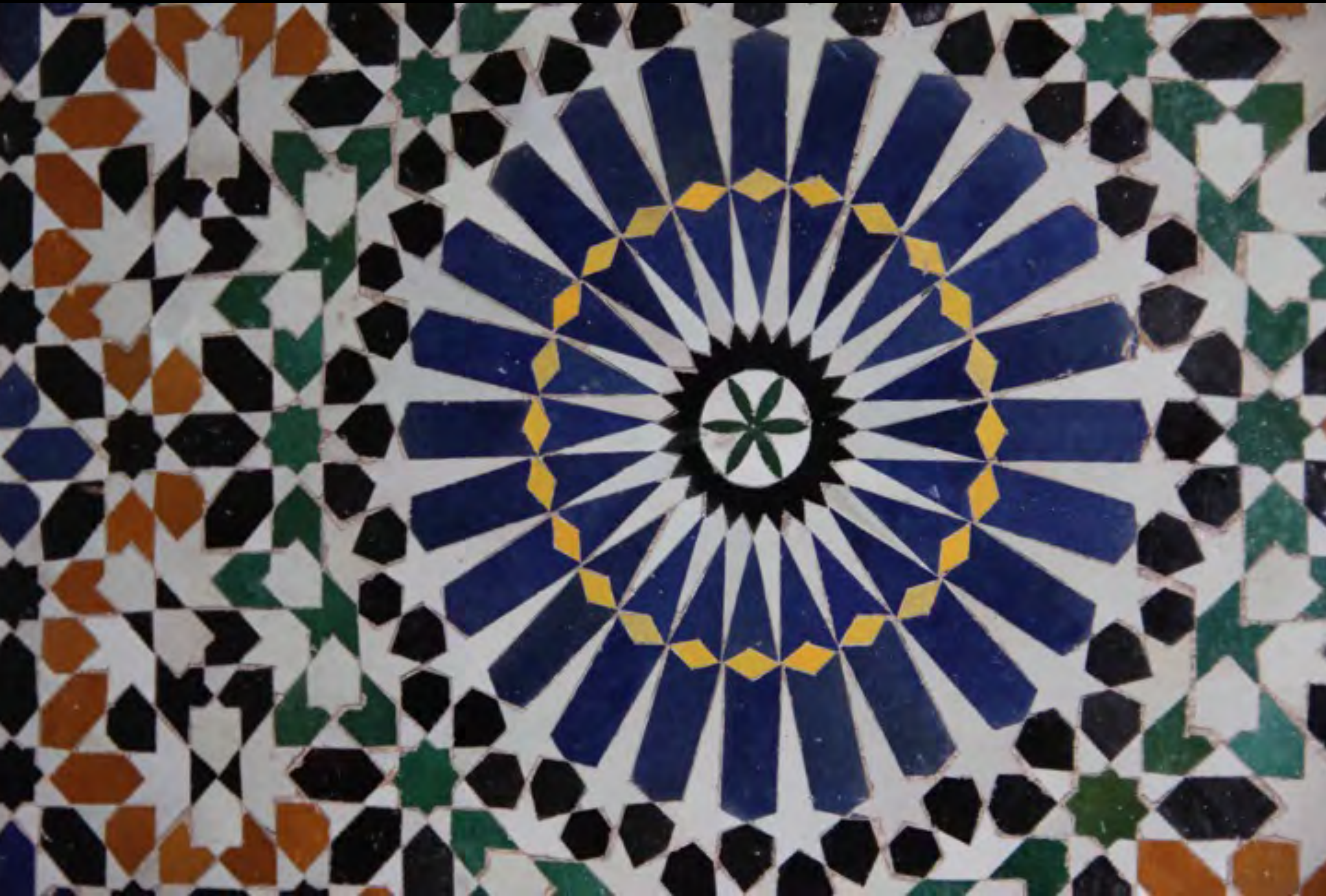


Conditions for matter/antimatter excess

Physics processes:

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

Symmetries



Exzellenzcluster Universe

Discrete Symmetries

anti-particle particle

e^+ e^-

following Escher ©

© idea taken from H.W. Wilschut

Exzellenzcluster Universe

Discrete Symmetries

Matter

mirror image

P

anti-particle **particle**

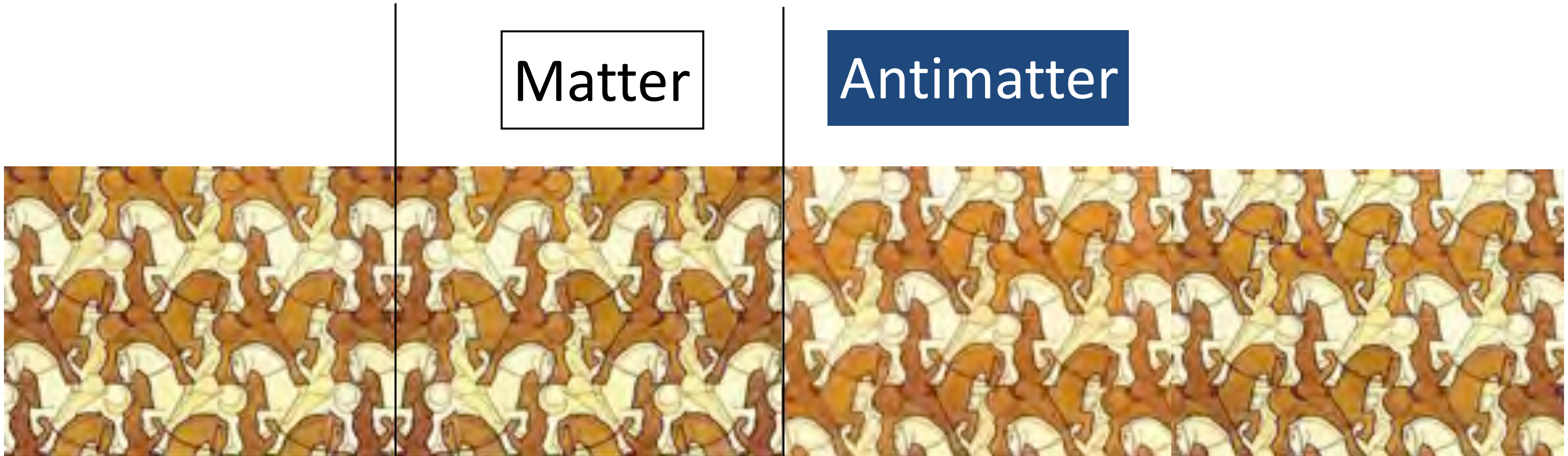
e^+ **e^-**

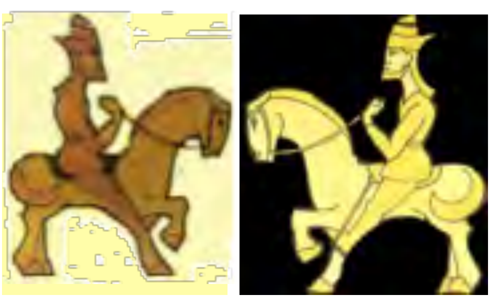
following Escher ©

© idea taken from H.W. Wilschut

Exzellenzcluster Universe

Discrete Symmetries





following Escher ©

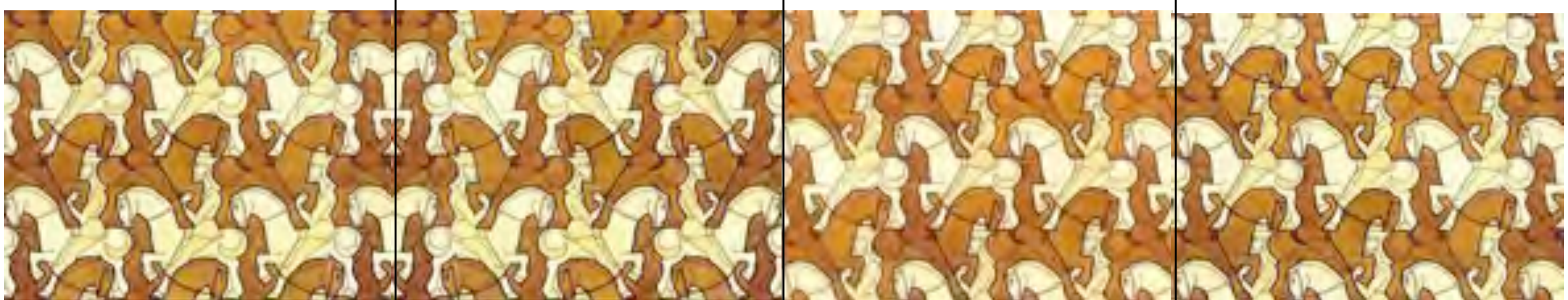
© idea taken from H.W. Wilschut

Exzellenzcluster Universe

Discrete Symmetries

Matter

Antimatter



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

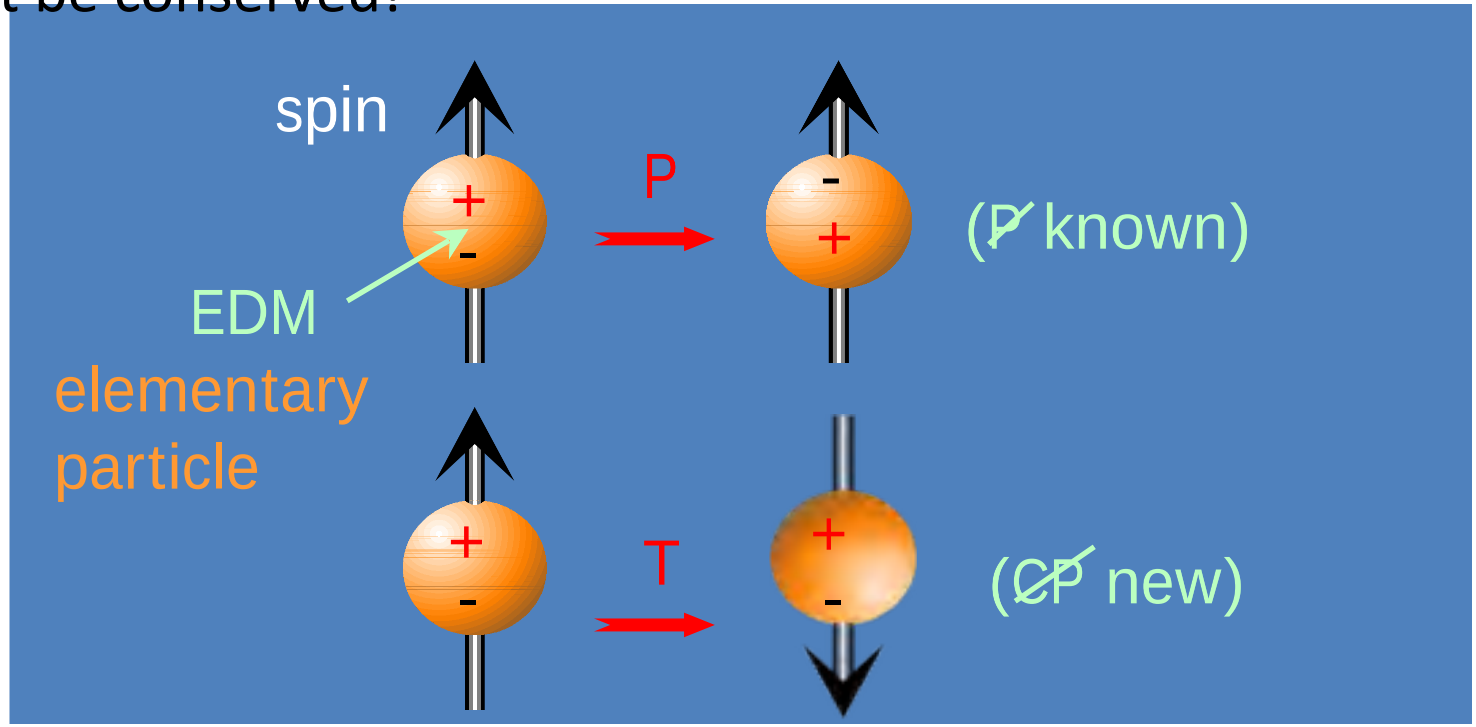
EDM and CP-Violation

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

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

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

CPT must be conserved!



The role of an n-EDM

Exzellenzcluster Universe

EDM is test for flavour diagonal C̸P

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

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 ($\theta < 10^{-9}$)

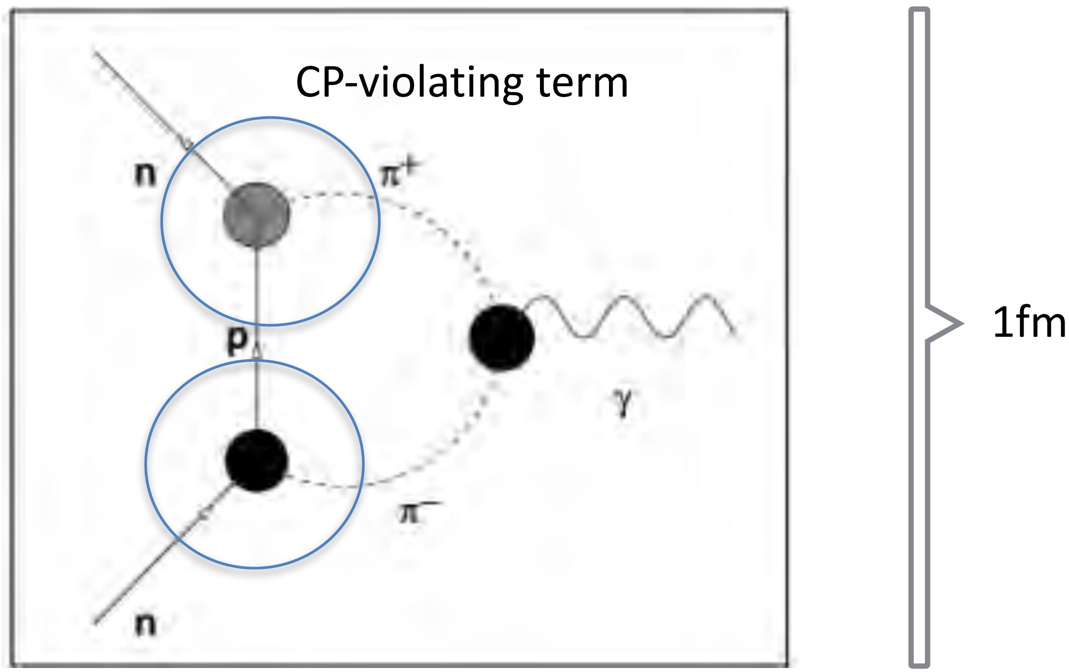
EDM is studied in

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

Exzellenzcluster Universe

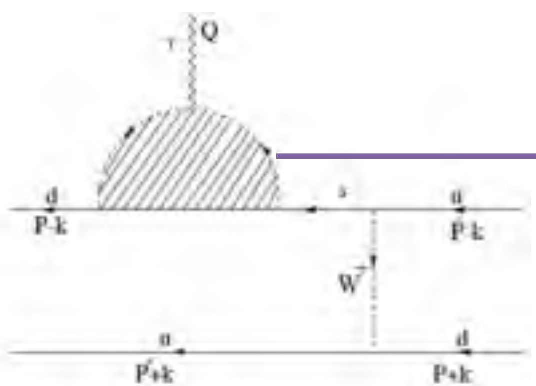
Neutron EDM

strong interaction

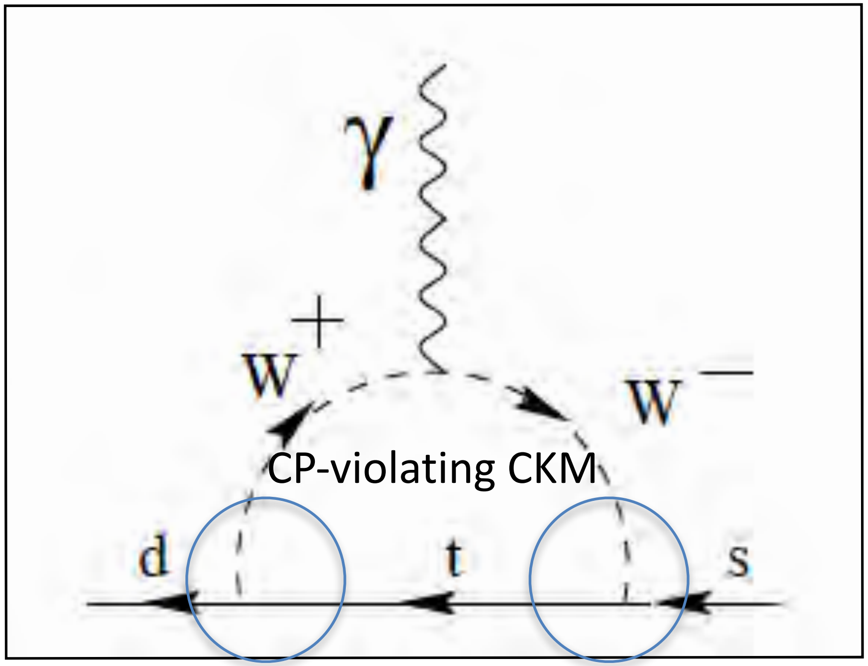


$$d_n \equiv D_n(k^2 = 0) = \frac{g_{\pi NN}\overline{g_{\pi NN}}}{4\pi^2 M_N} \ln\left(\frac{M_N}{m_\pi}\right)$$
$$\sim \overline{\theta} \times 2 \times 10^{-16} \mathrm{e-cm}$$

Exzellenzcluster Universe



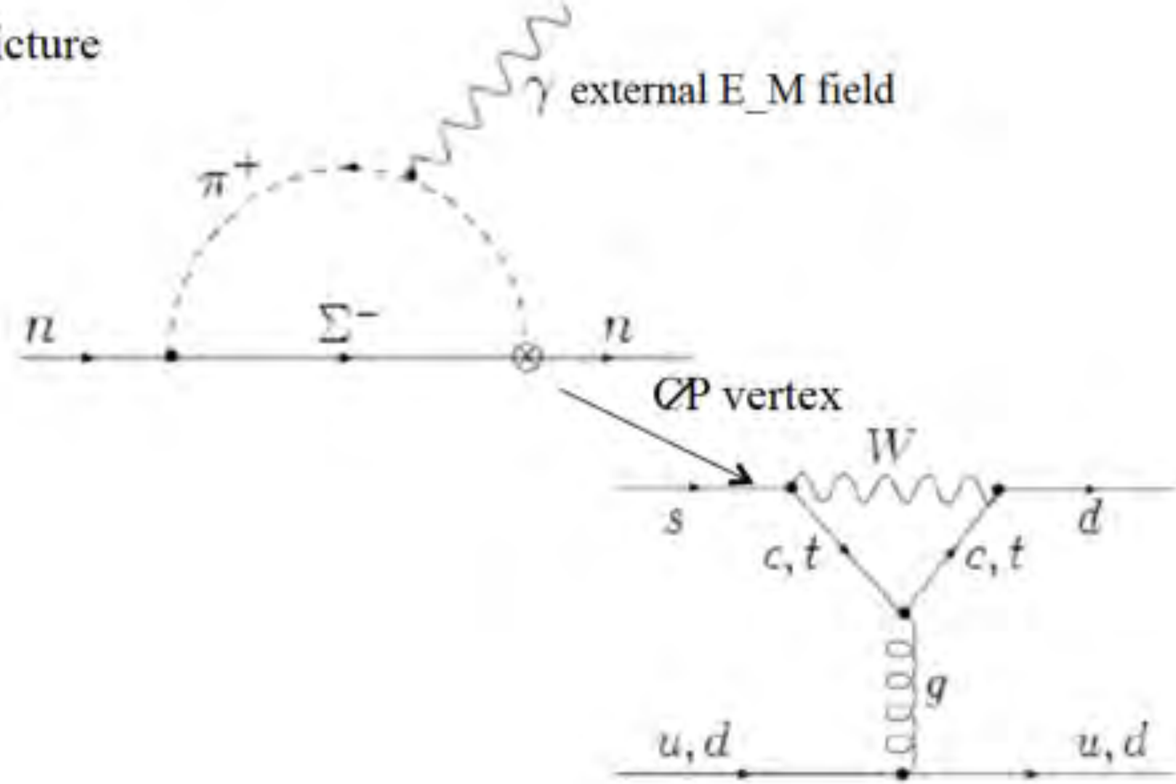
electroweak interaction



0.001fm

Standard Model EDM

Pion-nucleon picture
(d and μ)



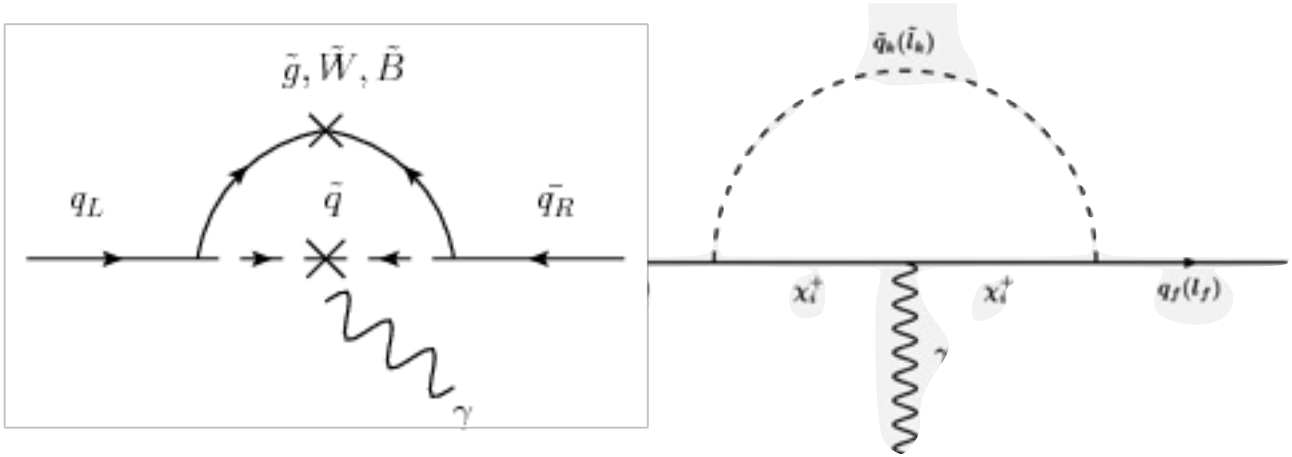
$$d_n^{SM} \approx 10^{-32}\ \text{e cm}$$

Exzellenzcluster Universe

Neutron EDM

Supersymmetry creates many CP violating phases

quark EDM

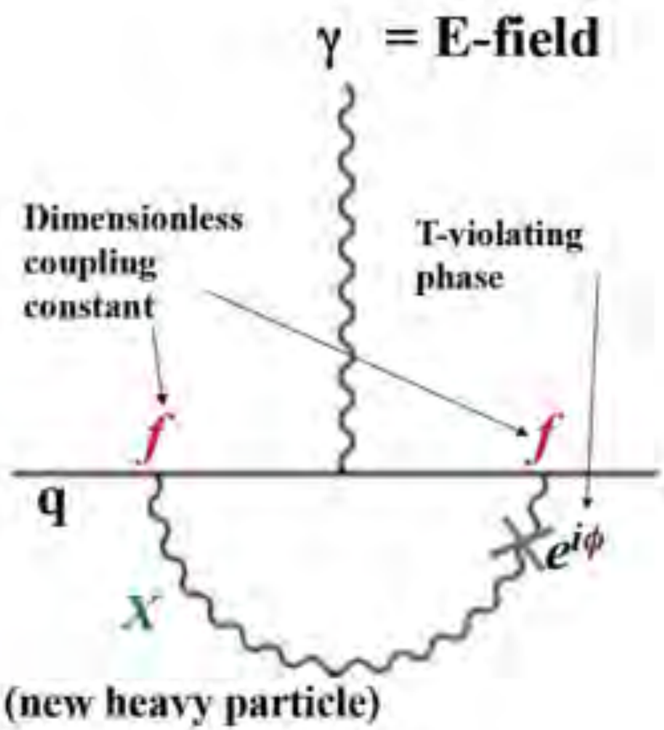


$0.2/M_{new}$ fm
10 TeV:
2 10^{-5} fm

New Physics at the TEV scale

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

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



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

$m_q \approx 1\ MeV$

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

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

$$\sin\varphi \sim 1$$

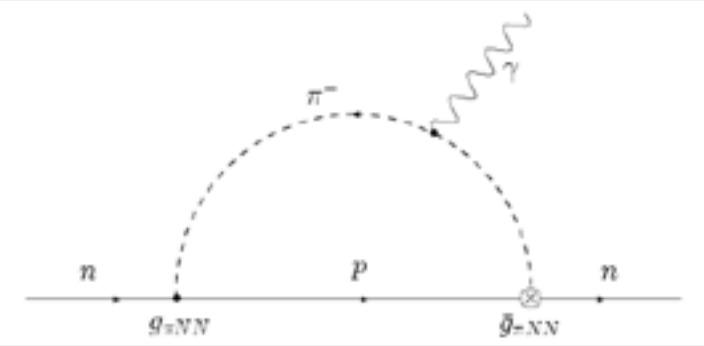
EDM – particle physics

Exzellenzcluster Universe

Strong interaction – 'strong CP'-Problem in QCD

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

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

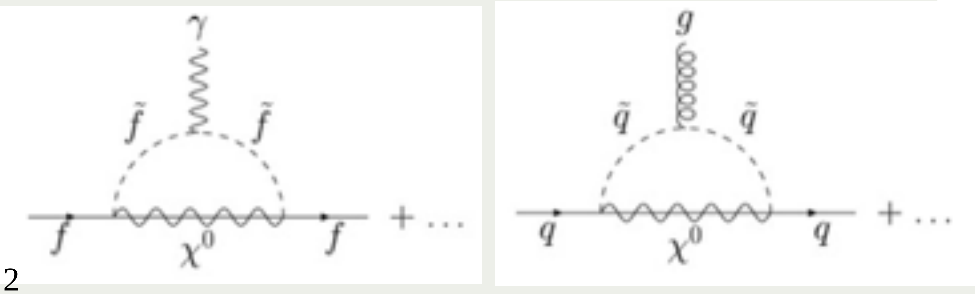


Supersymmetry

generate quark EDM d_q

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

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



Example: 1-loop SUSY

How to measure an EDM ?

Ramsey method

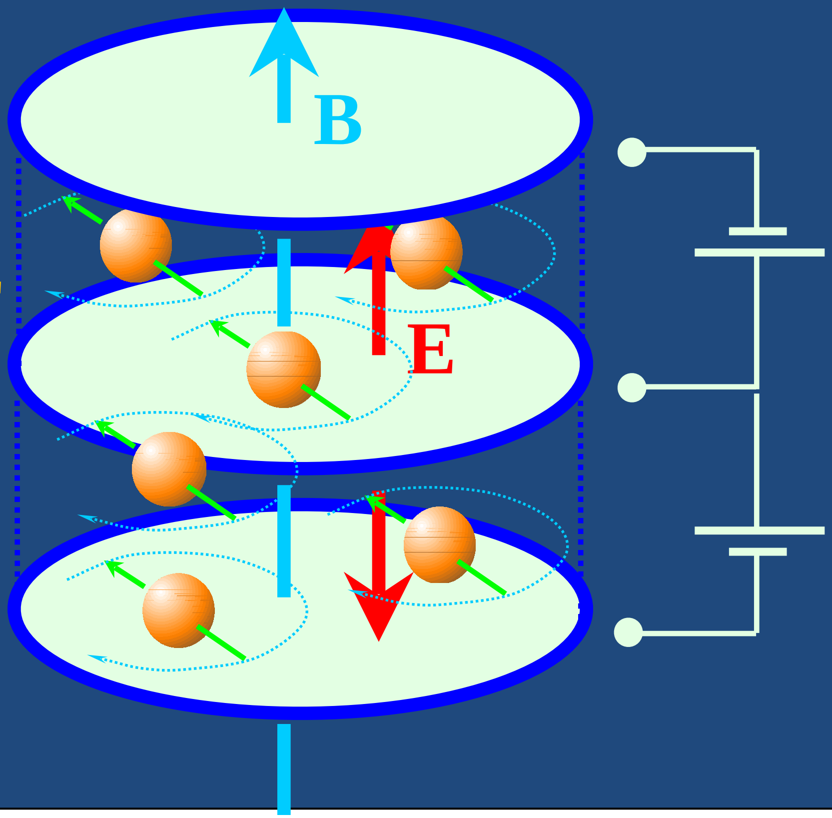
e.g. double chamber System

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

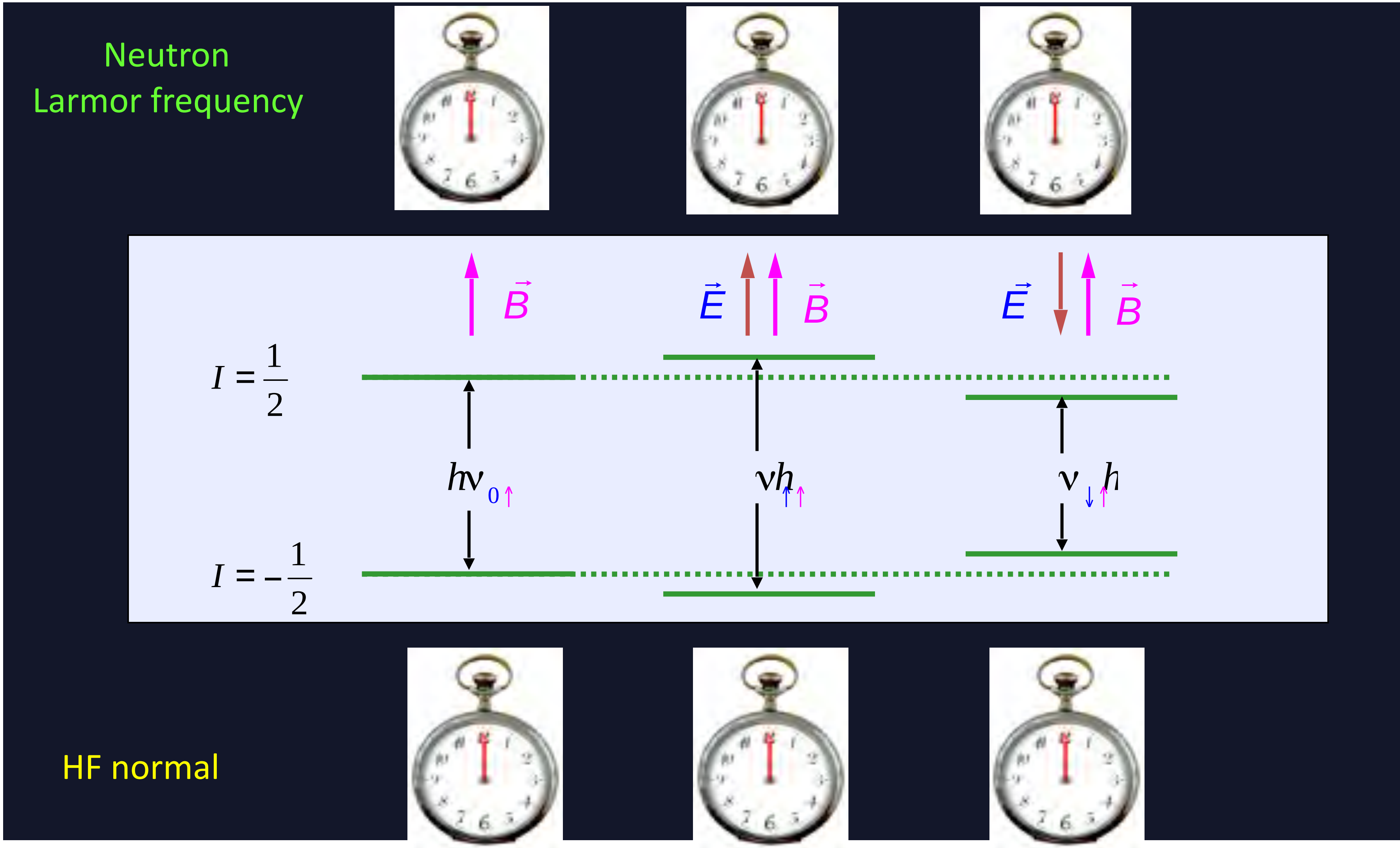
$$h\omega = \pm \mu B$$

+ dE

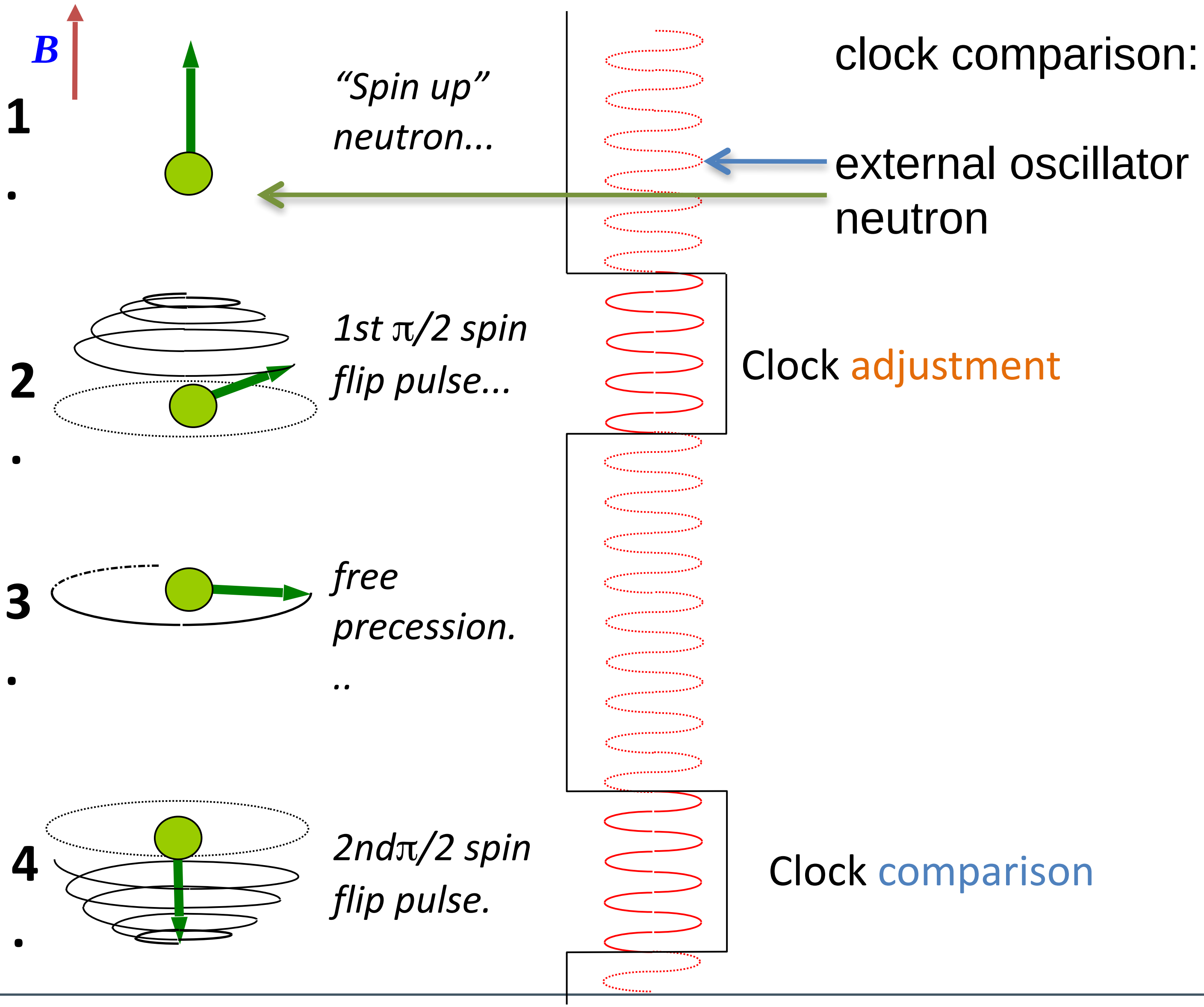
- dE



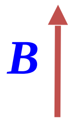
EDM-Measurement

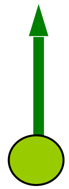


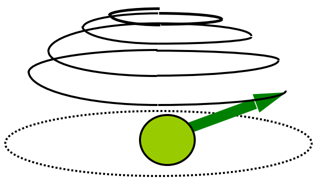
Measure: neutron EDM – Ramsey method

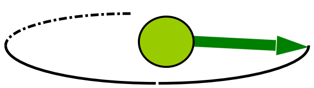


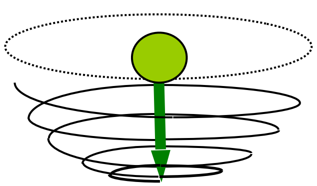
Measure: neutron EDM – Ramsey method

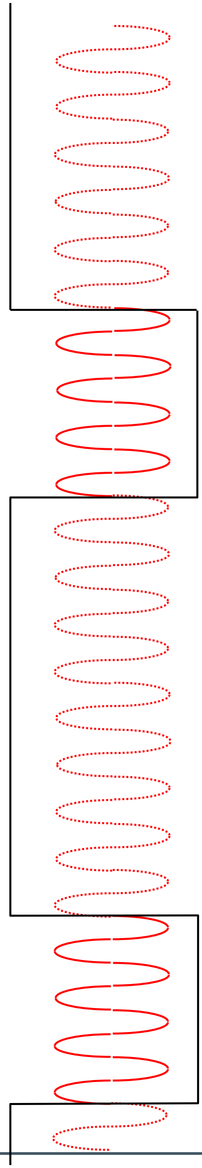


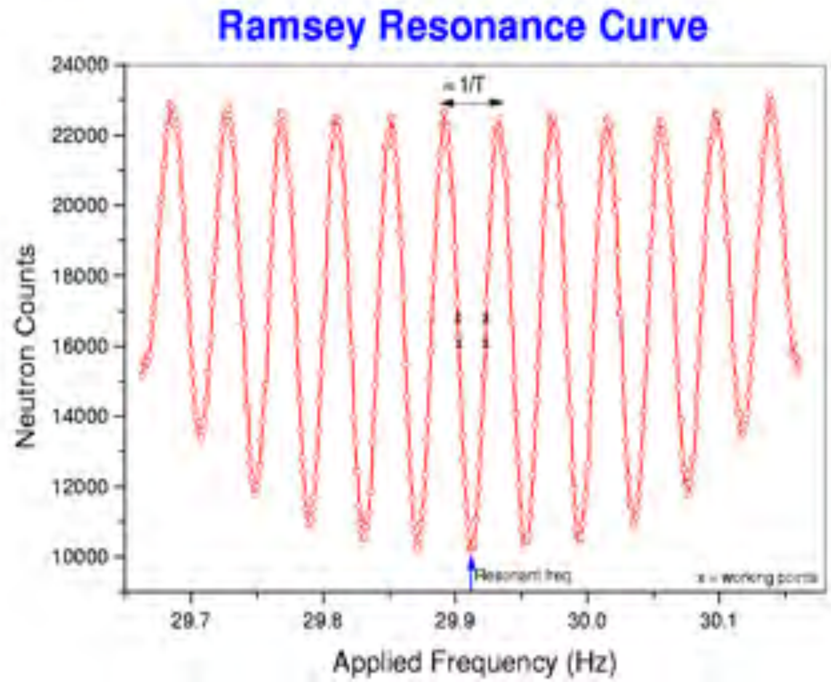
1.  *“Spin up” neutron…*

2.  *1st π/2 spin flip pulse…*

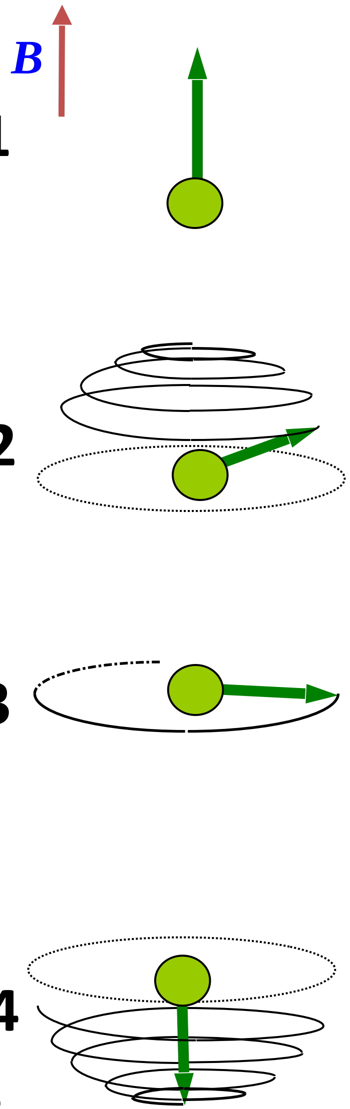
3.  *free precession. ..*

4.  *2ndπ/2 spin flip pulse.*

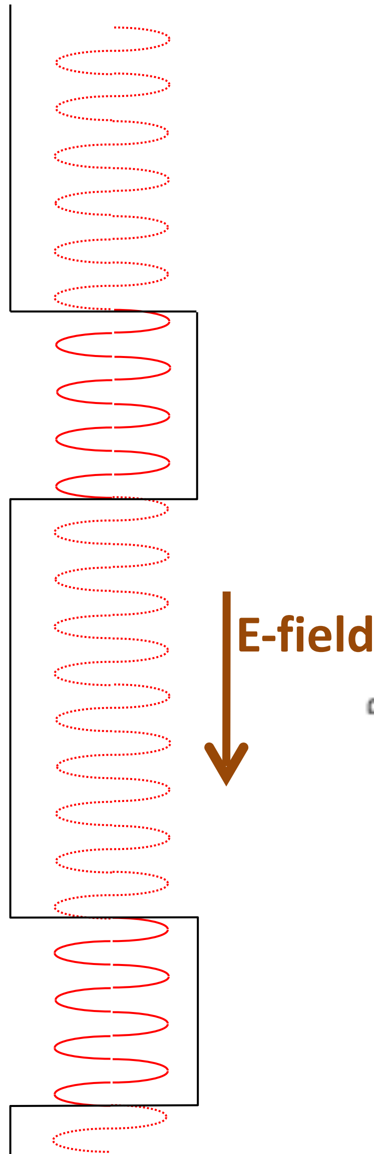


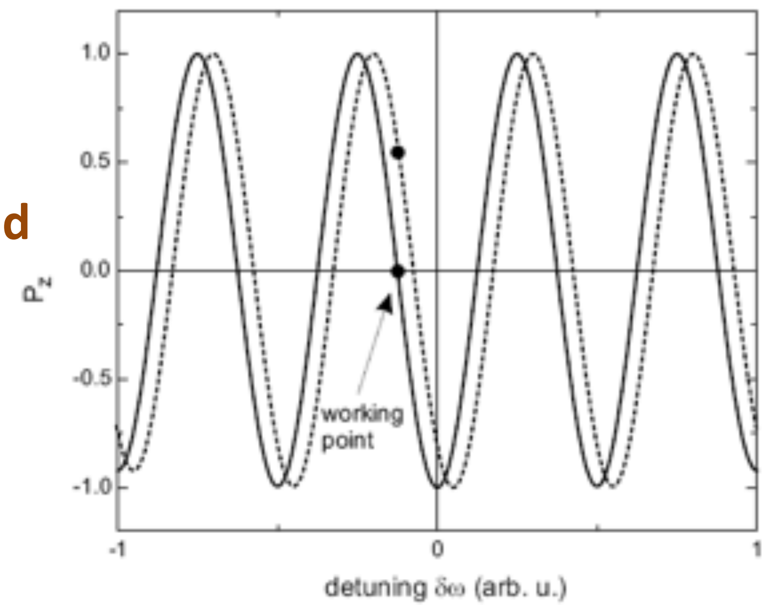


Measure: neutron EDM – Ramsey method



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

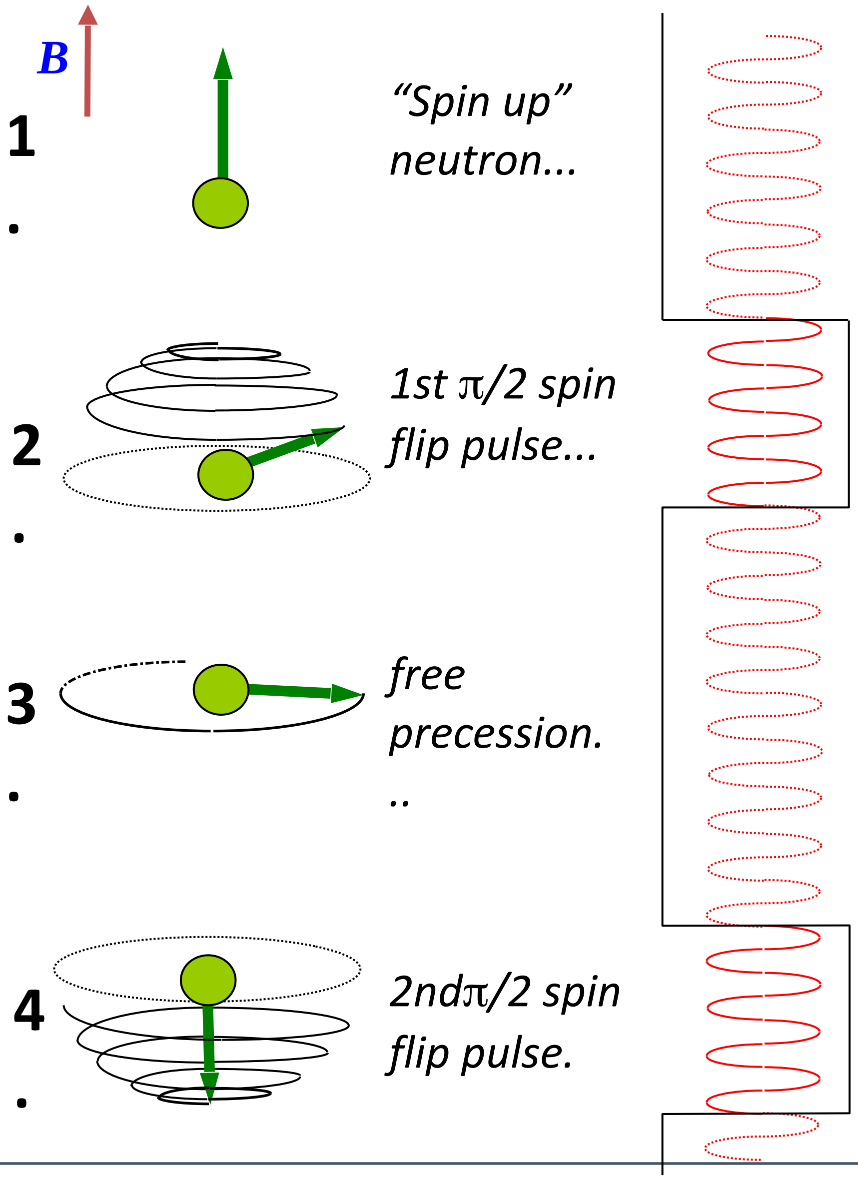
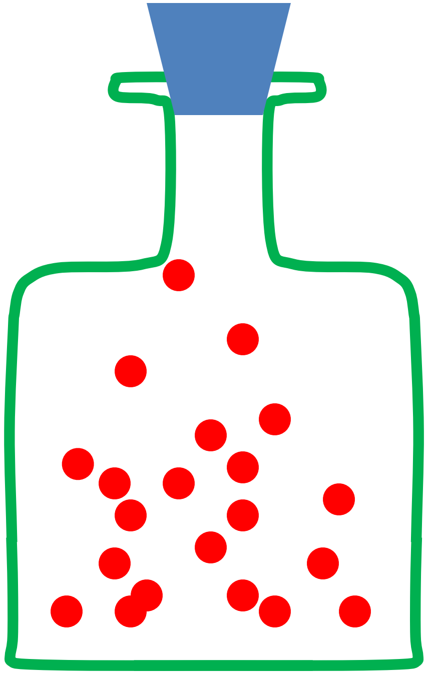


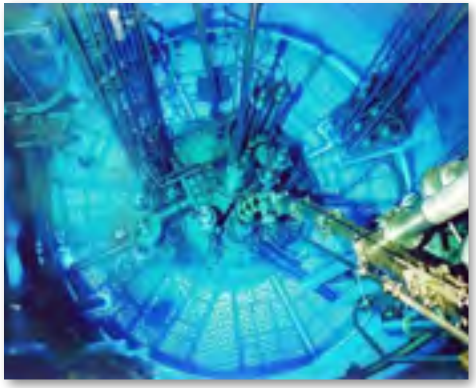
Figure of Merit

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

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)

Exzellenzcluster Universe

How accurately do we have to measure ?

Neutron(spin) precession of 30 Hz

Present sensitivity:

one spin-rotation in 180 days

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

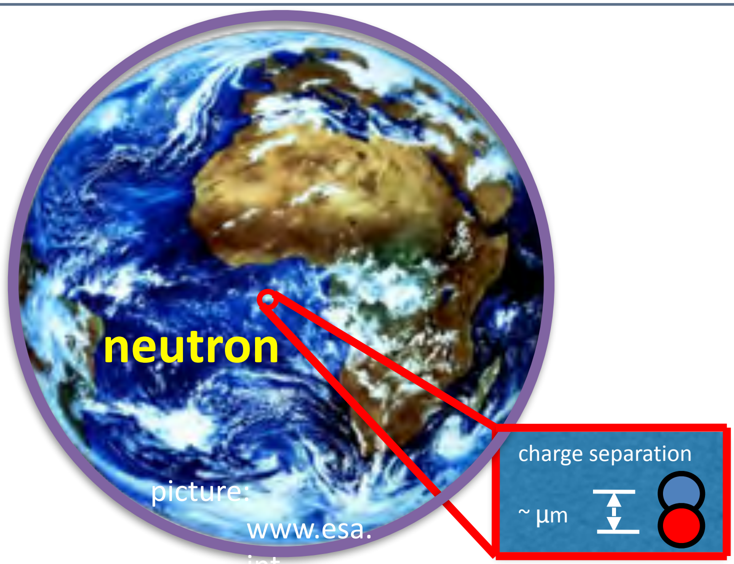
$$| d_n | < 3 \cdot 10^{-26} \ e \cdot cm$$

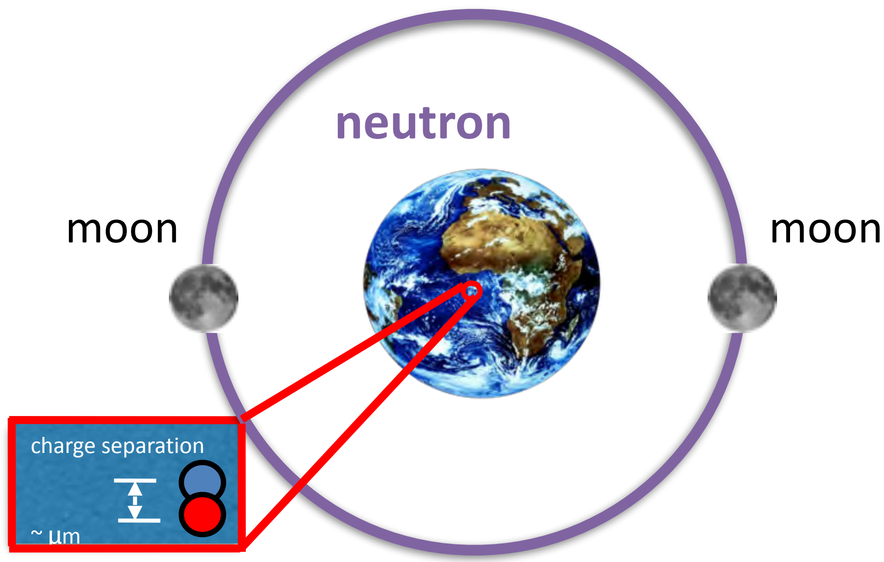
planned sensitivity (FRMII):

one spin rotation in 50 years

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

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

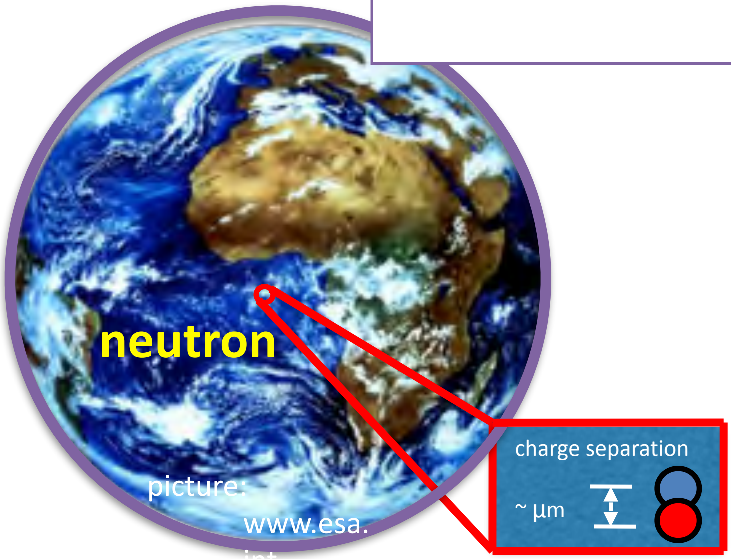


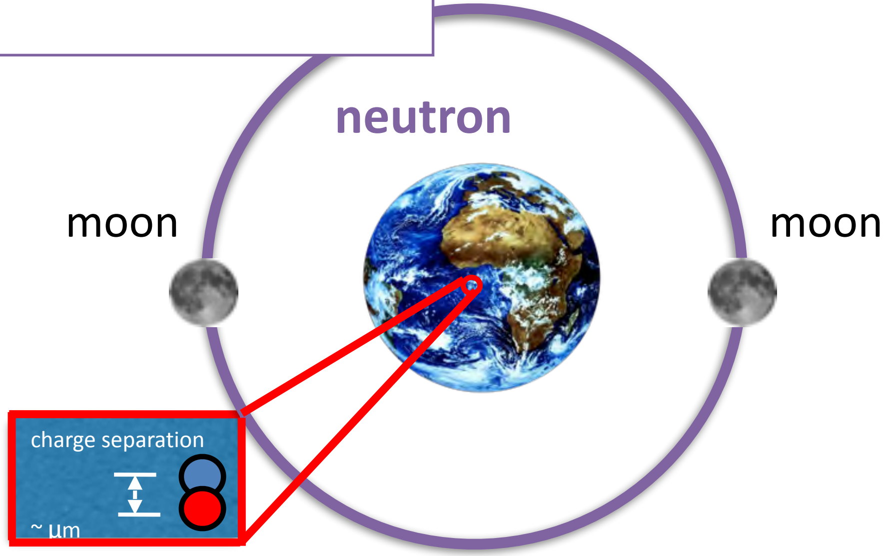


Exzellenzcluster Universe

How accurately do we have to measure ?

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



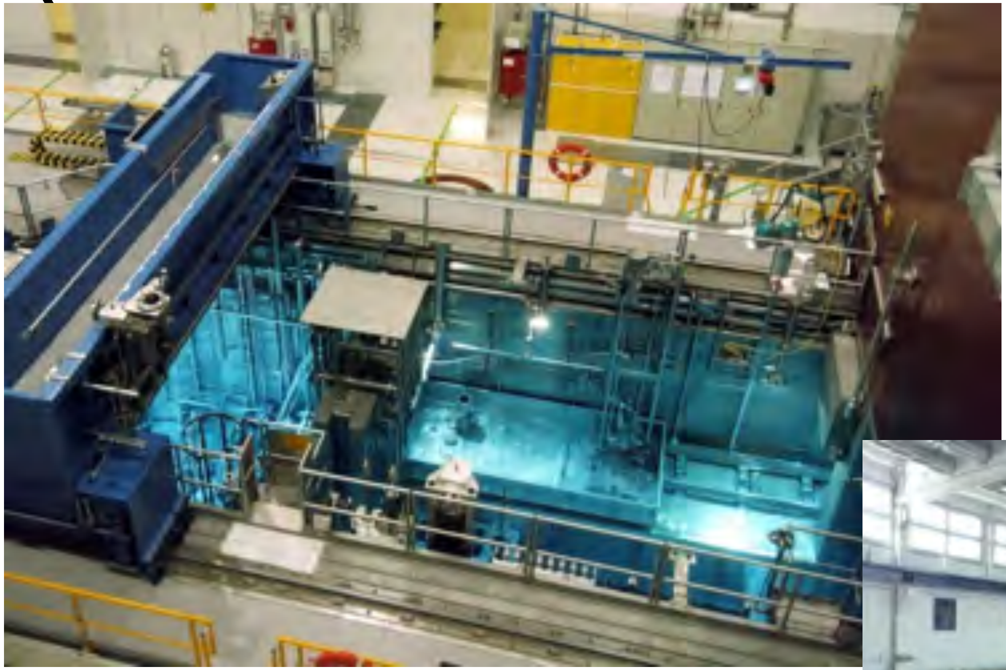


Exzellenzcluster Universe

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.

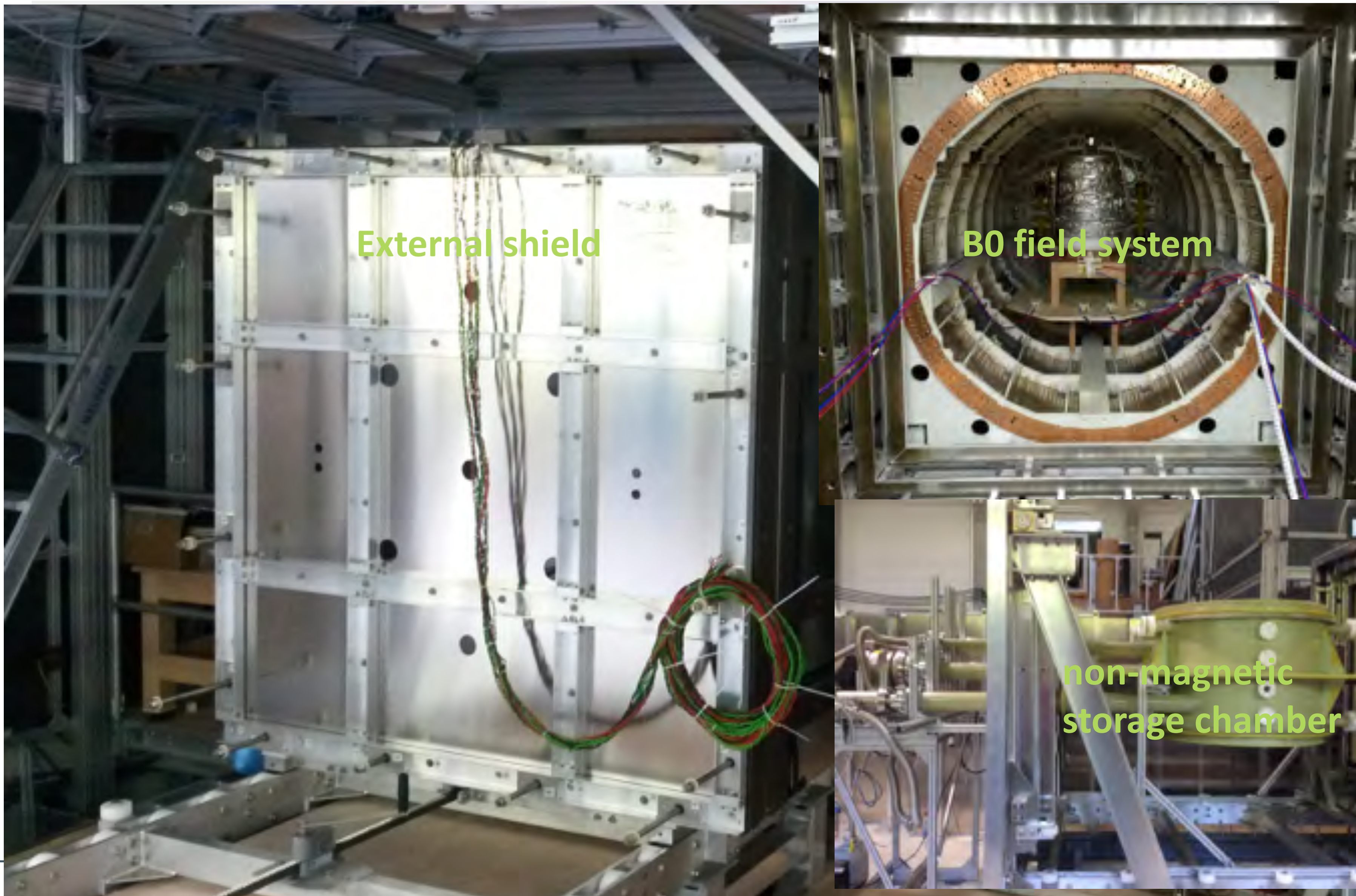
Exzellenzcluster Universe

The Real Setup

Fierlinger et al.

Exzellenzcluster Universe

Exzellenzcluster Universe



The Real Setup

Fierlinger et al.

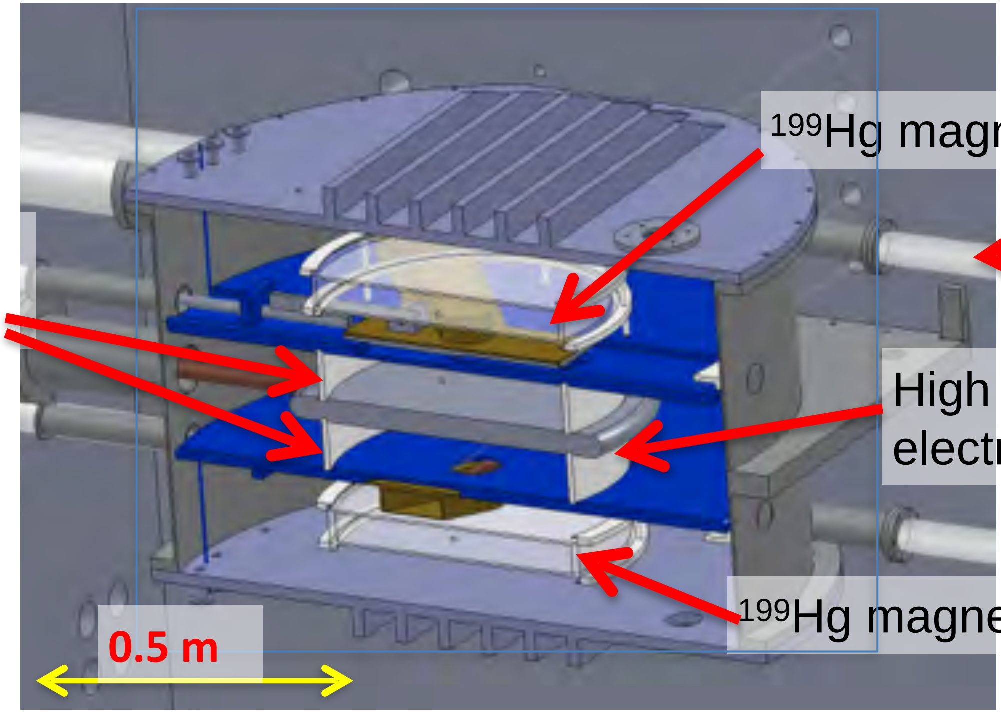
Exzellenzcluster Universe

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

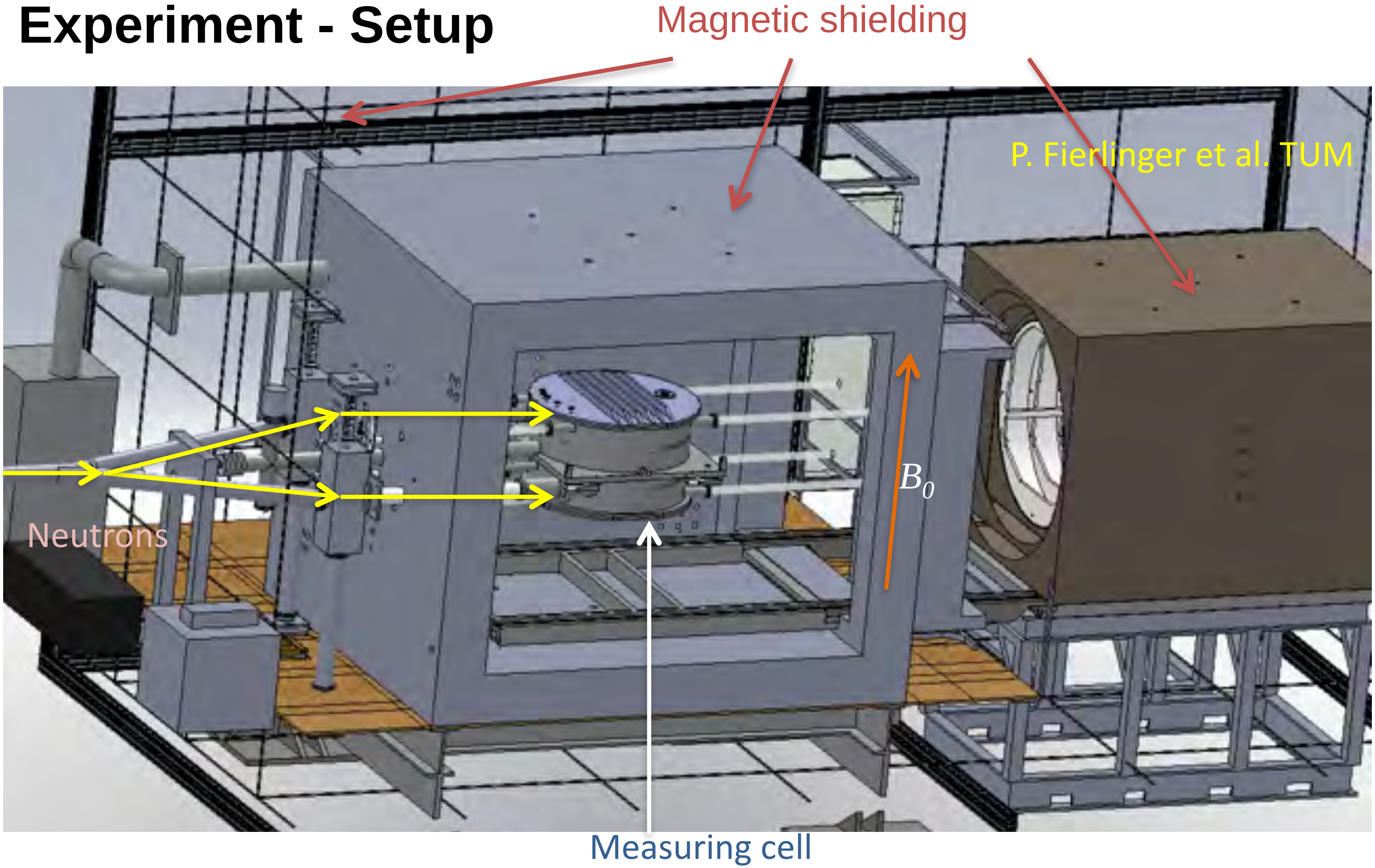
Exzellenzcluster Universe



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

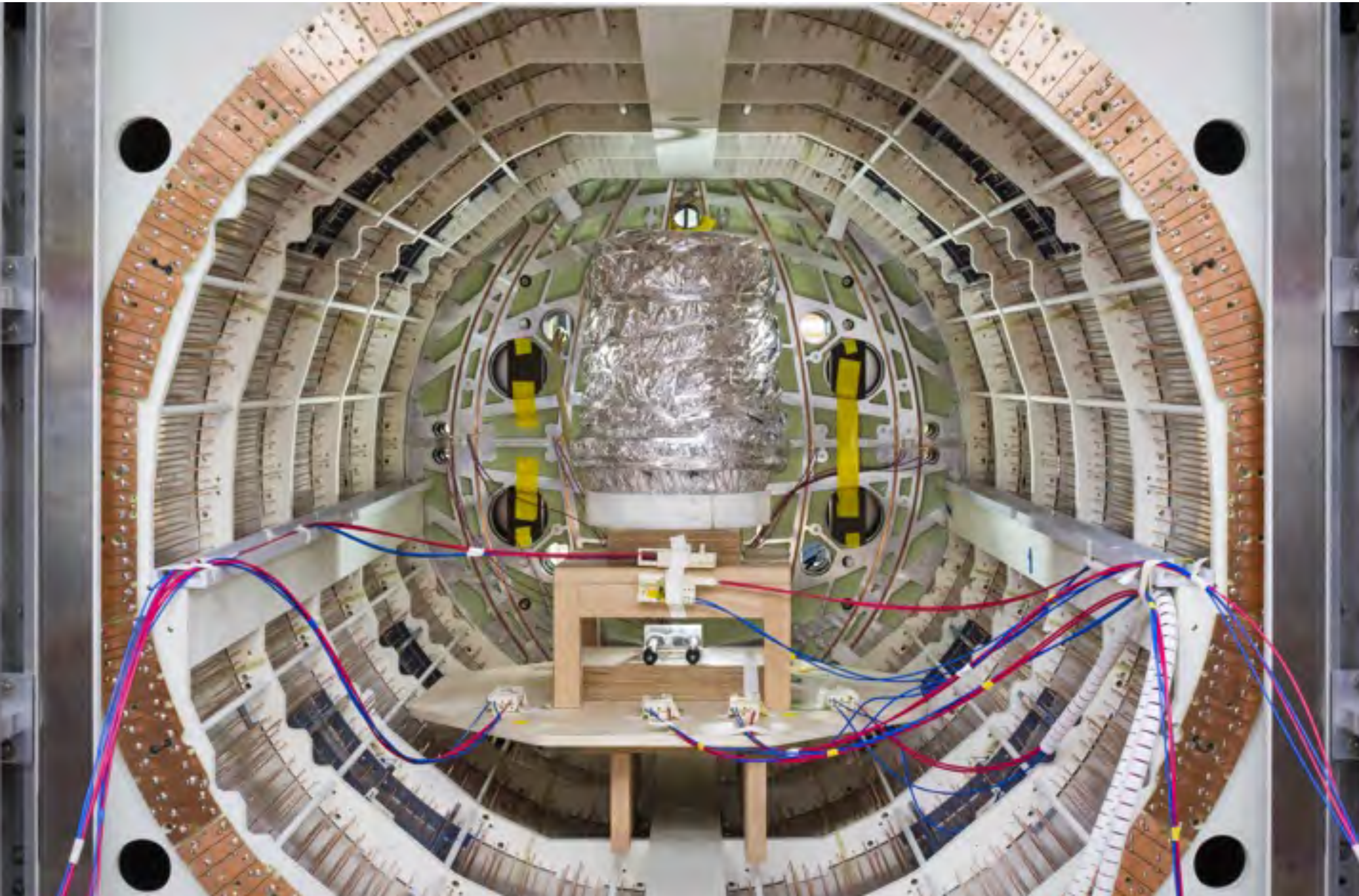
The new EDM apparatus at FRM2

Experiment - Setup



External Magnetic Shielding

Fierlinger et al.



External Magnetic Shielding

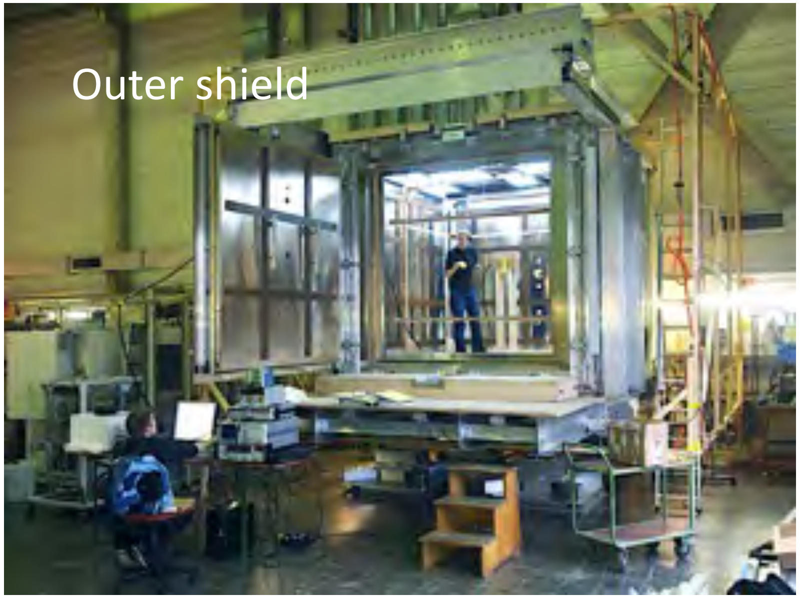
Fierlinger et al.

- 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

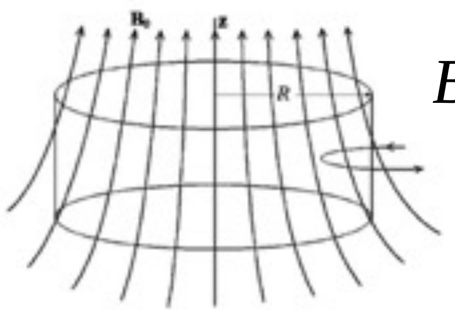
B-field in rest system of neutron

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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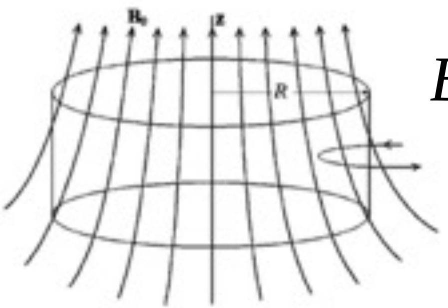
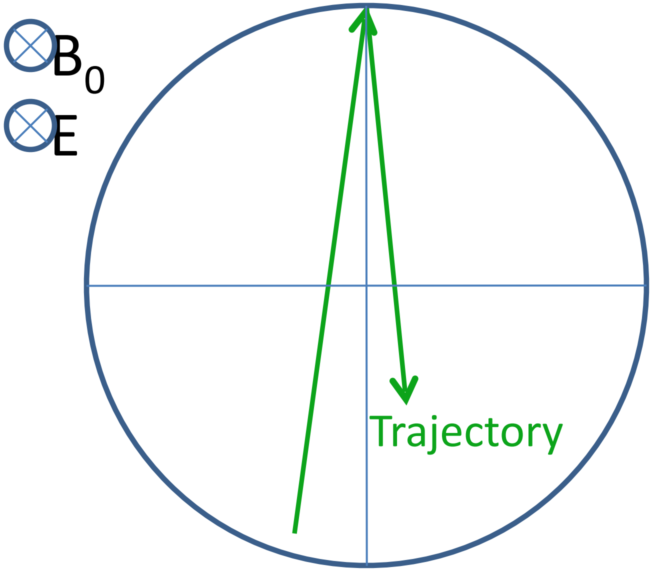


$$B_z \rightarrow B_r \propto r$$

Motional fields and gradient cause 'geometrical' phase effect



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

Dominant Systematic Effects

Exzellenzcluster Universe

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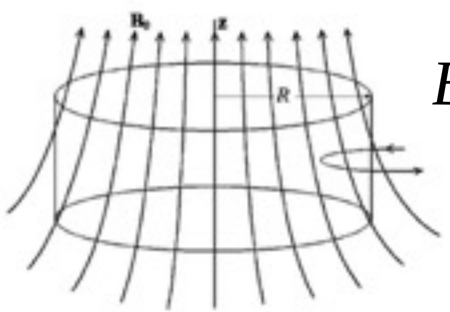

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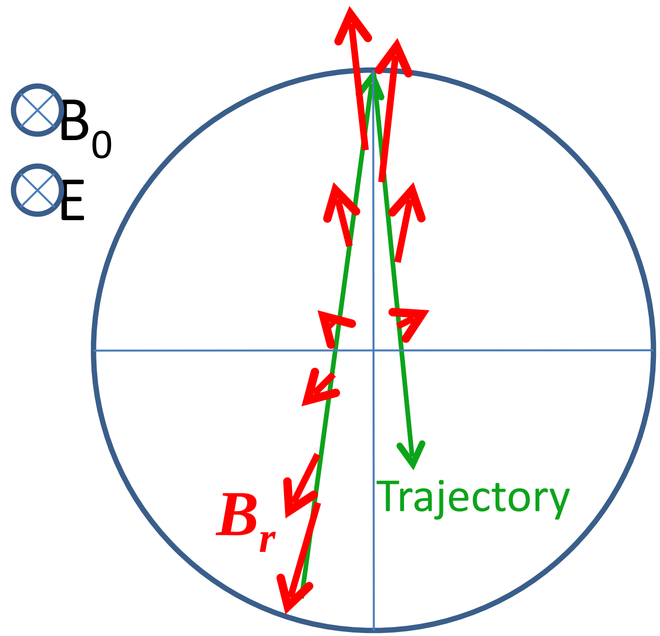

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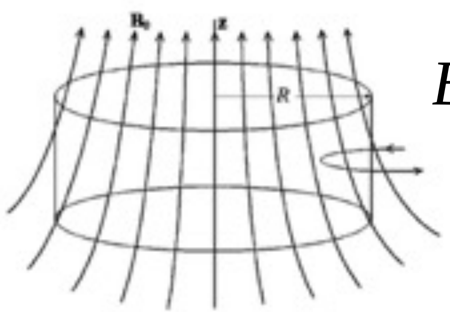

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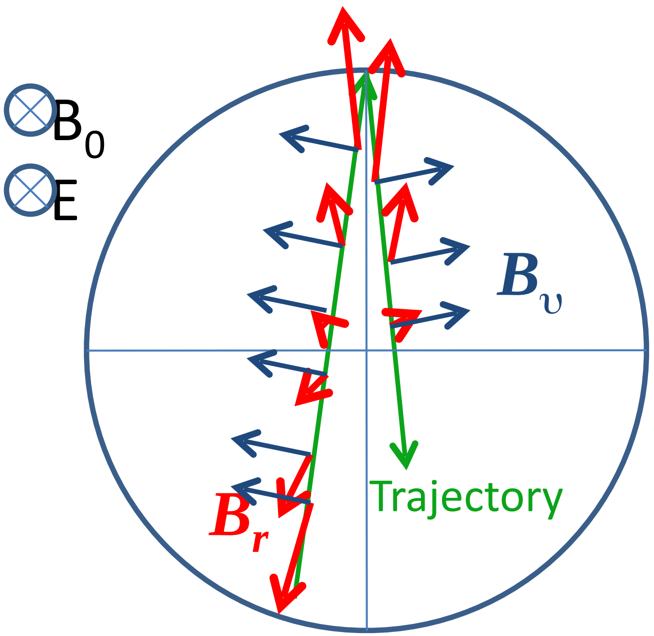

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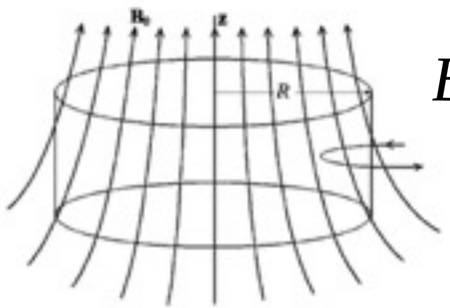
Vertical gradient



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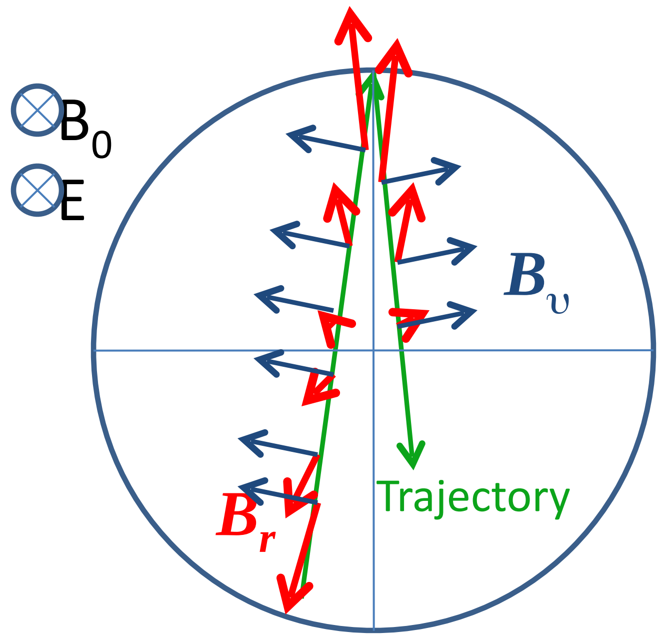
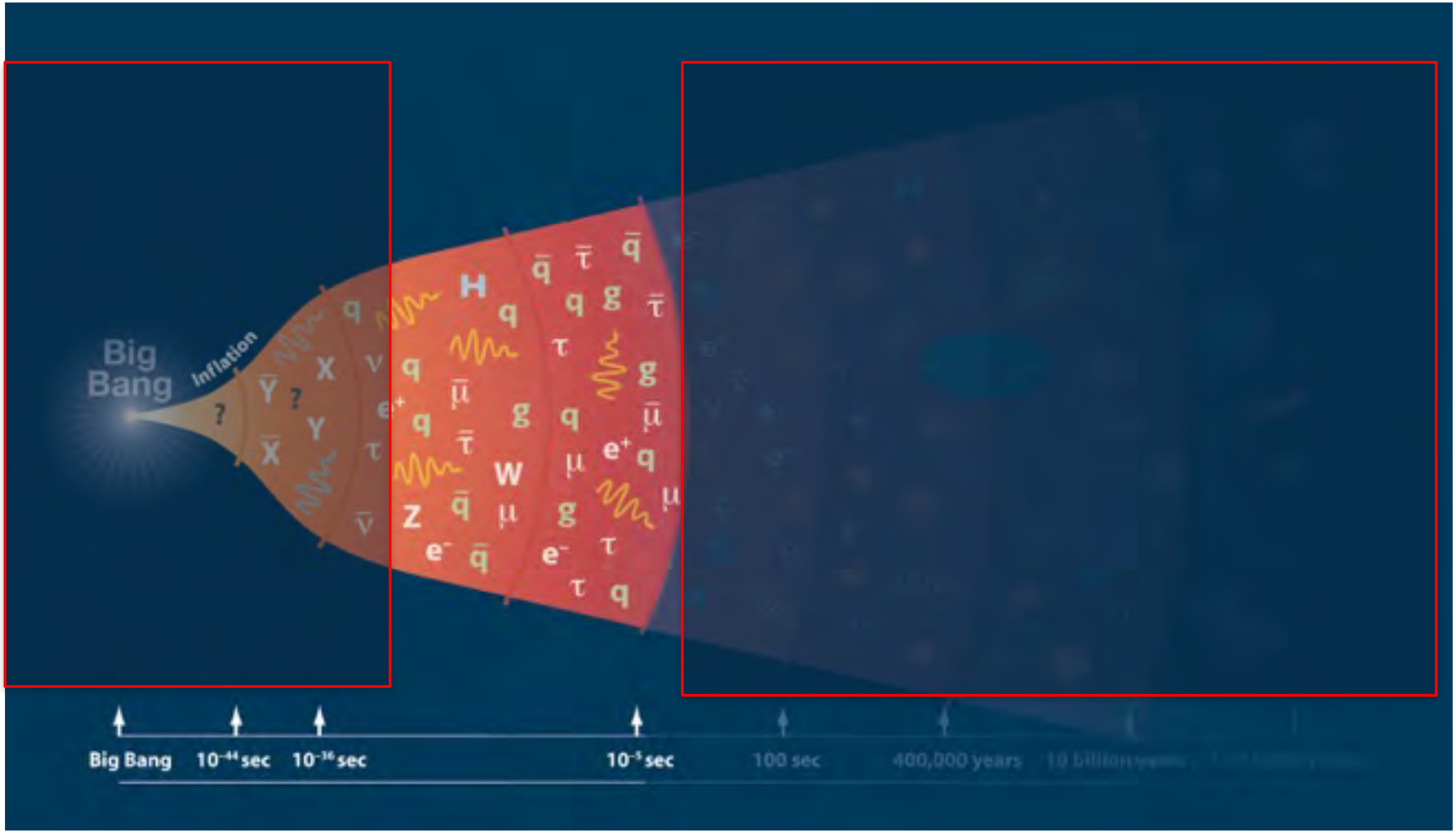


(view from above into neutron storage chamber B, E are vertical)

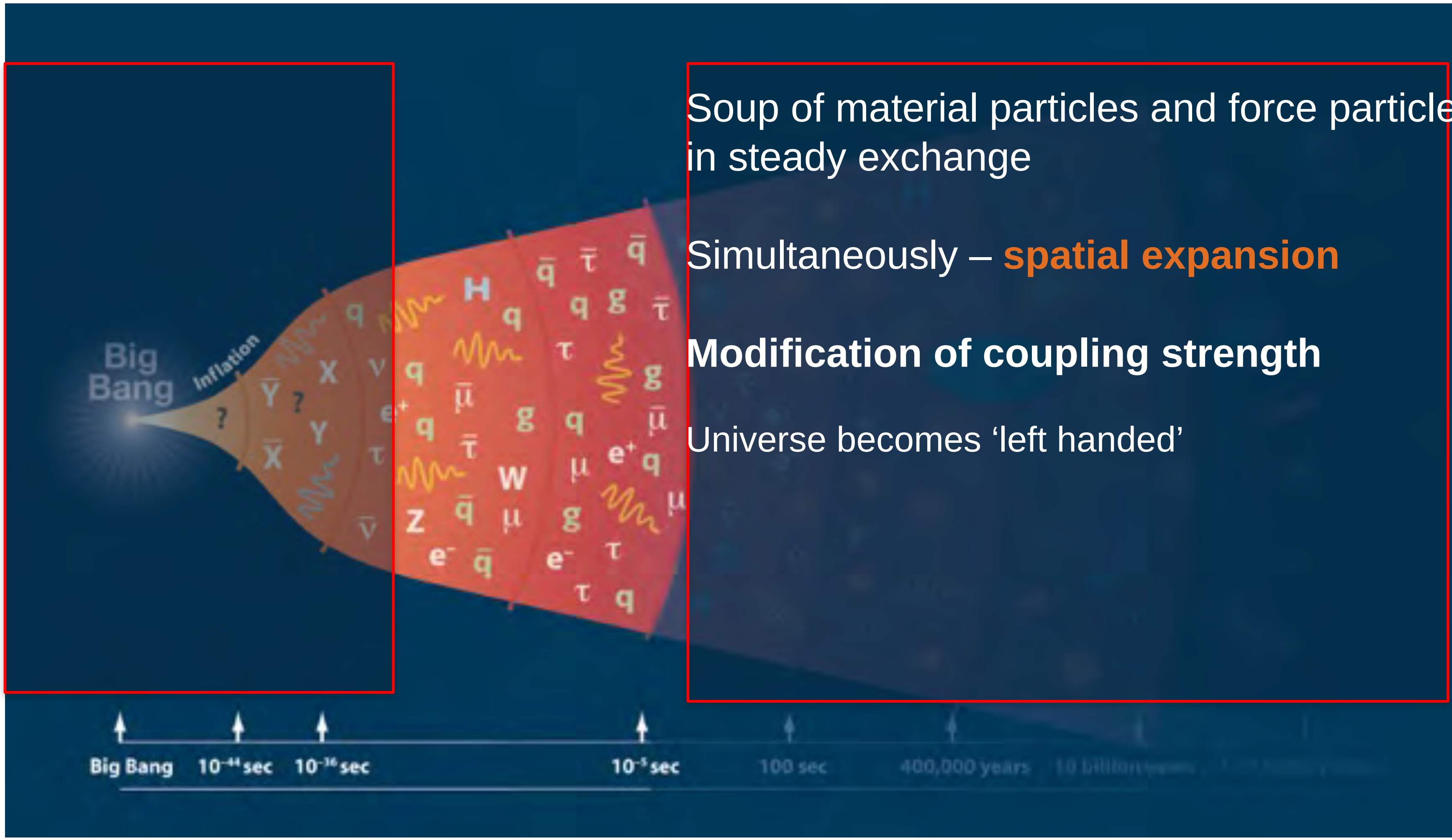
Different for UCN and comagnetometer:

10^{-26} e·cm level

Until 10^{-6} Seconds past Big Bang



Until 10^{-6} Seconds past Big Bang



Soup of material particles and force particles in steady exchange

Simultaneously – **spatial expansion**

Modification of coupling strength

Universe becomes ‘left handed’

β-Decay

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

β-decay rate:

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

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

β-Decay

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

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

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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

Exzellenzcluster Universe

Parameter

Strength: G_F

Quark mixing: V_{ud}

Ratio: $\lambda = g_A/g_V$

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

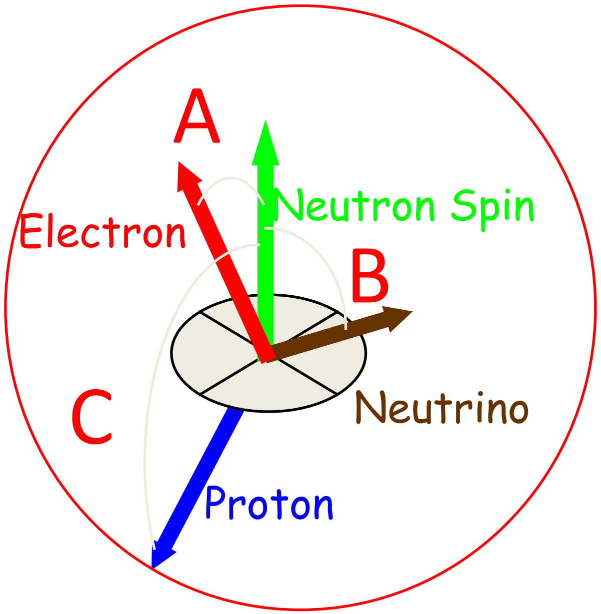
SM Parameter and Observables

Parameter

Strength: G_F

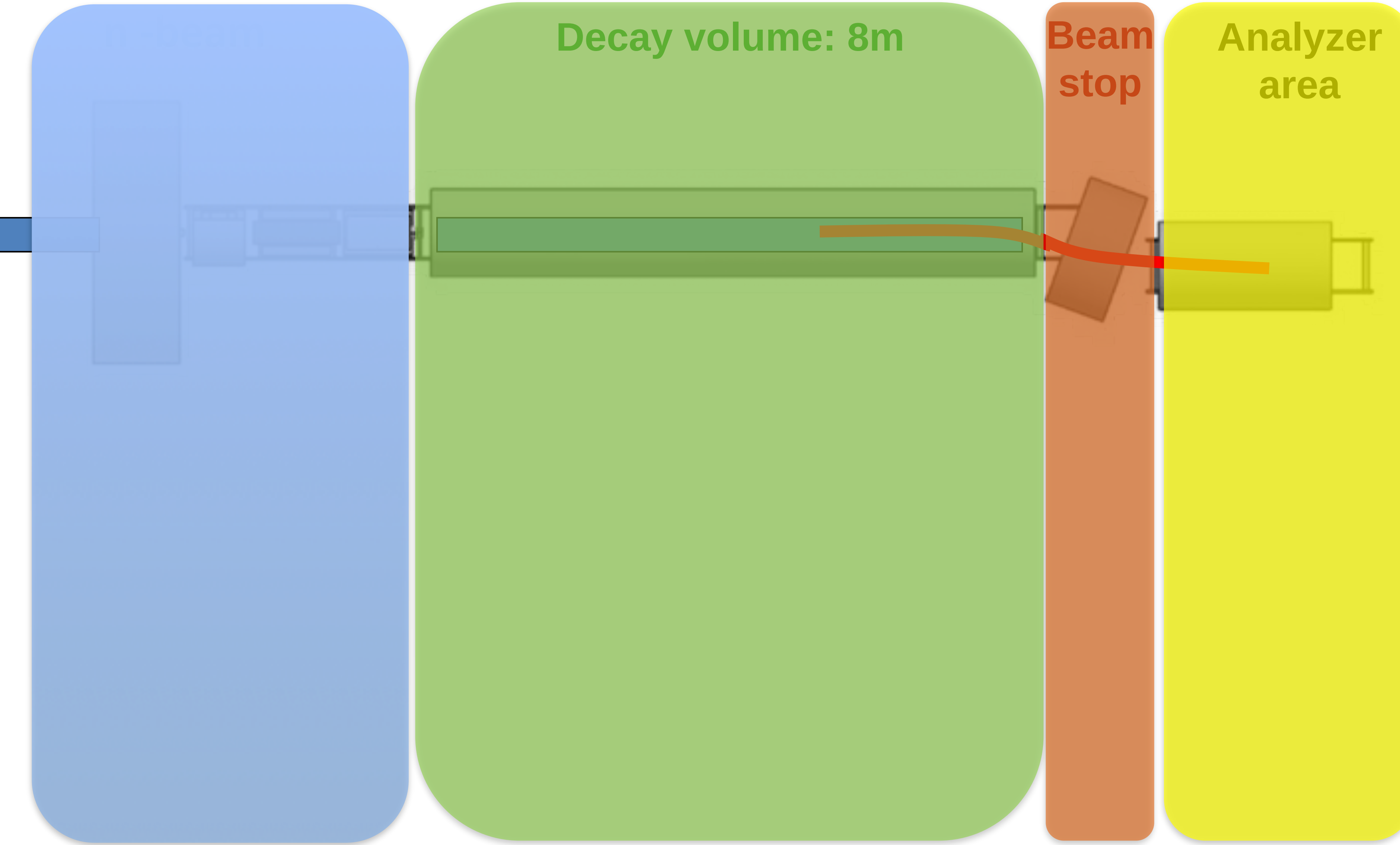
Quark mixing: V_{ud}

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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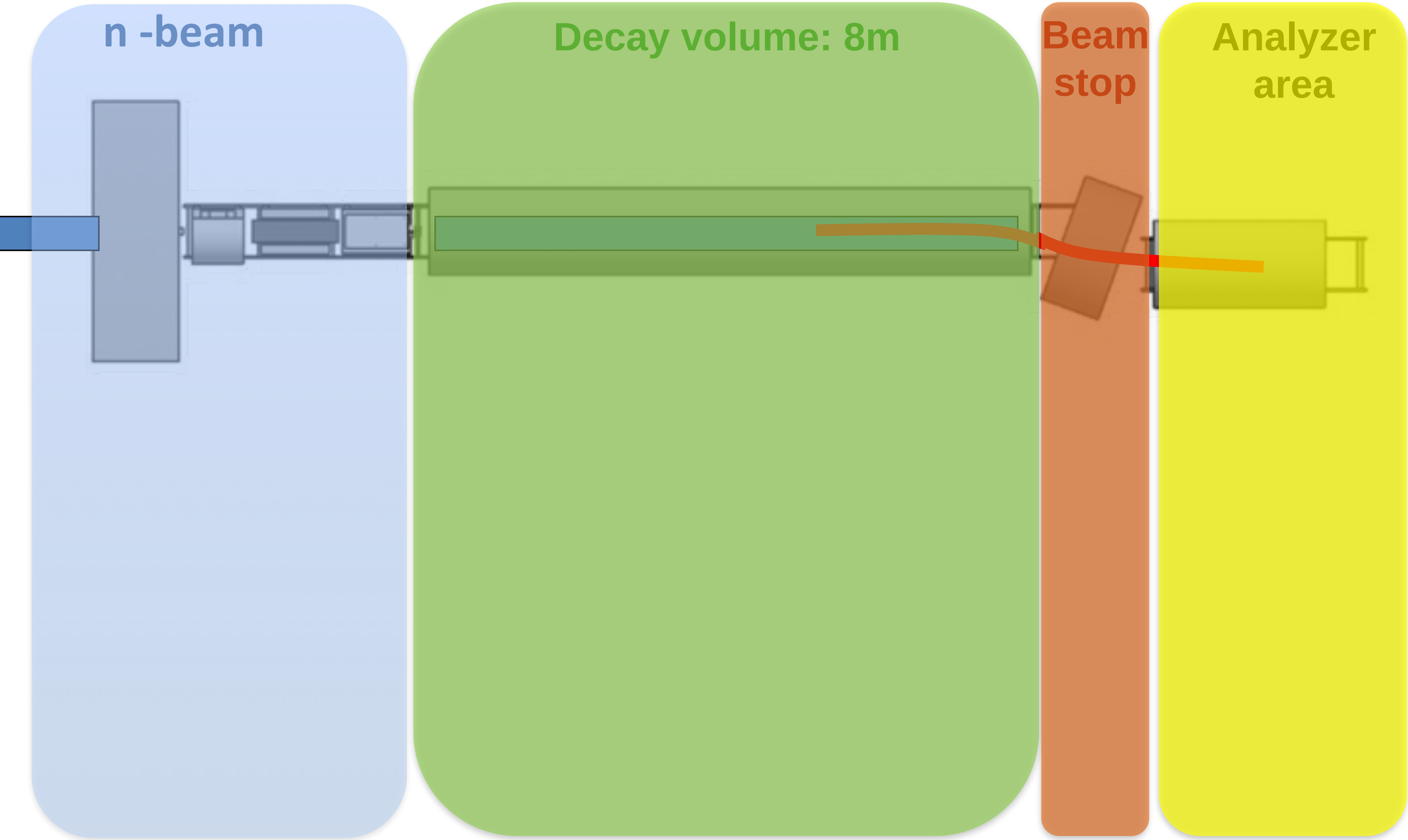

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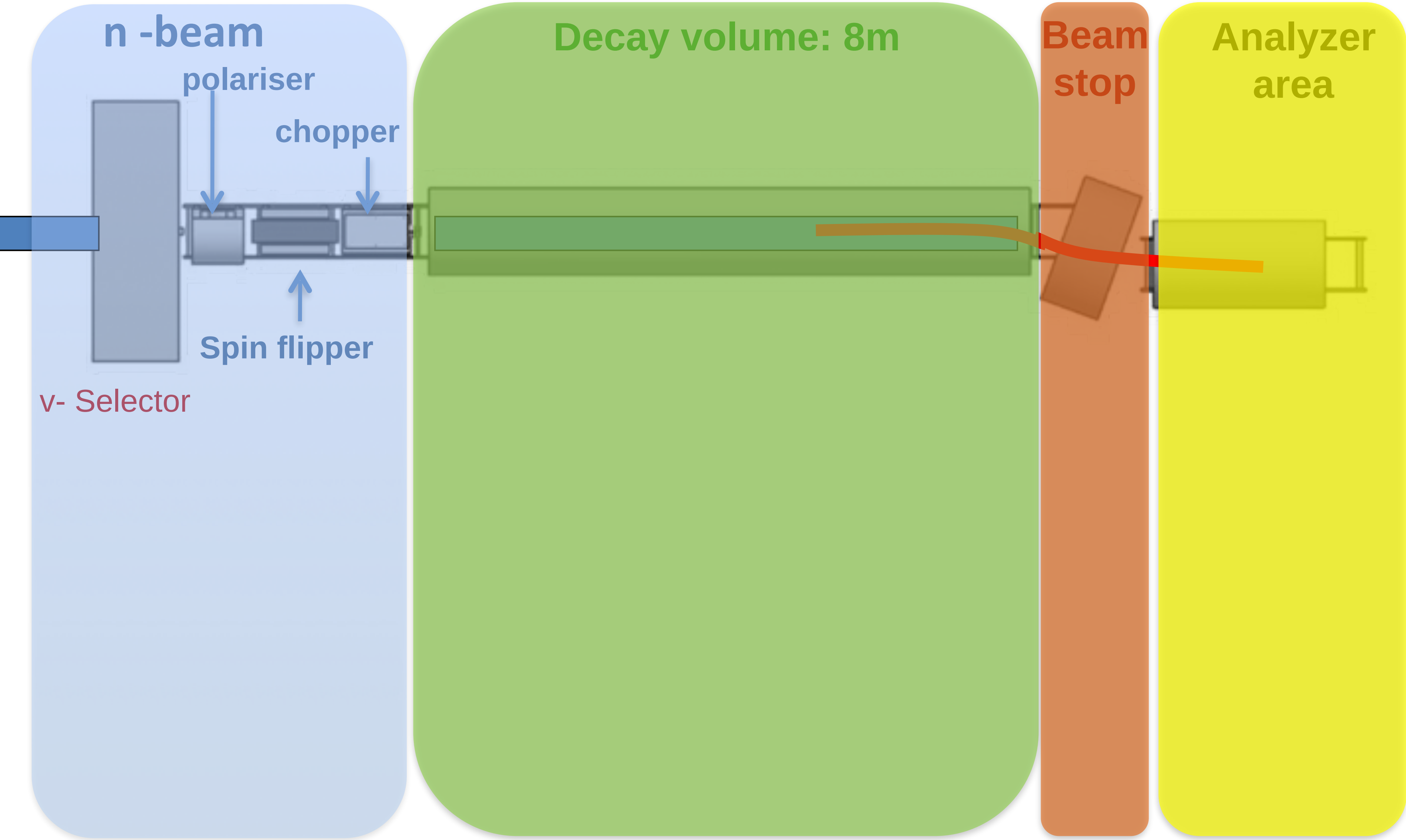

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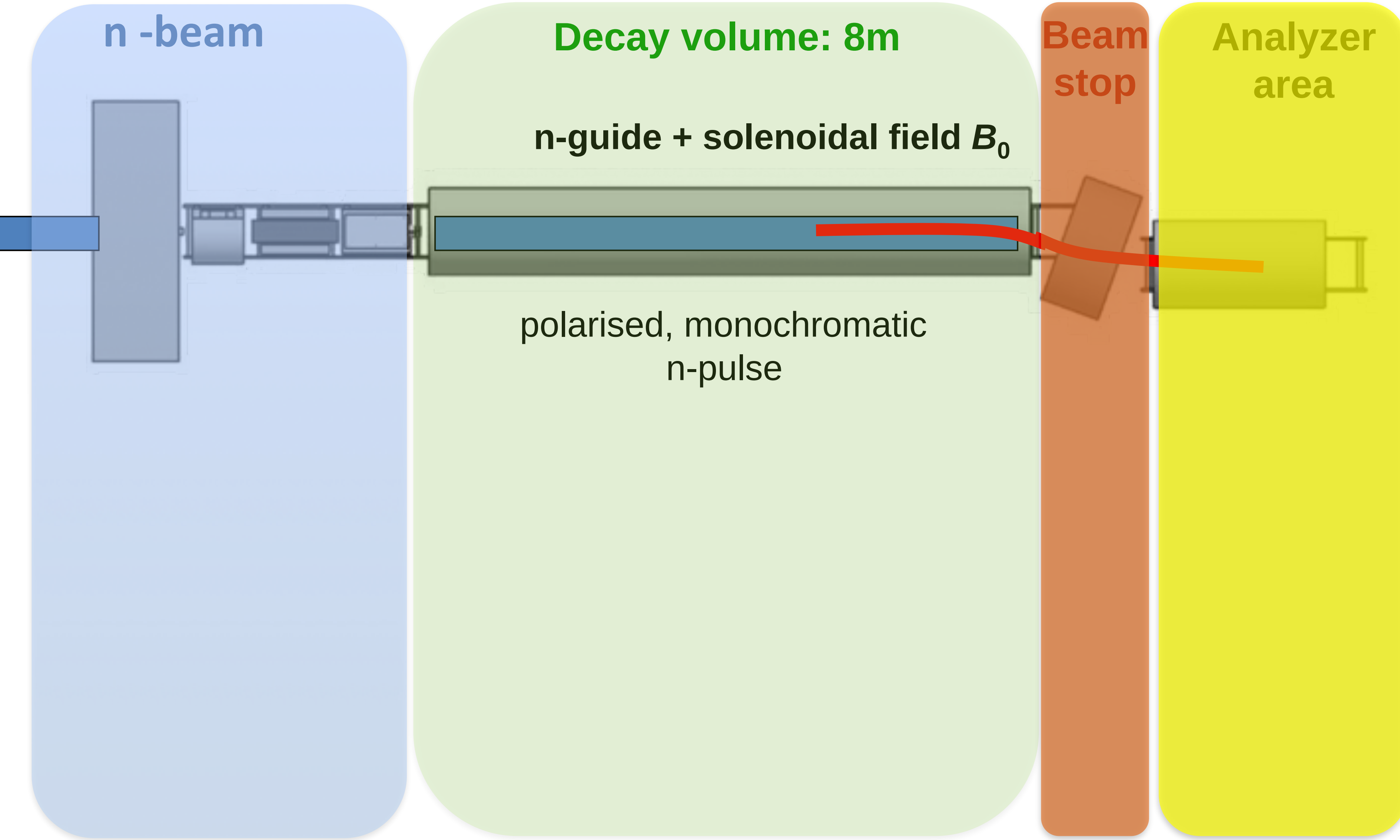
Exzellenzcluster Universe



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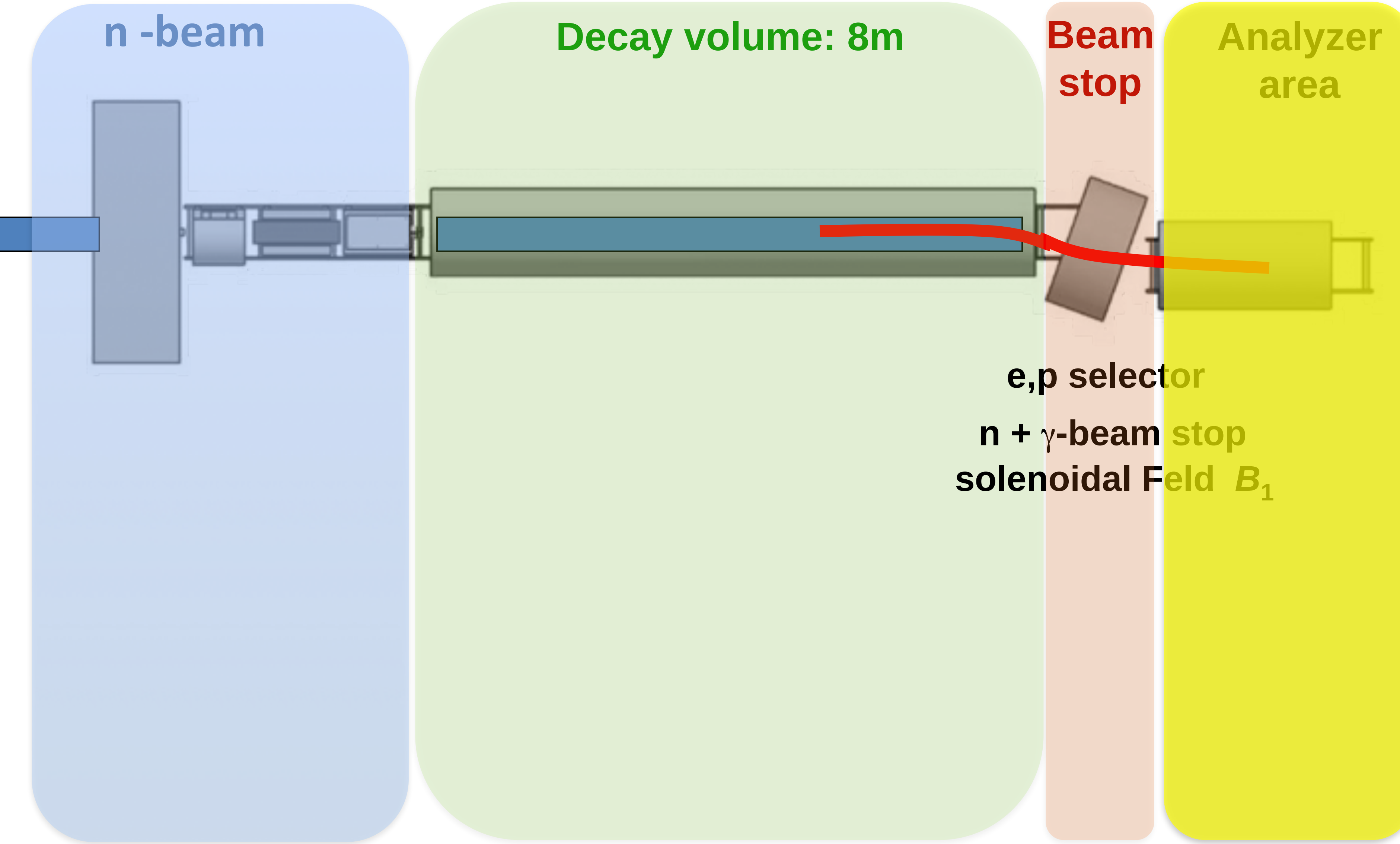
Exzellenzcluster Universe



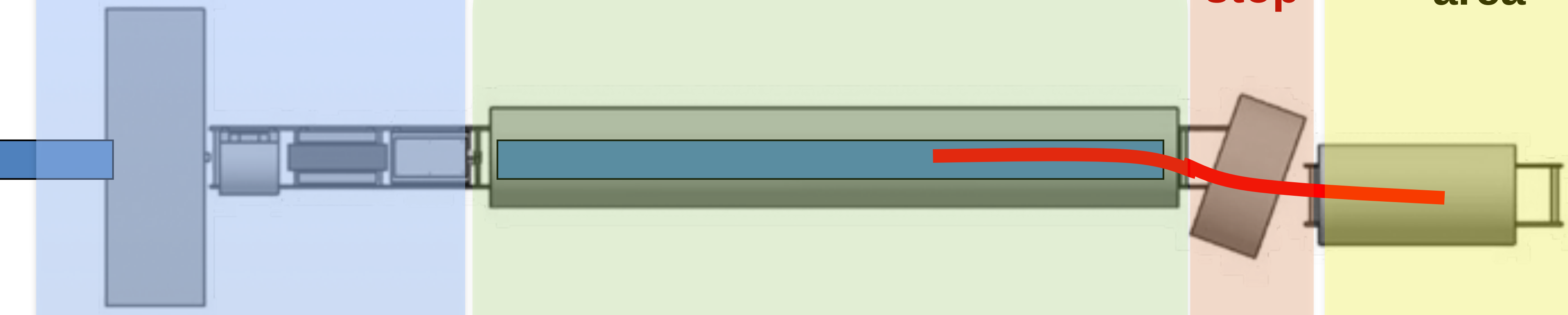
PERC:
Precision experiments for decay asymmetries

n -beam

Decay volume: 8m

Beam stop

Analyzer area

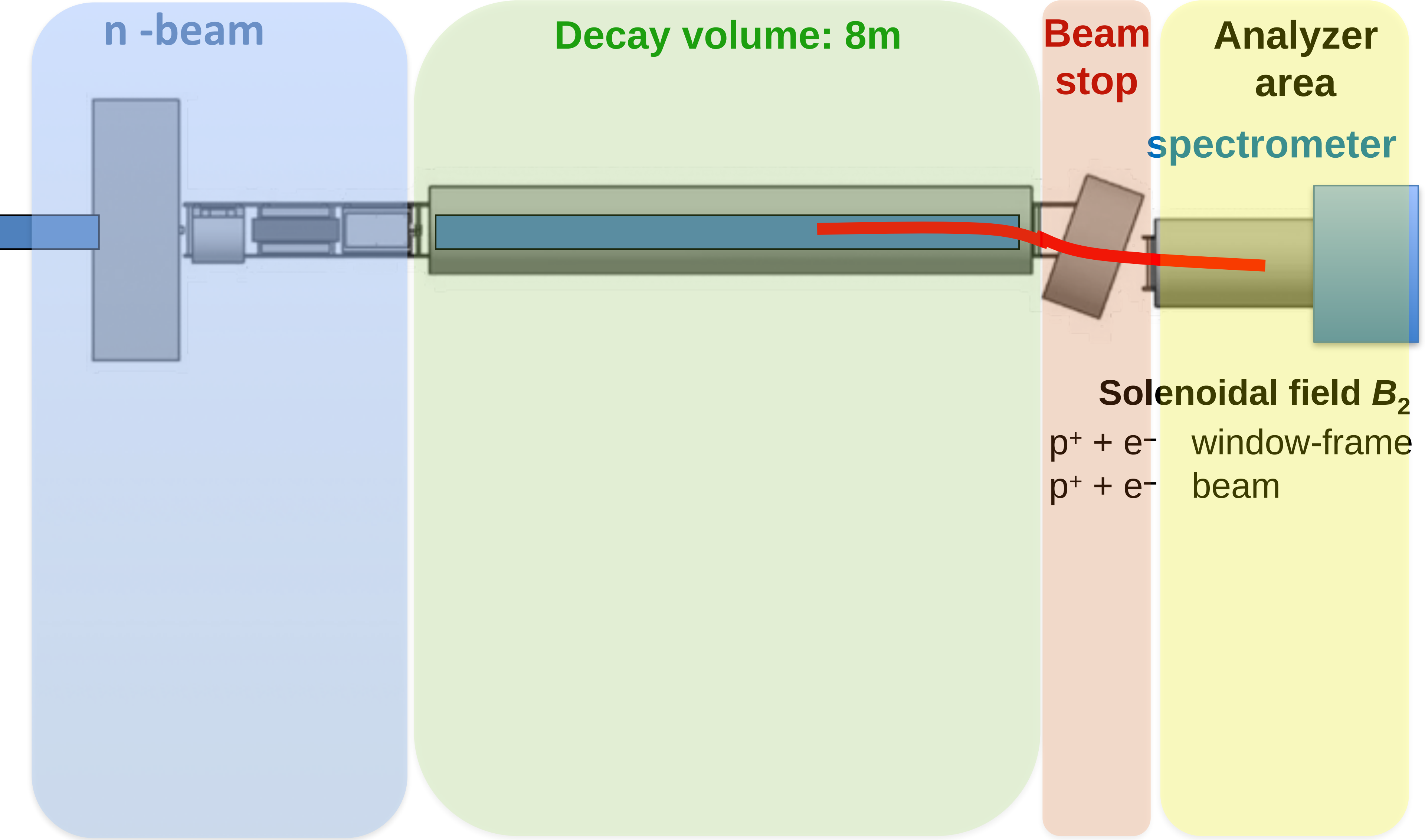


Solenoidal field B_2

$p^+ + e^-$ window-frame

$p^+ + e^-$ beam

PERC:
Precision experiments for decay asymmetries



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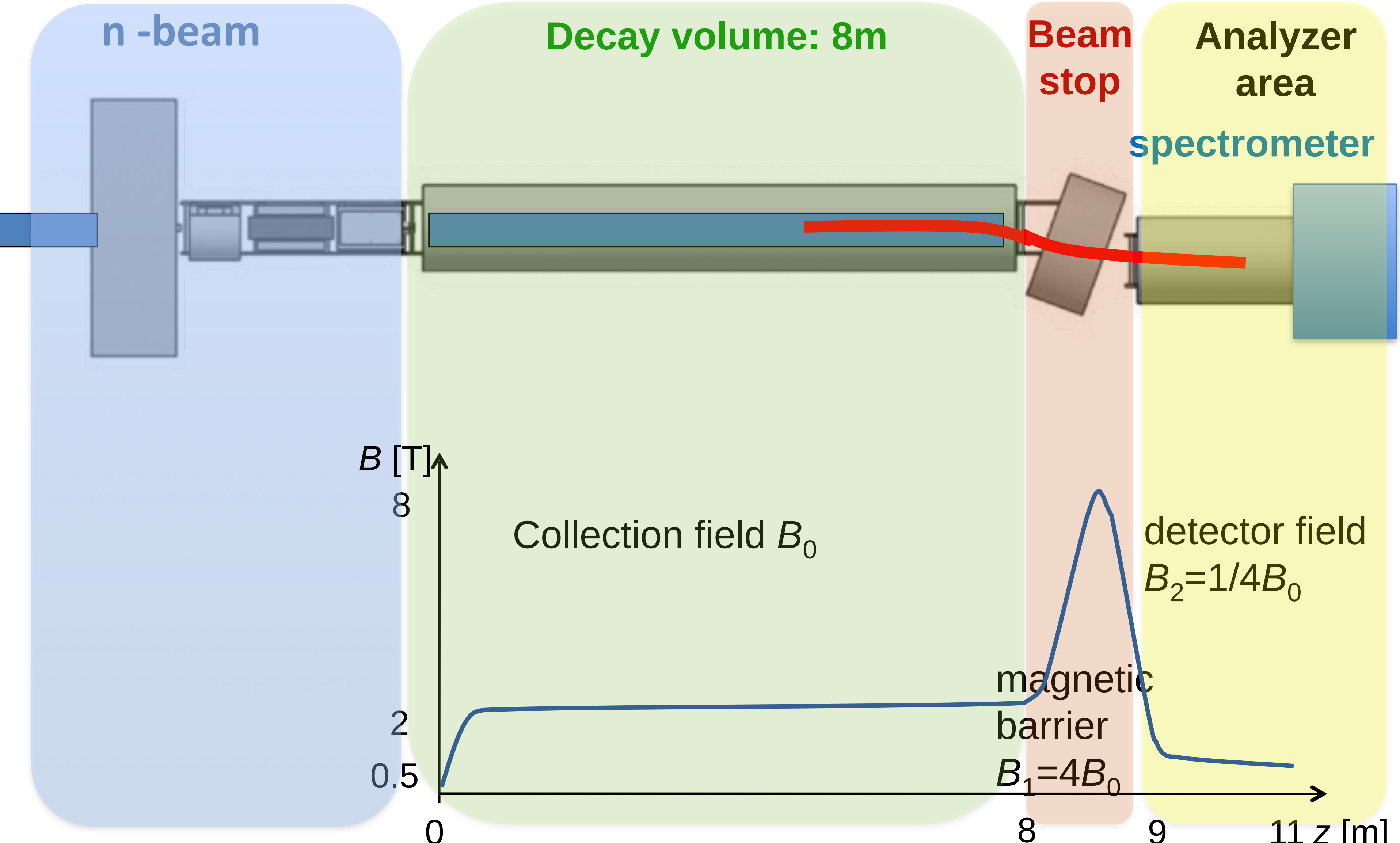


PERC

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

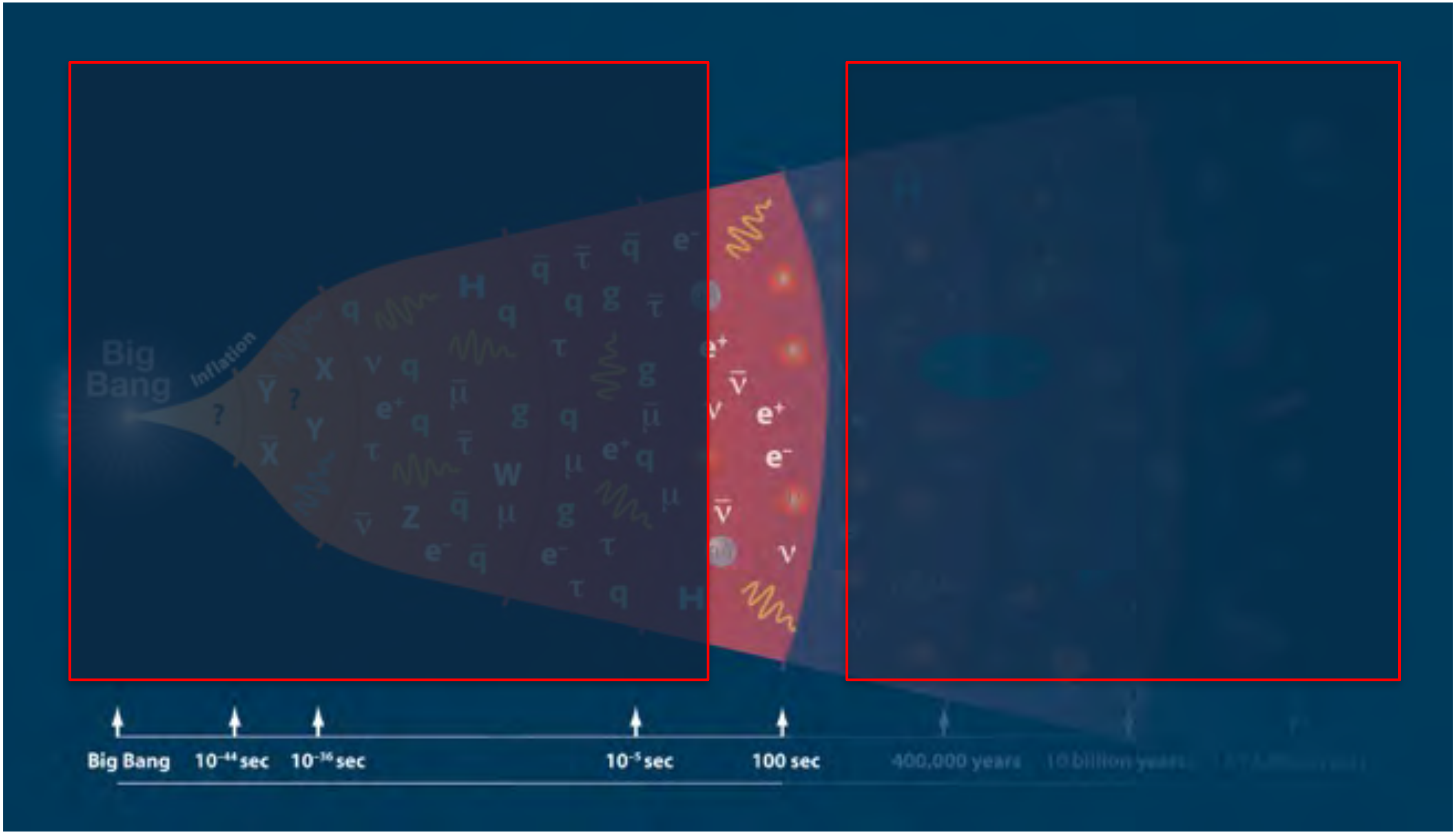
Goal: Improve precision on asymmetries by

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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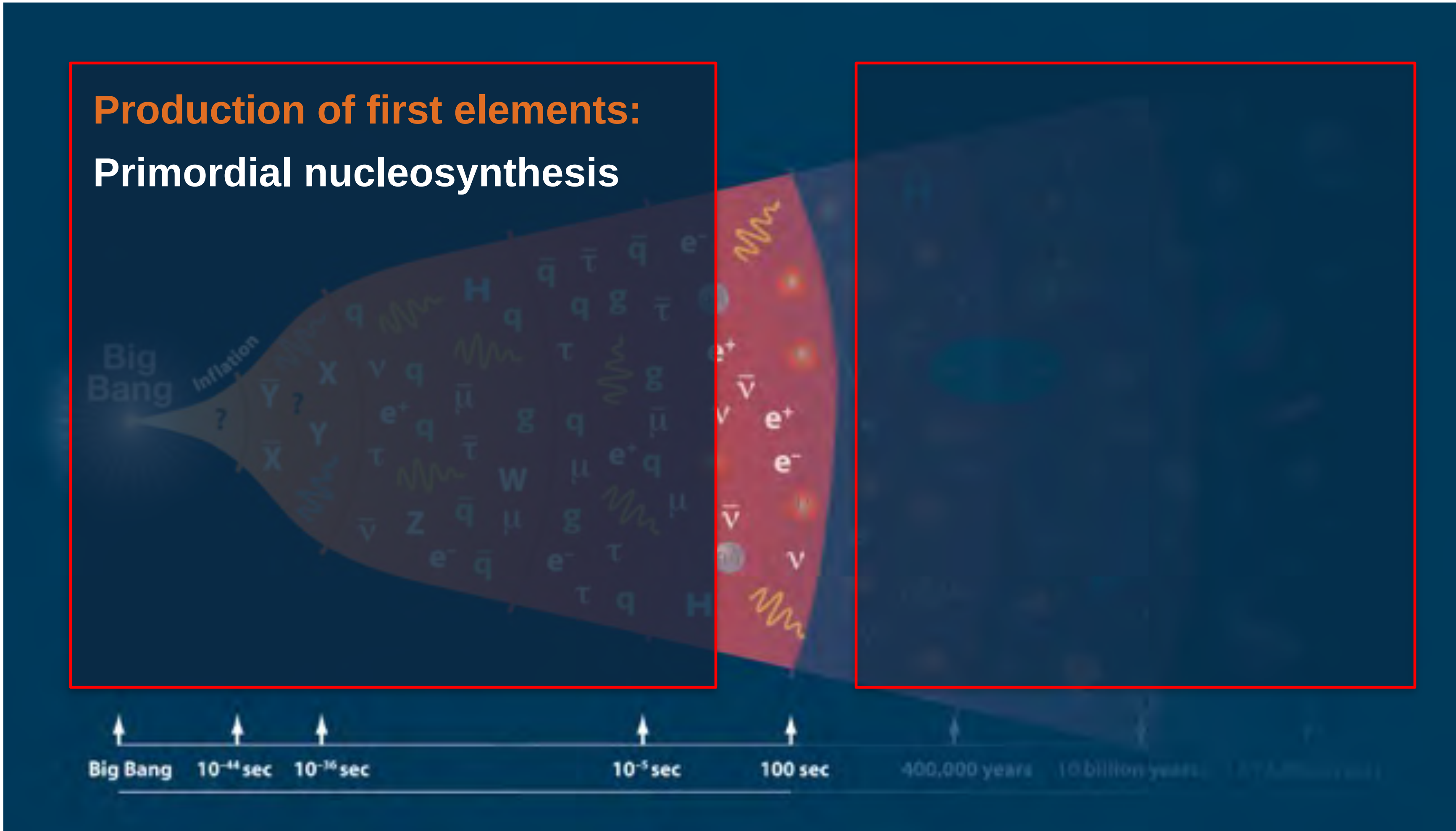


Primordial Nucleosynthesis

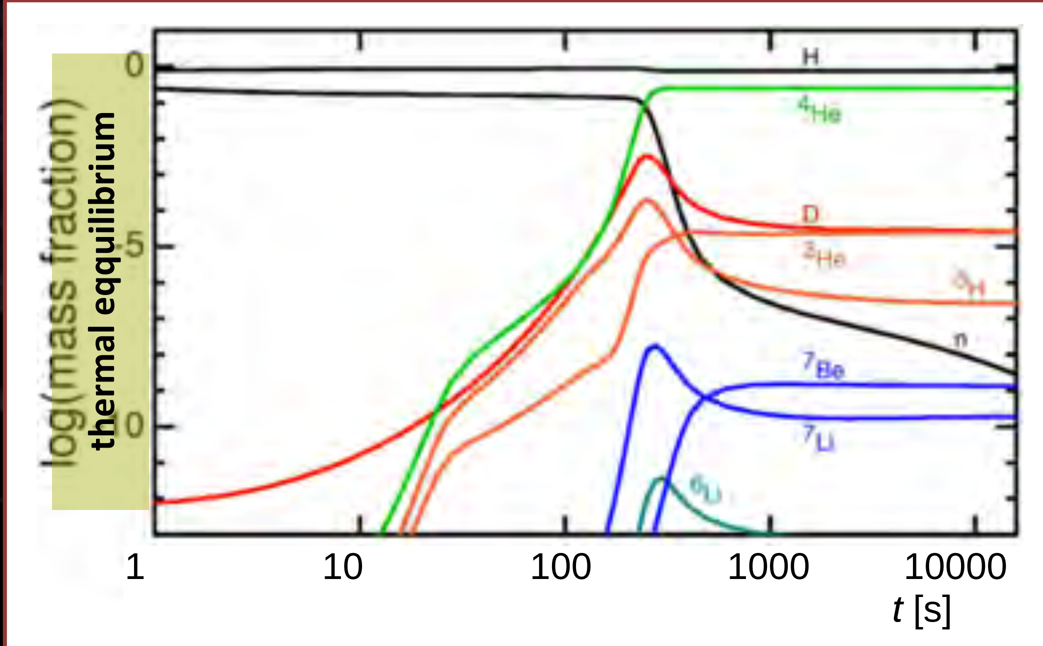
Exzellenzcluster Universe

$t < 1$ 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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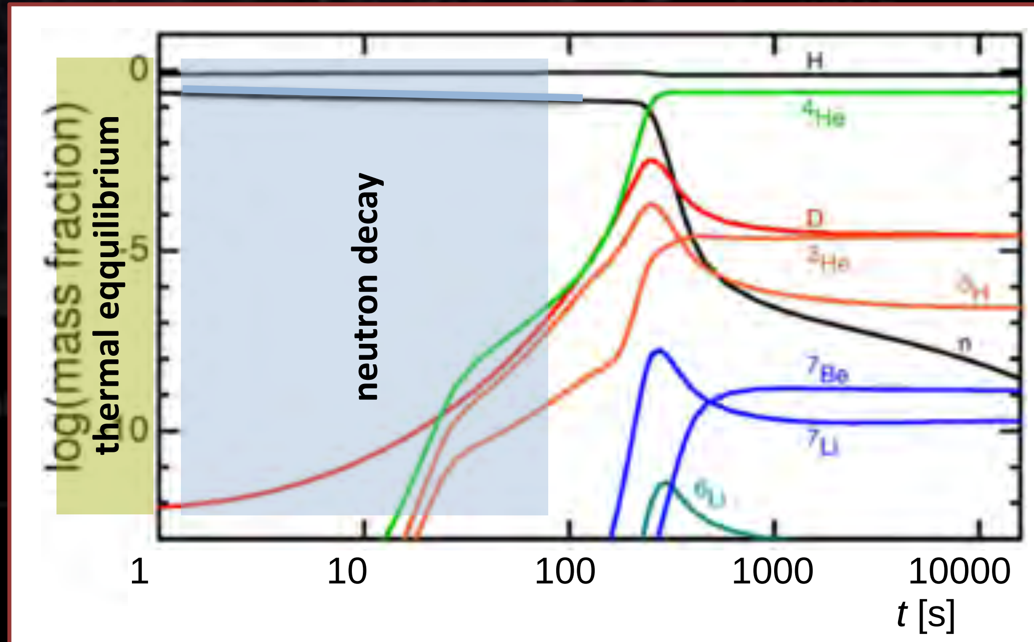
1 s < *t* < *100* s, *0.1* MeV < *kT* < *1.3* MeV

neutron decay

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

n/p: 1/6 ➢ 1/7



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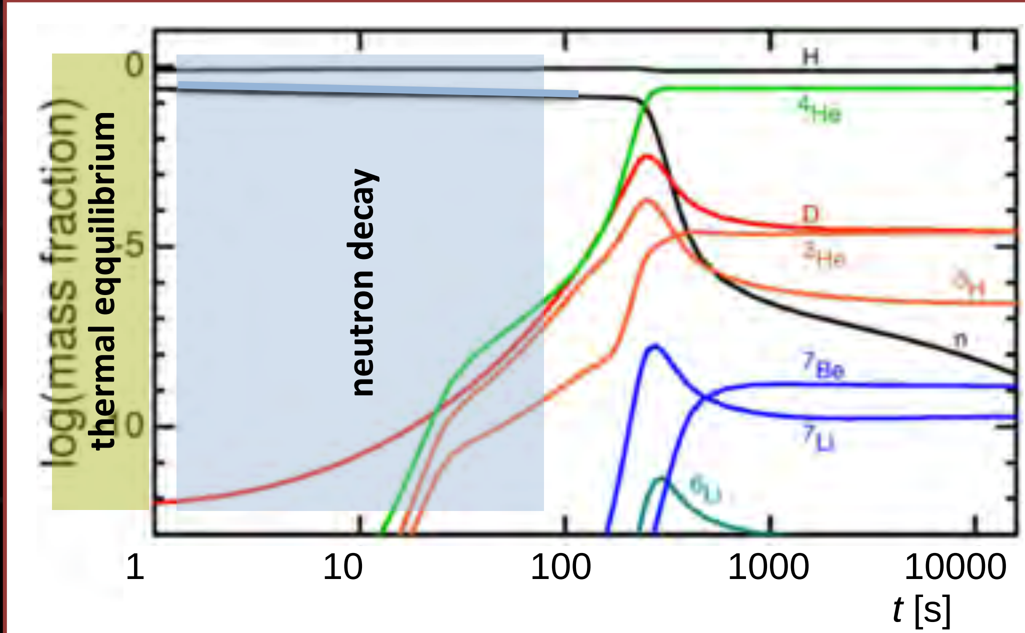
$$n \to p + e^- + \bar{\nu}$$

n/p: 1/6 ➢ 1/7

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

deuterium fusion

$$n + p \to d + \gamma$$



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

Primordial Nucleosynthesis

Exzellenzcluster Universe

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

$$\begin{aligned}
d + p &\rightarrow {}^3\mathrm{He} + \gamma & {}^3\mathrm{He} + n &\rightarrow {}^3\mathrm{H} + p \\
d + d &\rightarrow {}^3\mathrm{H} + p & {}^7\mathrm{Li} + p &\rightarrow {}^4\mathrm{He} + {}^4\mathrm{He} \\
d + d &\rightarrow {}^3\mathrm{He} + n & {}^7\mathrm{Be} + n &\rightarrow {}^7\mathrm{Li} + p \\
{}^3\mathrm{He} + {}^4\mathrm{He} &\rightarrow {}^7\mathrm{Be} + \gamma & {}^3\mathrm{He} + {}^4\mathrm{He} &\rightarrow {}^7\mathrm{Be} + \gamma \\
{}^3\mathrm{He} + d &\rightarrow {}^4\mathrm{He} + p & &
\end{aligned}$$

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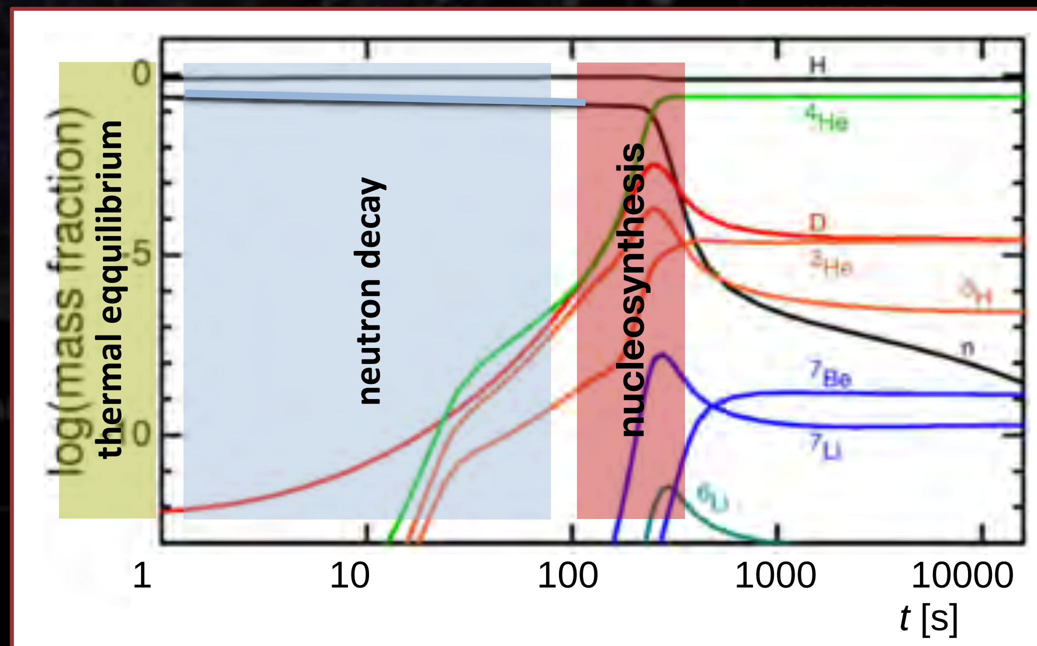

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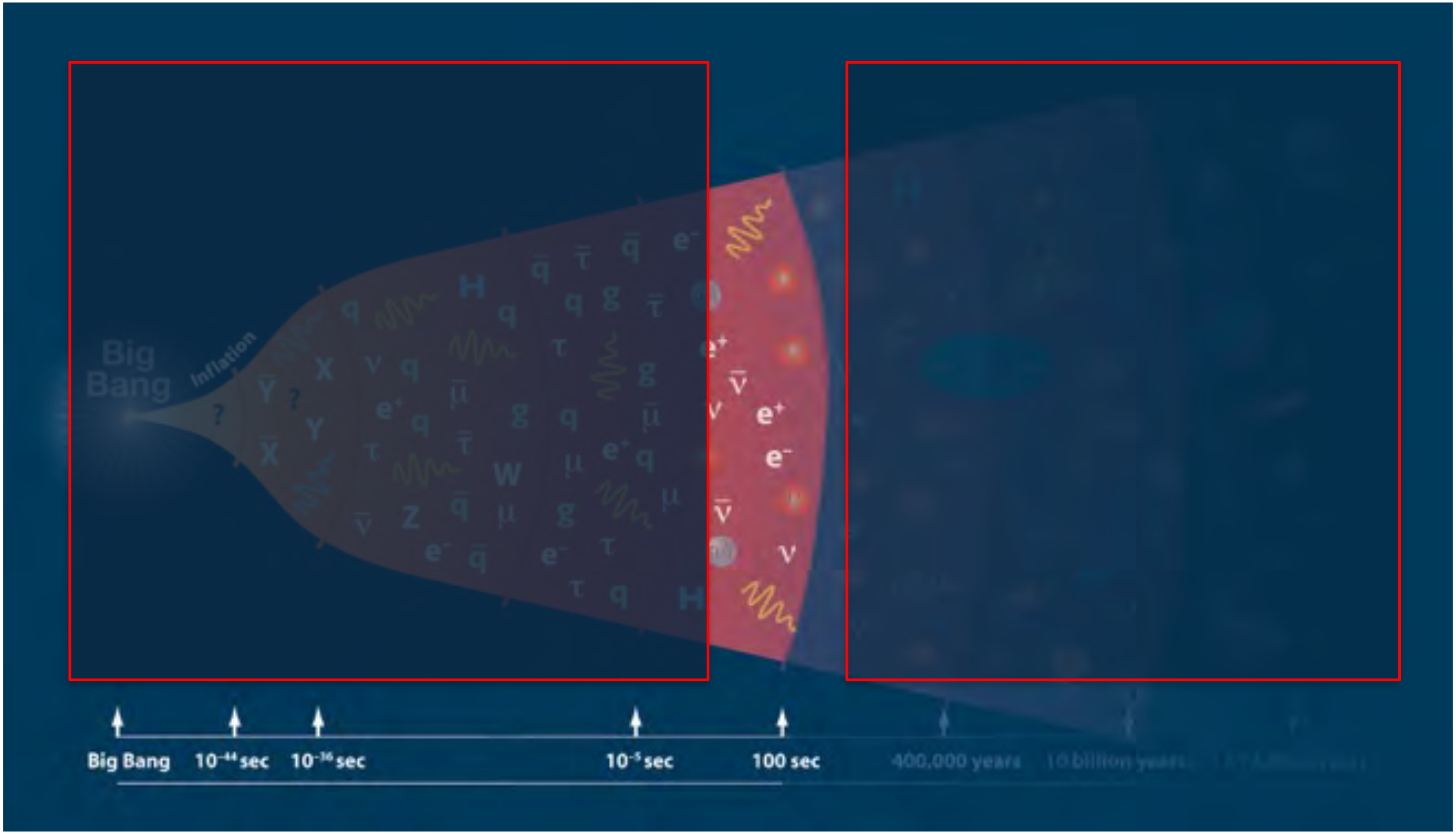
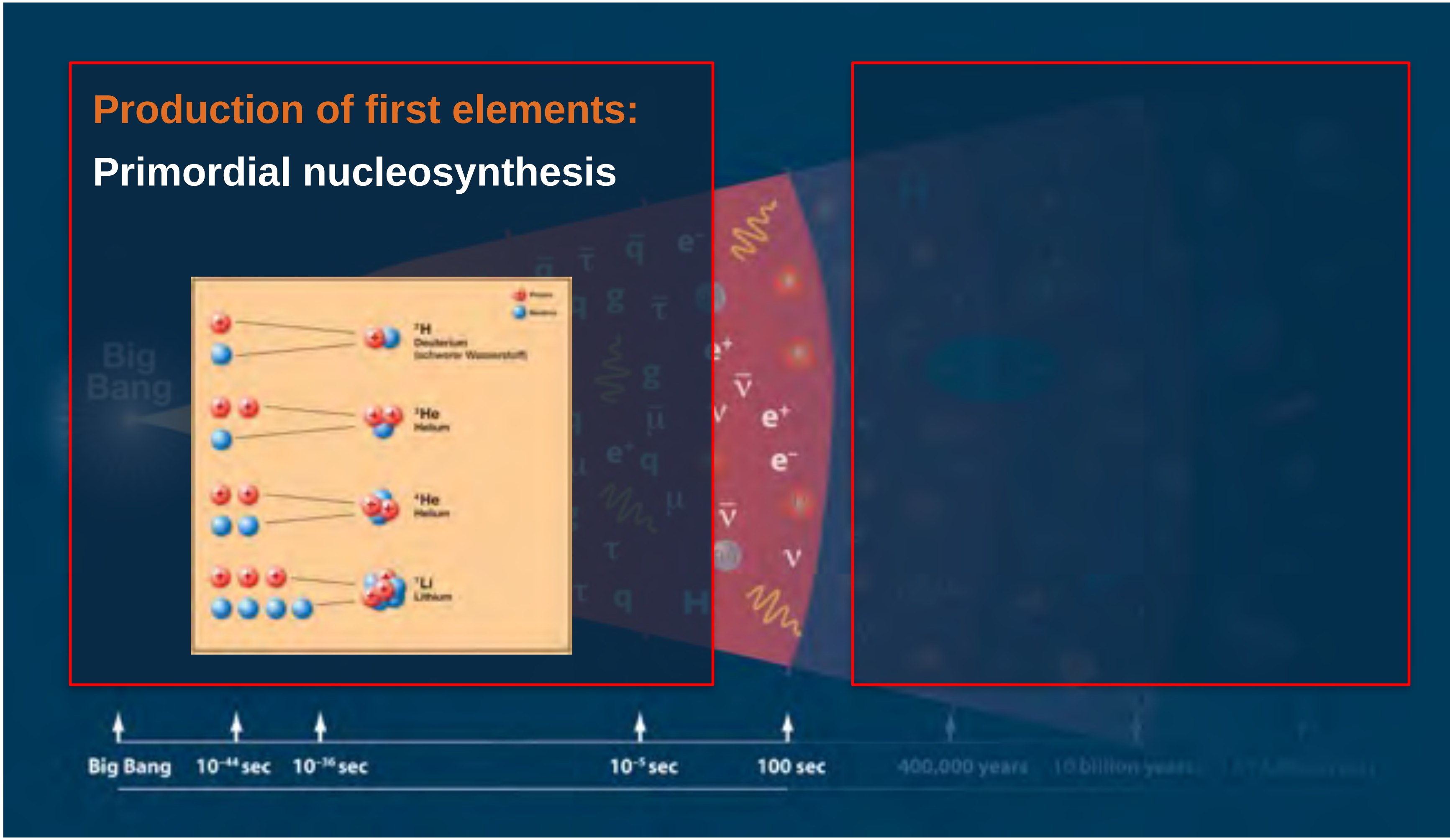
10^{-2} – 10^{3} Seconds past Big Bang



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

Production of first elements:

Primordial nucleosynthesis



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

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

first 3 Minutes are over

Neutron Lifetime and Nucleosynthesis

Exzellenzcluster Universe

Three parameters:

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

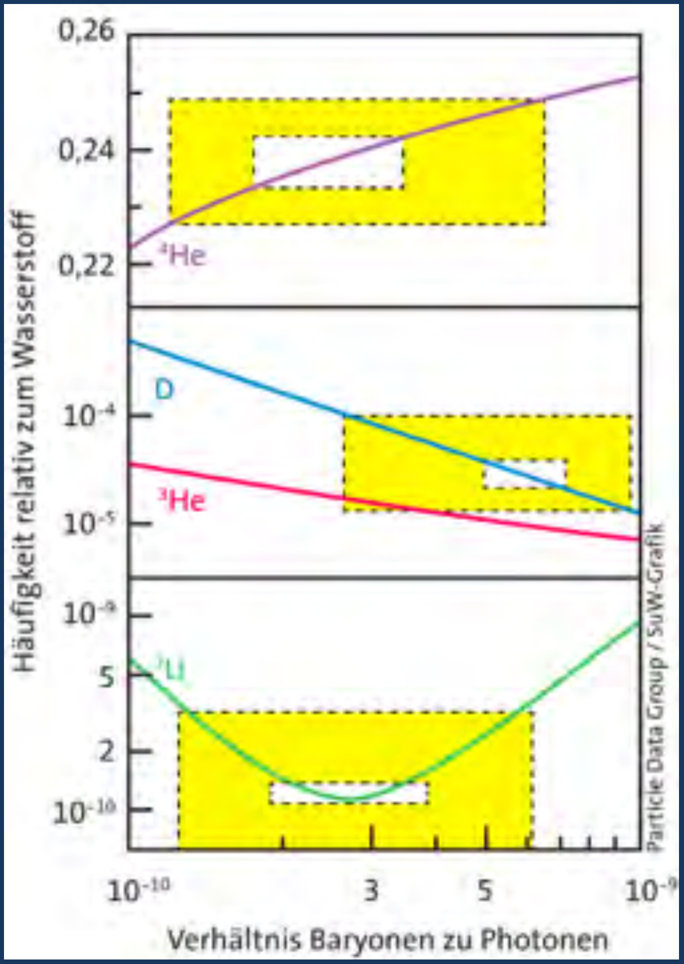
- CMB (WMAP-Satellit)

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

- Low metallicity (early) stars/galaxies

τ_n

- Experiments



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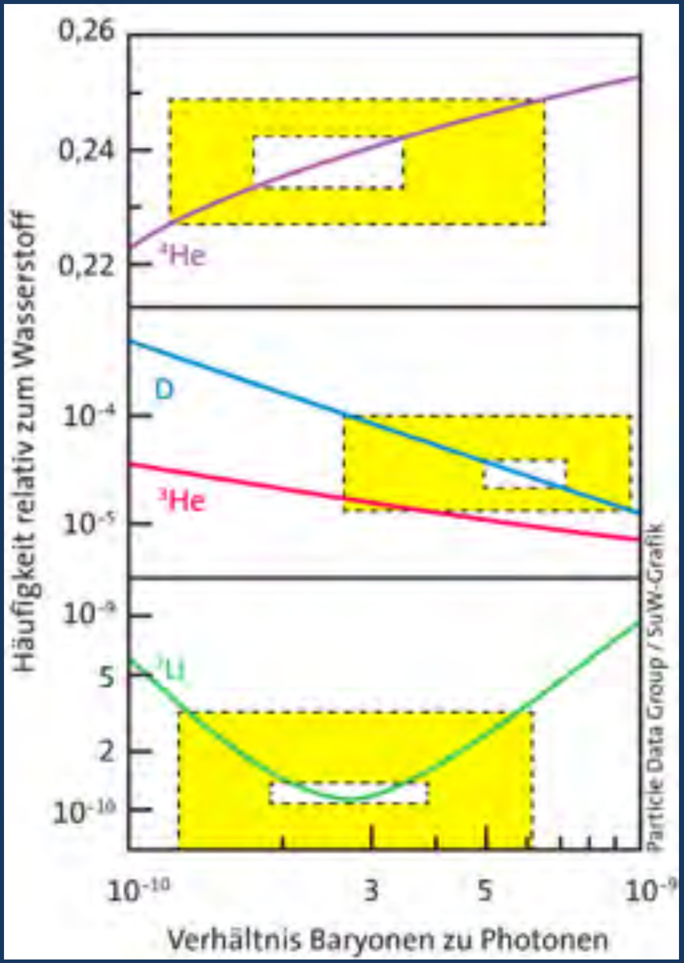
- Experiments

Knowledge of weak and nuclear force:

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



Neutron Lifetime and Nucleosynthesis

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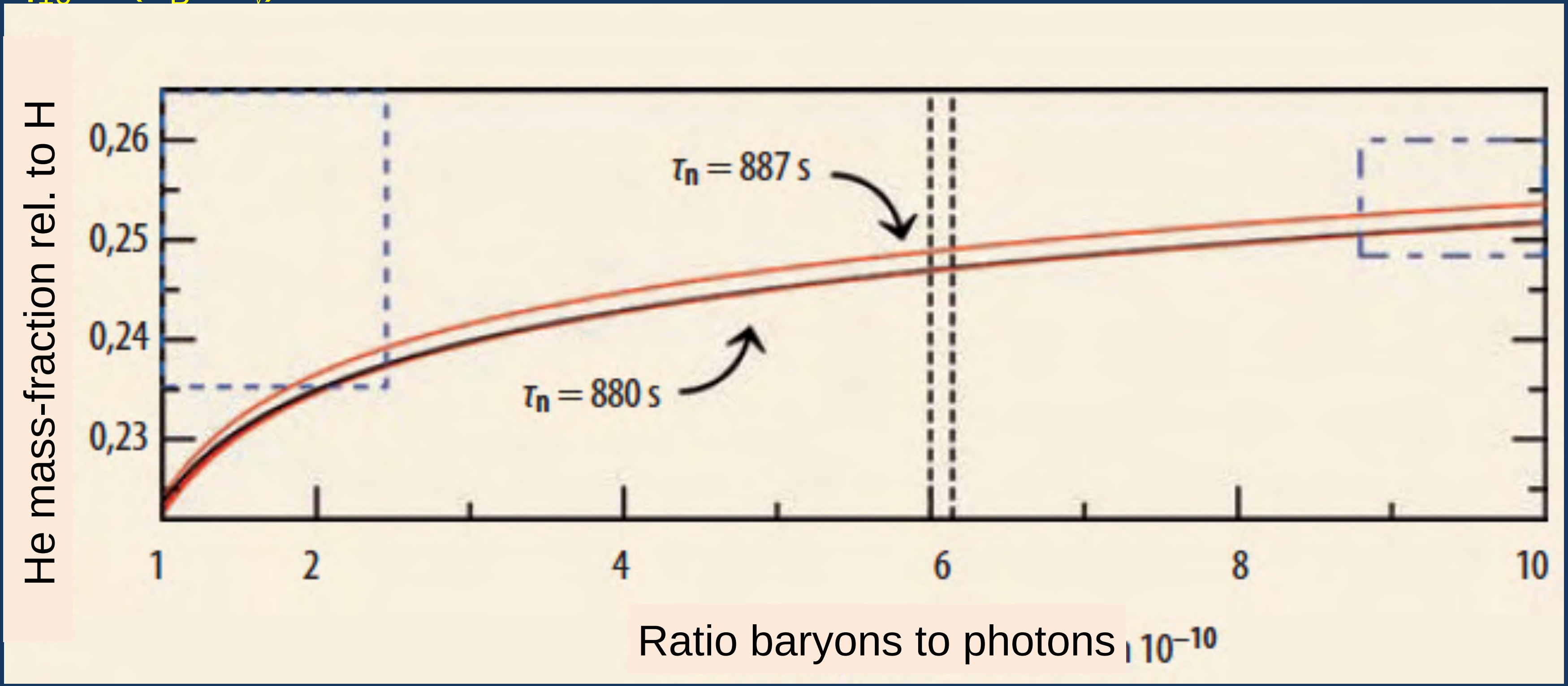

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Neutron Lifetime and Nucleosynthesis

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

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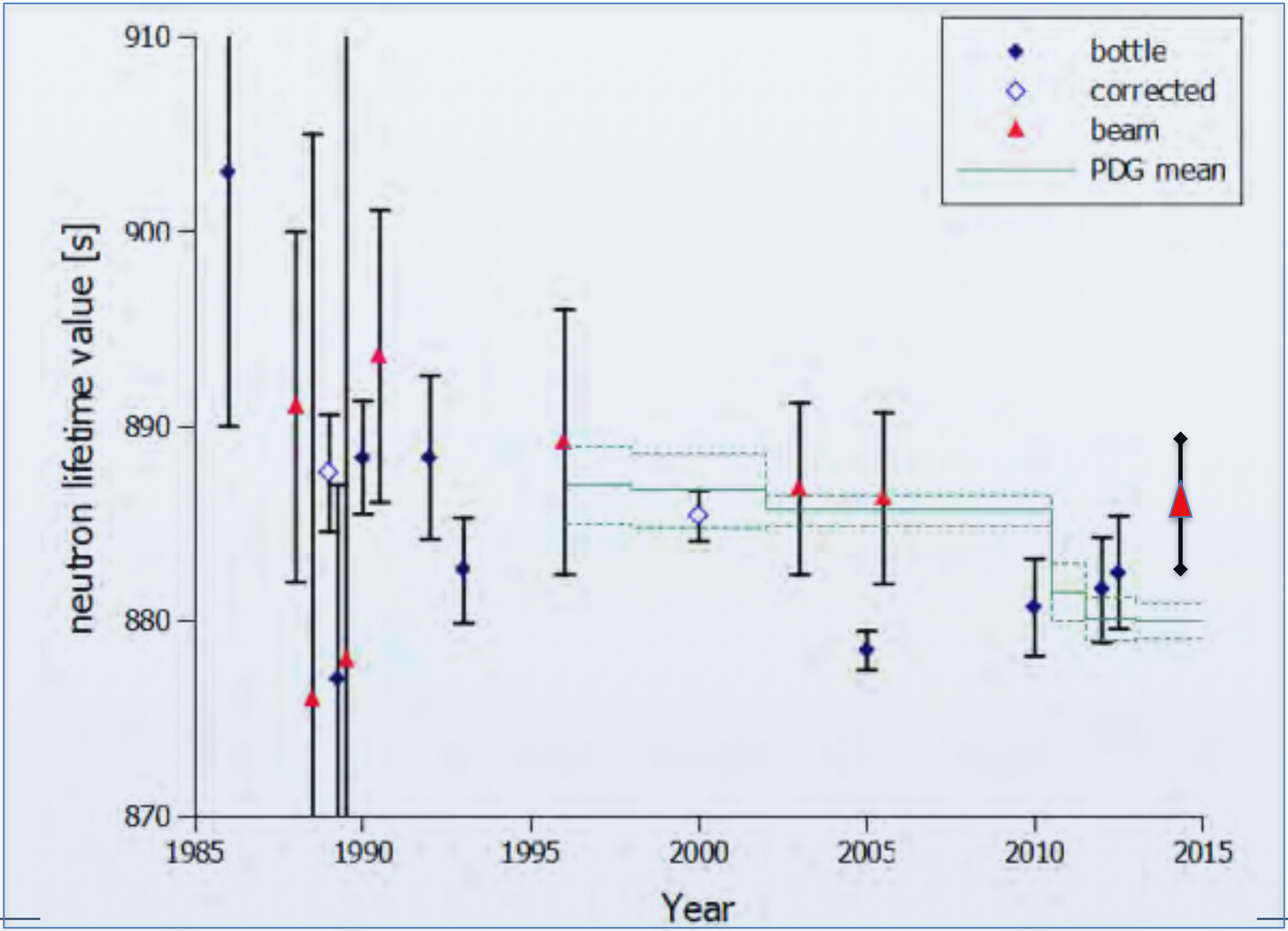
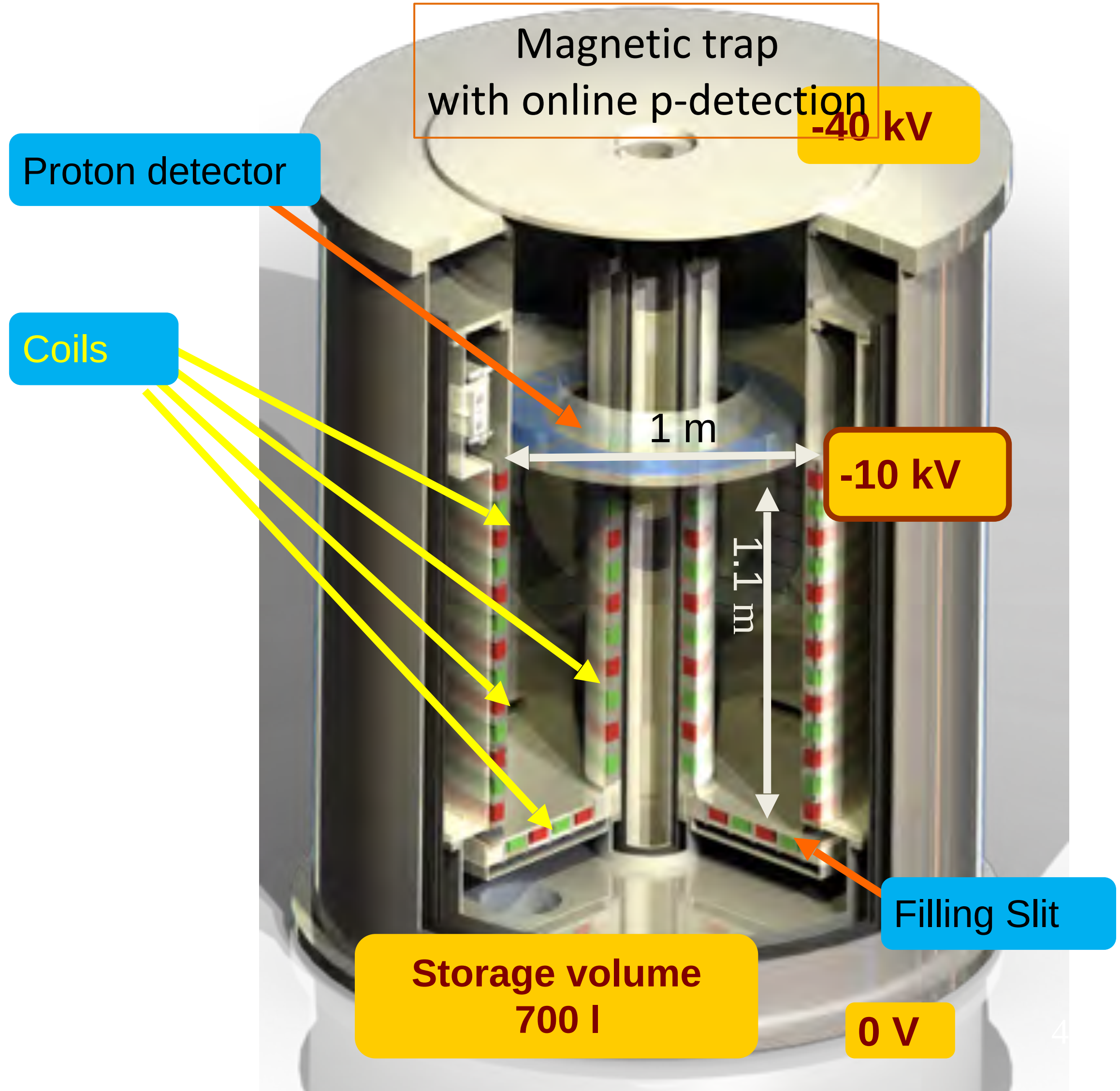
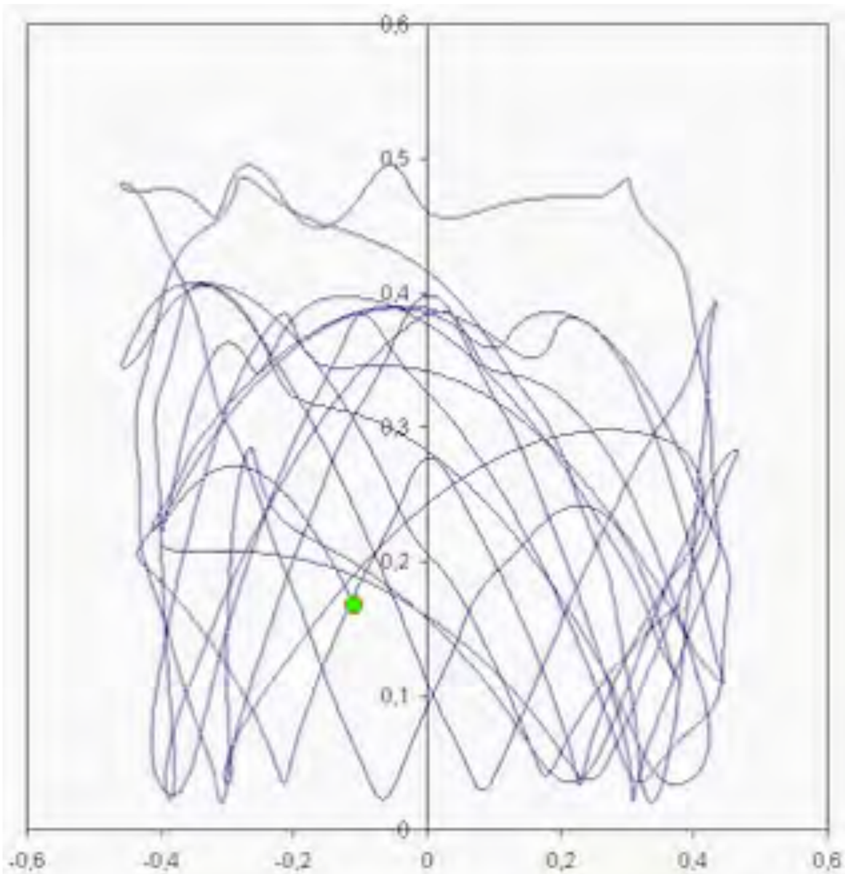
Lifetime - Overview

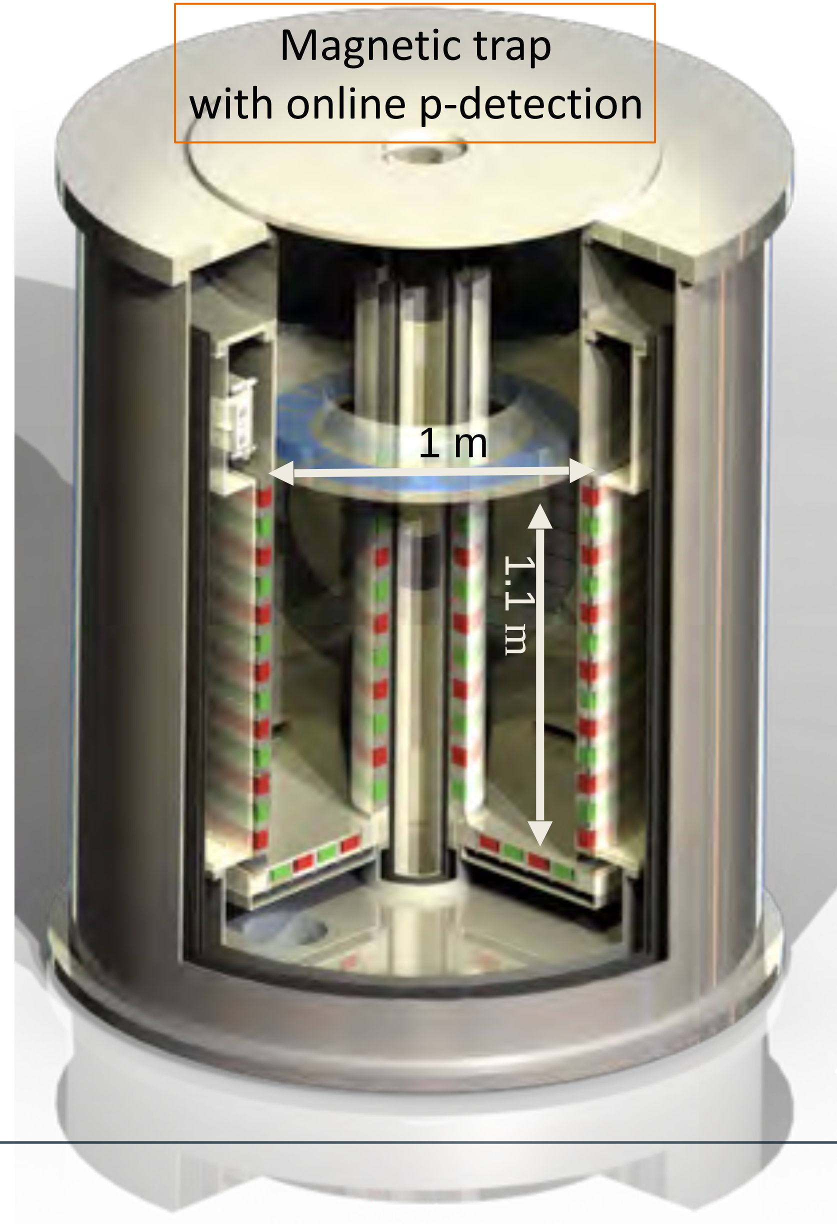


Lifetime - Overview


Magnetic trap
with online p-detection
-40 kV
Proton detector
Coils
1 m
-10 kV
1.1 m
Filling Slit
Storage volume
700 l
0 V

Measurement of n-Lifetime with PENeLOPE





Measurement of n-Lifetime with PENeLOPE

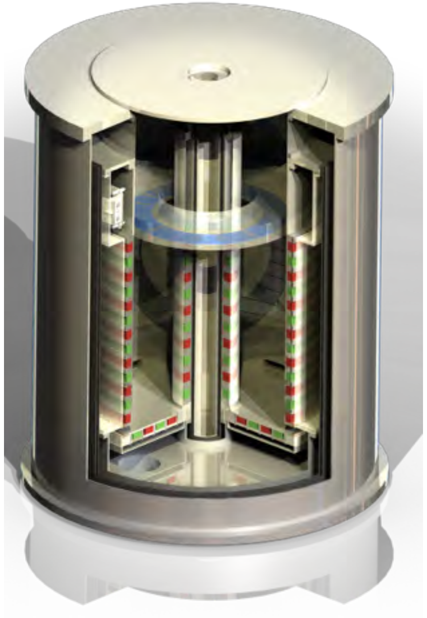
Detect protons online

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

Detect neutrons past storage time t

- Many cycles to get exponential

Magnetic trap
with online p-detection



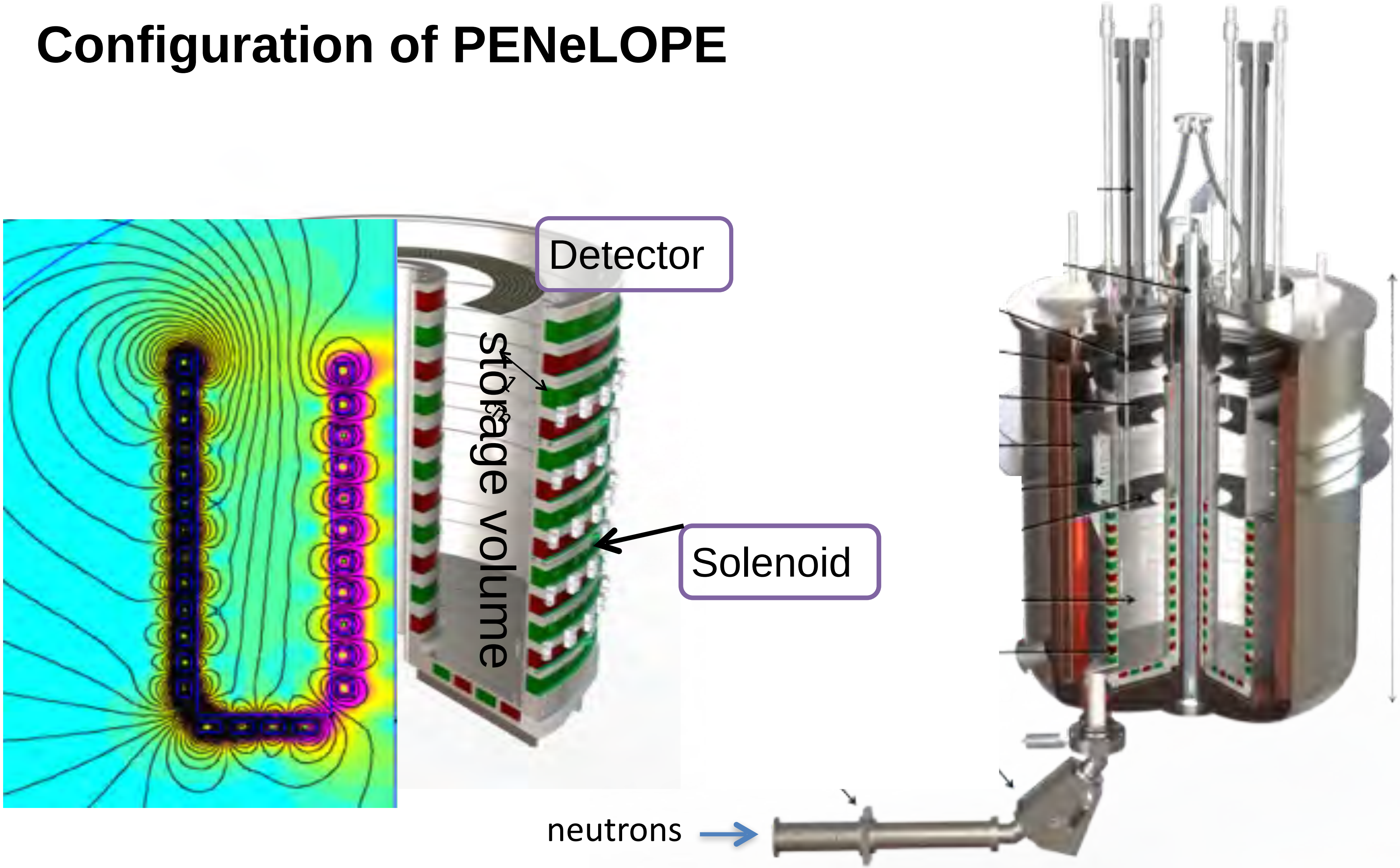
Assumption:

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

Statistical accuracy:

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

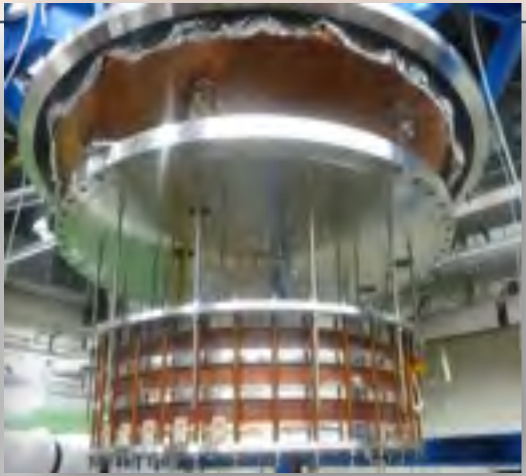
Configuration of PENeLOPE



Magnet/Coil Design and Test

First-of-series coils in CoTEx 2.0

Magnet/Coil Design and Test



First-of-series coils in CoTEx 2.0

Source for ultra cold Neutrons

FRM II of TUM

Source for ultra cold Neutrons

Production of Ultracold Neutrons

Reactor neutrons : E_0 = ~ 2 MeV

from nuclear fission of ^{235}U

↓

Moderator (heavy water) T = 300K

thermal neutrons E_0 = 25 meV 2.2 km/s

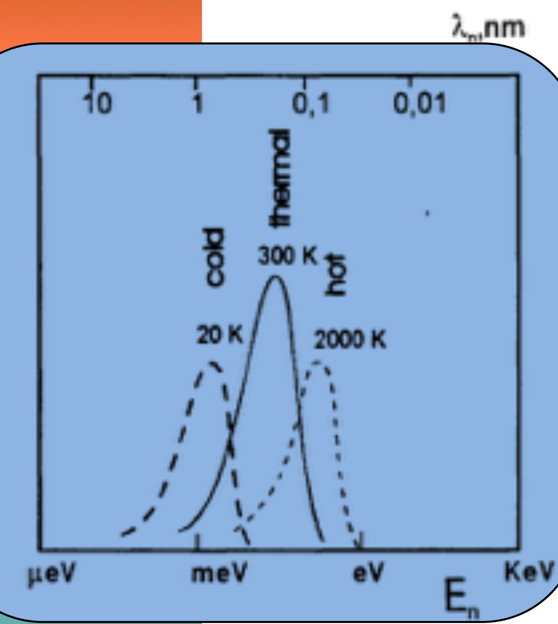
↓

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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↓

Near reactor core:

Cold moderator (Deuterium) T = 20 K

Cold neutrons E_0 = 4 meV 1.1 km/s

Velocity distribution

↓

Selection or further cooling ?

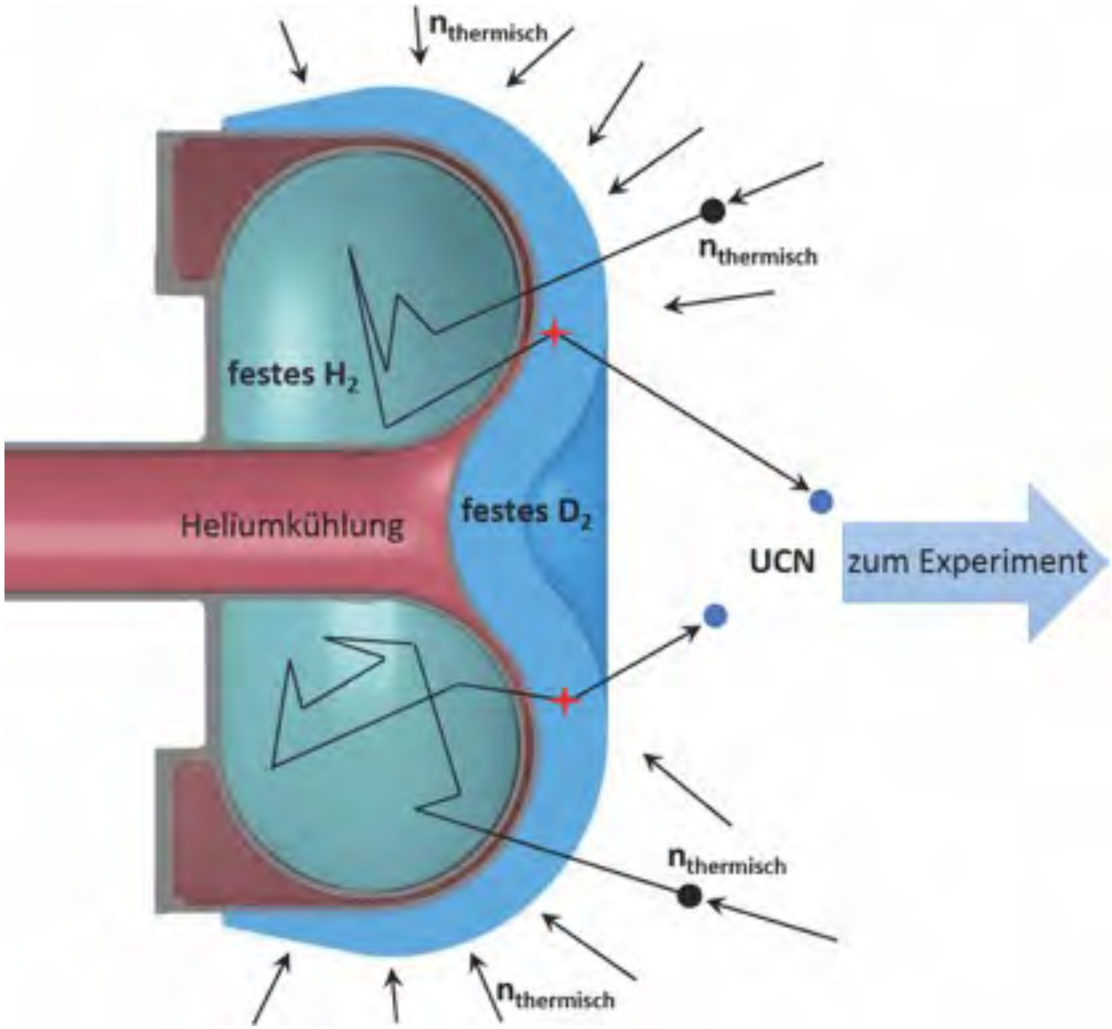
Very cold (VCN) $E_0 = 10^{-5}$ -10^{-6} eV 50-15 m/s

↓

Selection or further moderation ?

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

UCN Source: Generating Ultra Cold Neutrons



UCN Source: Generating Ultra Cold Neutrons

strong new UCN source :

superthermal D_2-source at FRM-II

UCN Source: Generating Ultra Cold Neutrons

strong new UCN source :
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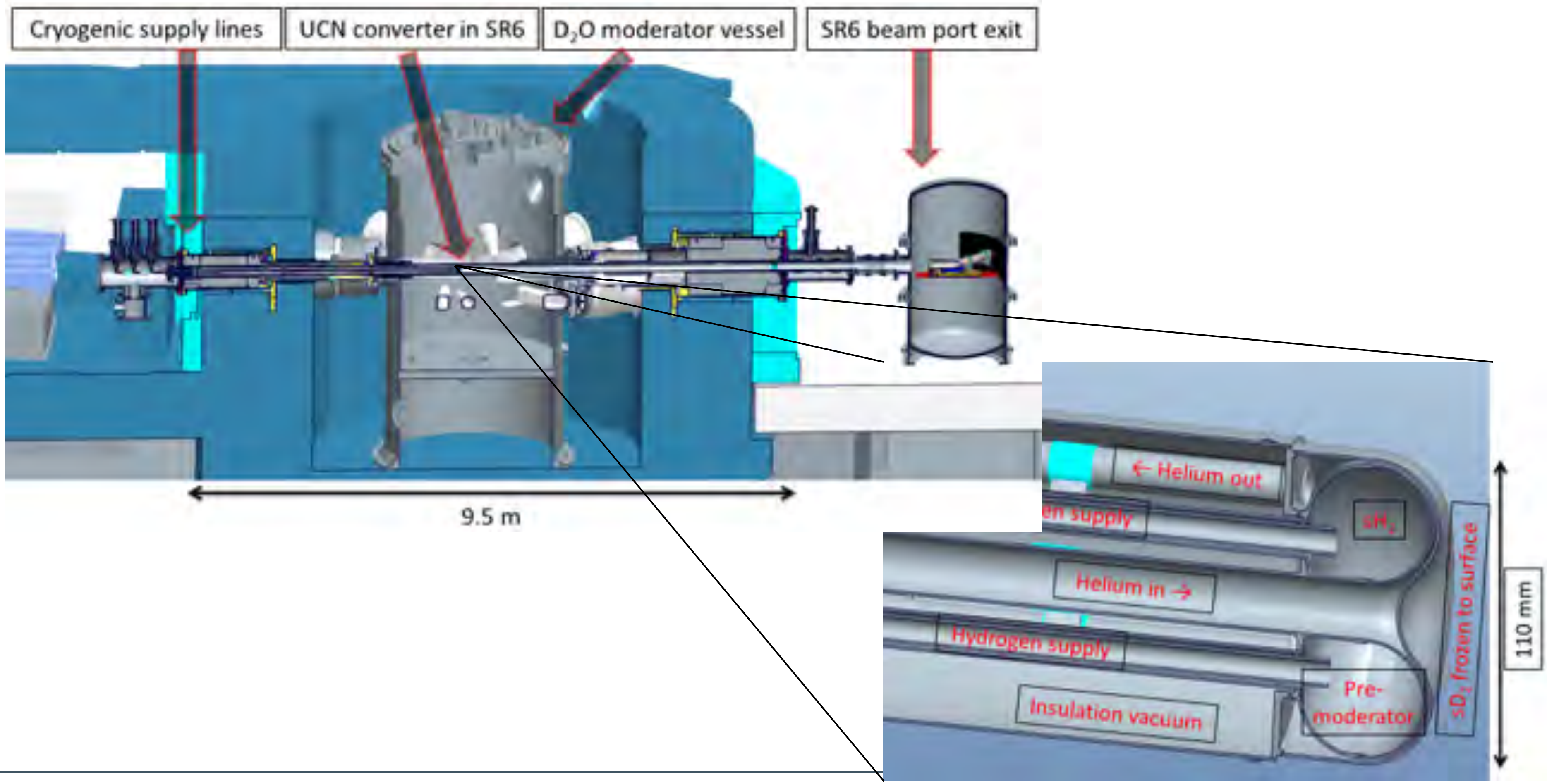
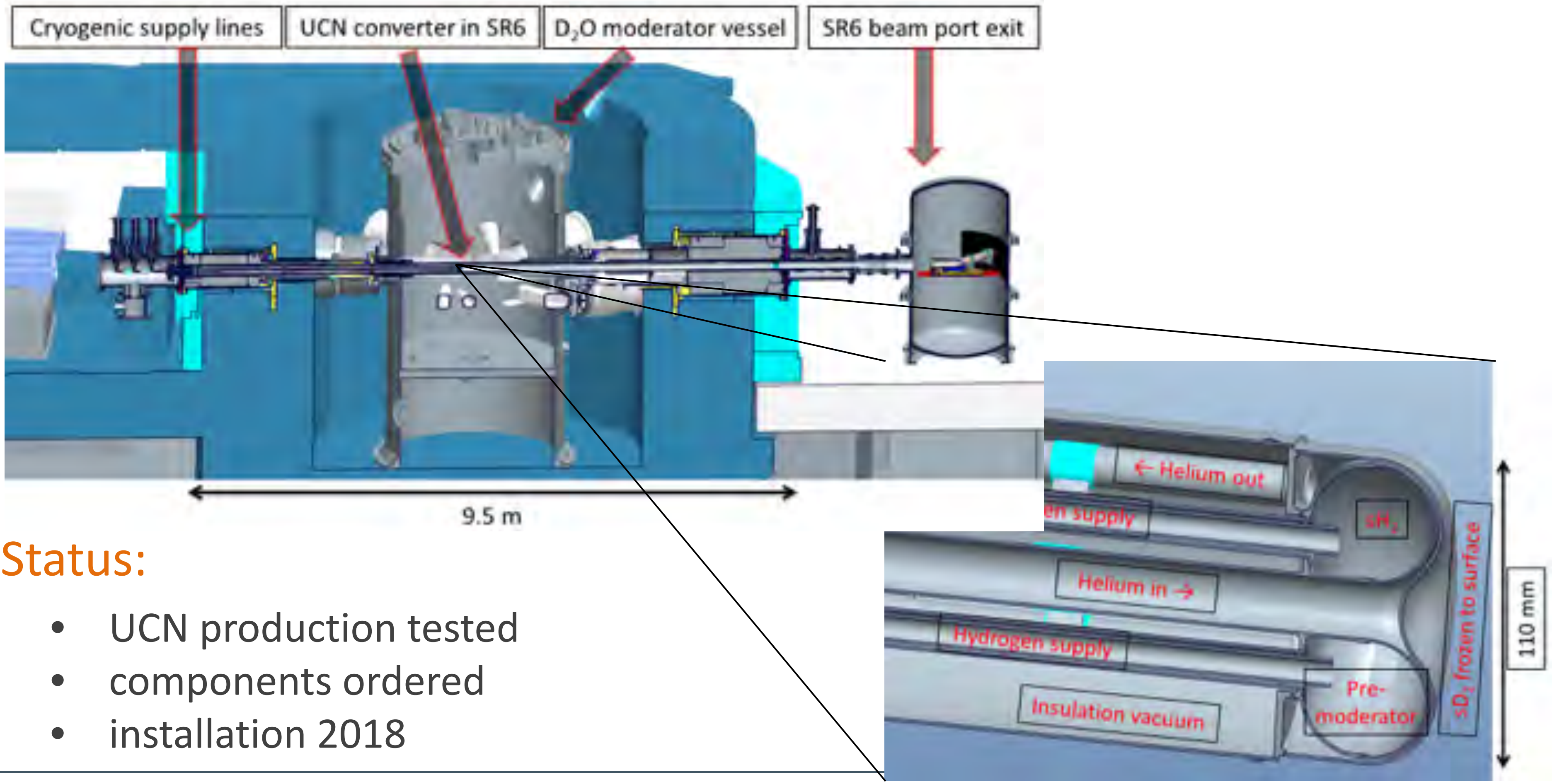
FRM II
Forschungs-Neutronenquelle
Heinz Maier-Leibnitz



UCN Source: Generating Ultra Cold Neutrons

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

FRM II
Forschungs-Neutronenquelle
Heinz Maier-Leibnitz



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

Some items not coverred

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

A neutron walks into a bar...

- Neutrino helicity

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