The neutron and the Universe
History of a Relationship

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‚From the origin of the Universe to the first building blocks of life'

The Neutron

weight: 53 kg

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

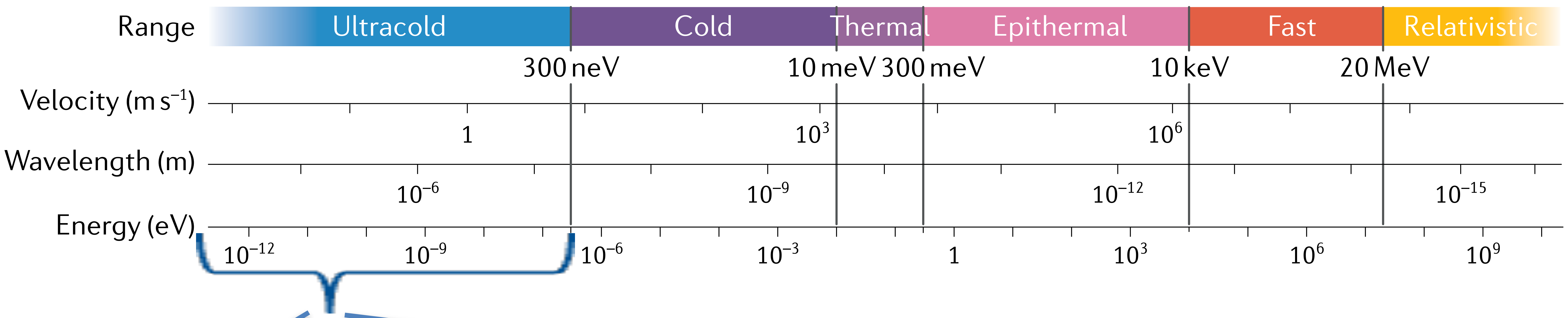
proton

neutron

electron

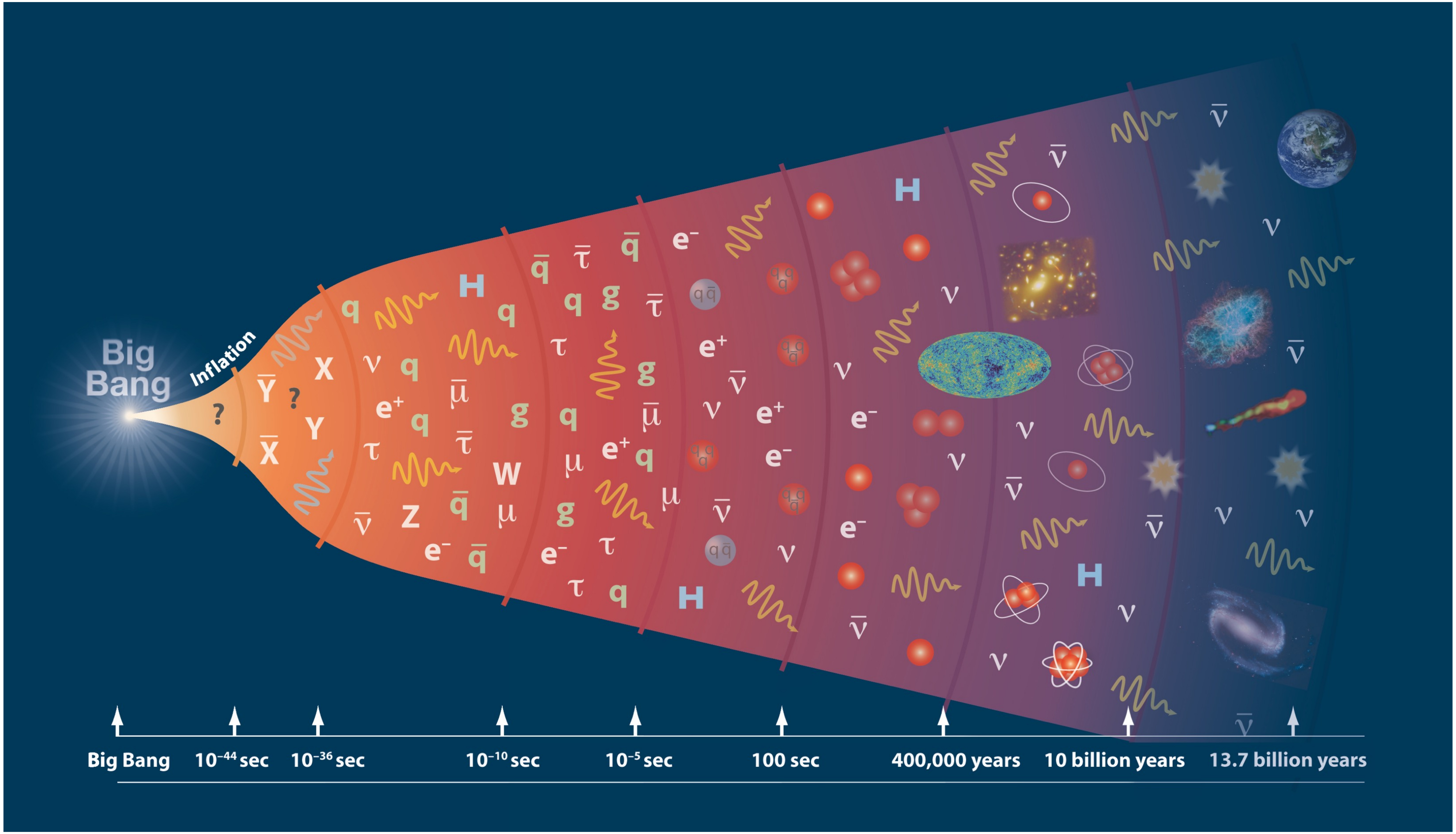
The Neutron and its surrounding

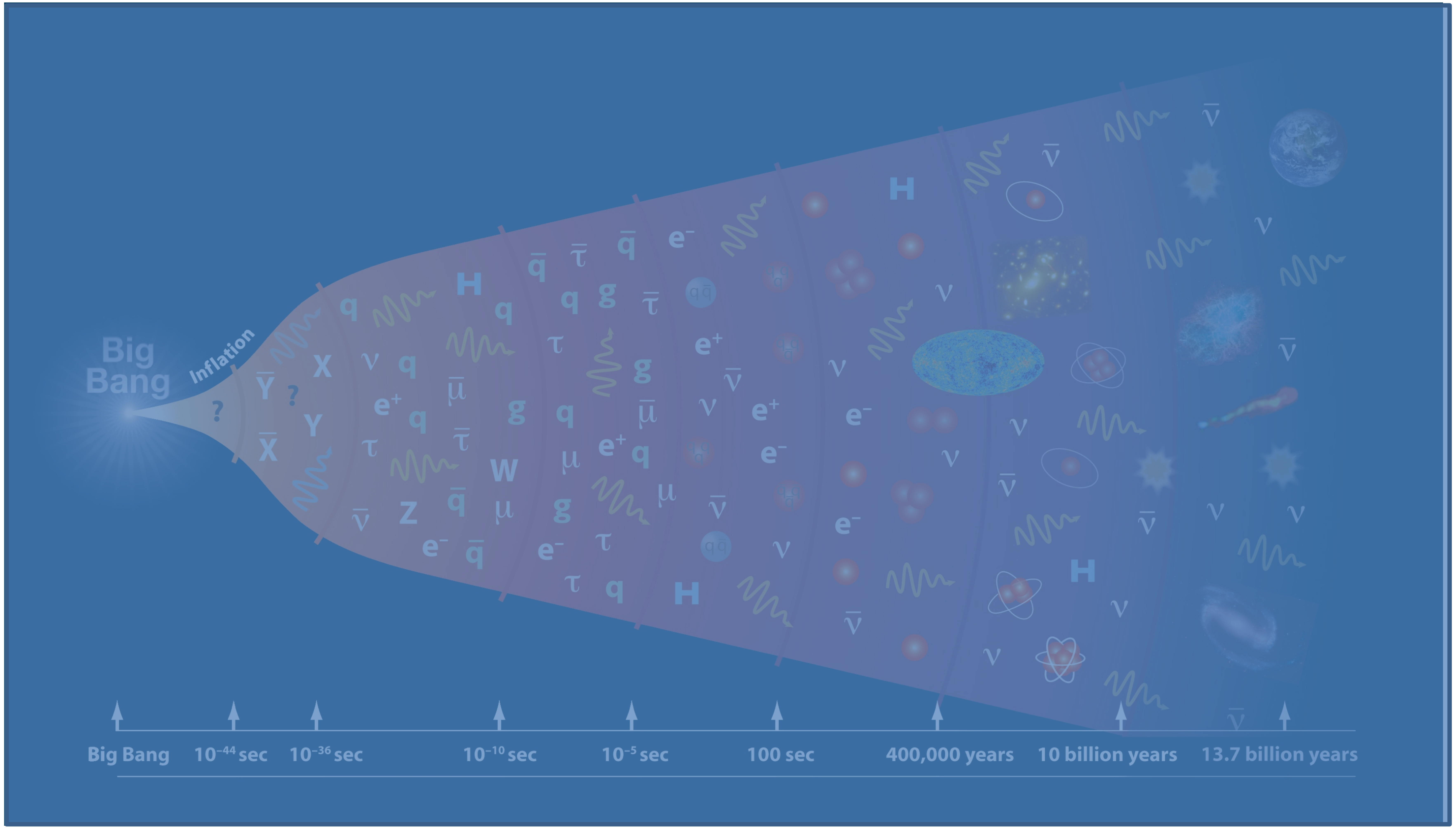
„practical“ neutrons and their energy range



Interaction	**Potential**	**Typical numbers**
Nuclear (optical)	$2\pi\hbar^2 b_c \delta(\mathbf{r})/m_n$	$V_{Si} \sim 50$ neV
Gravitational	$m_n \boldsymbol{g} \cdot \boldsymbol{r}$	~100 neV per m
Magnetic	$-\boldsymbol{\mu} \cdot \boldsymbol{B}(\boldsymbol{r}, t)$	~60 neV per T

The Universe





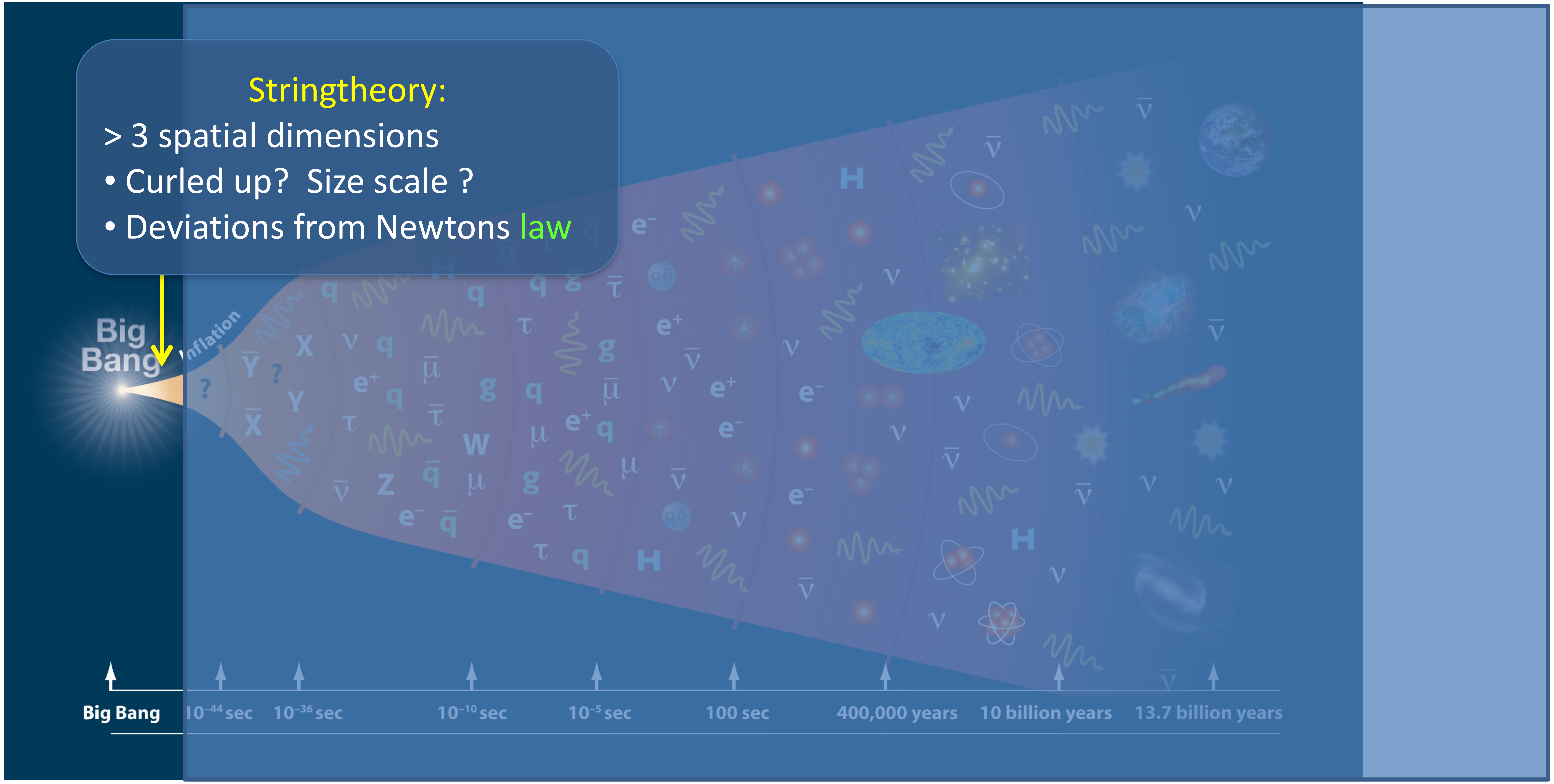
Big Bang
Inflation
Big Bang
10^{-44} sec
10^{-36} sec
10^{-10} sec
10^{-5} sec
100 sec
400,000 years
10 billion years
13.7 billion years

The Neutron and the History of the Universe

Stringtheory:

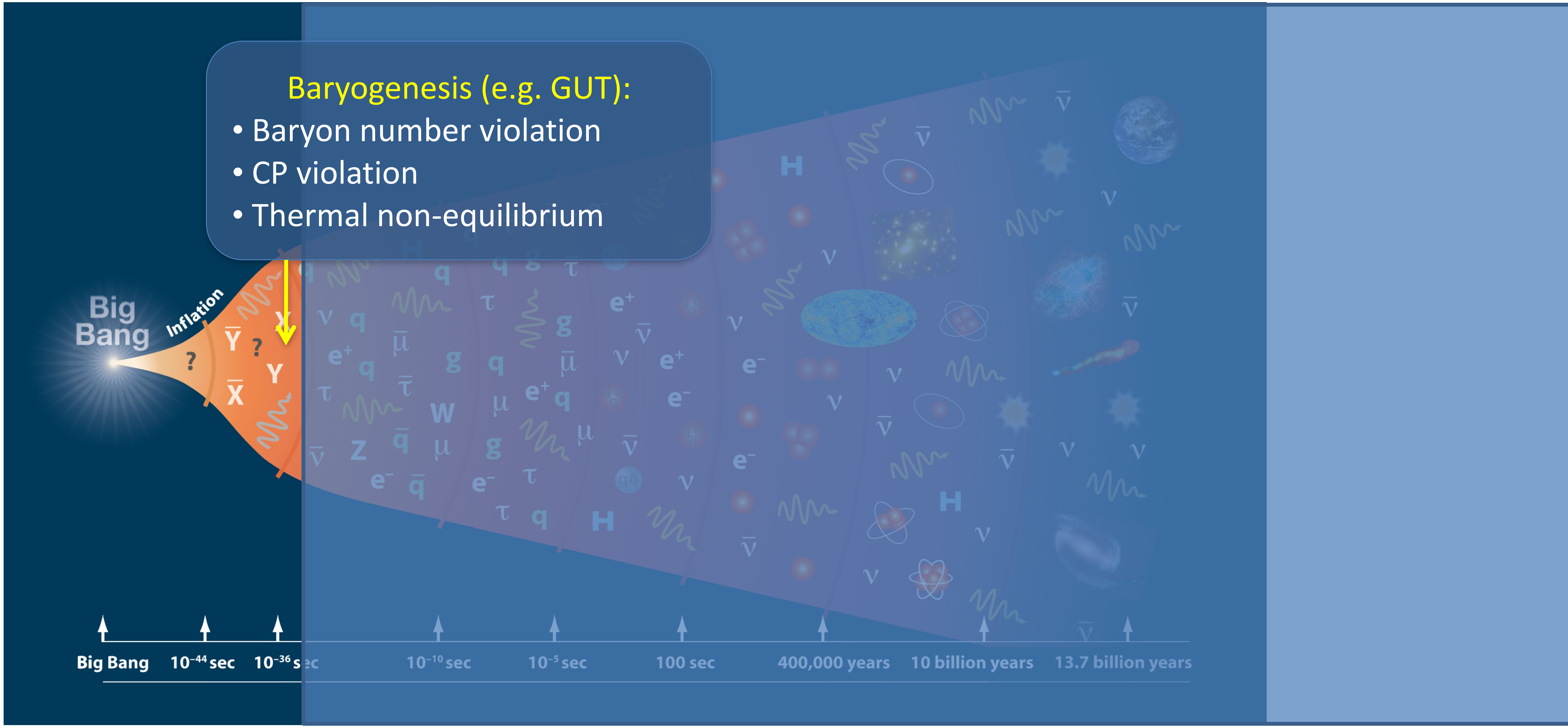
> 3 spatial dimensions

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



The Neutron and the History of the Universe

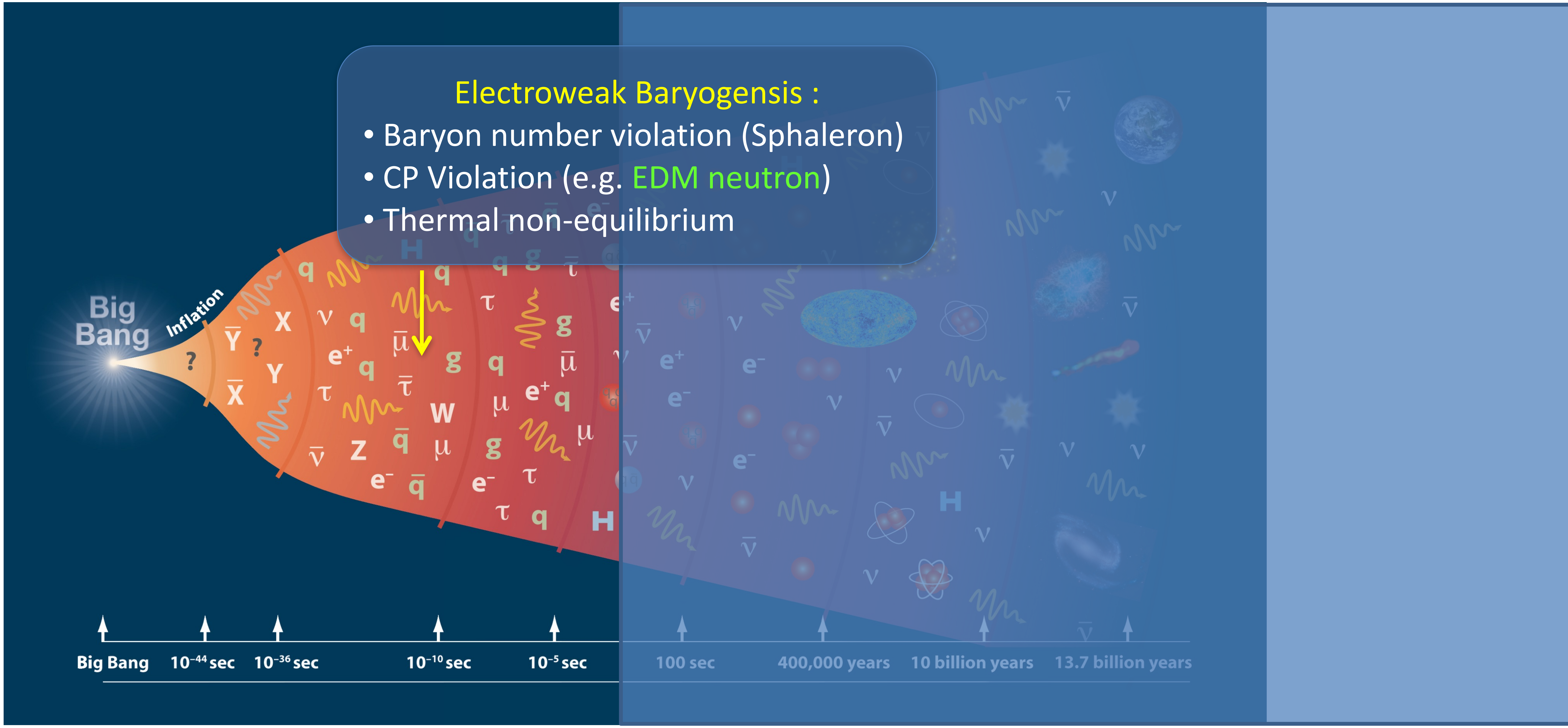
Baryogenesis (e.g. GUT):
- Baryon number violation
- CP violation
- Thermal non-equilibrium



The Neutron and the History of the Universe

Electroweak Baryogensis :

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



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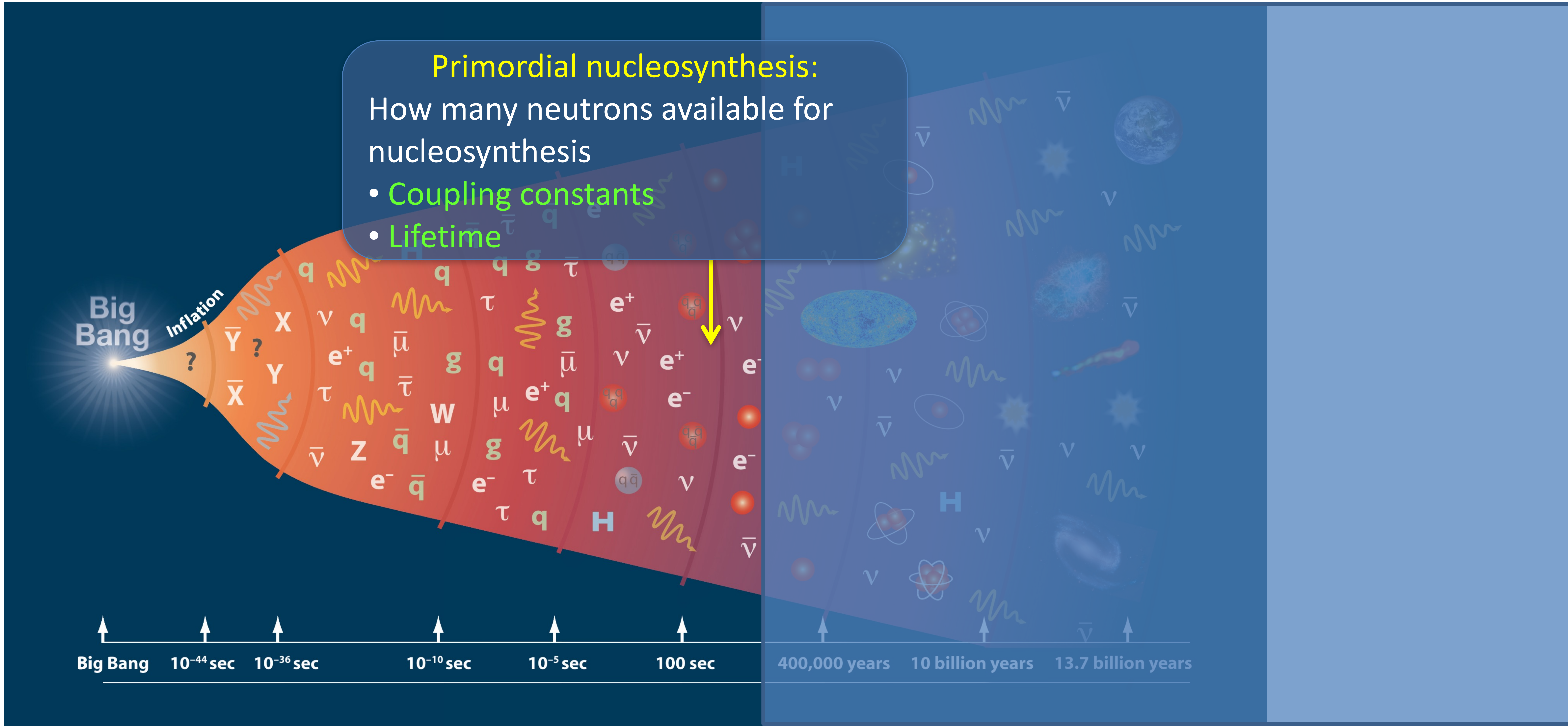

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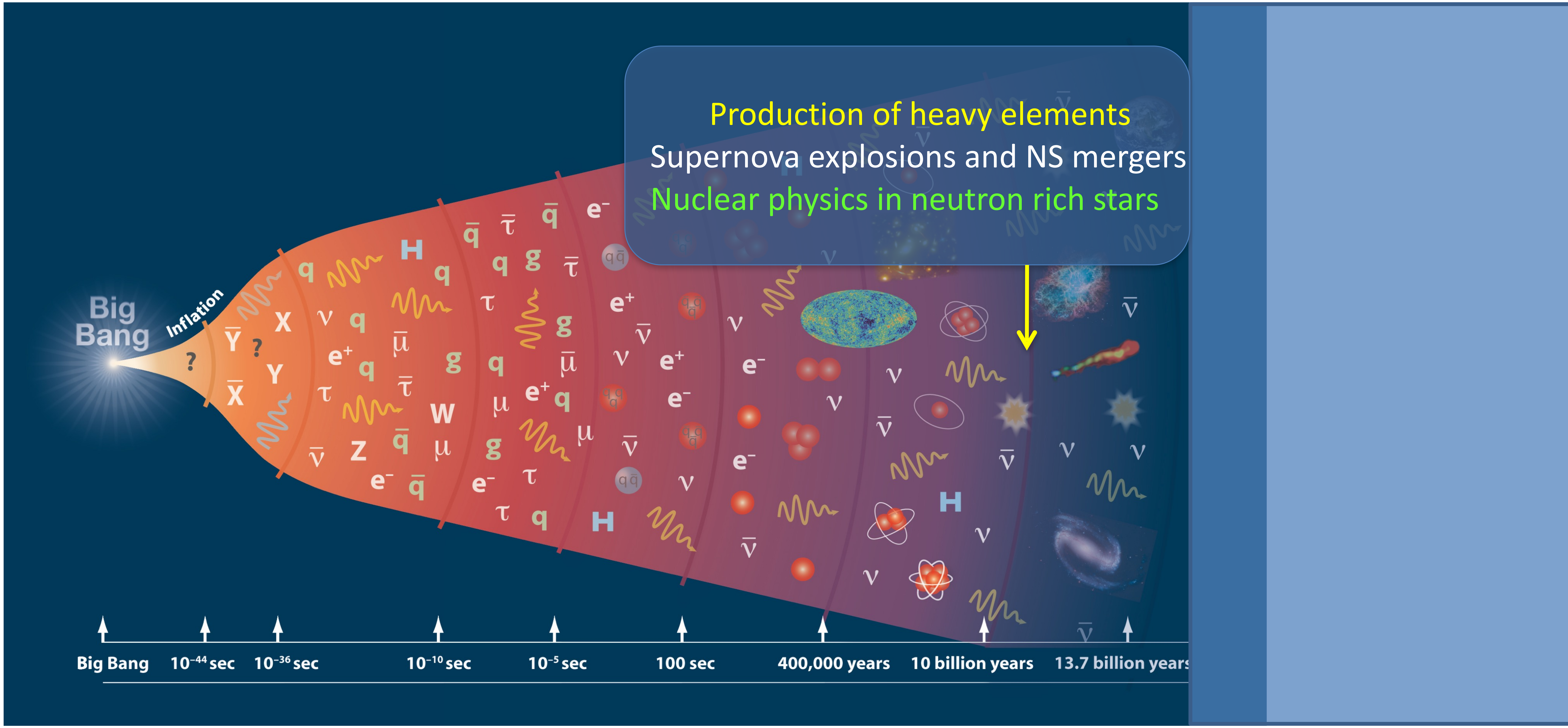

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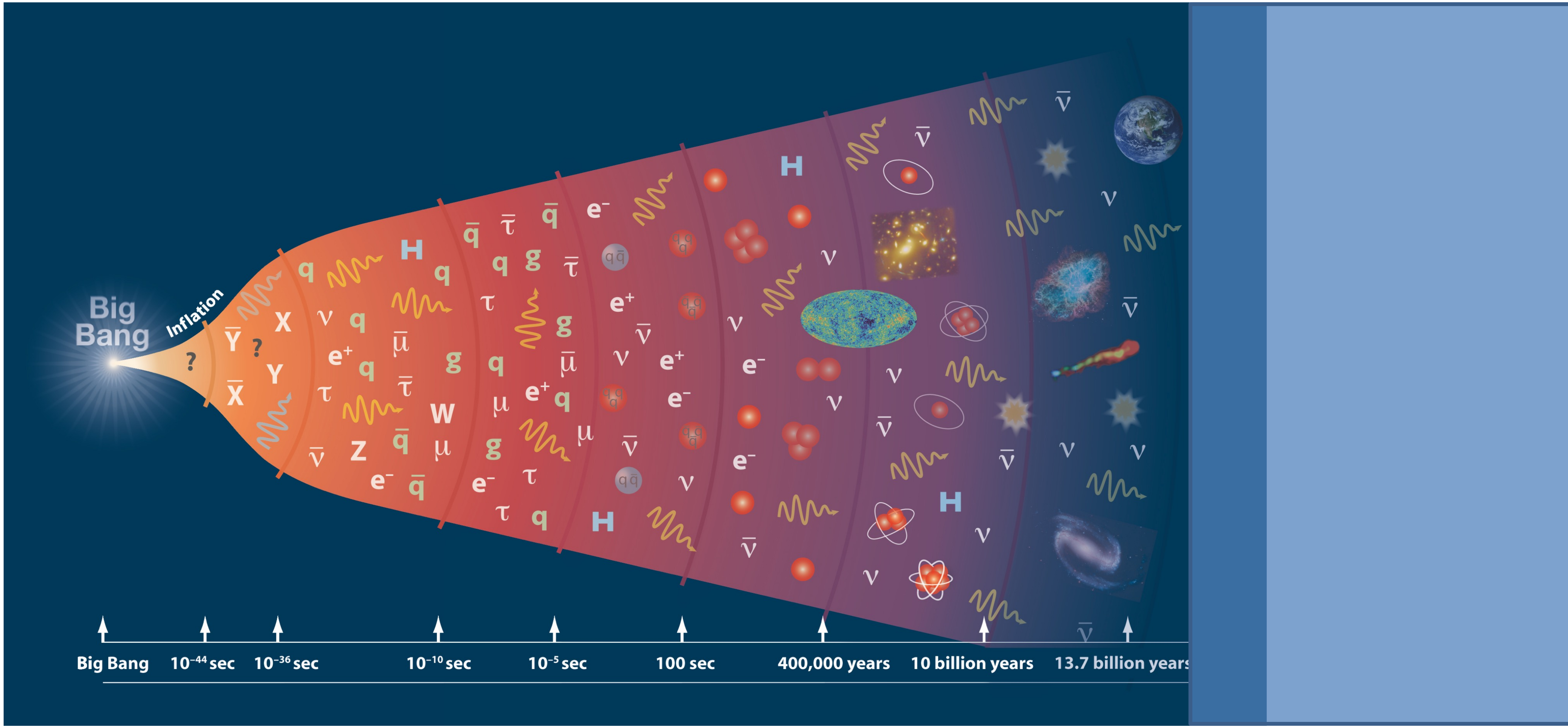
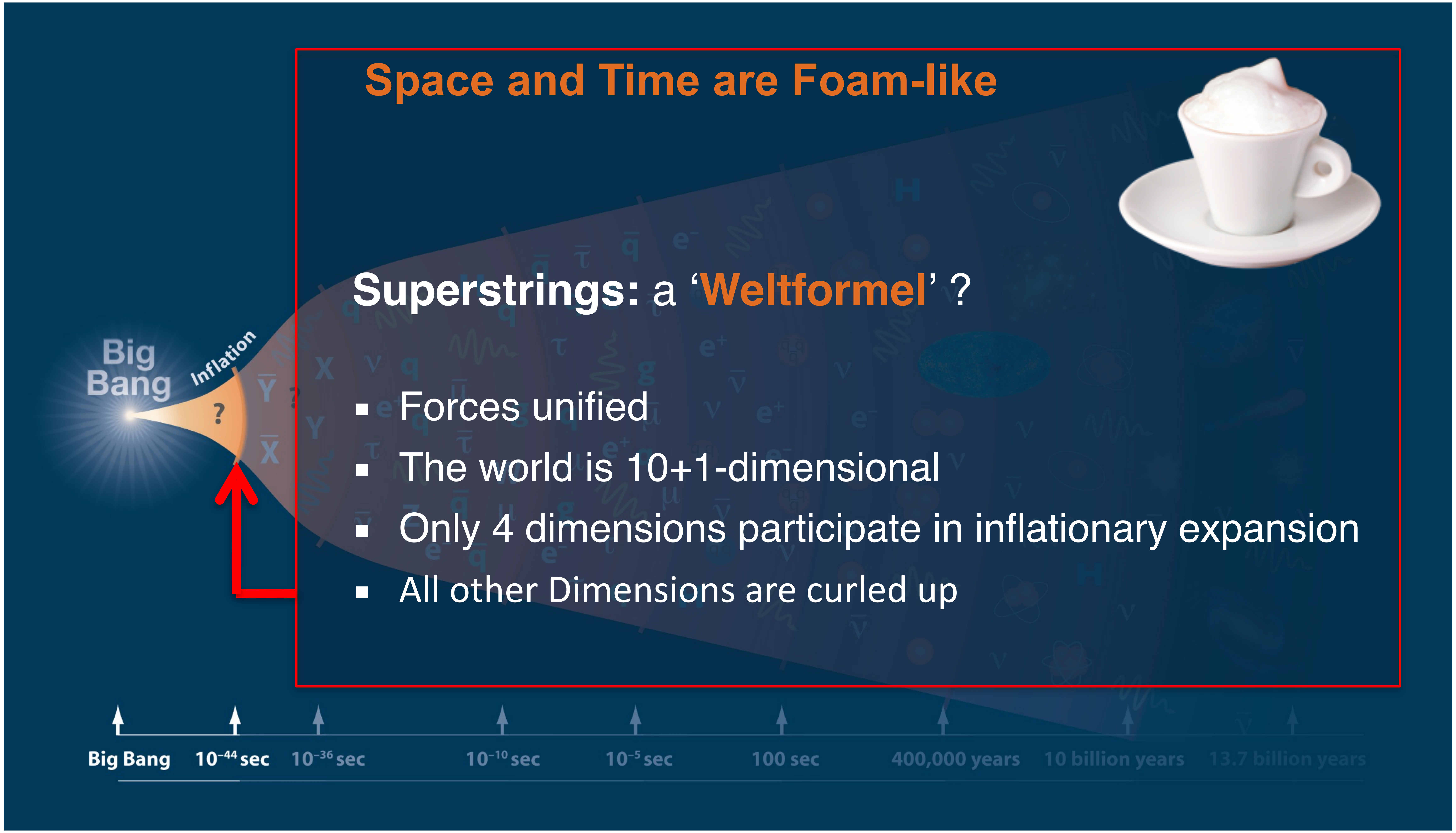


10^{-43} Sec. past Big-Bang: How it all began

Space and Time are Foam-like

Superstrings: a '**Weltformel**' ?

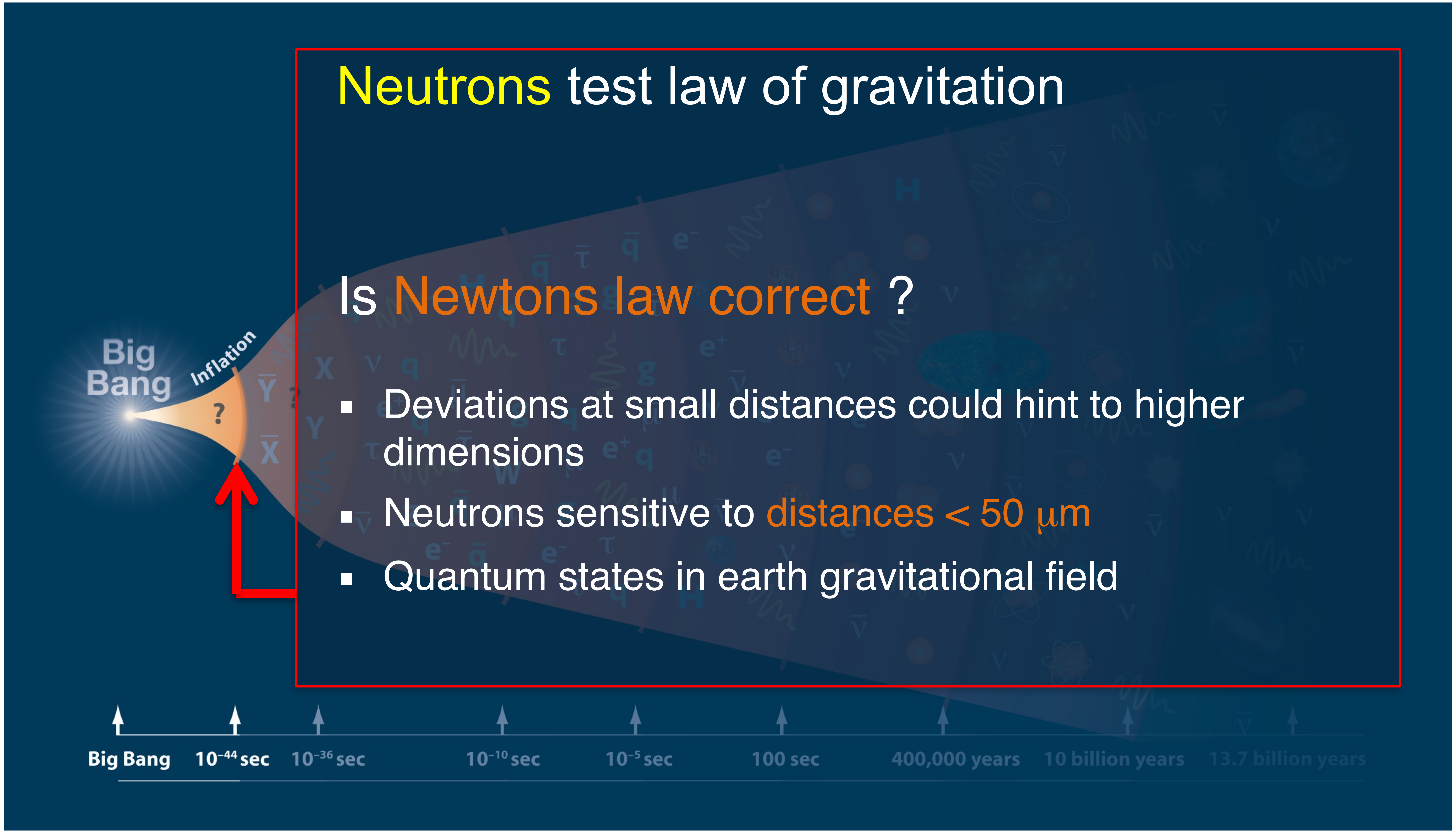
- Forces unified
- The world is 10+1-dimensional
- Only 4 dimensions participate in inflationary expansion
- All other Dimensions are curled up



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

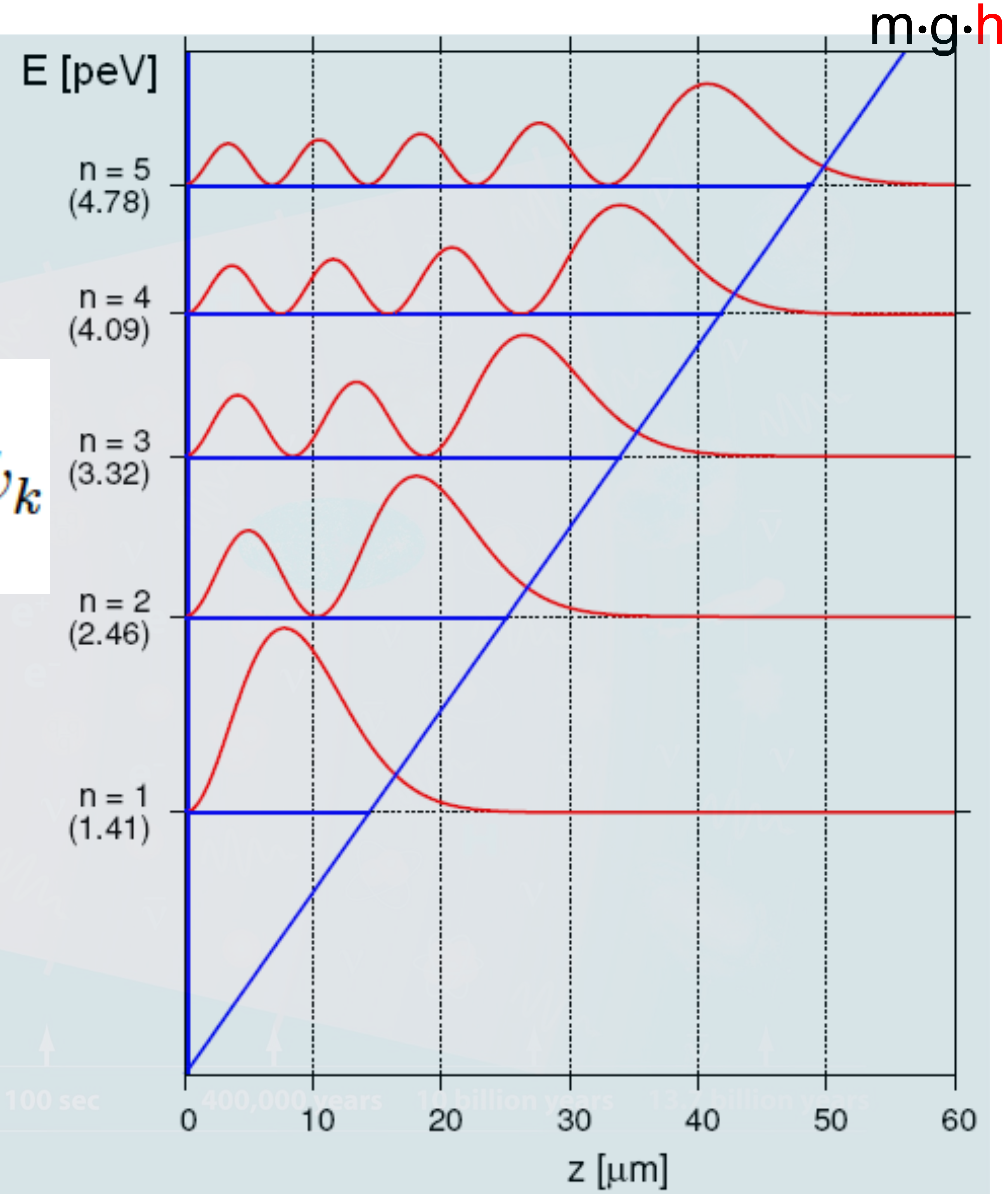


Gravitation – Quantisation in Earth Gravitational field

Gravitation – Quantisation in Earth Gravitational field

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

8



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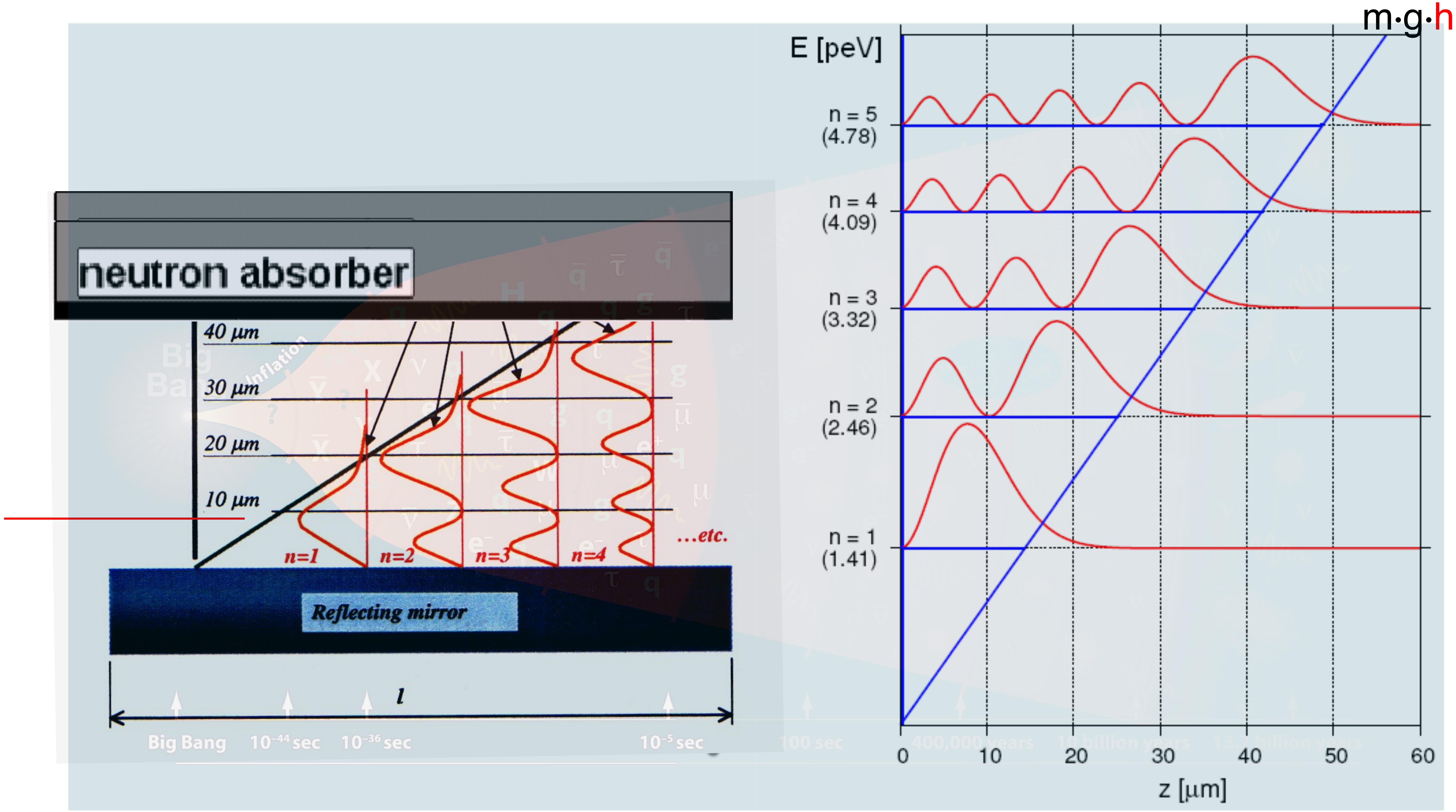
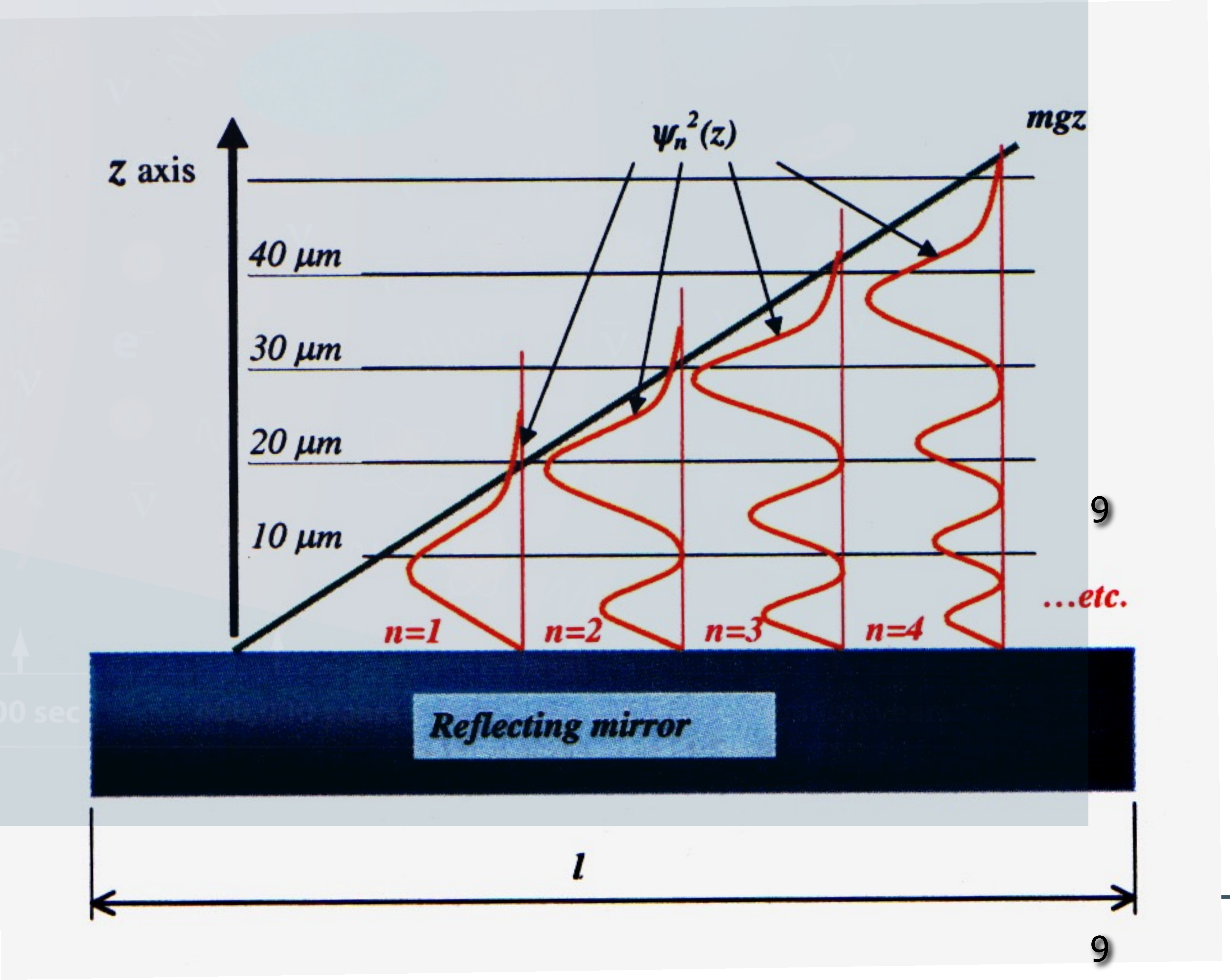


Sensitivity: peV

Distance scales : <10μm

Nature 415 299 (2002)



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Hartmut Abele, Universität Heidelberg

Gravitation – Bound states in Earth‘s field

Sensitivity: peV

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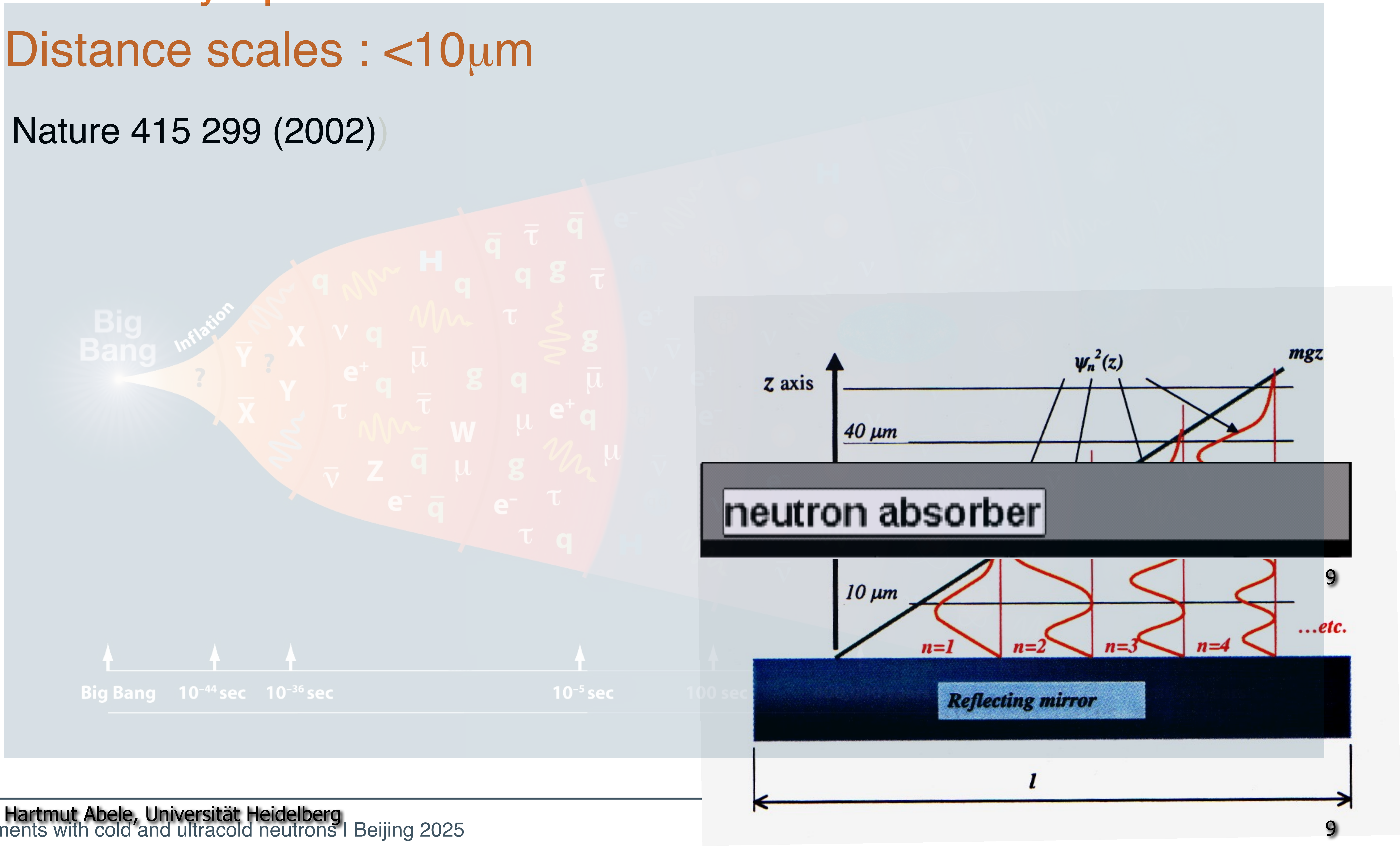

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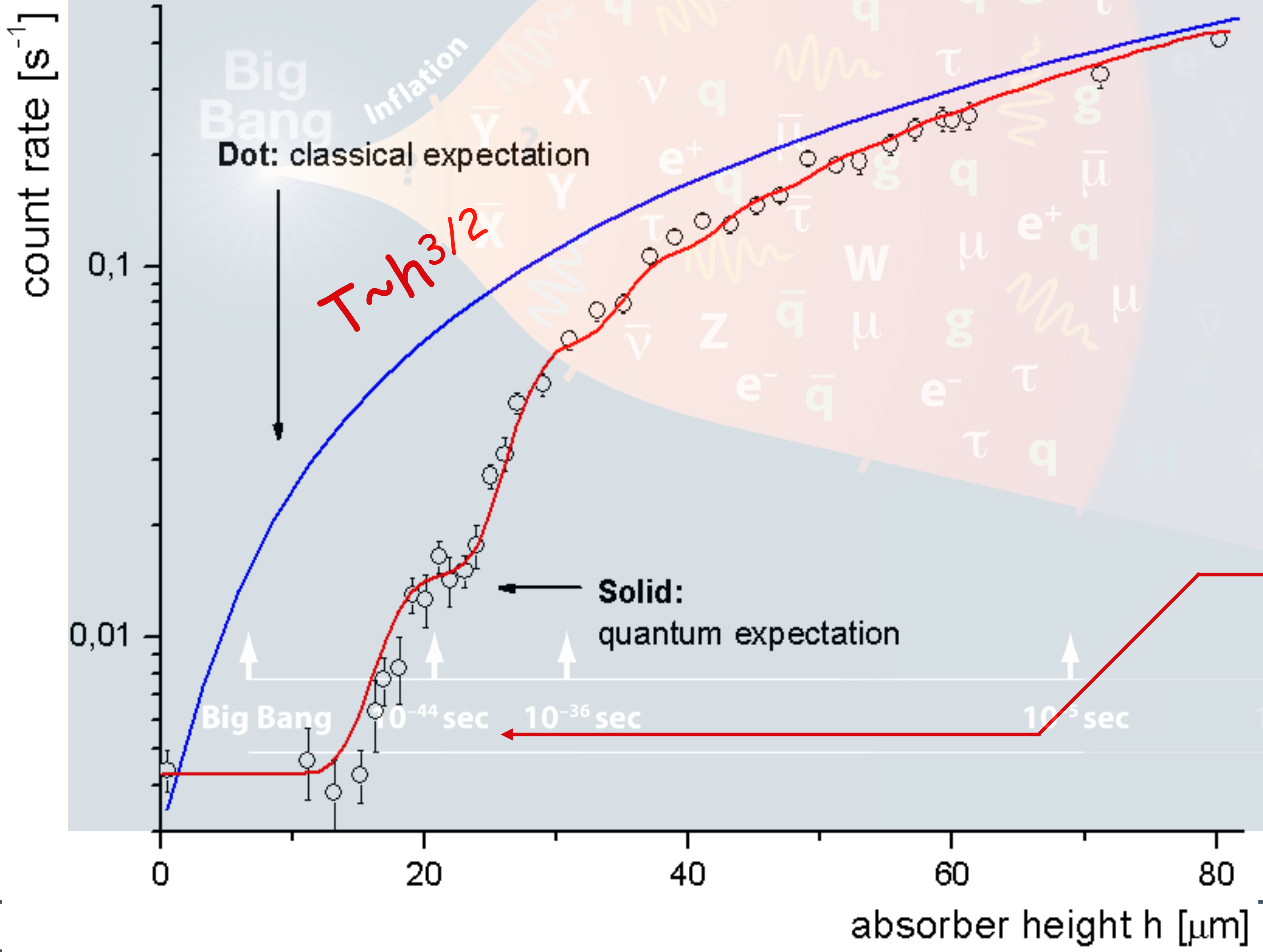

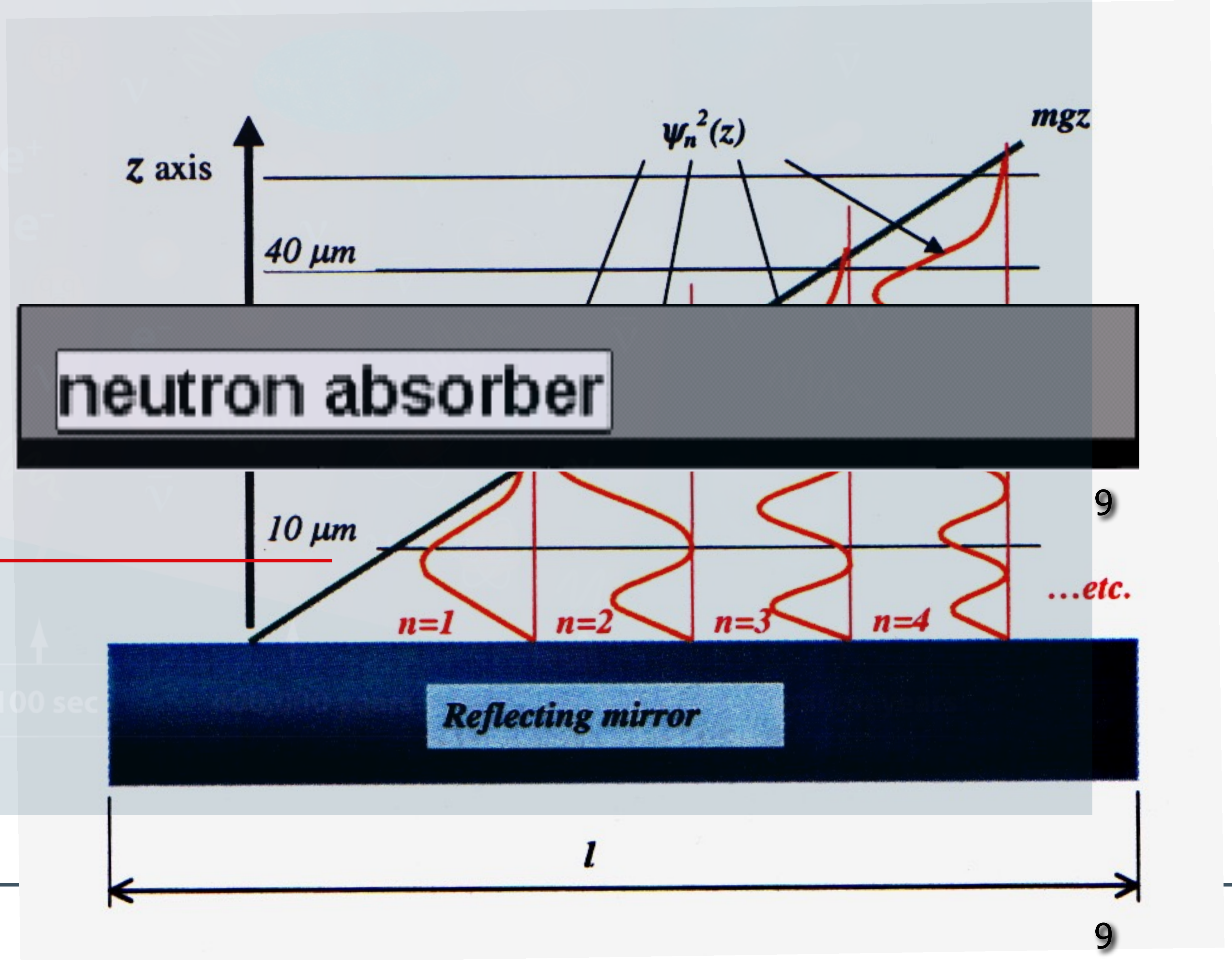

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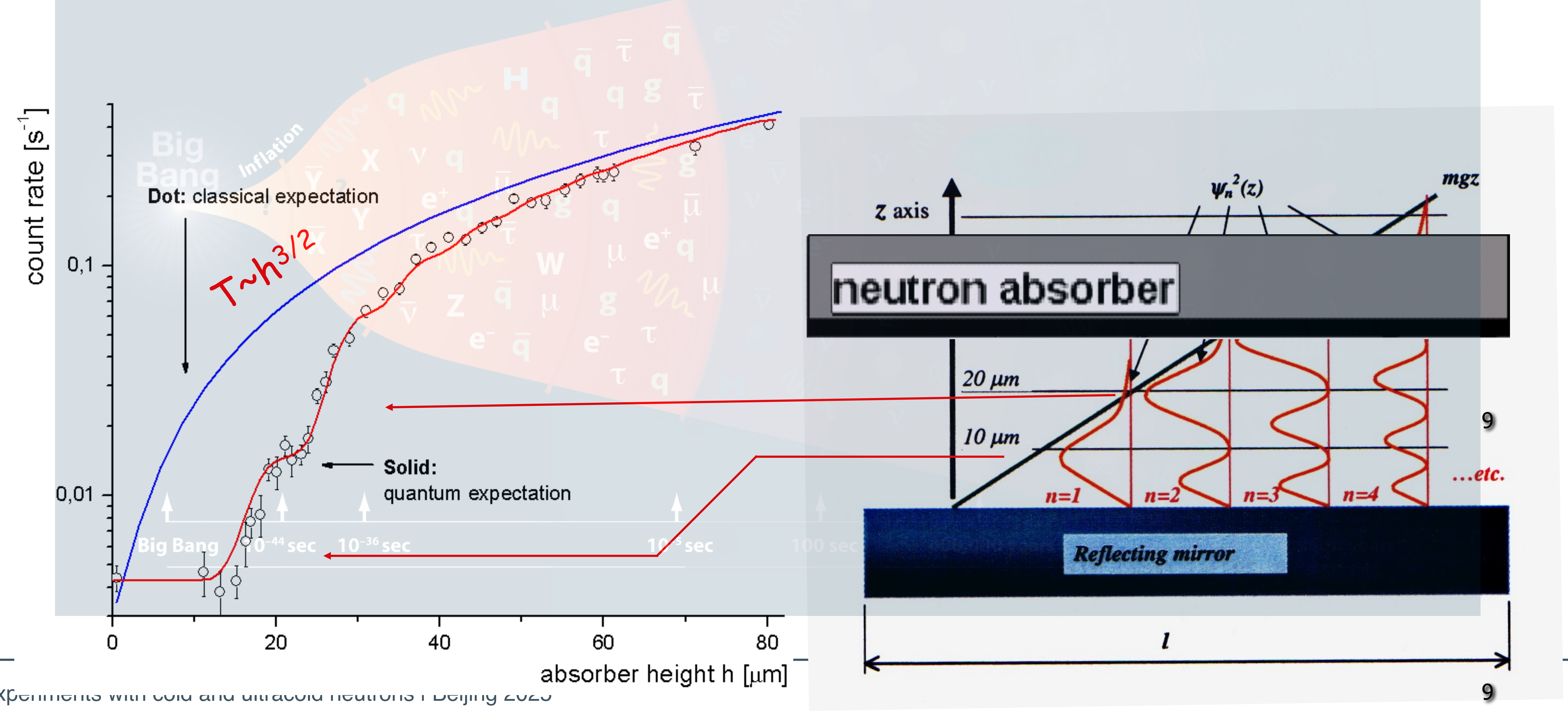

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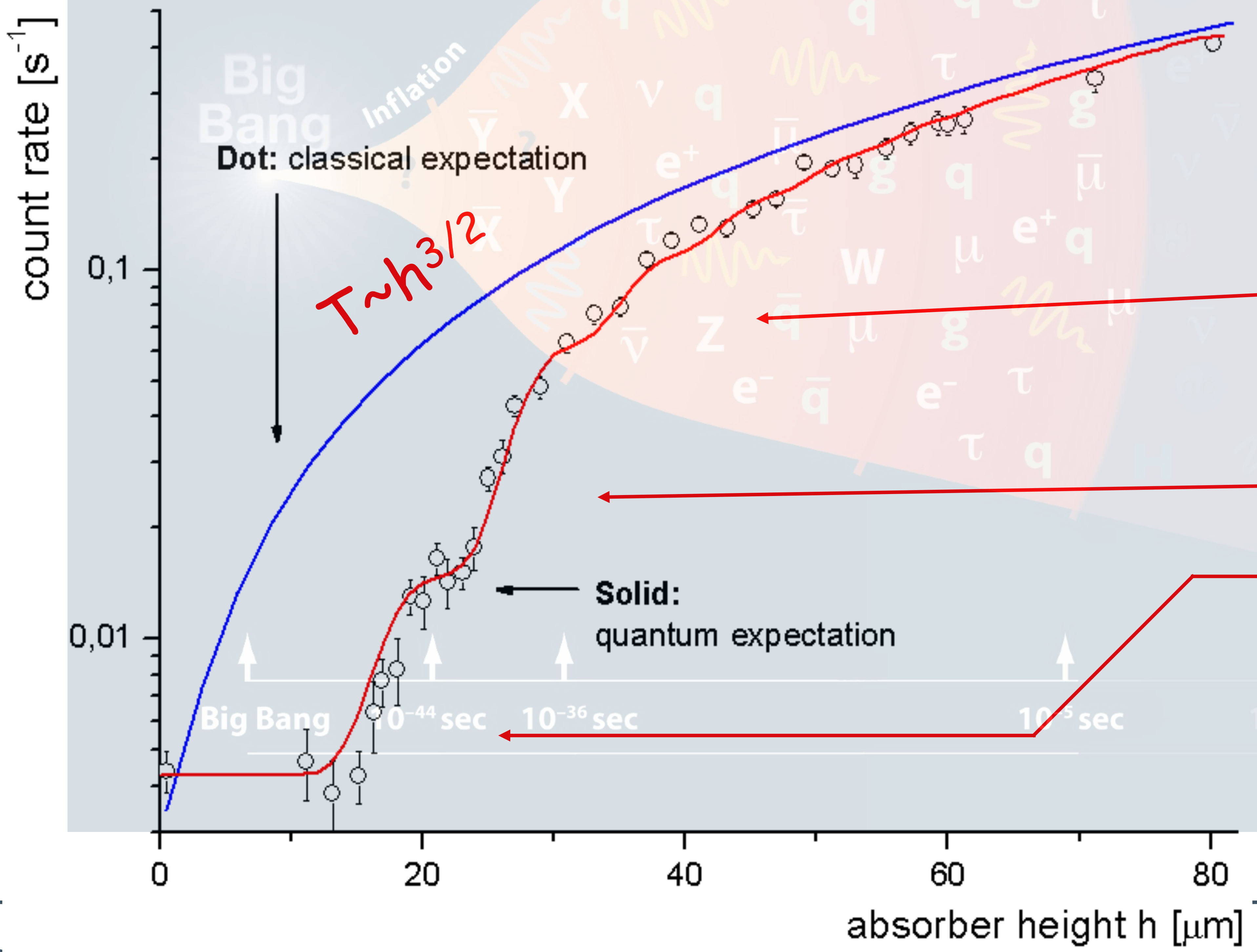
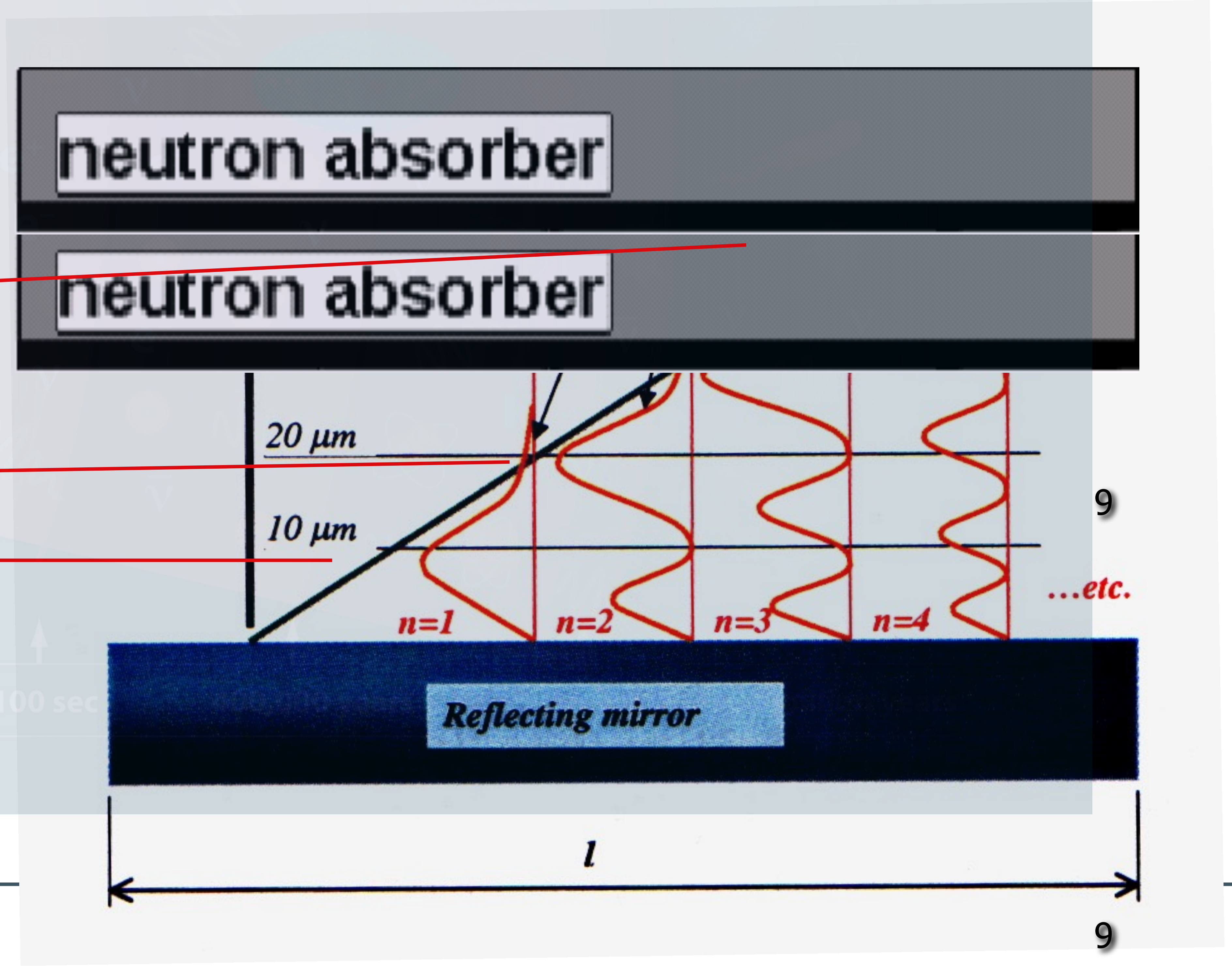




Gravitation – Quantization in Earth Field II

Yukawa coupling:

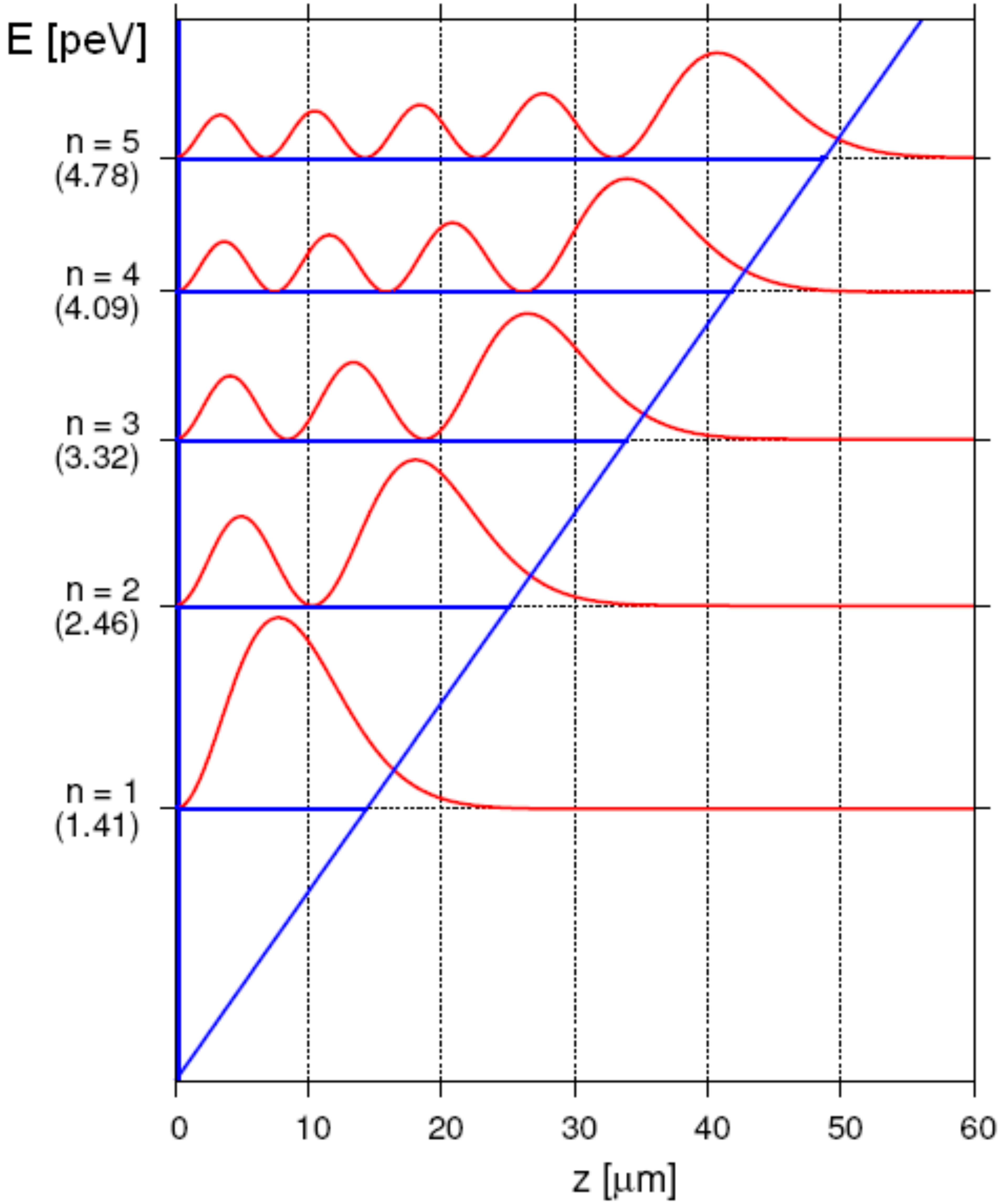
- strength α
- range λ

Until now:

Atomic force microscope:
- Newton r > 10μm

Problem: Casimir effect („falsch“-effect)

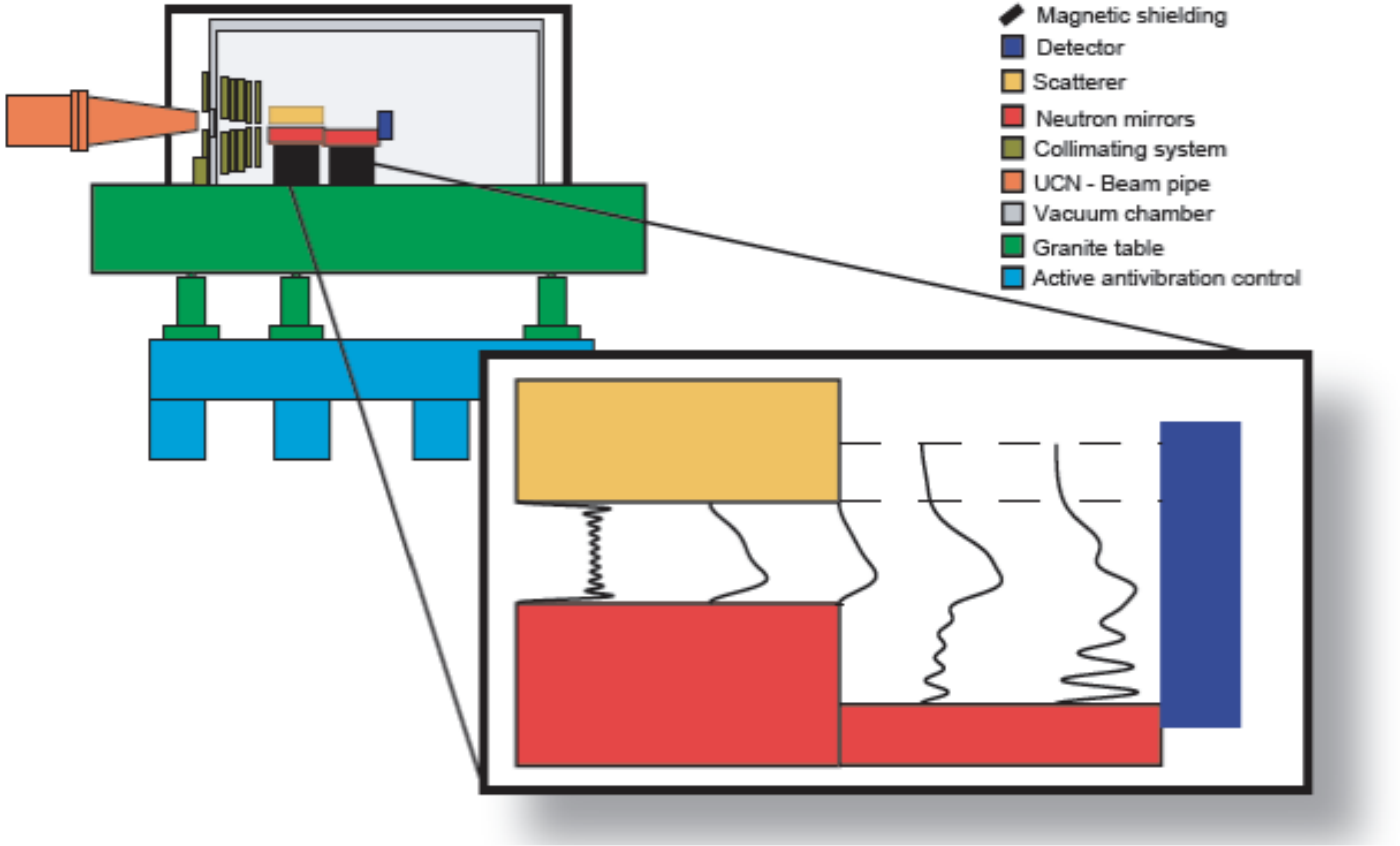
Neutrons:
- limits for Newton: r < 10μm
- range: 1 nm < λ < 100 μm
- strength: $\alpha \sim 10^8$
-



Gravitation: Q-Bounce

Abele et al.: arXiv:1510.03078v1

H. Abele et al.



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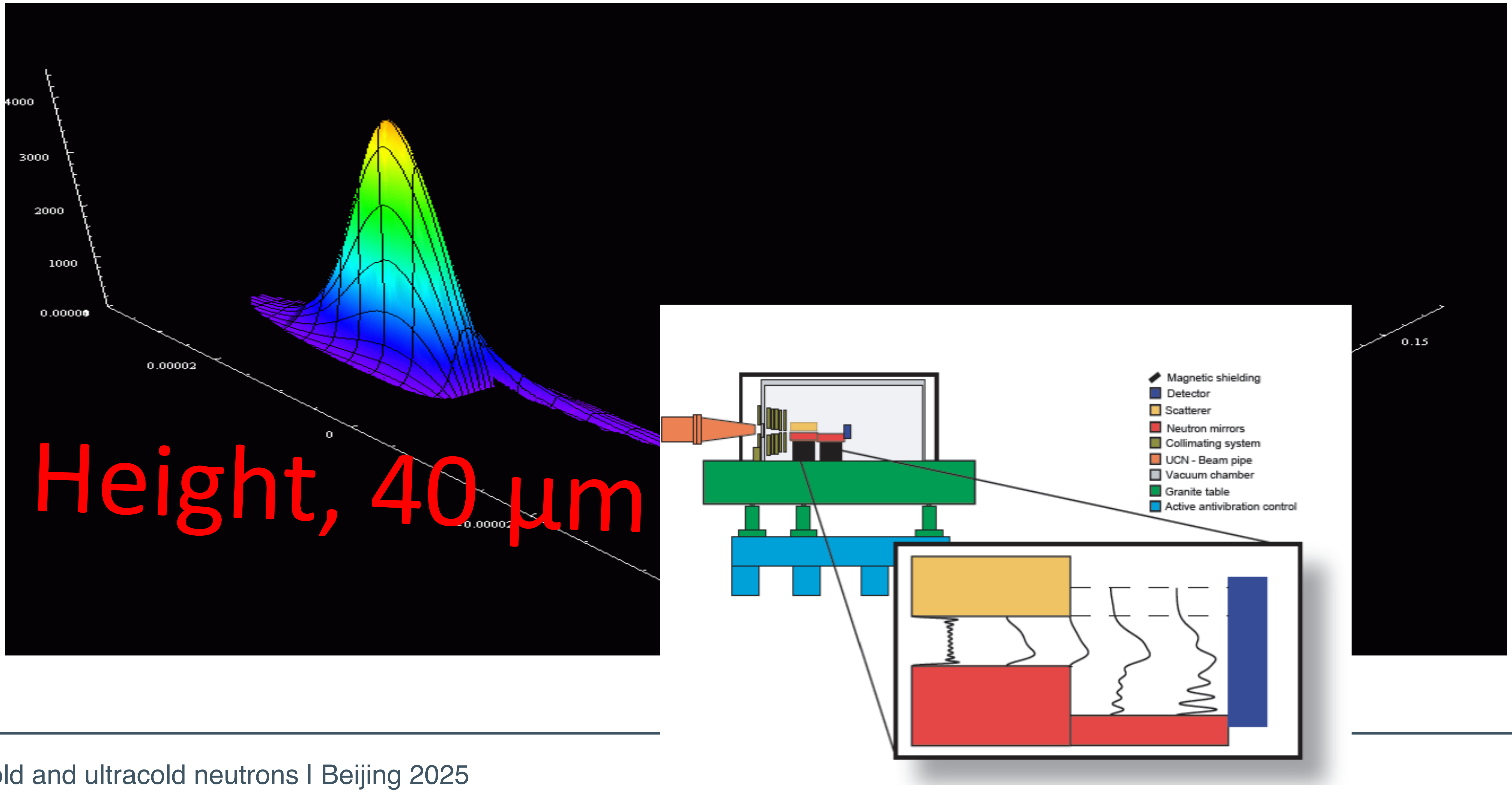

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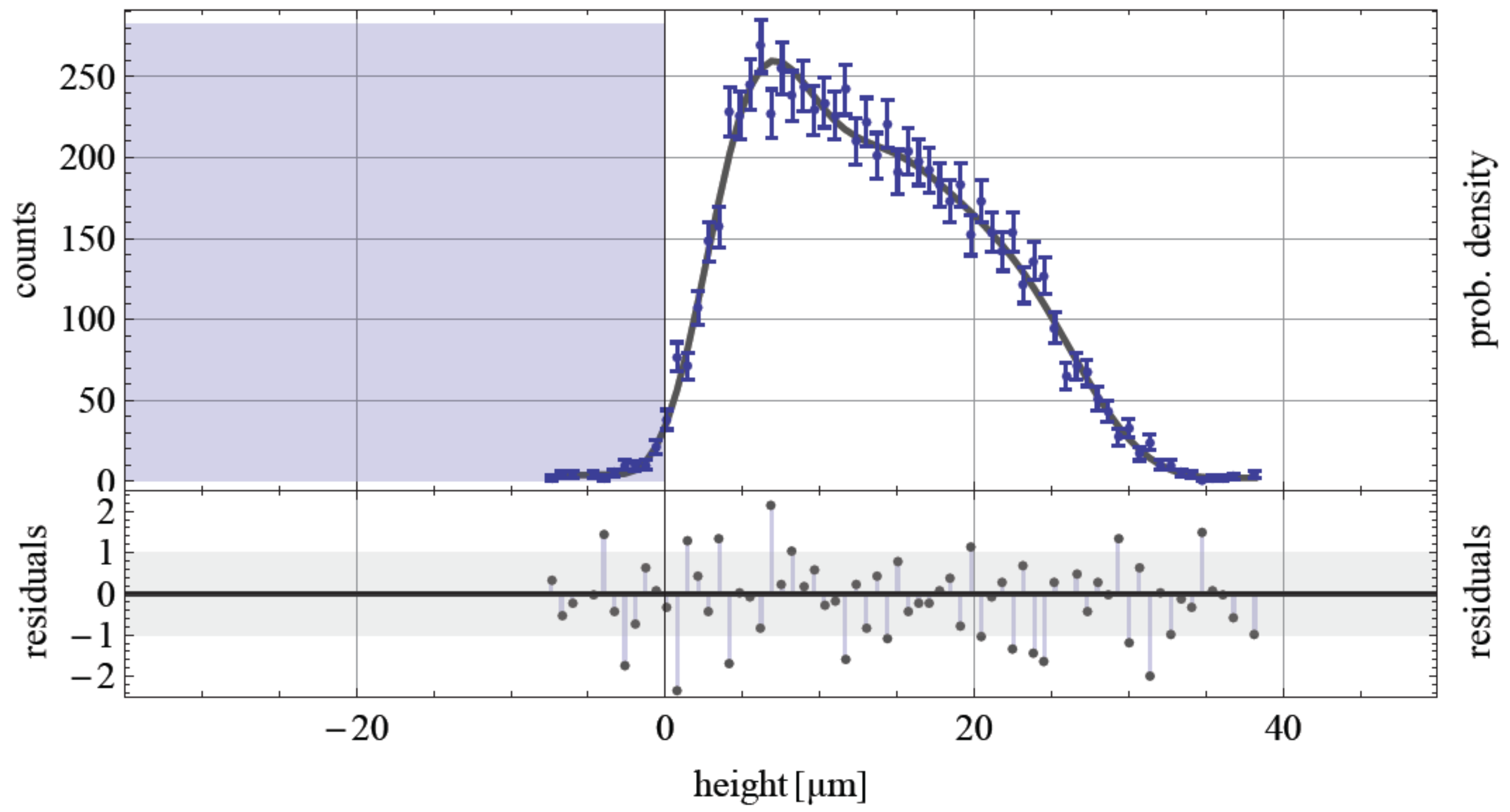

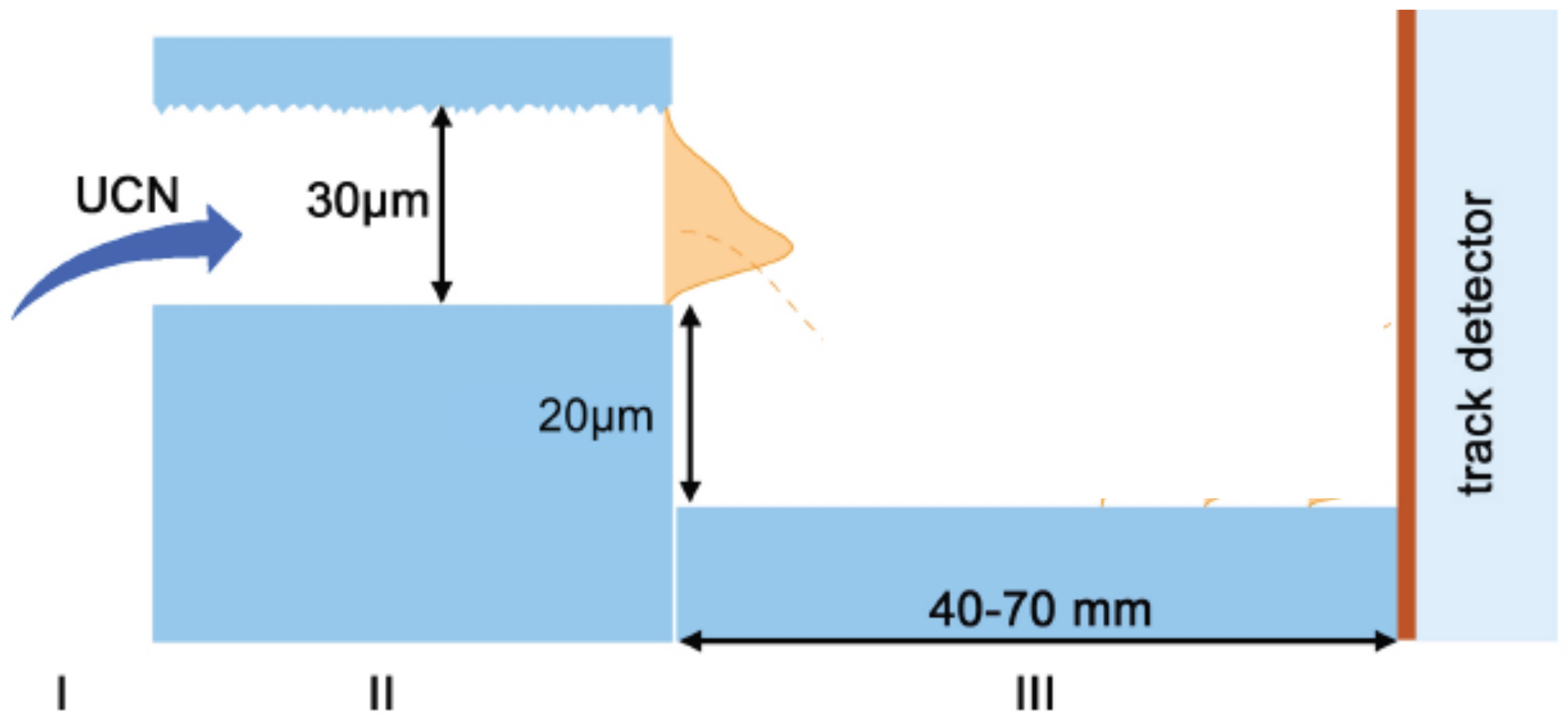

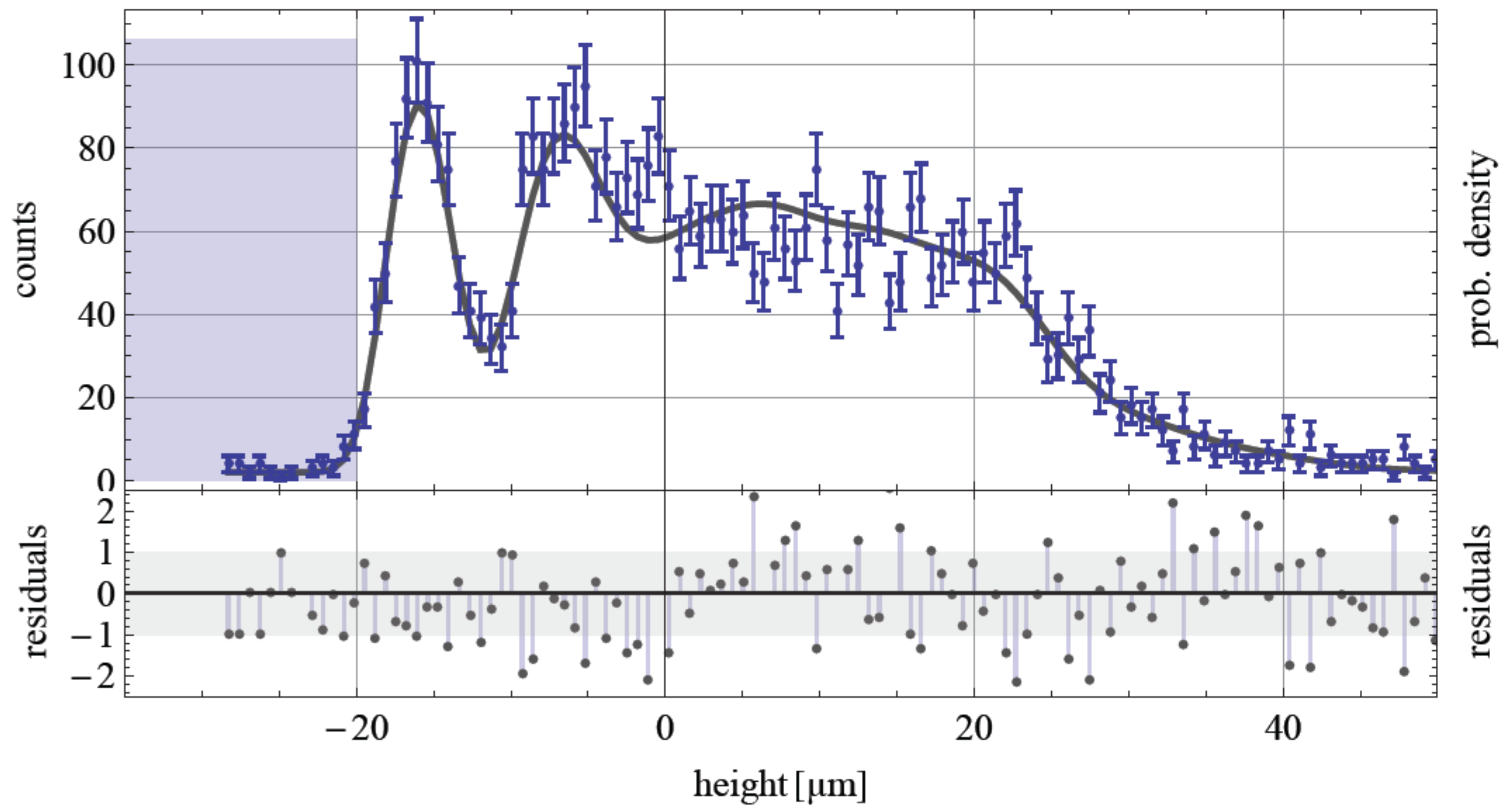

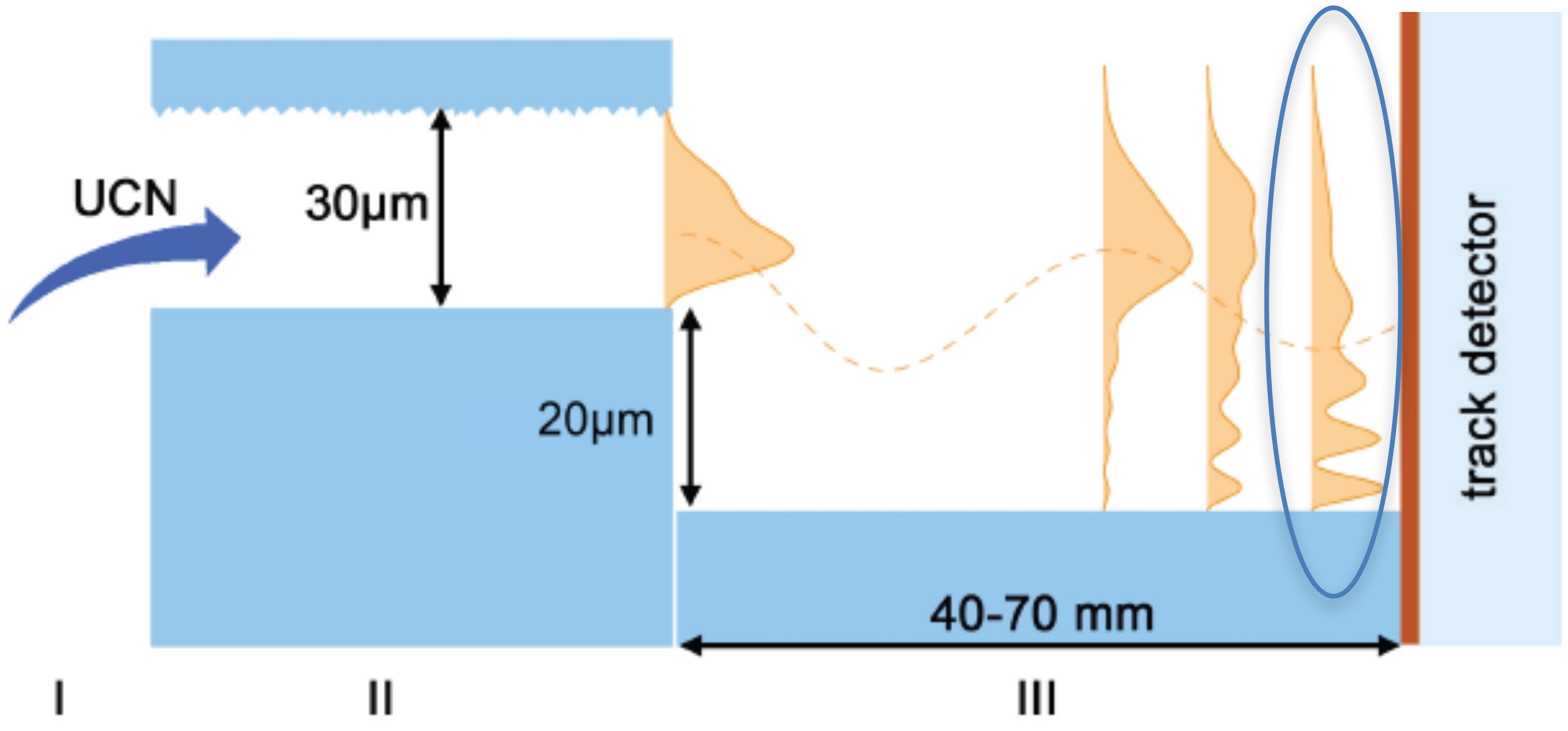

Gravitation: New Generation Measurements (measure time/frequency)

- **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)

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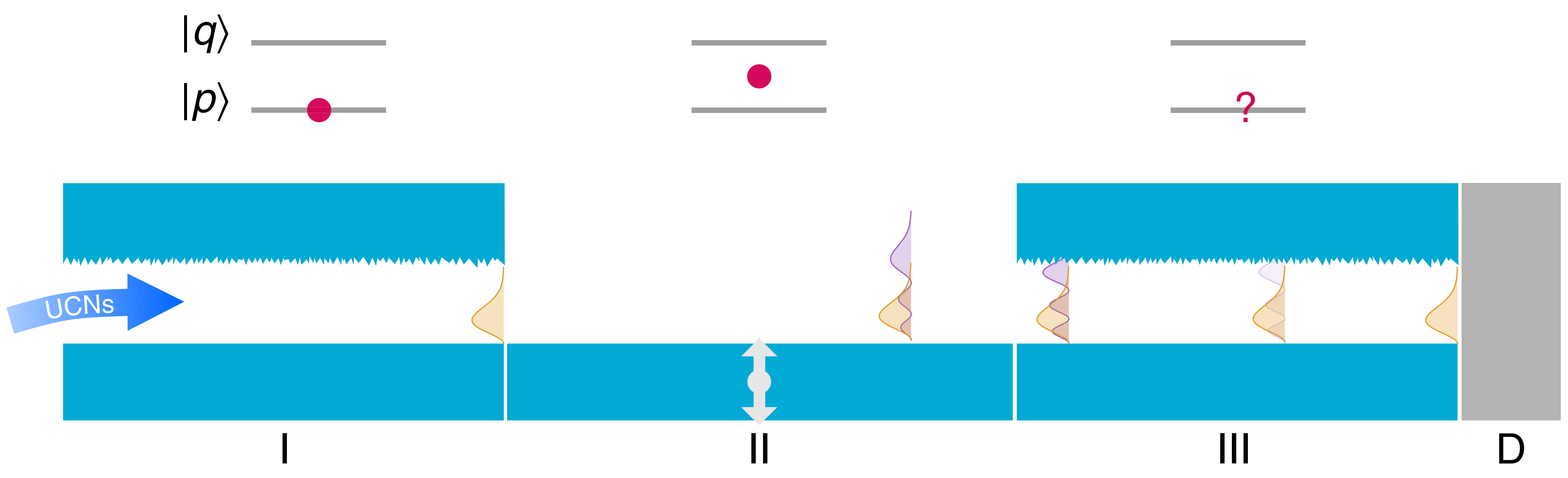

- **Sensitivity**

$$V(z) = \underbrace{m_n g z(t)}_{\text{Gravity}} + \underbrace{V_F \Theta(z - z_m)}_{\text{Fermi-pseudopotential}} + \underbrace{V_{hyp}(z)}_{\text{hypothetical potential}}$$

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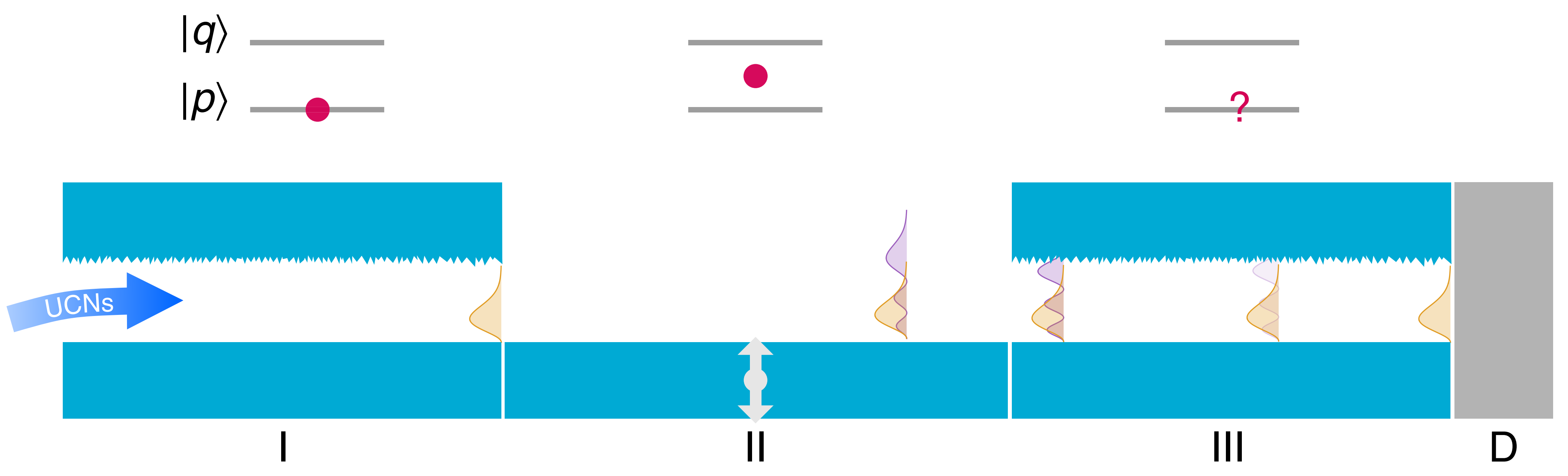
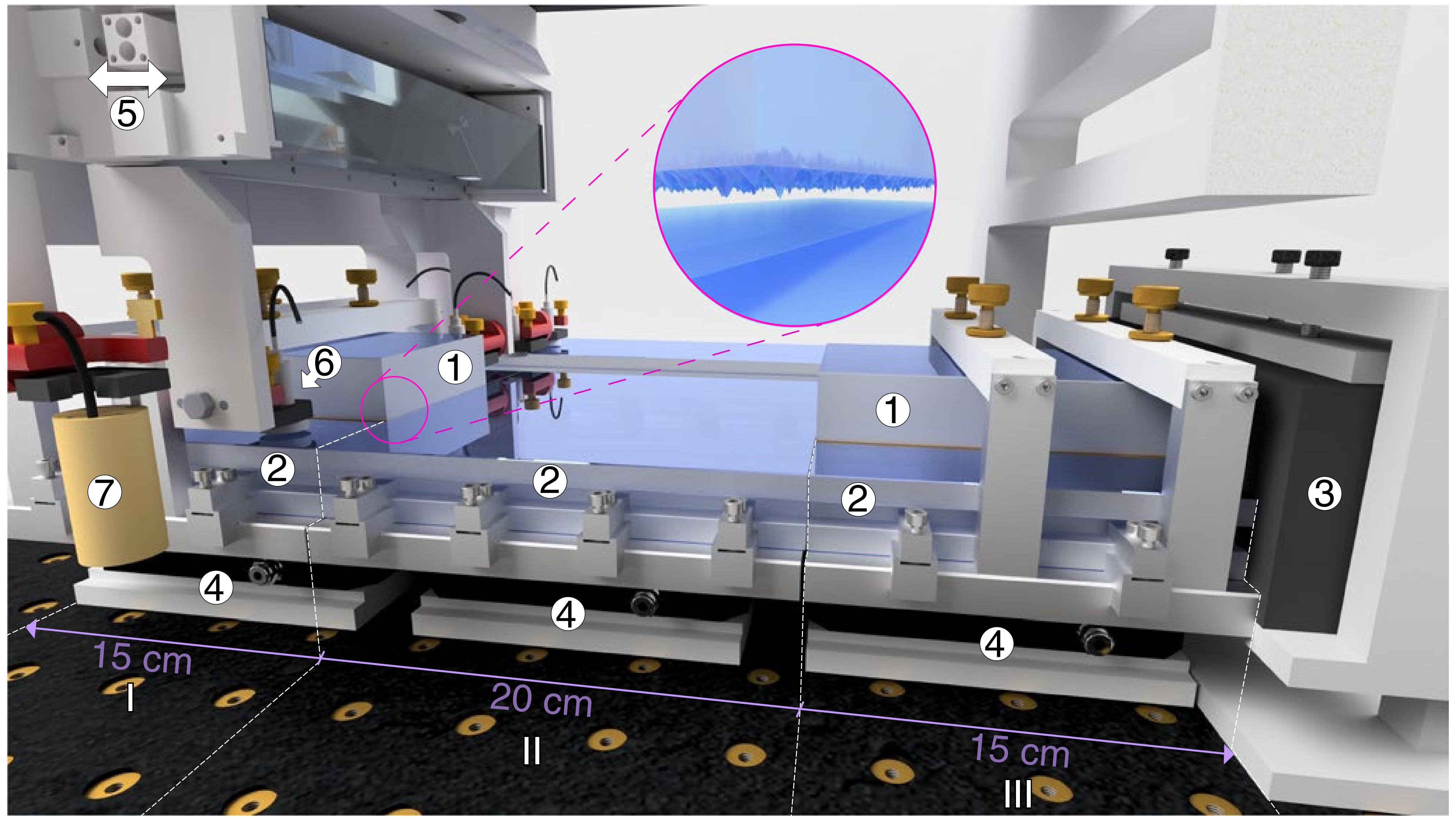
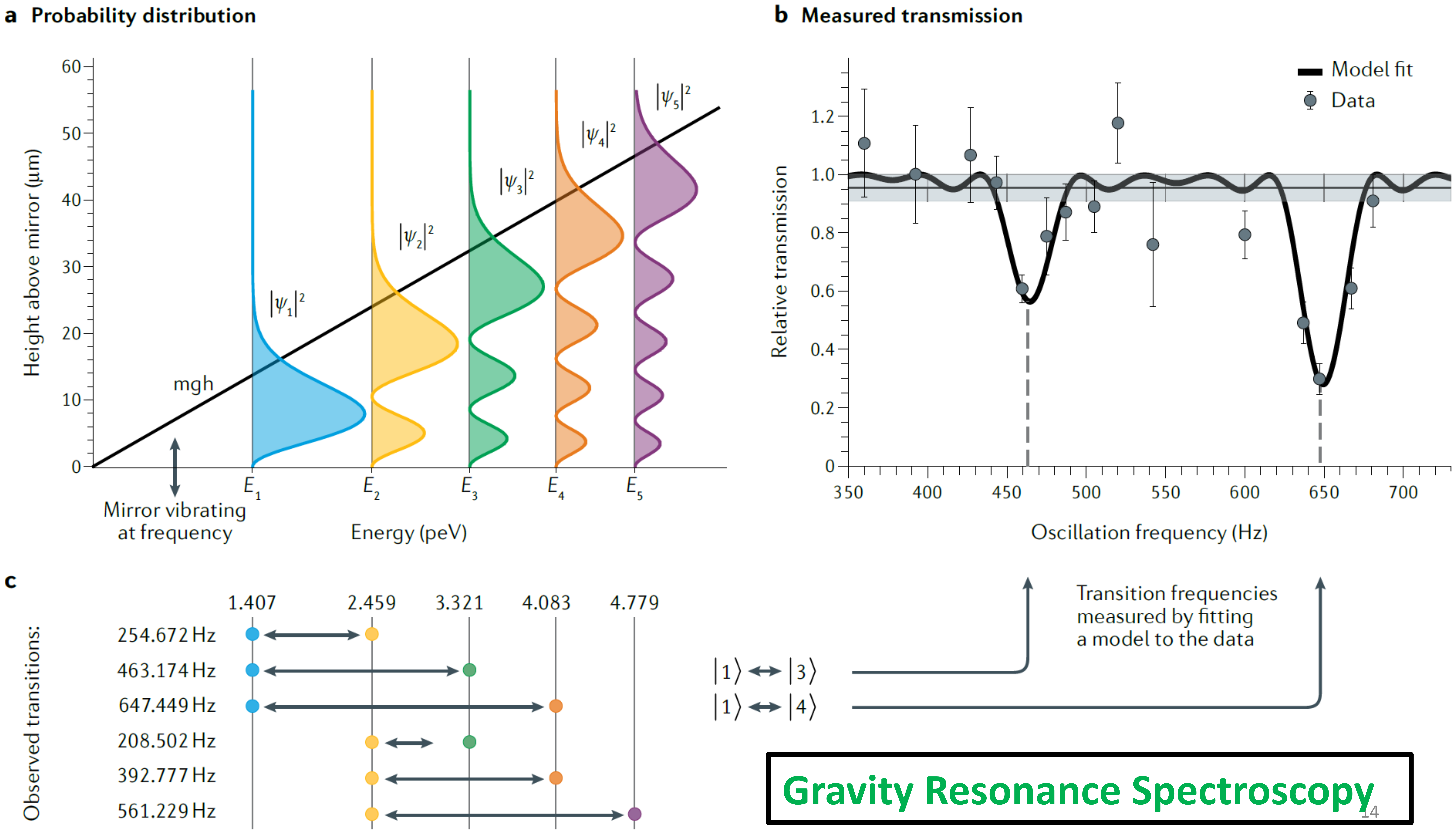
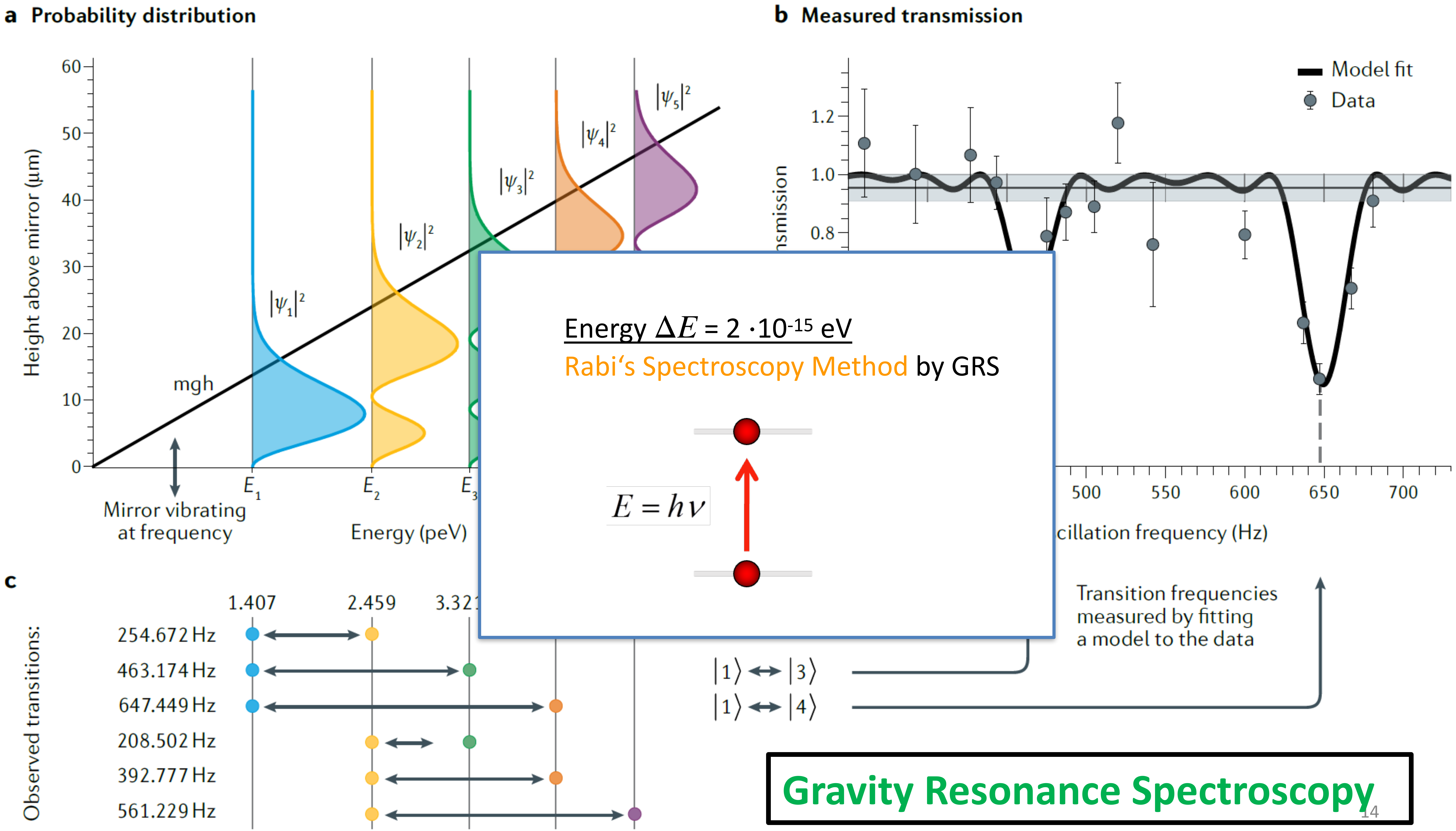






Gravity Resonance Spectroscopy

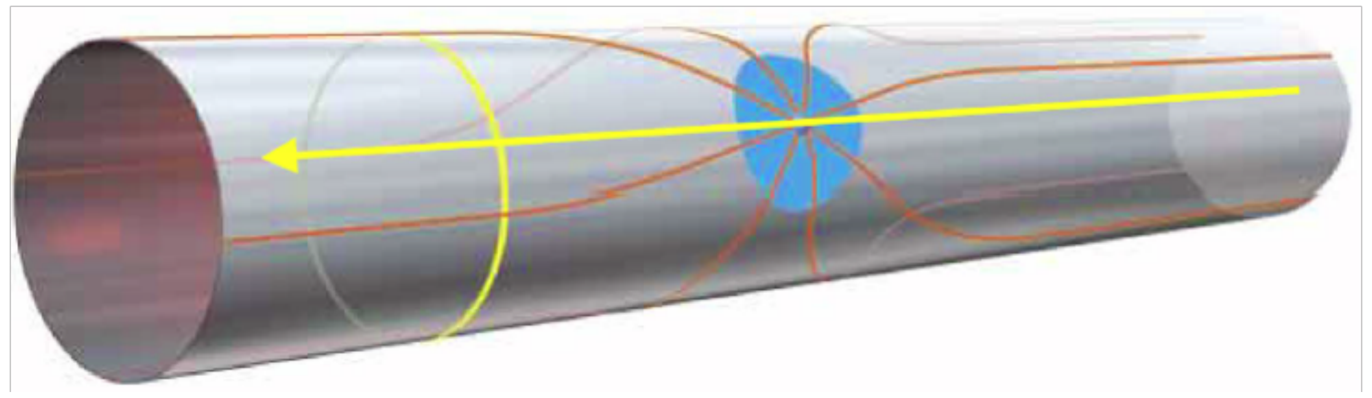


Gravity Resonance Spectroscopy

Models, Sensitivity and distance scales

- Yukawa type force $V(r) = -G\frac{m_i \cdot m_j}{r}(1 - \alpha \cdot e^{-r/\lambda})$

- Extra dimensions:



$$V(r) \propto \frac{1}{r^{1+n}}$$

- Symmetrons dark energy with new scalar field

$$V(z) = mgz + \frac{mc^2}{2M^2}\varphi^2(z)$$

……

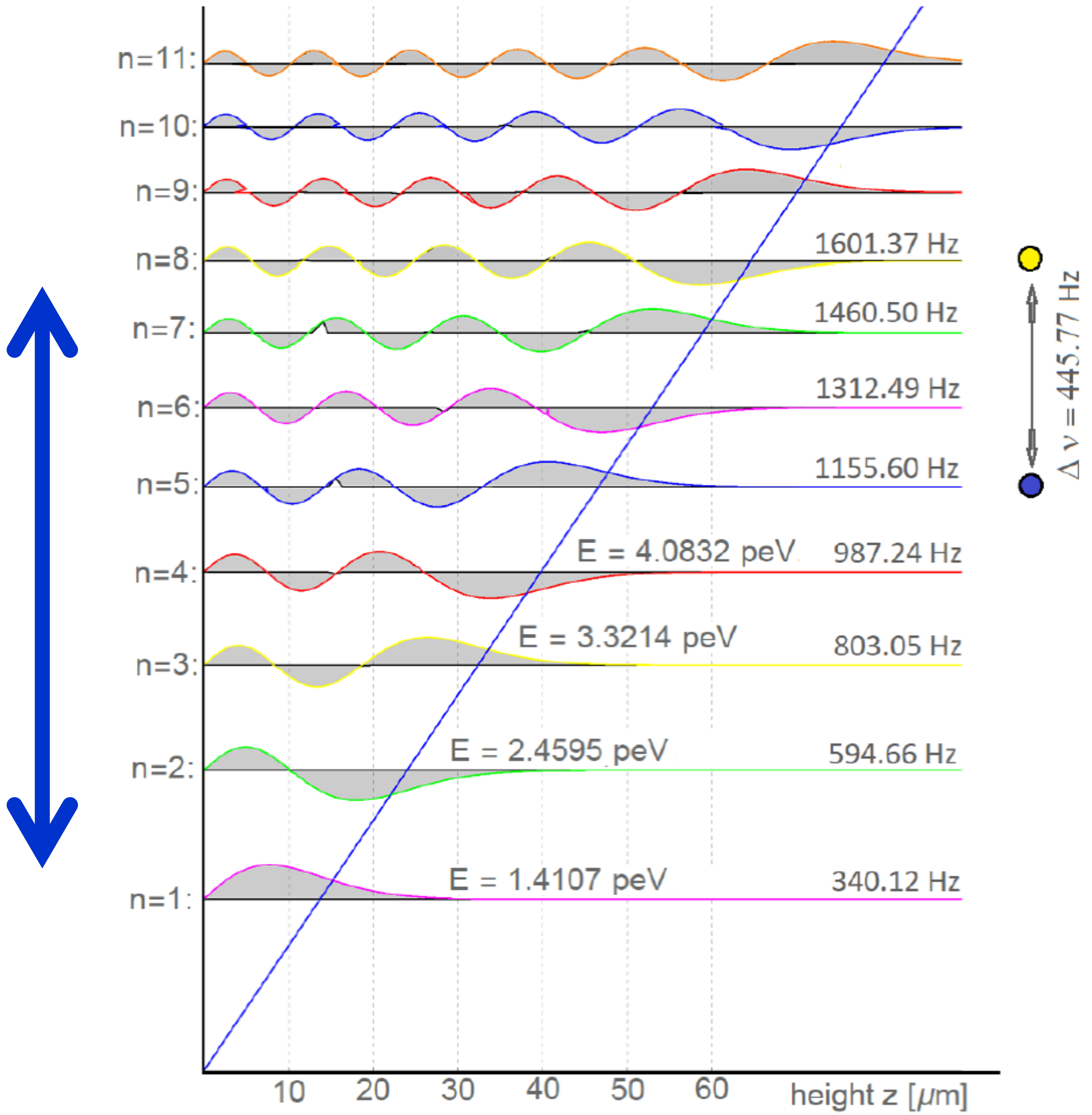
Which distance scale ?

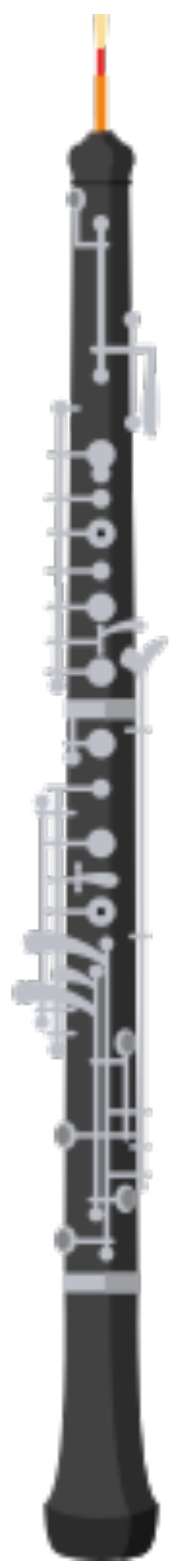
dark matter density: $\rho_d \approx 3.8$ keV/cm^3 corresponds to a distance scale $\lambda_d \approx \sqrt[4]{\hbar c/\rho_d} \approx 85\ \mu m$

Experiment Sensitivity

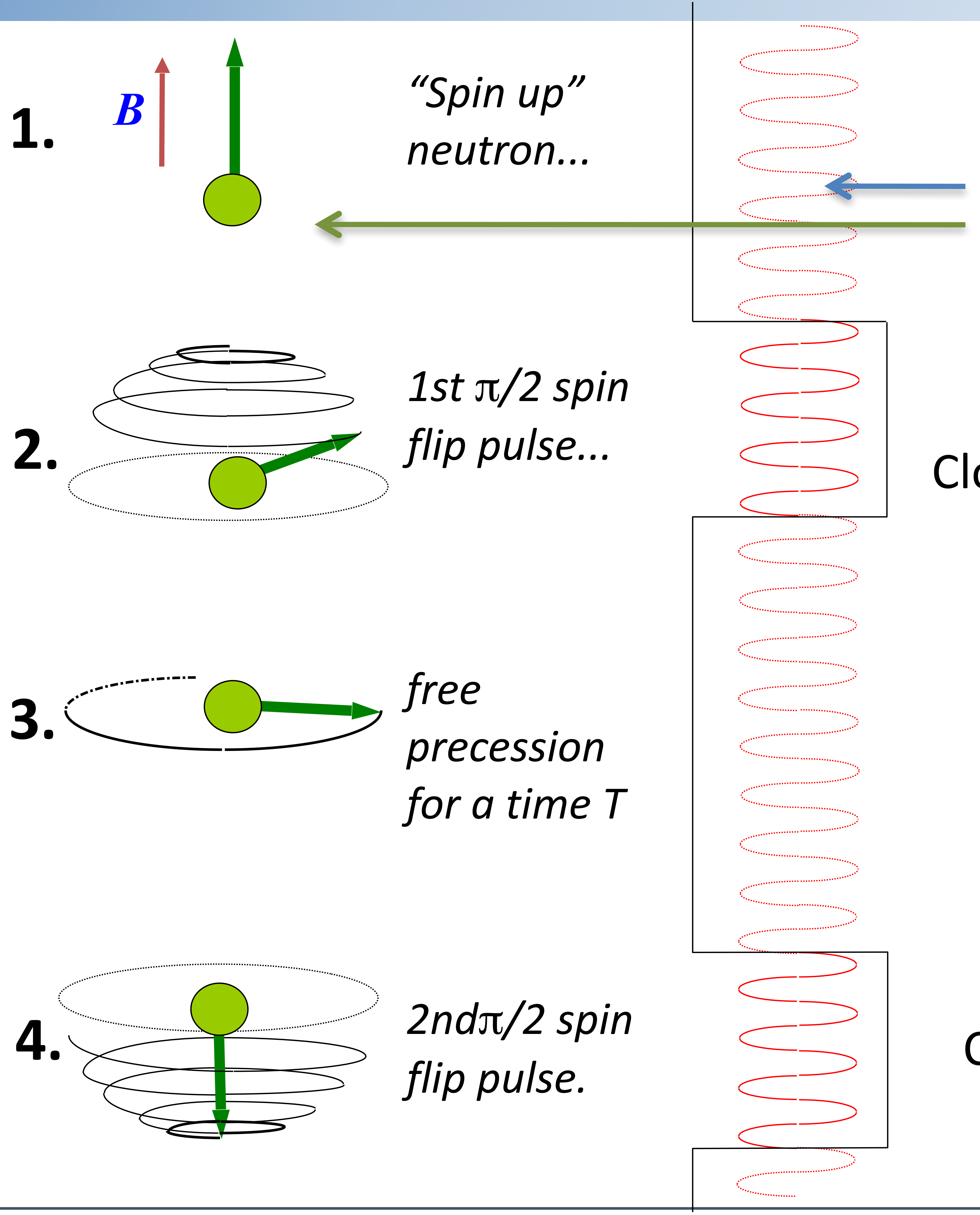
- Limits for Newtons law: about 1μm
- Sensitivity for Yukawa contribution:
  - Strength $\alpha \sim 10^8$
  - Range $\lambda \sim 20\mu$m

Using observed transitions





Precision Energy Measurements – Ramsey method



clock comparison:

external oscillator

neutron

Clock adjustment

Clock comparison

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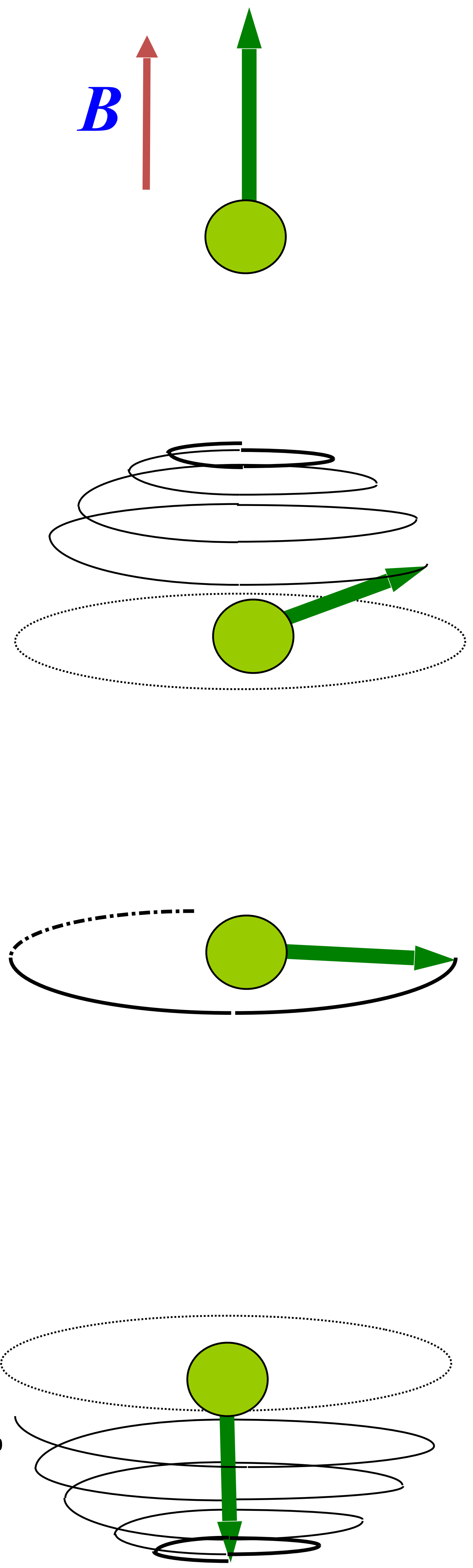
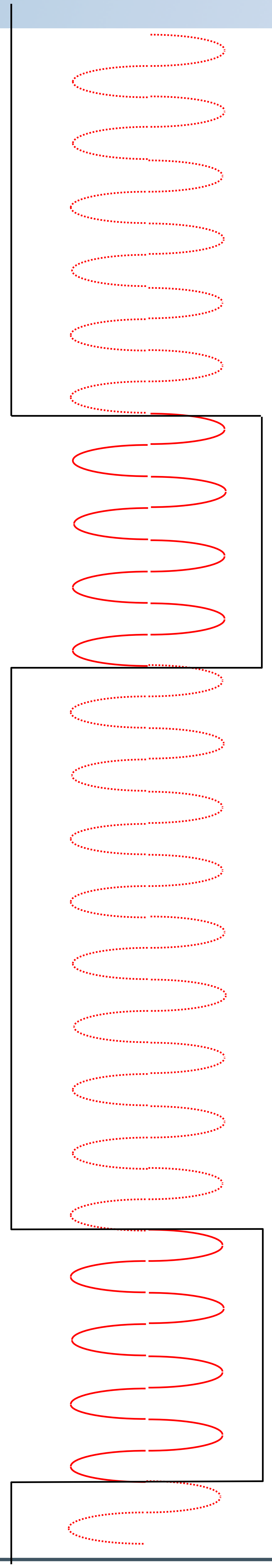
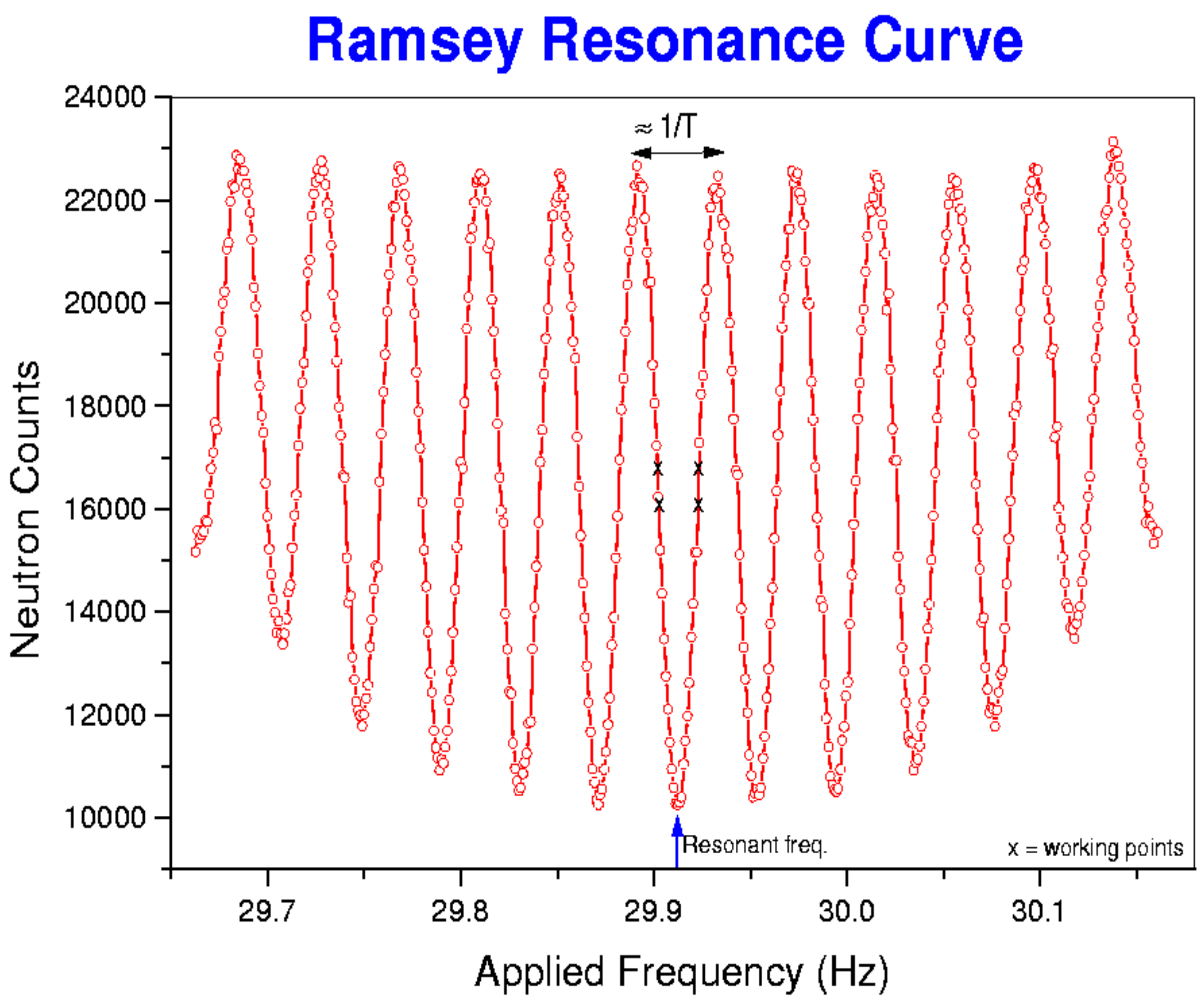


1. *"Spin up" neutron...*
2. *1st π/2 spin flip pulse...*
3. *free precession for a time T*
4. *2ndπ/2 spin flip pulse.*





$$P(T,\Delta) = \cos^2\left(\frac{\Delta T}{2}\right) = \cos^2\left(\frac{\Delta L}{2v}\right).$$

detuning Δ

velocity v

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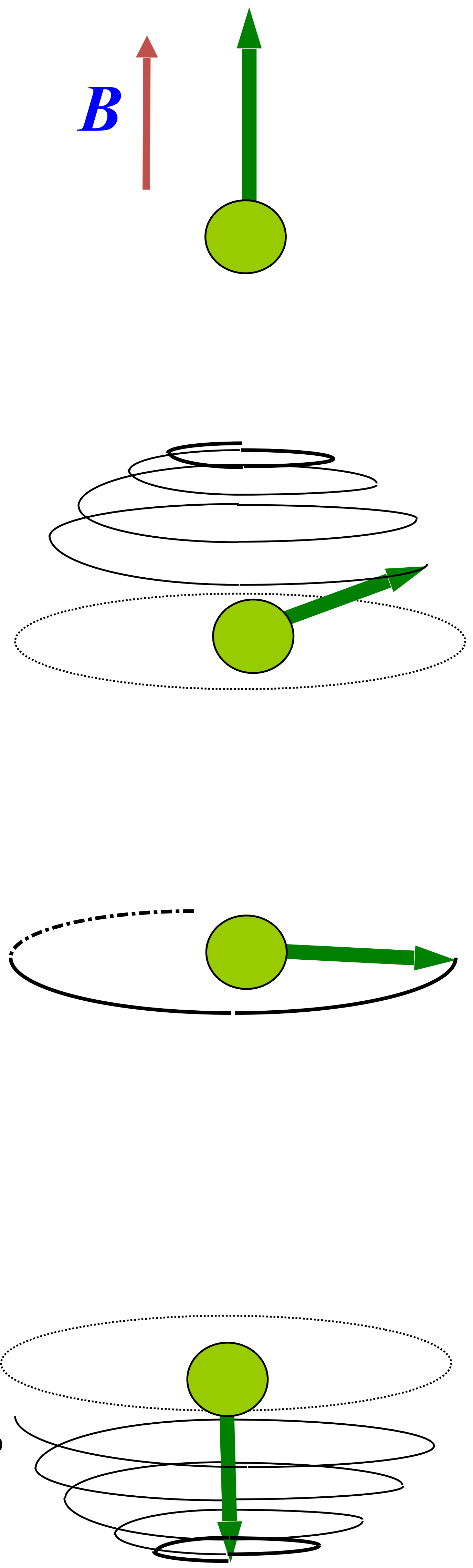

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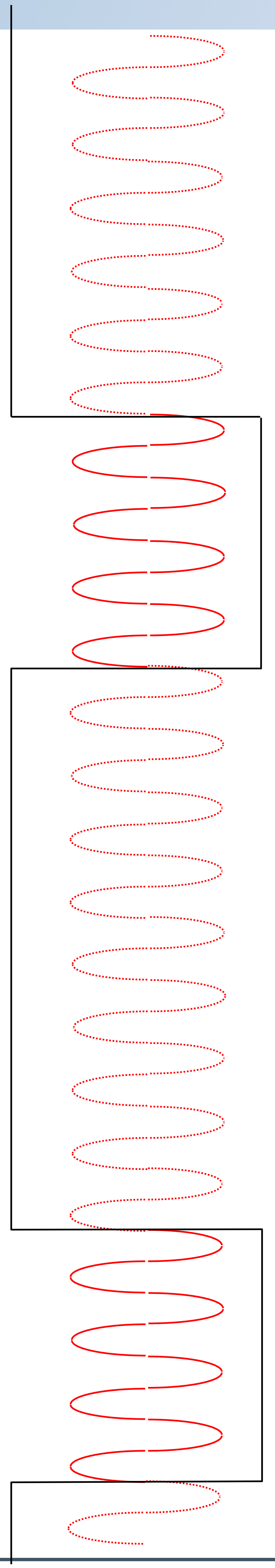


exploit $\Delta E \cdot \Delta t \leq \hbar$

make $\Delta t = T$ large (observation time)

Ramsey Separated Oscillatory field method - qBounce Expt

prepare ground state

induce $\pi/2$ flip (energy transfer)

create coherent superposition of two states

free propagation

wave functions propagate in time adjust

to the gravity potential

possible phase shift between states develops

induce $\pi/2$ flip (energy transfer)

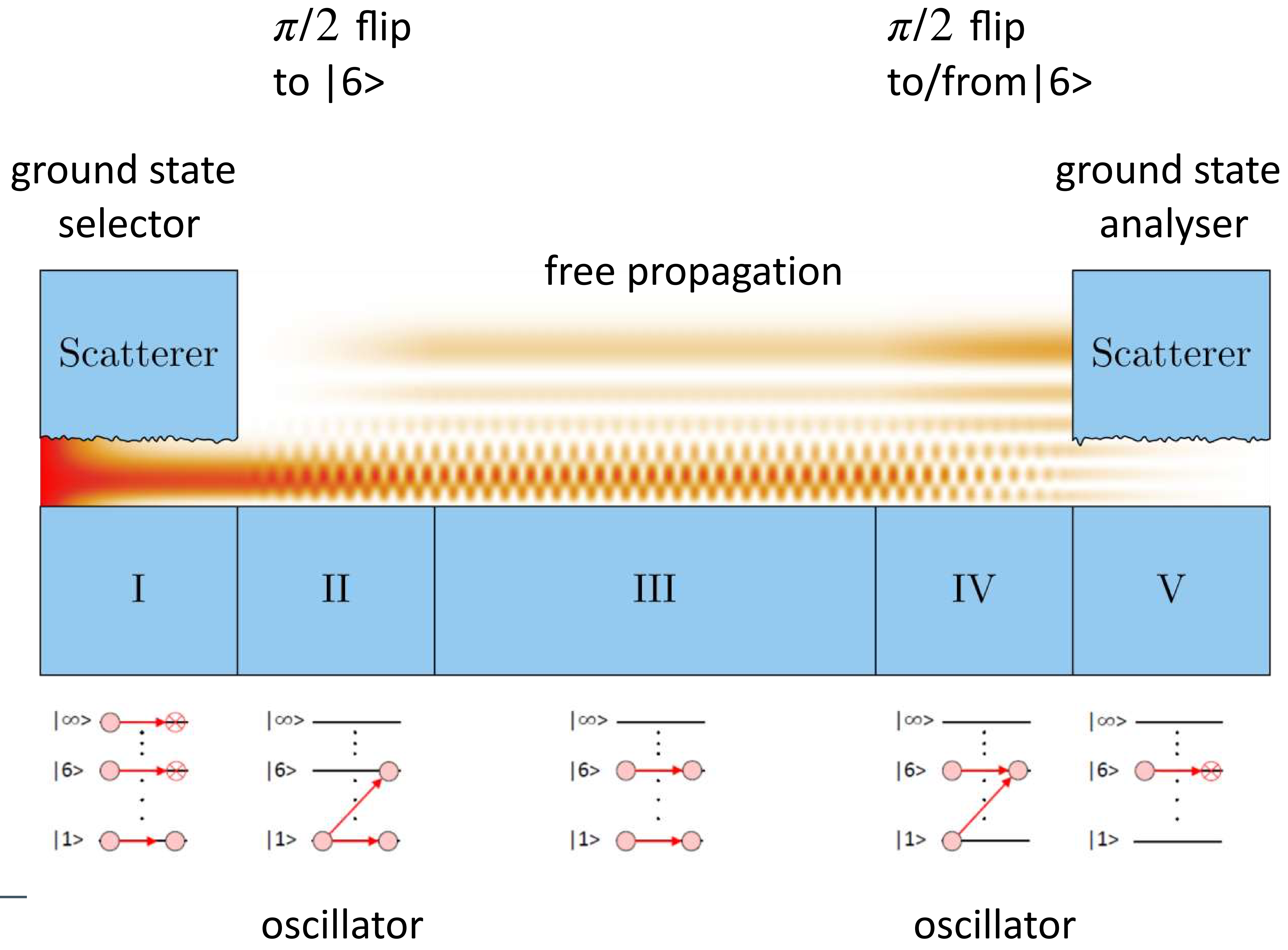
test resulting superposition

2 modes:

flip $+\pi/2$ (remove ground state)

flip $-\pi/2$ (repopulate ground state)

analyse intensity of ground state



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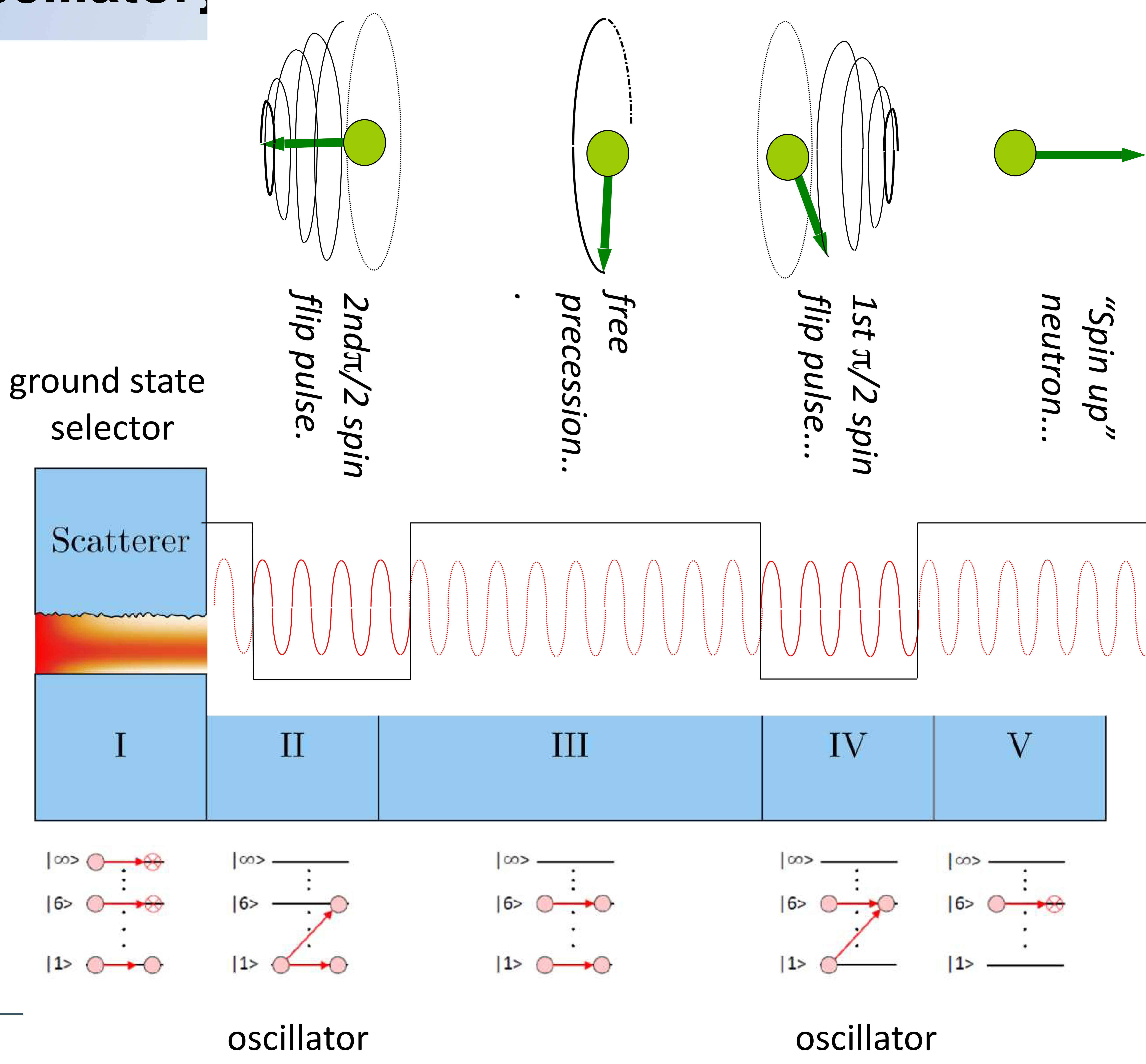
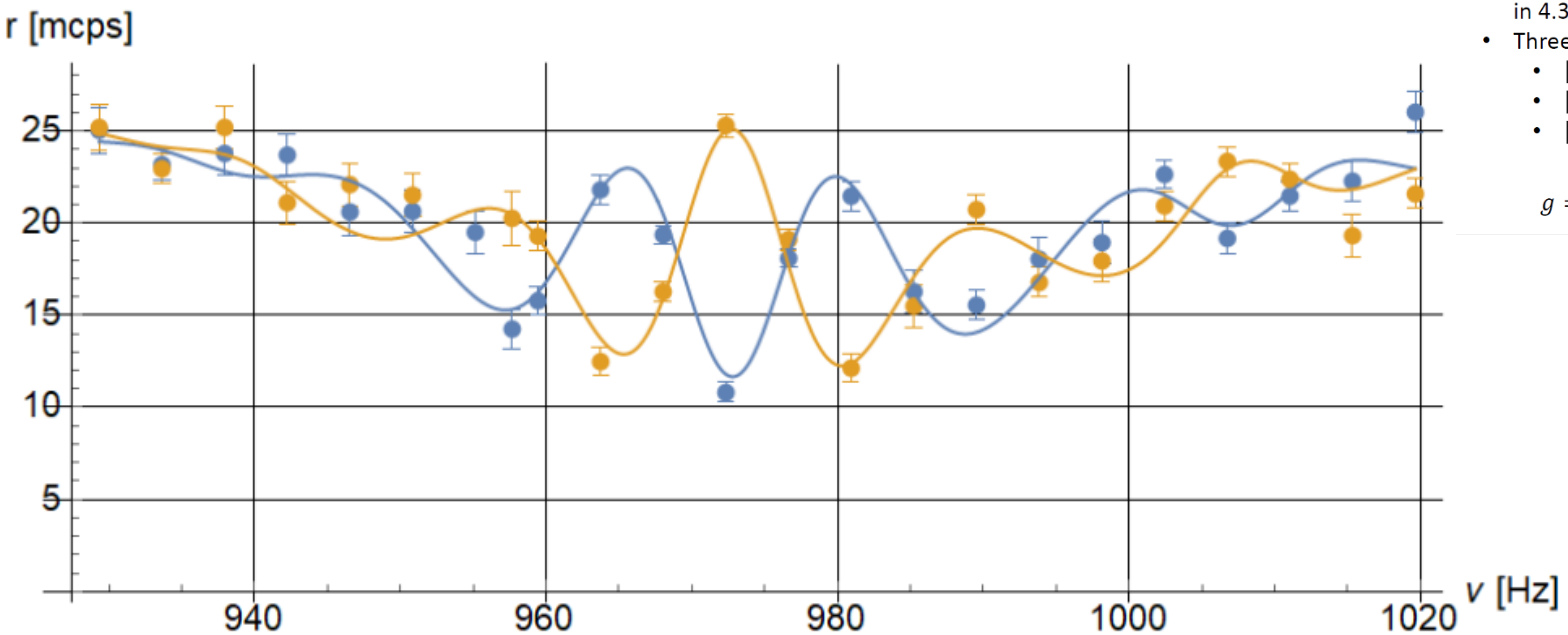
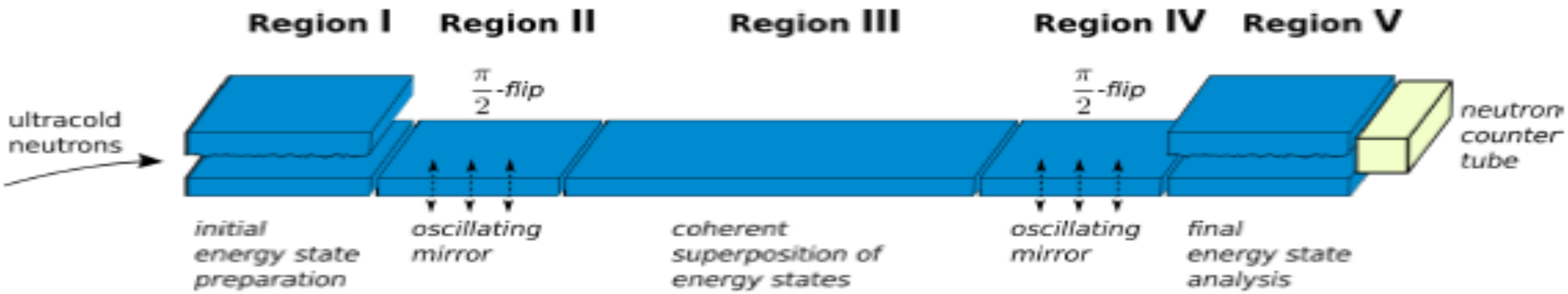


Ramsey Spectroscopy, qBOUNCE EXPERIMENT



- Frequency sweep 930-1020 Hz in 4.3 Hz steps
- Three transitions
  - $|3\rangle \rightarrow |9\rangle$
  - $|1\rangle \rightarrow |6\rangle$
  - $|2\rangle \rightarrow |8\rangle$

$$g = 9.814 \pm 0.001 \; [m/s^2]$$



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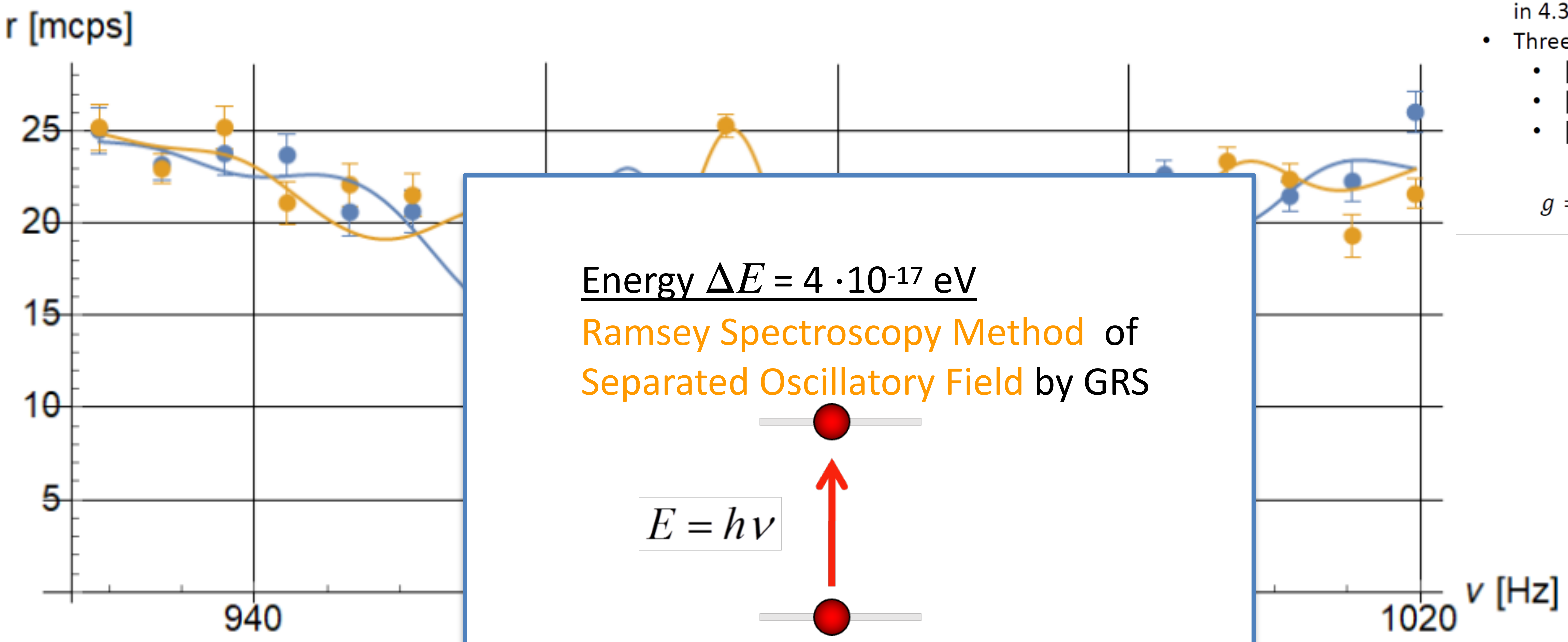
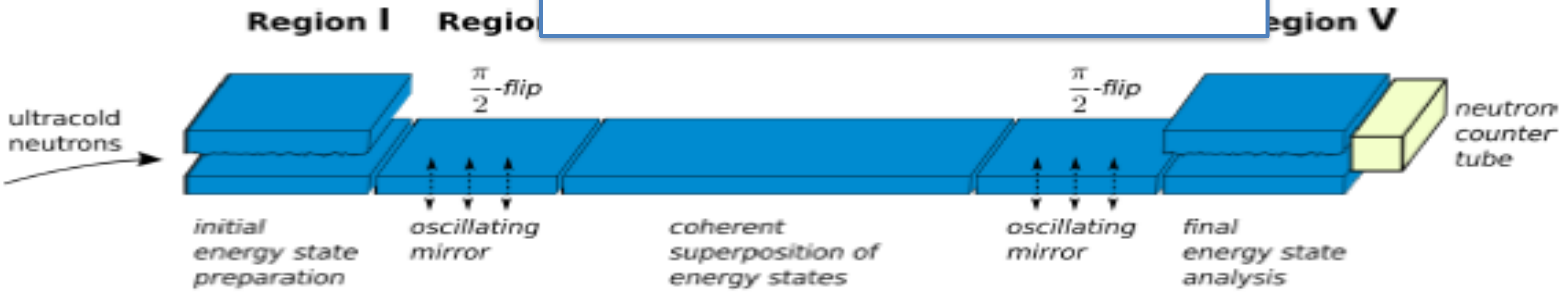


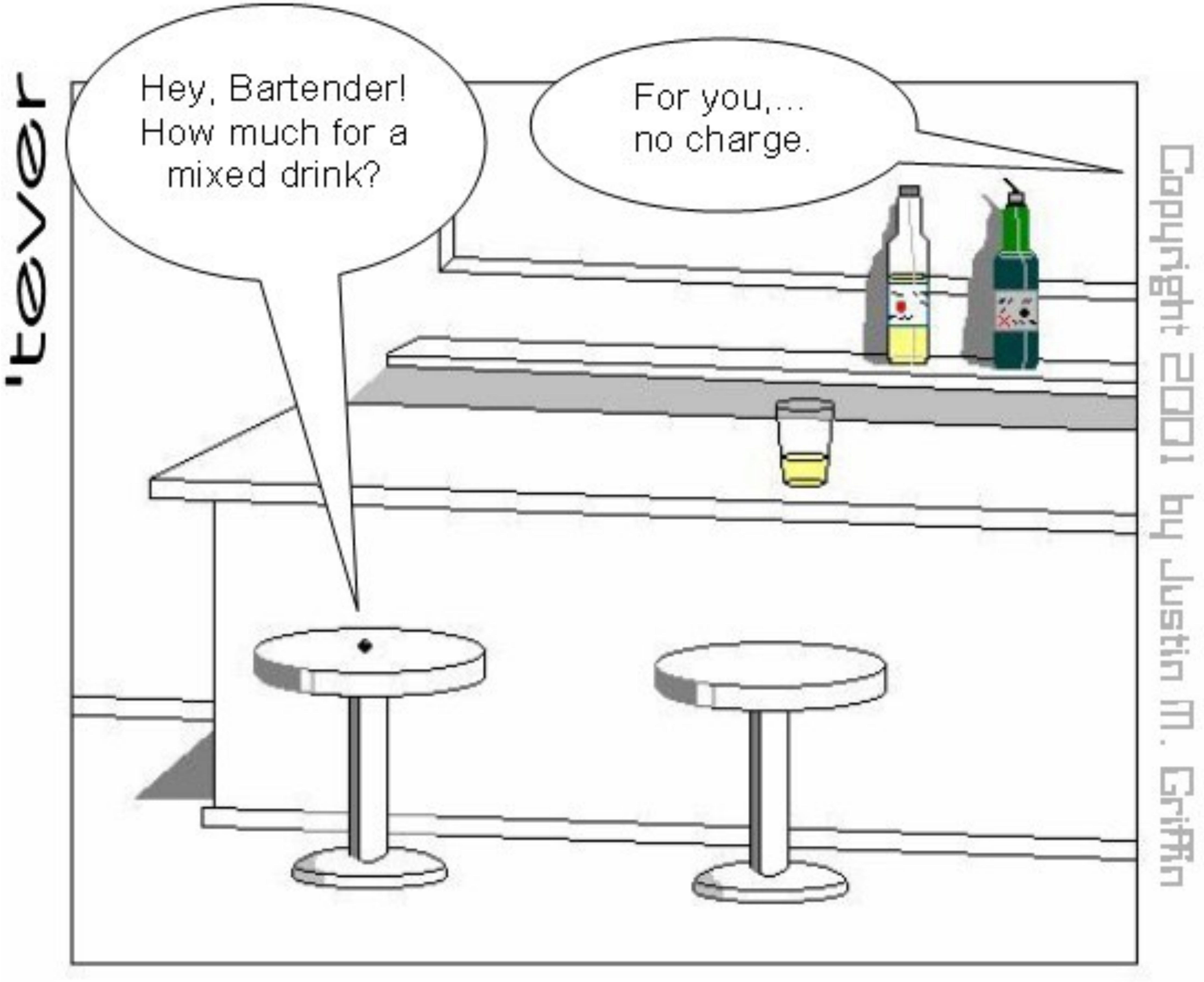
Energy ΔE = 4 ·10^{-17} eV

Ramsey Spectroscopy Method of Separated Oscillatory Field by GRS

$$E = h\nu$$



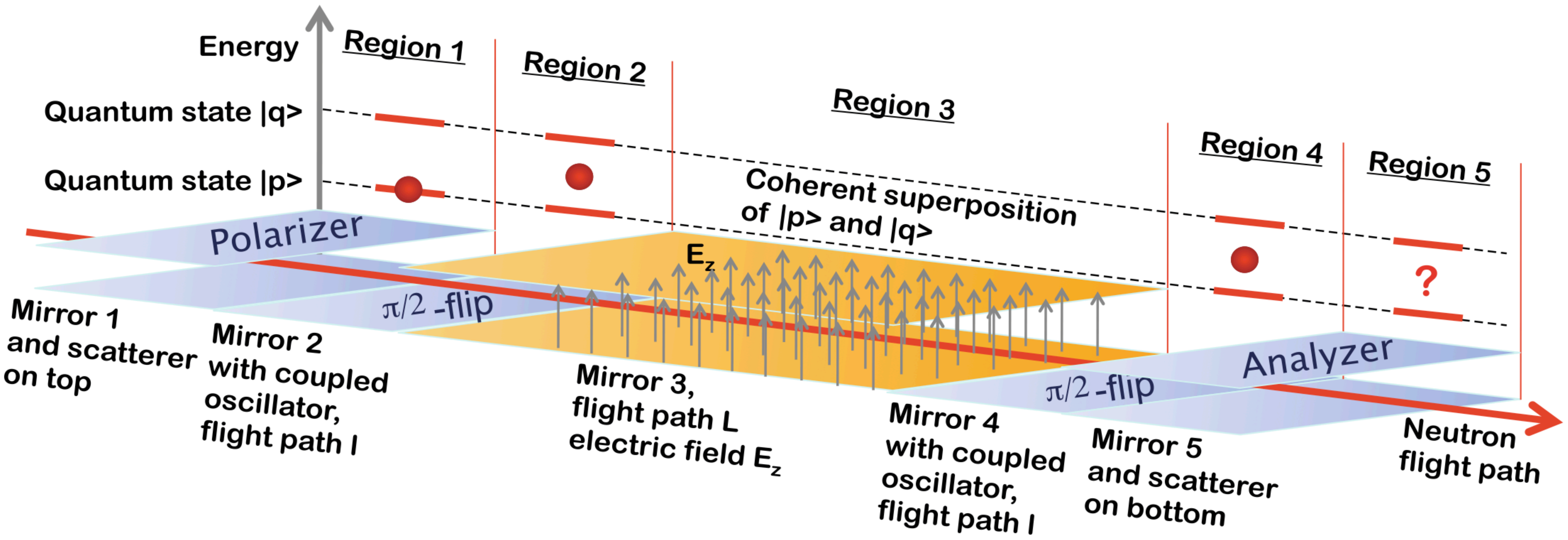
Gravitational Spectroscopy: Measure the Neutron’s Electric Charge



A neutron walks into a bar...

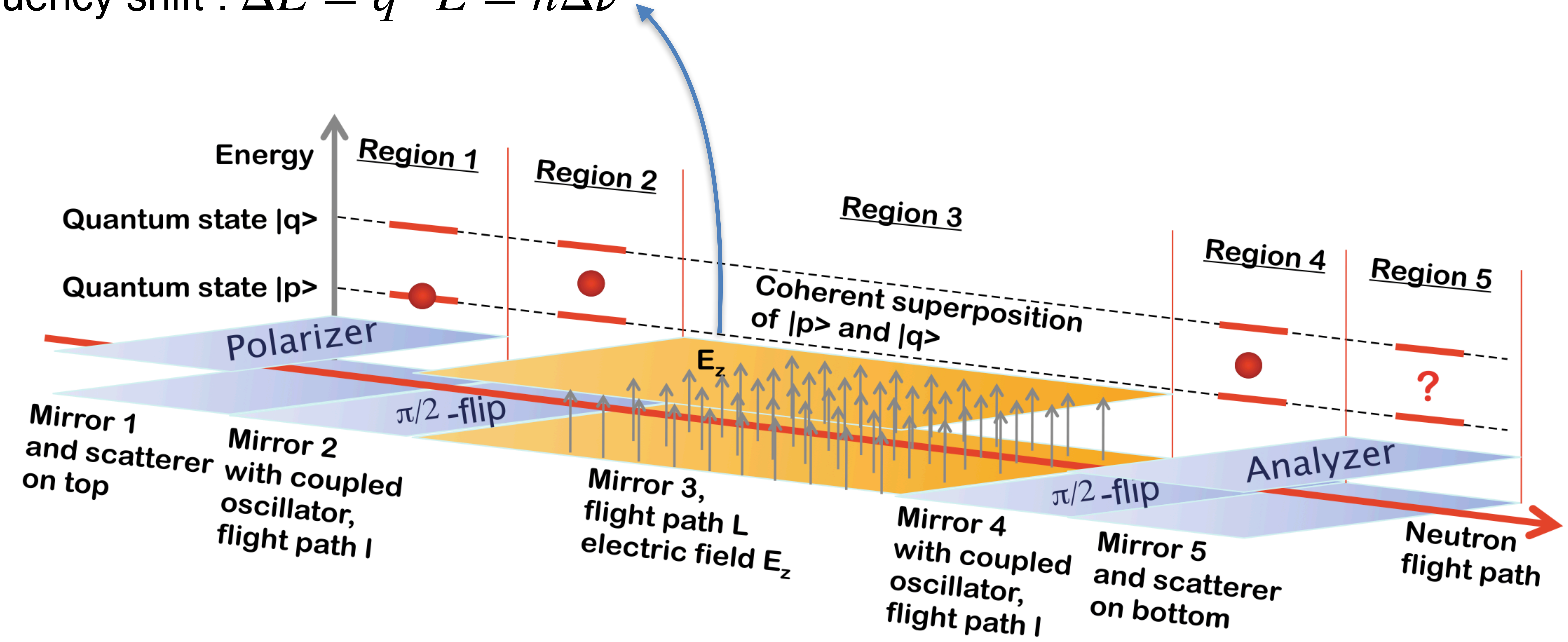
Use Ramseys method

- Sensitivity
  - Superimpose an electric potential on the gravitational potential



Use Ramseys method

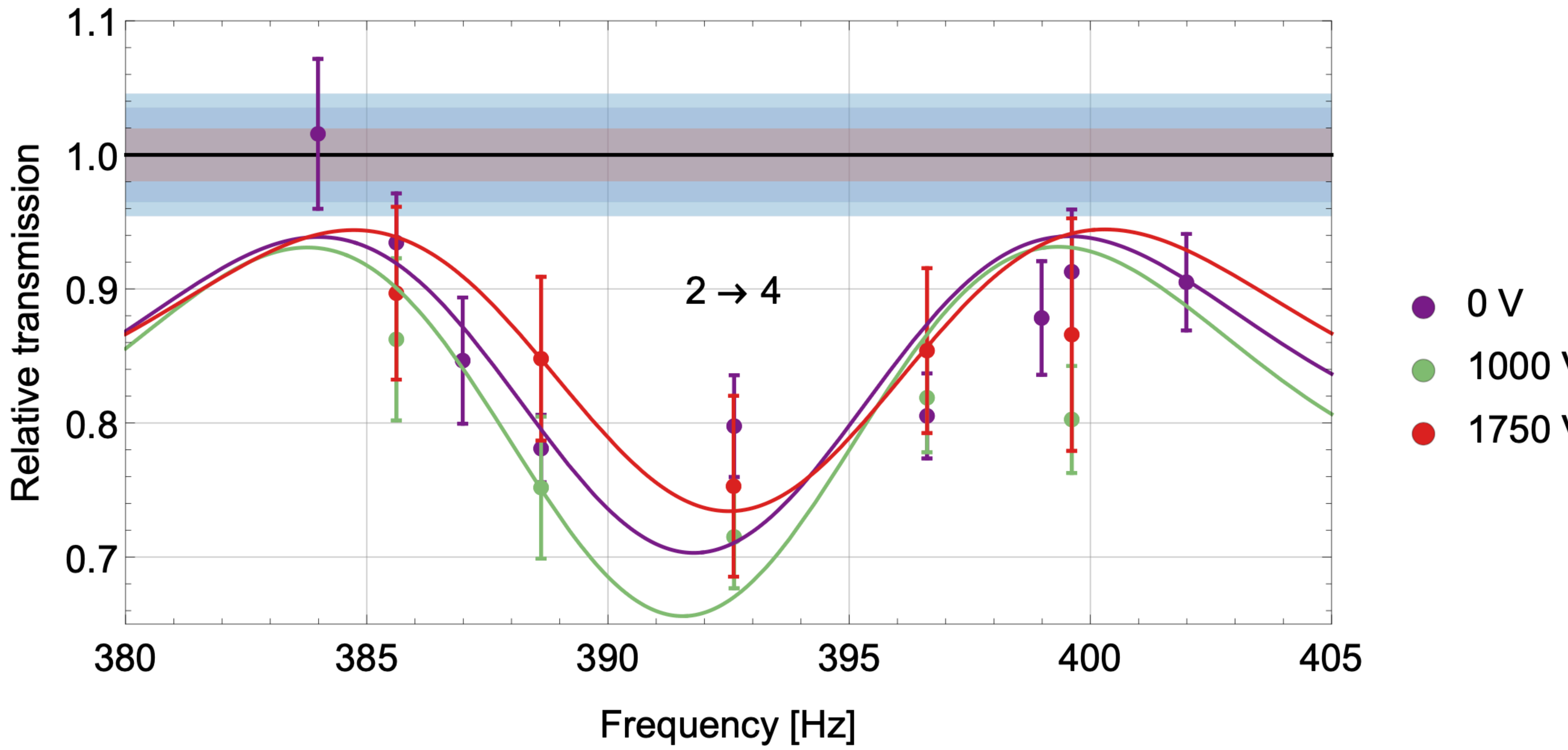
- Sensitivity
  - Superimpose an electric potential on the gravitational potential
  - Search for frequency shift : $\Delta E = q \cdot E = h\Delta\nu$



Use Ramseys method

H. Abele et al. 2023

- Sensitivity
  - Superimpose an electric potential on the gravitational potential
  - Search for frequency shift : $\Delta E = q \cdot E = h\Delta\nu$
    - prototype measurement: $q_n < 10^{-17} \cdot e$



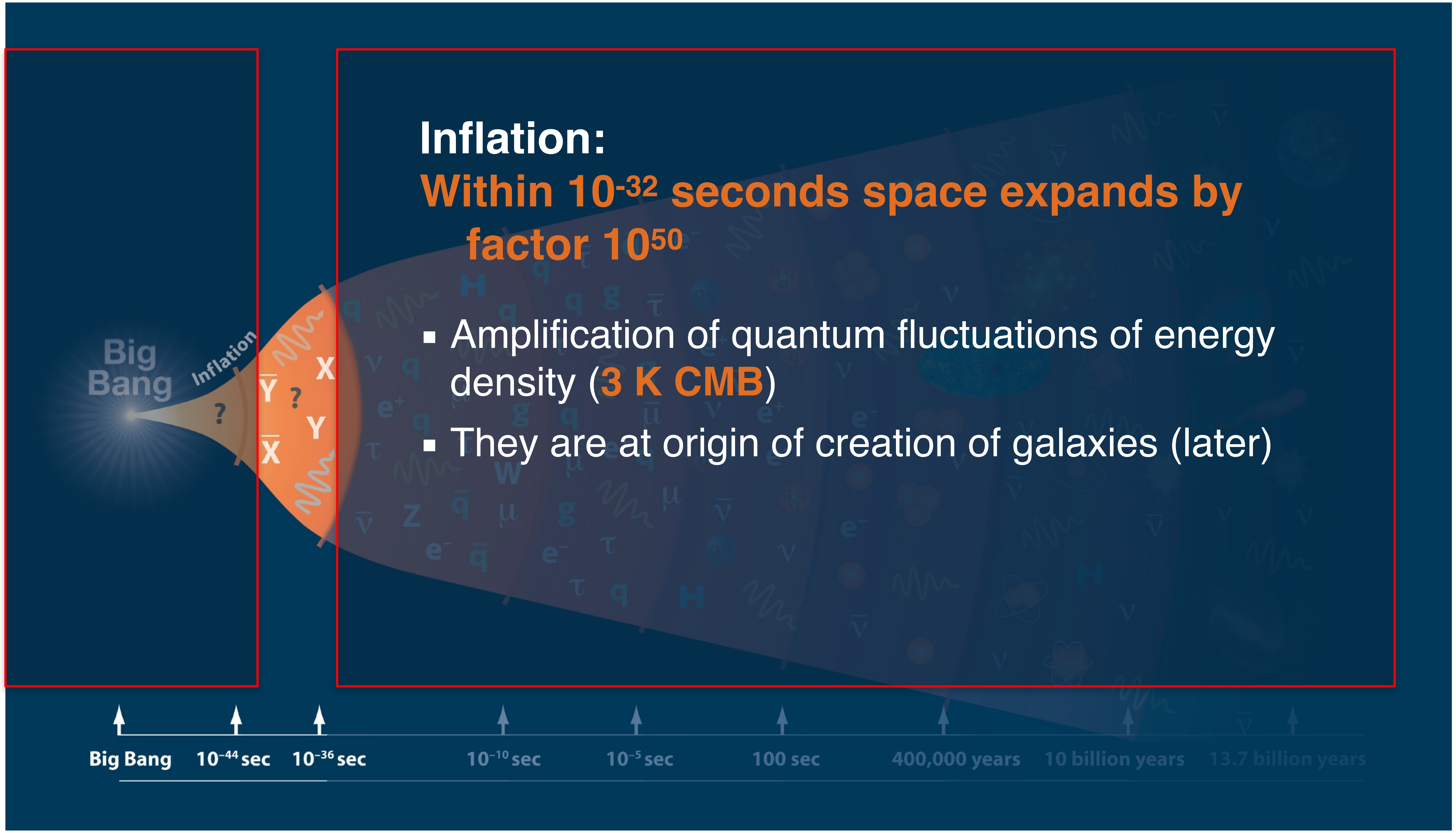
    - future: $q_n < 10^{-21} \cdot e$ (best present limit)

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

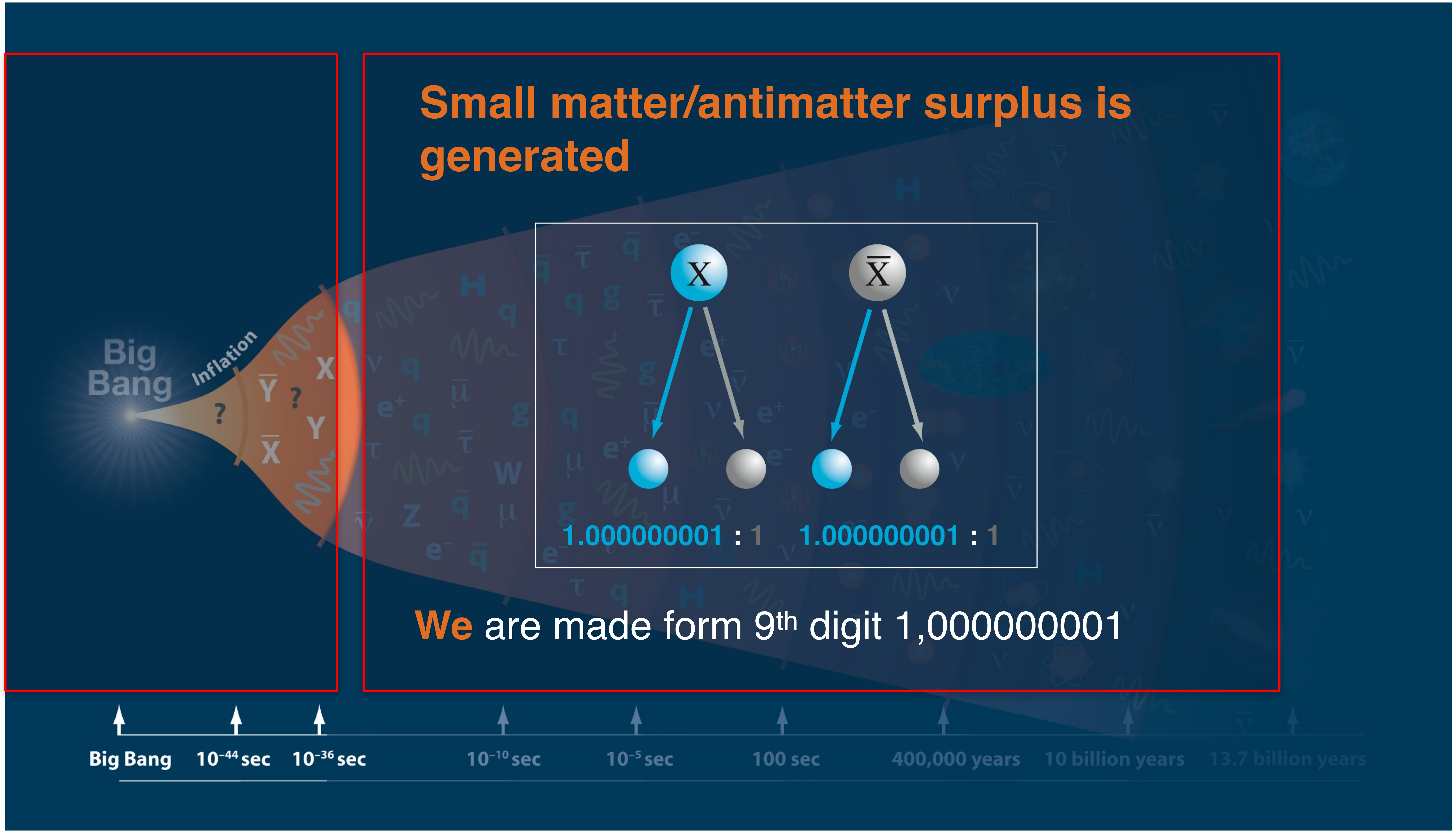
Inflation:

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

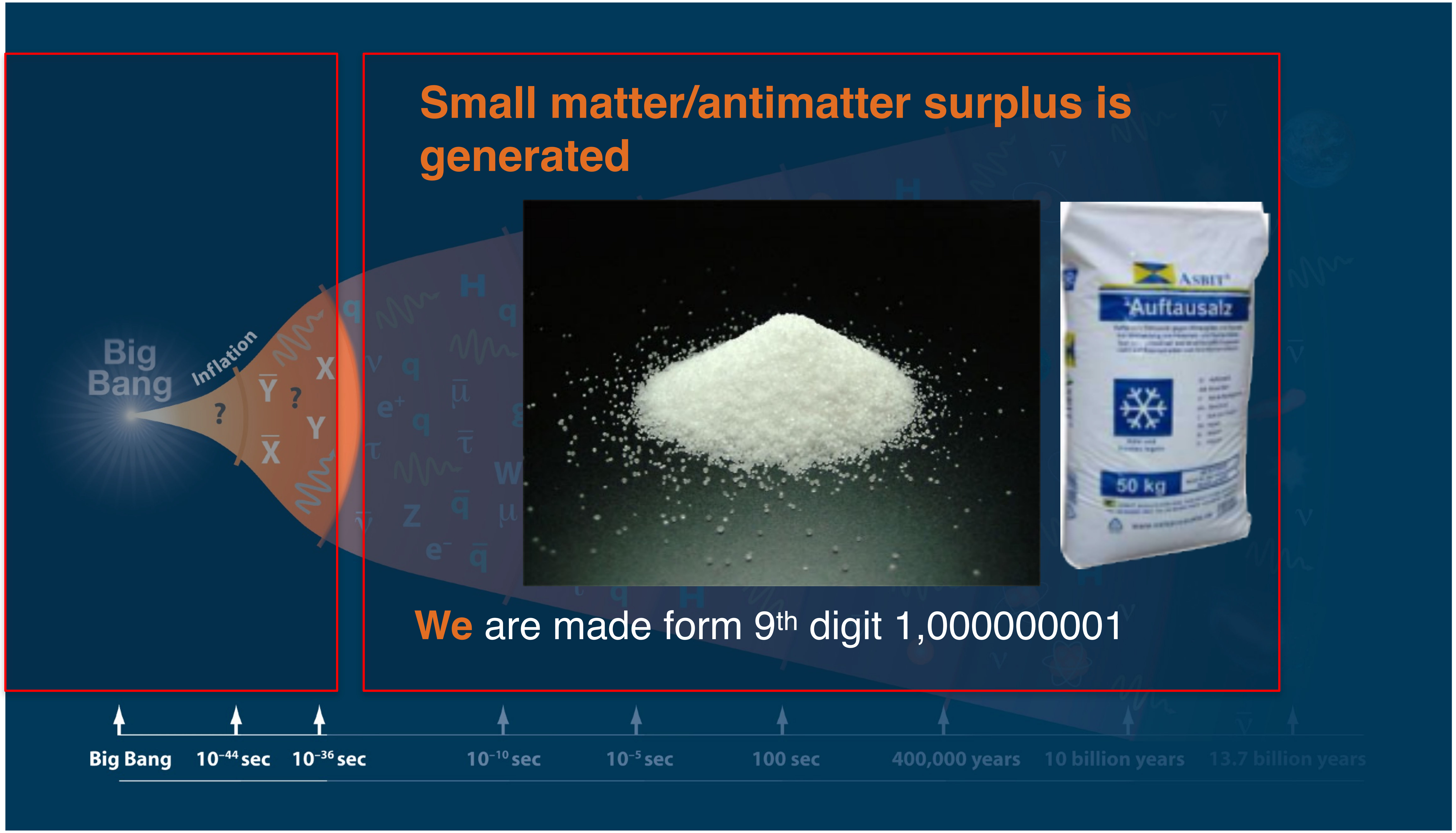
- Amplification of quantum fluctuations of energy density (**3 K CMB**)
- They are at origin of creation of galaxies (later)



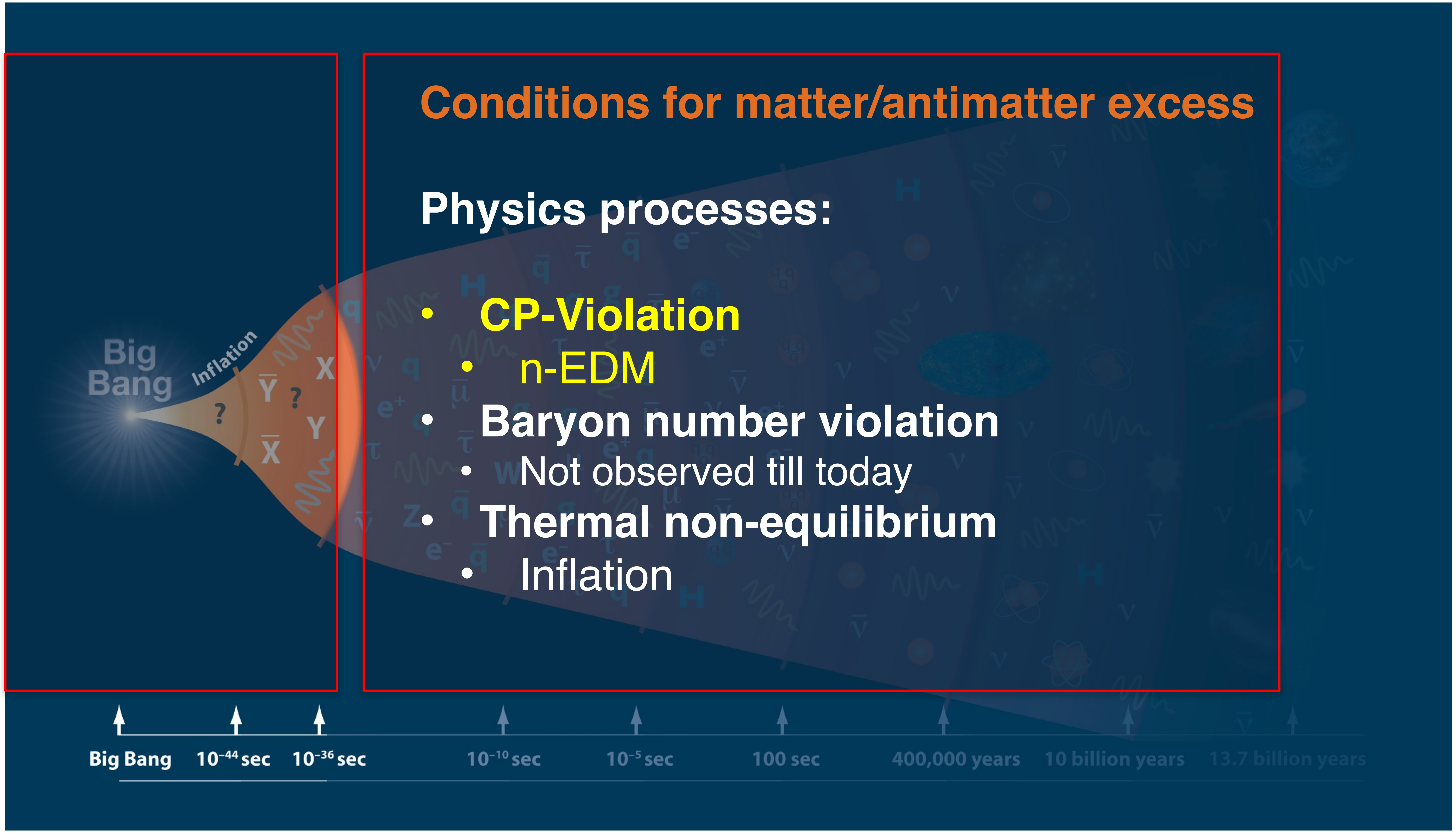
10^{-34} bis 10^{-33} Seconds after Big Bang



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



10^{-34} bis 10^{-33} 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

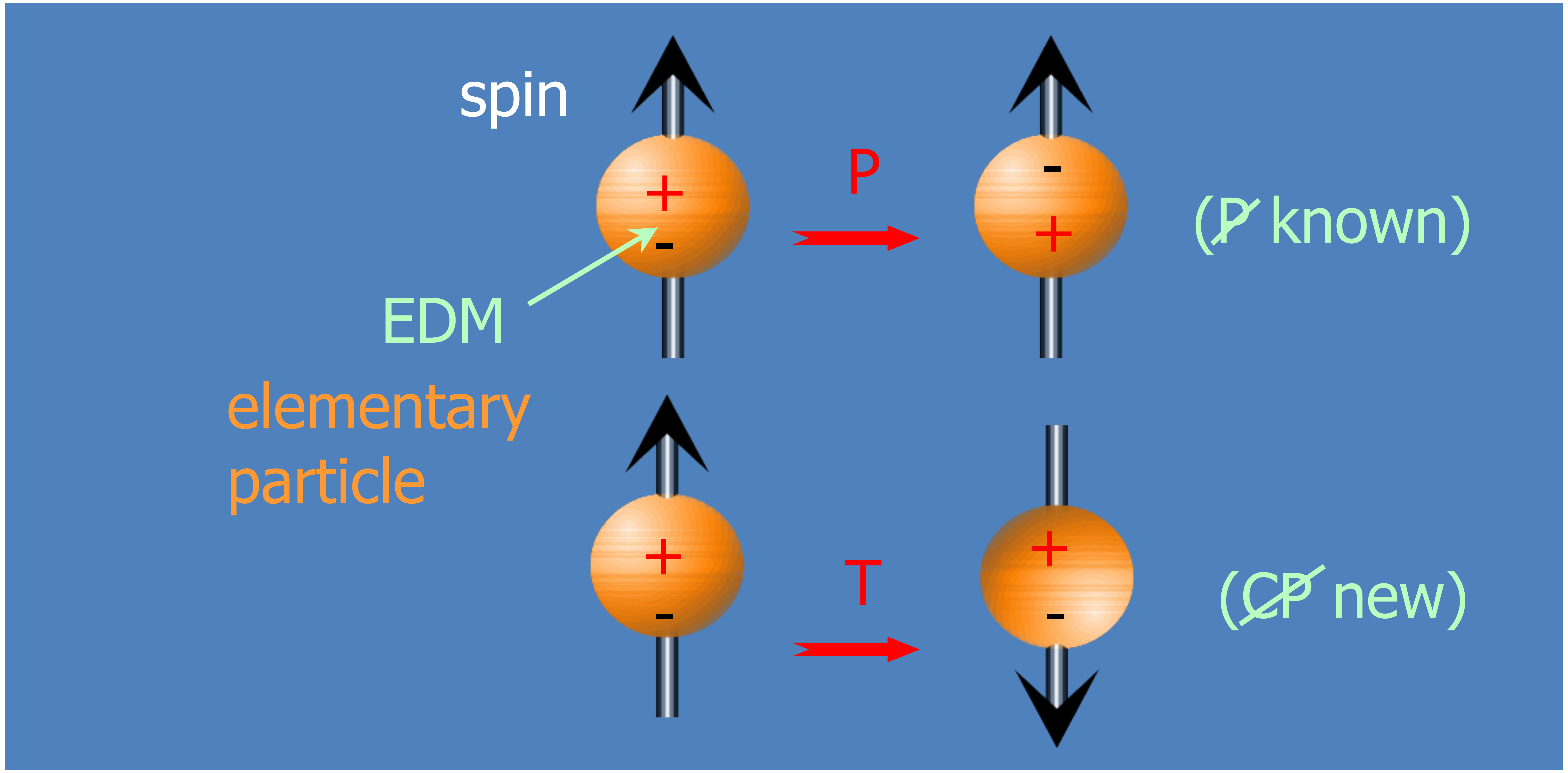
EDM and CP-Violation

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

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

$P = +1$ $\qquad$ $P = -1$

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)

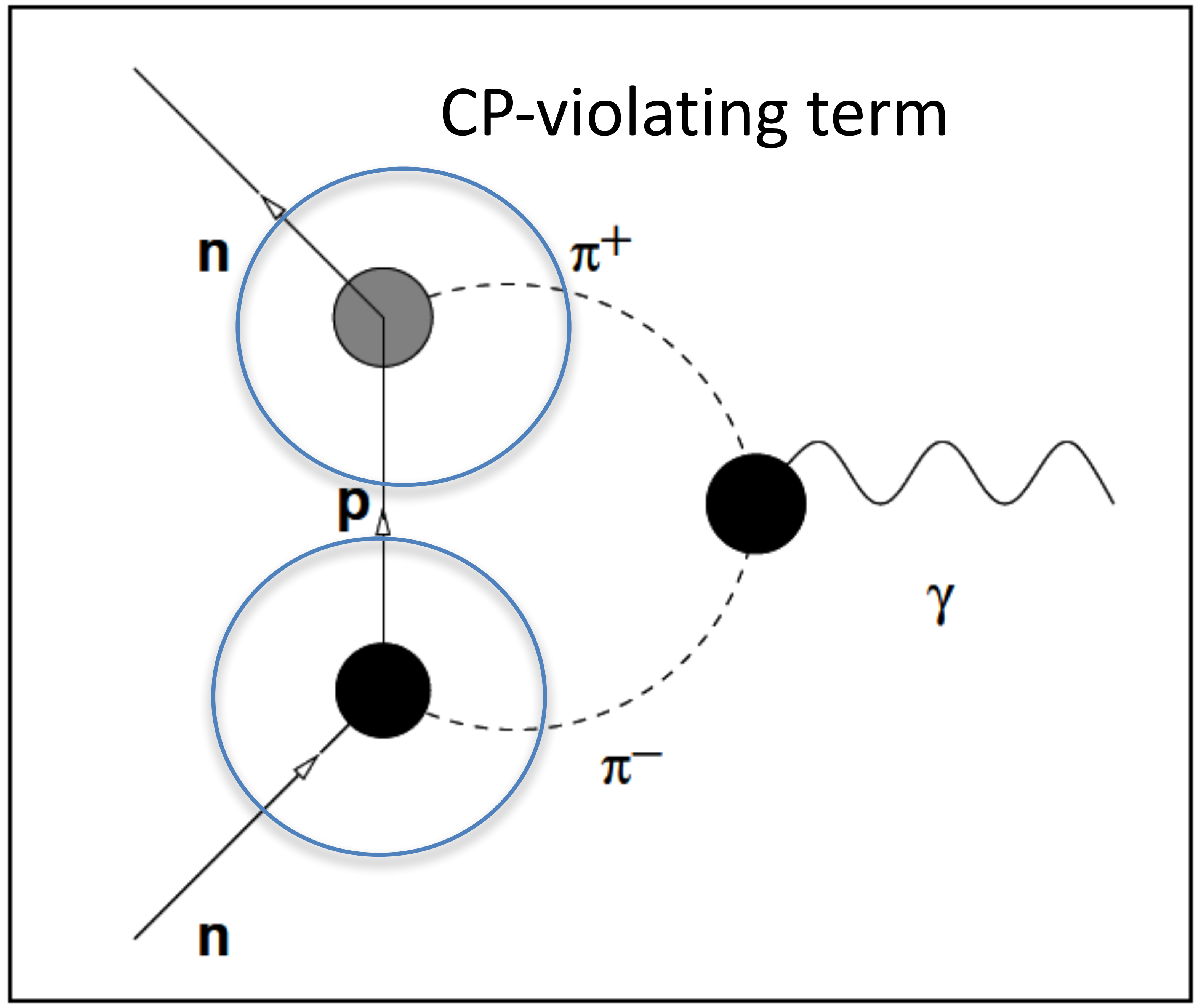
  cosmological necessity (Sakharov criteria)
- Test CP violating part in QCD (θ-term)

  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)

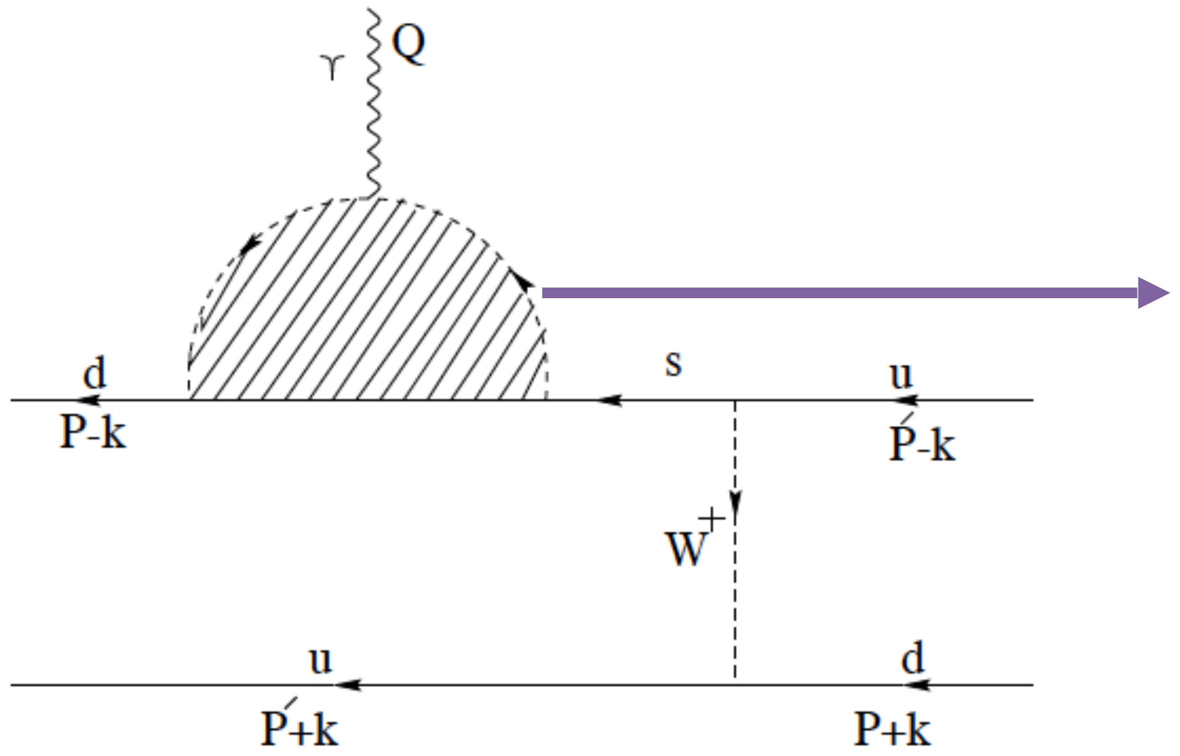
strong interaction



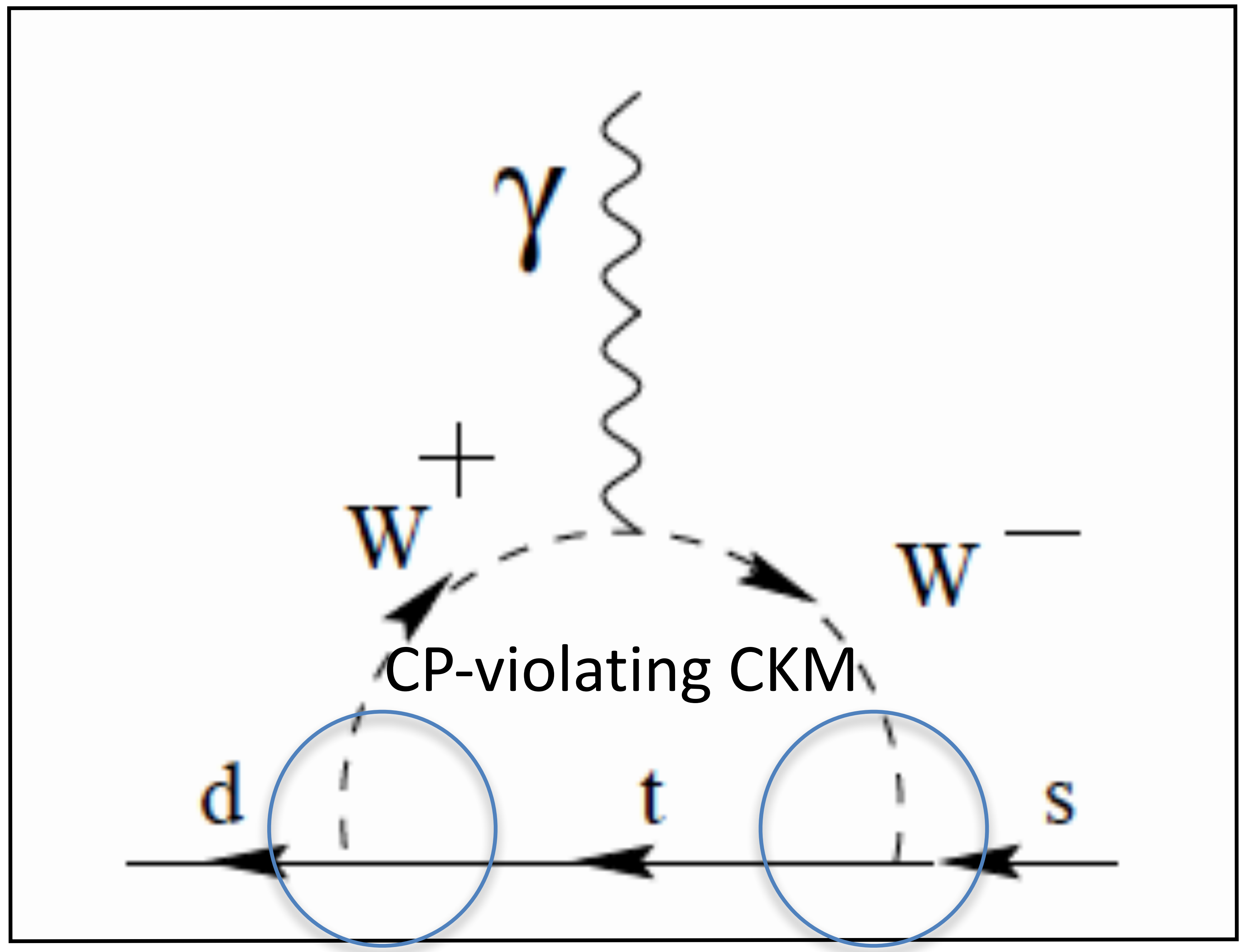
1fm

$$d_n \equiv D_n(k^2 = 0) = \frac{g_{\pi NN}\overline{g_{\pi NN}}}{4\pi^2 M_N} \ln\left(\frac{M_N}{m_\pi}\right)$$

$$\sim \overline{\theta} \times 2 \times 10^{-16} \mathrm{e-cm}$$



electroweak interaction

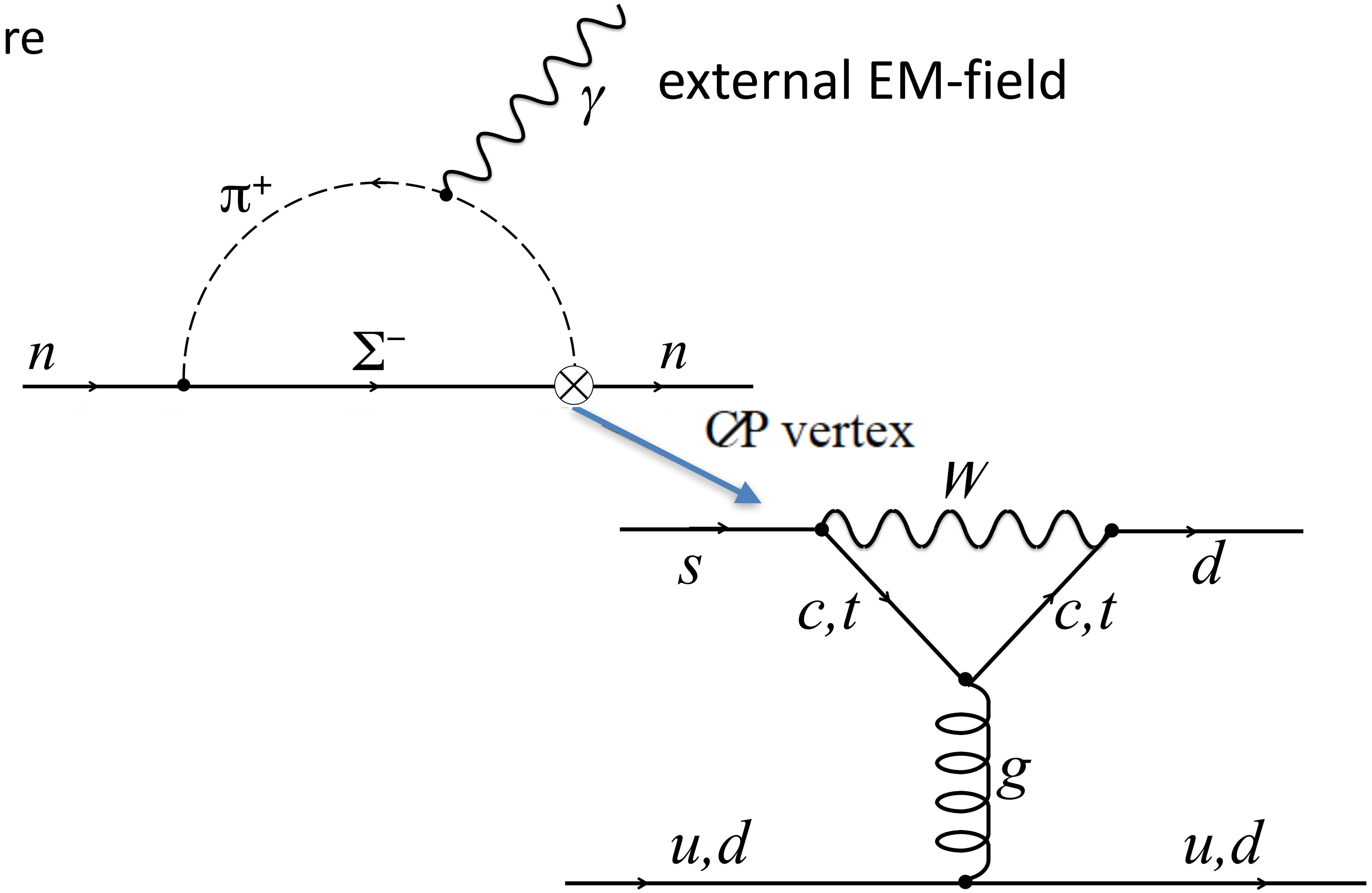


0.001fm

Standard Model EDM

pion-nucleon picture
(d and μ)

external EM-field



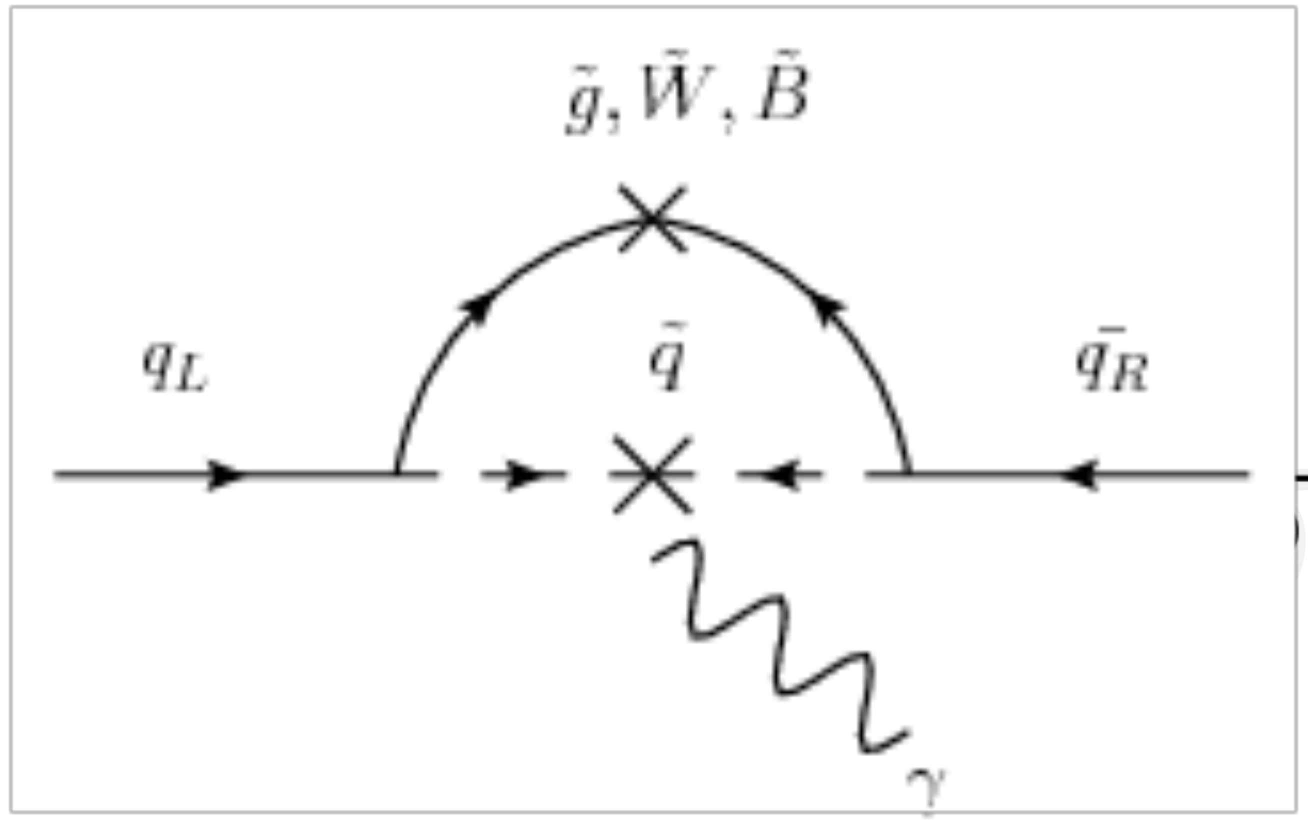
CKM

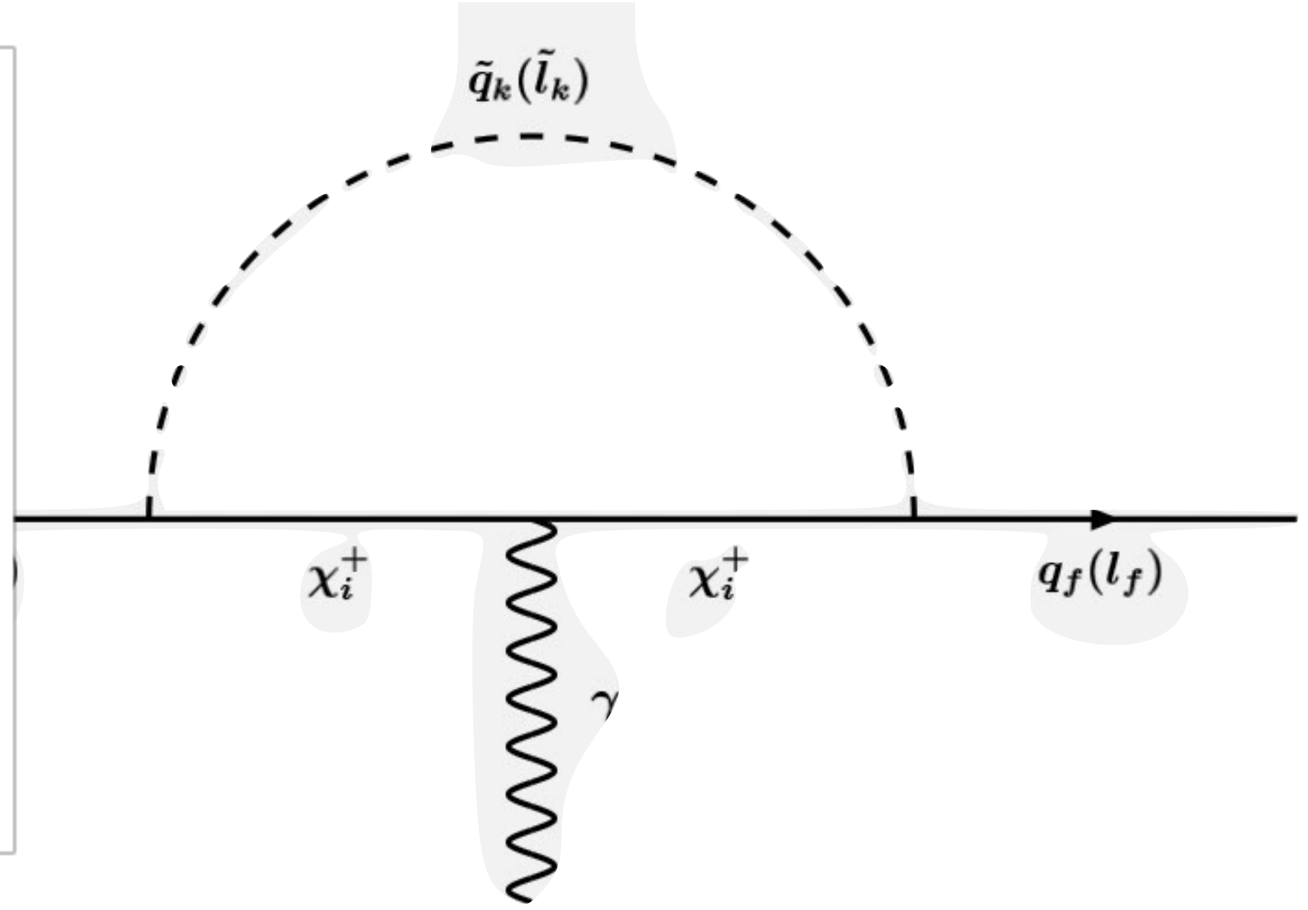
$$d_n^{SM} \approx 10^{-32}\ \mathrm{e\ cm}$$

Neutron EDM

Supersymmetry creates many CP violating phases

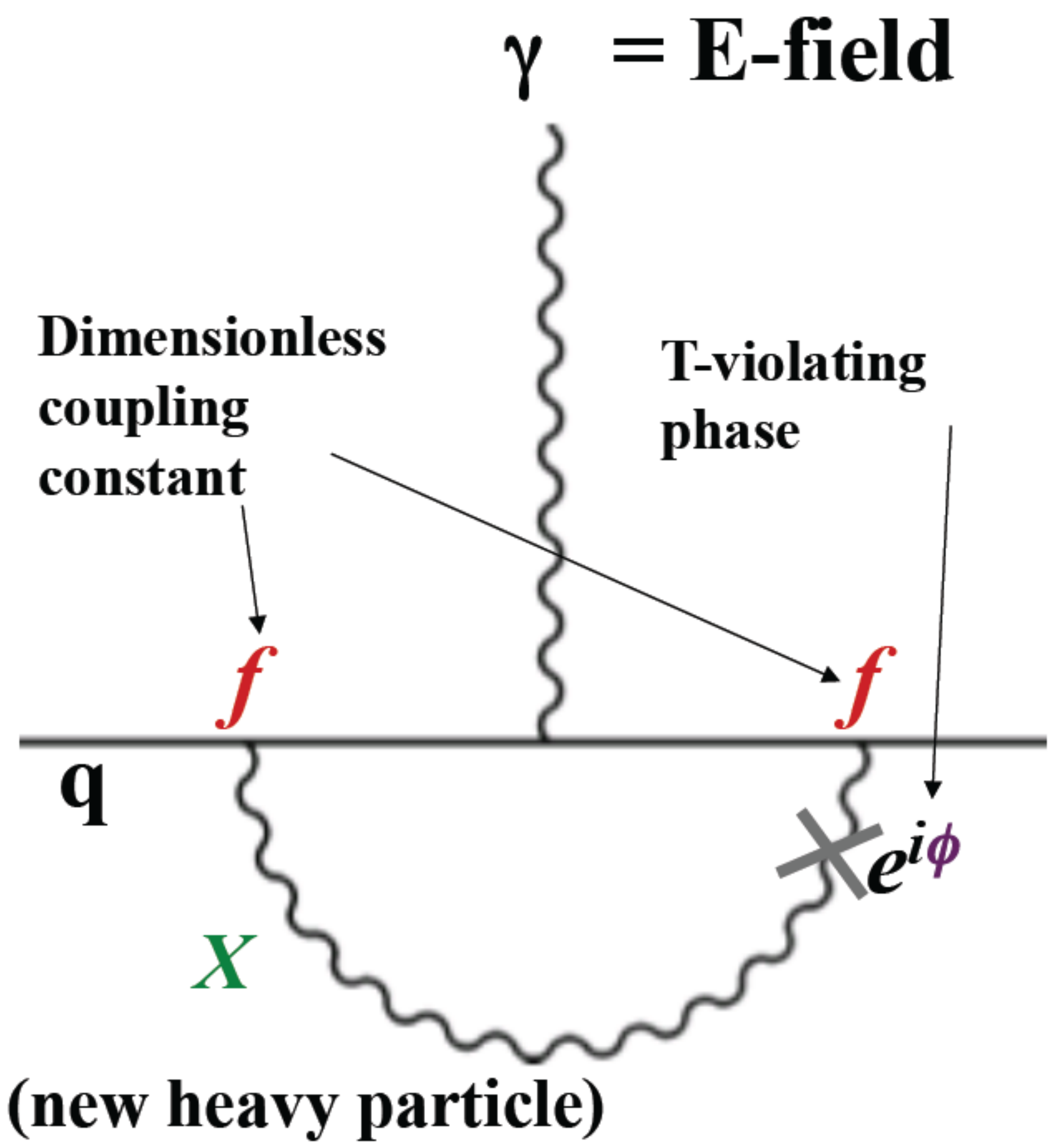
quark EDM





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

New Physics at the TEV scale



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

$m_q \approx 1\ MeV$

$d/e \approx 10^{-13}\ fm$

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

$$\sin\varphi \sim 1$$

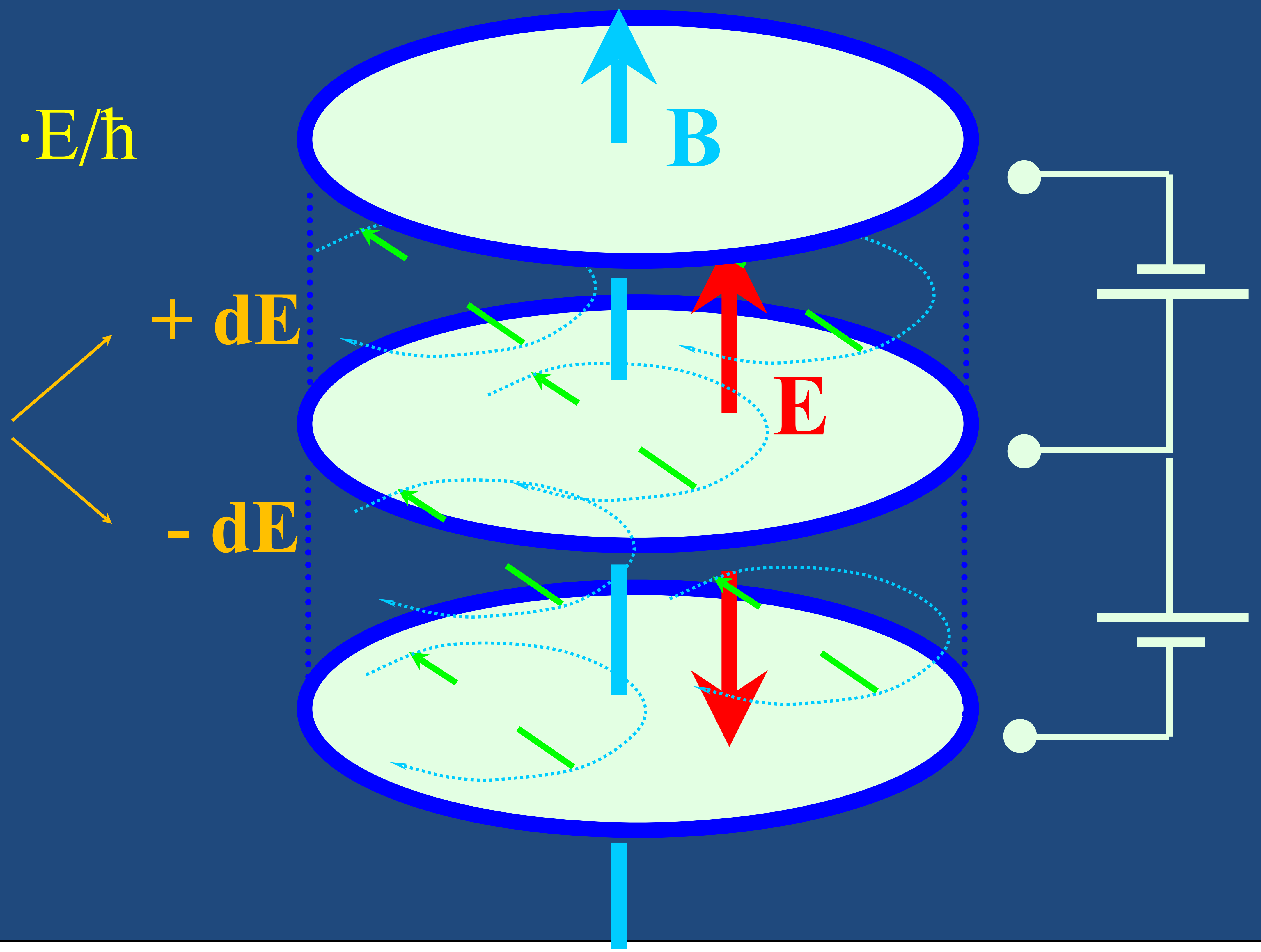
How to measure an EDM ?

Ramsey method

e.g. double chamber System

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

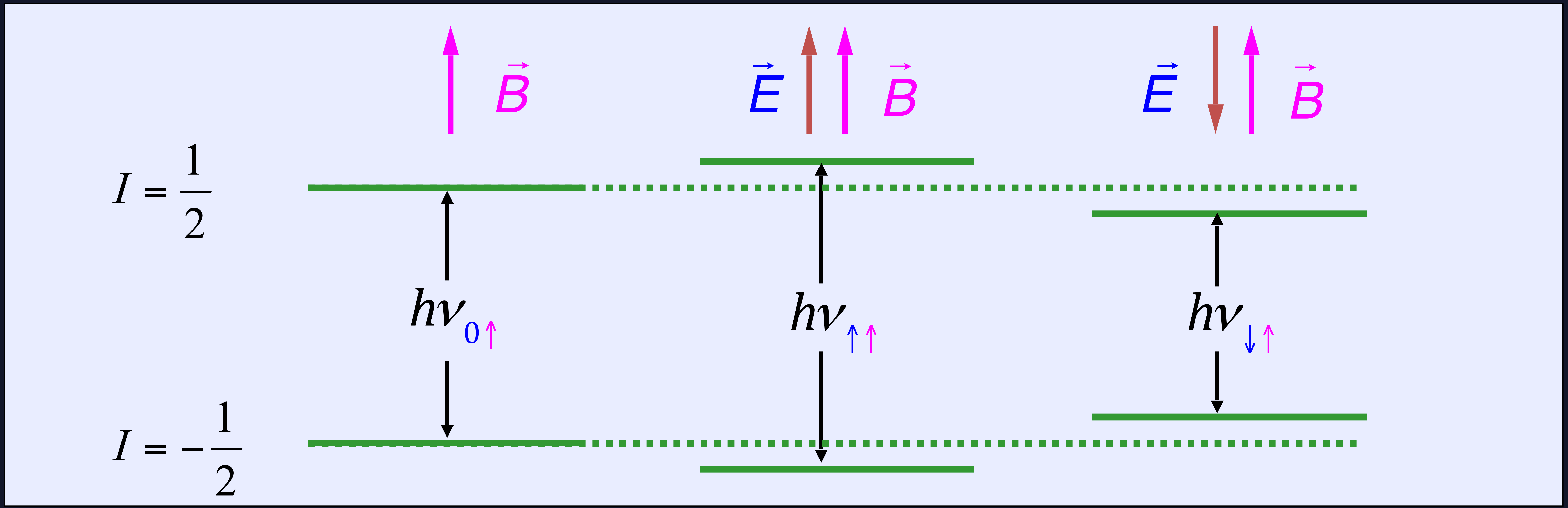
$$h\omega = \pm \mu B$$



EDM-Measurement

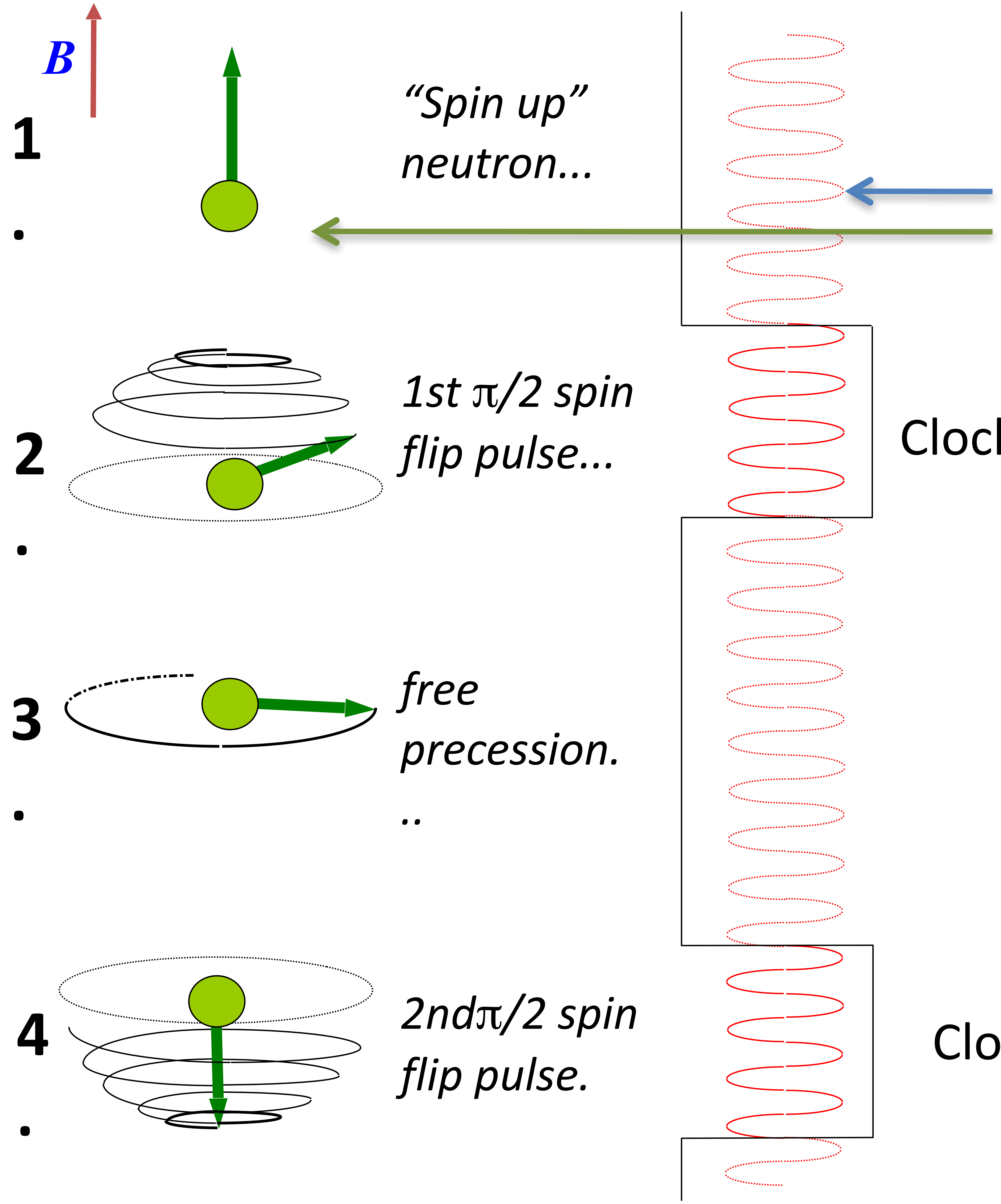
v

Neutron
Larmor frequency



HF normal

Measure: neutron EDM – Ramsey method



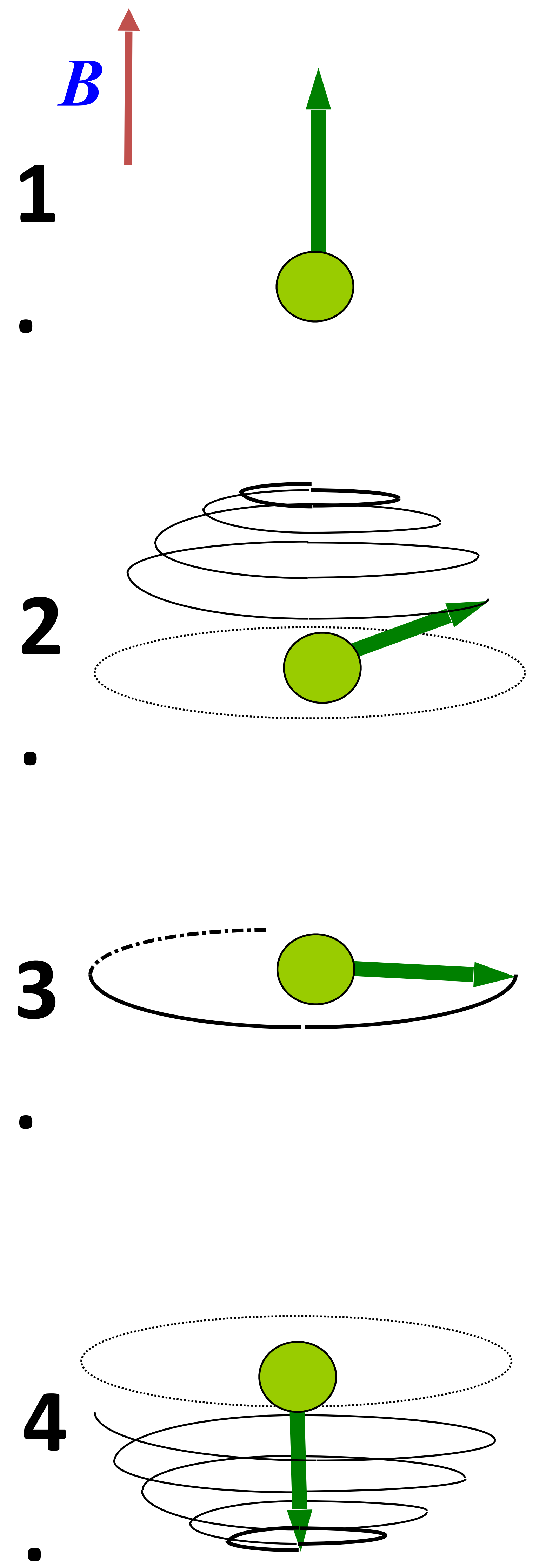
clock comparison:

external oscillator
neutron

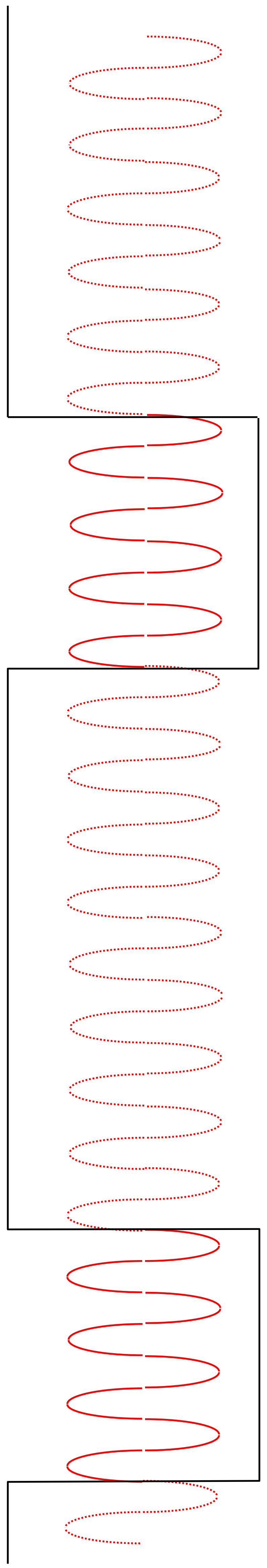
Clock adjustment

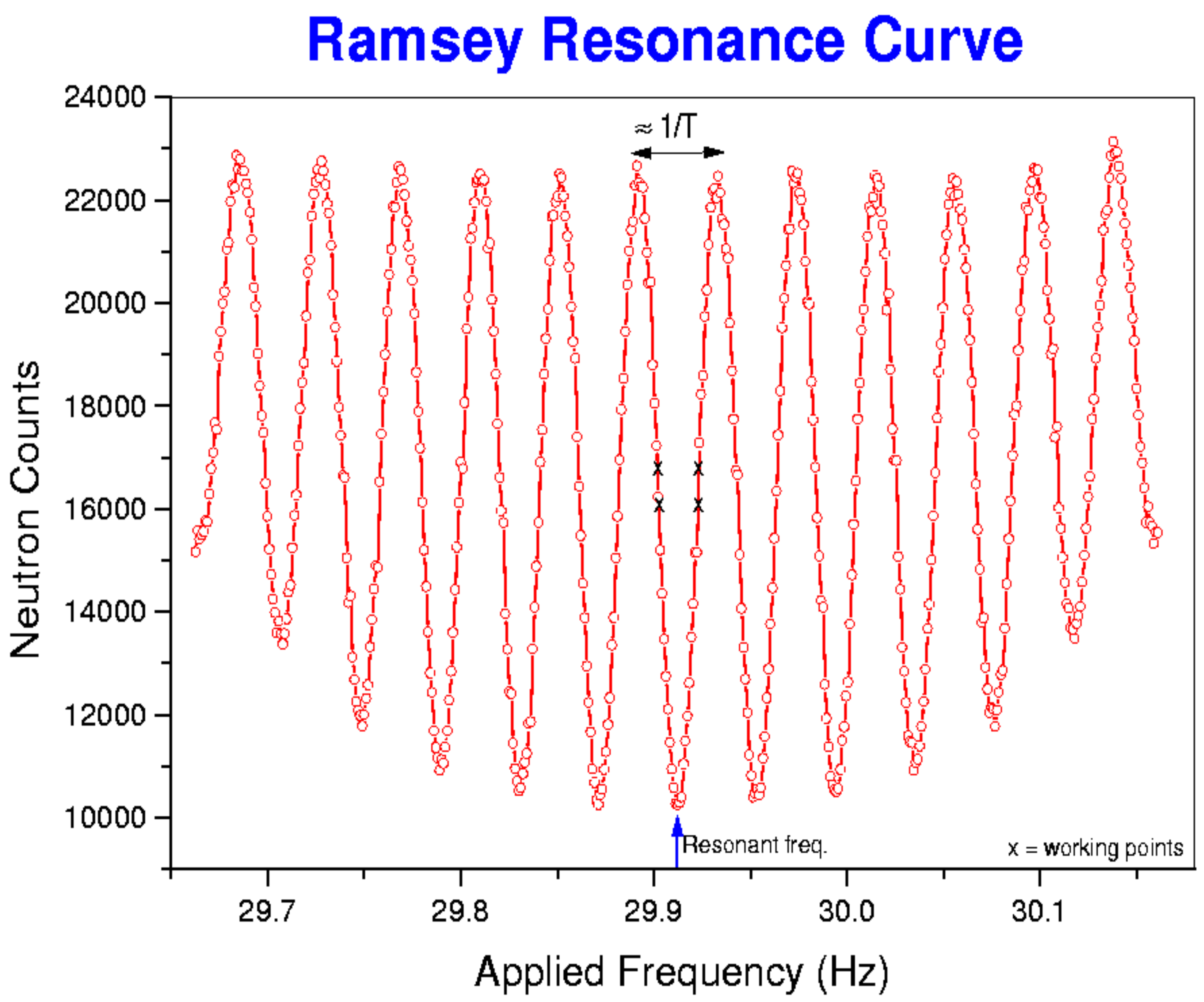
Clock comparison

Measure: neutron EDM – Ramsey method

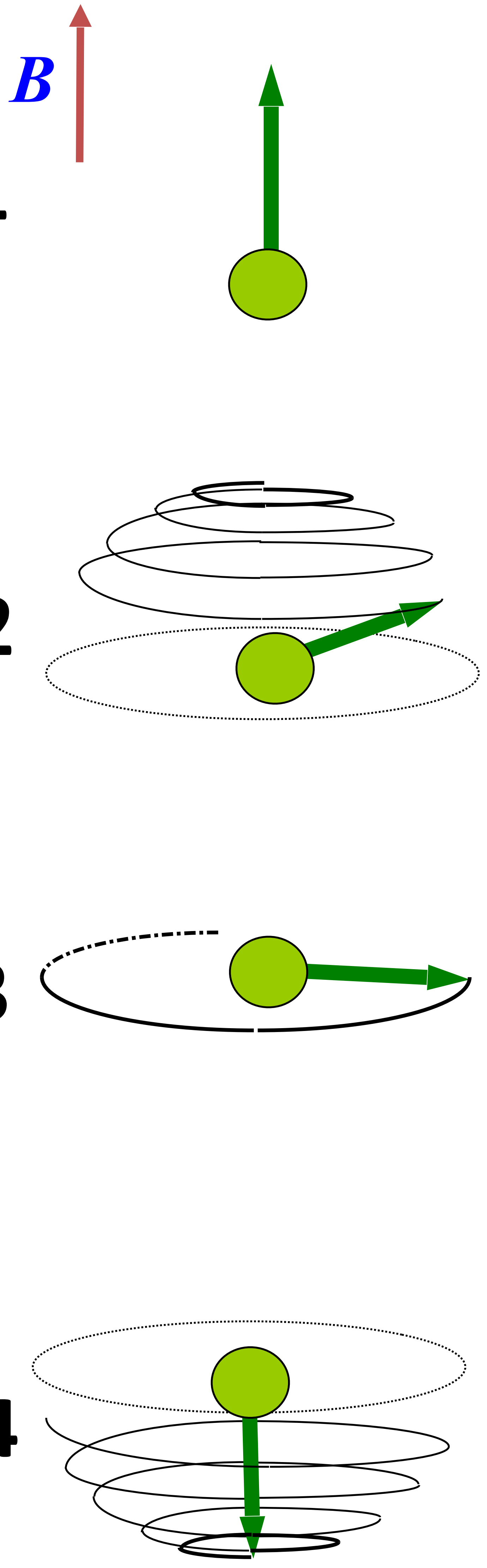


1. *"Spin up" neutron...*
2. *1st π/2 spin flip pulse...*
3. *free precession...*
4. *2ndπ/2 spin flip pulse.*





Measure: neutron EDM – Ramsey method



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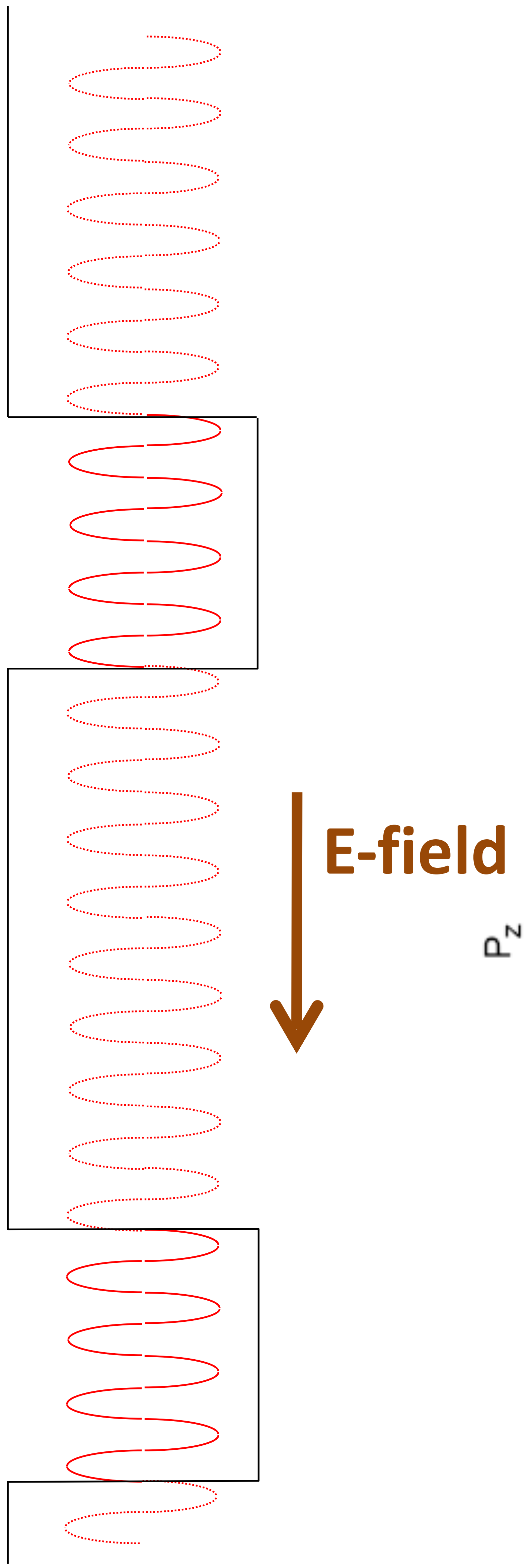

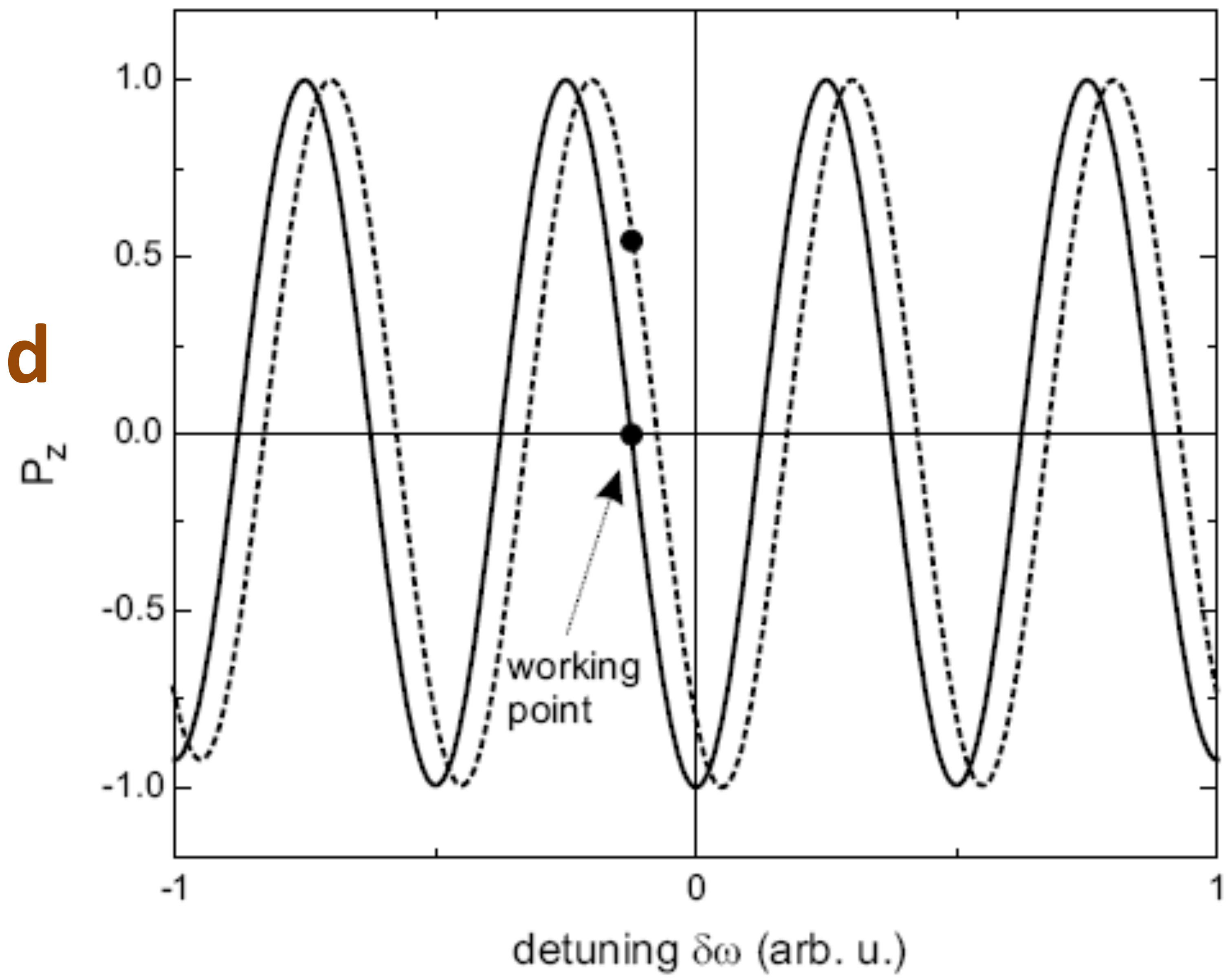

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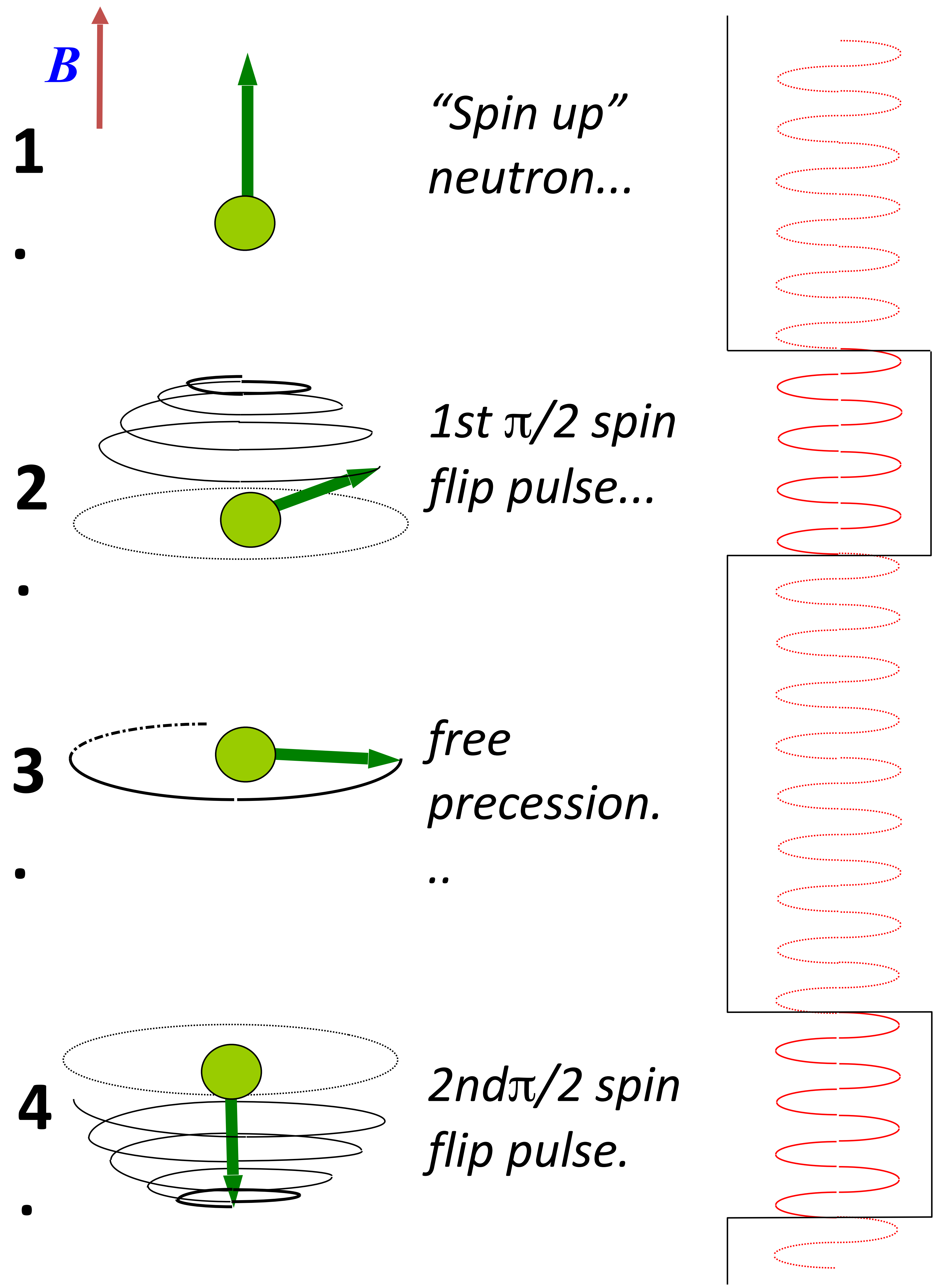
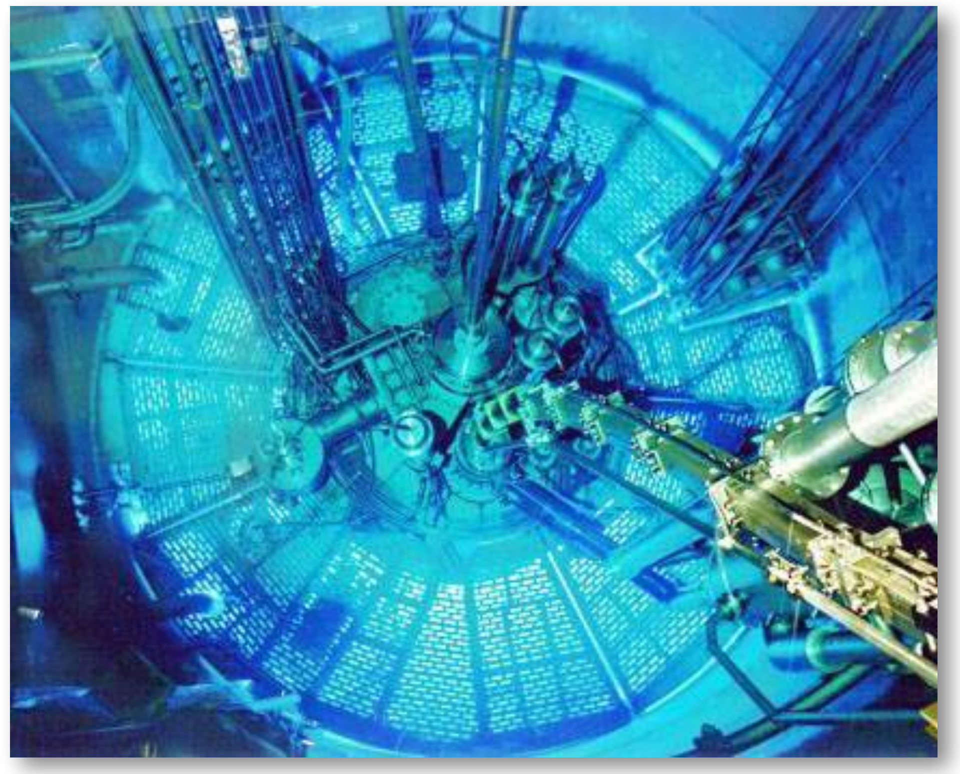


$$\mathcal{M} = \alpha E T \sqrt{N}$$

Figure of Merit

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

Ultra cold Neutrons (UCN)

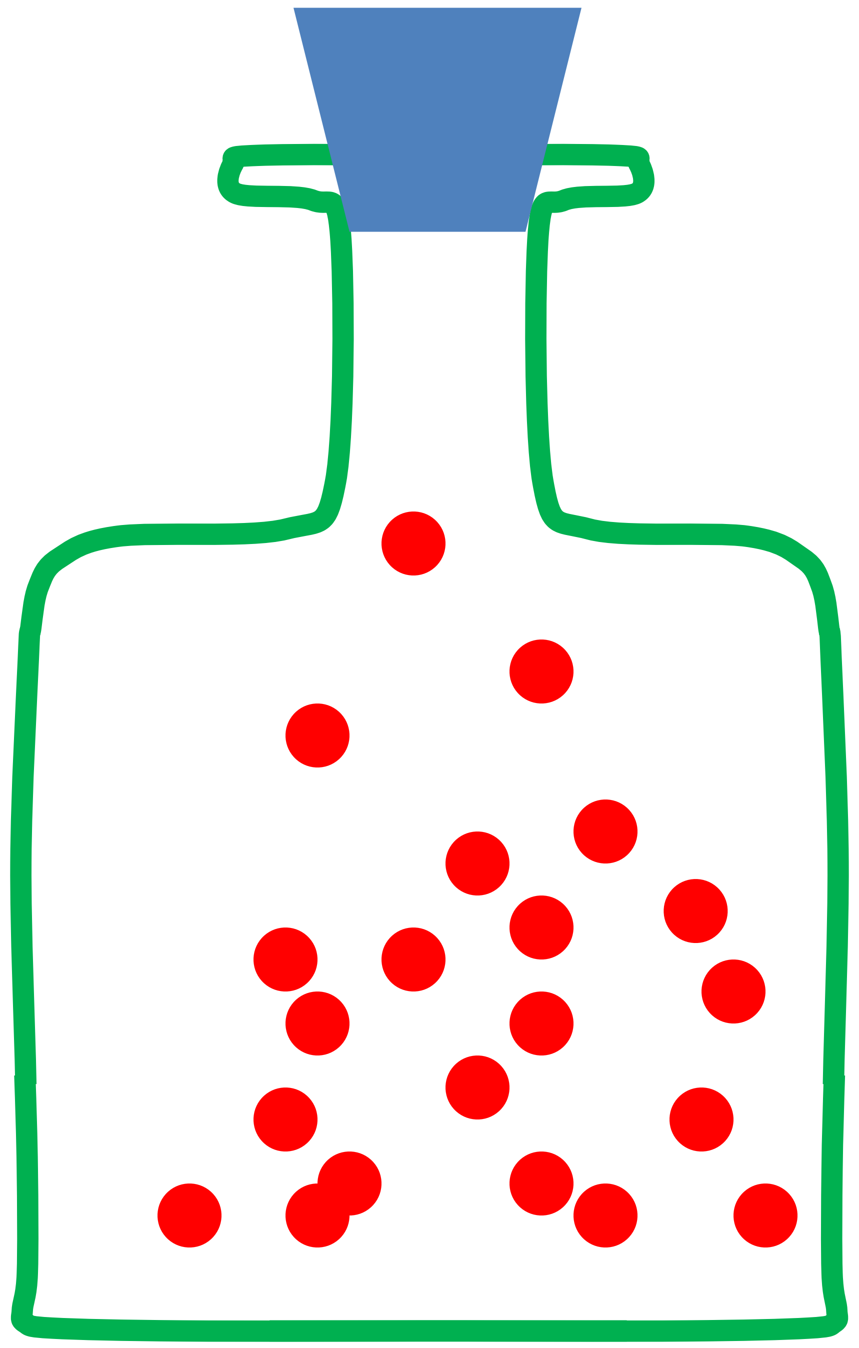


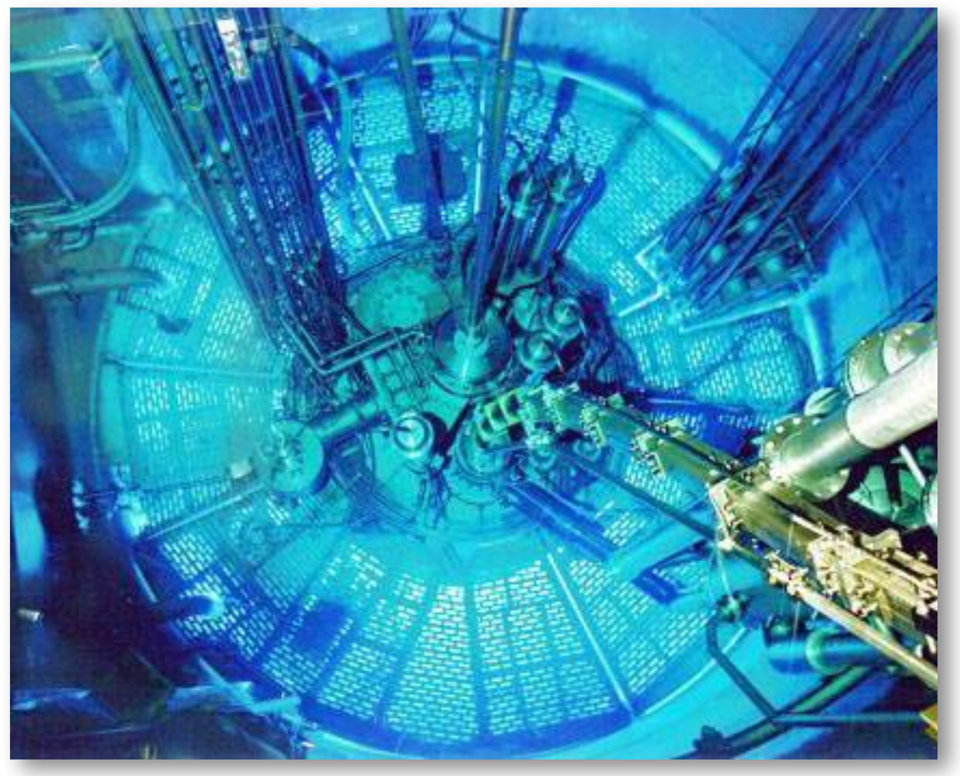
Source @ ILL Grenoble

- 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)

Ultra cold Neutrons (UCN)





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  Fermi-potential < 340 neV

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

How accurately do we have to measure ?

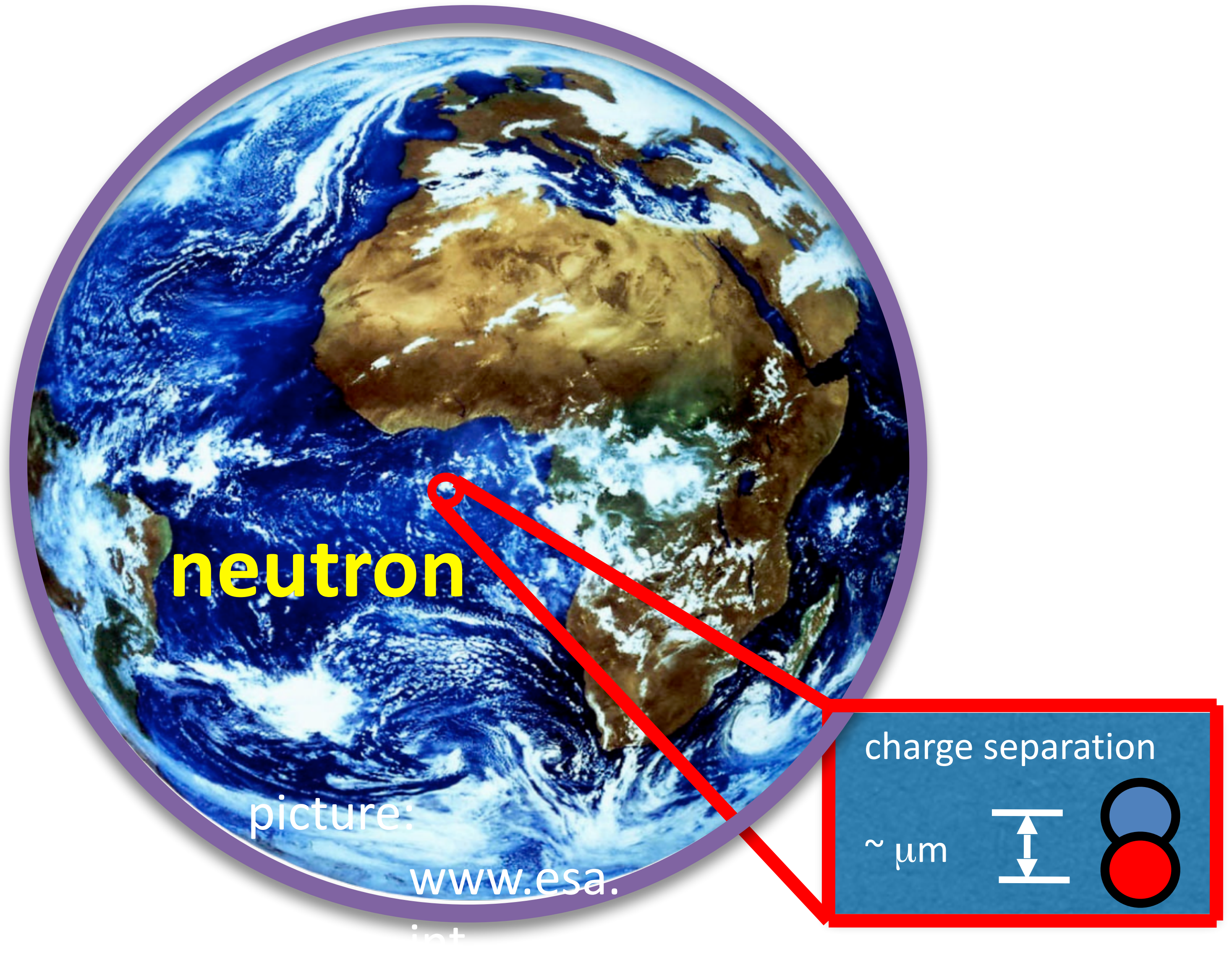
Neutron(spin) precession of 30 Hz

Present sensitivity:

one spin-rotation in 180 days

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

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



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

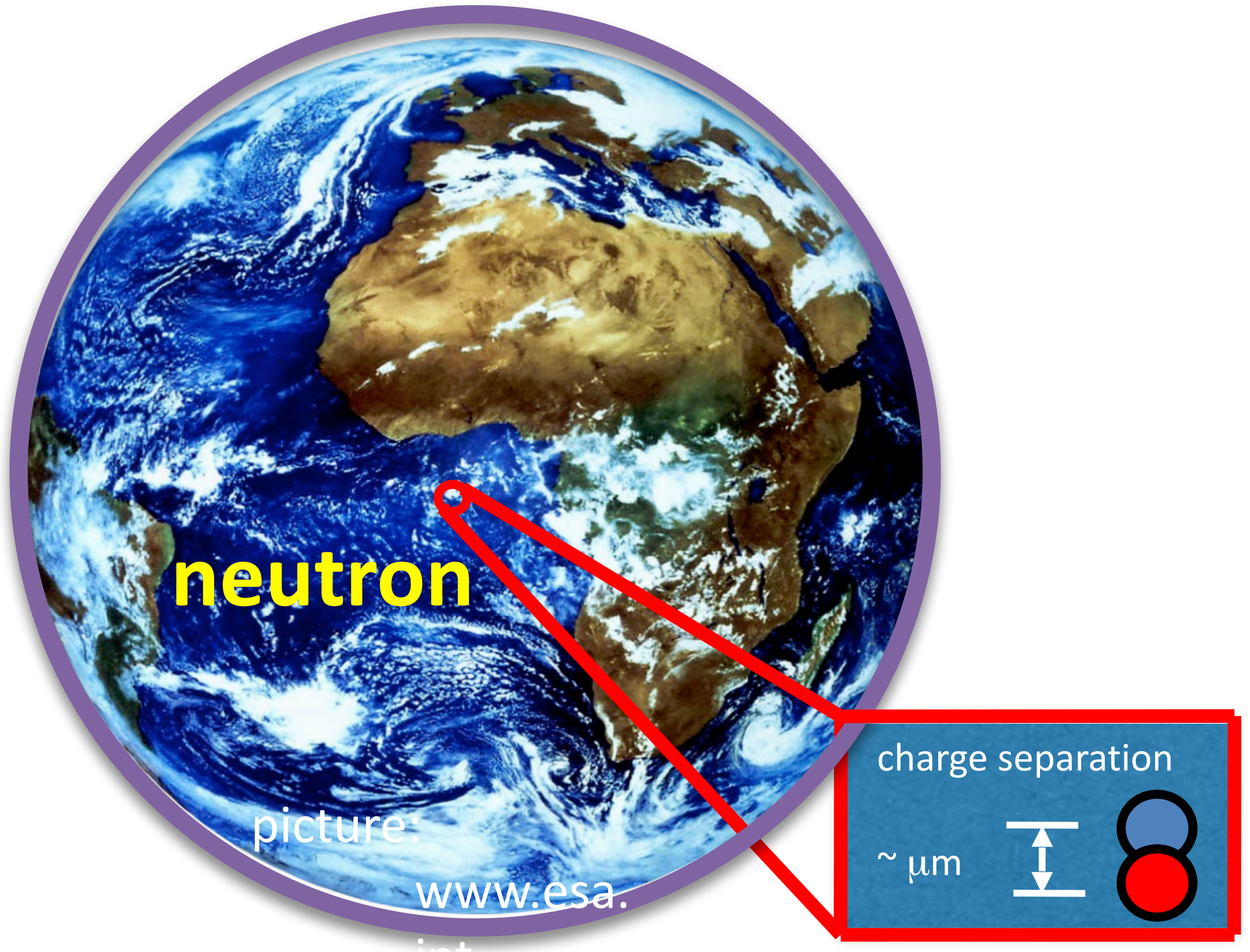
$$|d_n| < 3 \cdot 10^{-26}\ e \cdot cm$$

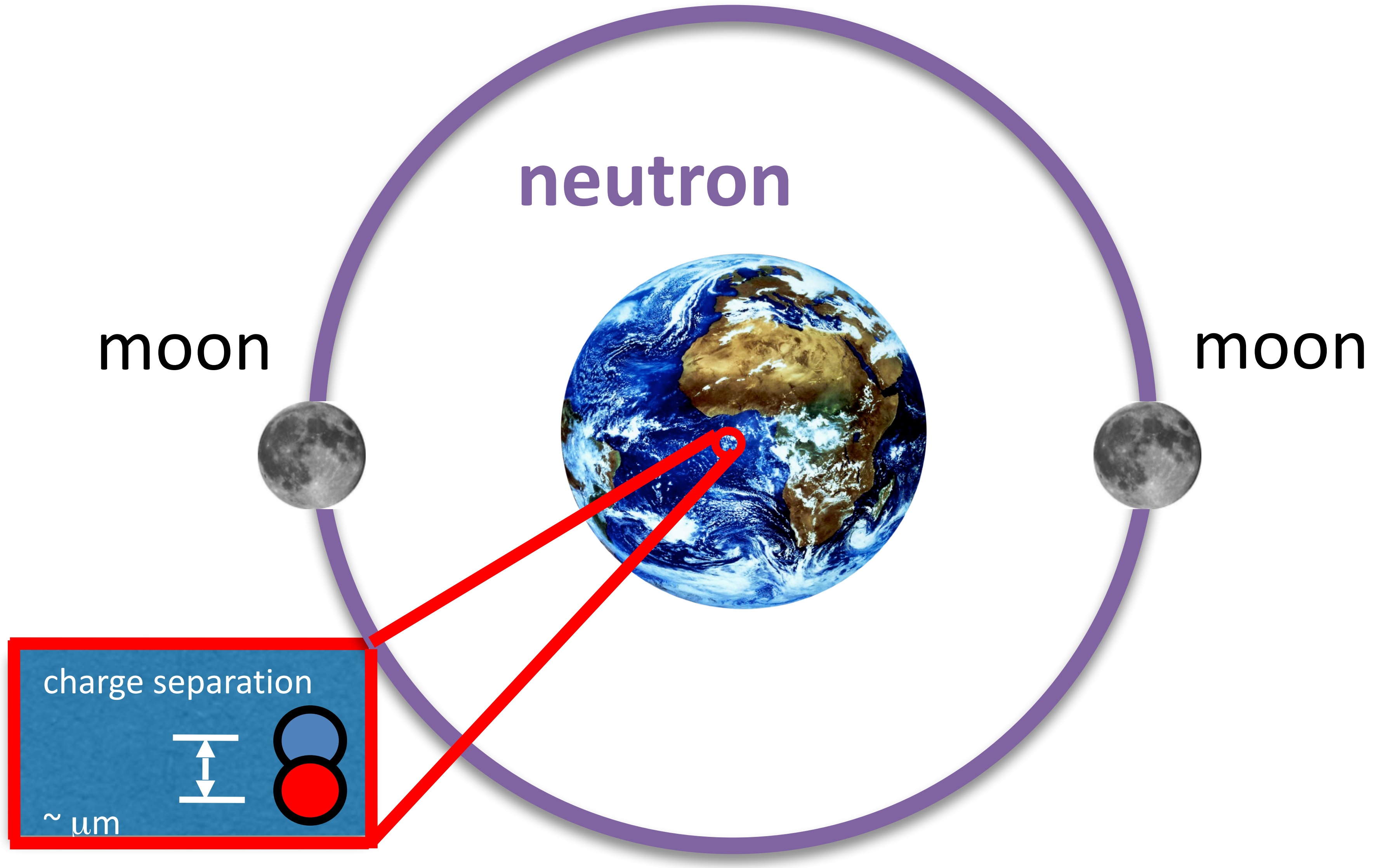
planned sensitivity:

one spin rotation in 50 years

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

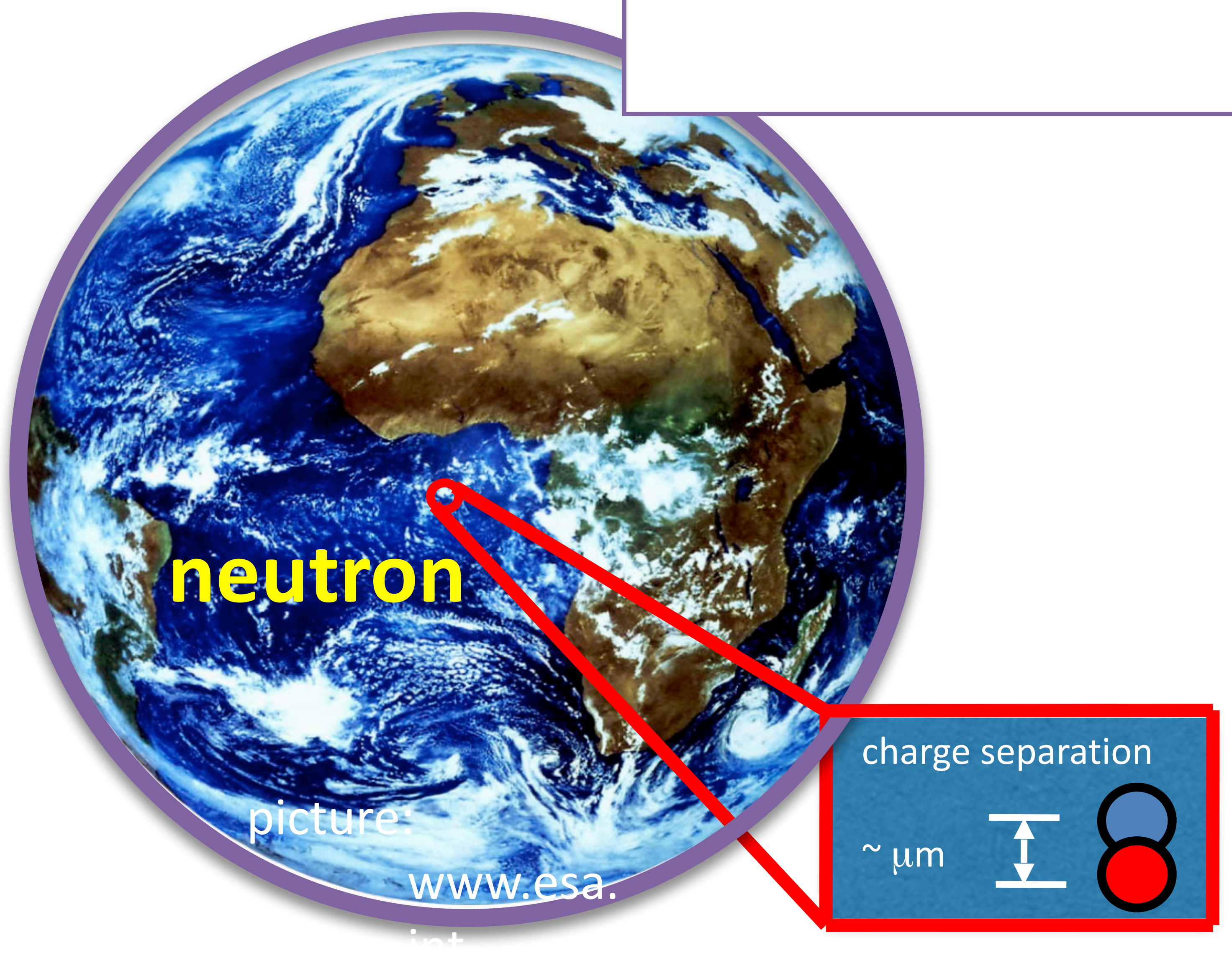
$$|d_n| < 3 \cdot 10^{-28}\ e \cdot cm$$

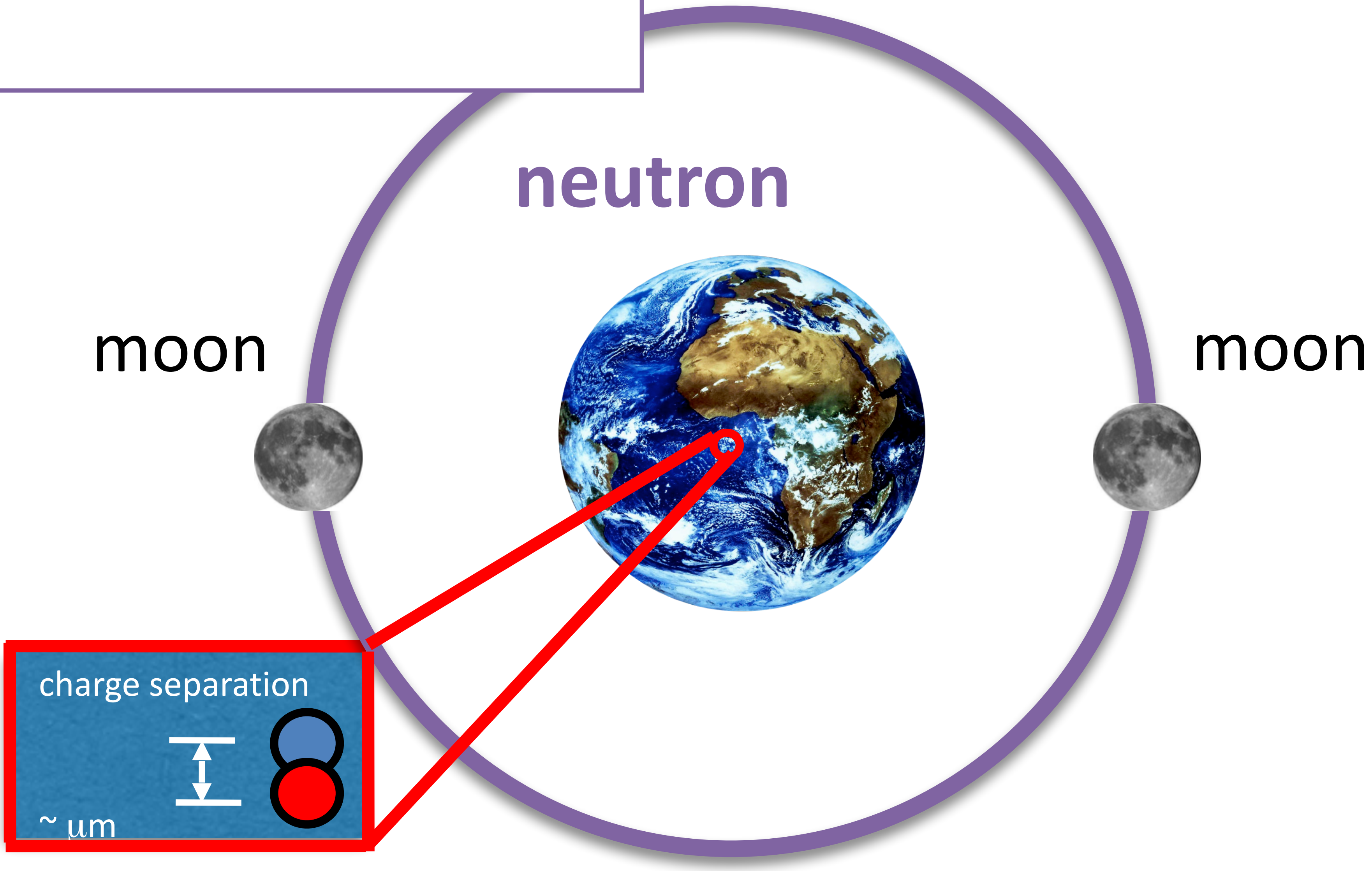




How accurately do we have to measure ?

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





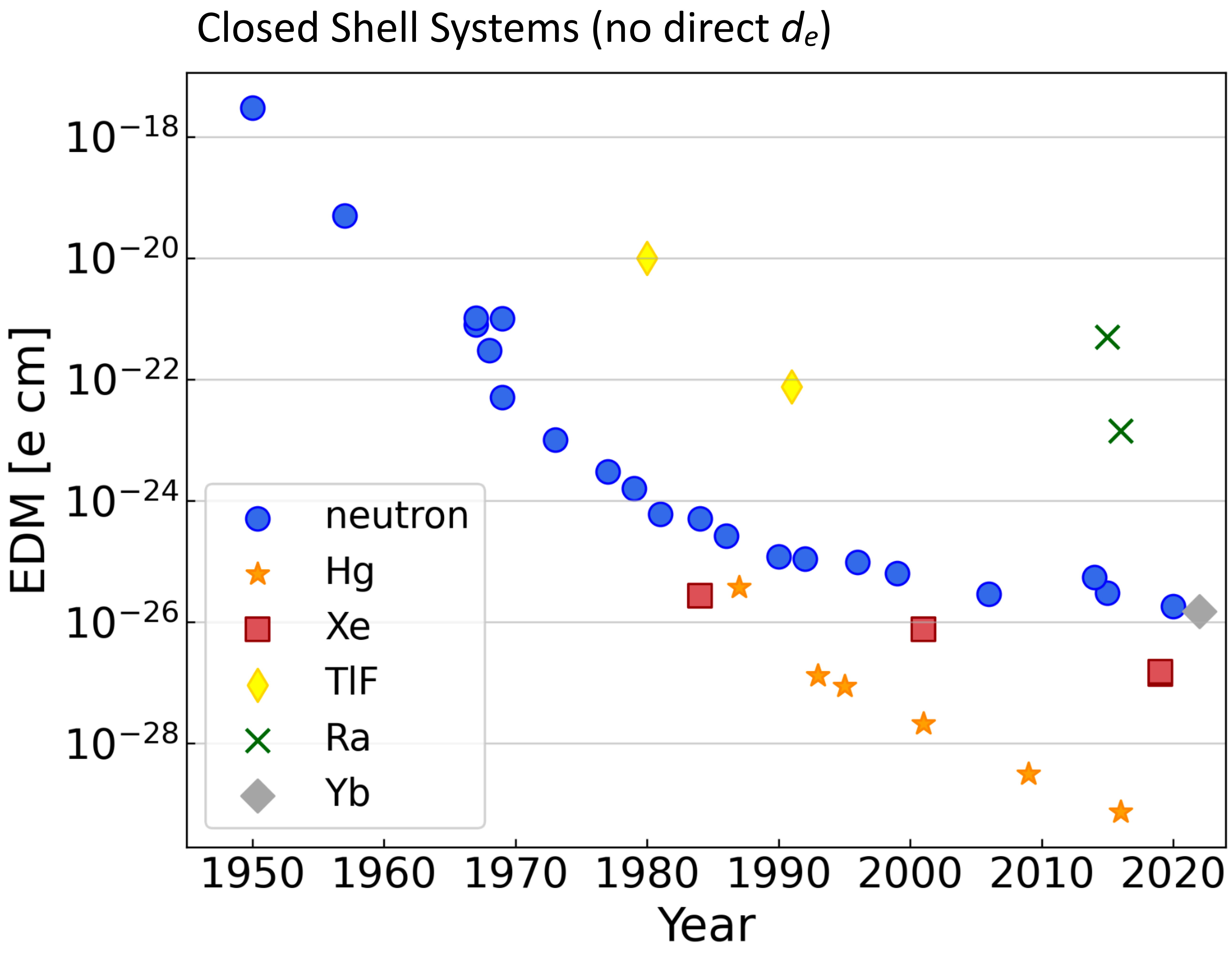
Neutron EDM searches and friends

Neutron EDM is purest system

Closed shell systems probe variety of underlying CP violating effects

Requires theory to

- extract signal strength
- interpretation (static: electron, nucleon, quark, dynamic: e-N interaction)



Neutron EDM searches and friends

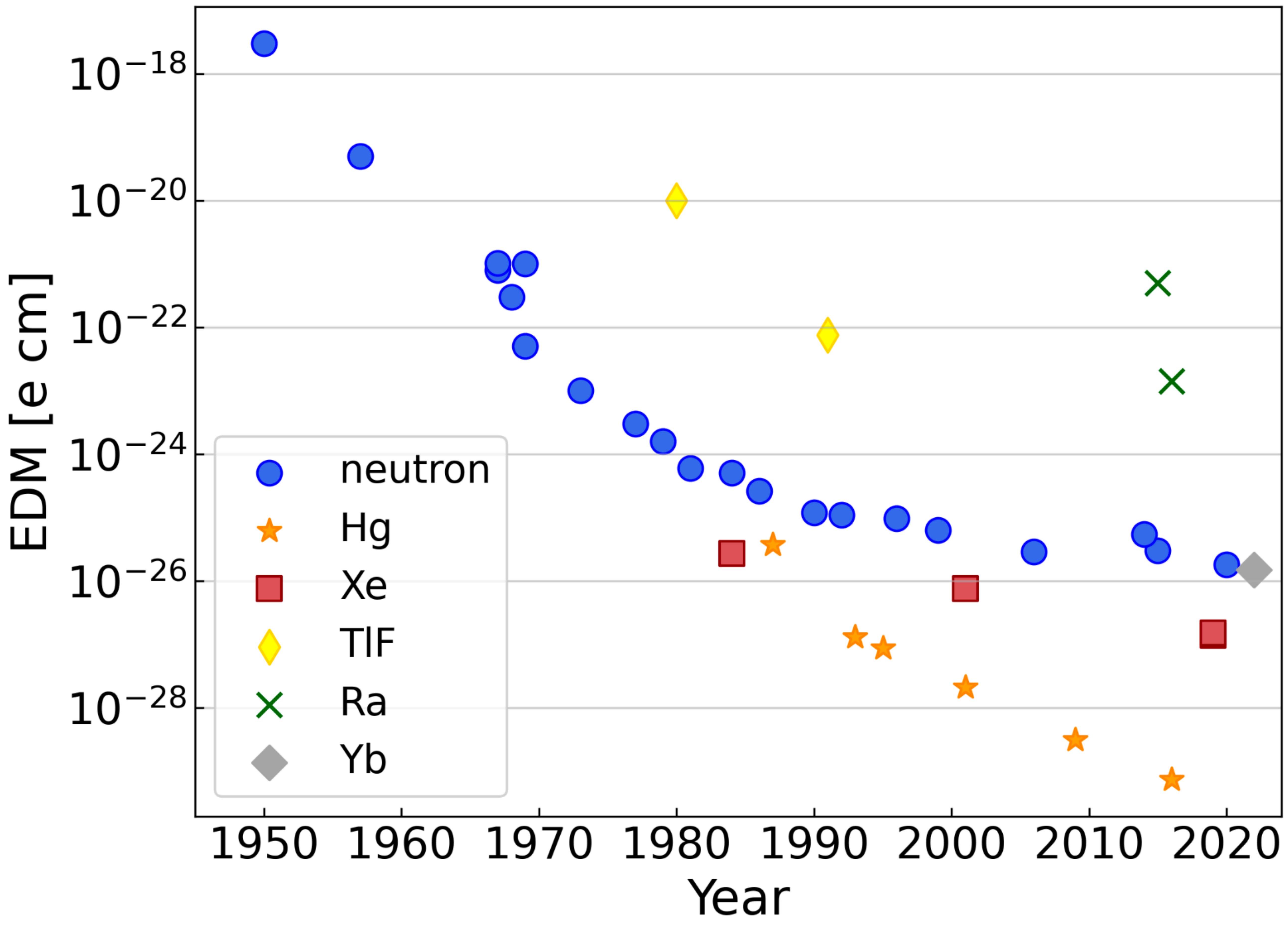
New/planned activities

Collaboration	Species	Method	Sensitivity (10^{-29} $e$cm)	Status
PanEDM I	n	UCN	380	Commissioning
PanEDM II	n	UCN	79	Commissioning
Beam EDM	n	beam	500	proof-of-principle
n2EDM	n	UCN	110	Start data-taking
n2EDMagic	n	UCN	50	Construction
nEDMsf	n	UCN	20	Development

time scale: 5-15 years

aim: $d_n < 10^{-27}\ e \cdot cm$

Closed Shell Systems (no direct d_e)

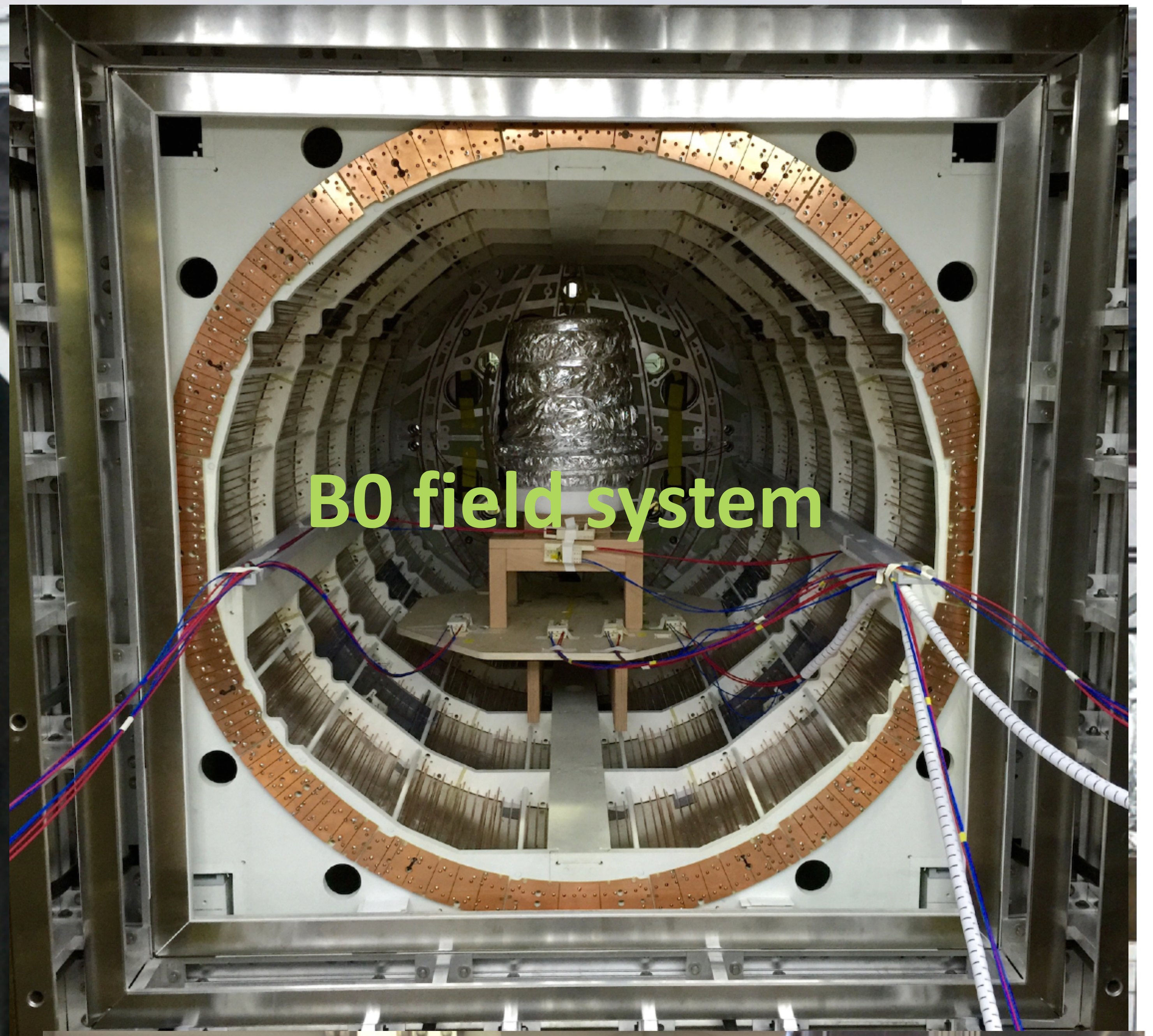


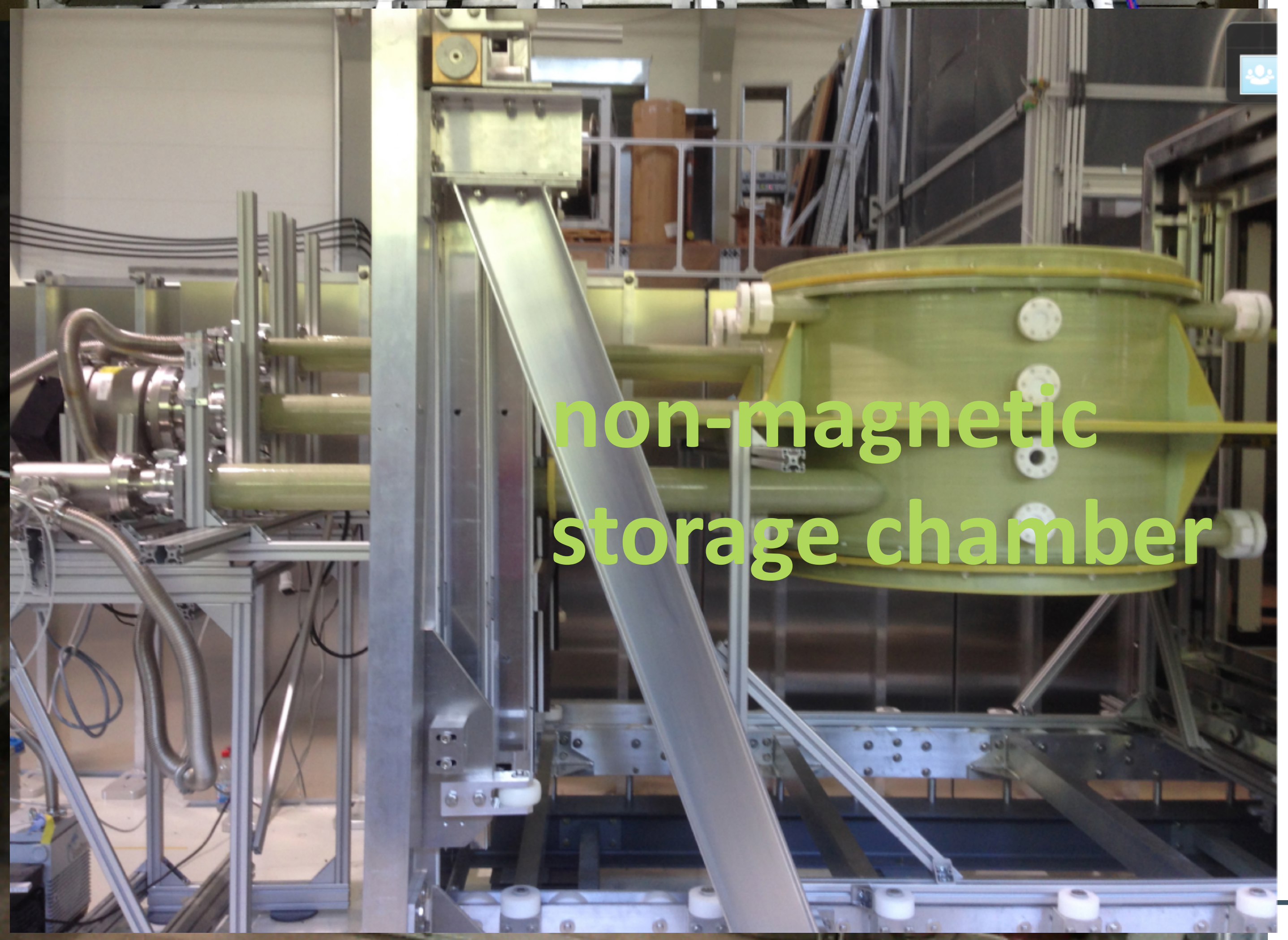
The Real Setup

Fierlinger et al.

The Real Setup

Fierlinger et al.





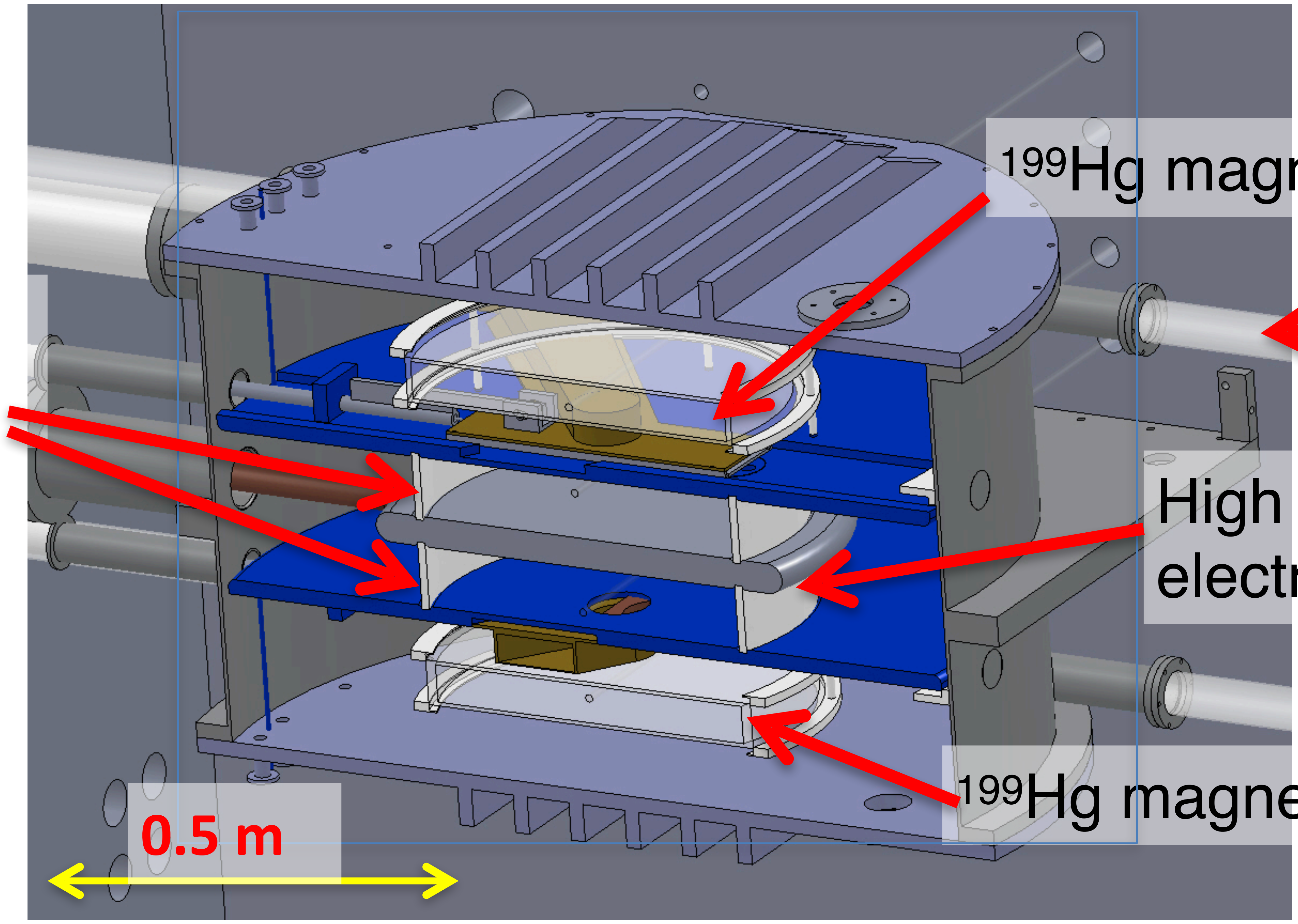
The Real Setup

Fierlinger et al.

Key: avoid magnetic false effects

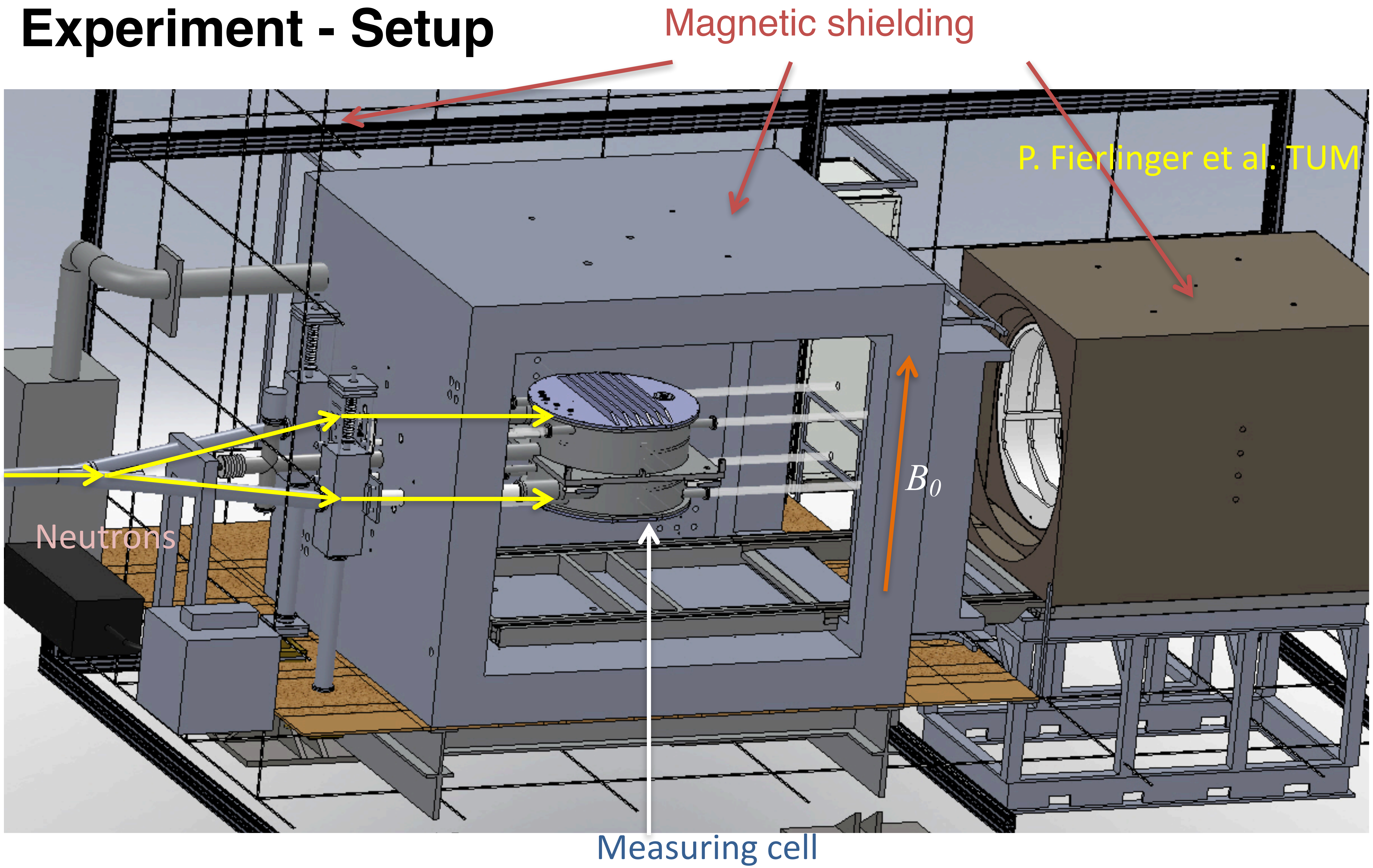
- „perfect" magnetic shielding - best room worldwide (remaining field few fT)
- „Perfect" control over non-magnetic material
- Frequent and rapid demagnetization
- Co-magnetometry (^{199}Hg)
- nEDM < 10^{-28} e cm in reach
- missing : UCN !!

The new EDM apparatus PanEDM



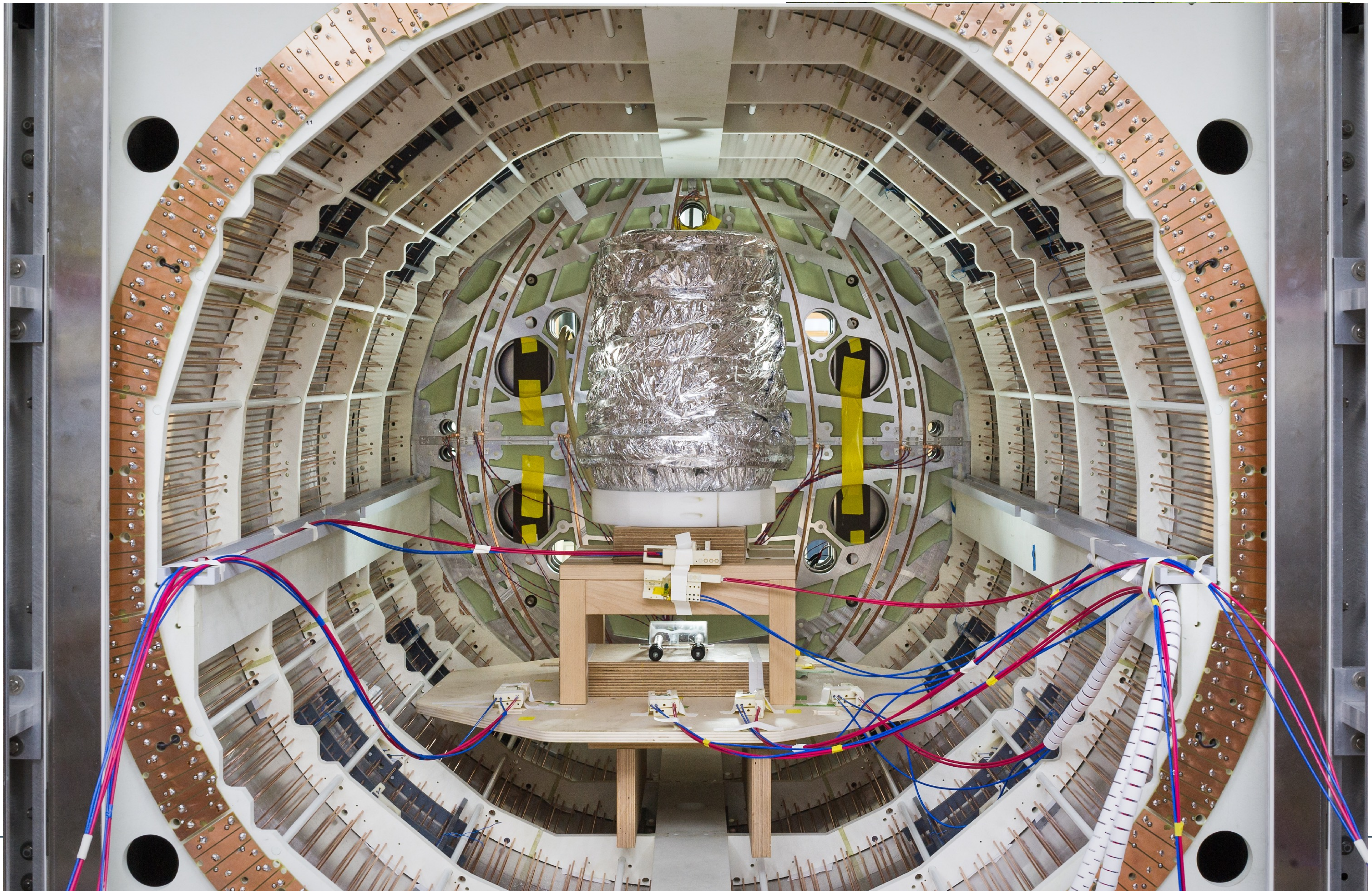
Goal: $\sigma(d_n) < 5.10^{-28}$ ecm (3σ) with 200 days data, stat.+syst.

Experiment - Setup



External Magnetic Shielding

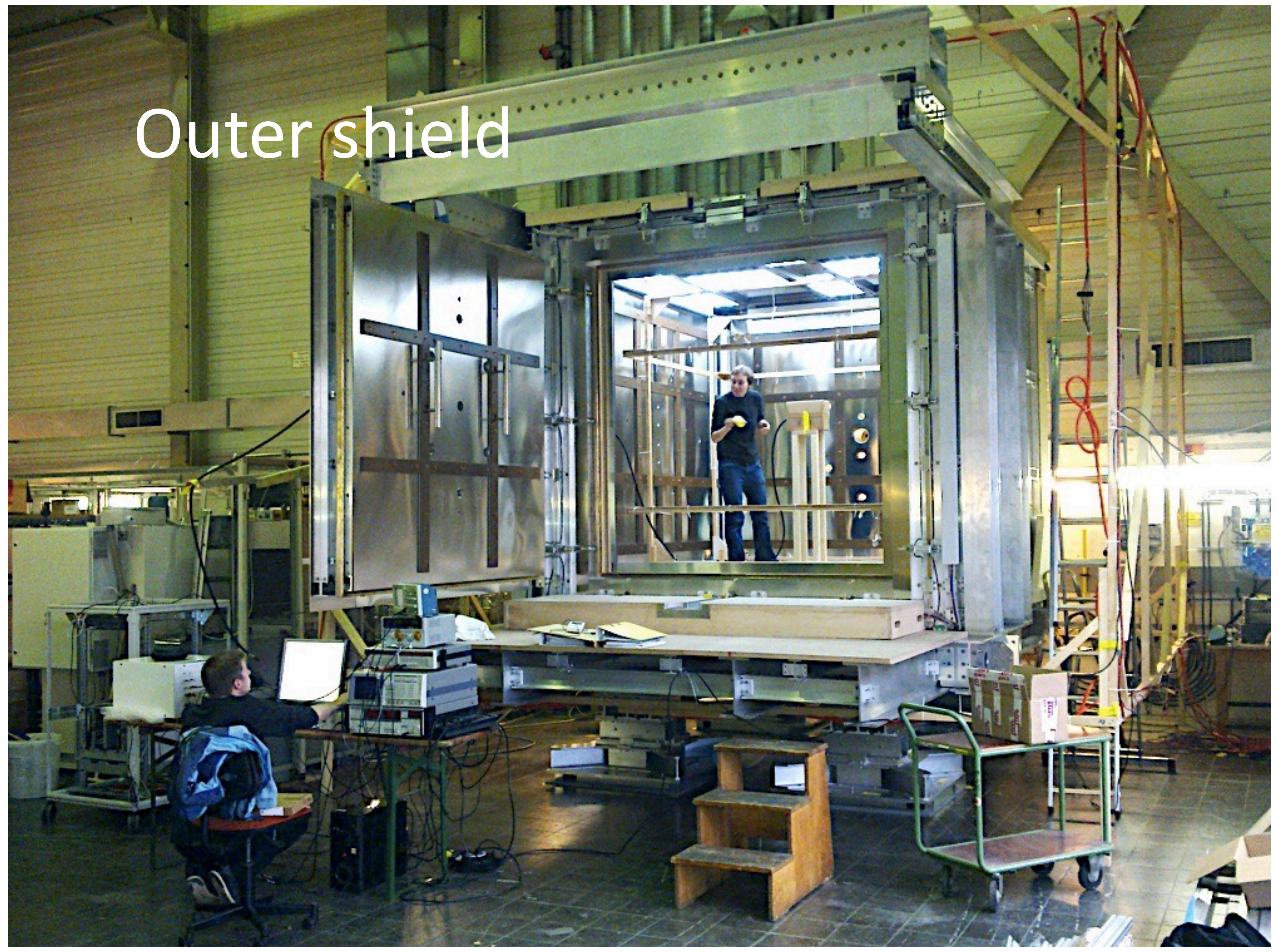
Fierlinger et al.



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

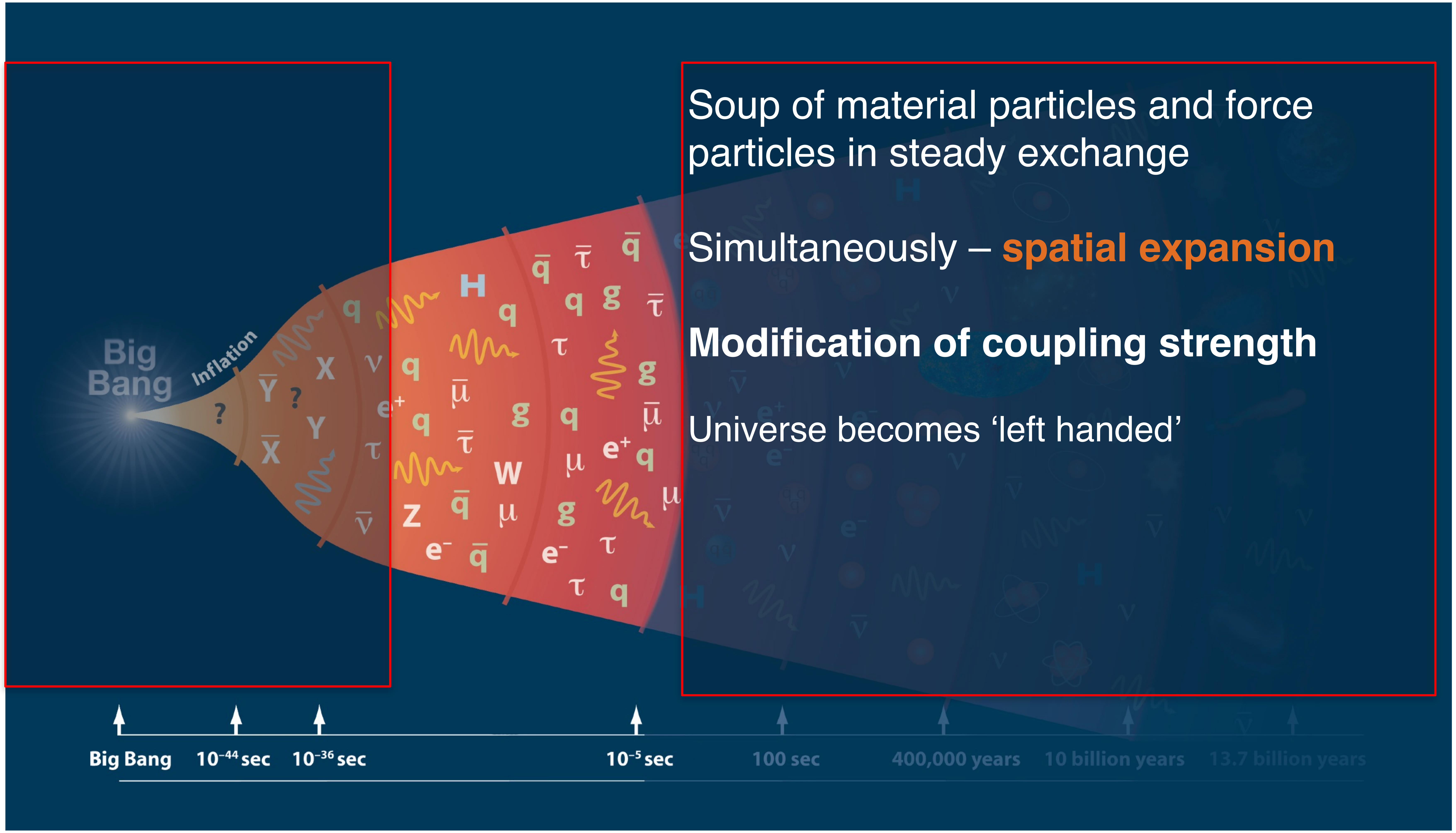


- Measured field in outer shield:
  < 3 nT in 5 cm distance from shield walls
  < 0.5 nT in 1 m^3 volume
  < 150 pT in EDM cell volume
  < 1 pT/cm gradient in
  0.5 m diameter

Key issue: magnetometry

- Cs magnetometers and Hg co-magnetometer

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’

A modern Goldhaber experiment

Helicity of Neutrinos*

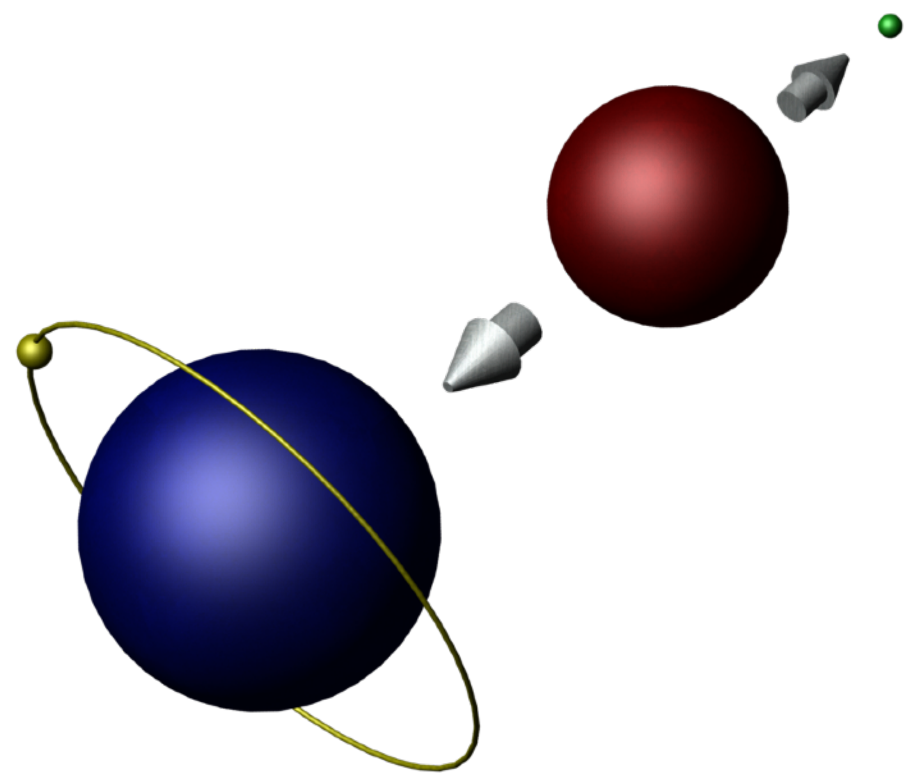
M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] $0-$, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

A Modern Goldhaber Experiment

Observe neutron decay:

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



2-body decay : properties of the *H* are a mirror of the ν_e properties

$$H_H = \frac{\vec{\sigma} \cdot \vec{p}}{|\vec{\sigma}| \cdot |\vec{p}|} = 0, H_{\bar{\nu}_e} \qquad \vec{p}_H = -\vec{p}_{\bar{\nu}_e}$$

with HFS analysis: $\vec{\sigma}_p \cdot \vec{\sigma}_e$ and $(\vec{\sigma}_p + \vec{\sigma}_e) \cdot \vec{\sigma}_{\bar{\nu}_e}$

Small decay width (BR=$4 \cdot 10^{-6}$) (83% 1s, 10% 2s)

Measurement technique

Unpolarised n decays in the magnetic field in a reactor tube

Selection: F, m_F of hydrogen atom with spin filter method

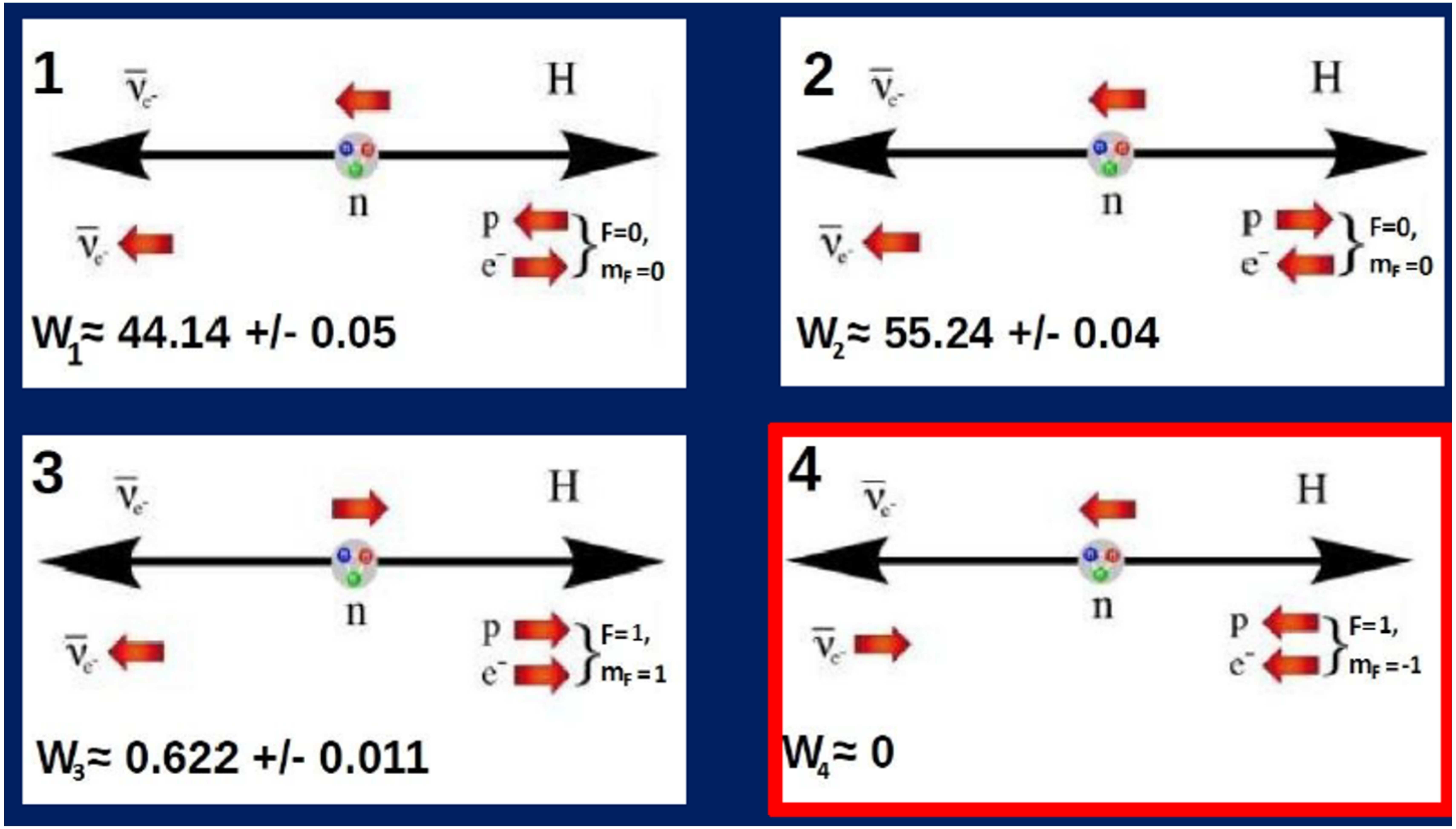
Identify: Hydrogen from n-decay via

- Doppler shift Laser ionisation process
- Ar charge exchange ionisation in H^- (1S-2S state selectivity ~1:100)
- Magnetic spectroscopy

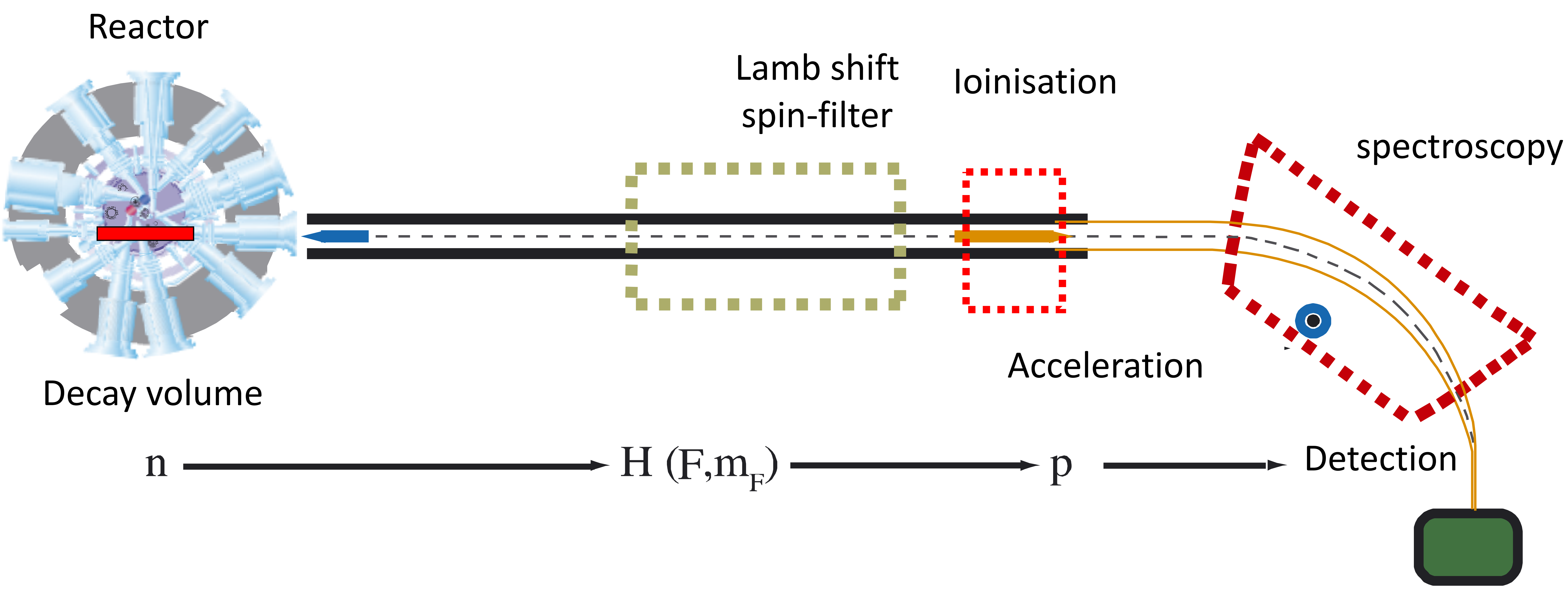
Rate: 0.3 H atoms/s in the 2S state

Physics:

- Relative rates F=0.1, m_F =0.1 Signature of g_S and g_T
- Rate of F=1, m_F = -1 shows (V+A)

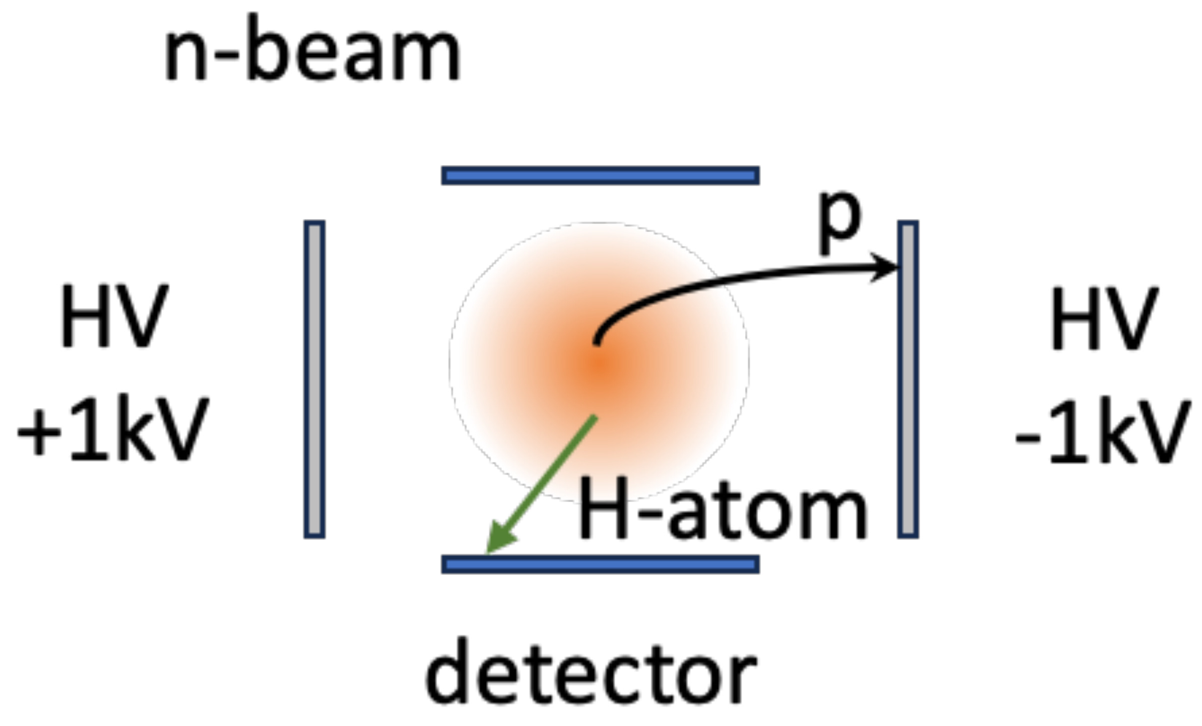

1
$\bar{\nu}_{e^-}$
H
n
$\bar{\nu}_{e^-}$
p
e^-
F=0, m_F=0
$W_1 \approx$ 44.14 +/- 0.05
2
$\bar{\nu}_{e^-}$
H
n
$\bar{\nu}_{e^-}$
p
e^-
F=0, m_F=0
$W_2 \approx$ 55.24 +/- 0.04
3
$\bar{\nu}_{e^-}$
H
n
$\bar{\nu}_{e^-}$
p
e^-
F=1, m_F=1
$W_3 \approx$ 0.622 +/- 0.011
4
$\bar{\nu}_{e^-}$
H
n
$\bar{\nu}_{e^-}$
p
e^-
F=1, m_F=-1
$W_4 \approx$ 0

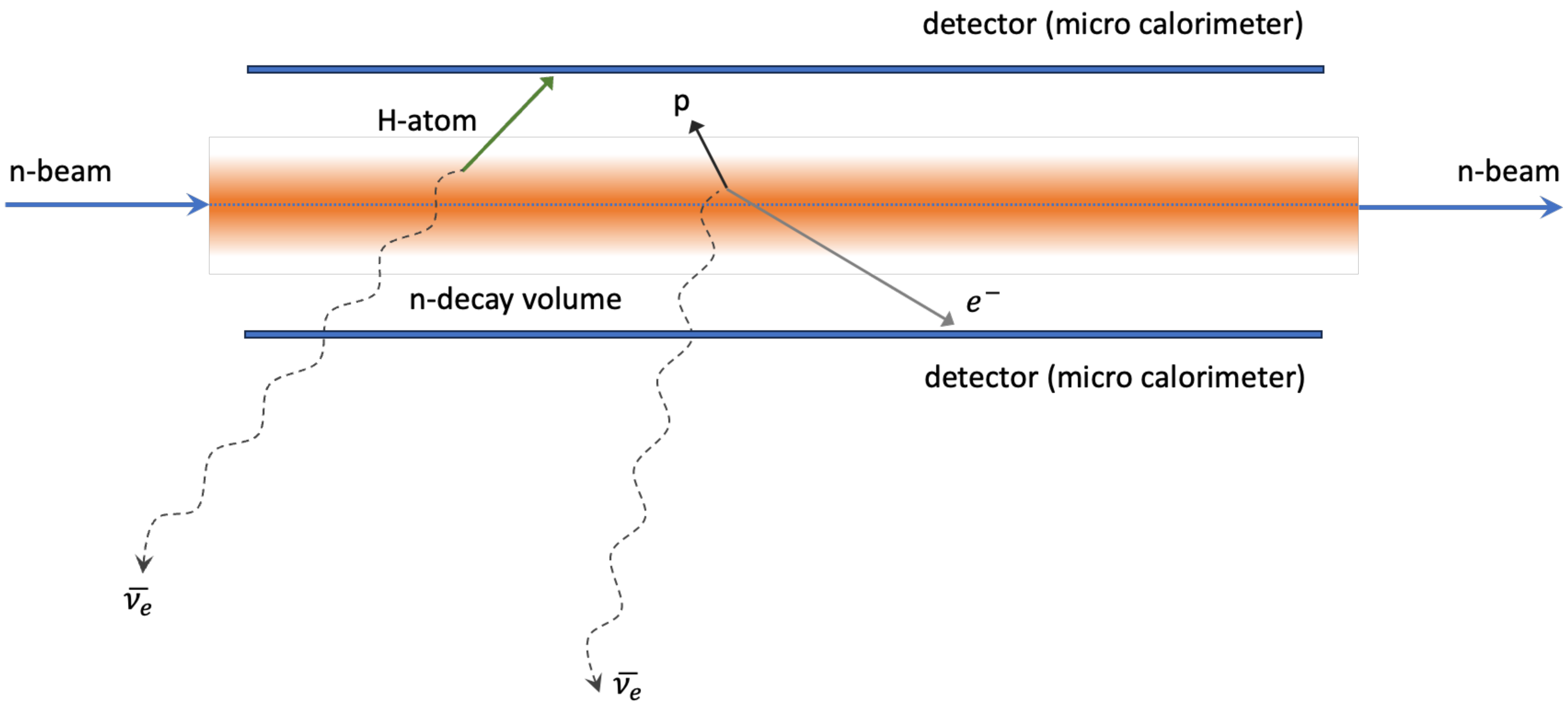
Principle of set-up



How to Detect 2-body Neutron Decay (nBOB)

- Use neutron source - FRMII (cold beam, core), ILL, CSNS
- Define decay volume
- Detect hydrogen atoms - microcalorimeter*
  - Measure their energy - 326 eV with $\Delta E \approx 1$ eV





*together with Shuo Zhang (CSNS)

Precision and competition of BoB

Expected precision:

- Improvement of g_S (upper limit): Factor 10 in 4 δαψσ/ε (ε=εφφιιενχψ)
  - Previously: lg/g_{sV} l< 0.067*
- Improvement of g_T (upper limit): Factor 20 in 4 days/e
  - Previously: lg/g_{TA} l<0.09 *
- Improvement of H_ν : factor 100 in 60 δαψσ/ε (statistically)
  - Previous realisation: 15% from μ,τ decays

Competition

- Neutron decay correlations
- Direct search of W_R at the LHC
- Muon and tau decays (Michel parameter) - presently best limits

At ILL: decay rates 10 times higher than in Munich

*Severijns et al. 2006: global fit with/without τ_n new

Structure of the Weak Interaction

- Right-handed currents (left-right symmetrical models)
  - W_R , ν_R
  - Measure left-handedness of the ν
- Tensor or scalar forces
  - g_T , g_S
  - Measure ratio of (V-A) coupling and total coupling

Structure of the Weak Interaction

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- Tensor or scalar forces
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  - Measure ratio of (V-A) coupling and total coupling

- Use neutron decay: observe
  - $n \to pe\bar{\nu}_e \to H\bar{\nu}_e$ with HFS analysis
  - Small branching ratio (BR=4·10^{-6}) (83% 1s, 10% 2s)

    $\vec{\sigma}_p \cdot \vec{\sigma}_e$ and $(\vec{\sigma}_p + \vec{\sigma}_e) \cdot \vec{p}_{\bar{\nu}_e}$
  - Rate: 0.3 H atoms/s in 2s state

Structure of the Weak Interaction

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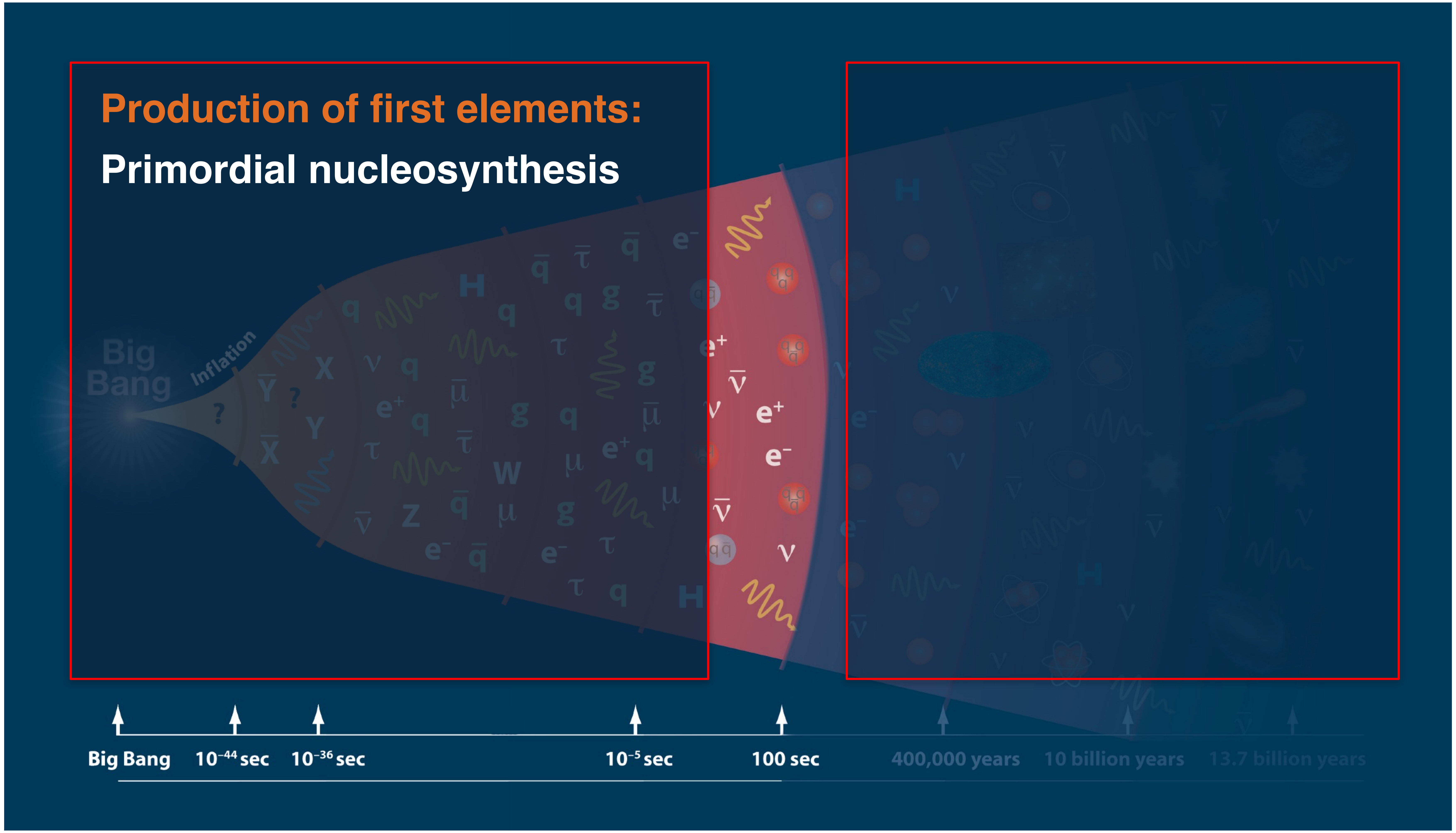
  - Measure ratio of (V-A) coupling and total coupling

- Use neutron decay: observe
  - $n \to pe\bar{\nu}_e \to H\bar{\nu}_e$ with HFS analysis
  - Small branching ratio (BR=$4\cdot 10^{-6}$) (83% 1s, 10% 2s)
    $\vec{\sigma}_p \cdot \vec{\sigma}_e$ and $(\vec{\sigma}_p + \vec{\sigma}_e) \cdot \vec{p}_{\bar{\nu}_e}$
  - Rate: 0.3 H atoms/s in 2s state
- Physics:
  - Relative rates of F=0.1, m_F =0.1 give signature of g_S and g_T
  - Rate of F=1, m_F = -1 shows (V+A)

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



Primordial Nucleosynthesis

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

thermal equilibrium

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

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

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

neutron decay

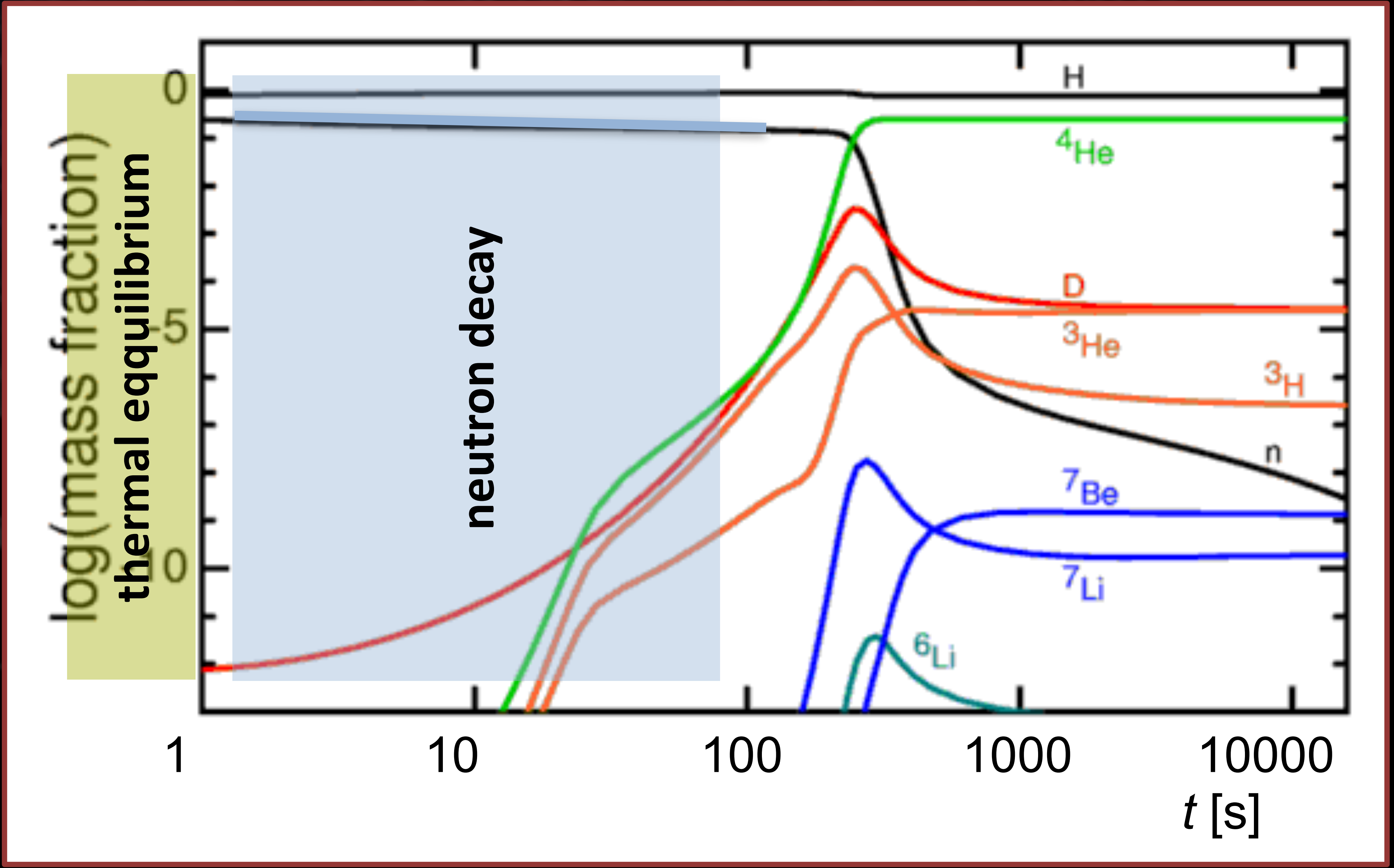
$$n \rightarrow p + e^- + \bar{\nu}$$

n/p: 1/6 ➢ 1/7

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

deuterium fusion

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



*T in sun 6000ºC at surface to 15 MioºC in the core

Primordial Nucleosynthesis

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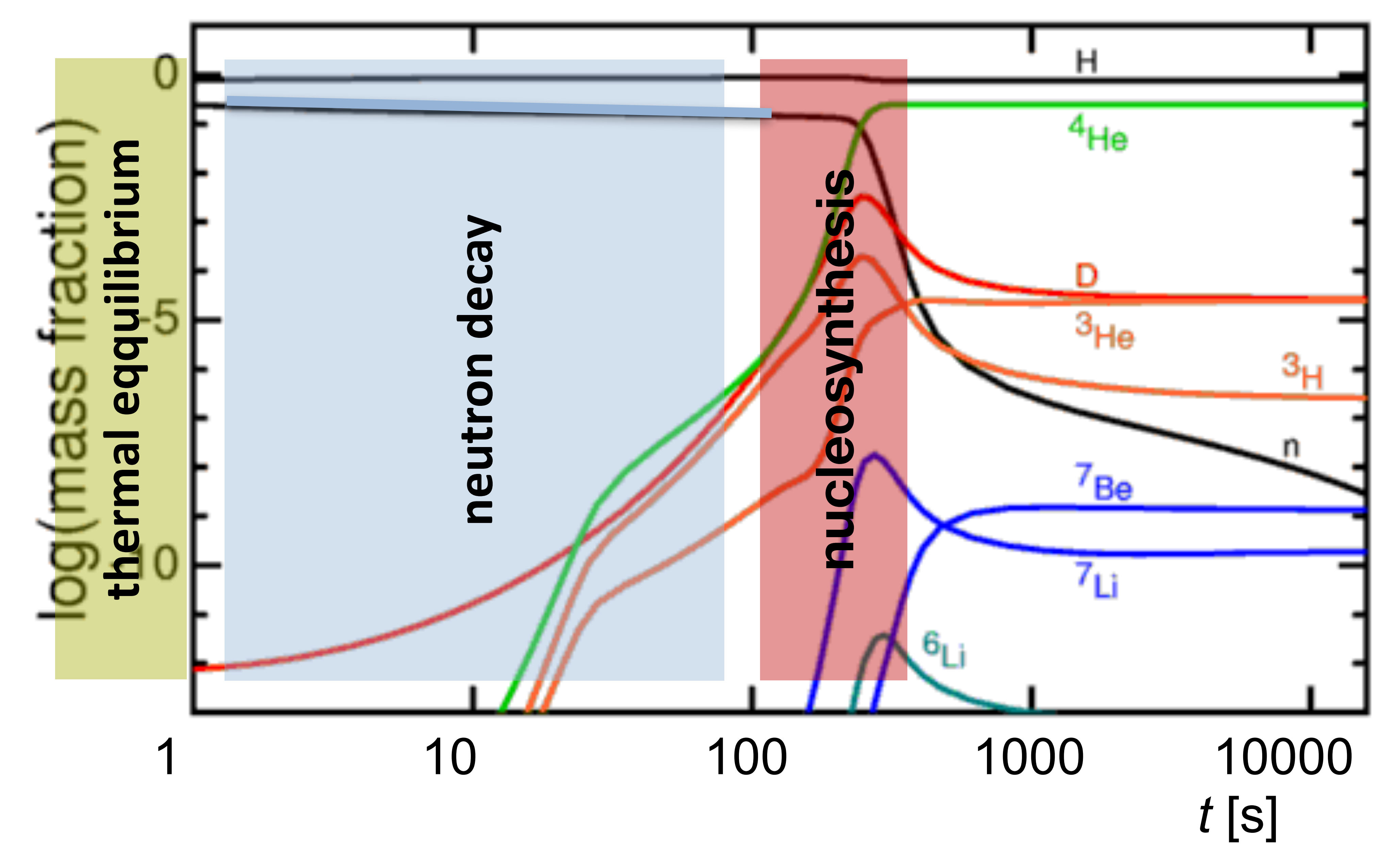
n/p: 1/6 ≻ 1/7

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

$$n + p \longrightarrow d + \gamma$$

t > *100* s, *kT* < *0.1* MeV (1.2 billion ºC)
nucleosynthesis

$$d + p \longrightarrow {}^3\mathrm{He} + \gamma$$
$$d + d \longrightarrow {}^3\mathrm{H} + p$$
$$d + d \longrightarrow {}^3\mathrm{He} + n$$
$${}^3\mathrm{He} + {}^4\mathrm{He} \longrightarrow {}^7\mathrm{Be} + \gamma$$
$${}^3\mathrm{He} + d \longrightarrow {}^4\mathrm{He} + p$$
$${}^3\mathrm{He} + n \longrightarrow {}^3\mathrm{H} + p$$
$${}^7\mathrm{Li} + p \longrightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$$
$${}^7\mathrm{Be} + n \longrightarrow {}^7\mathrm{Li} + p$$
$${}^3\mathrm{He} + {}^4\mathrm{He} \longrightarrow {}^7\mathrm{Be} + \gamma$$



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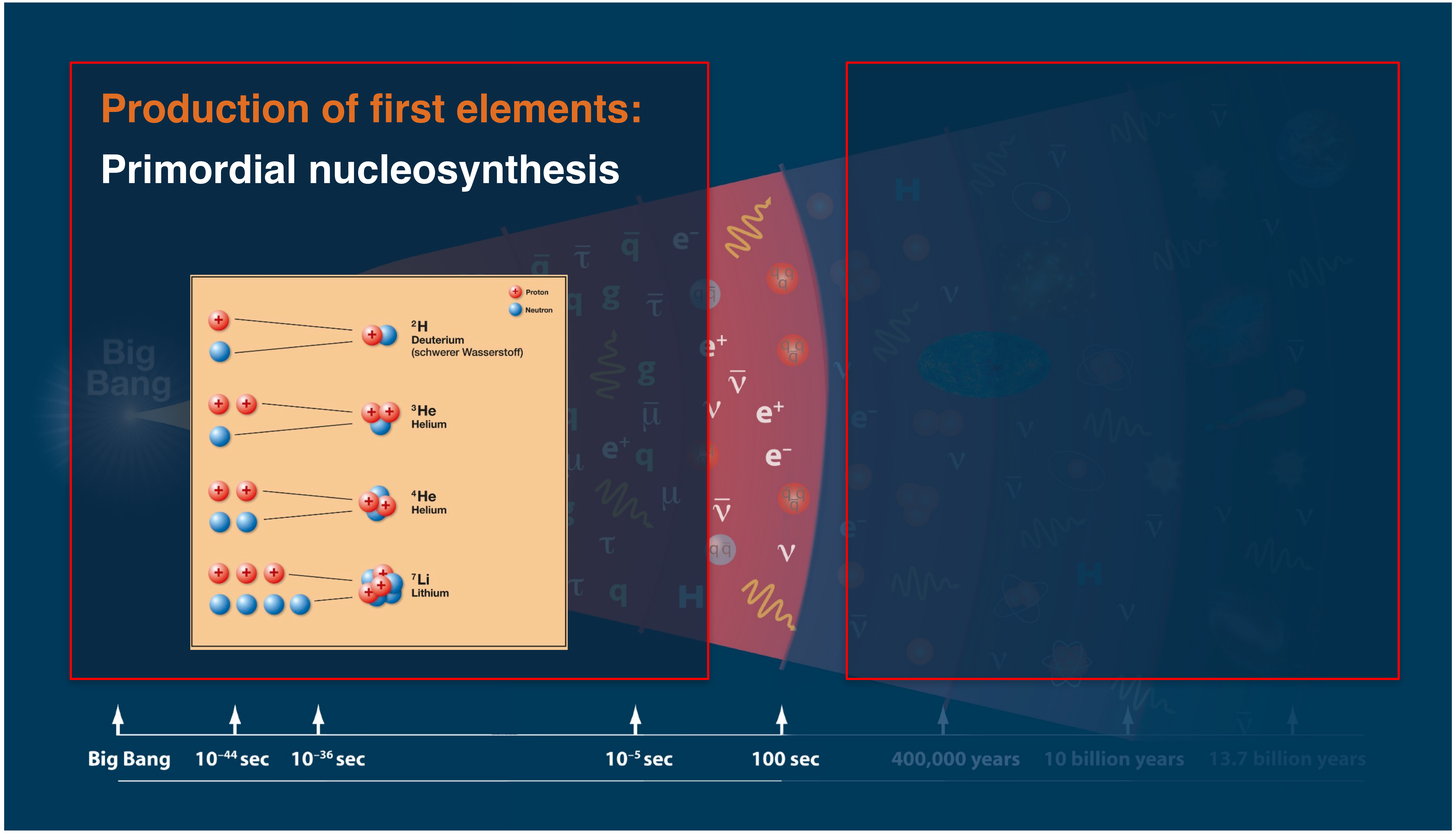
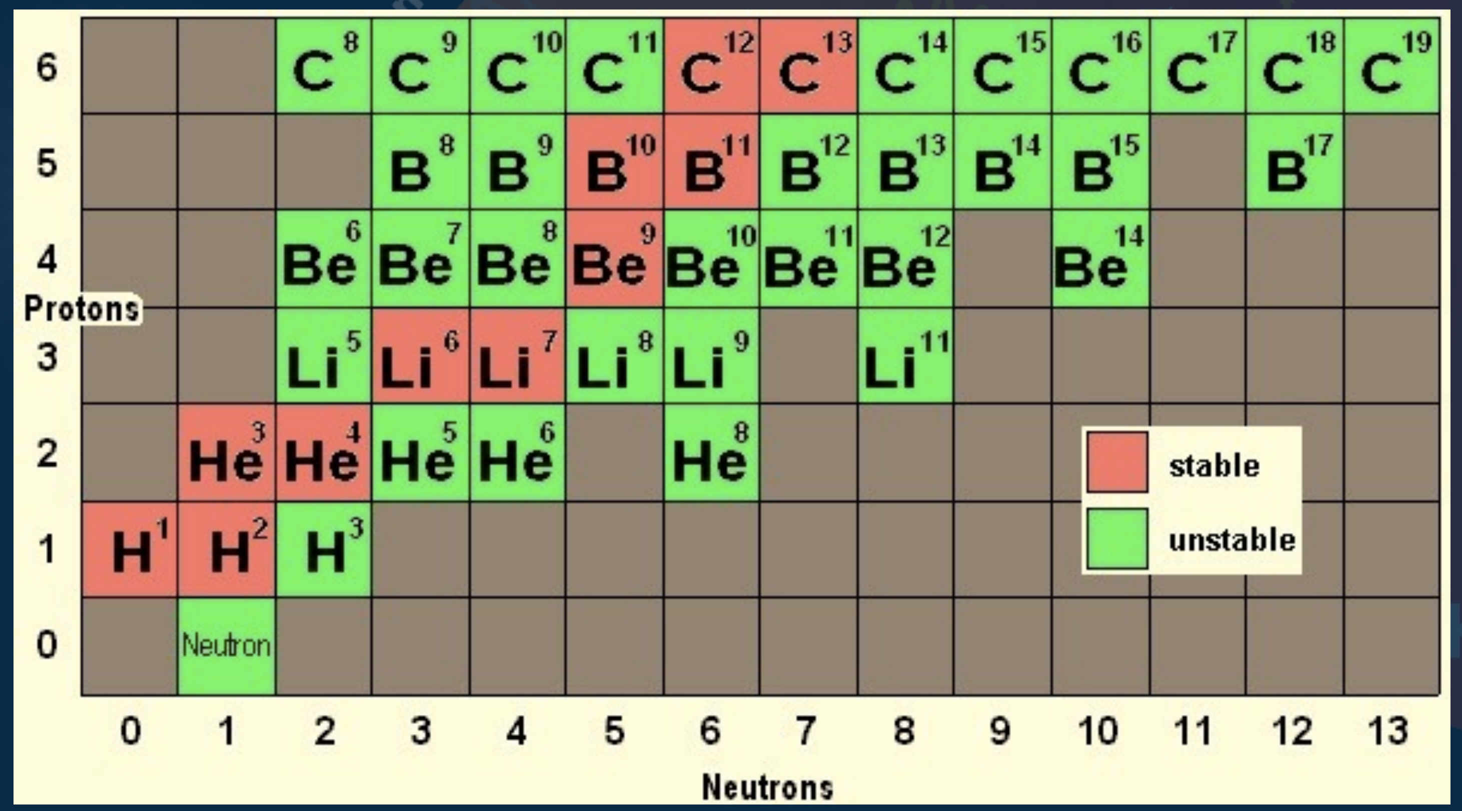


Production of first elements:
Primordial nucleosynthesis
Proton
Neutron
²H
Deuterium
(schwerer Wasserstoff)
³He
Helium
⁴He
Helium
⁷Li
Lithium
Big Bang
Big Bang
10⁻⁴⁴ sec
10⁻³⁶ sec
10⁻⁵ sec
100 sec
400,000 years
10 billion years
13.7 billion years

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

first 3 Minutes are over

Neutron Lifetime and Nucleosynthesis

Three parameters:

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

- CMB (WMAP-Satellit)

$Y_p = 4\text{ He} / (p + 4\text{ He})$

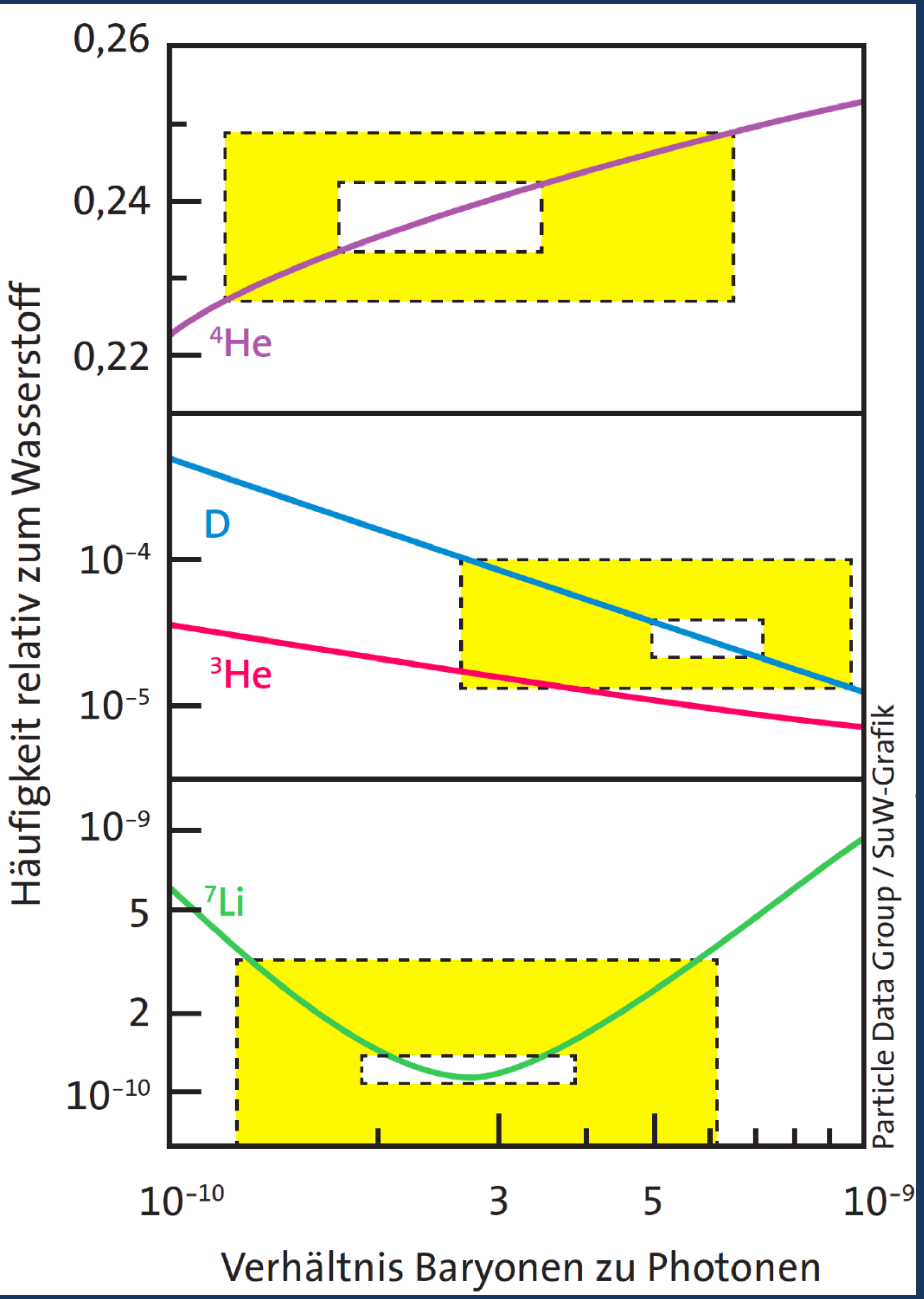
- Low metallicity (early) stars/galaxies

τ_n

- Experiments

Knowledge of weak and nuclear force:

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



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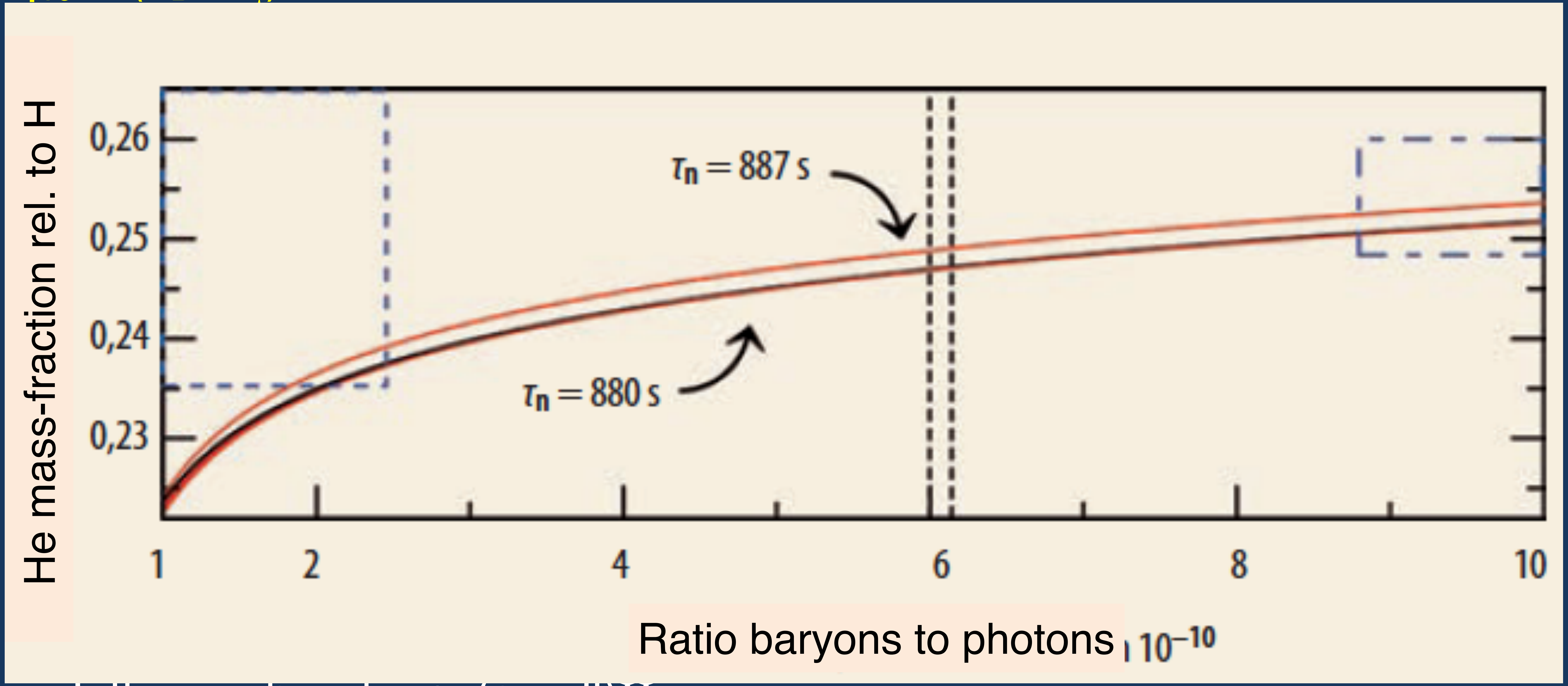

- Lithium abundance(small)**

Neutron Lifetime and Nucleosynthesis

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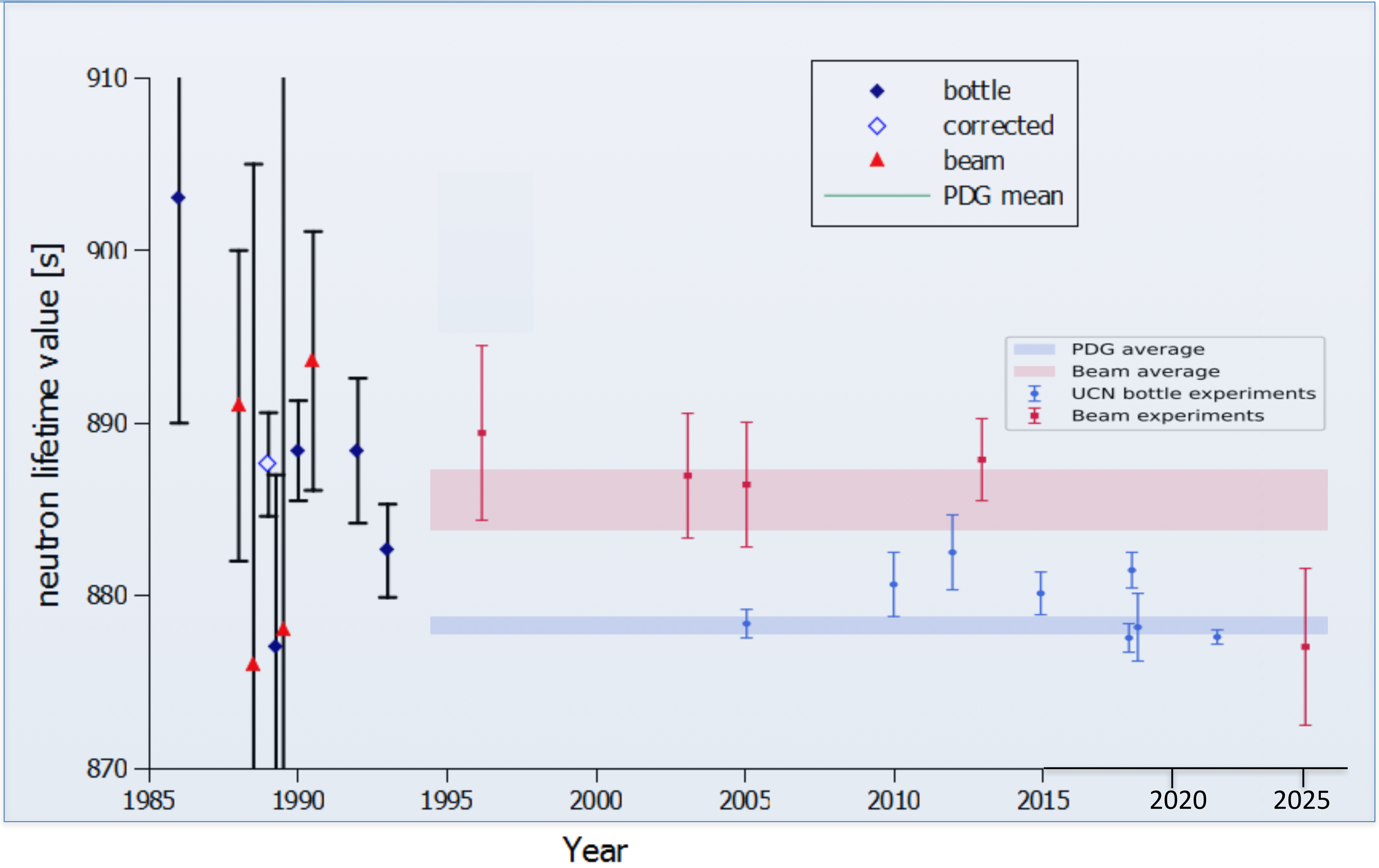
Lifetime - Overview

Measurements

Plagued by

- systematic effects
- personal bias
- competition for smallest quoted uncertainties



Lifetime - Overview

Measurements

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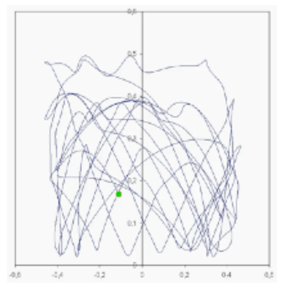
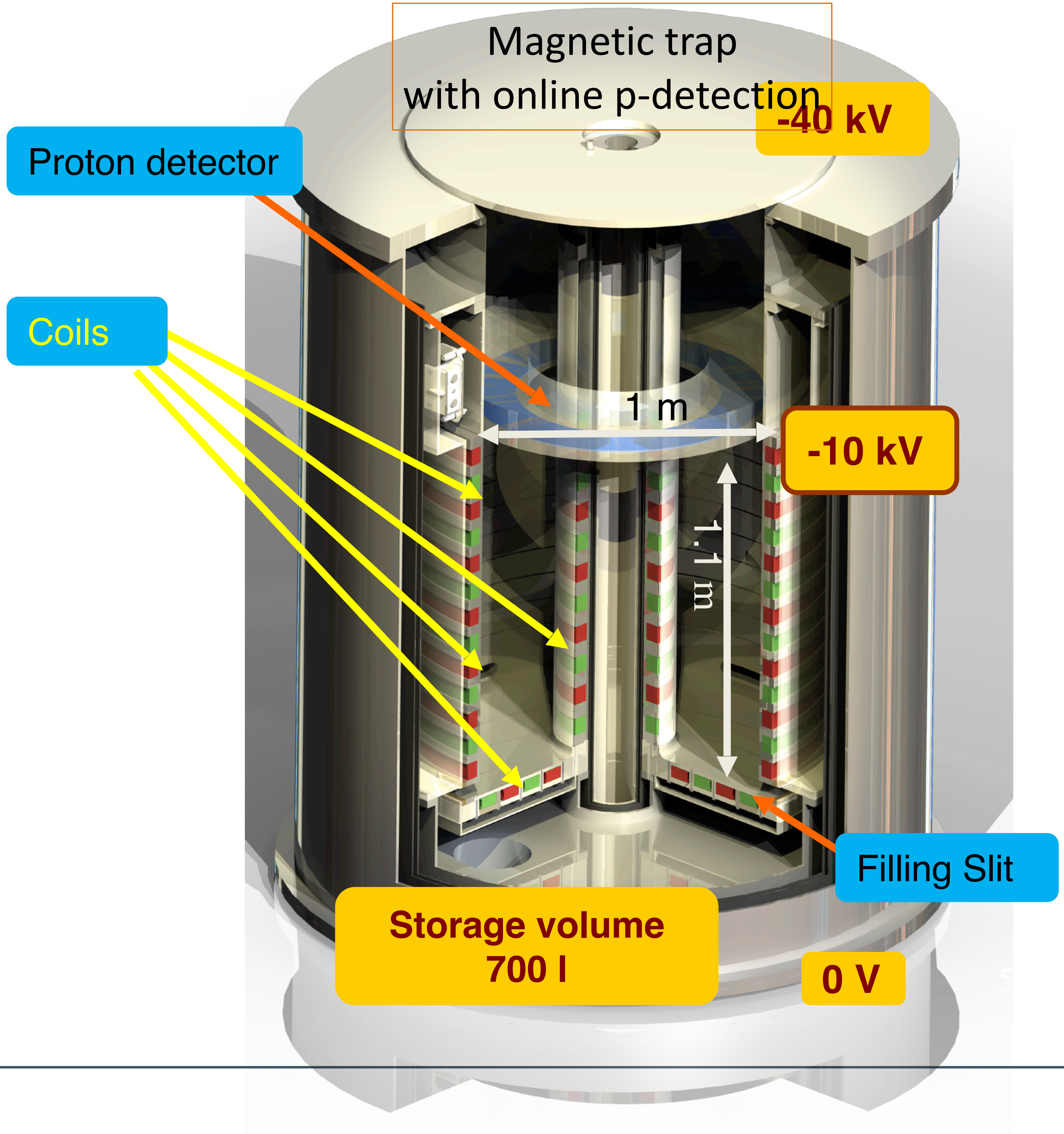
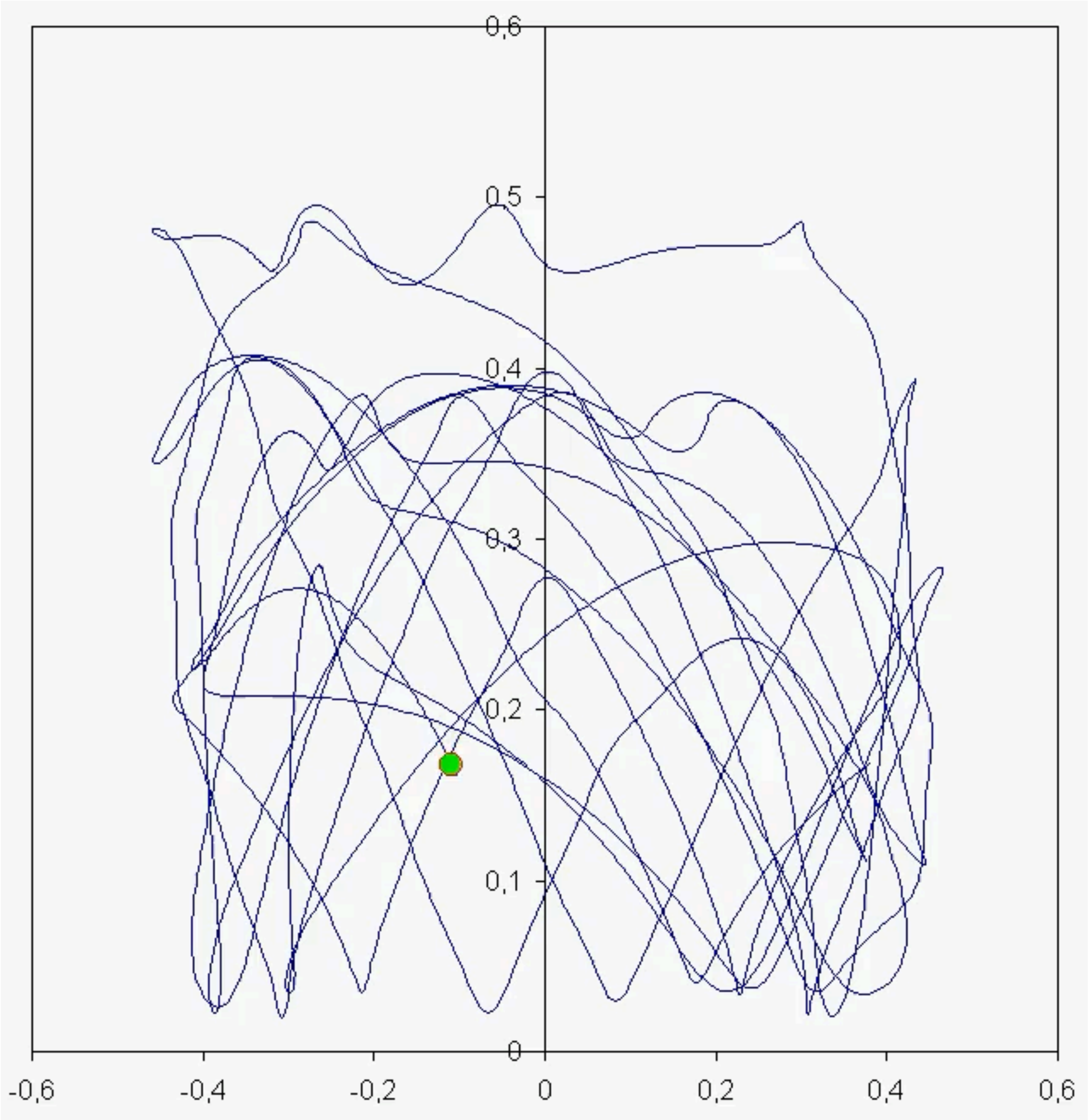
Measurement of n-Lifetime with PENeLOPE

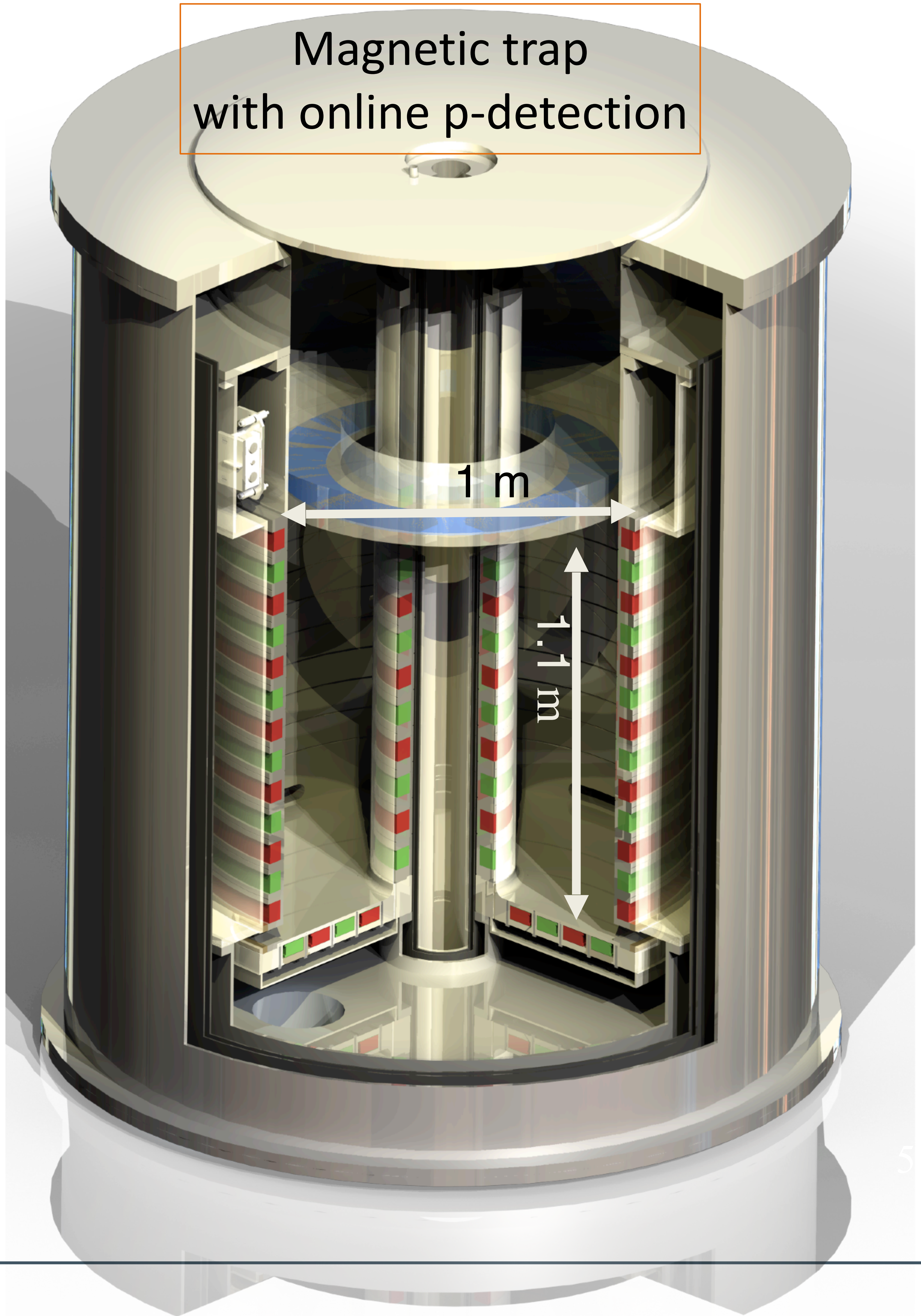




42 superconducting coils

Measurement of n-Lifetime with PENeLOPE





42 superconducting coils

Measurement of n-Lifetime with PENeLOPE

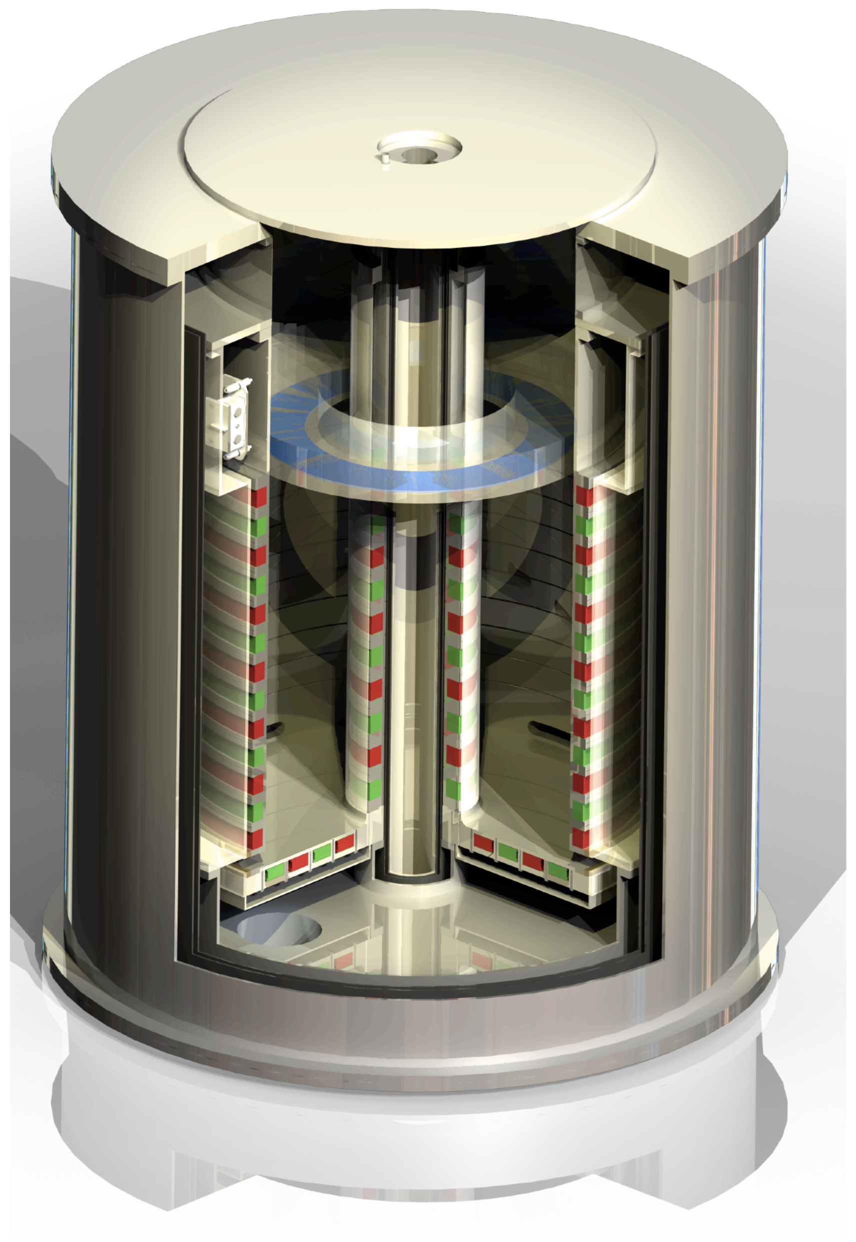
Detect protons online

- 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



42 superconducting coils

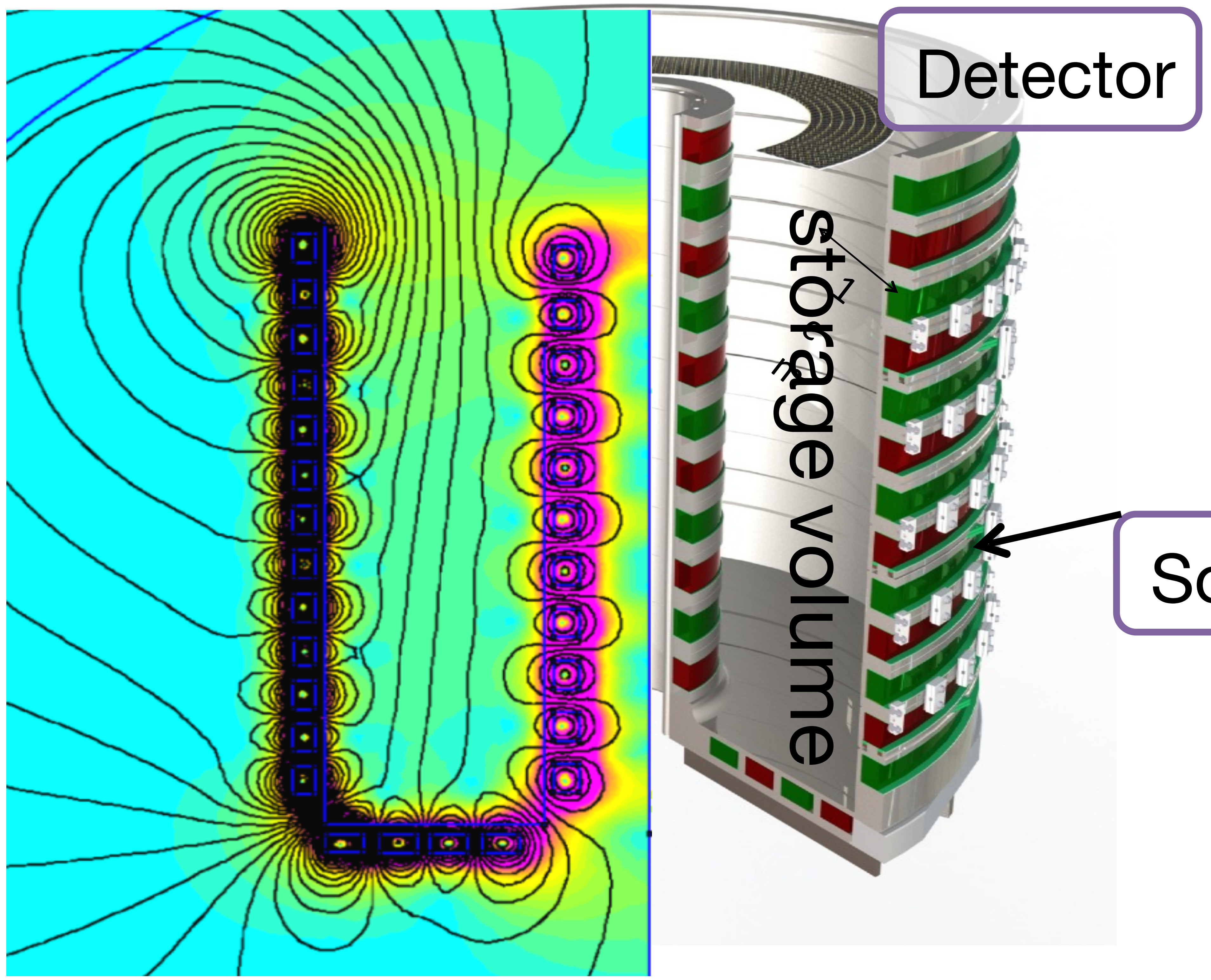
Assumption:

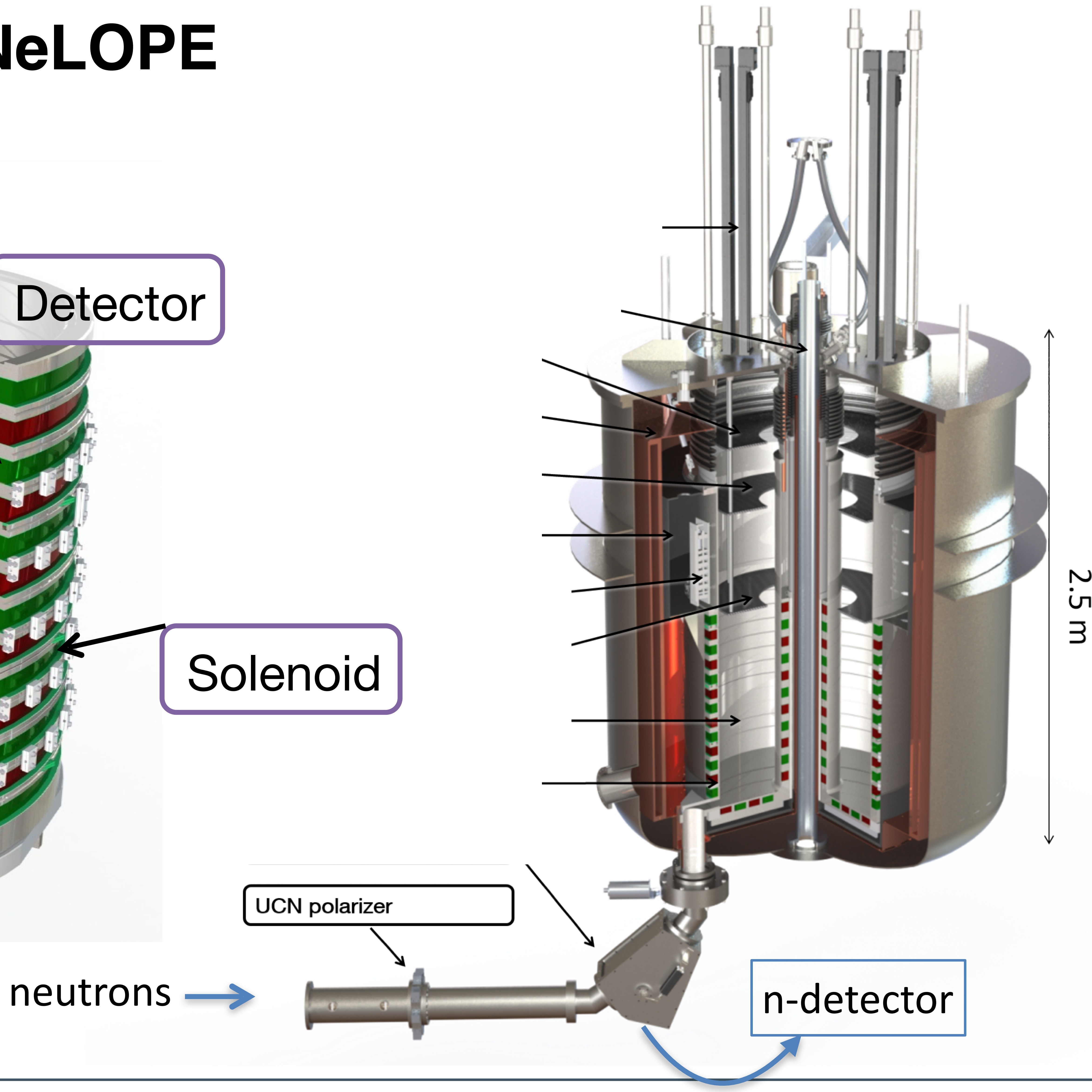
- new intense UCN source(FRMII, TRIUMF)
- UCN (gas-) density: $\rho = 10^3$-10^4 cm^{-3}
- B_{max}= 2 T B_{min}= 10^{-3} T
- Volume: 700 l
- $N_{storage}$= 10^7 -10^8
- Real time detection of p,e

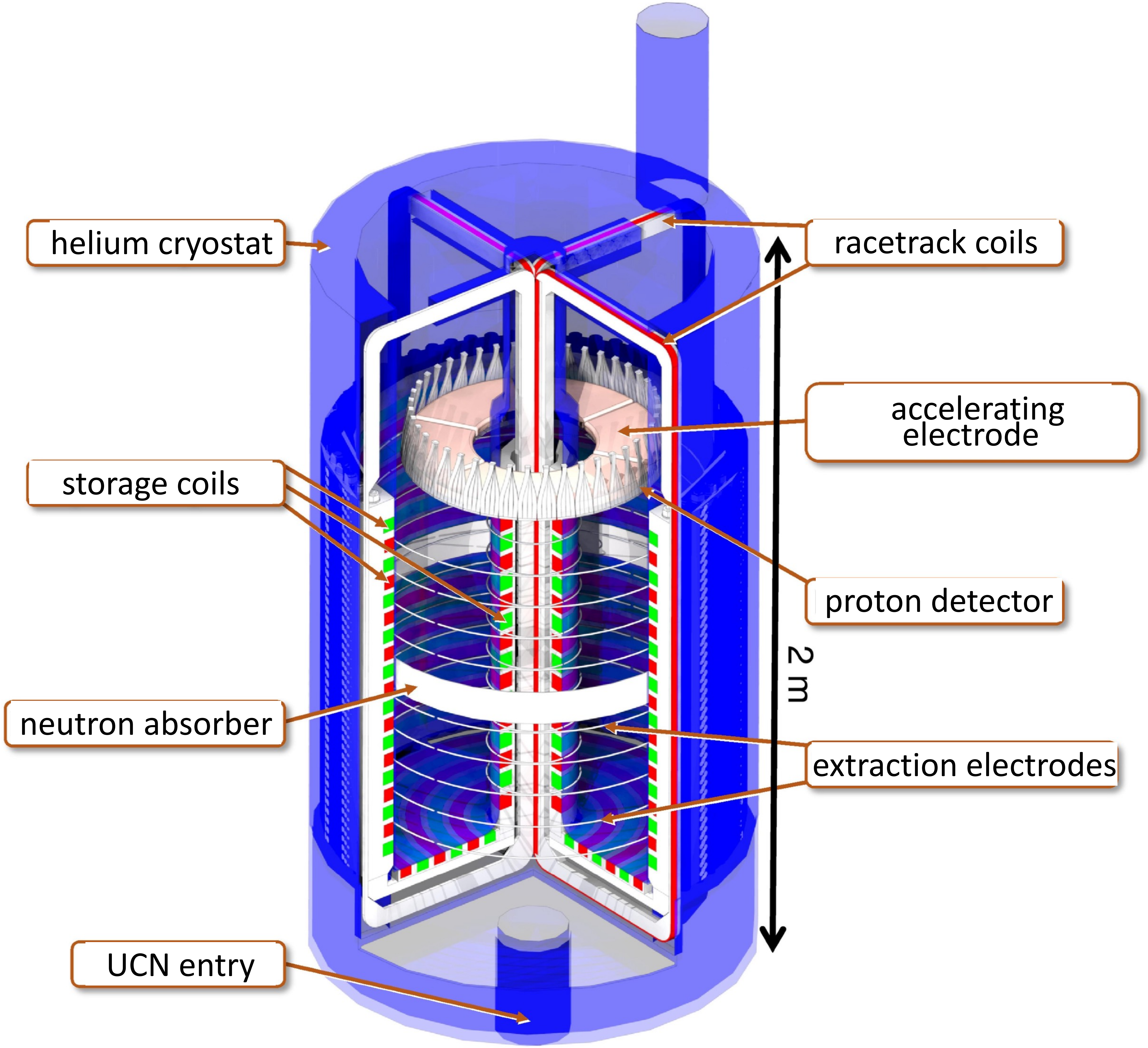
Statistical accuracy:

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

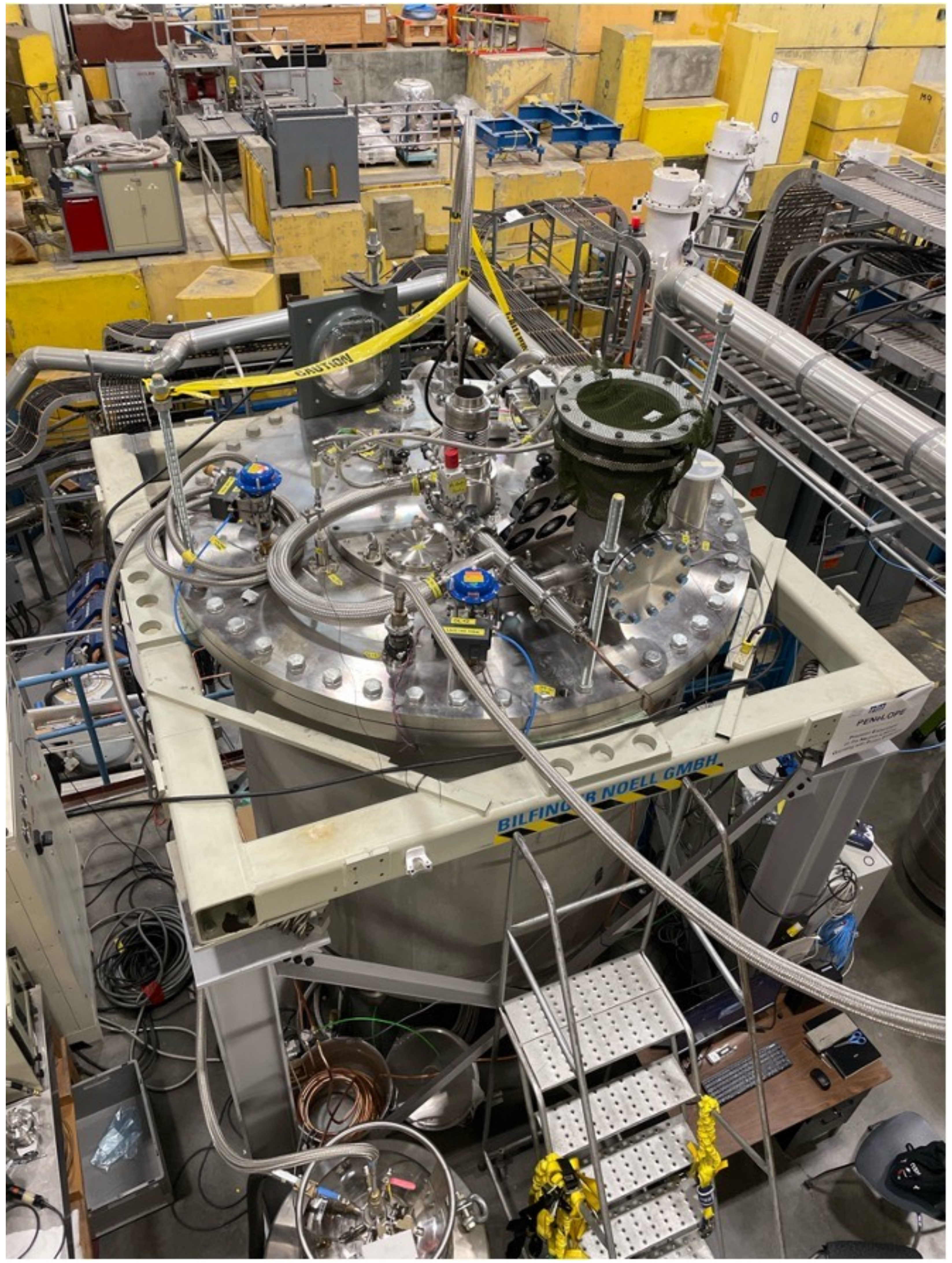
Configuration of PENeLOPE






helium cryostat
racetrack coils
accelerating electrode
storage coils
proton detector
2 m
neutron absorber
extraction electrodes
UCN entry

Magnet/Coil Production - Setup at TRIUMF



Source for ultra cold Neutrons

FRM II of TUM

Source for ultra cold Neutrons

UCN Sources

best source: SuperSun@ILL 235 UCN/cm³ with $3.6 \cdot 10^6$ total (new) (SFHe)

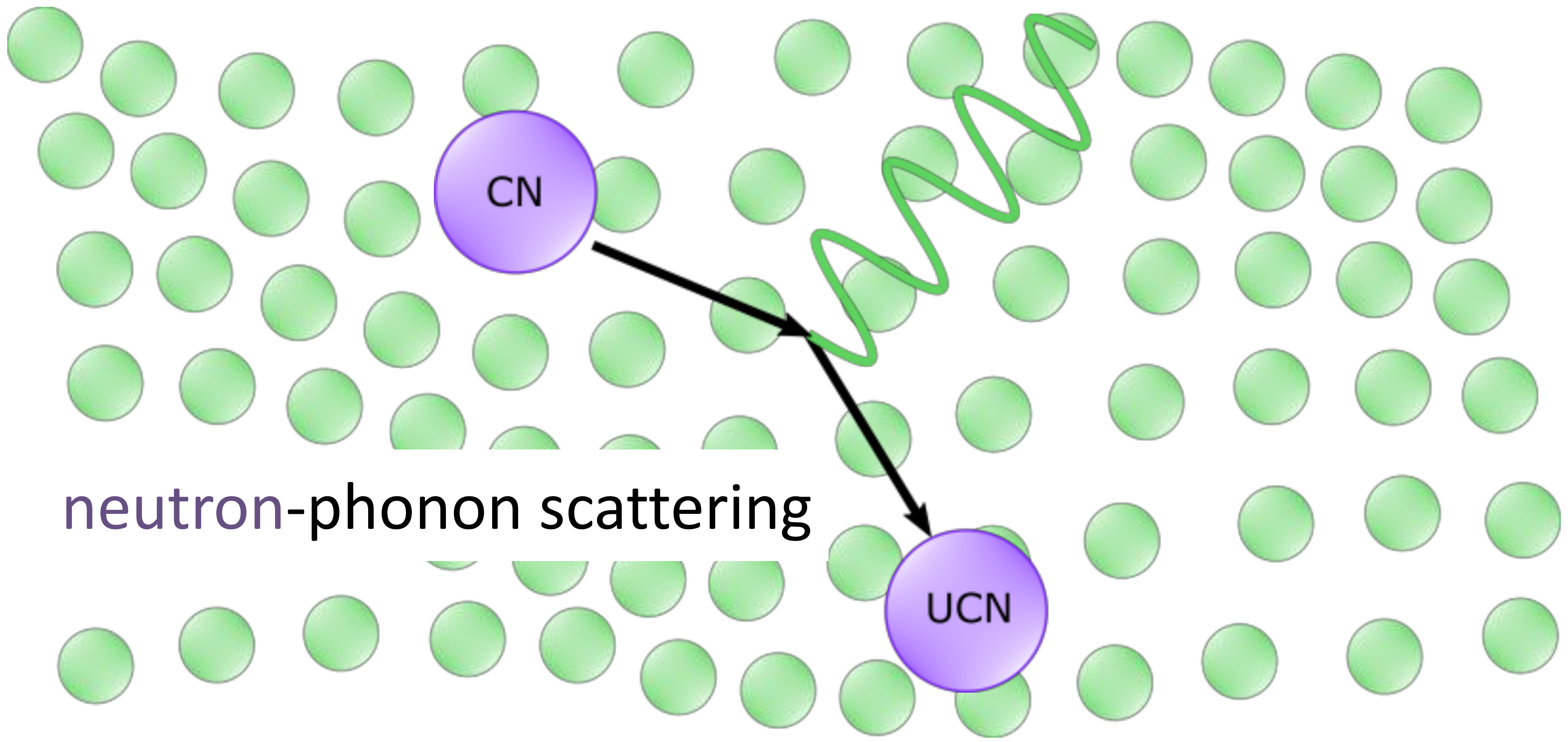
planned source: TUCAN@TRIUMF $1.6 \cdot 10^7/s$ - steady source (SFHe)

operating source: UCN@PSI 12 UCN/cm³ with $4 \cdot 10^5$ total (since 2011)

upgraded source: UCN@LANL 180 UCN/cm³ - pulsed

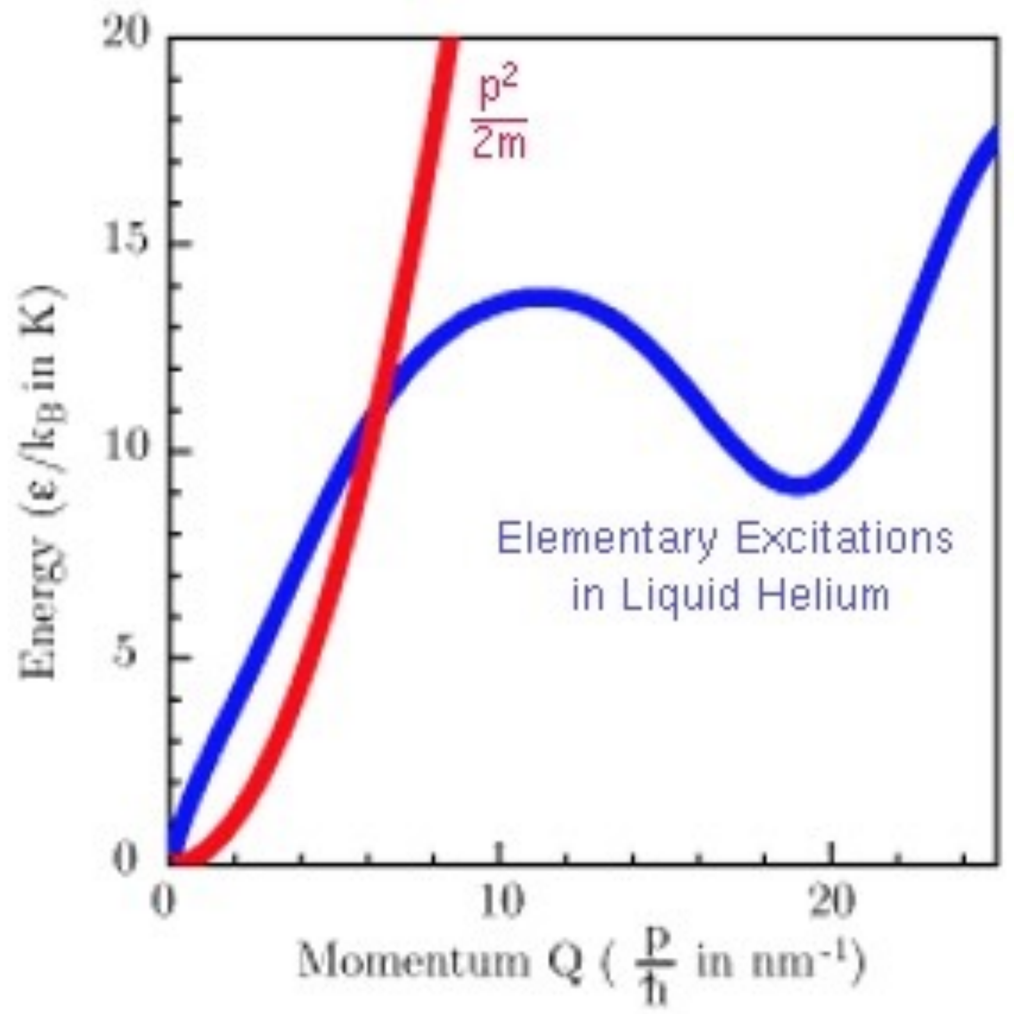
planned source*: UCN@FRMII 5000 UCN/cm³ - steady state source

use solid deuterium @ 5K



neutron-phonon scattering

use superfluid He @ 0.5K



* a similar source planned at CSNS

UCN Source: Generating Ultra Cold Neutrons

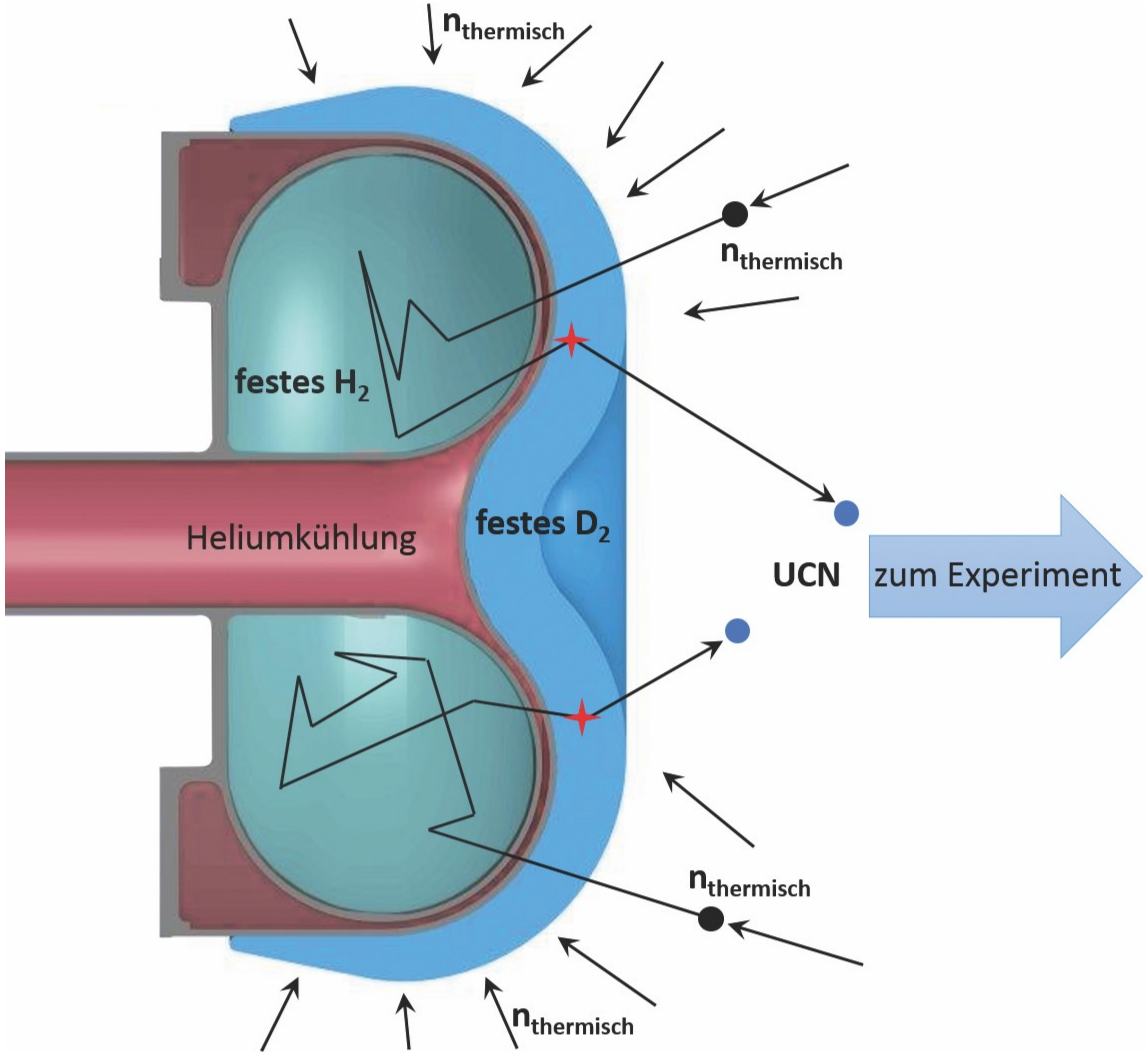
decelerating neutrons:

moderation:

- water (heavy water)
- liquid deuterium

cooling - superthermal source

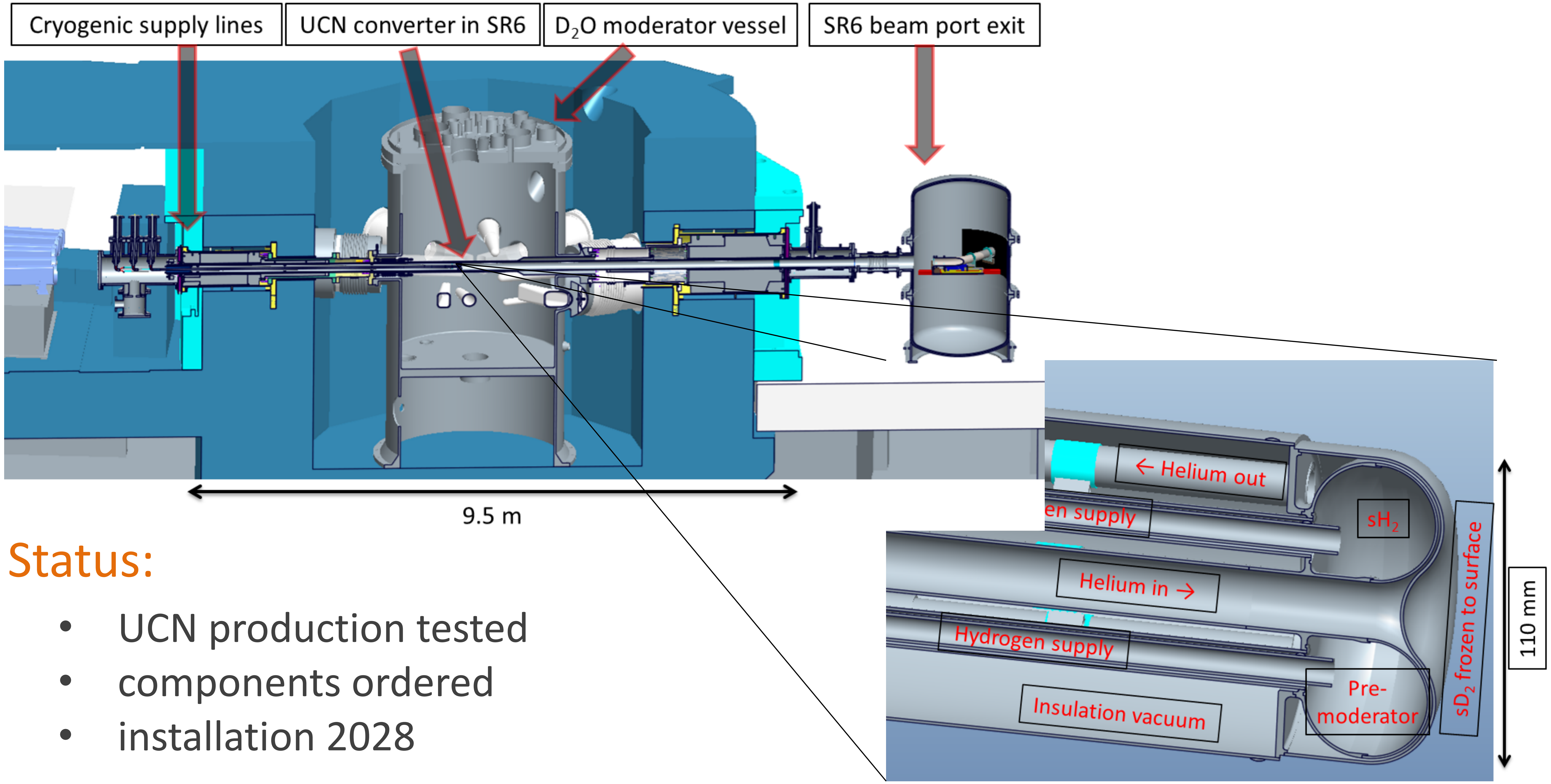
- solid deuterium (5K)
- superfluid helium



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 2028

Summary

- Particle physics with neutrons adresses the 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) erected (ILL) or in construction (FRMII, TRIUMF, CSNS)
- Internationally active field of science