Search for ultralight axions with neutron EDM experiments

Michał Rawlik

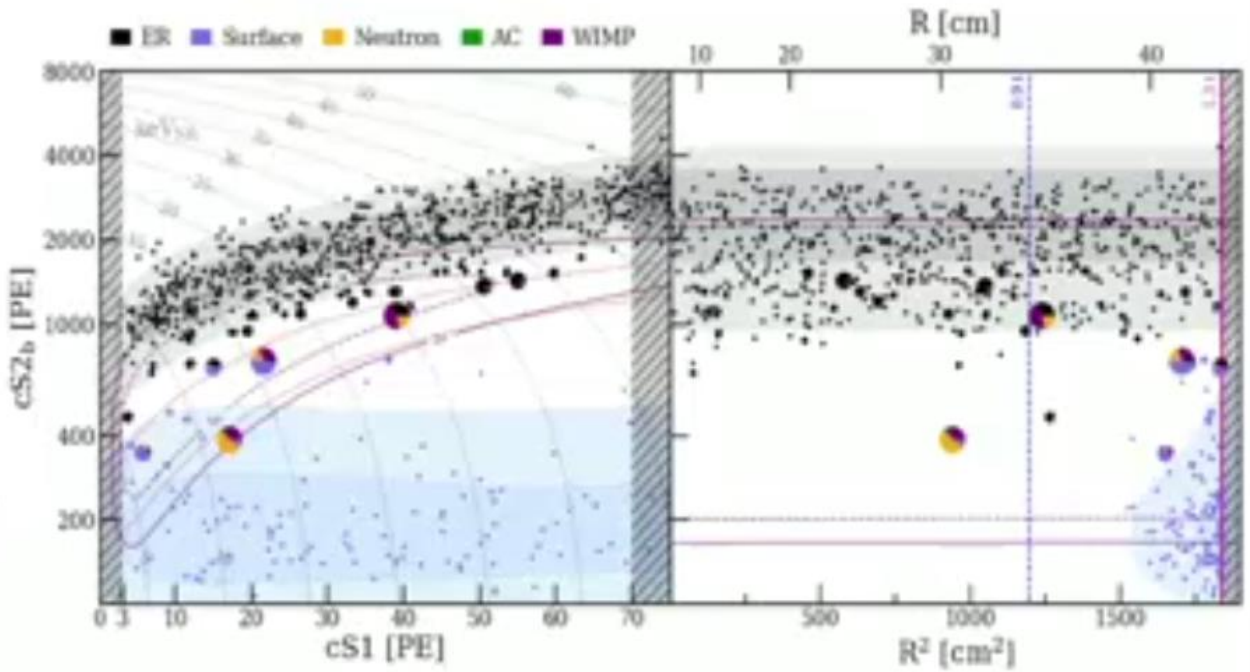
ETH Zürich

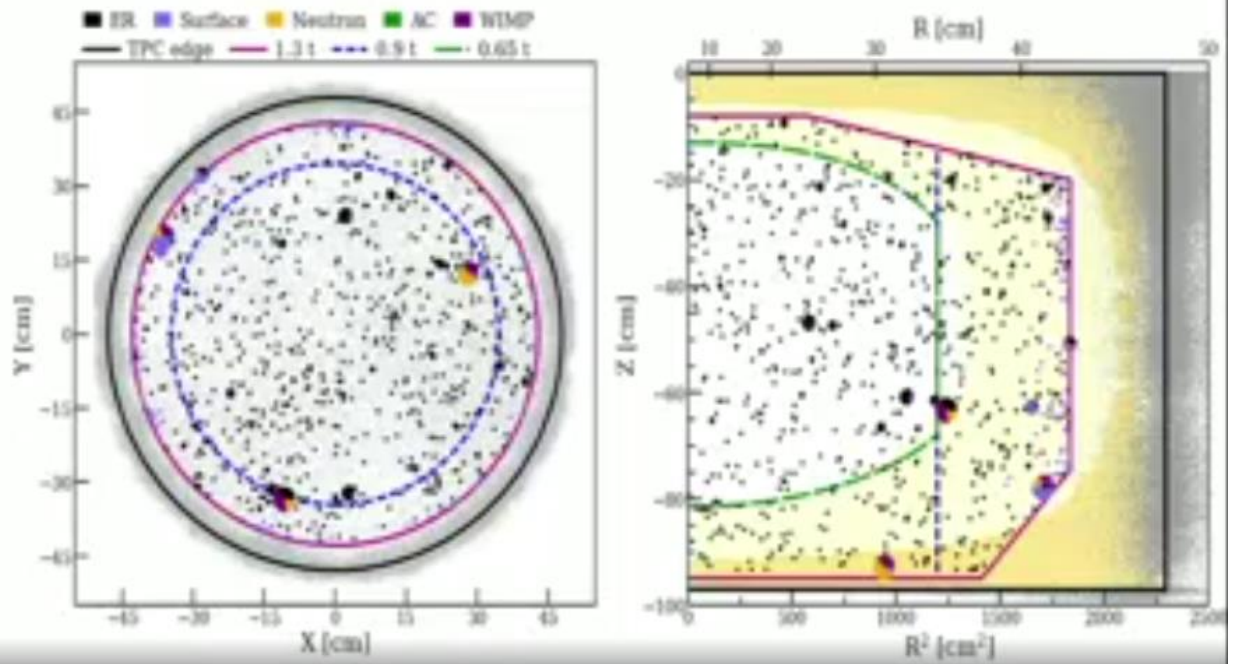
on behalf of the nEDM at PSI collaboration

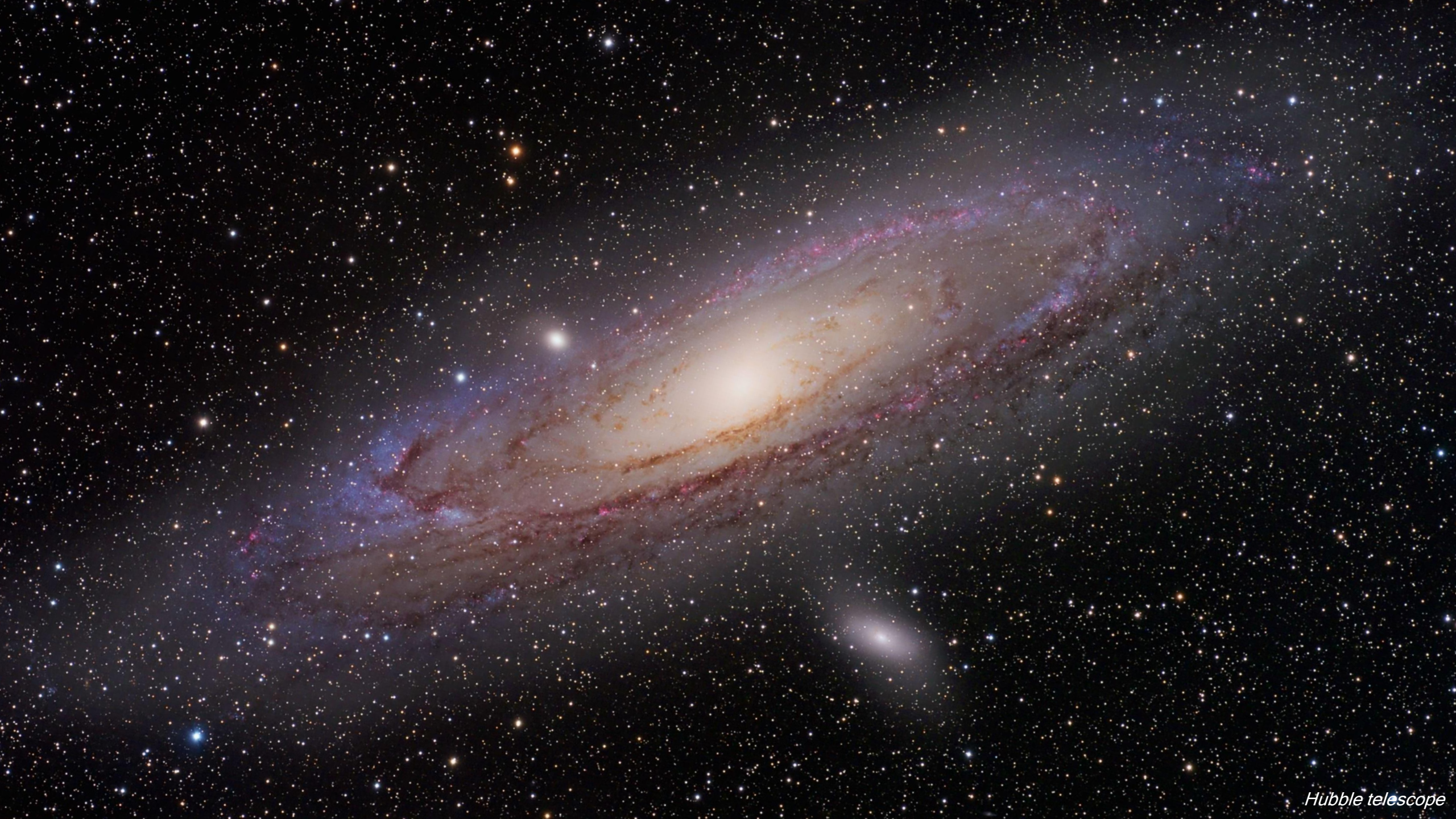
unbinned profile likelihood analysis in cs1, cs2, r space

1 σ, 2 σ for a 200 GeV/c² WIMP

pie charts show relative probabilities of this event to be of a certain class for a best fit to a 200 GeV WIMP






Hubble telescope

The chief forms of beauty are order and symmetry and definiteness,
Which the mathematical sciences demonstrate in a special degree.

- Aristotle *(Metaphysics)*

$$H = -2\,\mu\,\mathbf{B}\cdot\mathbf{S}$$

$$H = -2\,\mu\,\mathbf{B}\cdot\mathbf{S}$$

$$H = -2\,(\mu\,\mathbf{B} + d\,\mathbf{E})\cdot\mathbf{S}$$

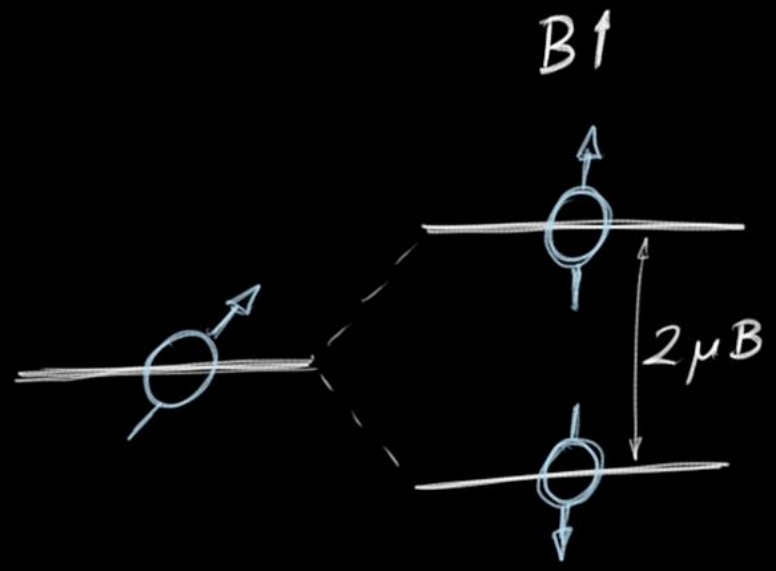
$$H = -2\,\mu\,\mathbf{B}\cdot\mathbf{S}$$

$$H = -2\,(\mu\,\mathbf{B} + d\,\mathbf{E})\cdot\mathbf{S}$$

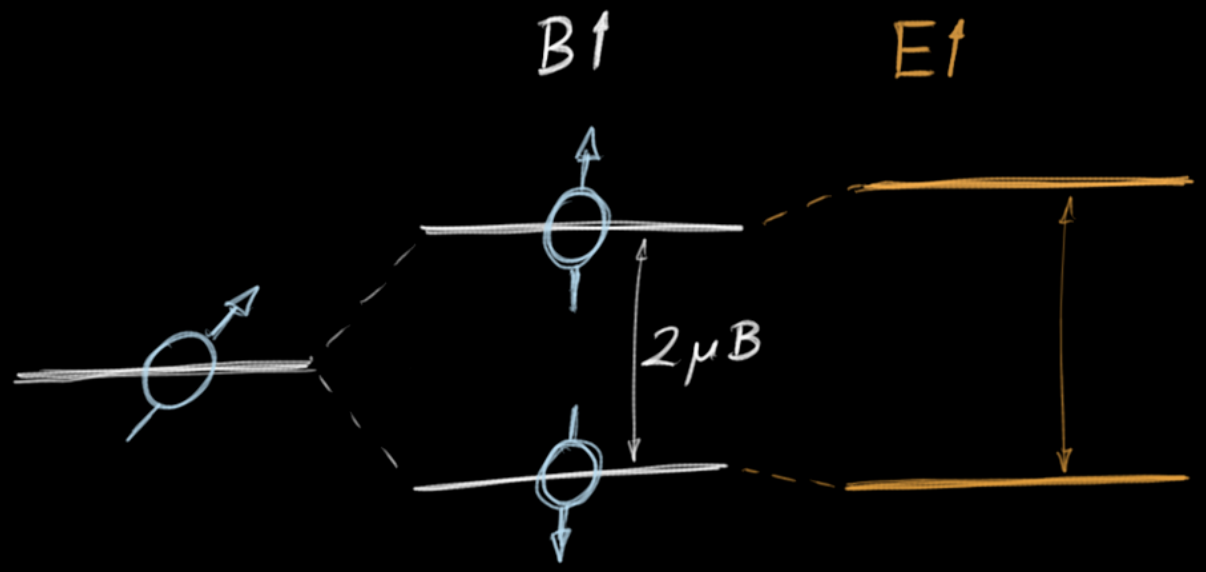
$$H_{CP} = H_T = +2\,(-\mu\,\mathbf{B} + d\,\mathbf{E})\cdot\mathbf{S} =$$

$$= -2\,(\mu\,\mathbf{B} - d\,\mathbf{E})\cdot\mathbf{S} \neq H$$

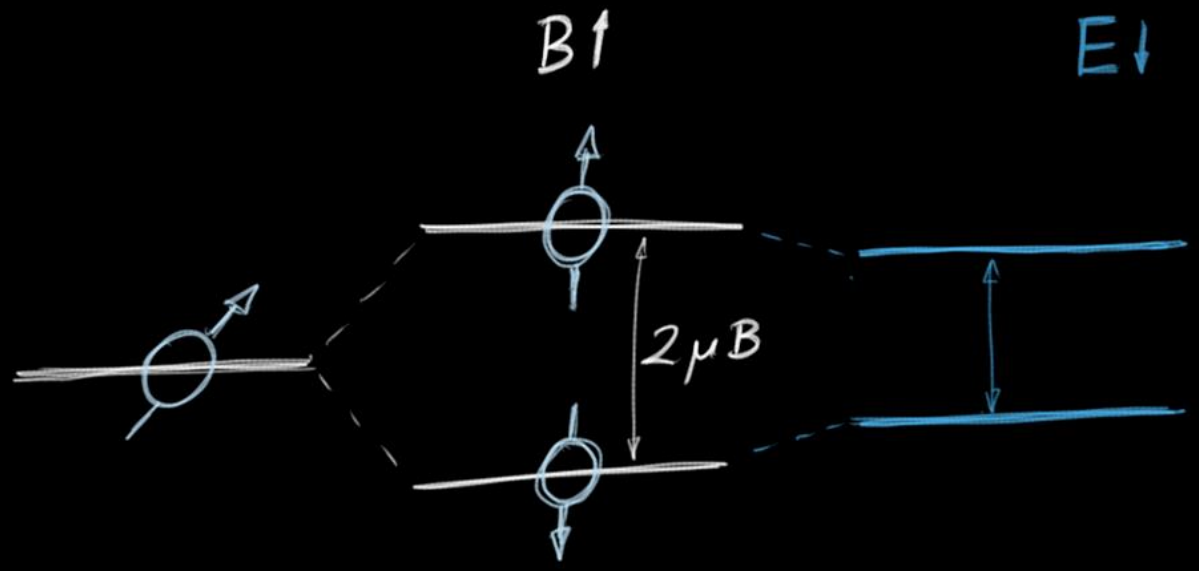
$$H = -2\,\mu\,\mathbf{B}\cdot\mathbf{S}$$



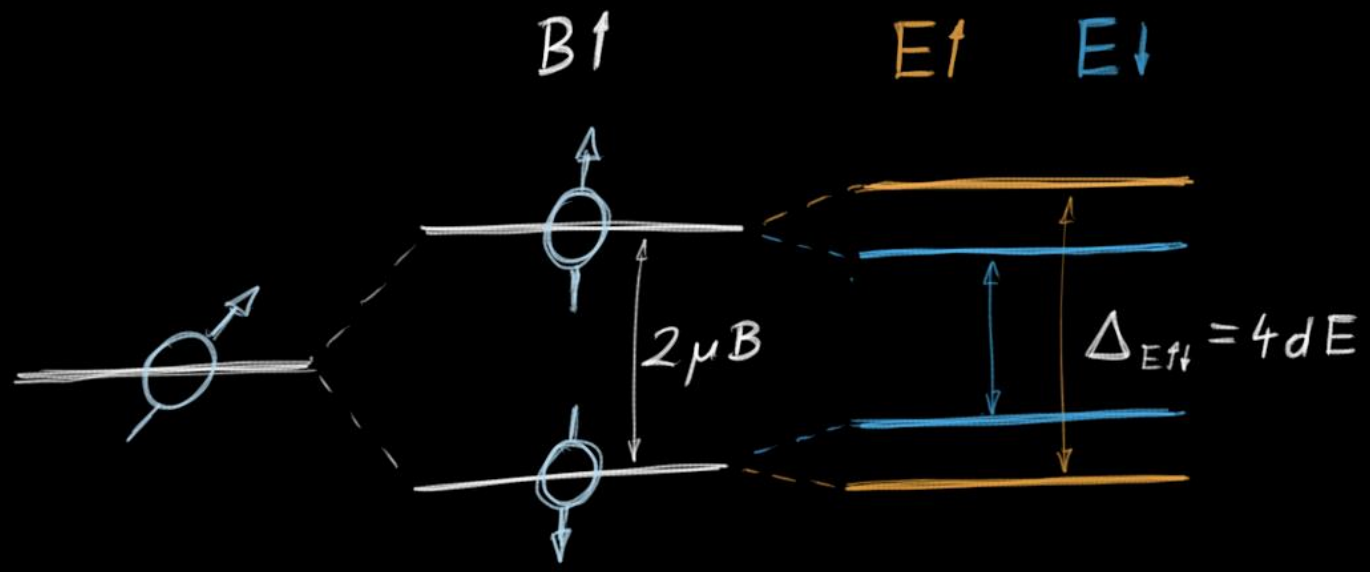
$$H = -2\left(\mu\,\mathbf{B} + d\,\mathbf{E}\right)\cdot\mathbf{S}$$



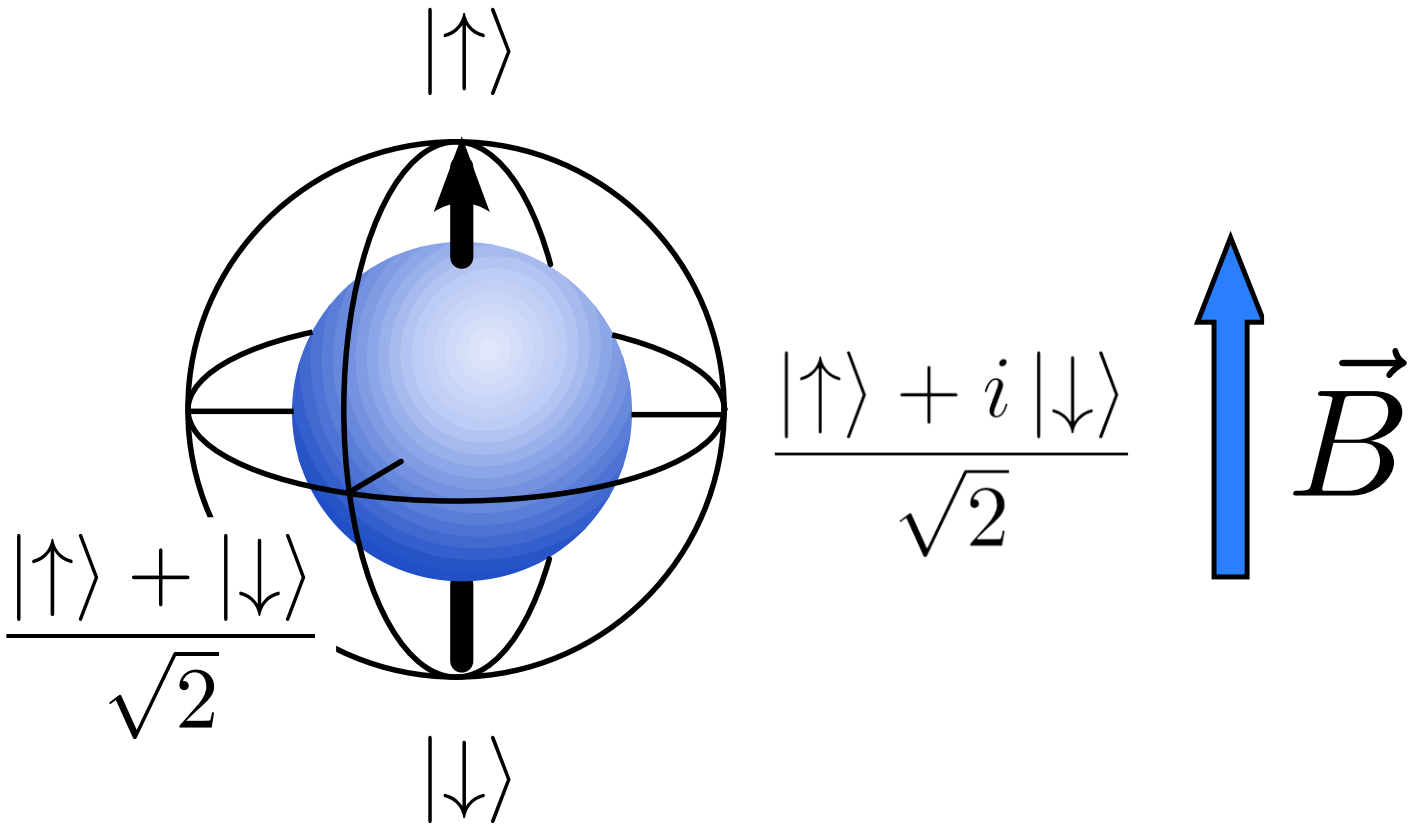
$$H = -2\left(\mu\,\mathbf{B} + d\,\mathbf{E}\right)\cdot\mathbf{S}$$

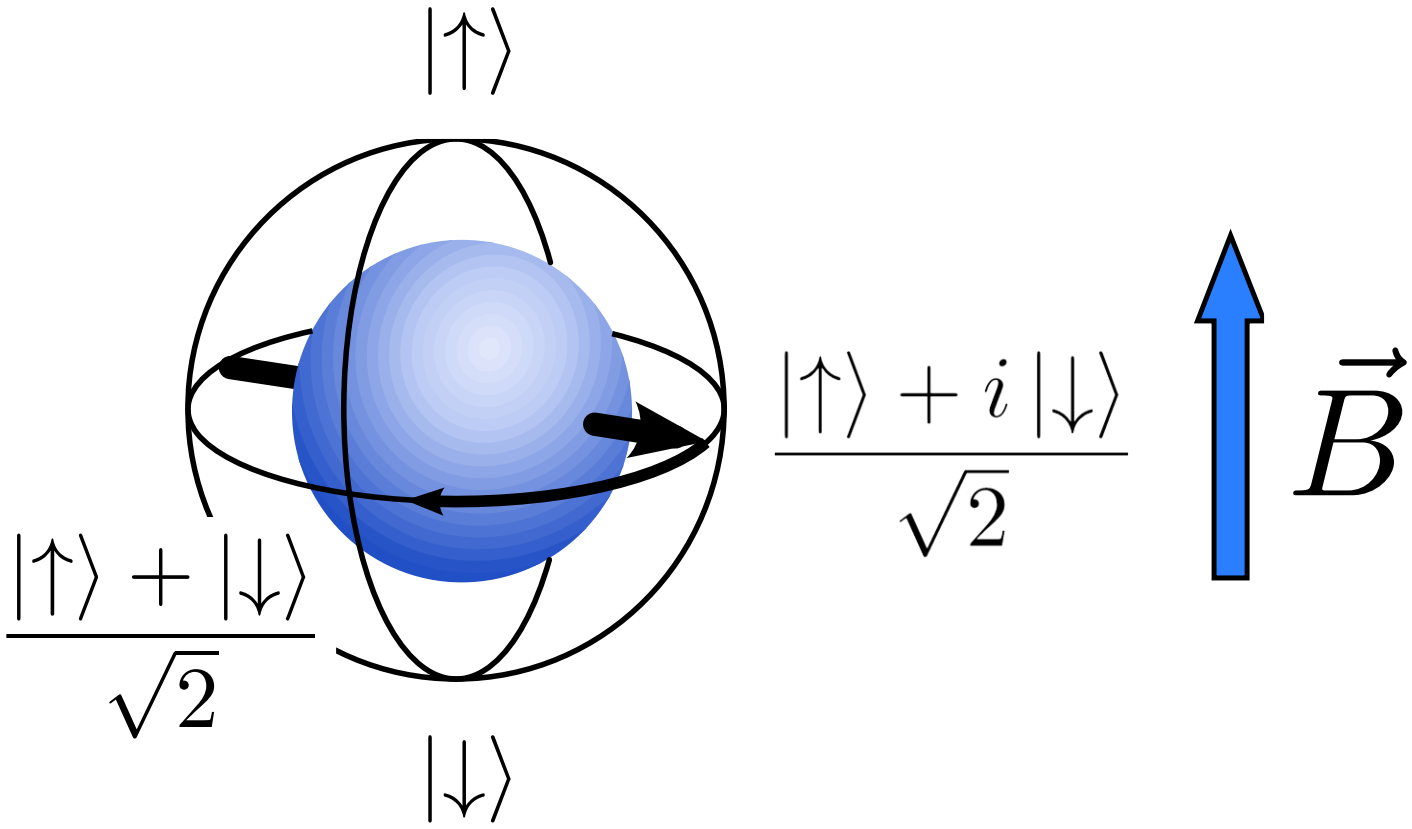


$$H = -2\left(\mu\,\mathbf{B} + d\,\mathbf{E}\right)\cdot\mathbf{S}$$



Bloch sphere





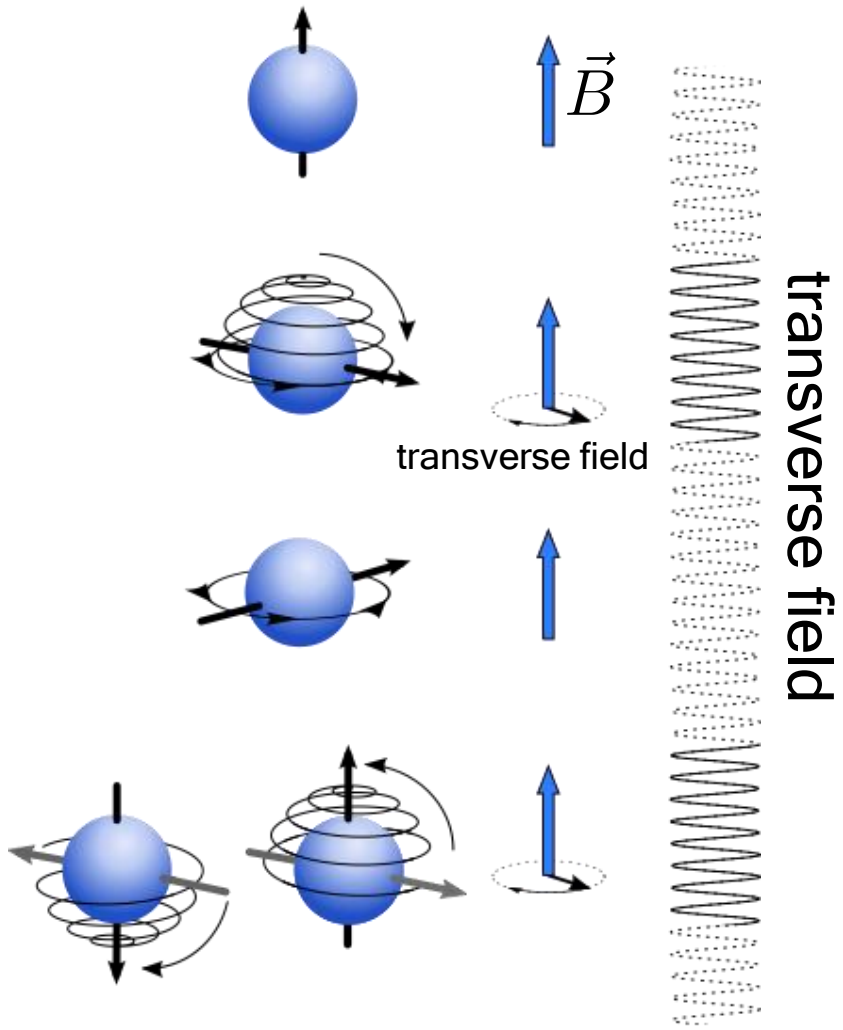
Gyromagnetic ratio of the neutron: $-29.1646943(69)\ \frac{\mathrm{Hz}}{\mu\mathrm{T}}$

polarised sample

π/2 flip

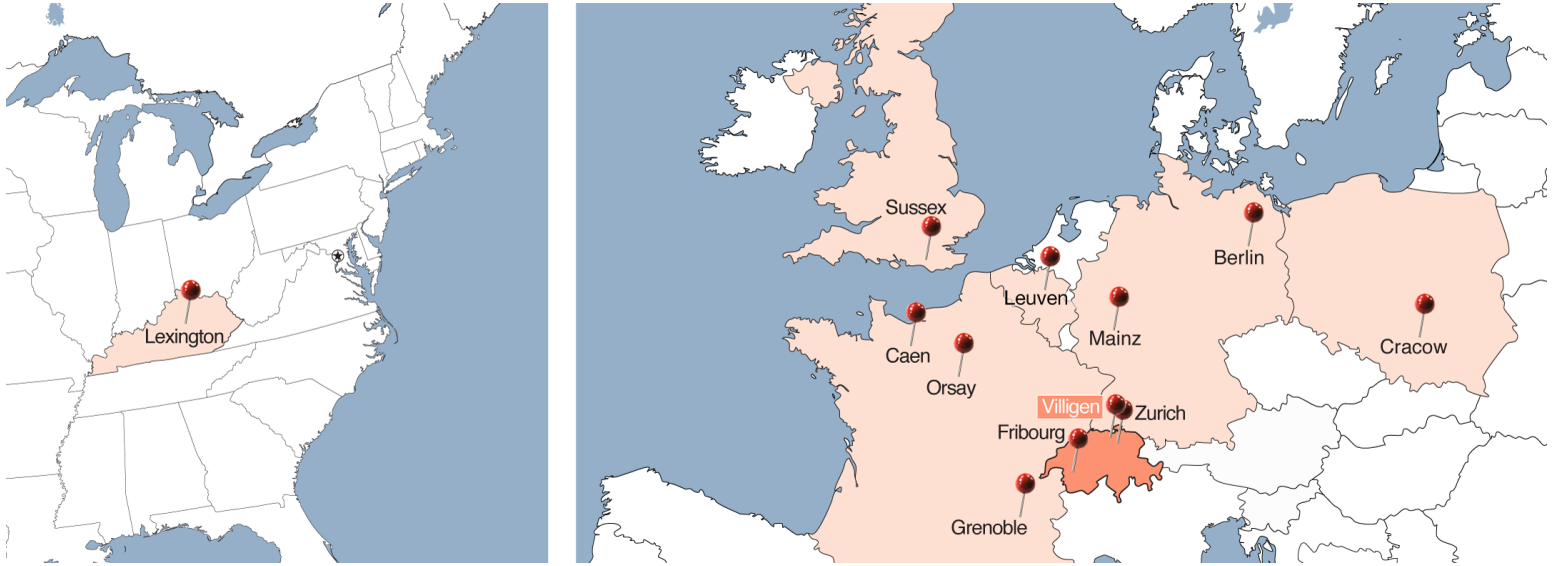
free precession

π/2 flip



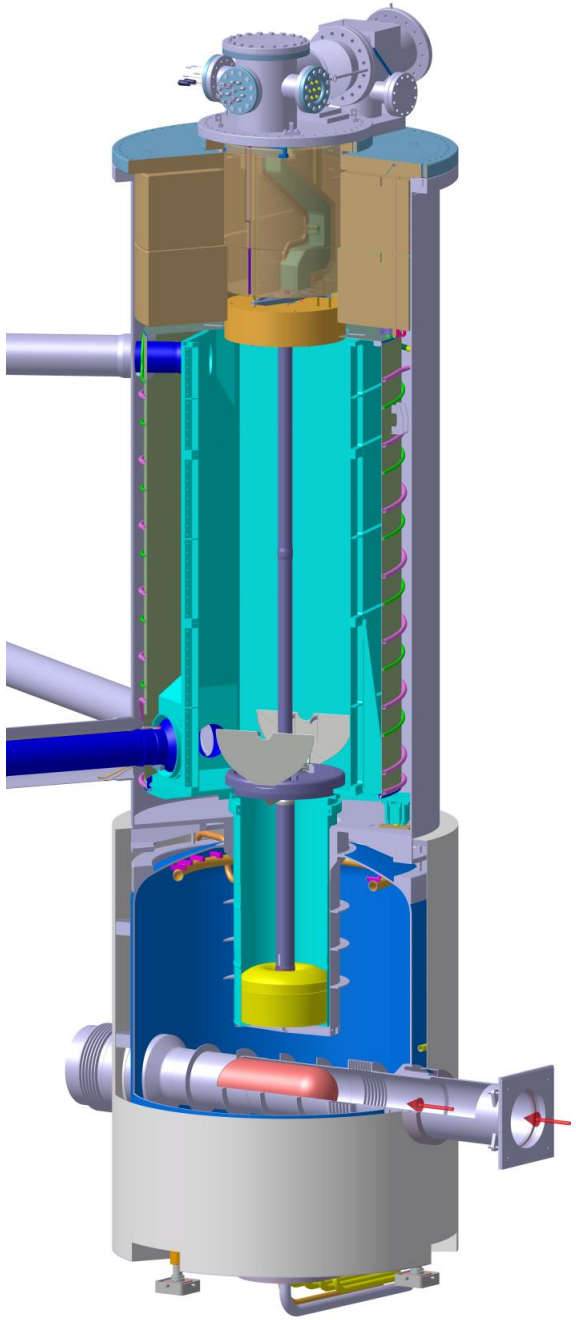
Harris, P. G. et al. Phys. Rev. Lett. **82**, 7 (1999)

the nEDM at PSI collaboration

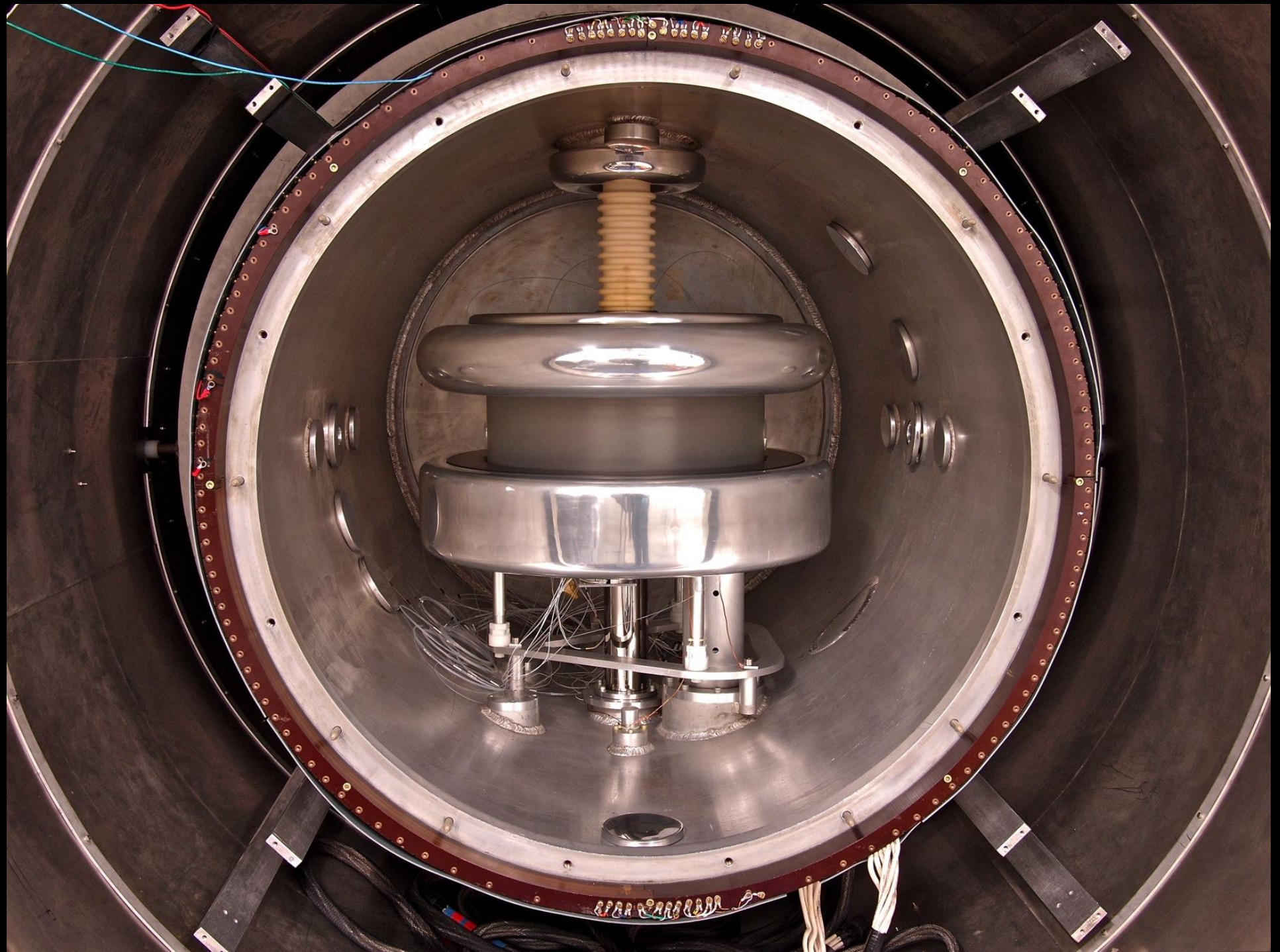


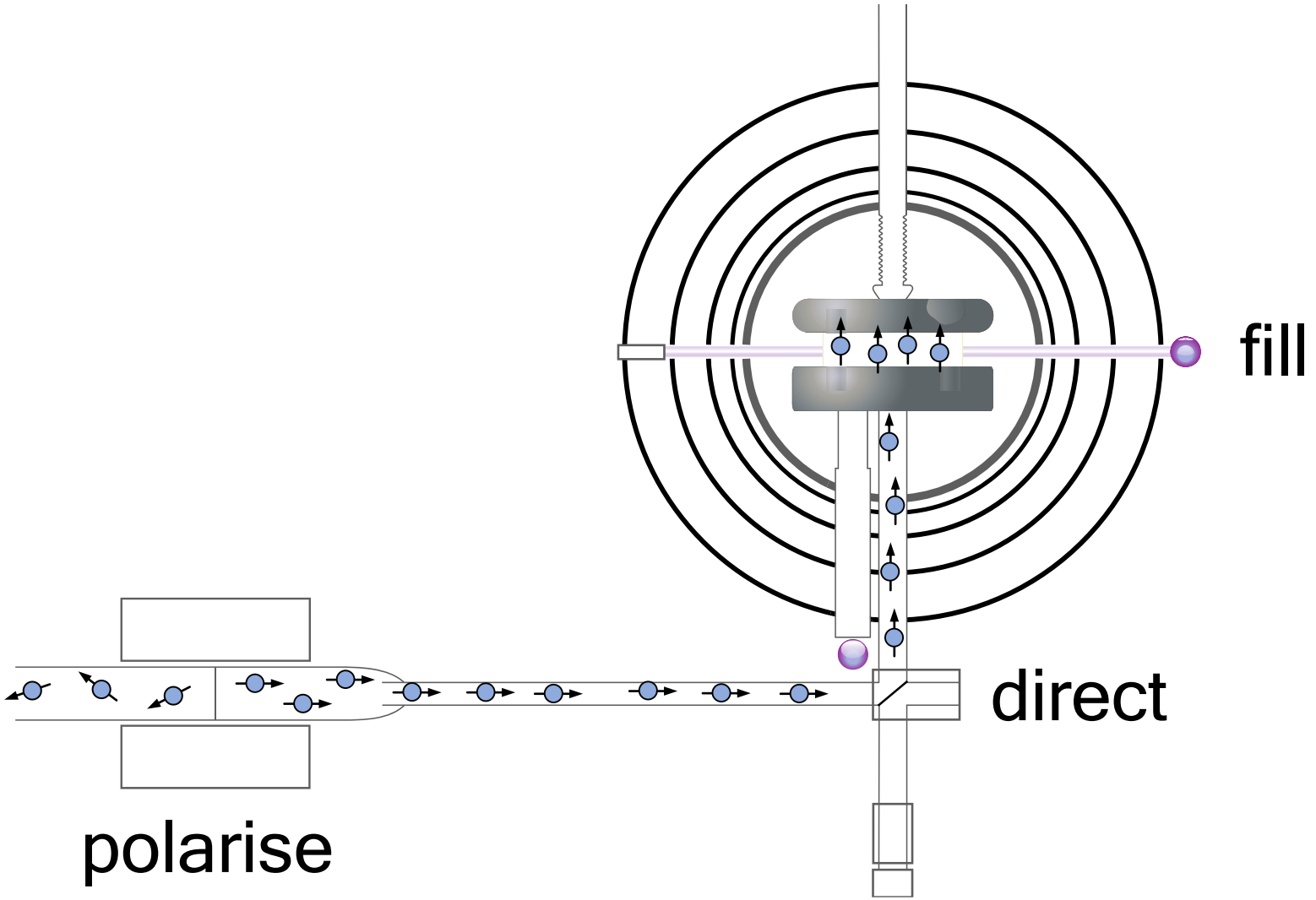
UCN storage in
high Fermi potential
bottle

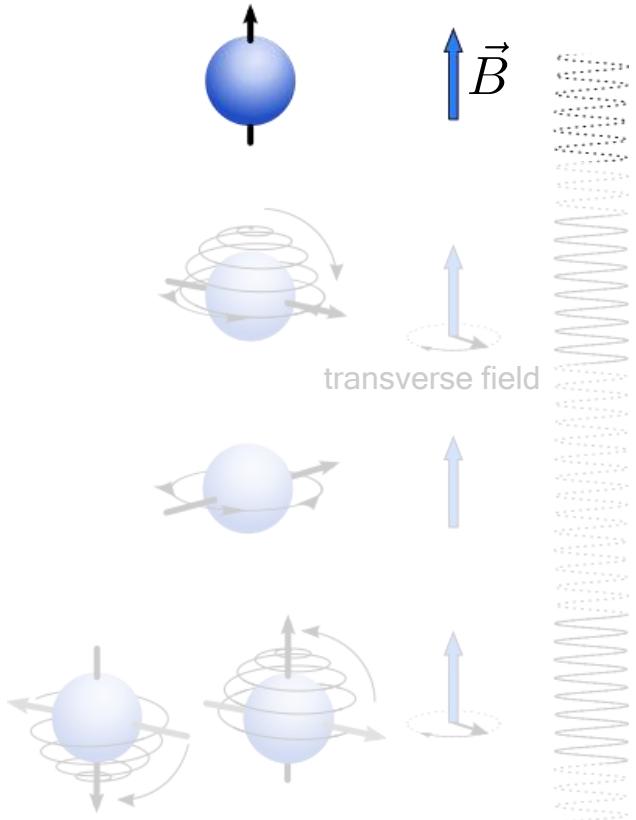
moderation and cooling
down to < **300 neV**

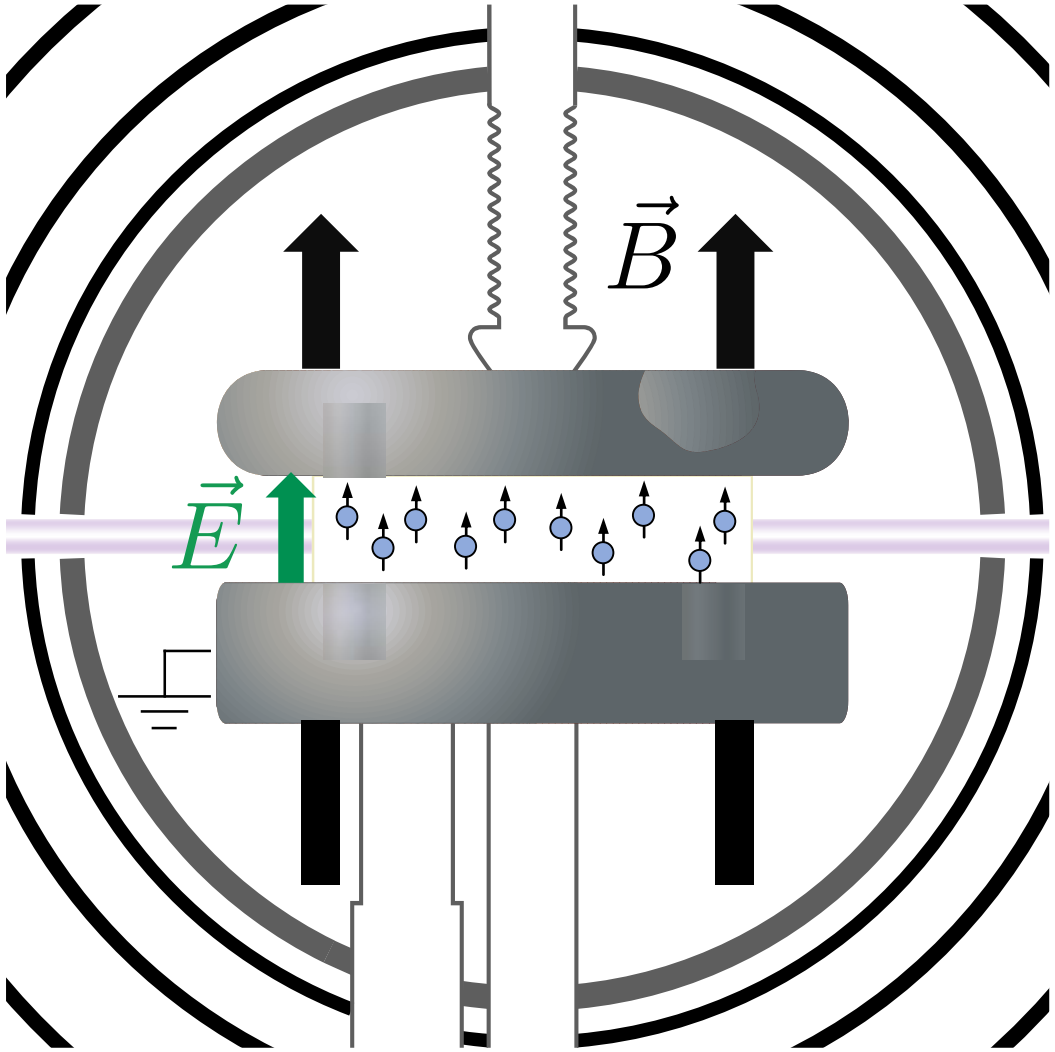


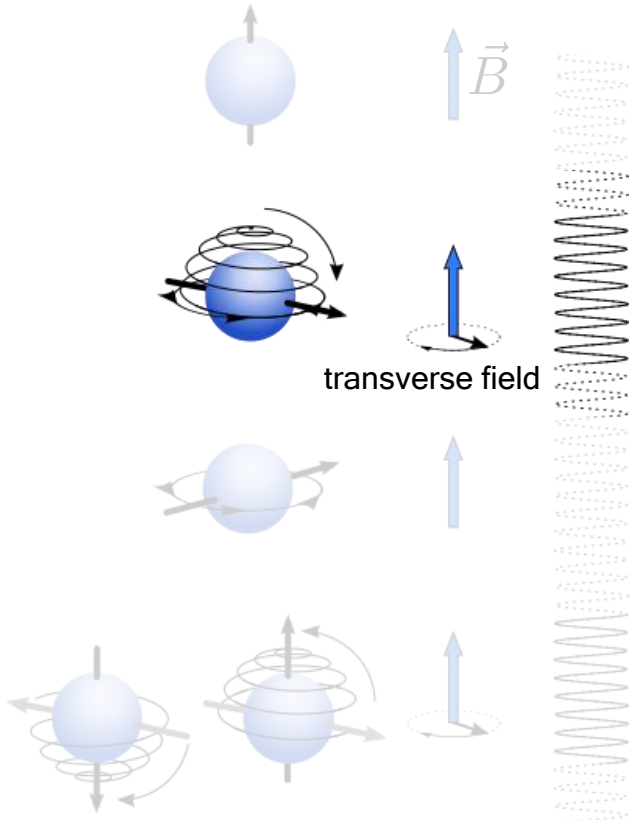
2 mA of
590 MeV
protons




fill
direct
polarise


$\vec{B}$
transverse field


$\vec{B}$
$\vec{E}$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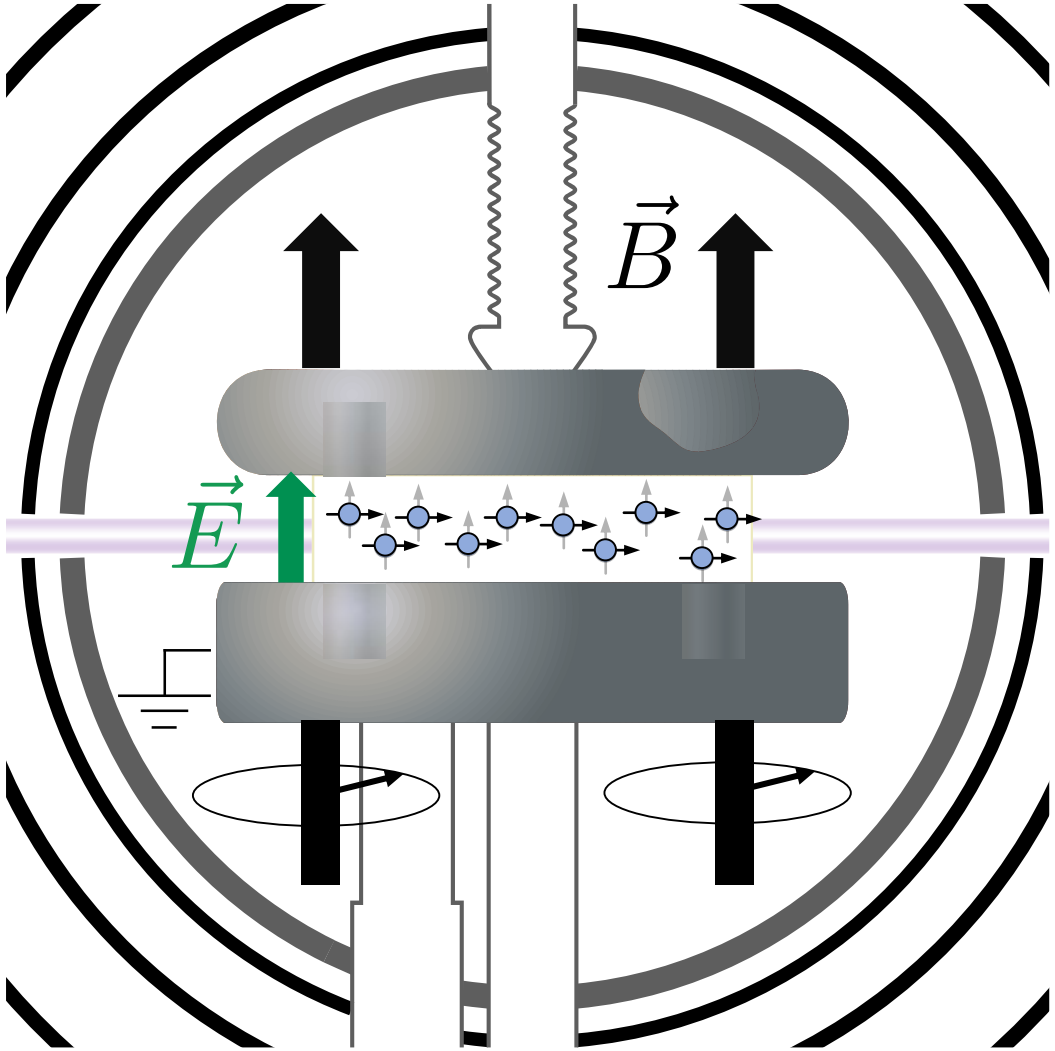
$\vec{B}$
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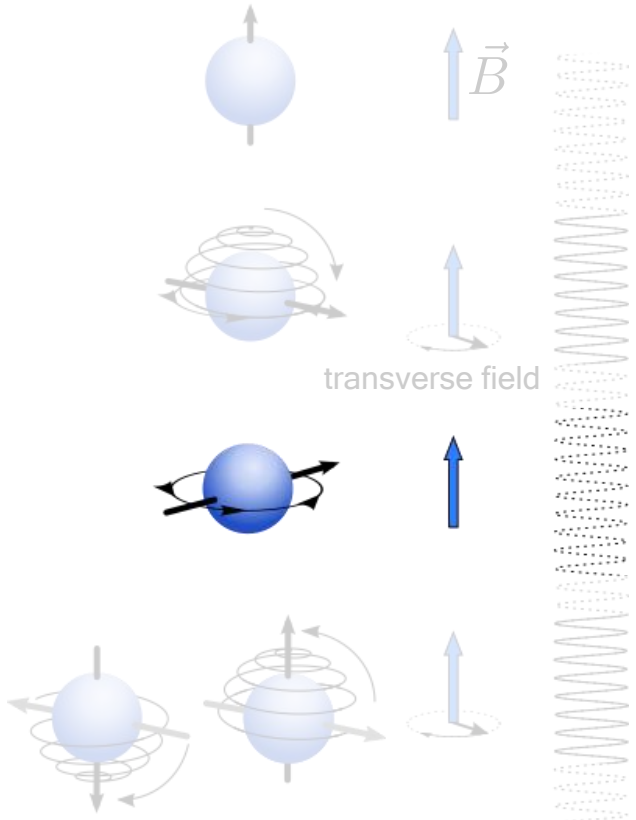
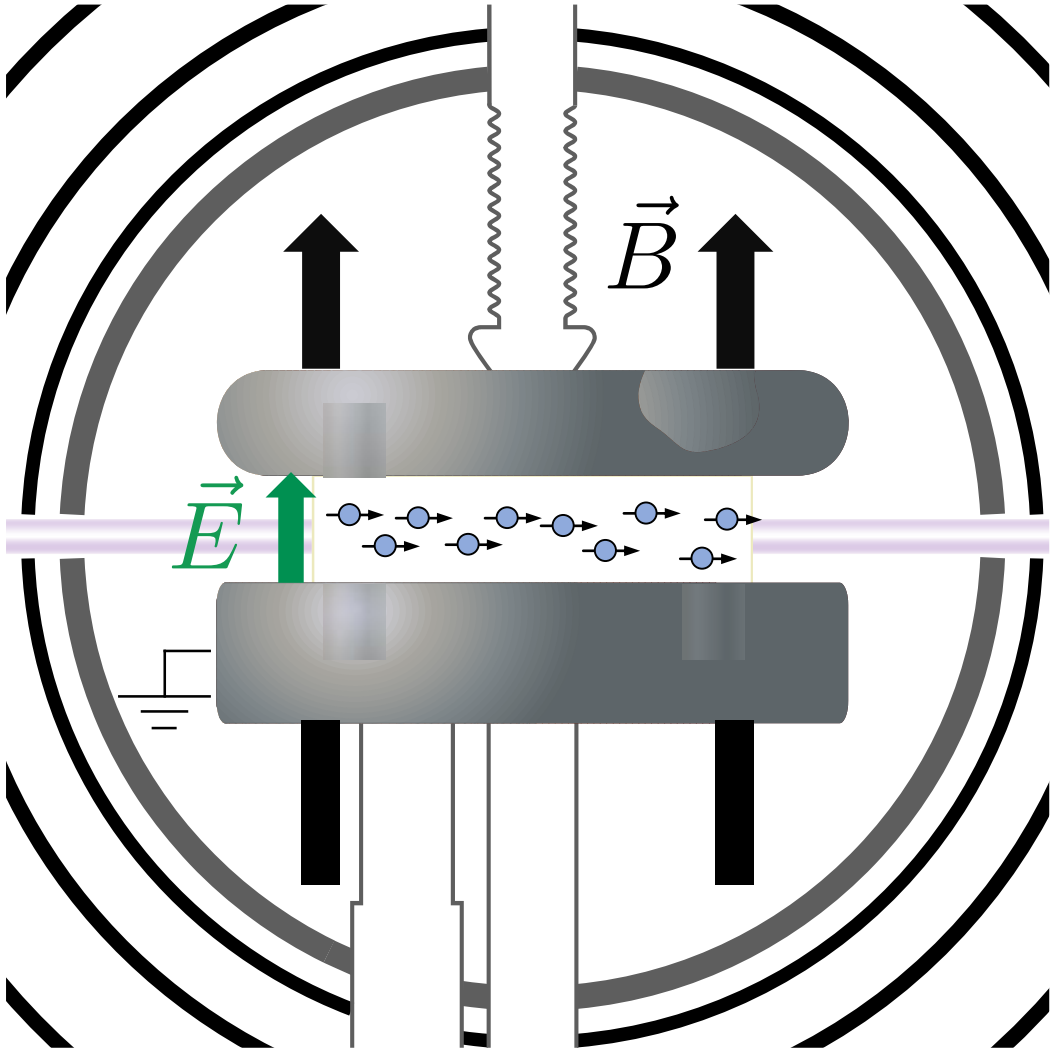

$\vec{B}$
transverse field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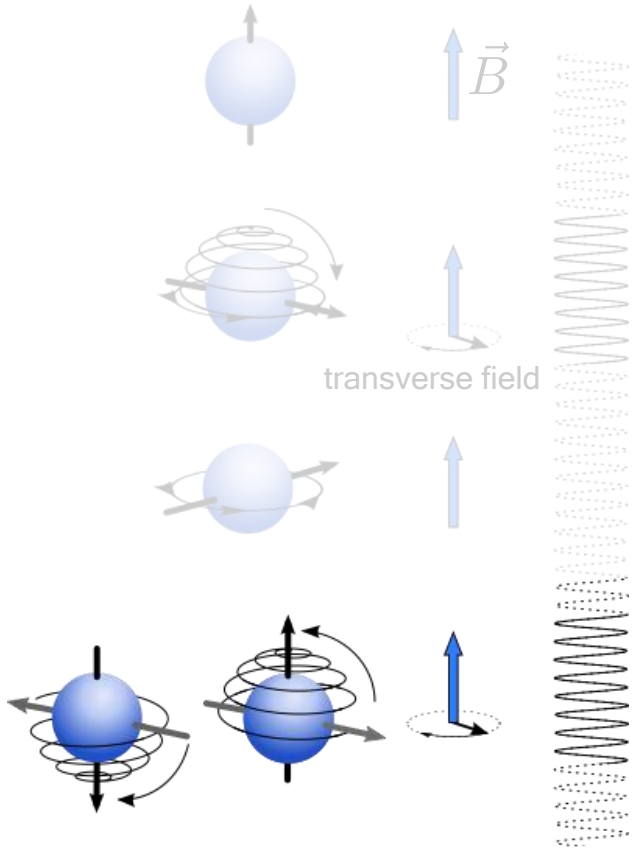
$\vec{E}$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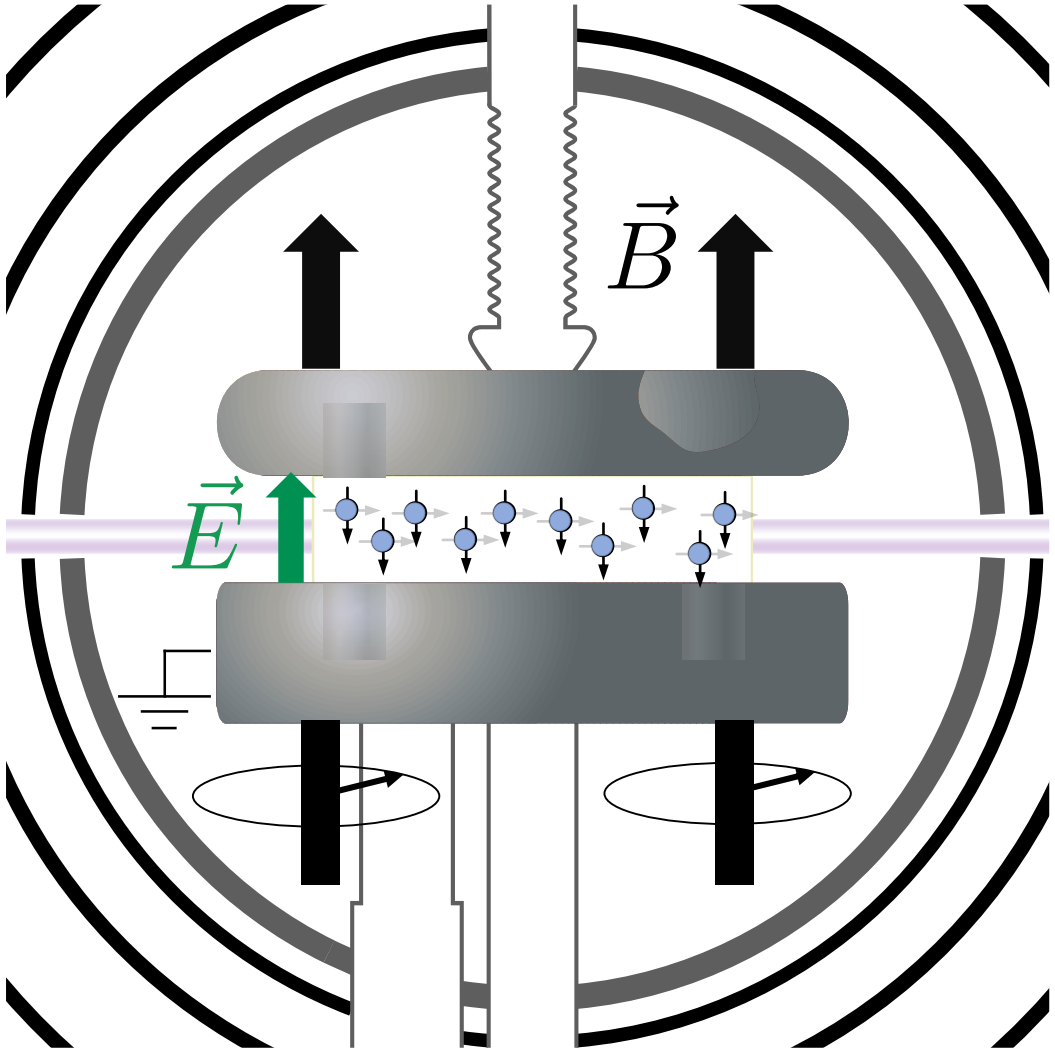
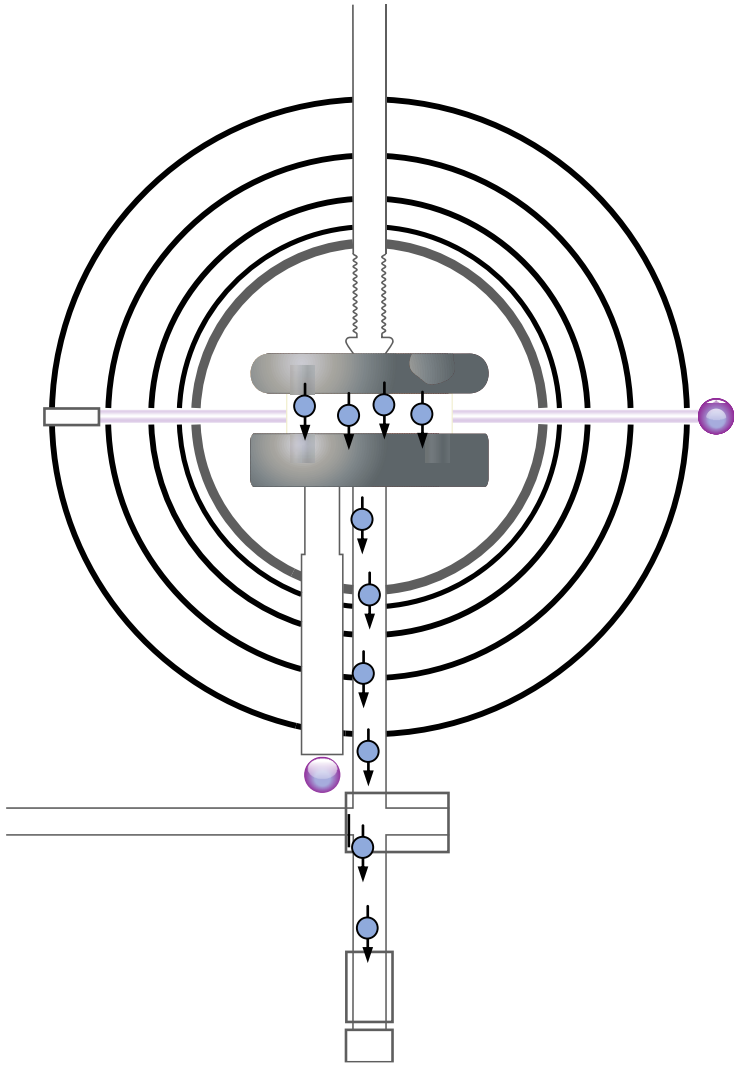
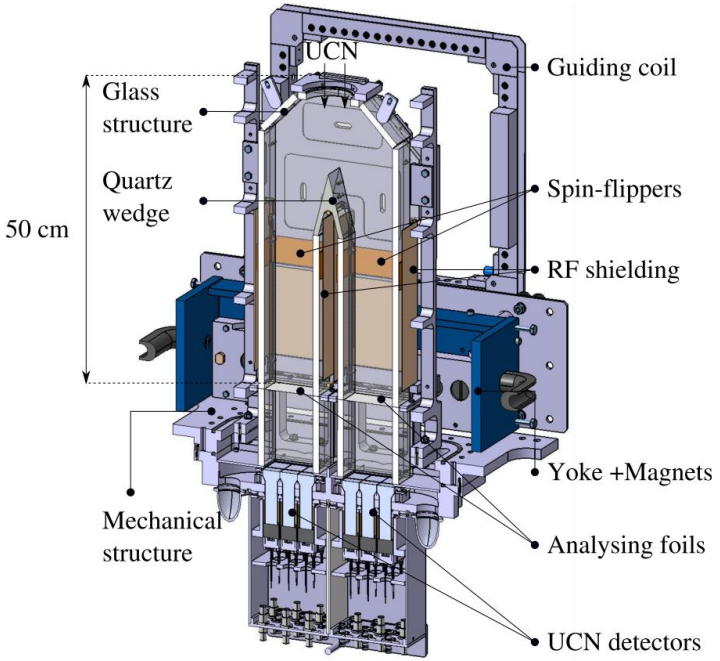
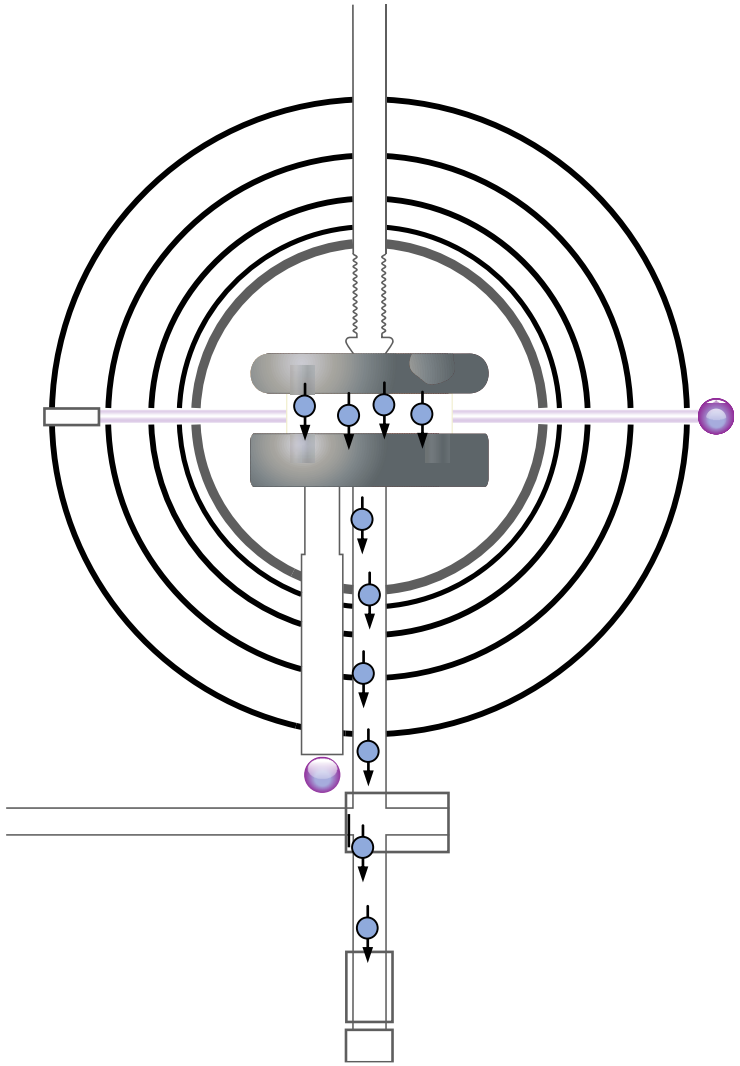
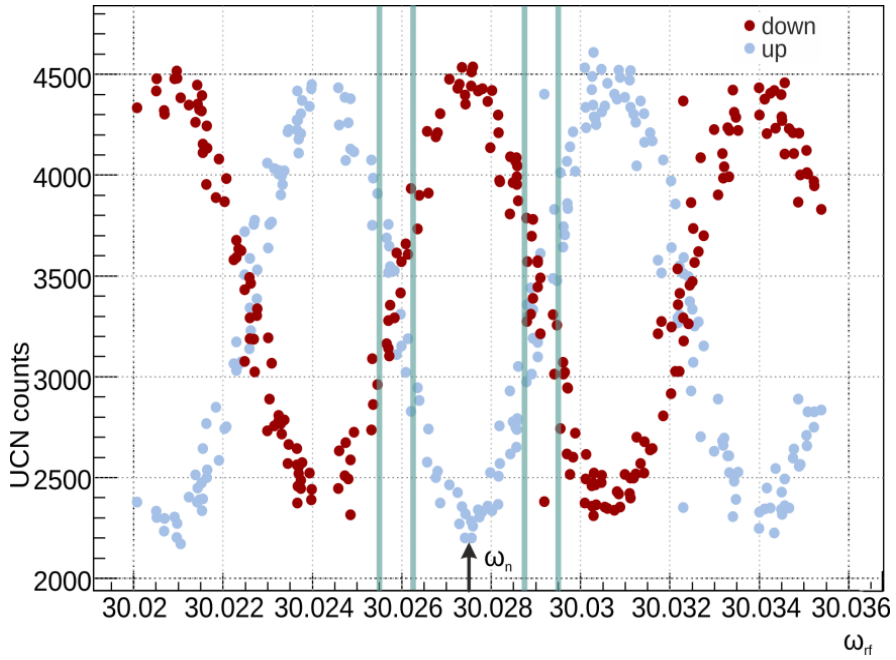
transverse field

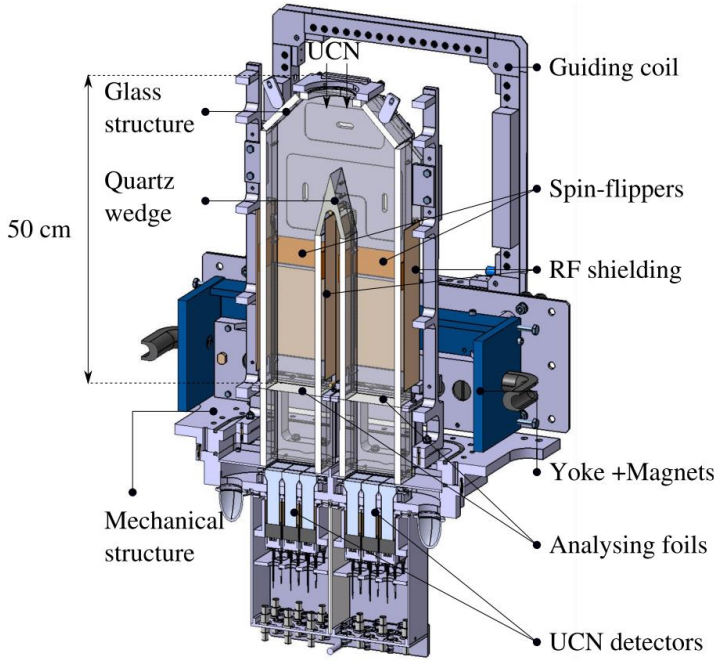

$\vec{B}$
$\vec{E}$




UCN
Guiding coil
Glass
structure
Quartz
wedge
50 cm
Spin-flippers
RF shielding
Yoke +Magnets
Mechanical
structure
Analysing foils
UCN detectors




down
up
UCN counts
4500
4000
3500
3000
2500
2000
30.02
30.022
30.024
30.026
30.028
30.03
30.032
30.034
30.036
ω_n
ω_{rf}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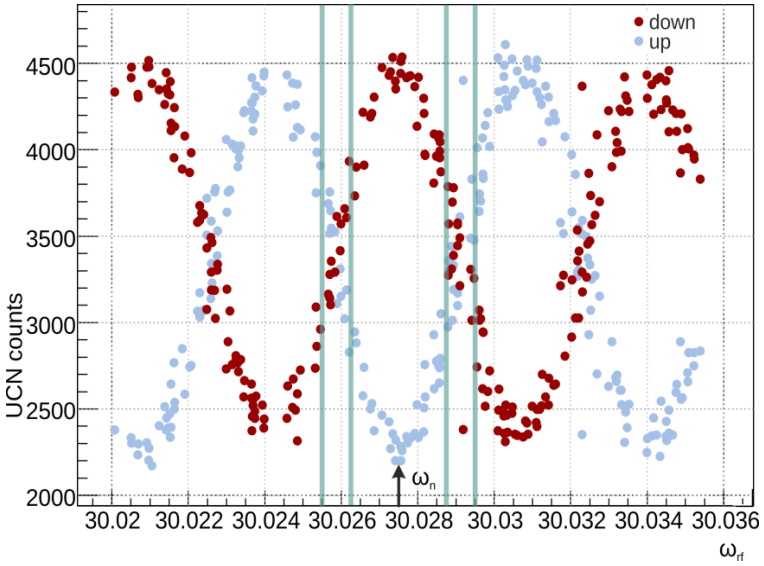
down
up
UCN counts
4500
4000
3500
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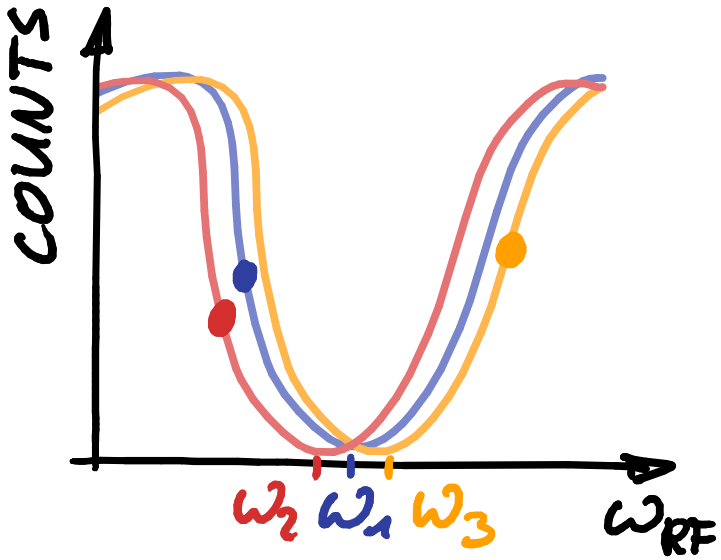
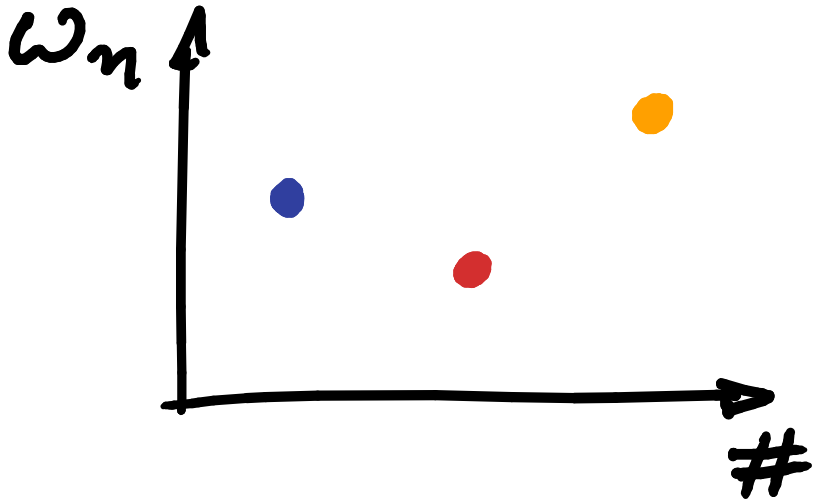
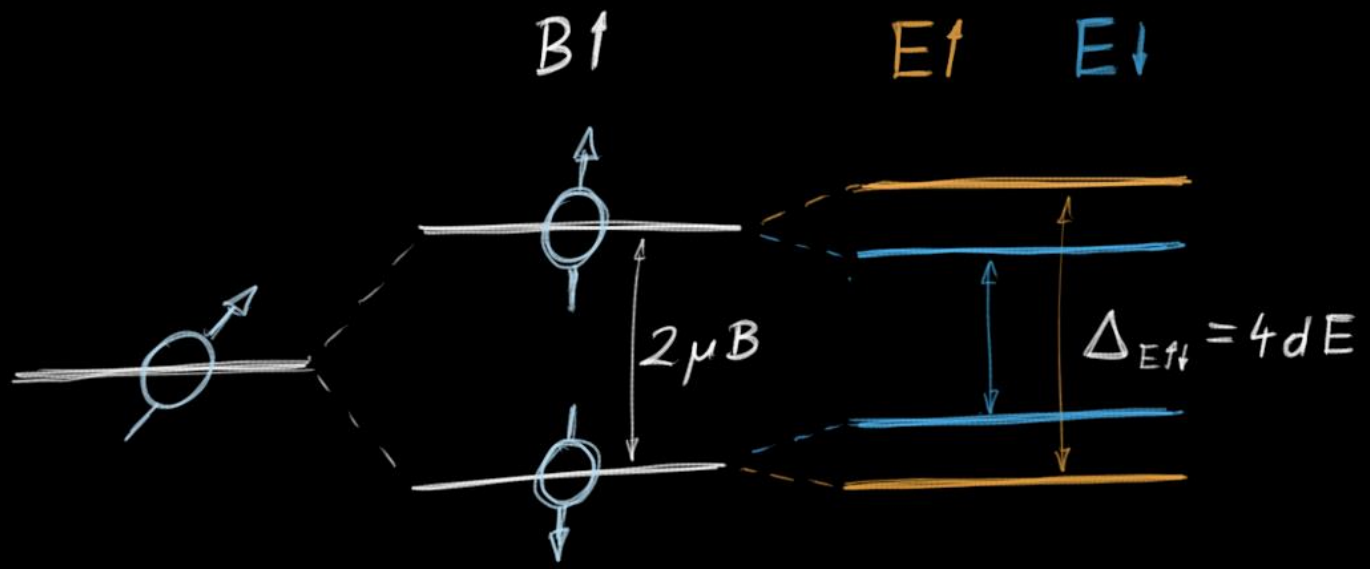
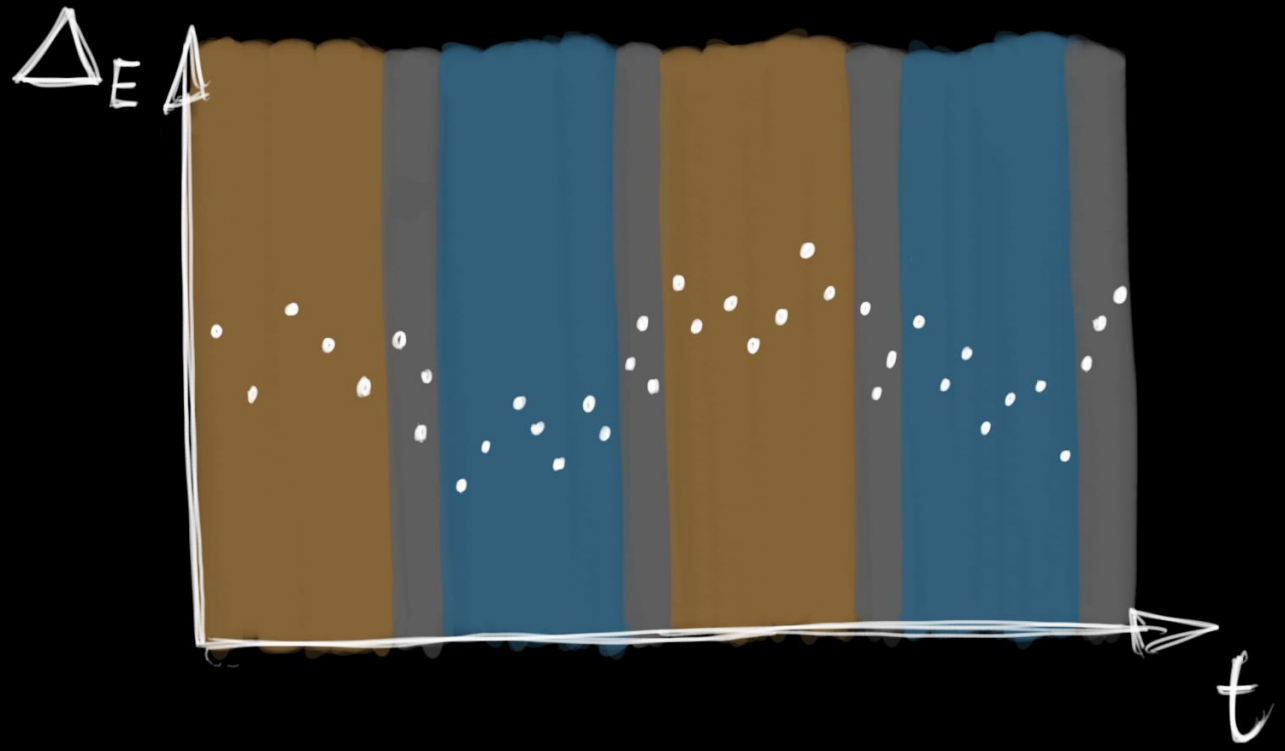
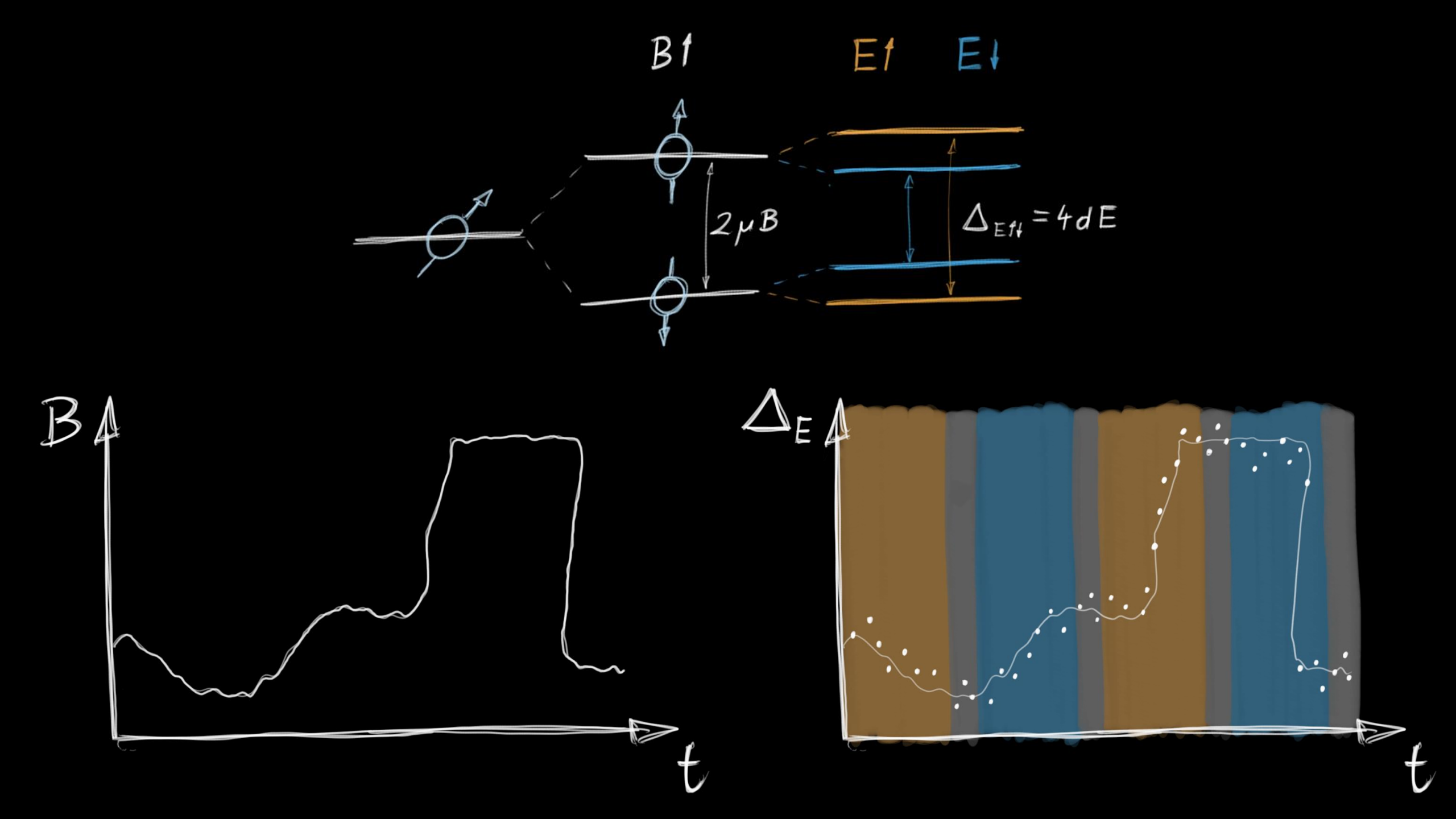
2500
2000
30.02
30.022
30.024
30.026
30.028
30.03
30.032
30.034
30.036
ω_n
ω_{rf}

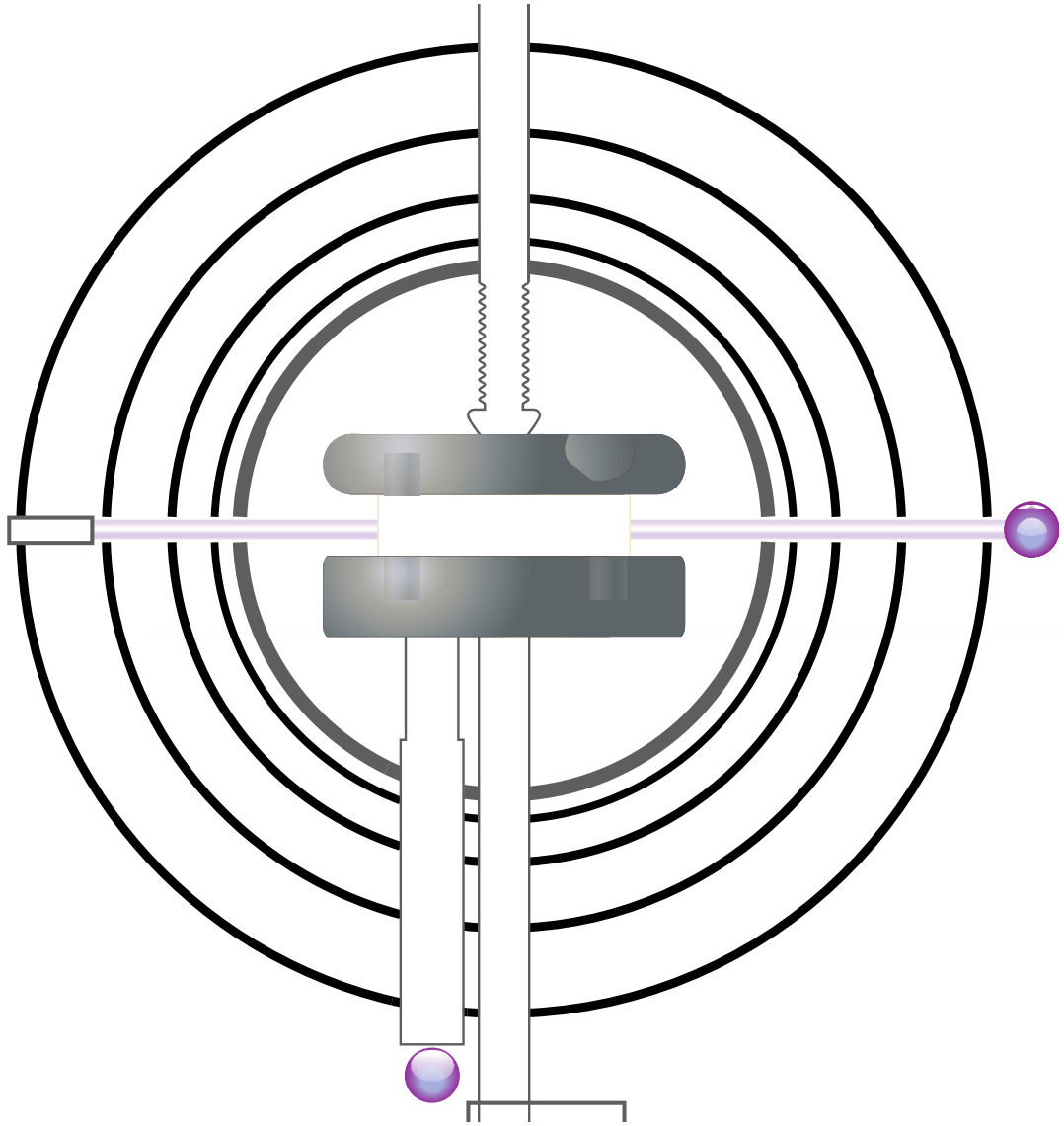

COUNTS
ω_2 ω_1 ω_3
ω_{RF}

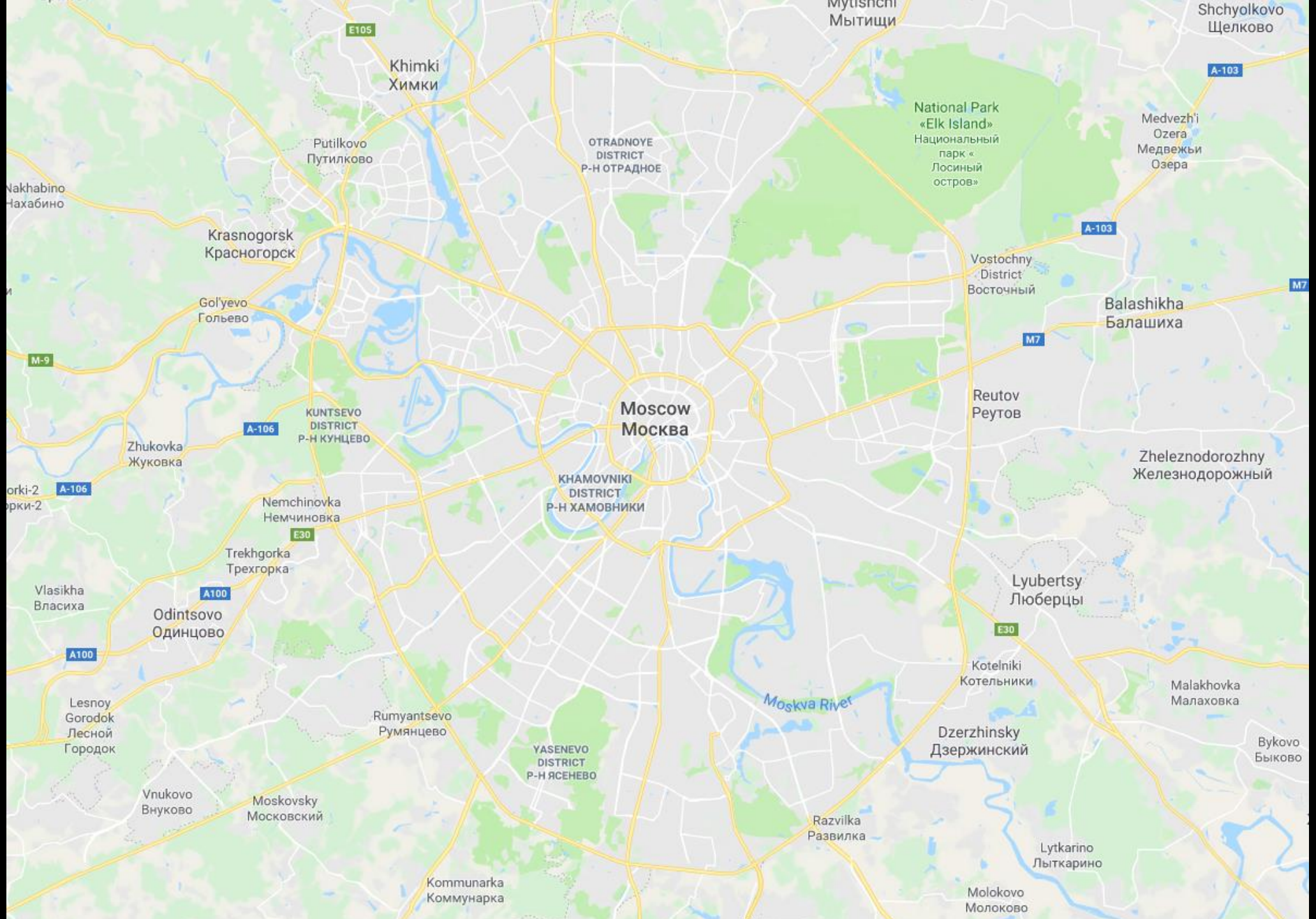

ω_n
#


B↑
E↑
E↓
2μB
Δ E↑↓ = 4dE

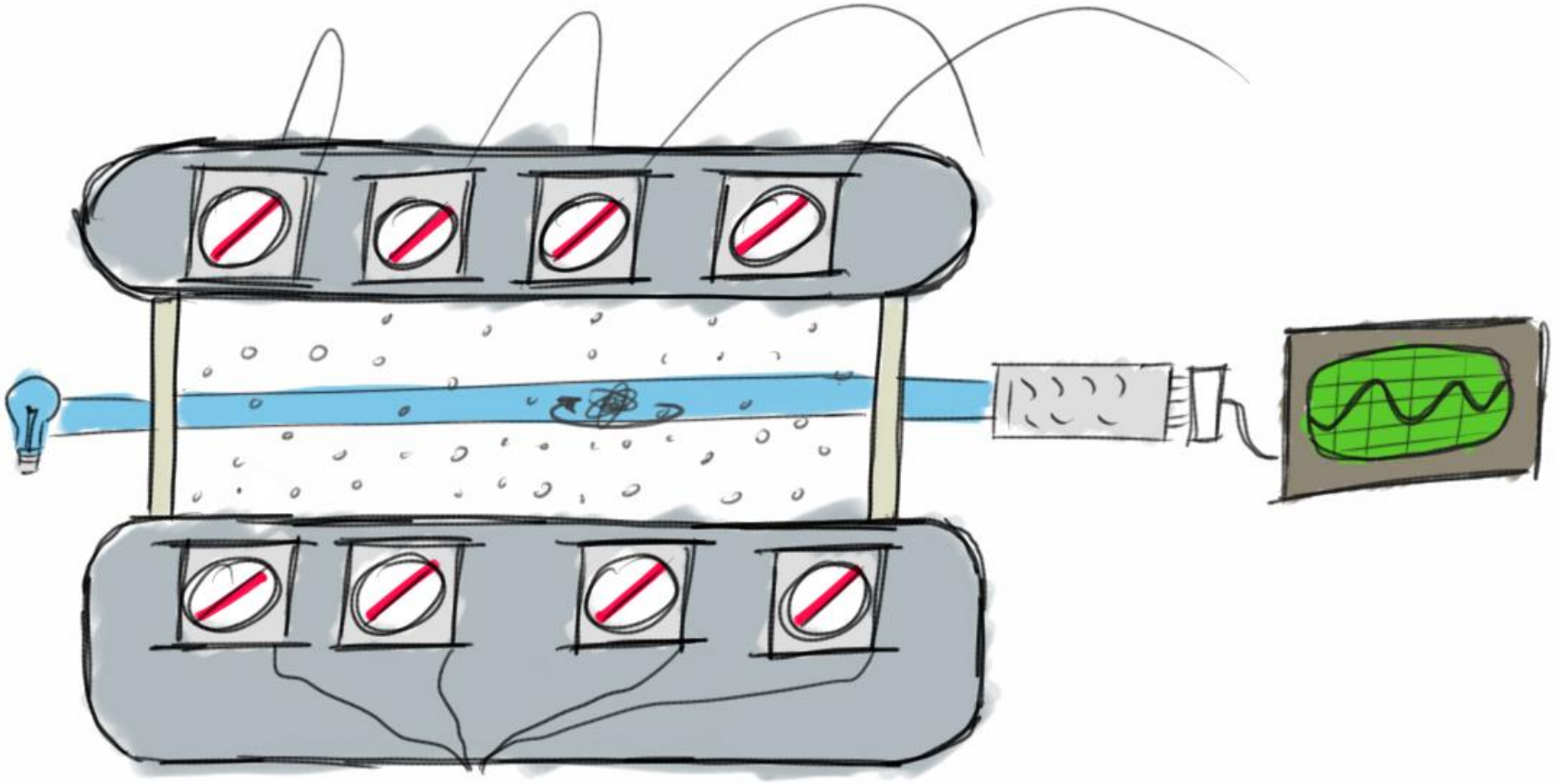

Δ E
t


B↑
E↑
E↓
2μB
Δ E↑↓ = 4dE
B
t
Δ E
t



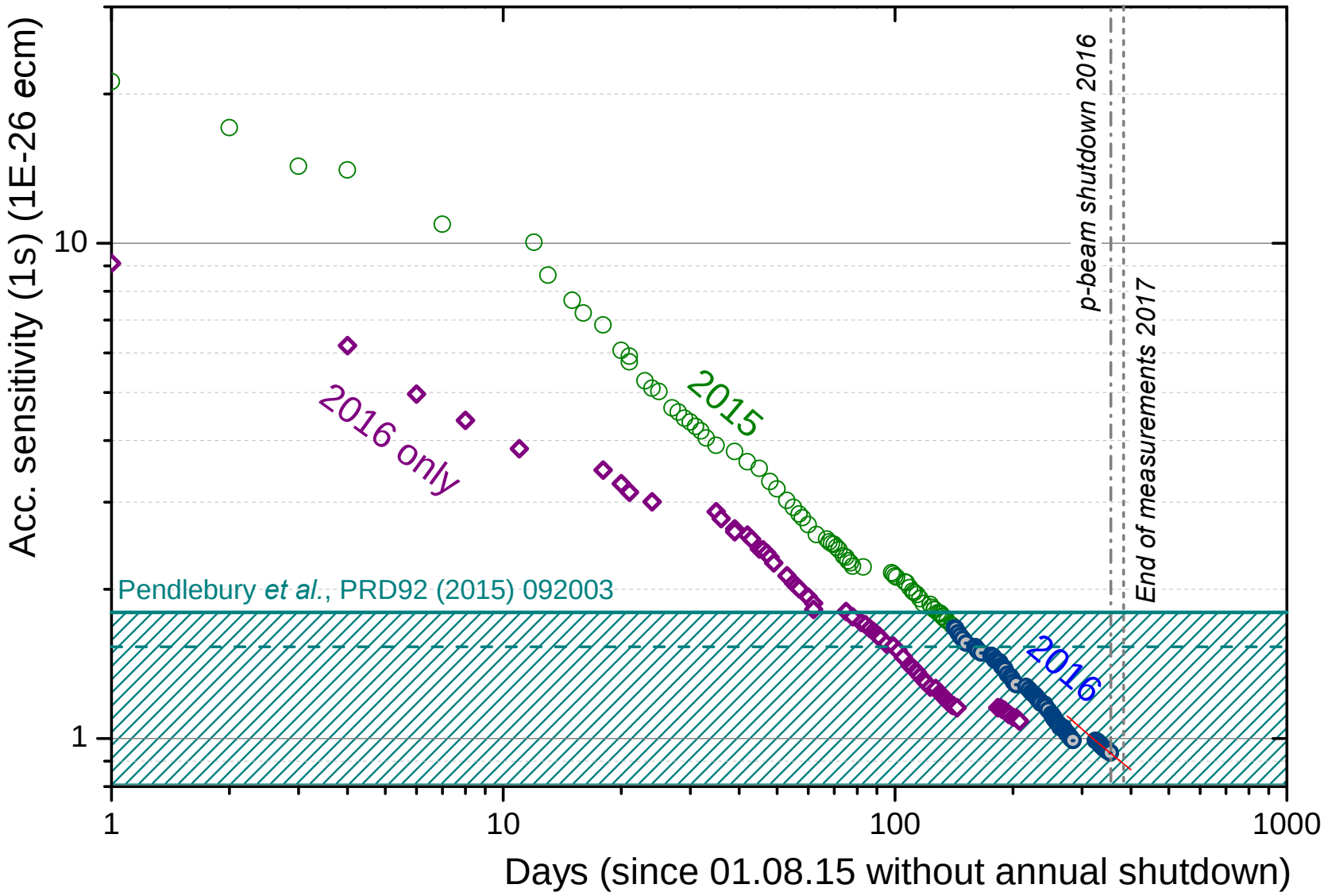


source: google maps



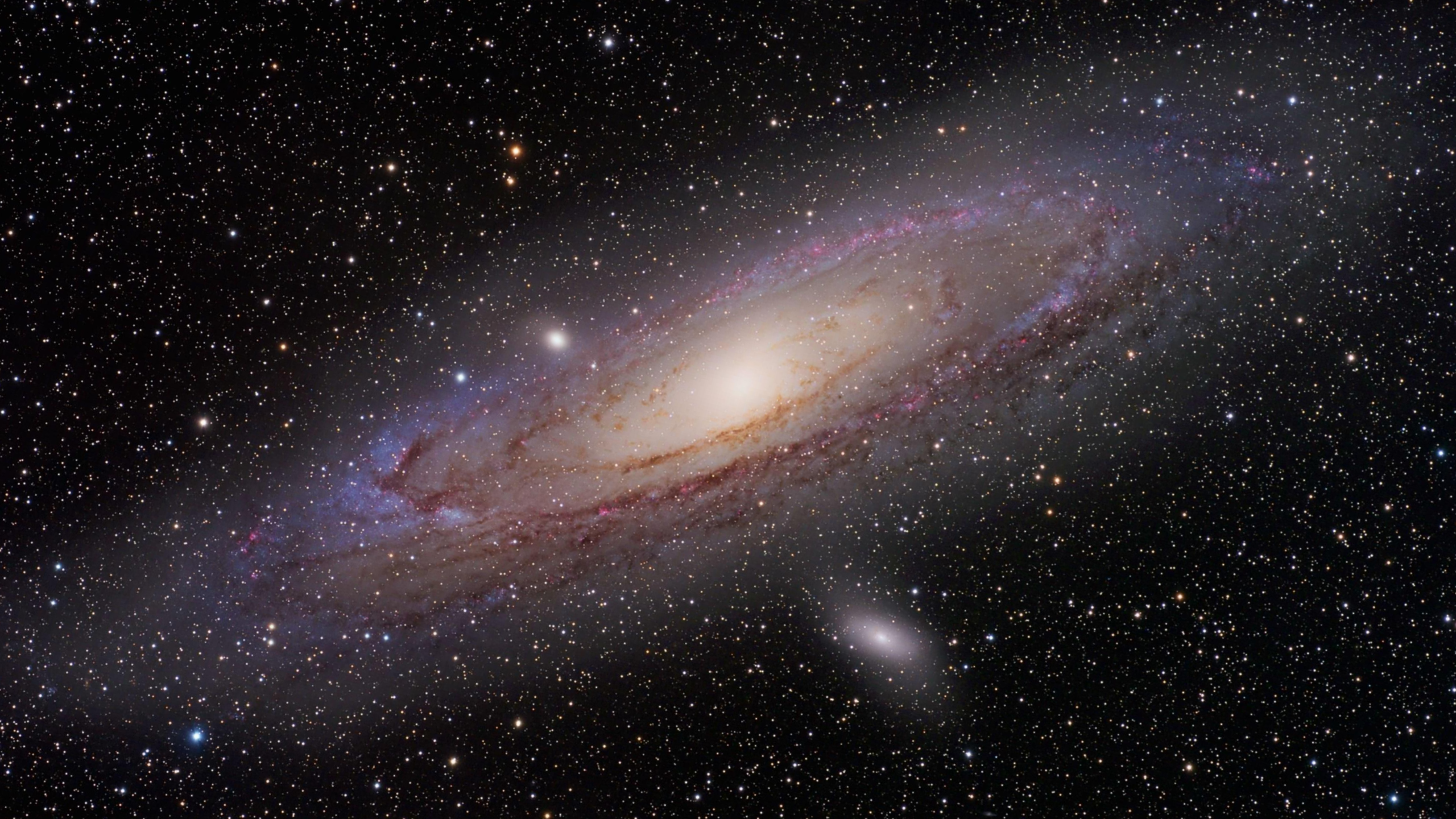
^{199}Hg

UCN



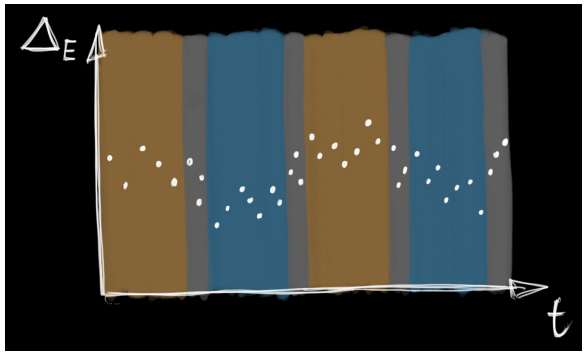
Courtesy of Dr. Philipp Schmidt-Wellenburg

obrist gerüste
obrist
obrist gerüste
obrist
obrist gerüste
obrist

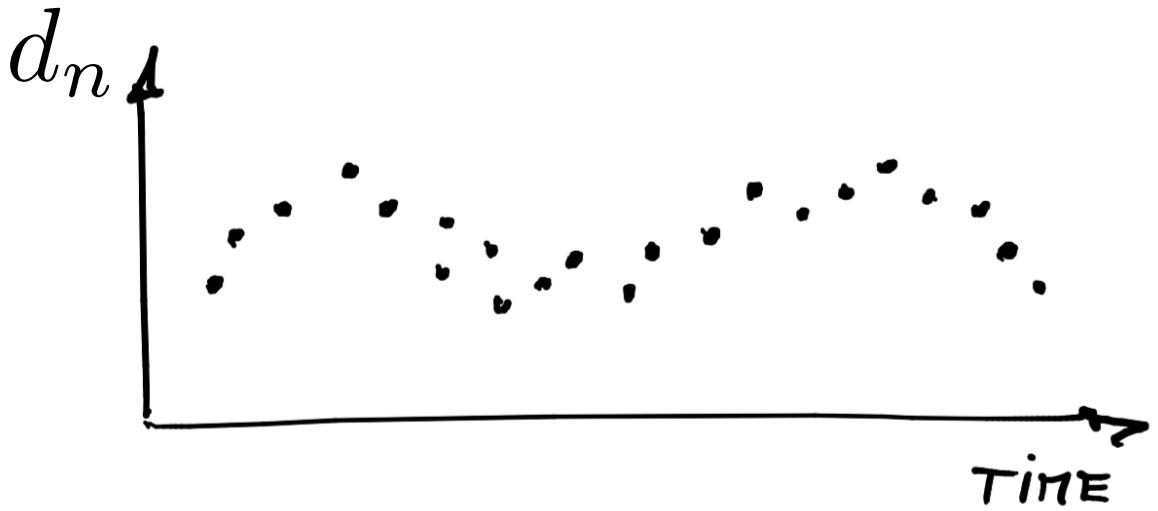


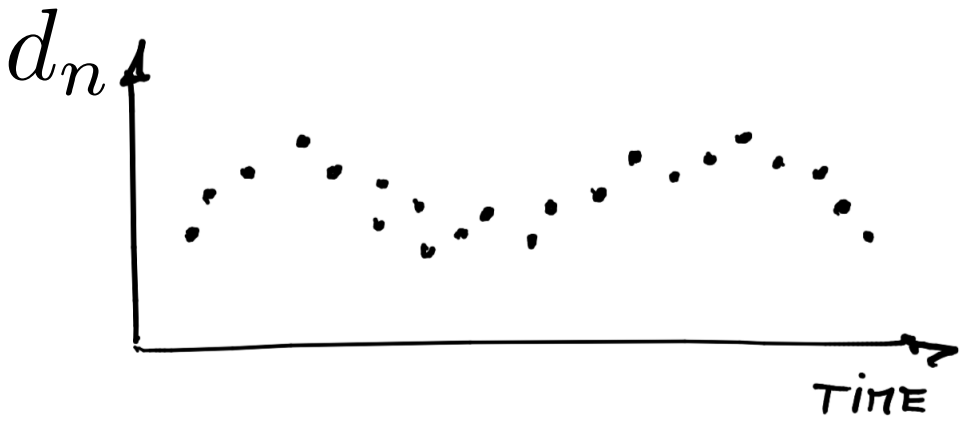
$$d_n(t) = 5.9 \times 10^{-22}\, C_G \left(\frac{10^{-22}\,\mathrm{eV}}{m_a}\right) \left(\frac{10^{16}\,\mathrm{GeV}}{f_a}\right) \cos(m_a t)\ e \cdot \mathrm{cm}$$

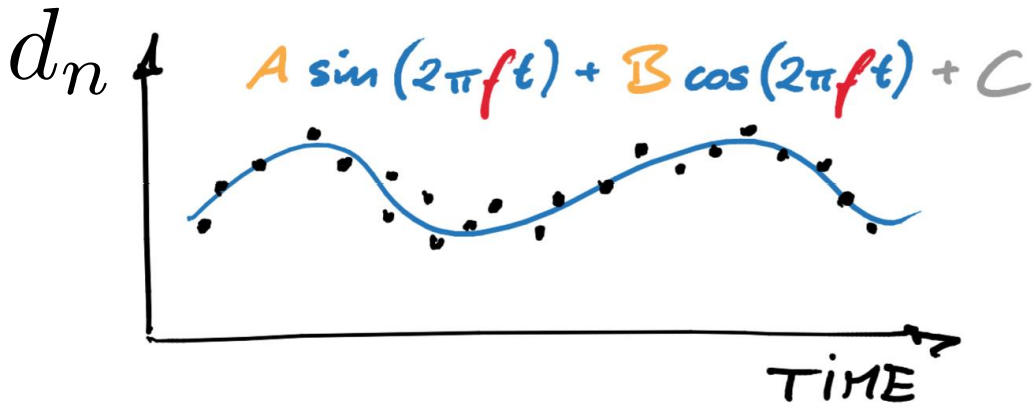
$$d_n(t) = 5.9 \times 10^{-22}\, C_G \left(\frac{10^{-22}\,\mathrm{eV}}{m_a}\right)\left(\frac{10^{16}\,\mathrm{GeV}}{f_a}\right)\cos(m_a t)\ e\cdot\mathrm{cm}$$

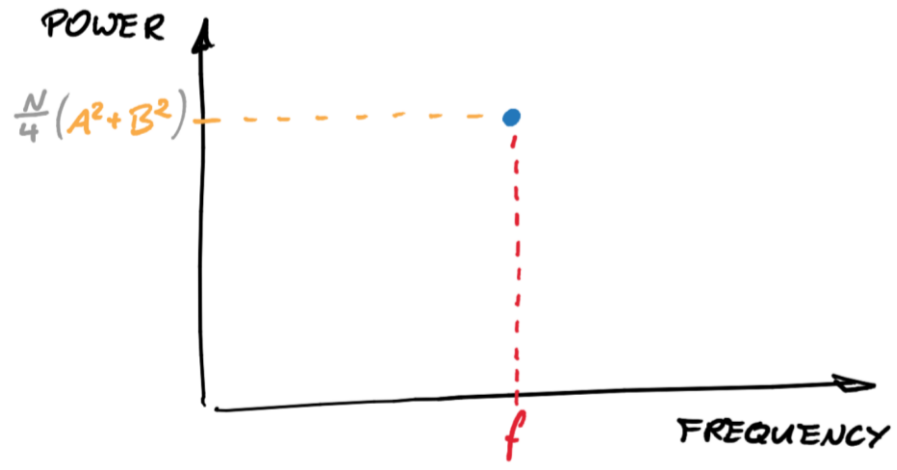


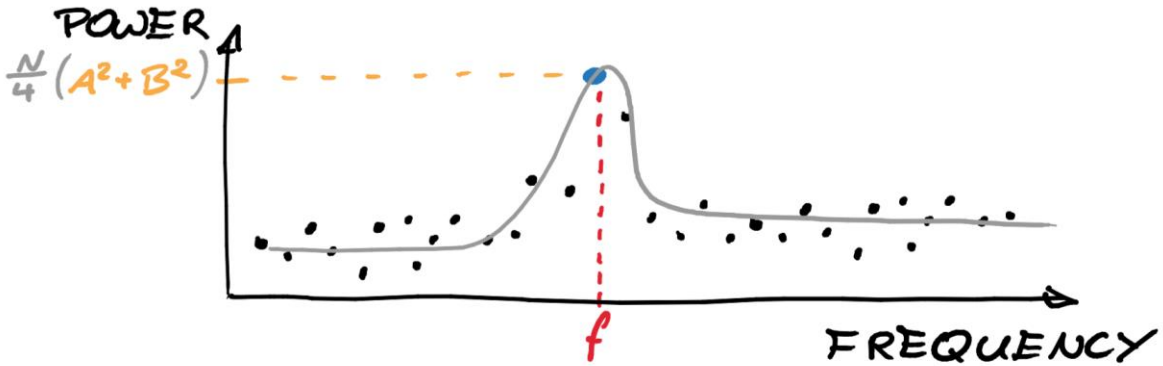
We got an d_n estimate every 1-73 hours.

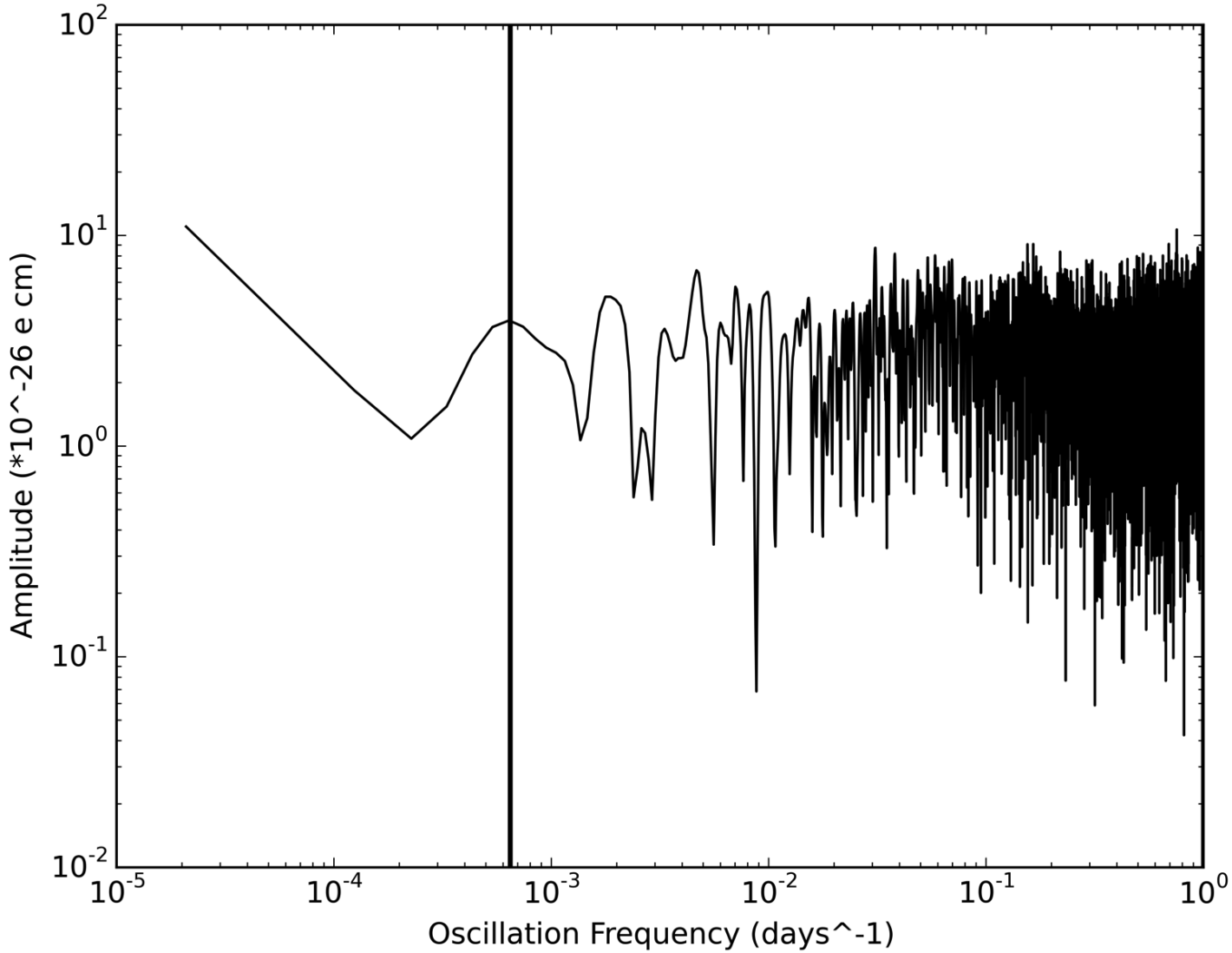


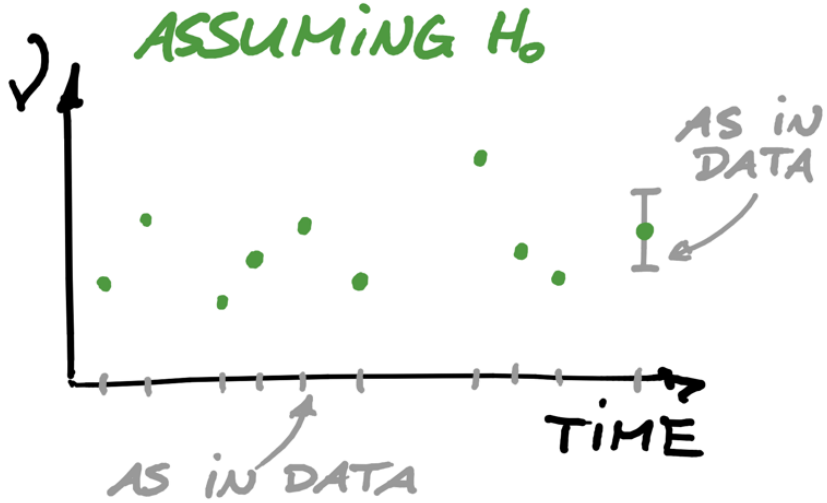

d_n
TIME

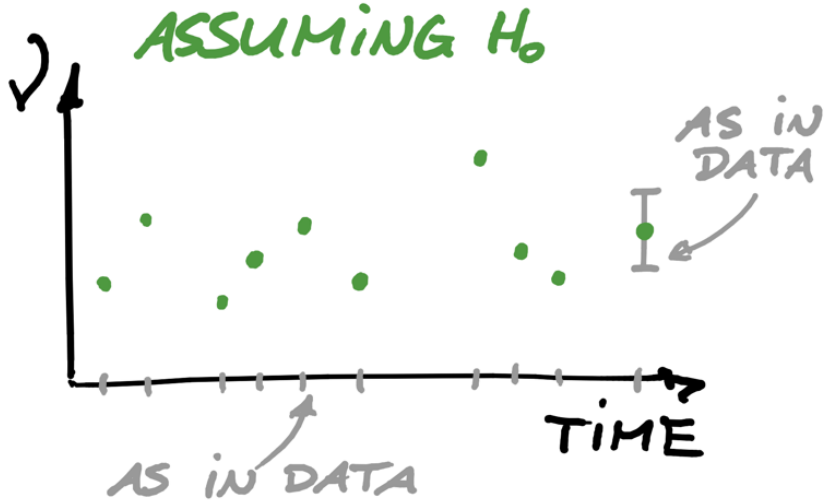

d_n
$A\sin(2\pi ft) + B\cos(2\pi ft) + C$
TIME

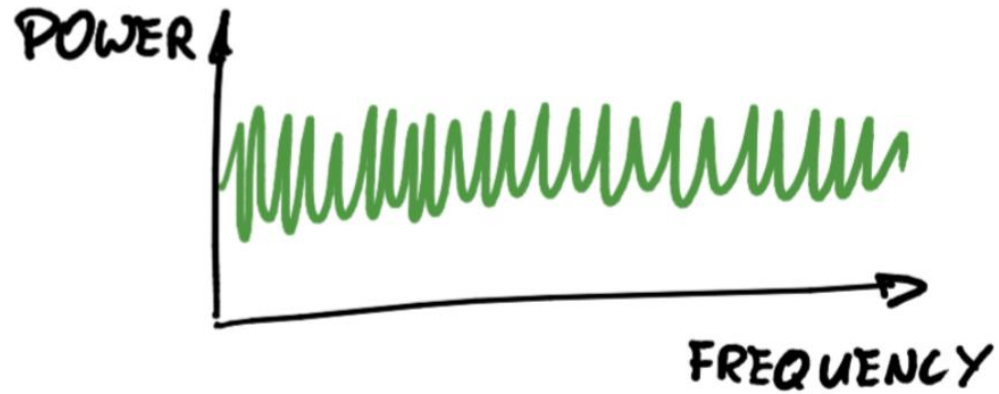

POWER
$\frac{N}{4}(A^2+B^2)$
f
FREQUENCY

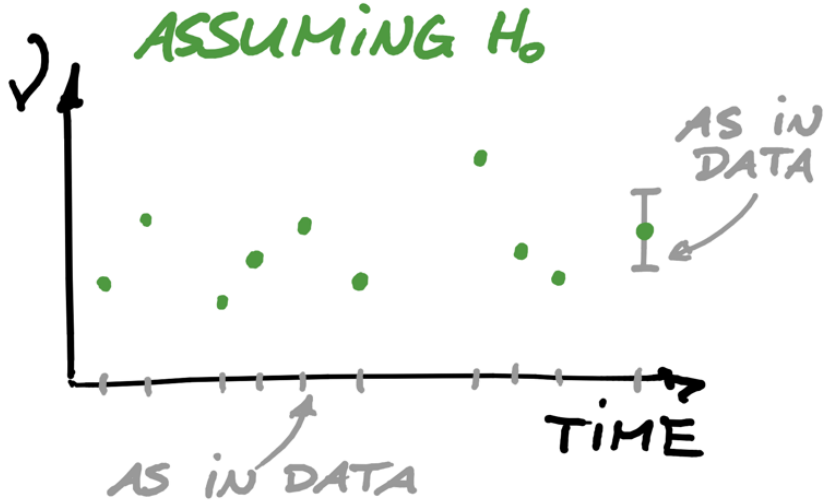

POWER
$\frac{N}{4}(A^2+B^2)$
f
FREQUENCY

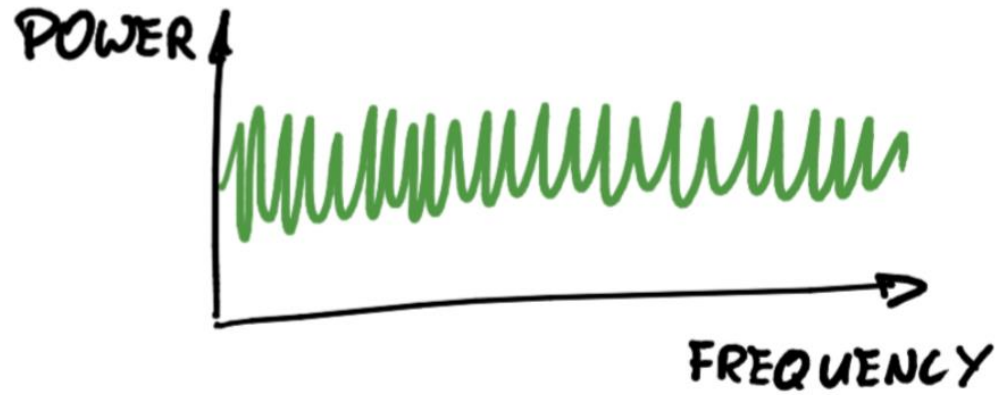

10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
Amplitude (*10^-26 e cm)
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Oscillation Frequency (days^-1)

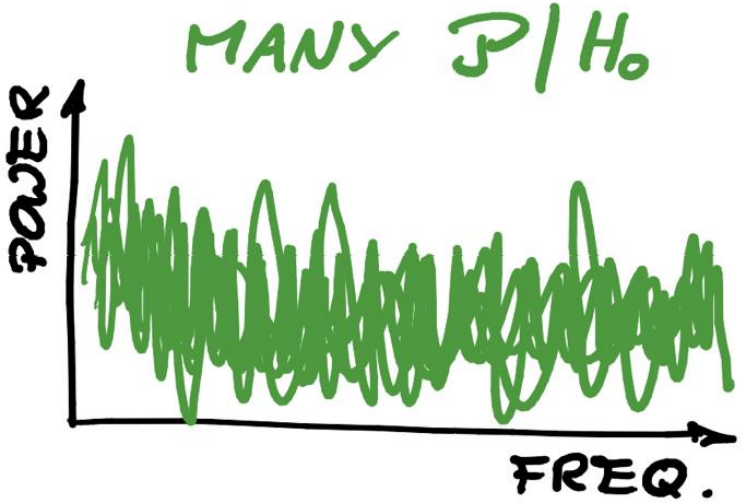

ASSUMING H_0
AS IN DATA
TIME
AS IN DATA

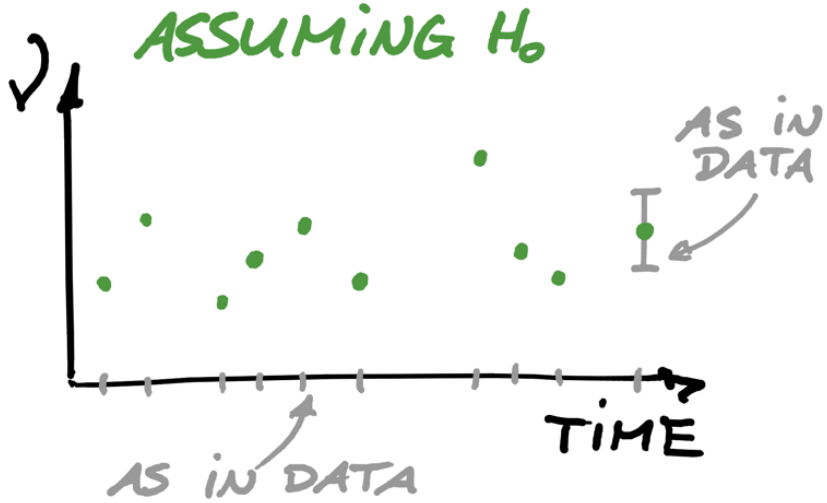

ASSUMING H_0
AS IN DATA
TIME
AS IN DATA

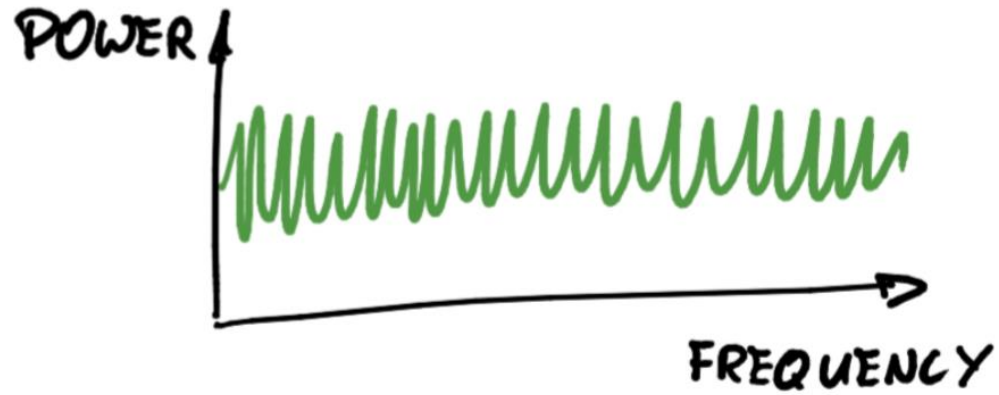

POWER
FREQUENCY

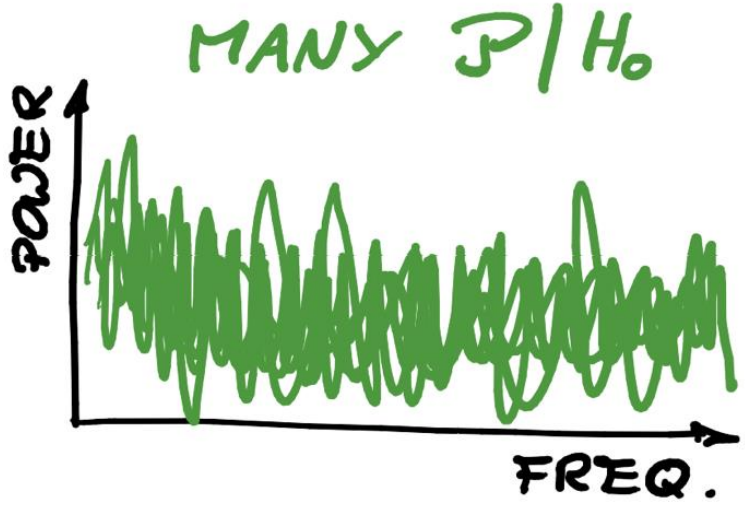

ASSUMING H_0
AS IN DATA
TIME
AS IN DATA

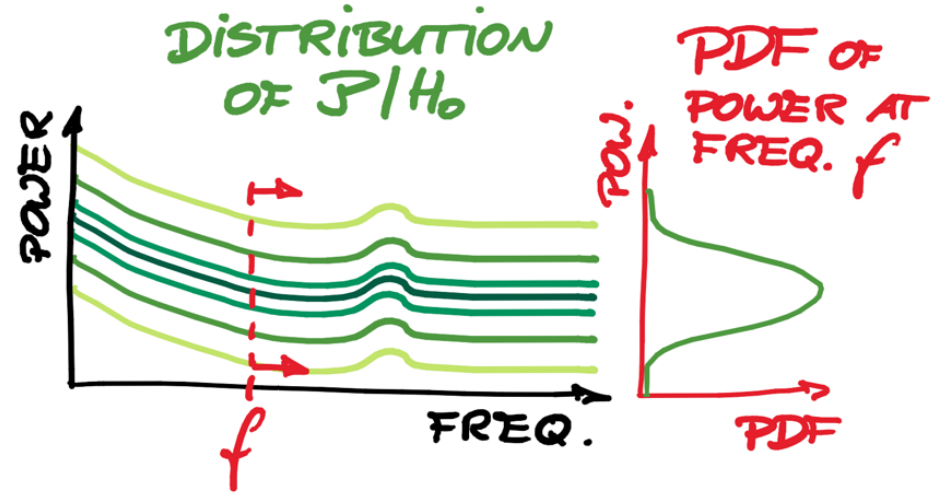

POWER
FREQUENCY

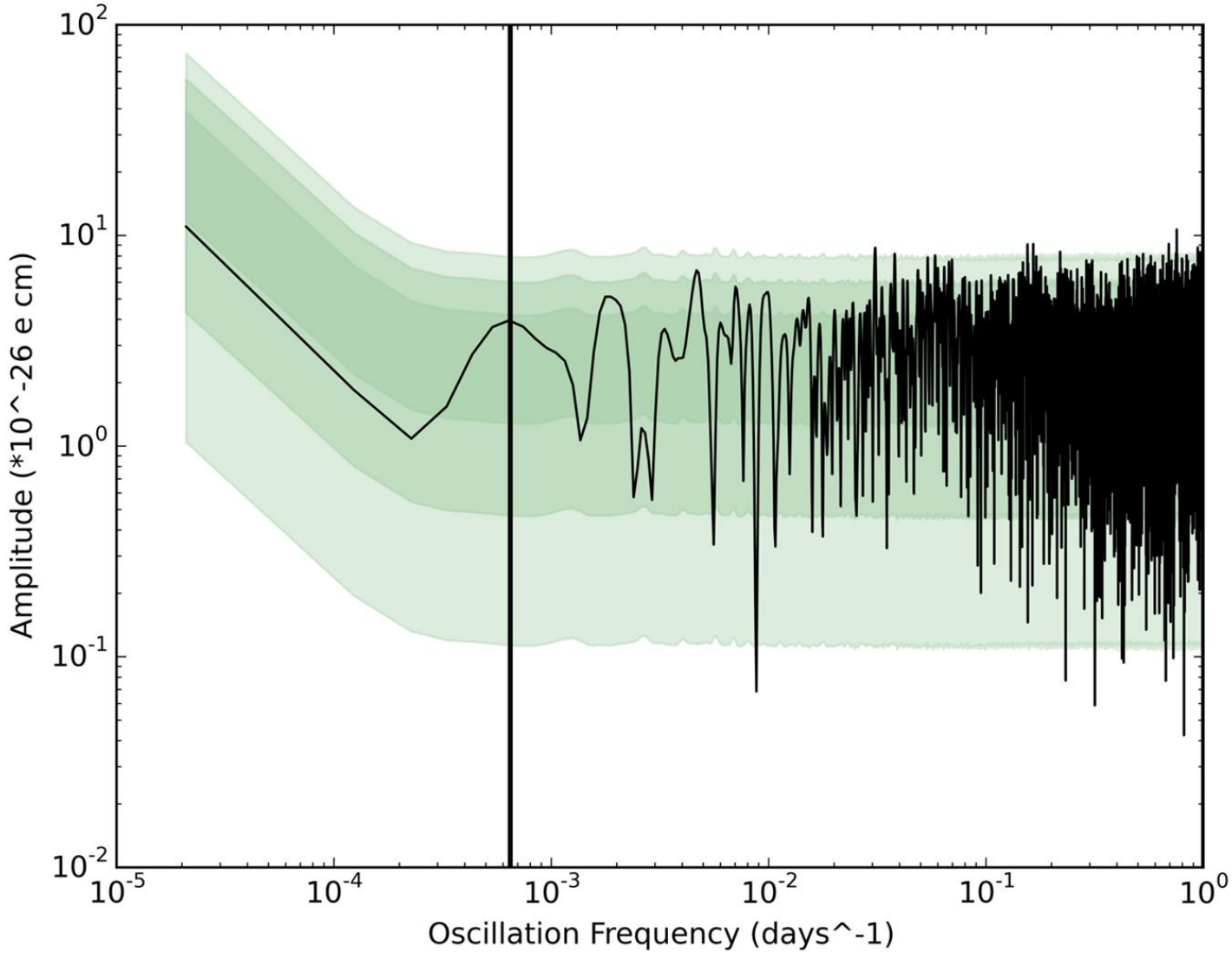

MANY P|H_0
POWER
FREQ.

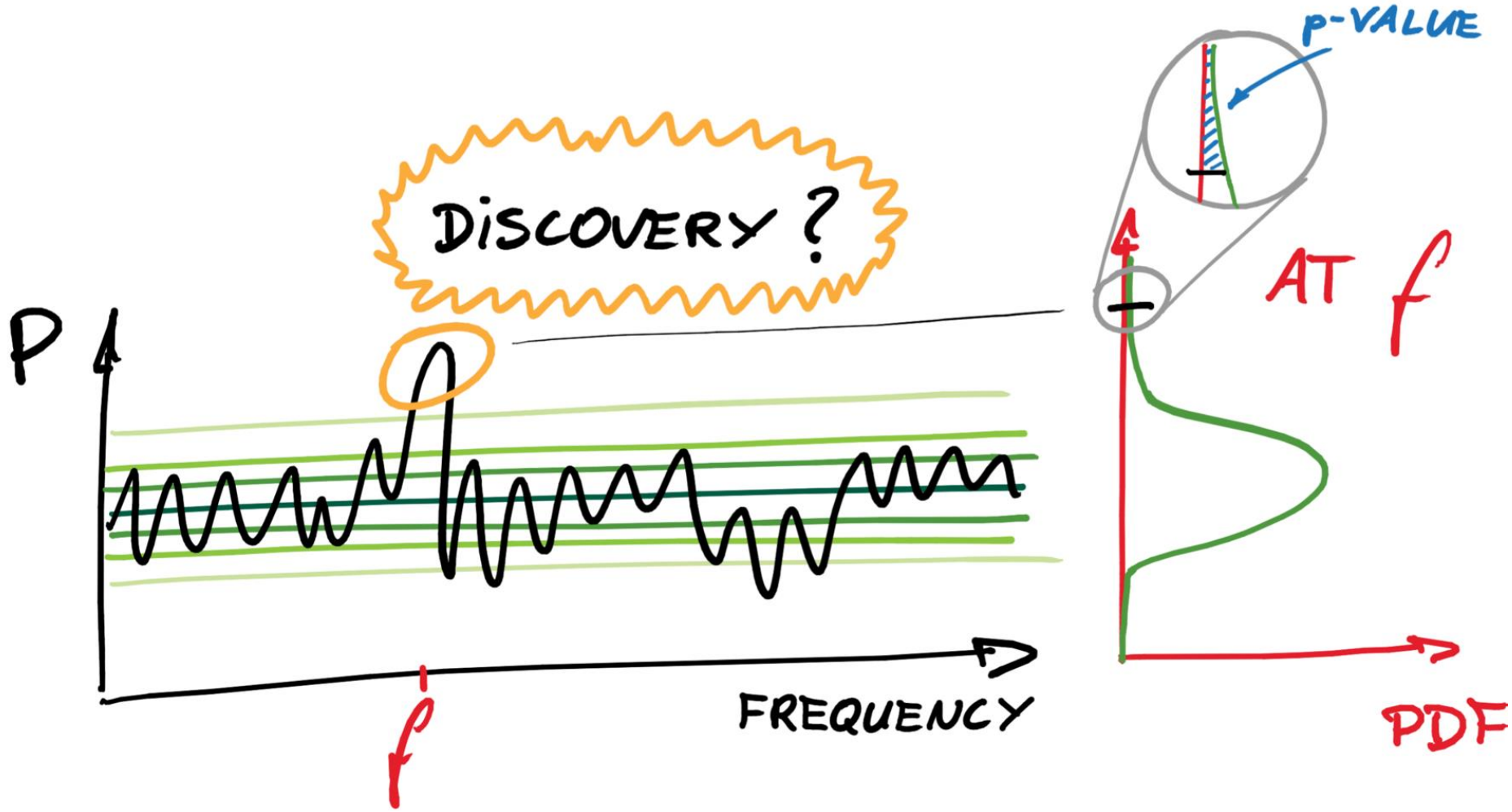

ASSUMING H_0
AS IN DATA
TIME
AS IN DATA

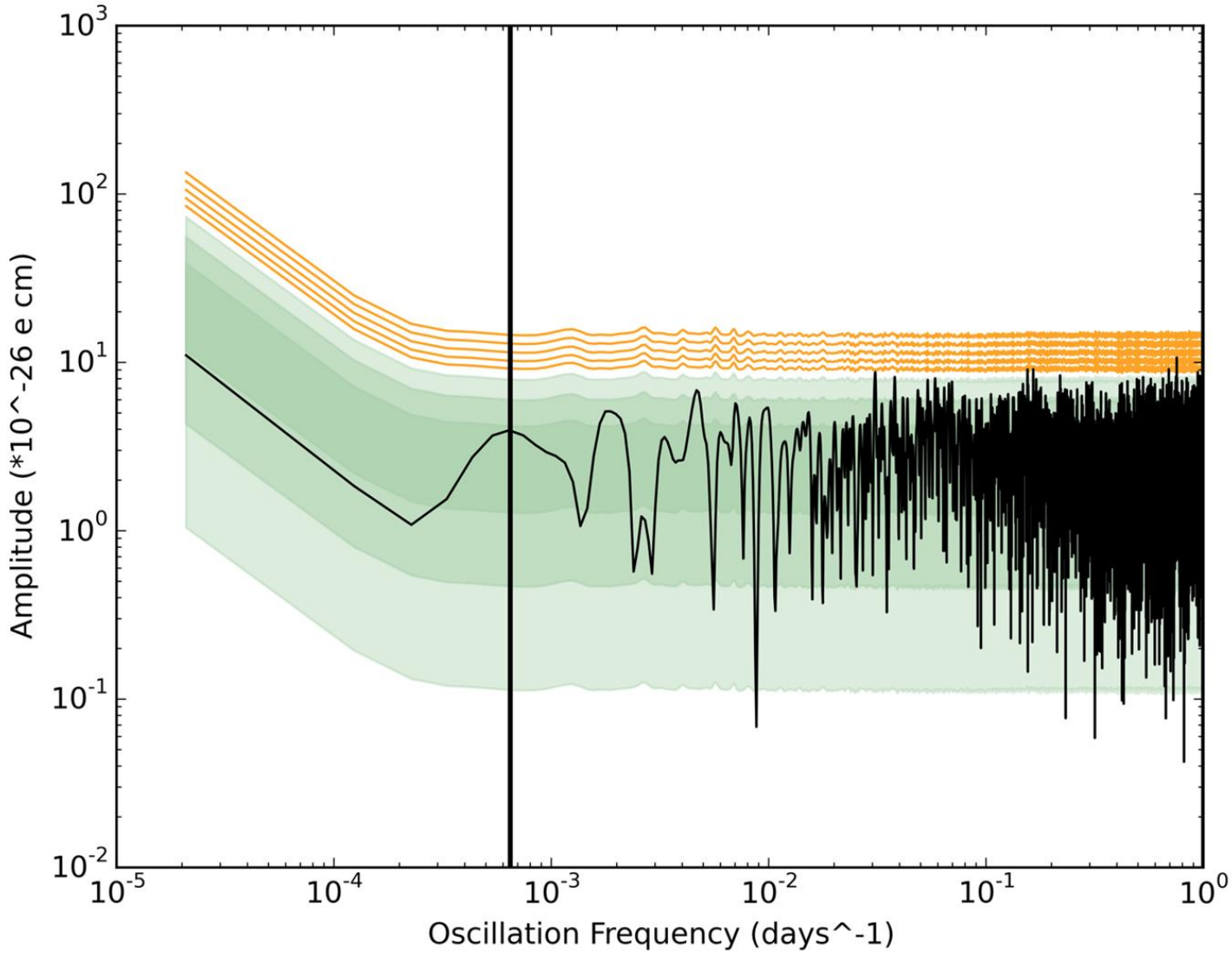

POWER
FREQUENCY

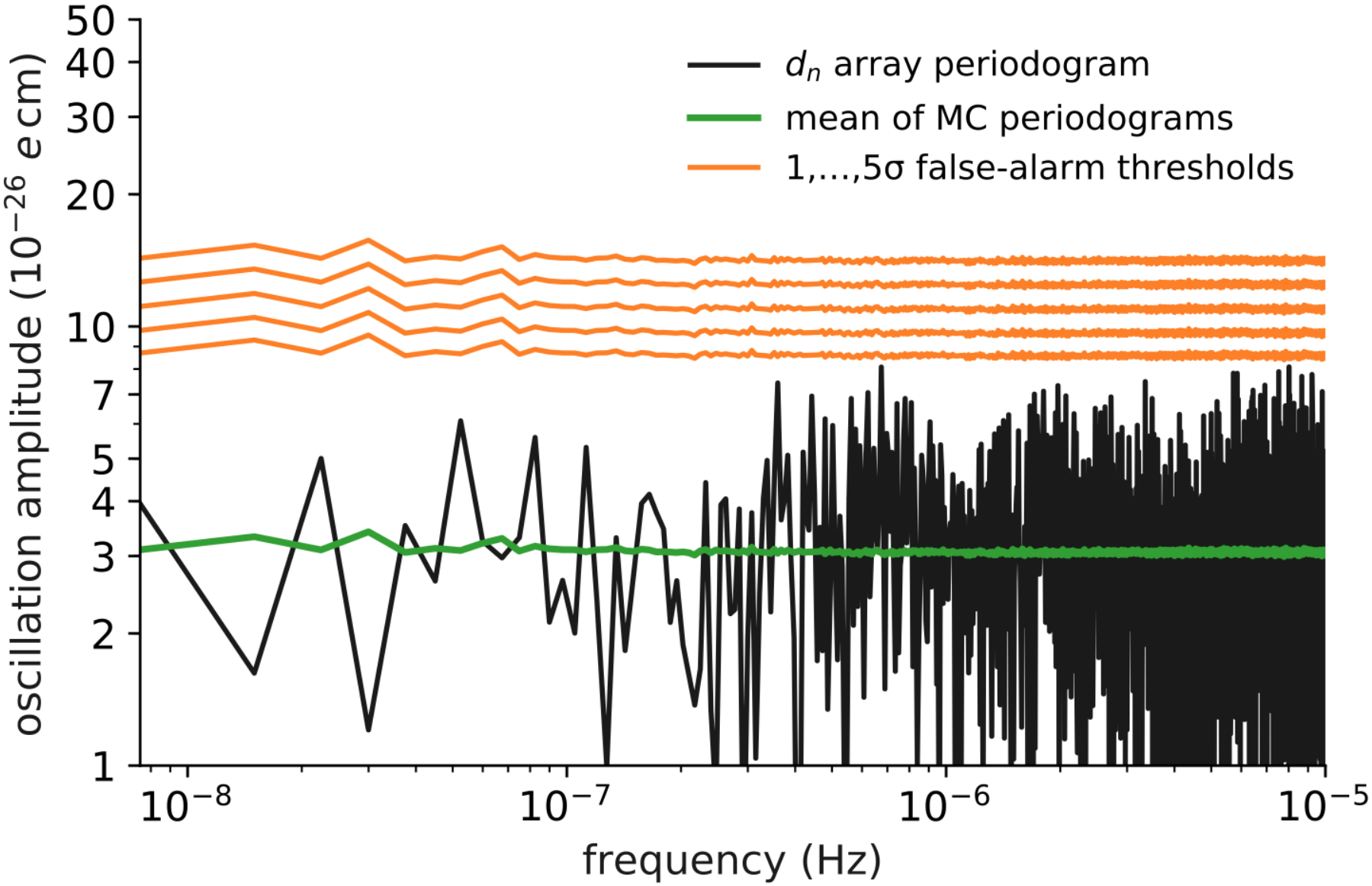

MANY $P|H_0$
POWER
FREQ.


DISTRIBUTION OF $P|H_0$
POWER
FREQ.
f
PDF OF POWER AT FREQ. f
PDF
PDF


Amplitude (*10^-26 e cm)
Oscillation Frequency (days^-1)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}


DISCOVERY ?
P
FREQUENCY
f
p-VALUE
AT f
PDF


Amplitude (*10^-26 e cm)
Oscillation Frequency (days^-1)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}



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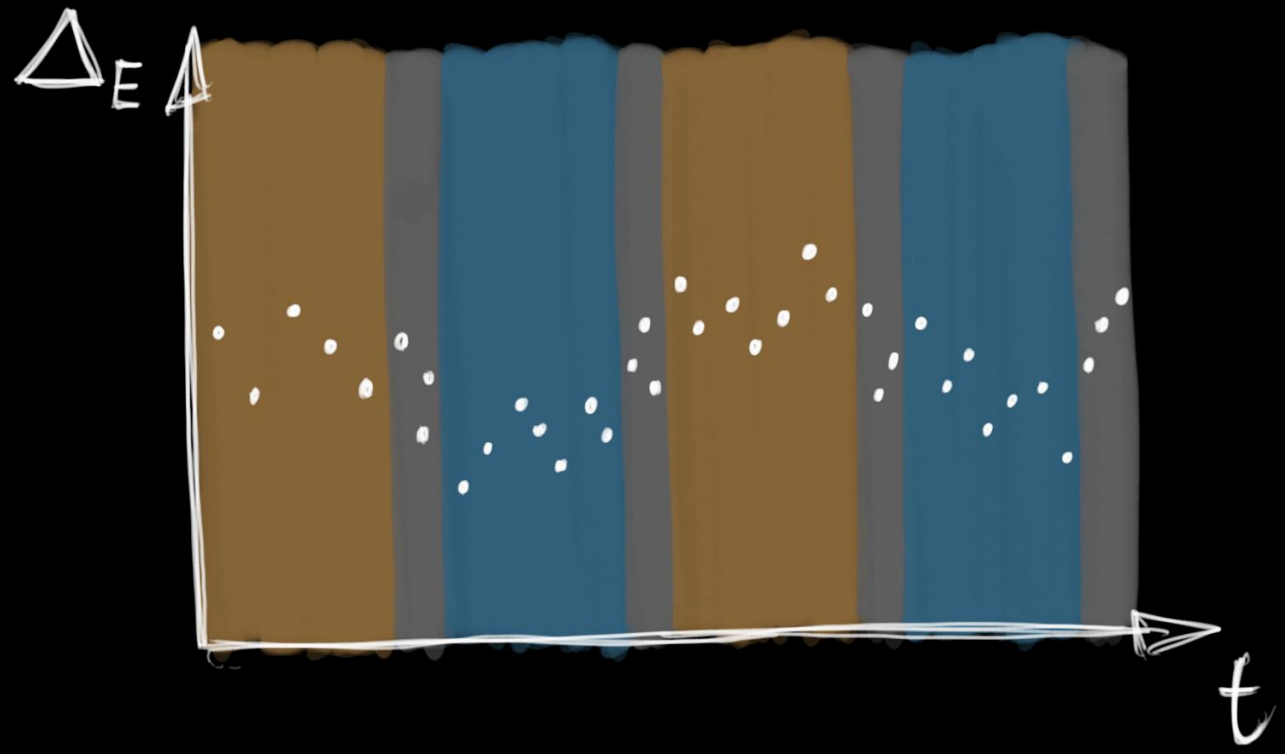
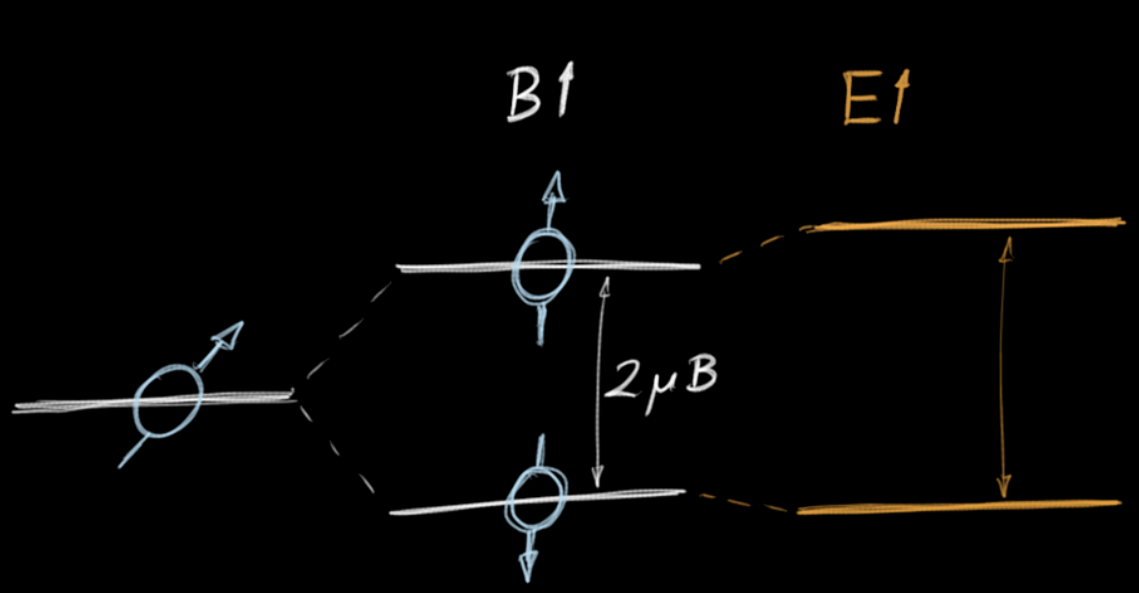
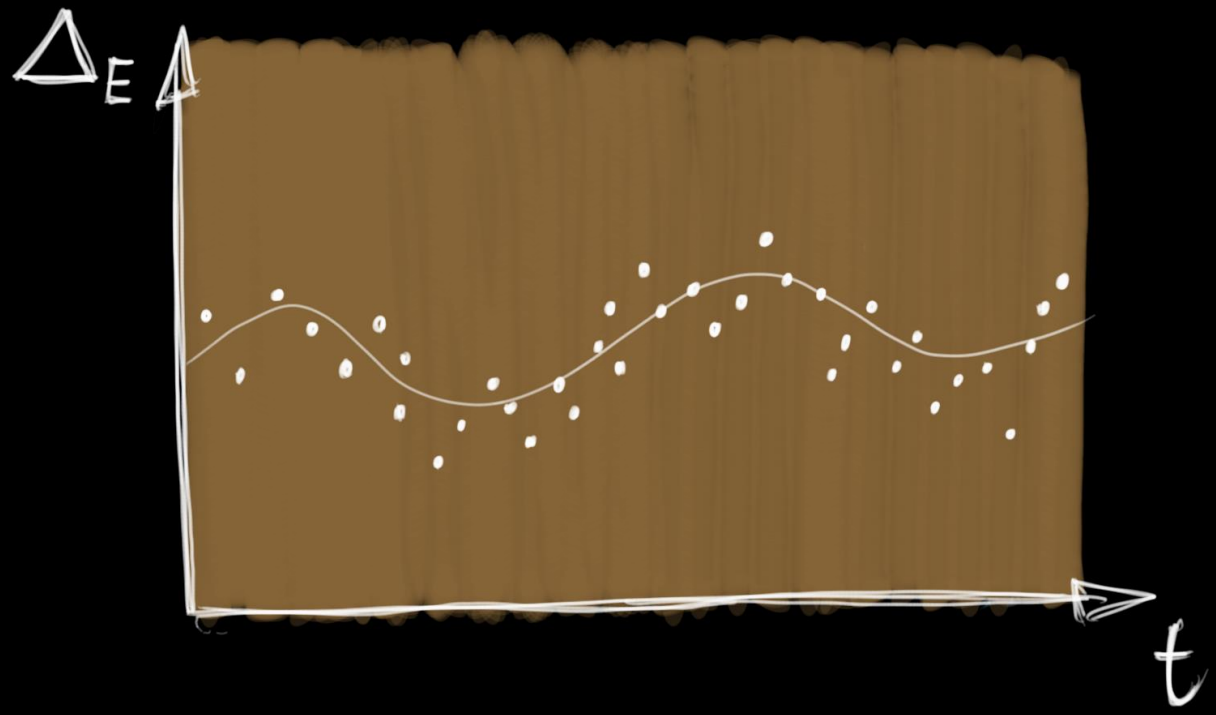
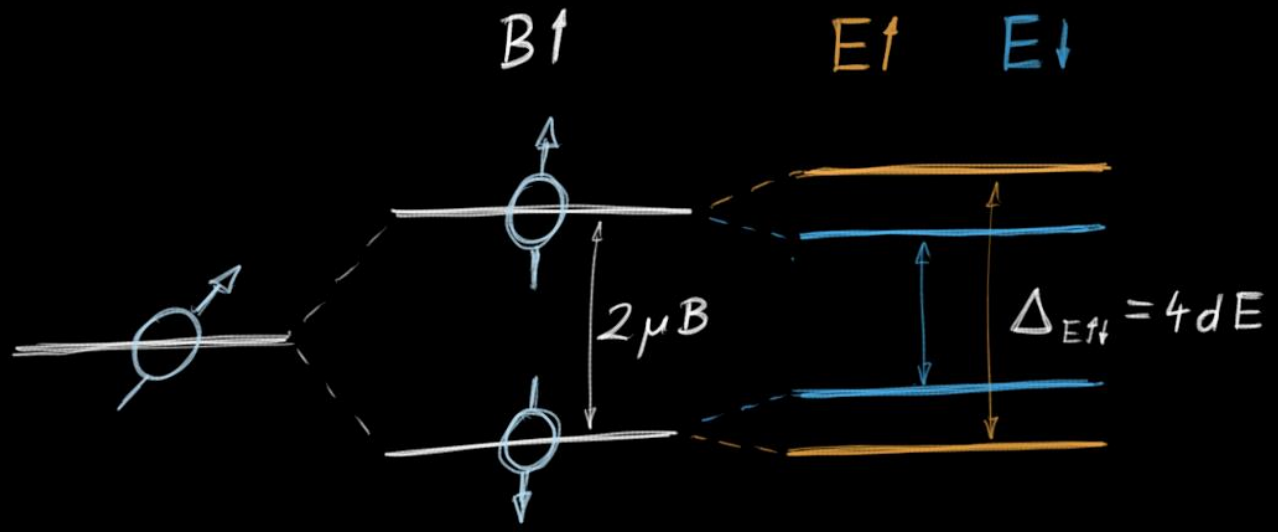
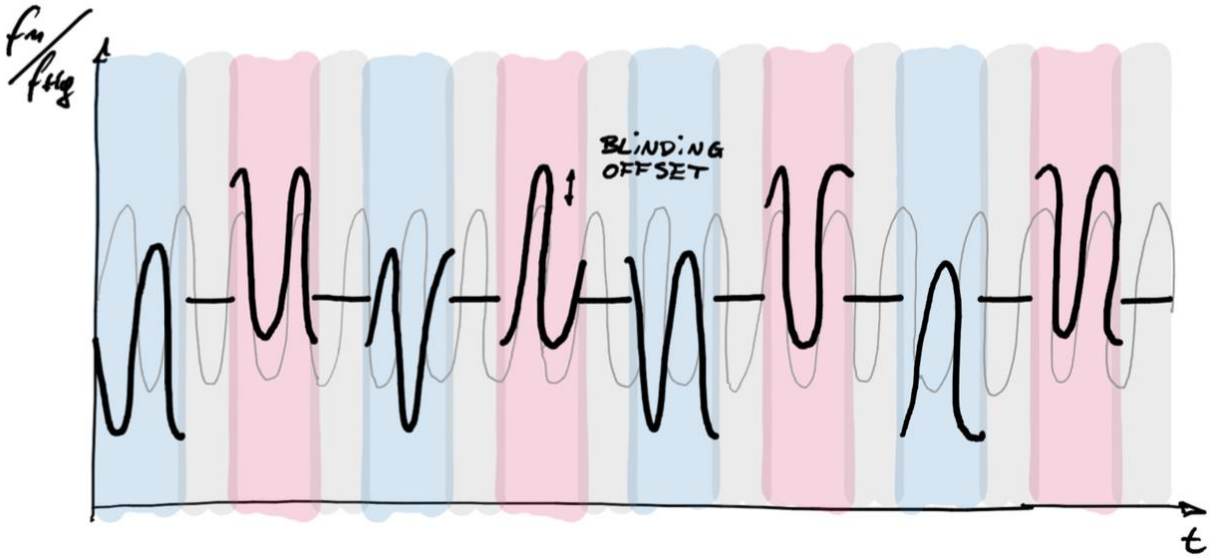

ΔE
t

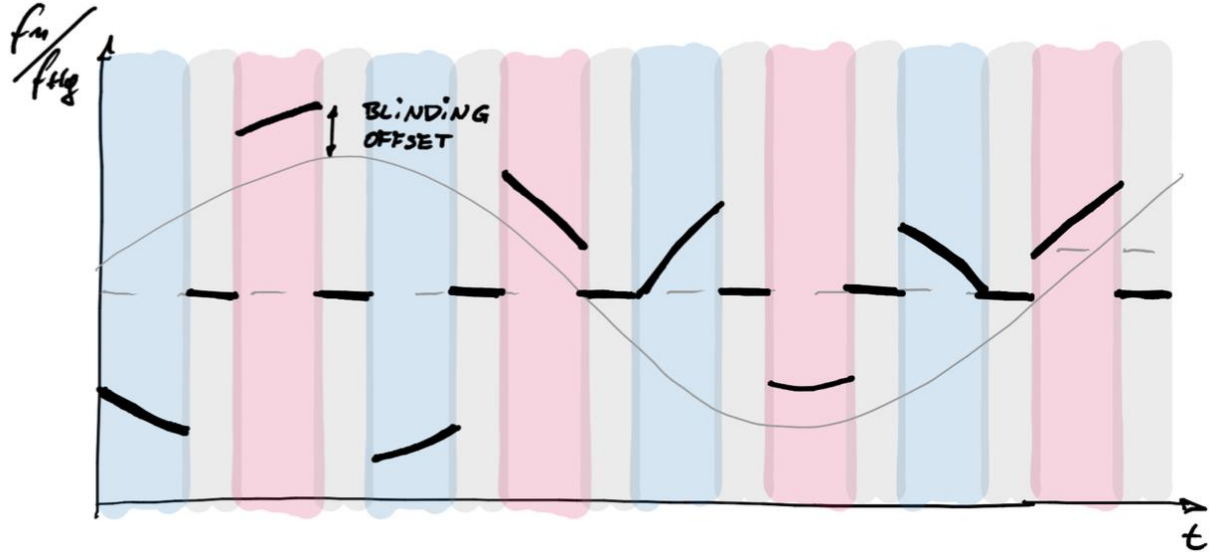
$$d_n(t) \approx 5.9 \times 10^{-22}\, C_G \left(\frac{10^{-22}\,\mathrm{eV}}{m_a}\right)\left(\frac{10^{16}\,\mathrm{GeV}}{f_a}\right)\cos(m_a t)\ e\cdot\mathrm{cm}$$

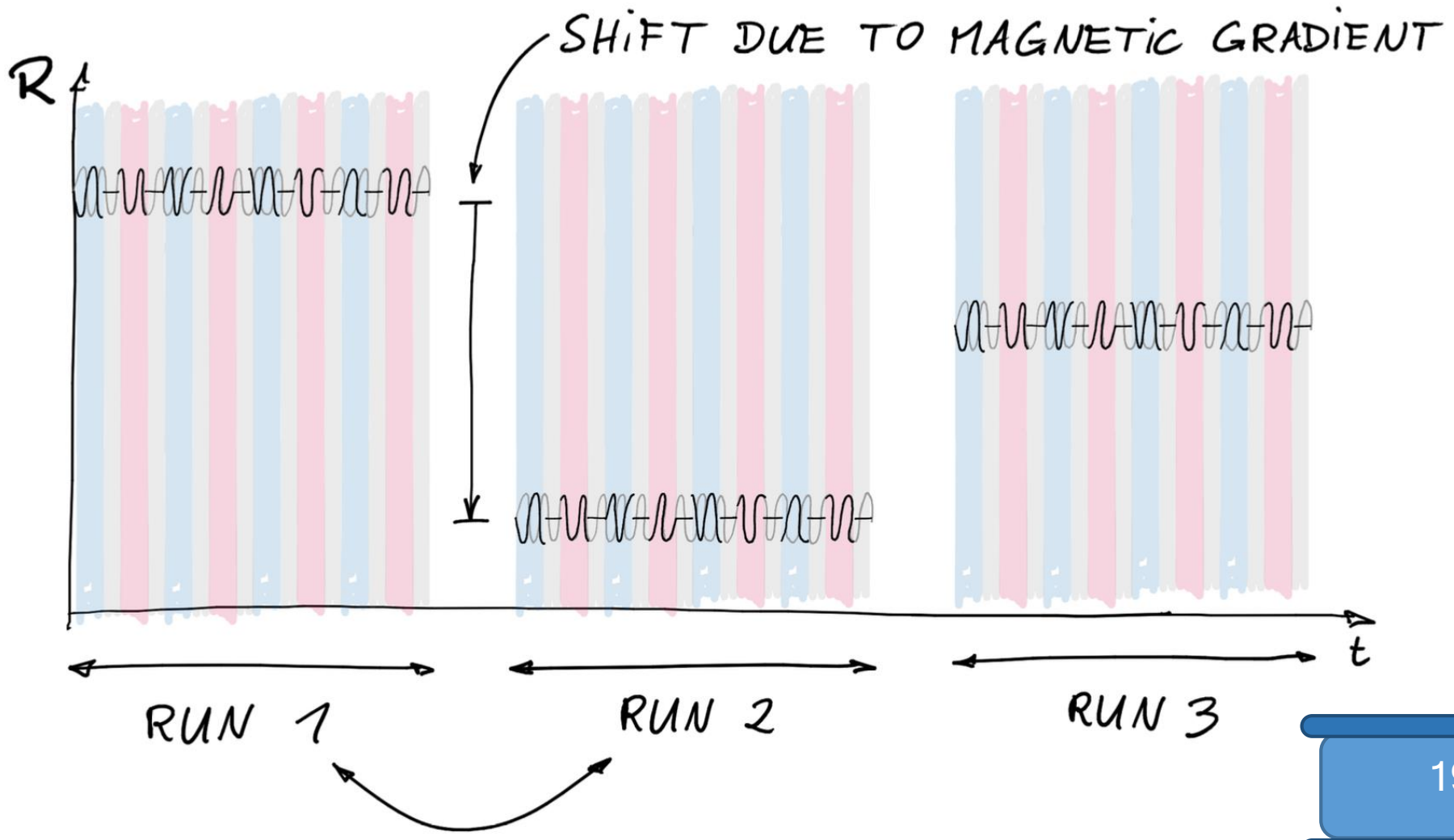





B↑
E↑
E↓
2μB
Δ E↑↓ = 4dE

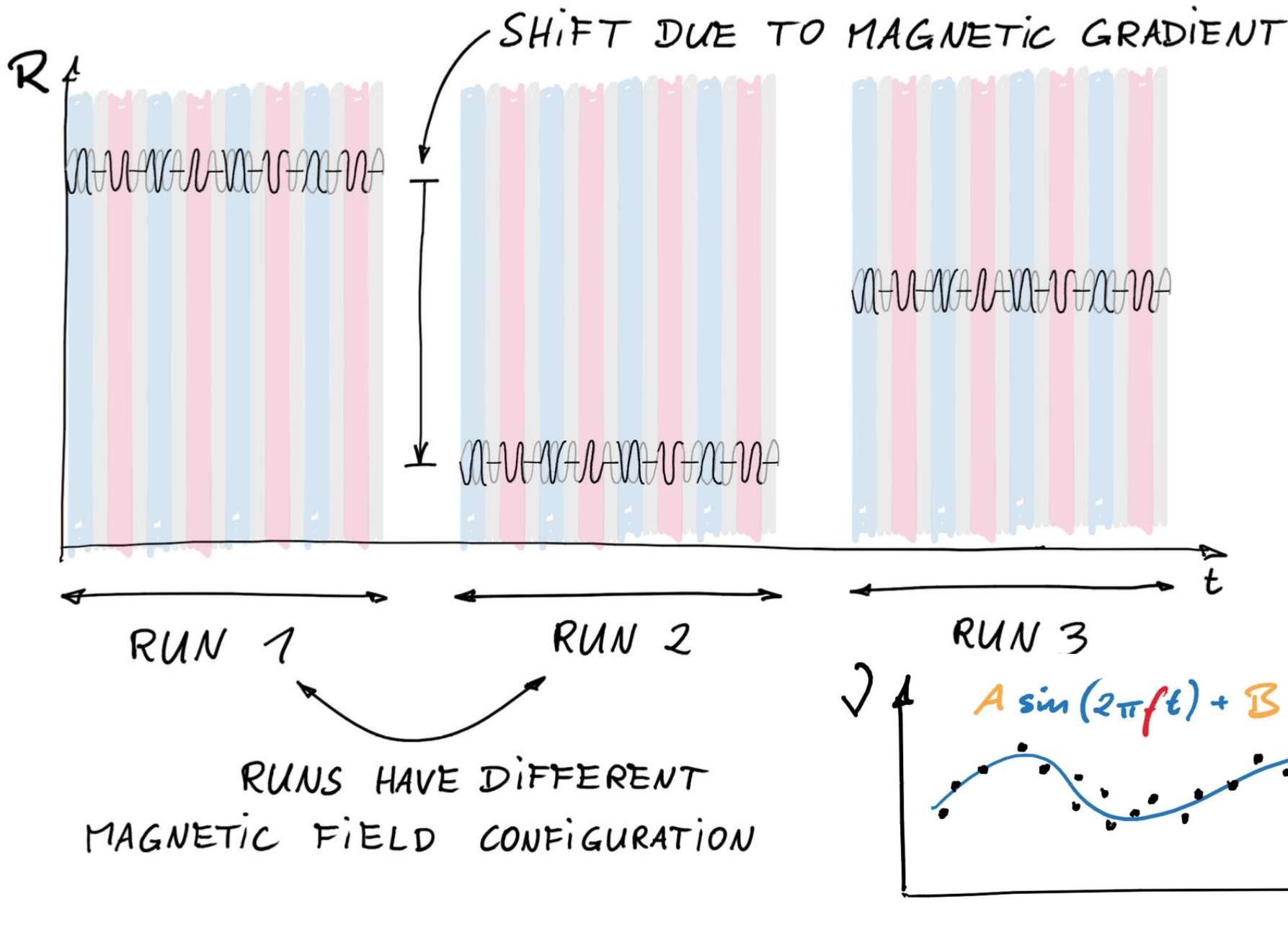

fm/fstg
t
BLINDING OFFSET
t

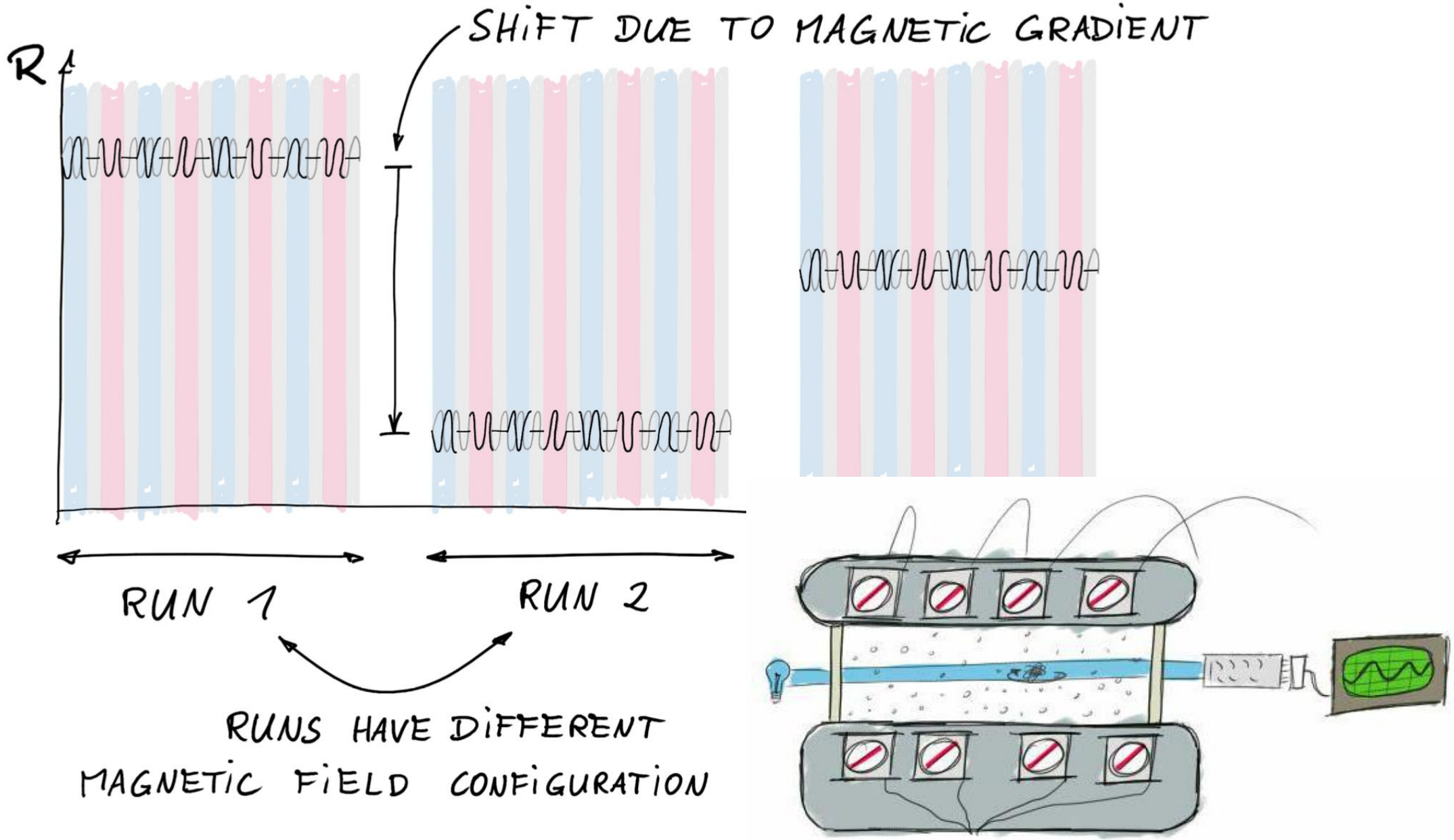

fm/fstg
t
BLINDING OFFSET
t

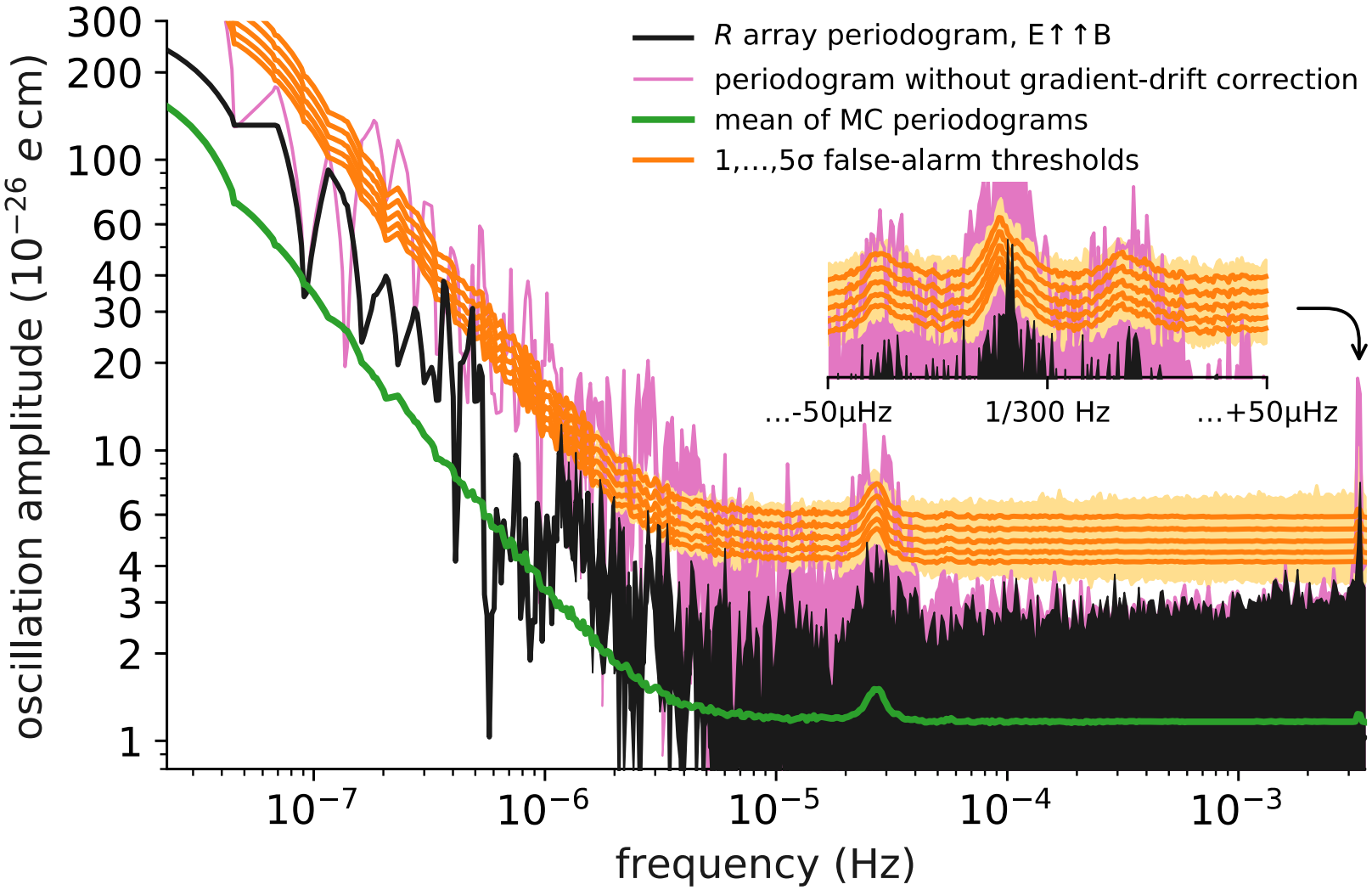

SHIFT DUE TO MAGNETIC GRADIENT
R
t
RUN 1
RUN 2
RUN 3
RUNS HAVE DIFFERENT
MAGNETIC FIELD CONFIGURATION

^{199}Hg

UCN


SHIFT DUE TO MAGNETIC GRADIENT
R
t
RUN 1
RUN 2
RUN 3
RUNS HAVE DIFFERENT
MAGNETIC FIELD CONFIGURATION
A sin(2πft) + B cos(2πft) + C
TIME


SHIFT DUE TO MAGNETIC GRADIENT
R
RUN 1
RUN 2
RUNS HAVE DIFFERENT
MAGNETIC FIELD CONFIGURATION



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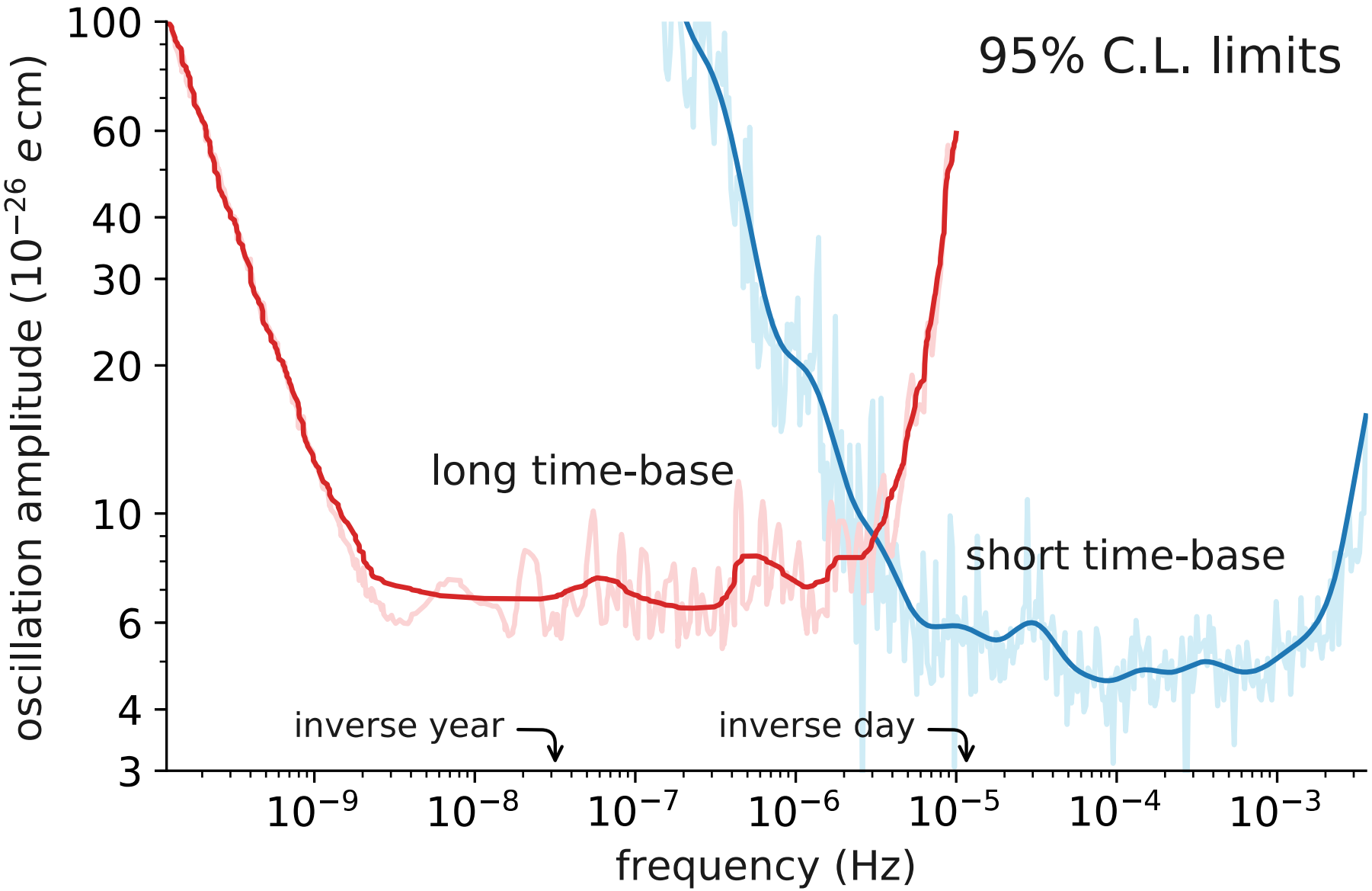

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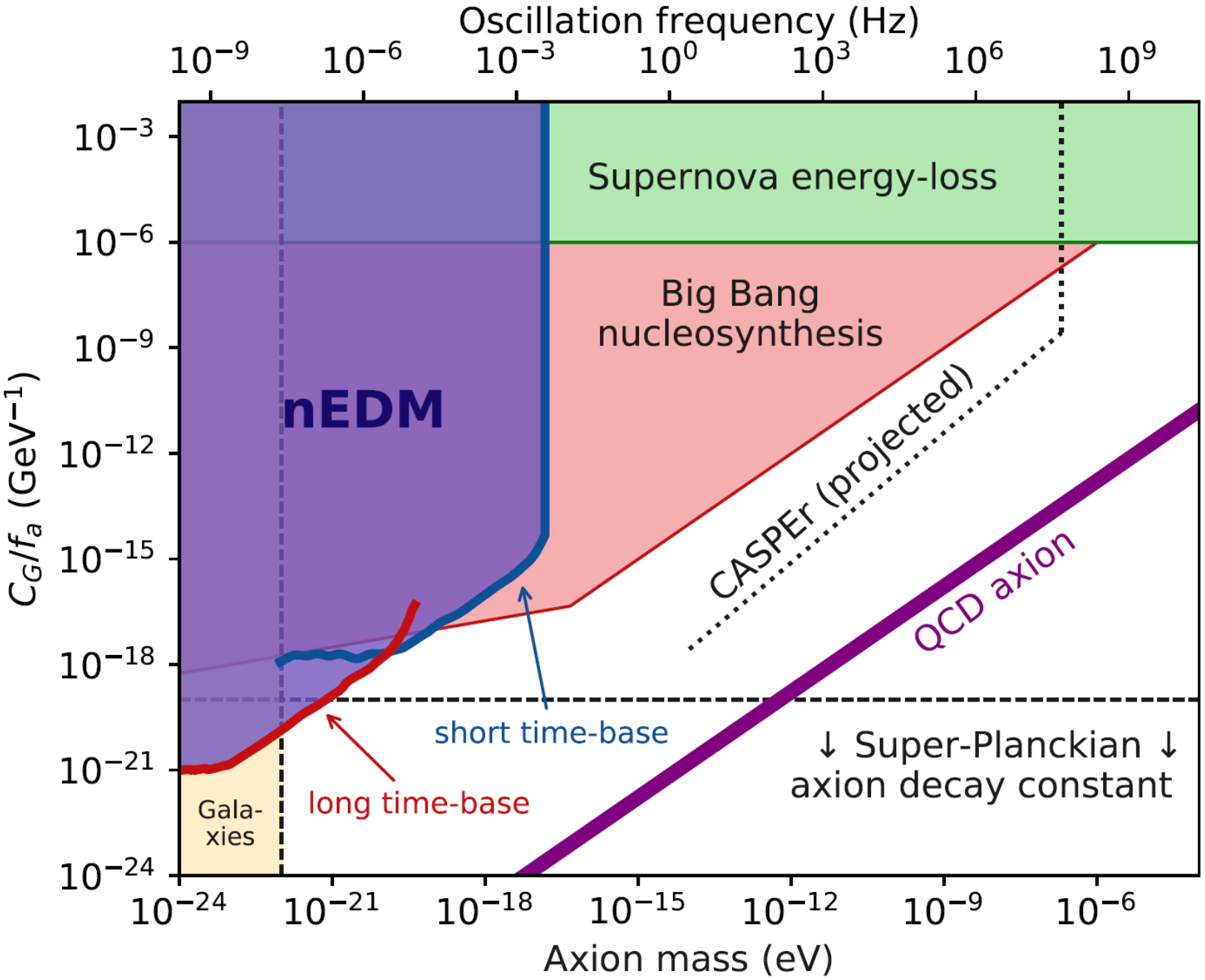
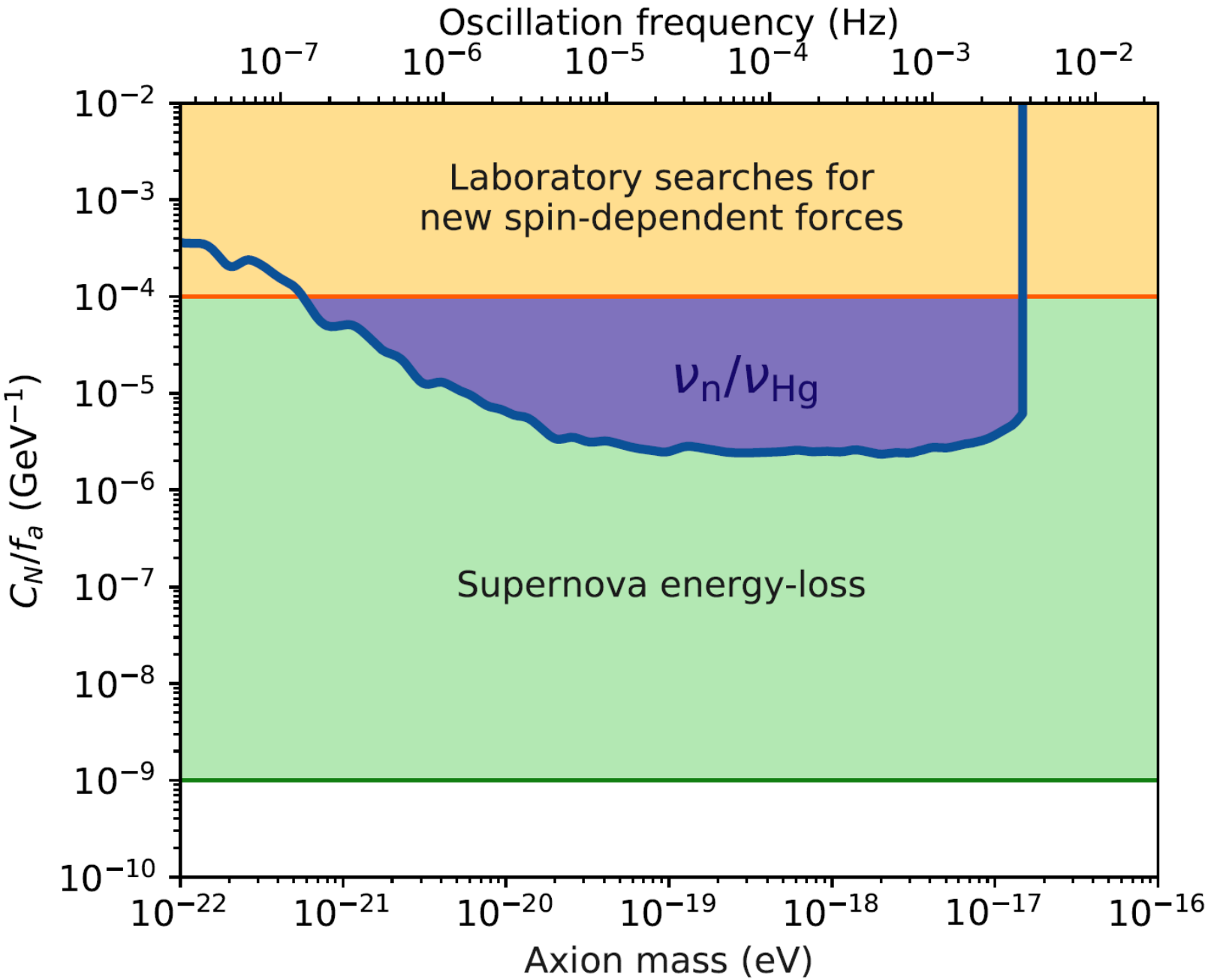
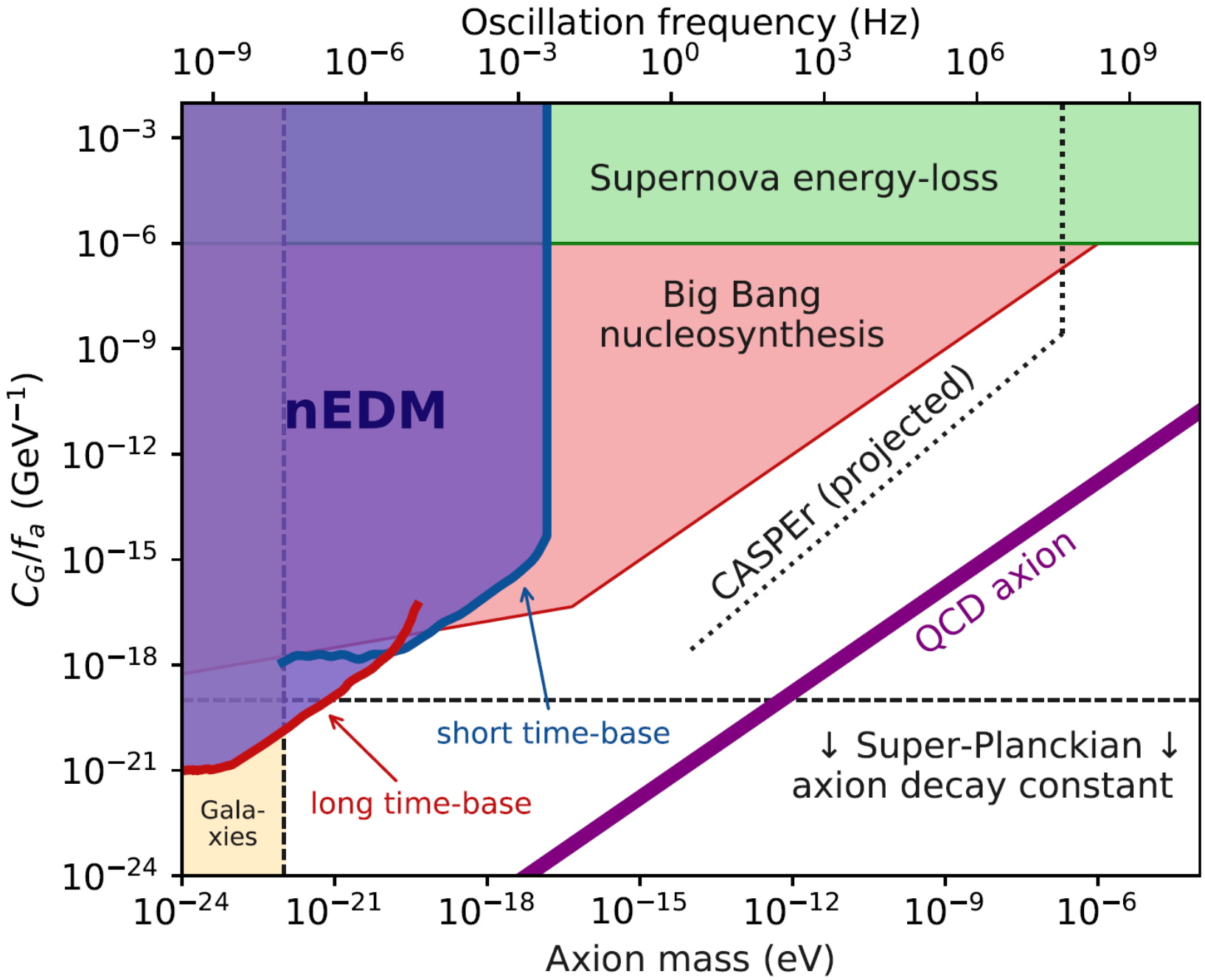
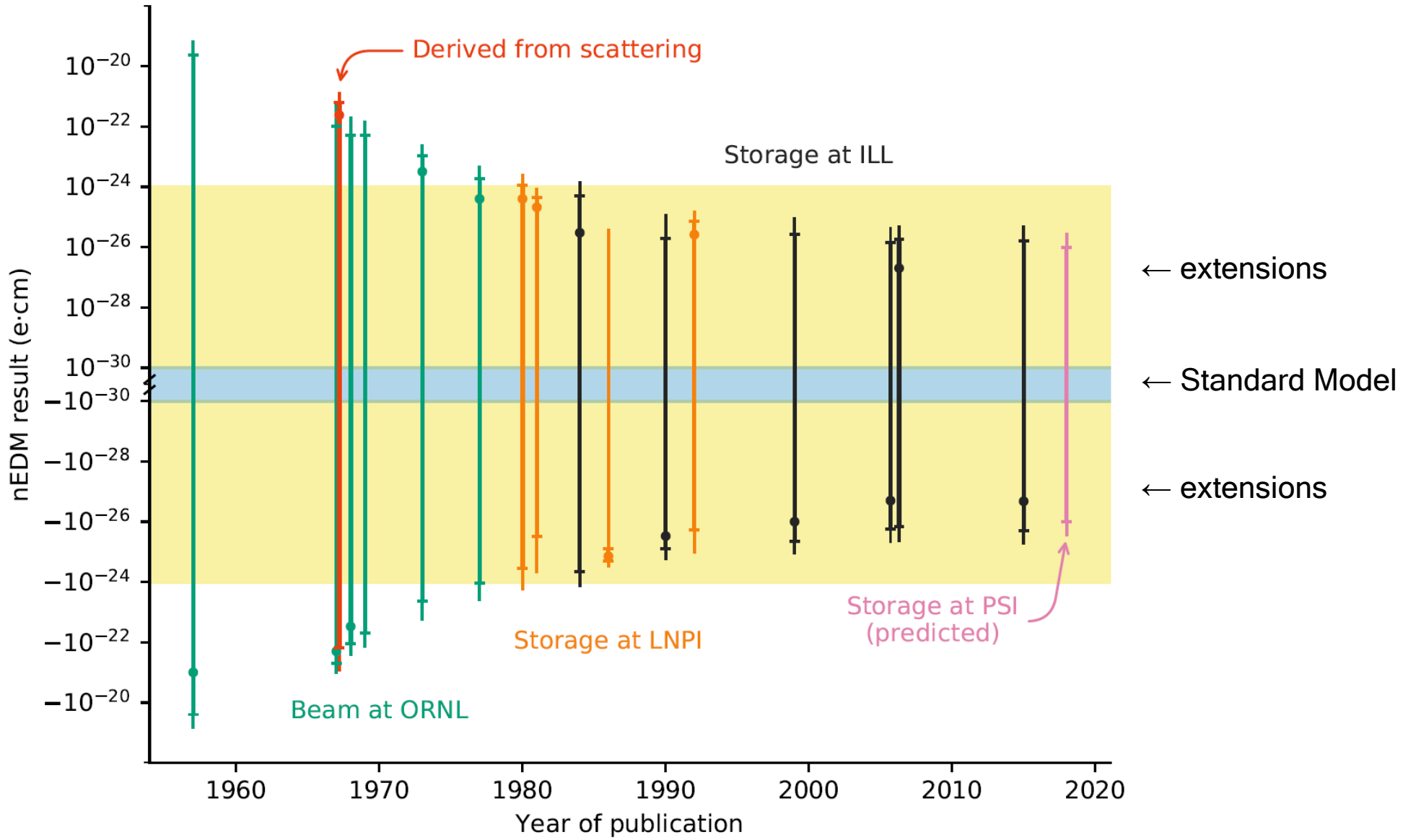
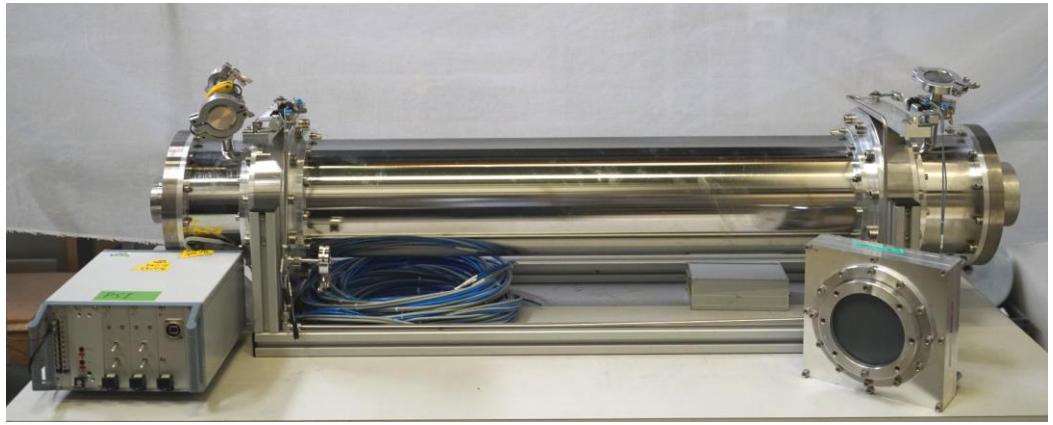

Oscillation frequency (Hz)
10^{-9} 10^{-6} 10^{-3} 10^{0} 10^{3} 10^{6} 10^{9}
C_G/f_a (GeV^{-1})
10^{-3} 10^{-6} 10^{-9} 10^{-12} 10^{-15} 10^{-18} 10^{-21} 10^{-24}
Supernova energy-loss
Big Bang nucleosynthesis
nEDM
CASPEr (projected)
QCD axion
short time-base
long time-base
↓ Super-Planckian ↓ axion decay constant
Gala-xies
10^{-24} 10^{-21} 10^{-18} 10^{-15} 10^{-12} 10^{-9} 10^{-6}
Axion mass (eV)

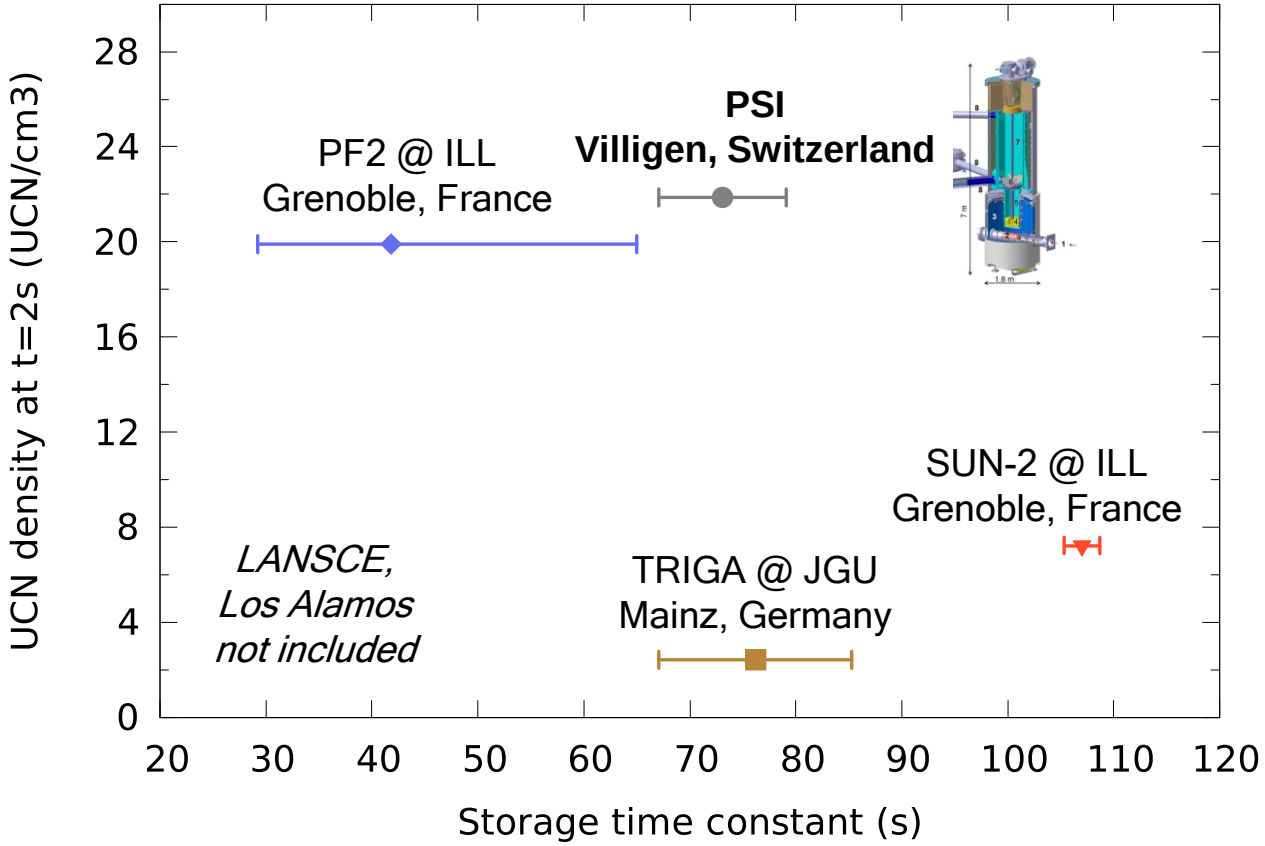

Oscillation frequency (Hz)
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
C_N/f_a (GeV^{-1})
Laboratory searches for
new spin-dependent forces
ν_n/ν_{Hg}
Supernova energy-loss
10^{-22}
10^{-21}
10^{-20}
10^{-19}
10^{-18}
10^{-17}
10^{-16}
Axion mass (eV)

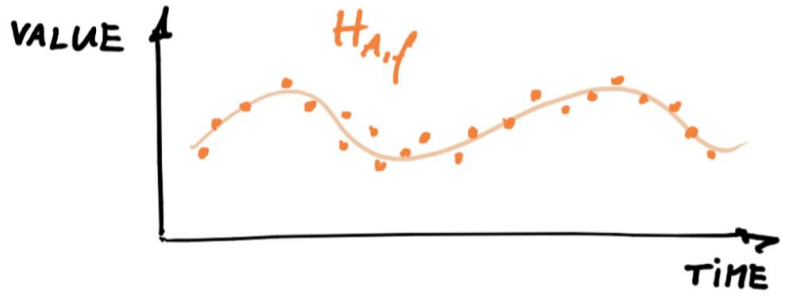

Oscillation frequency (Hz)
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
C_G/f_a (GeV^{-1})
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
10^{-21}
10^{-24}
Supernova energy-loss
Big Bang nucleosynthesis
nEDM
CASPEr (projected)
QCD axion
short time-base
long time-base
↓ Super-Planckian ↓ axion decay constant
Gala-xies
10^{-24}
10^{-21}
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
Axion mass (eV)

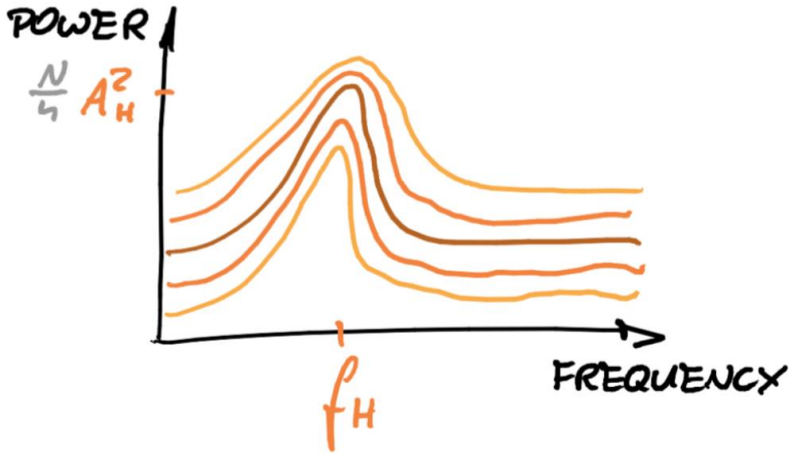
Measurements of the EDM of a free neutron

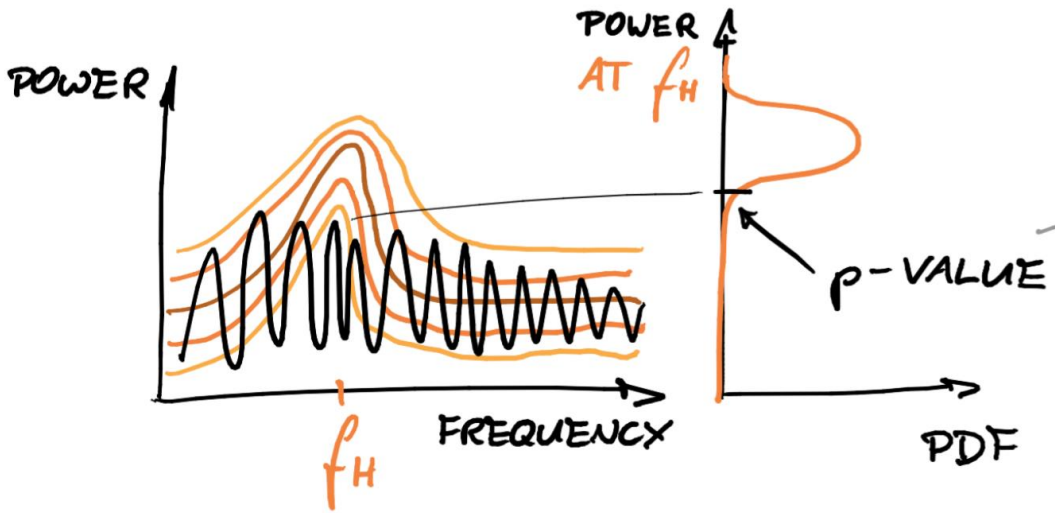




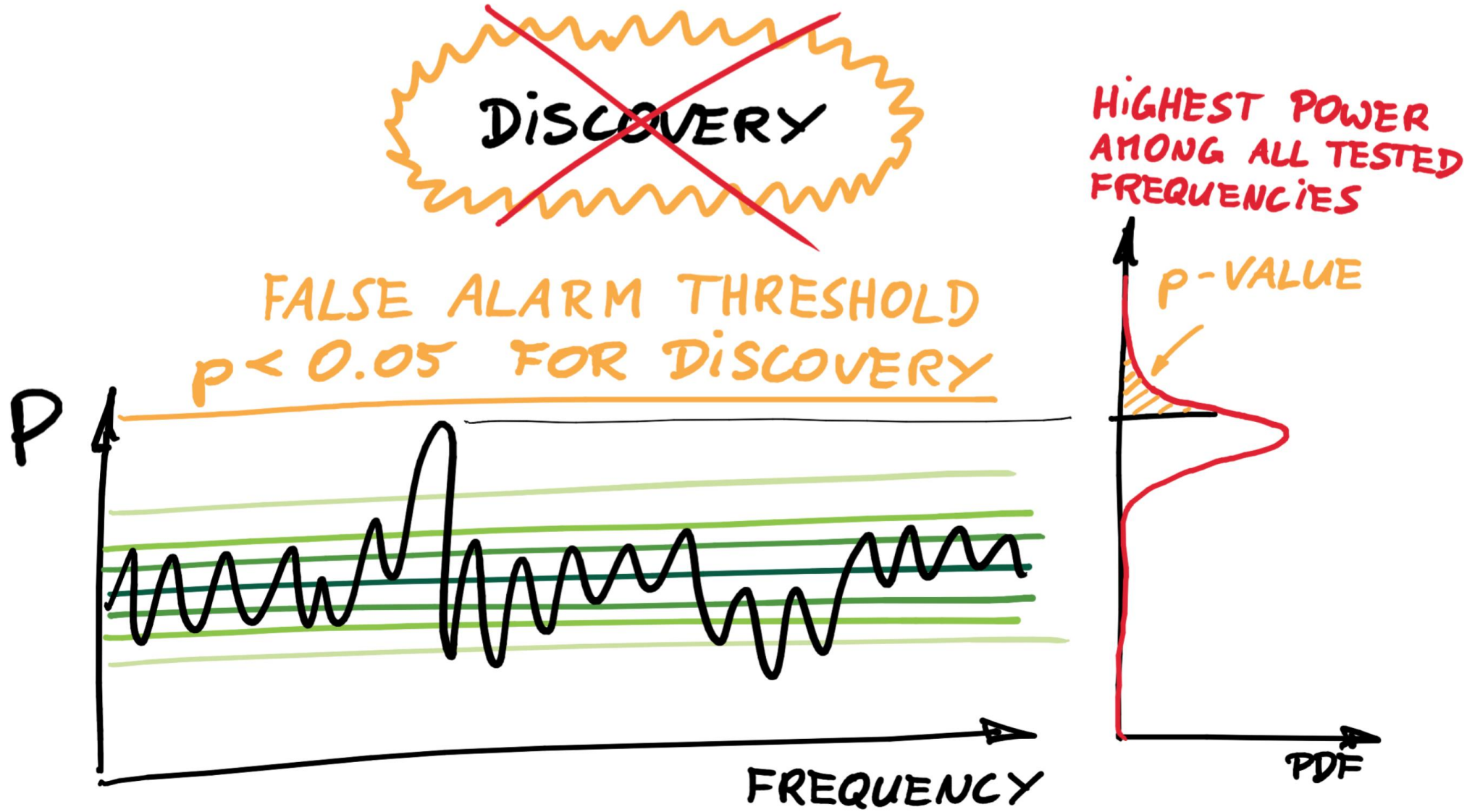

UCN density at t=2s (UCN/cm3)
28
24
20
16
12
8
4
0
20
30
40
50
60
70
80
90
100
110
120
Storage time constant (s)
PF2 @ ILL
Grenoble, France
PSI
Villigen, Switzerland
SUN-2 @ ILL
Grenoble, France
TRIGA @ JGU
Mainz, Germany
LANSCE,
Los Alamos
not included


VALUE
$H_{A,f}$
TIME


POWER
$\frac{N}{4} A_H^2$
f_H
FREQUENCY


POWER
POWER AT f_H
p-VALUE
PDF
FREQUENCY
f_H

SMALL P-VALUE ON EXCLUSION
↳ EXCLUDED
A_H
A_H
f_H
f_H
P-VALUE ON EXCLUSION
LARGE P-VALUE
↳ CAN'T EXCLUDE

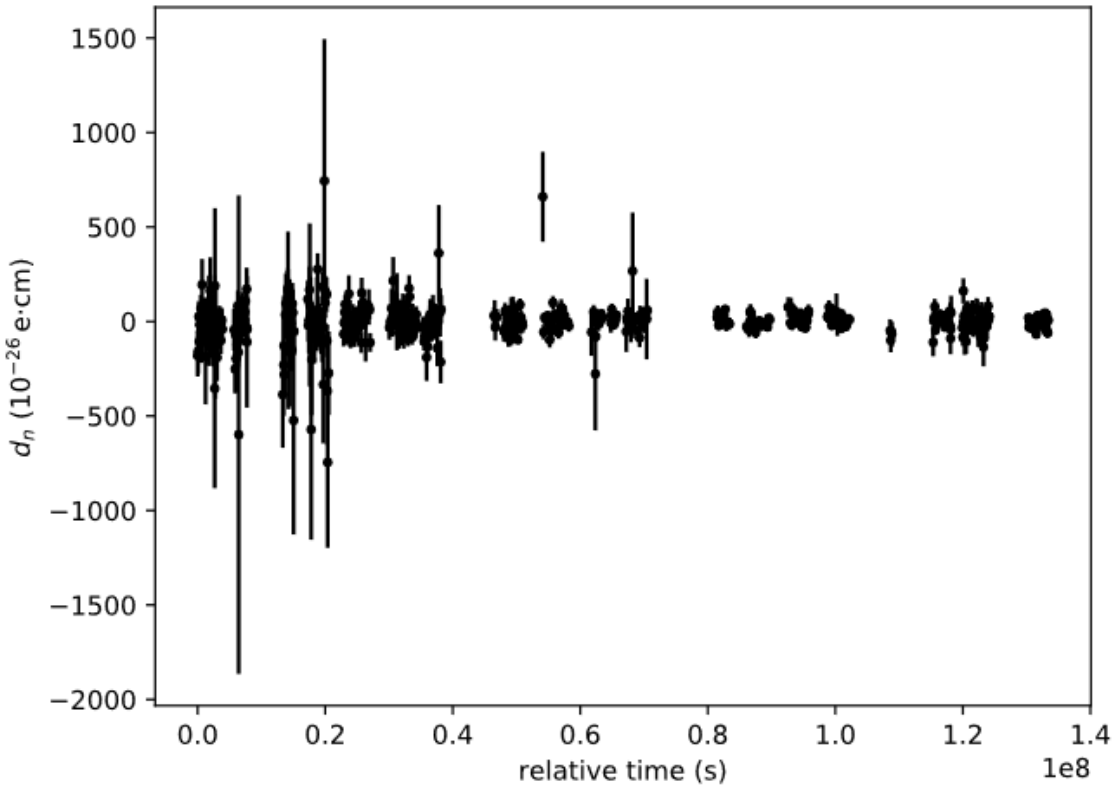

DISCOVERY
FALSE ALARM THRESHOLD
p < 0.05 FOR DISCOVERY
P
FREQUENCY
HIGHEST POWER AMONG ALL TESTED FREQUENCIES
p-VALUE
PDF

$$p_{\mathrm{global}} = 1 - (1 - p_{\mathrm{local}})^{\mathrm{number\ of\ frequencies}}$$

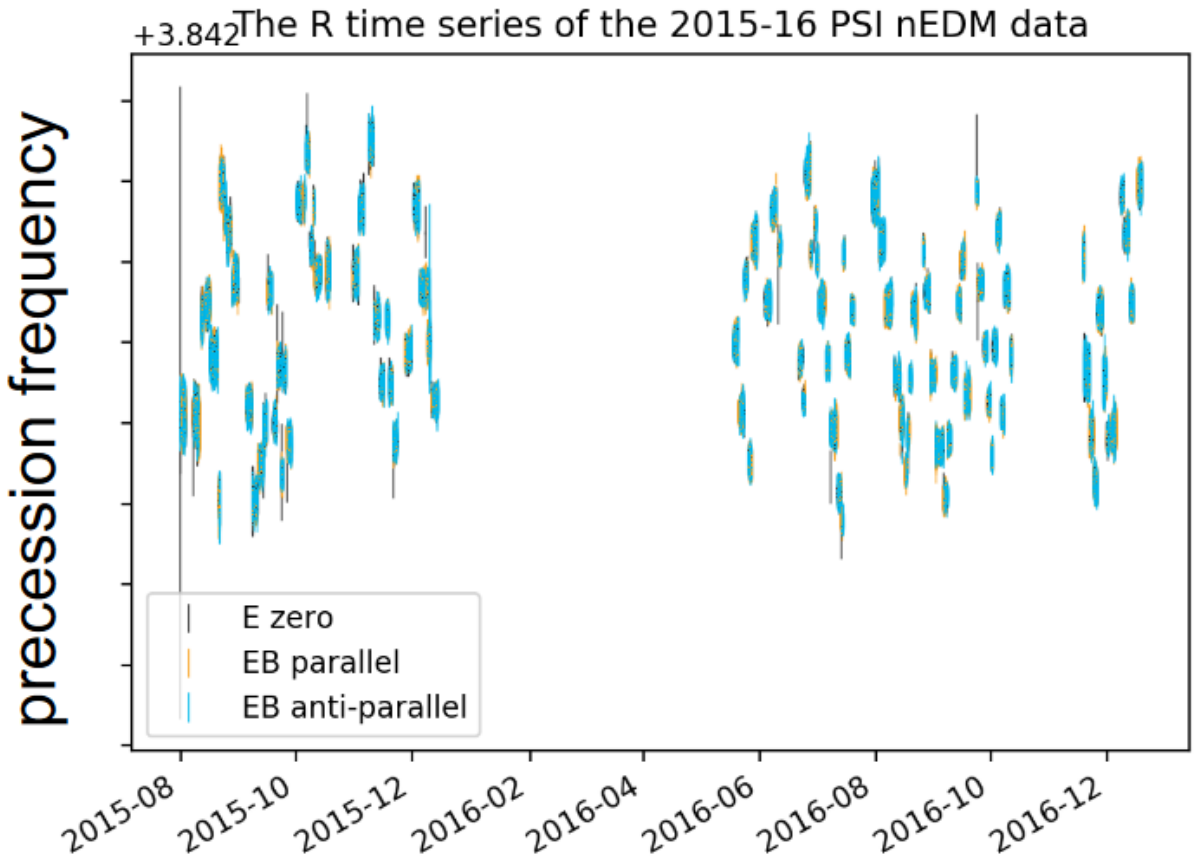
number of frequencies = 1 000 000

p_{global} = 3-sigma level

p_{local} = 6-sigma level


1500
1000
500
0
−500
−1000
−1500
−2000
d_n (10^{-26} e·cm)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1e8
relative time (s)

ILL


The R time series of the 2015-16 PSI nEDM data
+3.842
precession frequency
E zero
EB parallel
EB anti-parallel
2015-08
2015-10
2015-12
2016-02
2016-04
2016-06
2016-08
2016-10
2016-12

PSI