UCN optics simulations for the n2EDM experiment at PSI

Geza Zsigmond on behalf of the nEDM collaboration at PSI

Outline

- Scope of n2EDM simulations
- Benchmark of the PSI UCN source model (MCUCN)
- n2EDM simulation model
- Example simulations – spectra, guiding magnetic field
- Conclusions and outlook

Scope of n2EDM simulations

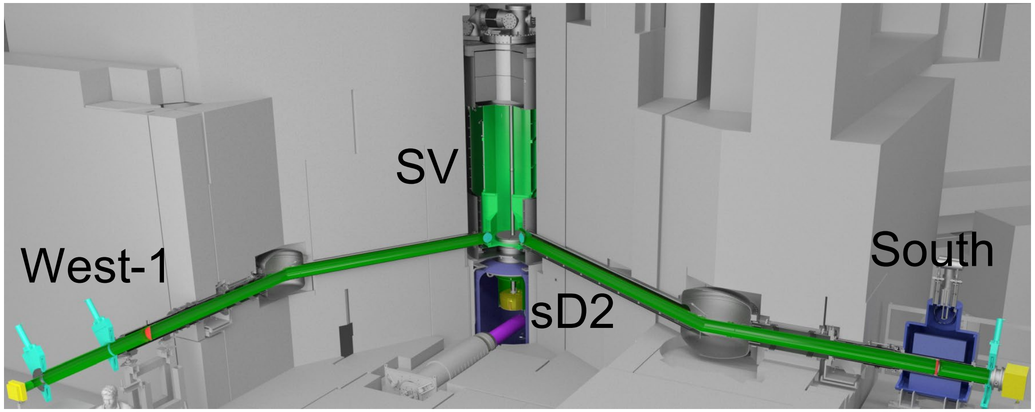
$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

- Technical design supported by detailed simulations of the UCN optics system with MCUCN (NIM A 881, 16 (2018))
- Maximize UCN density in the precession chambers as a function of the geometry and surface parameters
- Verify the asymmetry between the TOP and BOTtom chambers: *N*, energy spectrum and UCN center-of-mass offset
- Test depolarization effects during filling and emptying using detailed field maps and realistic energy spectra
- Depolarization estimates in the TOP/BOT chambers in inhomogeneous magnetic field configurations by using realistic energy spectra

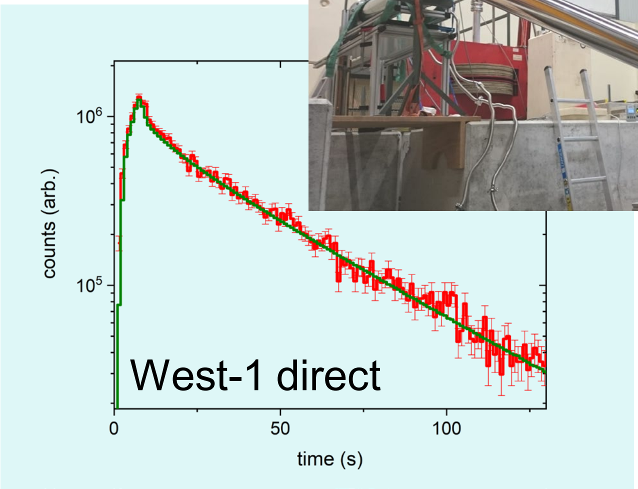
Benchmark of the PSI UCN source model

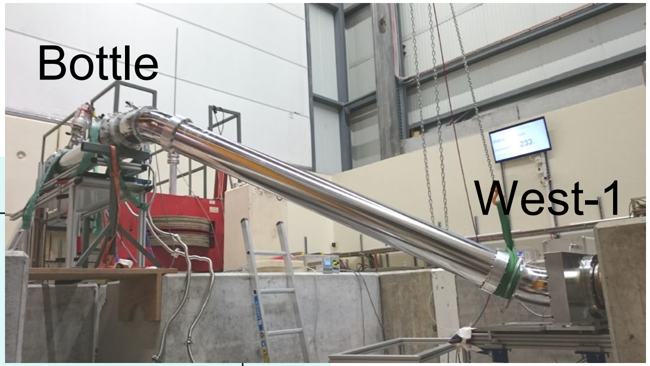
- n2EDM model includes the PSI source, benchmarked up to the beamport (BP) with various test measurements
  - UCN transmission from BP West-1 to South after pre-storage – constrain loss and diffuse reflection parameters of the guides
  - UCN storage at different heights above BP level – constrain the energy spectrum exiting the sD2
  - TOF spectra at BP,
    foil and guide transmissions
- Global benchmark Eur. Phys. J. A (2022)

  see also Eur. Phys. J. A 56, 33 (2020)



Phys. Rev. C 95 045503 (2017)

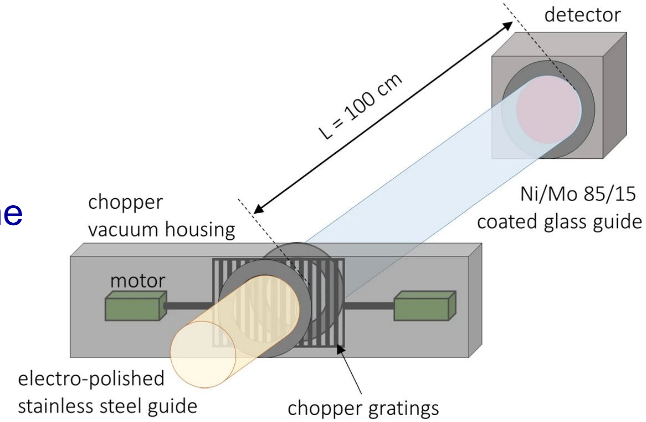


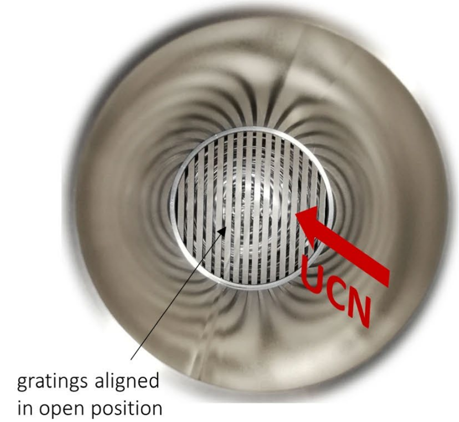


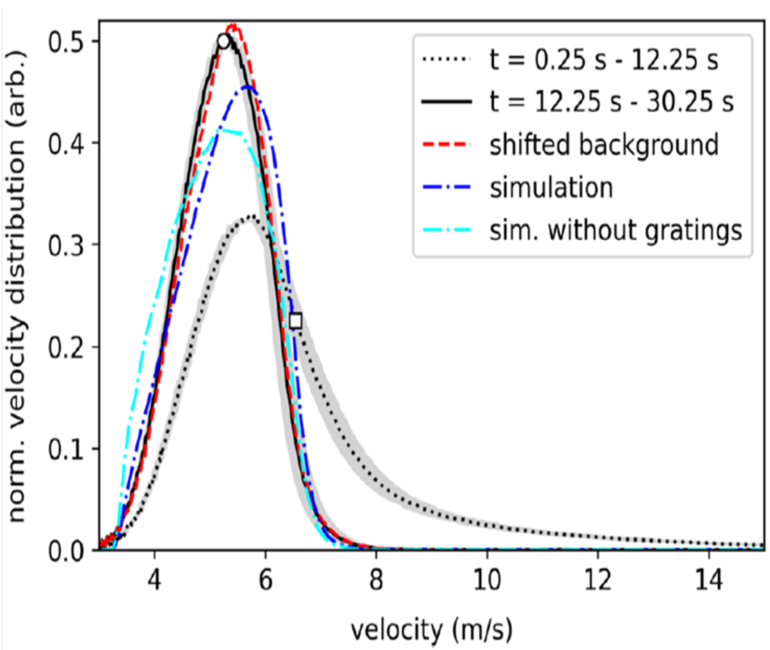
UCN time-of-flight spectroscopy

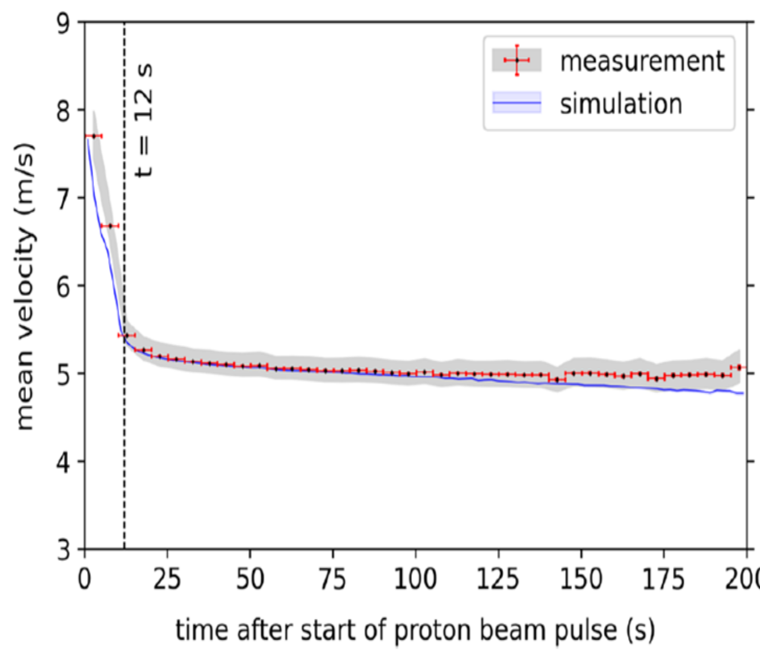
Eur. Phys. J. A 59 (2022) 215

- Evolution of the axial velocity distribution after the start of the 8 s proton beam pulse.
- Mean and statistical uncertainty of the axial velocity component at the detector position (including the chopper gratings).



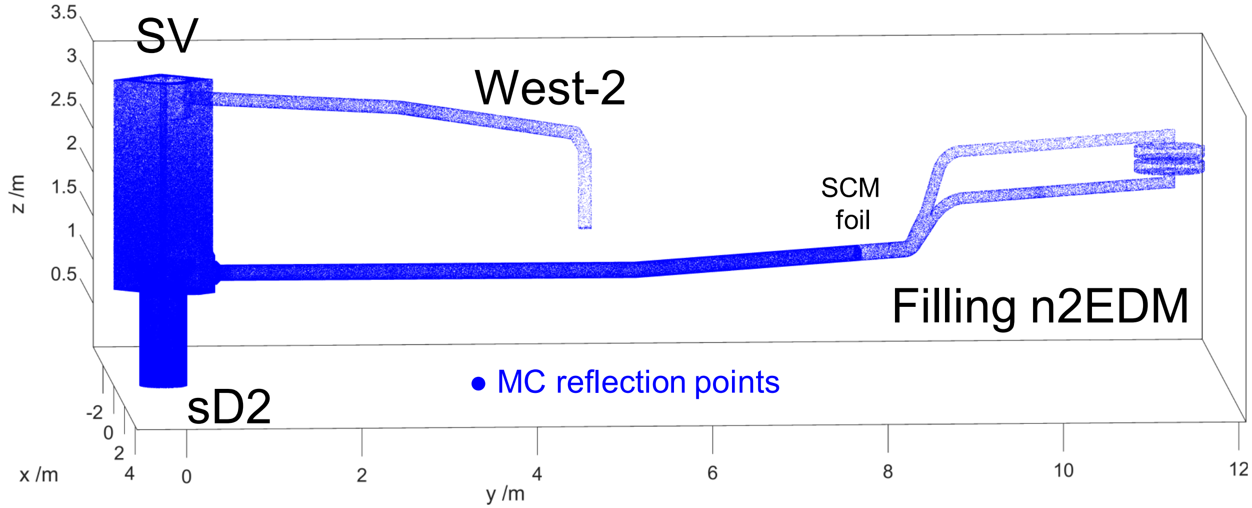


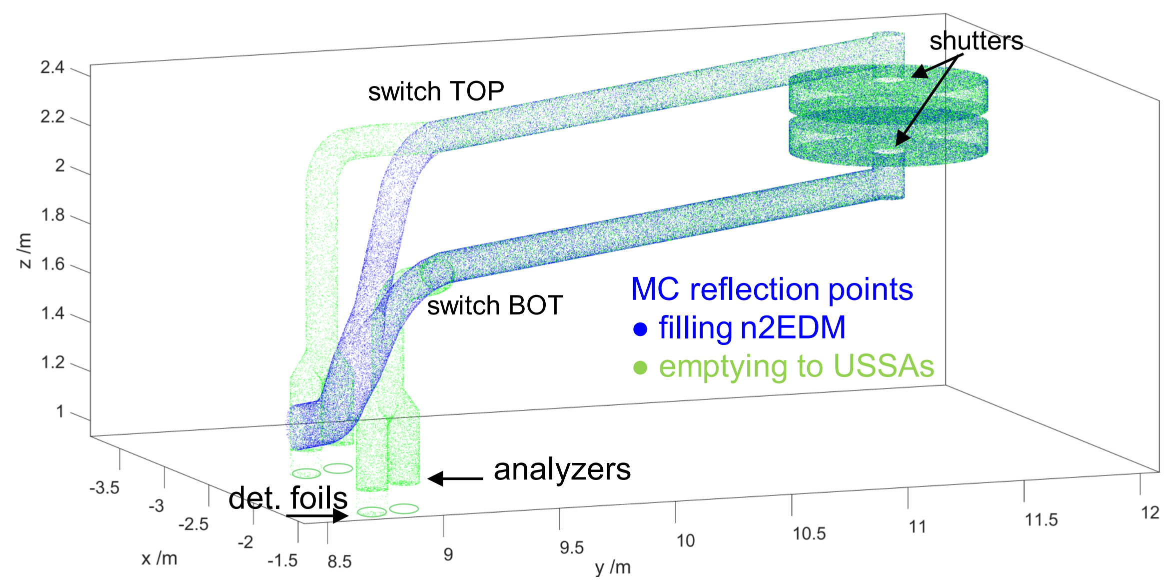




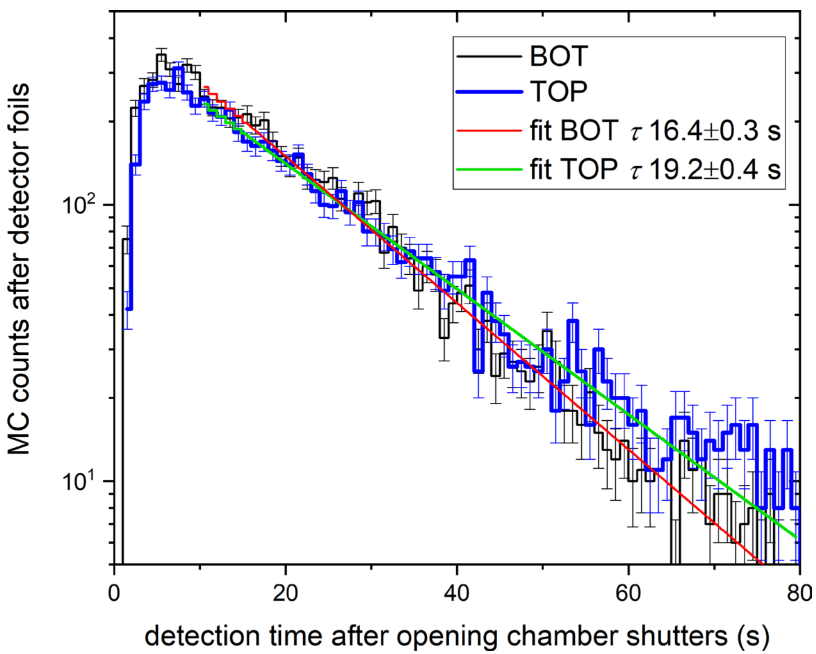
n2EDM model and input data

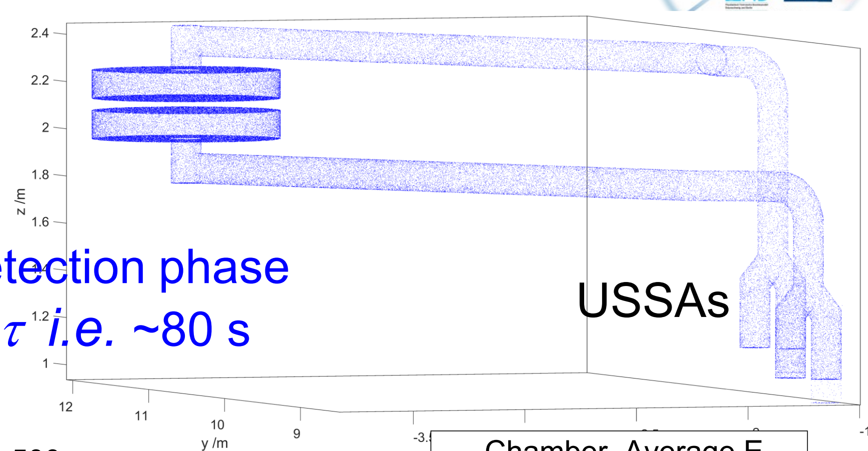
- Optimized geometry (UCN)
- Surface parameters:
  - V_F, η_{loss}, p_{diff} , loss in windows:
- NiMo coated guides:
  220 neV, $3x10^{-4}$, 2%
- Prec. chambers:
  - Electrodes 230 neV, 2%
  - Insulator 165 neV, 100%
  - Common $2.8x10^{-4}$
- Analyzer Fe: 90↓, 330↑ neV
- Details in n2EDM tech. design Eur. Phys. J. C (2021)
  10.1140/epjc/s10052-021-09298-z



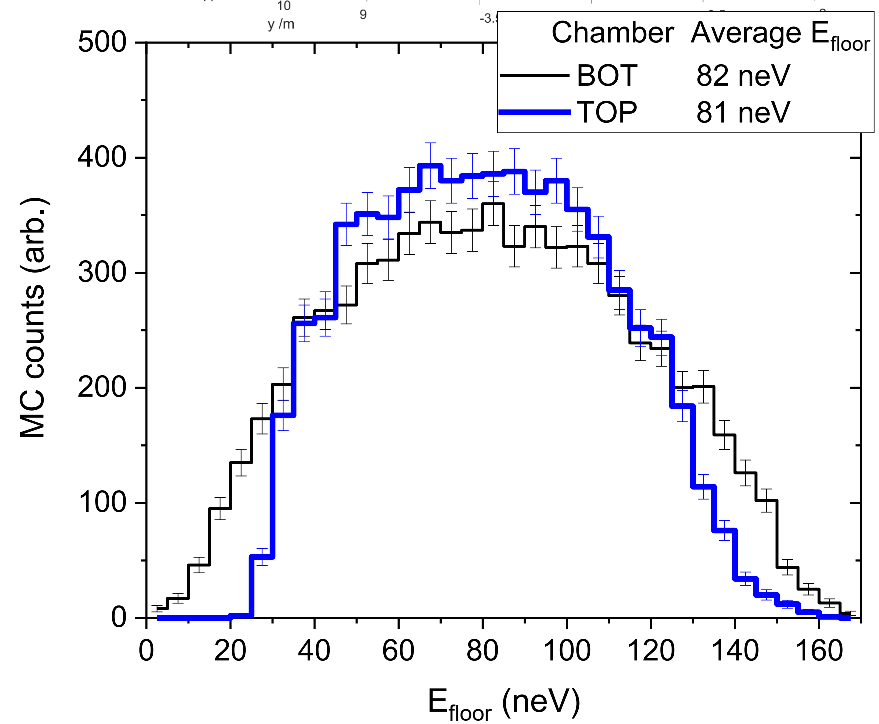


Detected spectra TOP/BOT in the USSAs





Detection phase
~4 τ *i.e.* ~80 s



Center-of-mass offsets h/cm:

TOP: -0.098

BOT: -0.130

Difference Δh TOP-BOT: -0.032 cm

Counts ratio TOP/BOT:

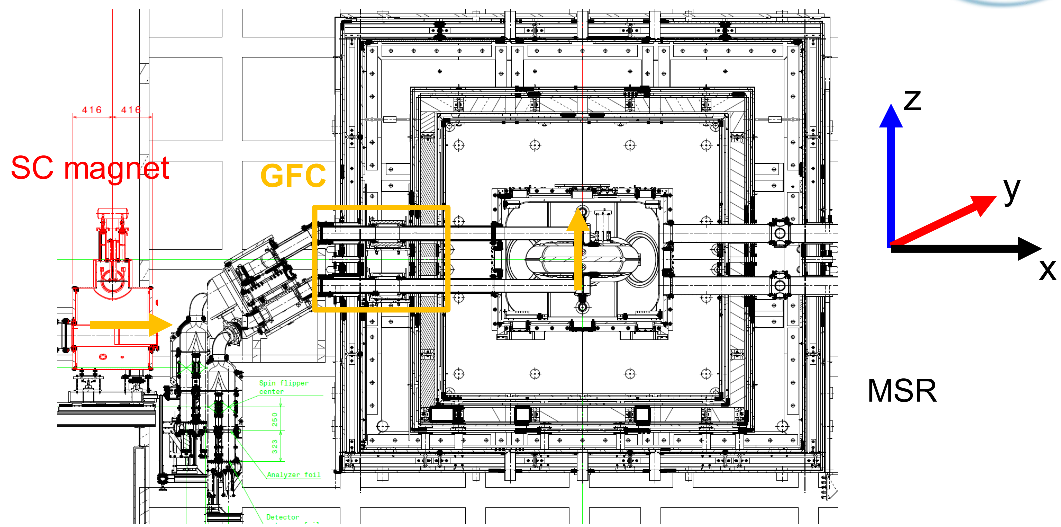
N_T / N_B 0.93

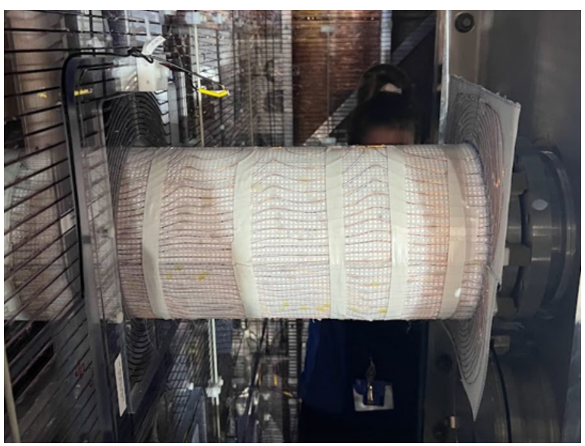
Simulations for the guiding field coils design

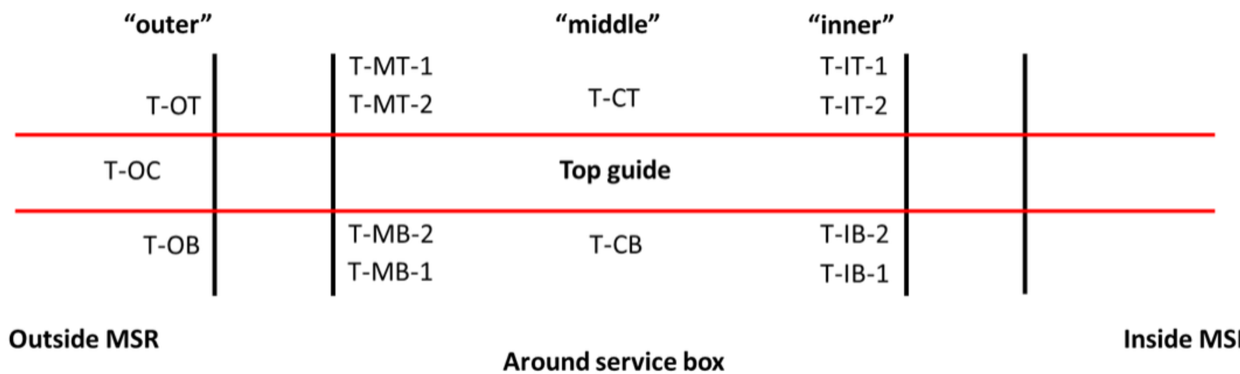
Field maps of guiding field (GF)
U. Kentucky group, exported from COMSOL (David Bowles)

Scope of MC

- Locate depolarization in regions of low adiabaticity
- Study the depolarization only from magnetic field inhomogeneity
- Realistic n2EDM energy spectrum

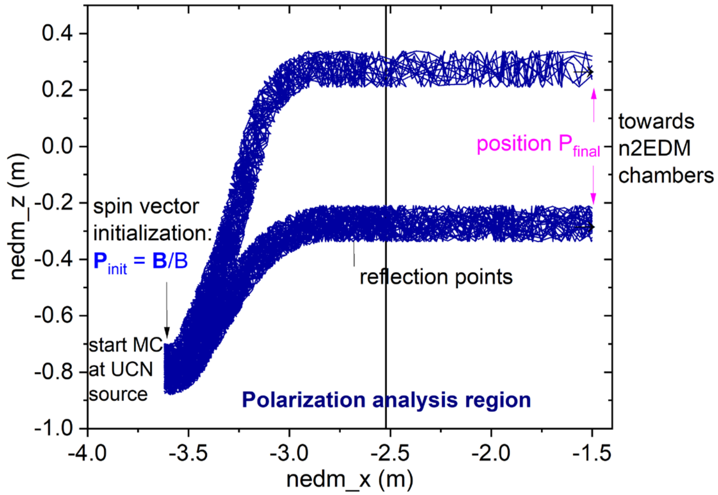






Schematic of the coil locations for the top UCN guide.

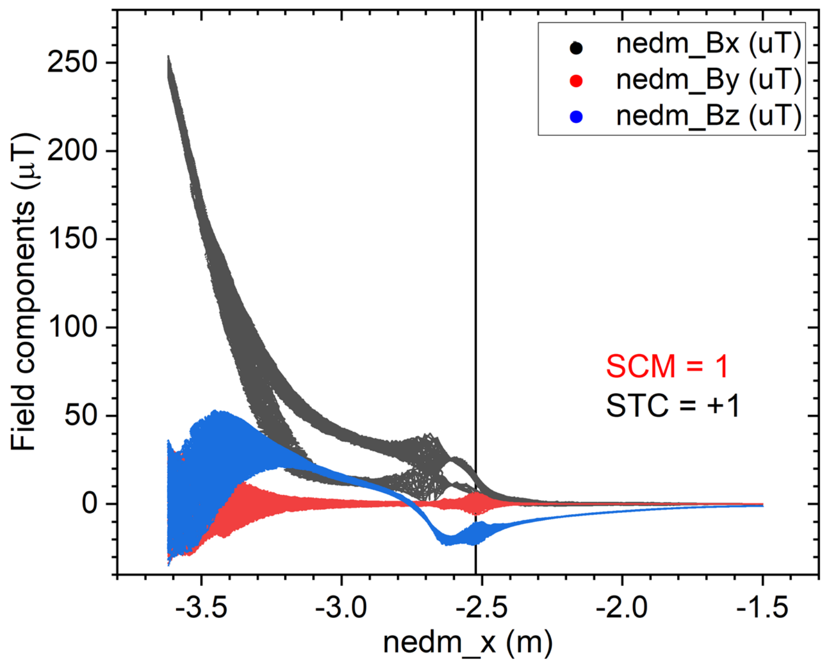
Guiding fields: **B** and **S** vectors in lab system

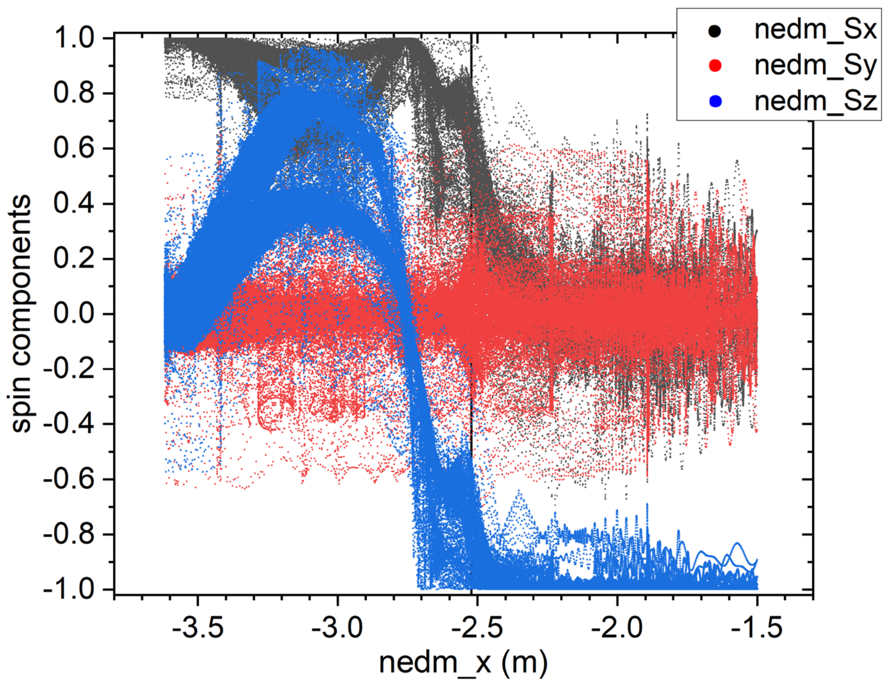


Example UCN trajectories in the map region

Vertical line: outermost wall of the MSR

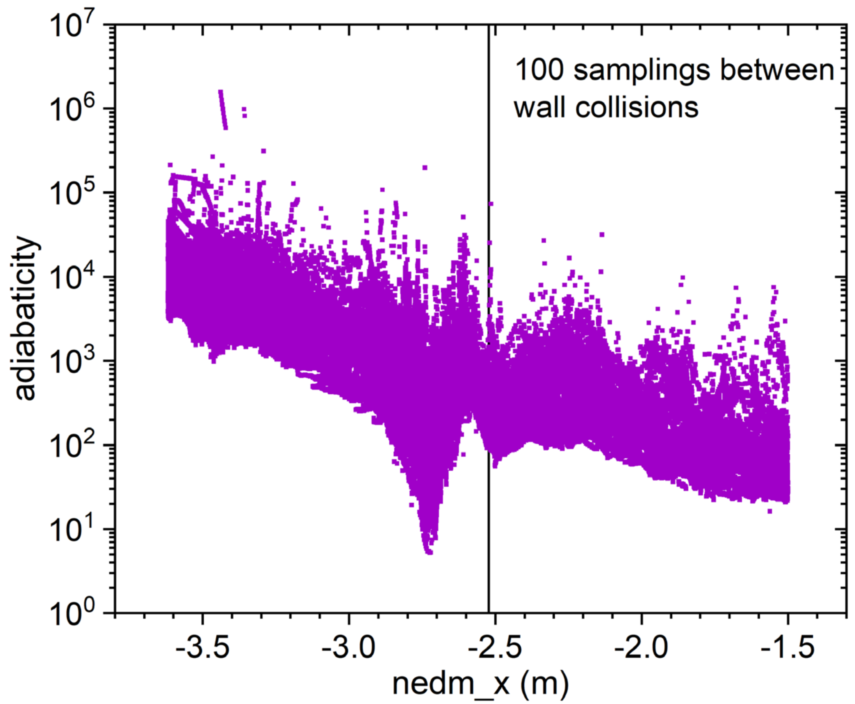
Solving Bloch equations with Runge-Kutta-Fehlberg



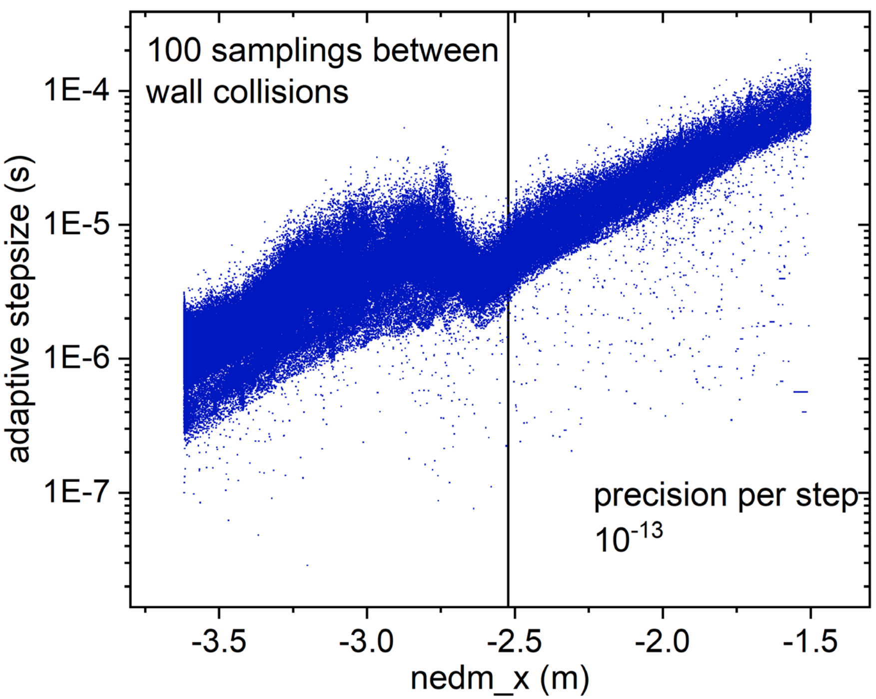


Guiding fields: adiabaticity and step size

Sampling adiabaticity ω_L/ω_B

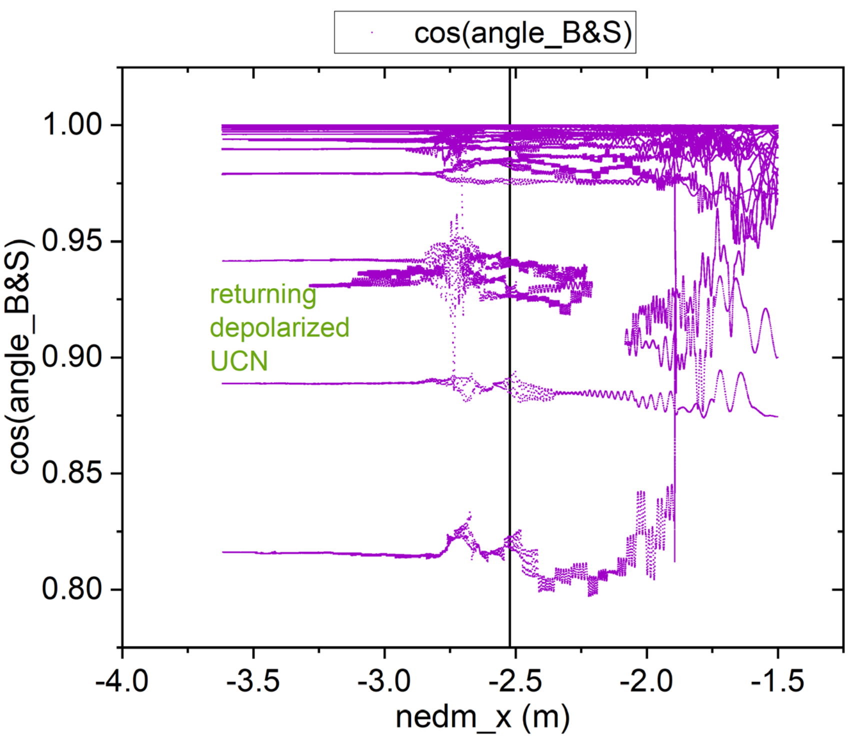


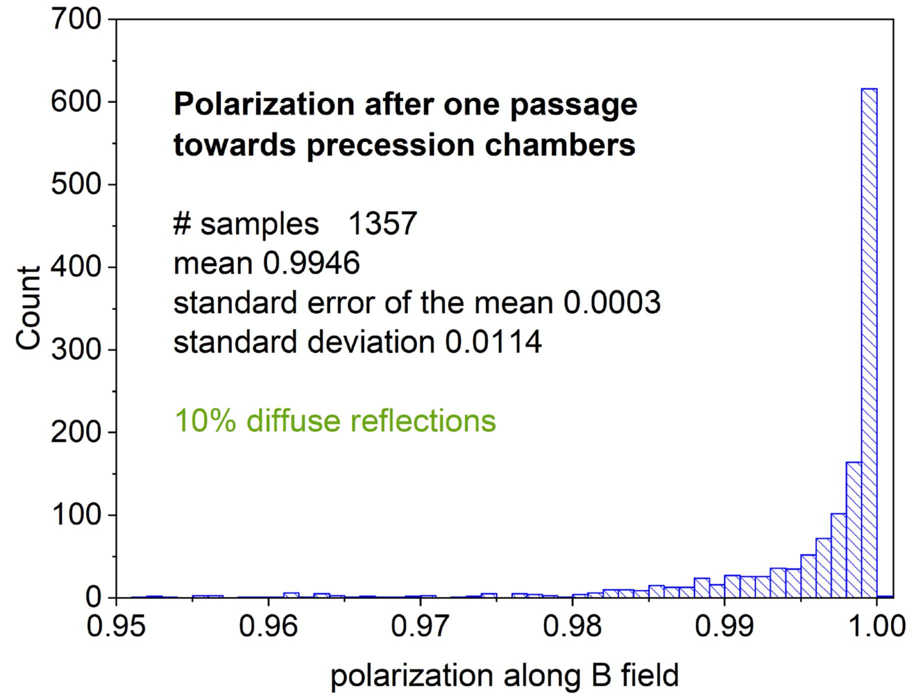
Adaptive stepsize δt (s)



Polarization: along path & final

P versus *x*-coordinate





Achieving 0.995 polarization efficiency

Conclusions and outlook

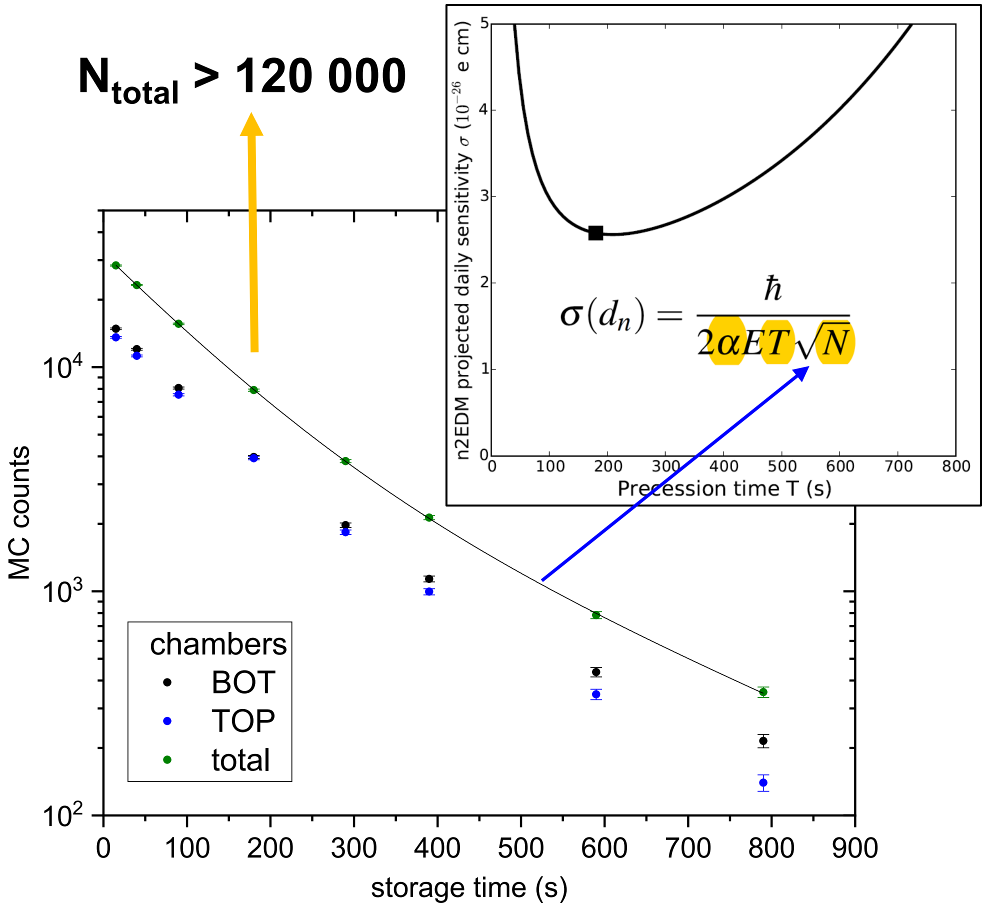
- Detailed benchmarks of MCUCN model and calibration of parameters
- Recent TOF measurements confirm the simulated mean UCN velocity, fine tunings follow
- Design of the n2EDM supported by detailed simulations of its UCN optics system. Distributions of detection time and energy spectra in the top and bottom chambers.
- Checking conditions of depolarization located in the guides. GF maps from COMSOL give very promising results
- Implement a complete field map of the n2EDM experiment
- Implement full Ramsey cycle and provide output for data analysis software tests
- Support test measurements of the n2EDM guides, chambers

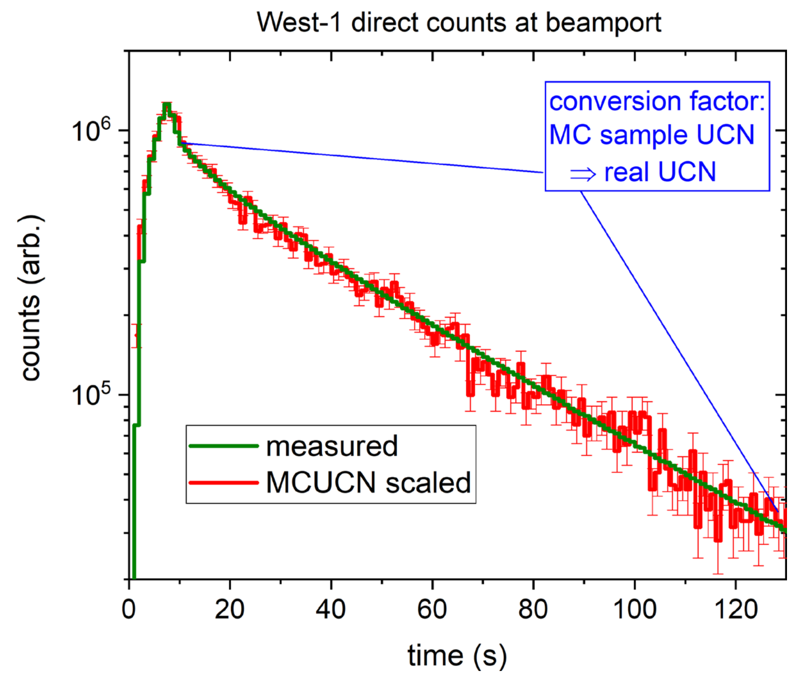
BACKUP

n2EDM storage properties and detected counts

- Storage curves TOP and BOT chambers
  - Optimize precession time T = T_{store} – 8s
  - Estimate final UCN counts N_{total}

N_{total} > 120 000





- West-1 2016 best 3.5×10^7 UCN per pulse gives conversion factor:

  UCN_real / UCN_MC
- Reference: 2016 nEDM average

  Average 15000 / Best: 20000 UCN
- **UCN_MC from n2EDM → N_{total}**
- MC uncertainty obtained from reproducing the steel bottle measurements ±15%

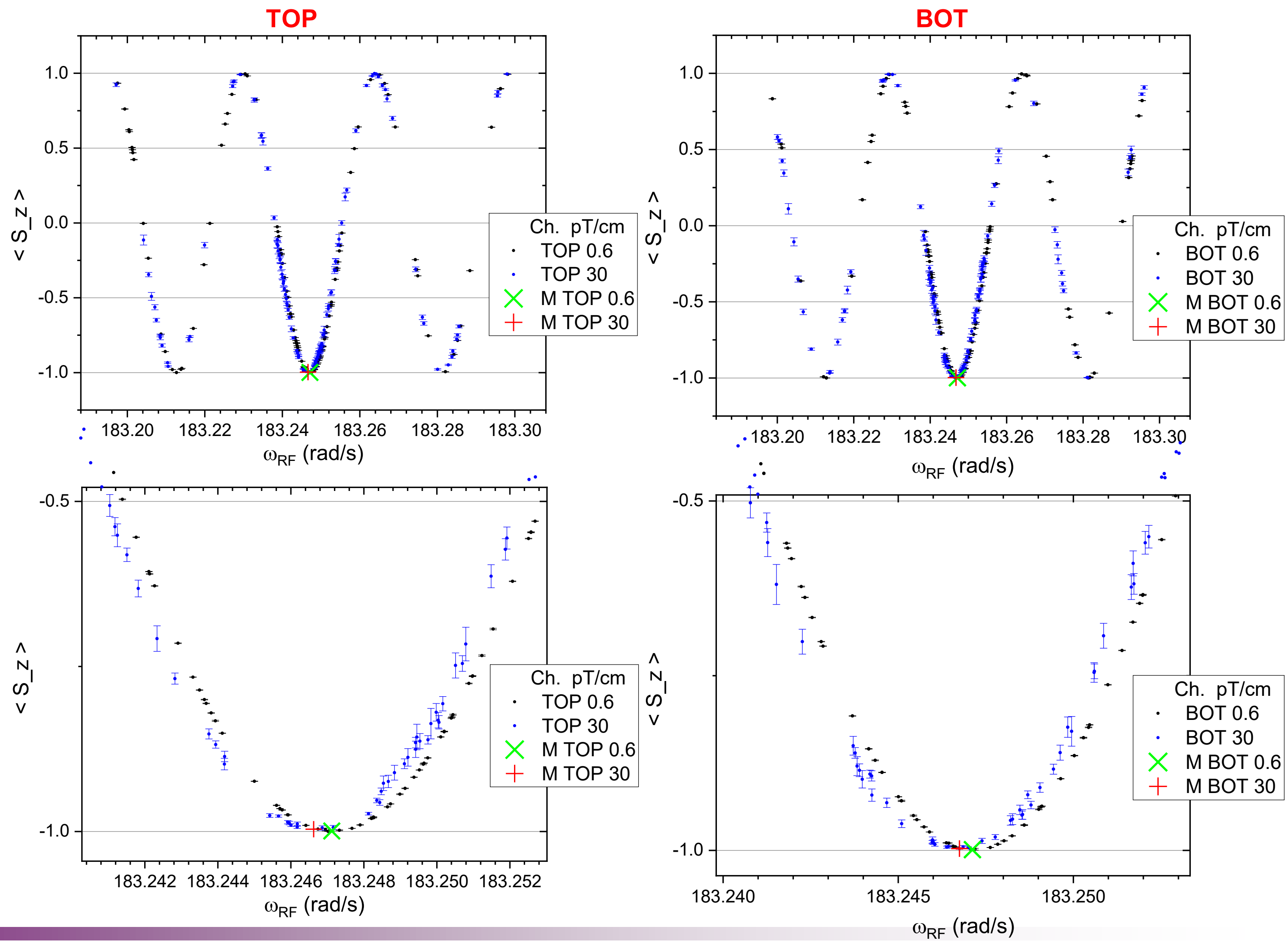
Ramsey cycles in TOP and BOT chambers

$$G_{1,0} = \partial_z B_z = -\partial_x B_x - \partial_y B_y$$

- Used energy spectra detected from the BOT and TOP chambers, **by the USSA detectors**

- MC of Ramsey cycles

Shifted for TOP / BOT chambers



MC of neutron depolarization in TOP/BOT

- Decay of polarization during storage

$$\frac{d\alpha}{dt} = -\frac{\alpha}{T_{\mathrm{wall}}} + \dot{\alpha}_{\mathrm{grav}} - \frac{\alpha}{T_{2,\mathrm{mag}}}$$

- E spectra TOP and BOT are slightly different

Gravitationally enhanced:

$$\dot{\alpha}_{\mathrm{grav}} = -\gamma_n^2 G_{1,0}^2 \mathrm{Var}[\bar{z}]\, T$$

$$\mathrm{Var}[\bar{z}] = \int (\bar{z}(\epsilon) - \langle z \rangle)^2 n(\epsilon) d\epsilon$$

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