Test of Lorentz invariance in the weak decay of polarized atoms

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Netherlands Organisation for Scientific Research

KVI, University of Groningen/
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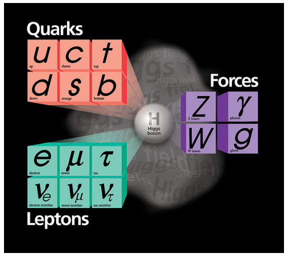
12th Meeting of the Working Group on Rad. Corrections and MC Generators for Low Energies

Mainz - September 27-28, 2012

Lorentz Symmetry

Lorentz symmetry is a fundamental basis of

- **the theory of Special Relativity**
- **the Standard Model of Particle Physics**



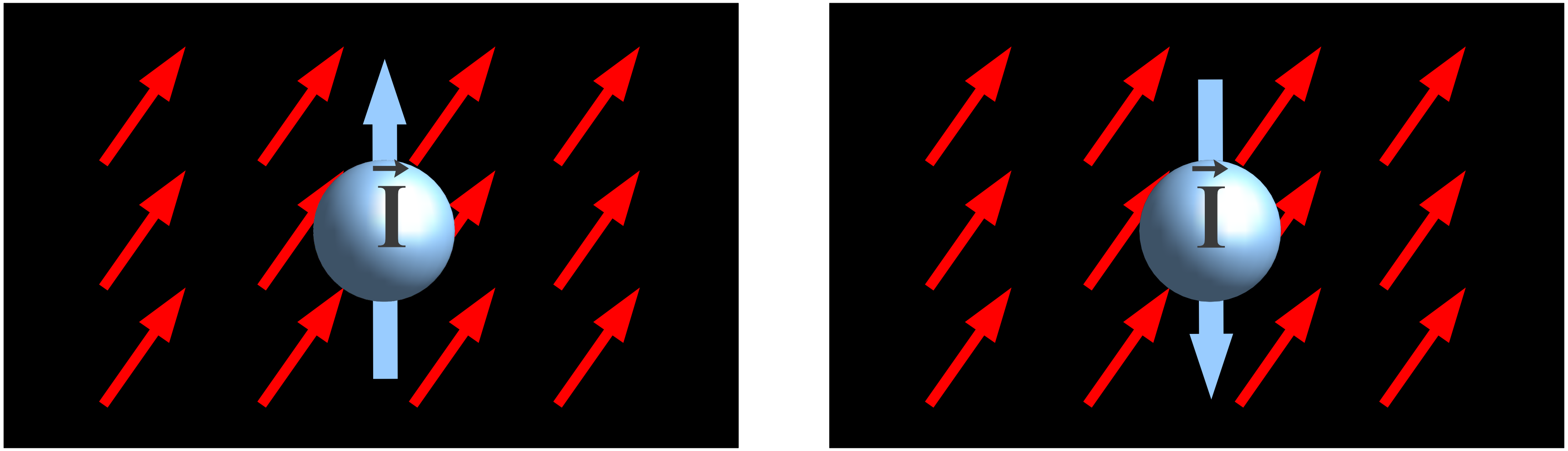
Connection to General Relativity and CPT symmetry

- **Lorentz symmetry breaking (LSB)**
  - Lorentz Symmetry spontaneously broken in Quantum Gravity models
  - "hidden" background fields ➞ preferred direction
  - precision experiments can look for signatures of LSB
- **Many experimental tests, no evidence of LSB**
  (mainly QED tests and gravity experiments)

Weak decay sector essentially unexplored!

Lorentz Symmetry Breaking

- assume nuclei interact with Lorentz-violating background fields



What is the change in the decay rate if the orientation of spin changes with respect to background fields?

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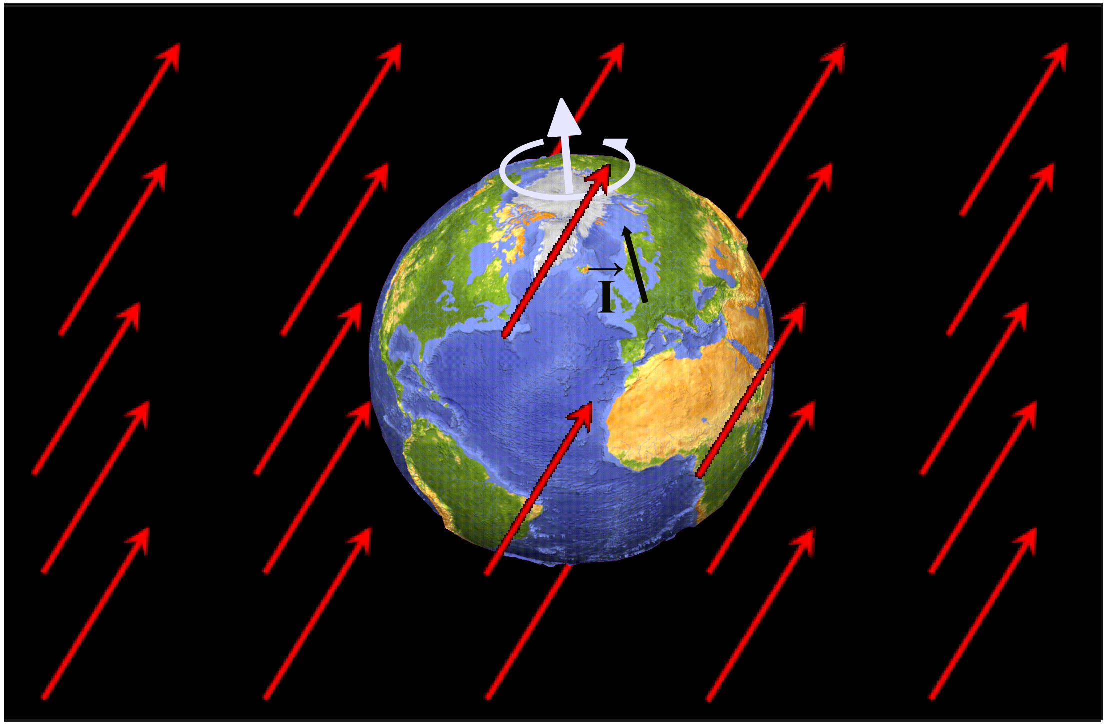
- assume nuclei interact with Lorentz-violating background fields



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*- search for variations induced by **daily**, yearly or "deliberate" reorientation of spin*

Lorentz Symmetry Breaking

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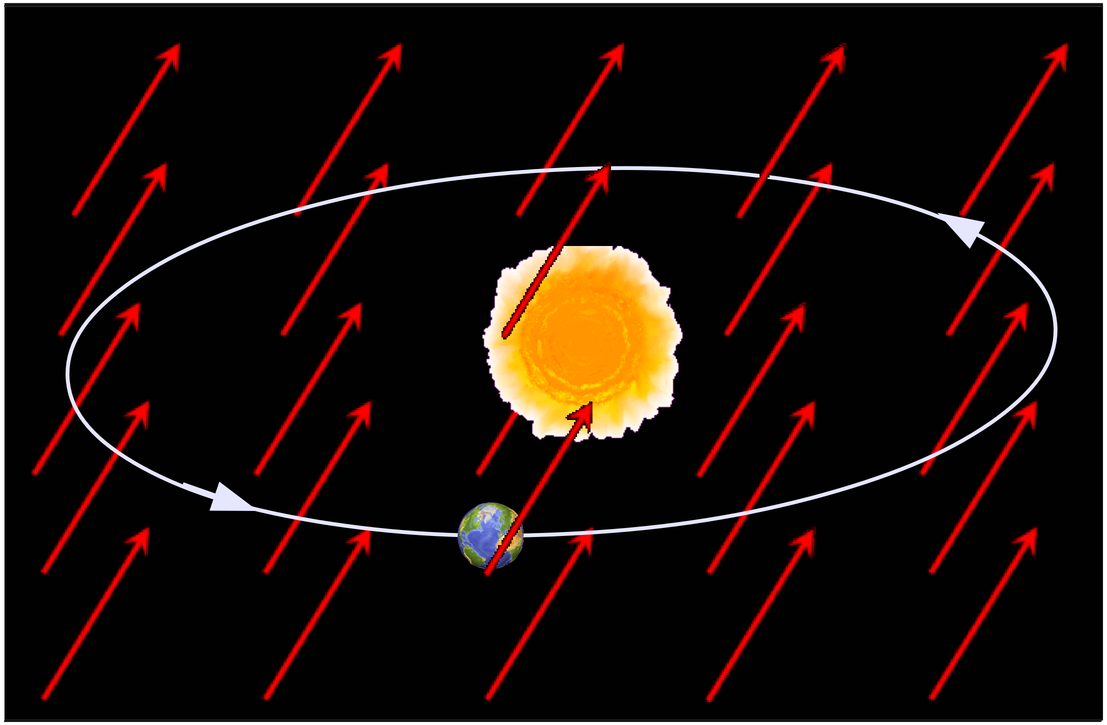

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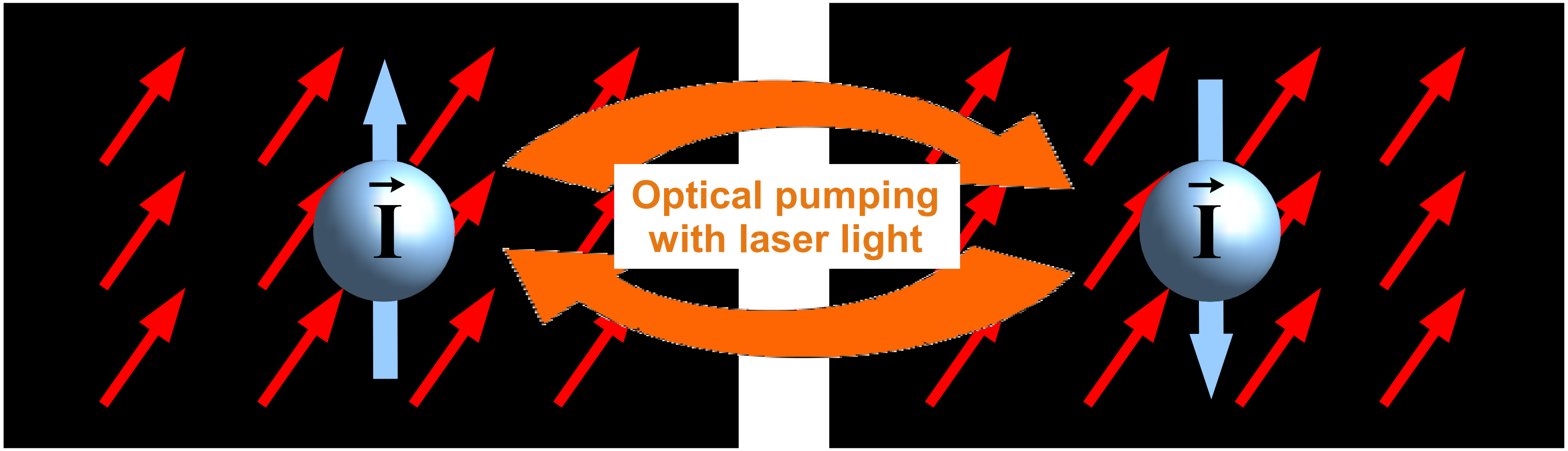

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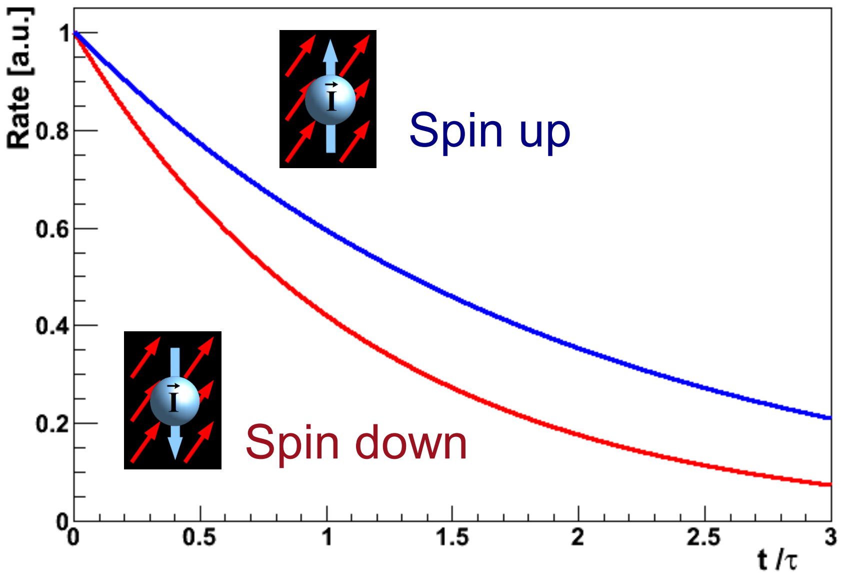
Experiment:

- **Change in decay rate** for different polarization orientations:



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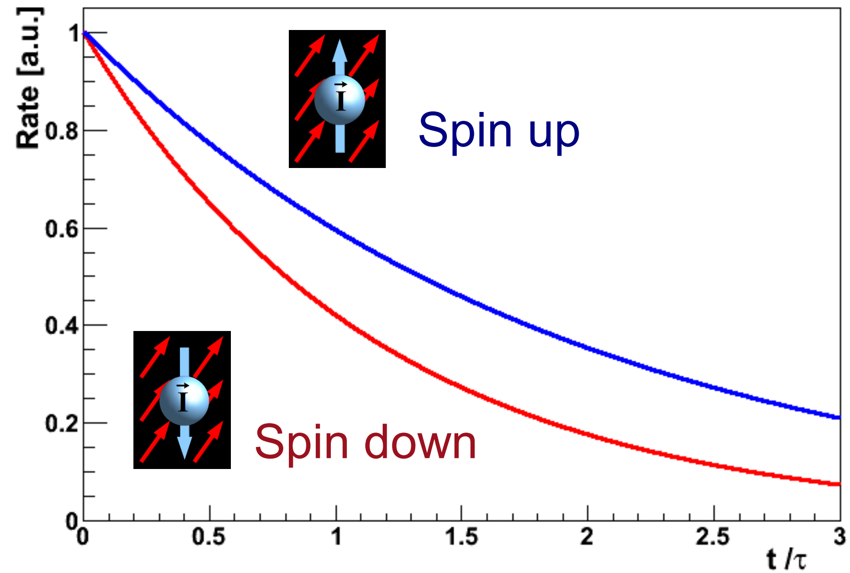

$$\frac{d\Gamma}{dE\,d\Omega} \sim \underbrace{\left(1 + A_0 \frac{\langle \vec{I} \rangle}{I} \cdot \frac{\vec{p}}{E}\right)}_{\text{SM}} + \xi_1 \left(1 + \xi_A \left(\hat{p} \cdot \frac{\langle \vec{I} \rangle}{I}\right)\right) \hat{p}\,\hat{n} + \xi_2 \frac{\langle \vec{I} \rangle}{I} \hat{n} + \xi_3\, \hat{p}_i \left(\frac{\langle \vec{I} \rangle}{I}\right)_j \rho^{ij}$$

I = nuclear spin; p, E = electron momentum and energy

$\xi_{1,2,3,A}$ = coupling strength to LIV fields $\hat{n}$, ρ^{ij}

Experiment:

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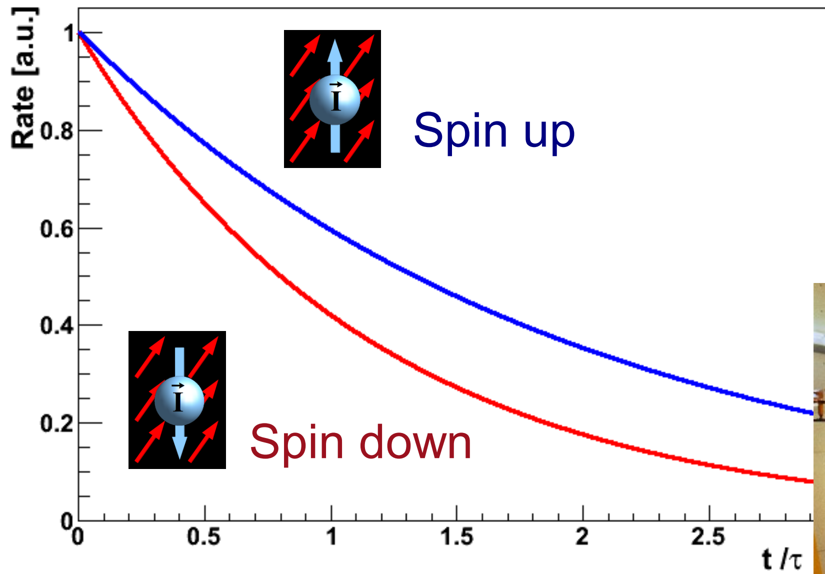
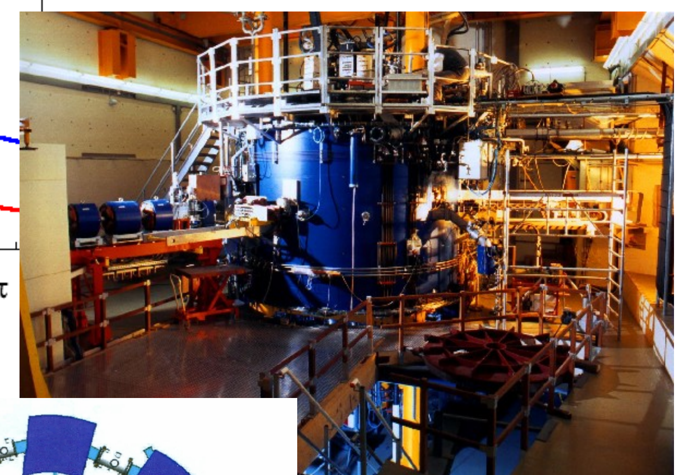


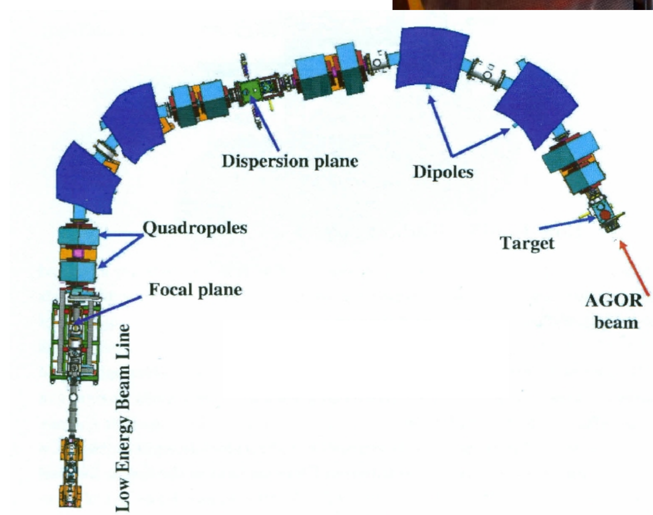


- **AGOR cyclotron at KVI**

  Produce short-lived isotopes

- **TRIμP isotope separator**

  Clean isotope beam

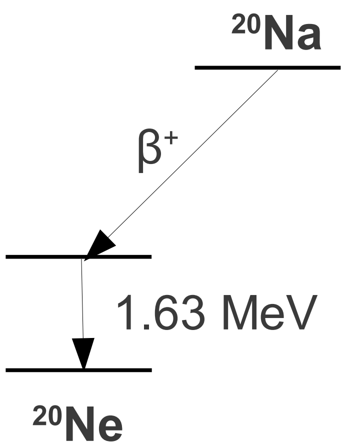


^{20}Na:

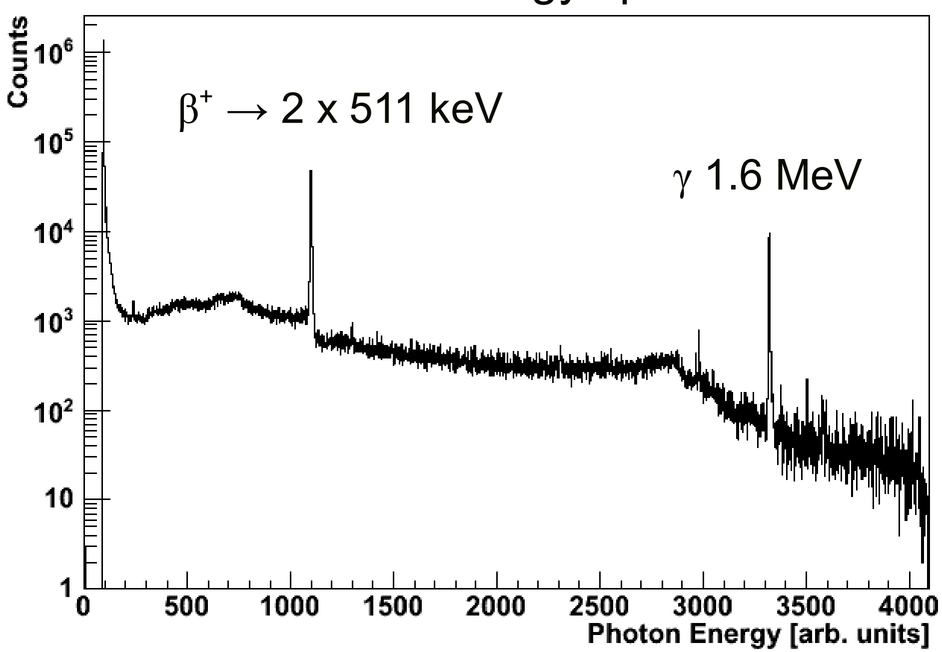
Choice of ^{20}Na:

- **Properties**: $2^+ \rightarrow 2^+$ (GT), β^+, $\tau_{1/2}$ = 0.448s, β-asymmetry parameter A_0=1/3
- **Produced** via ^{20}Ne+ p→^{20}Na+ n reaction: 10^6 decays/s
- **80% decay** to excited state of ^{20}Ne(1.63 MeV)

Level scheme

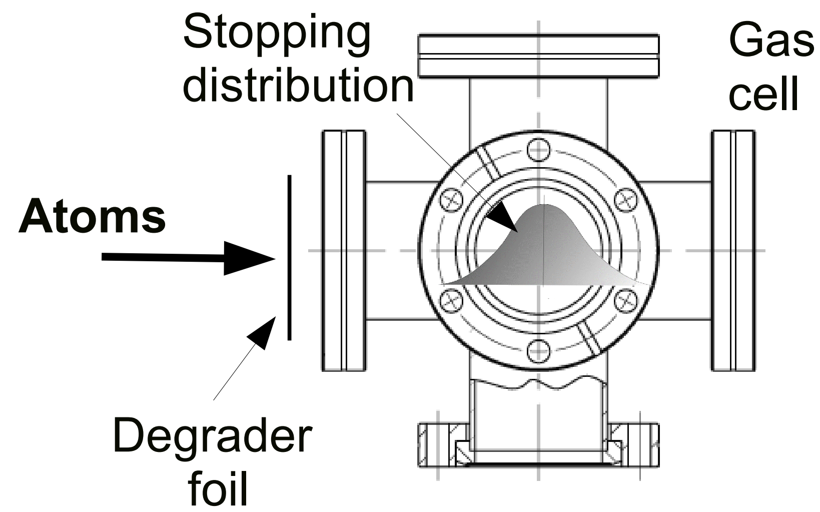


Gamma-energy spectrum



Experiment:

- **Isotope beam stopped** in buffer gas cell
  - Aluminum foil degraders & buffer gas pressure (noble gas, 2atm)



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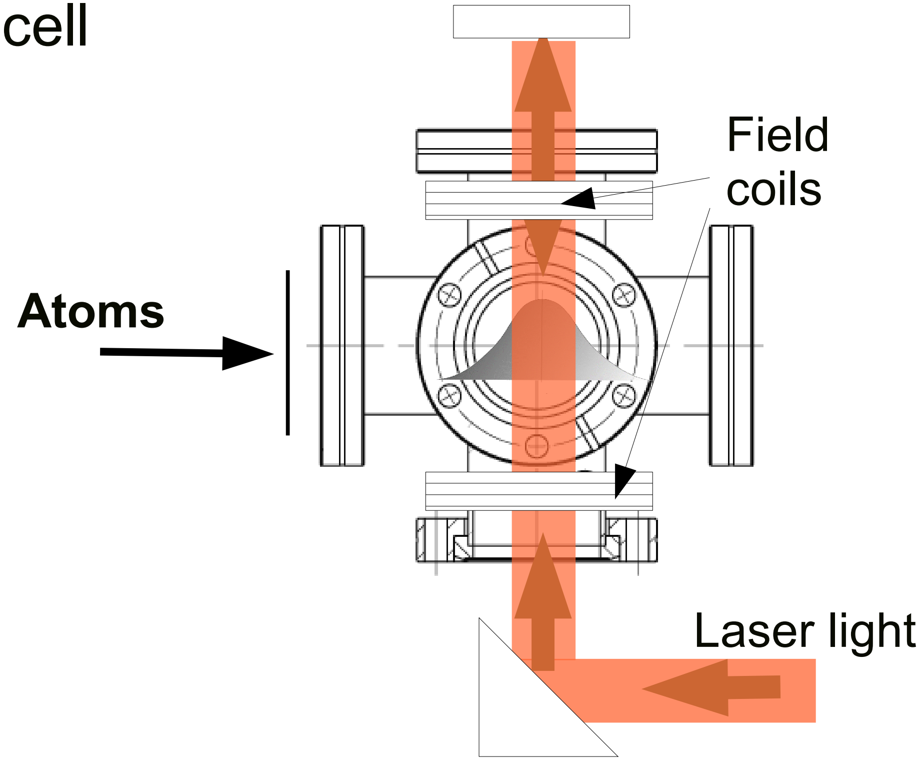

- **Polarized nuclei** via optical pumping:
  - magnetic holding field
  - circularly polarized σ± light

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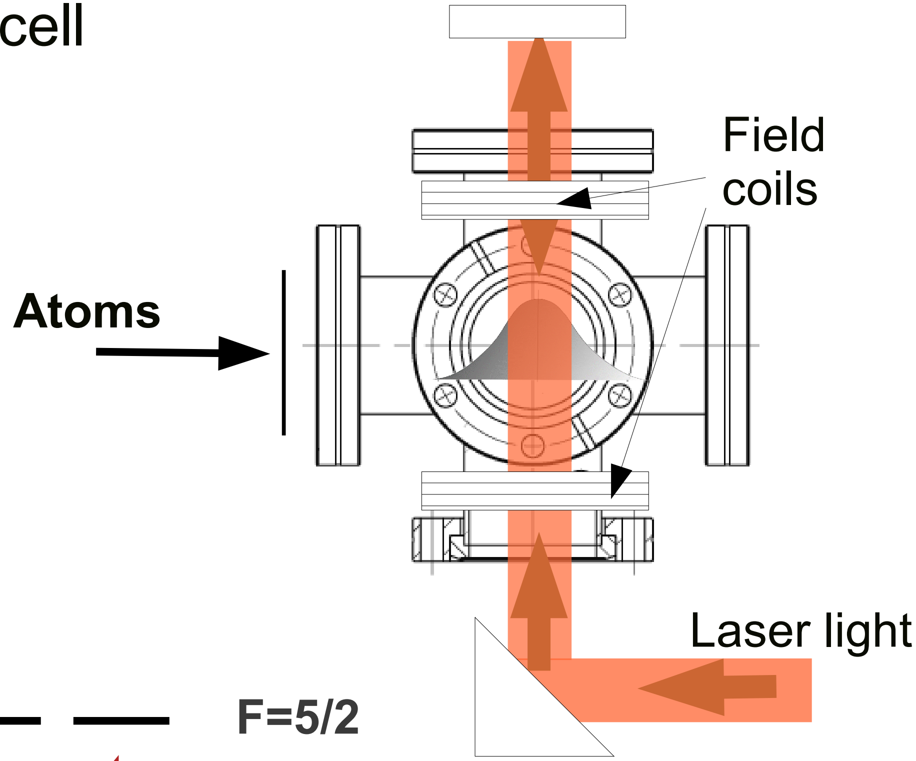

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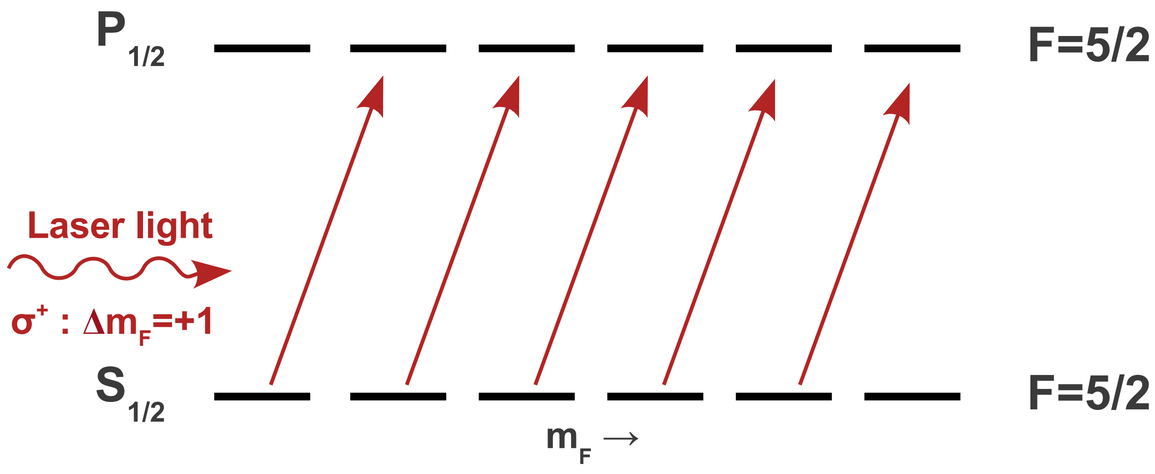

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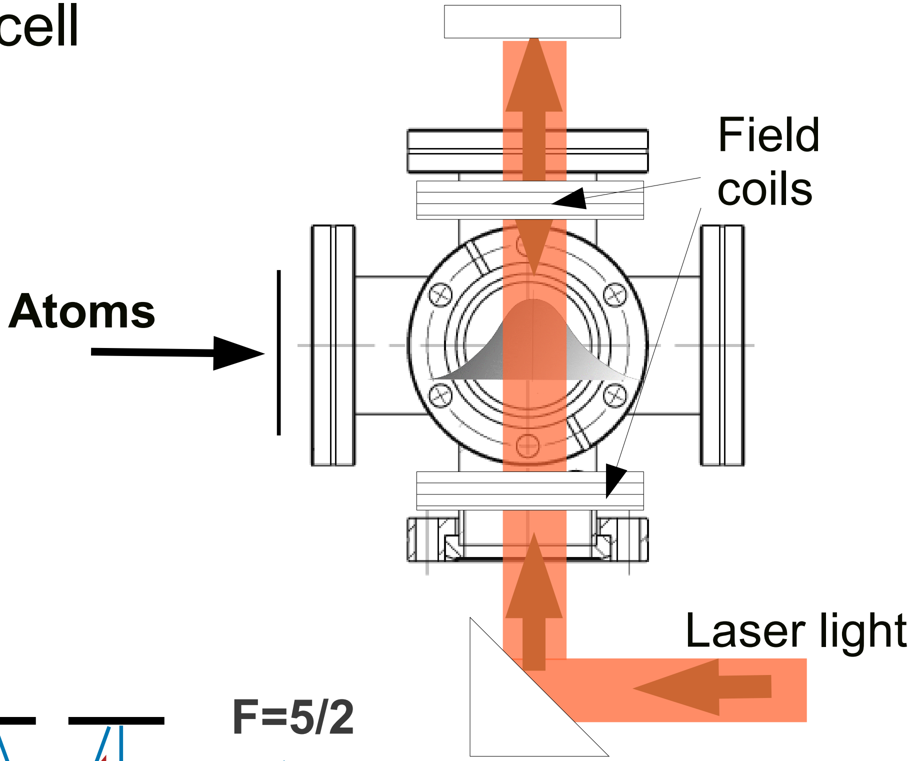

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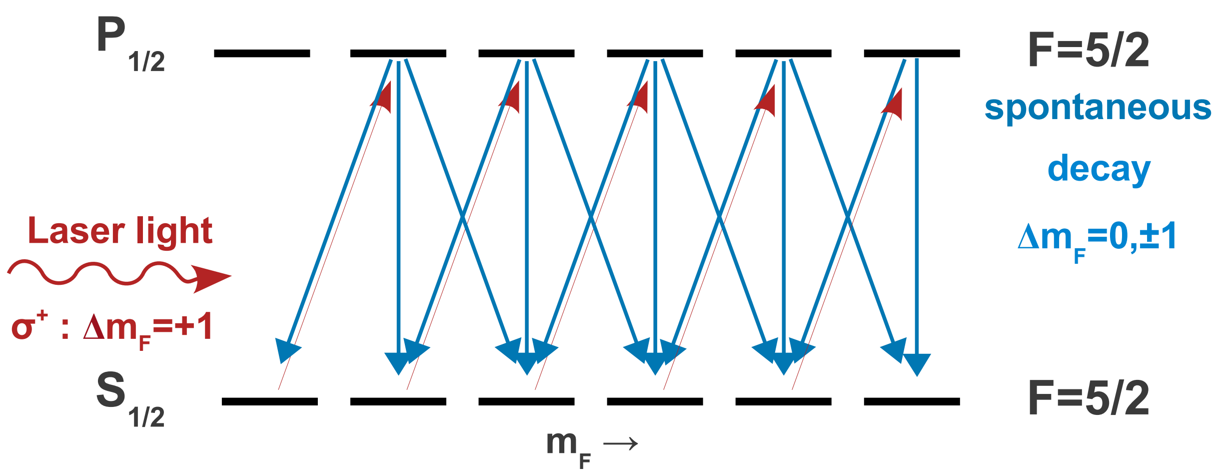

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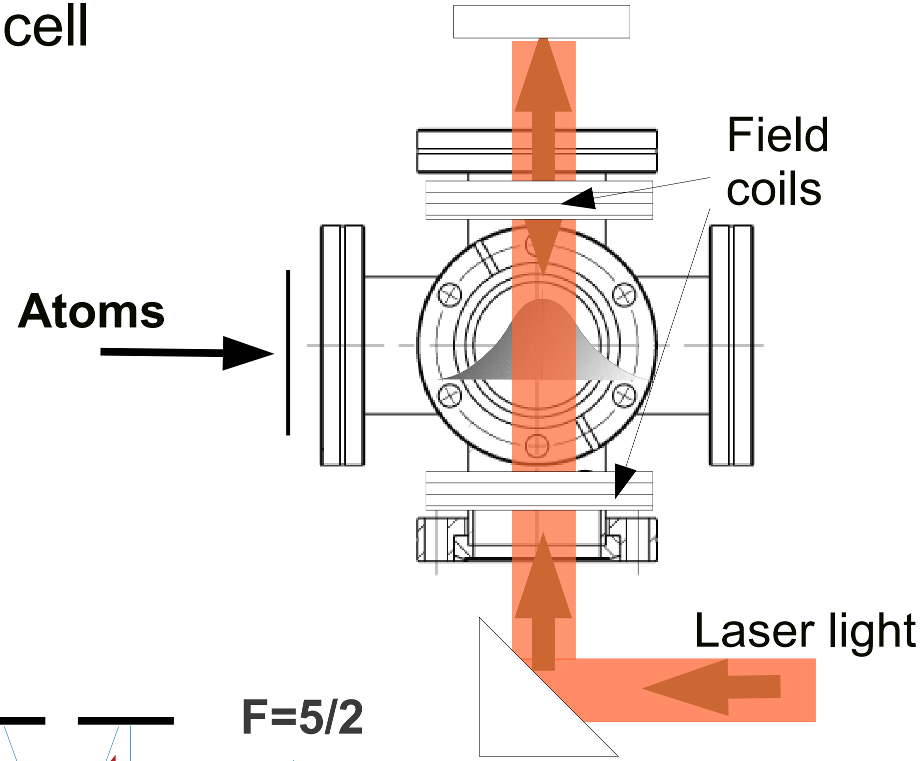

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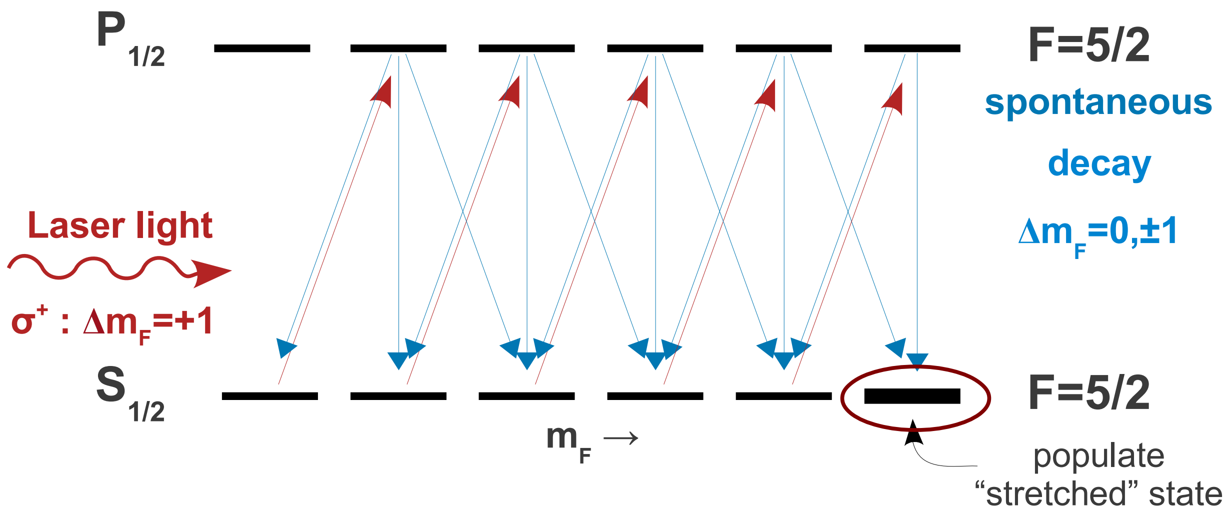

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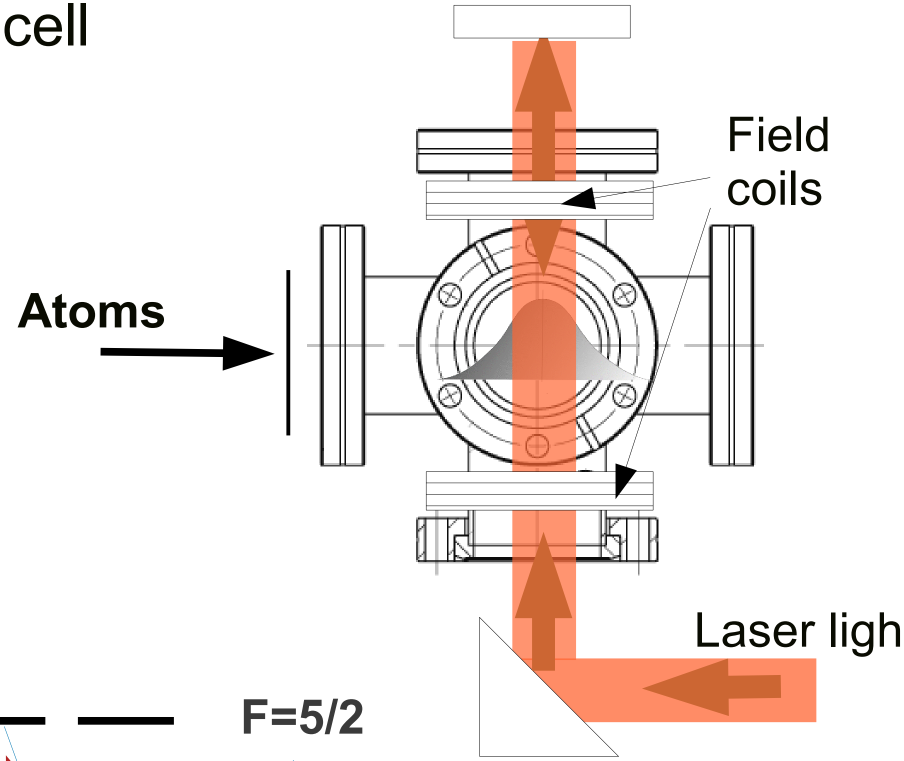

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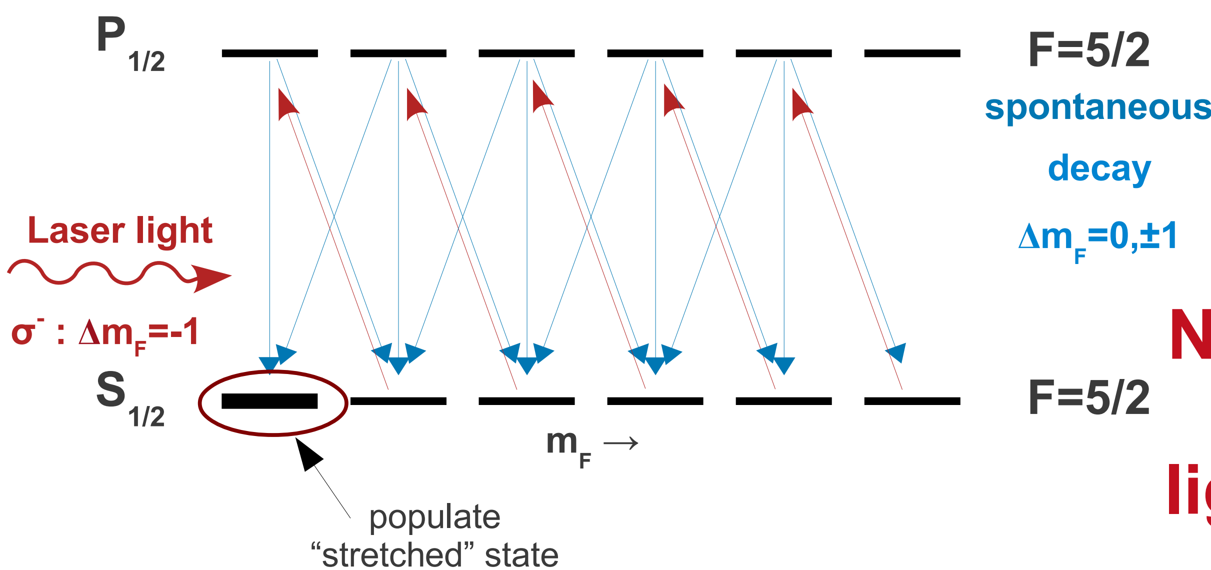
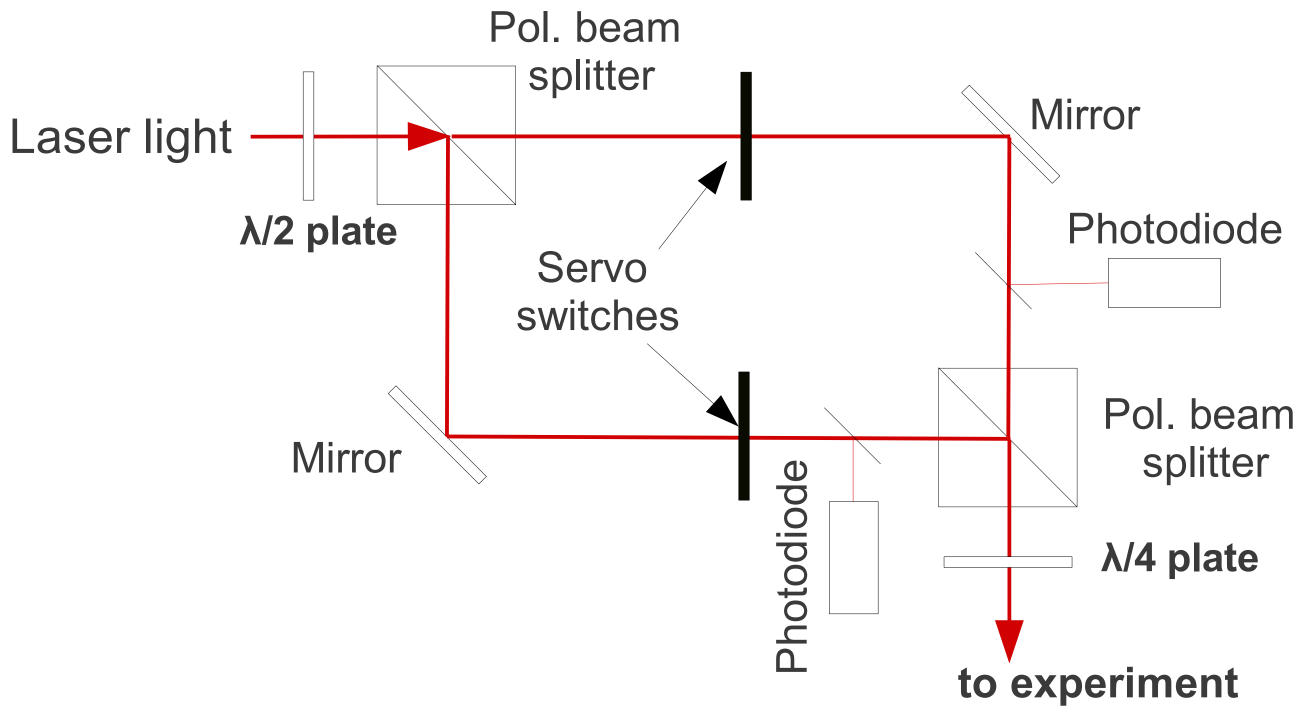


Nuclear spin follows light helicity

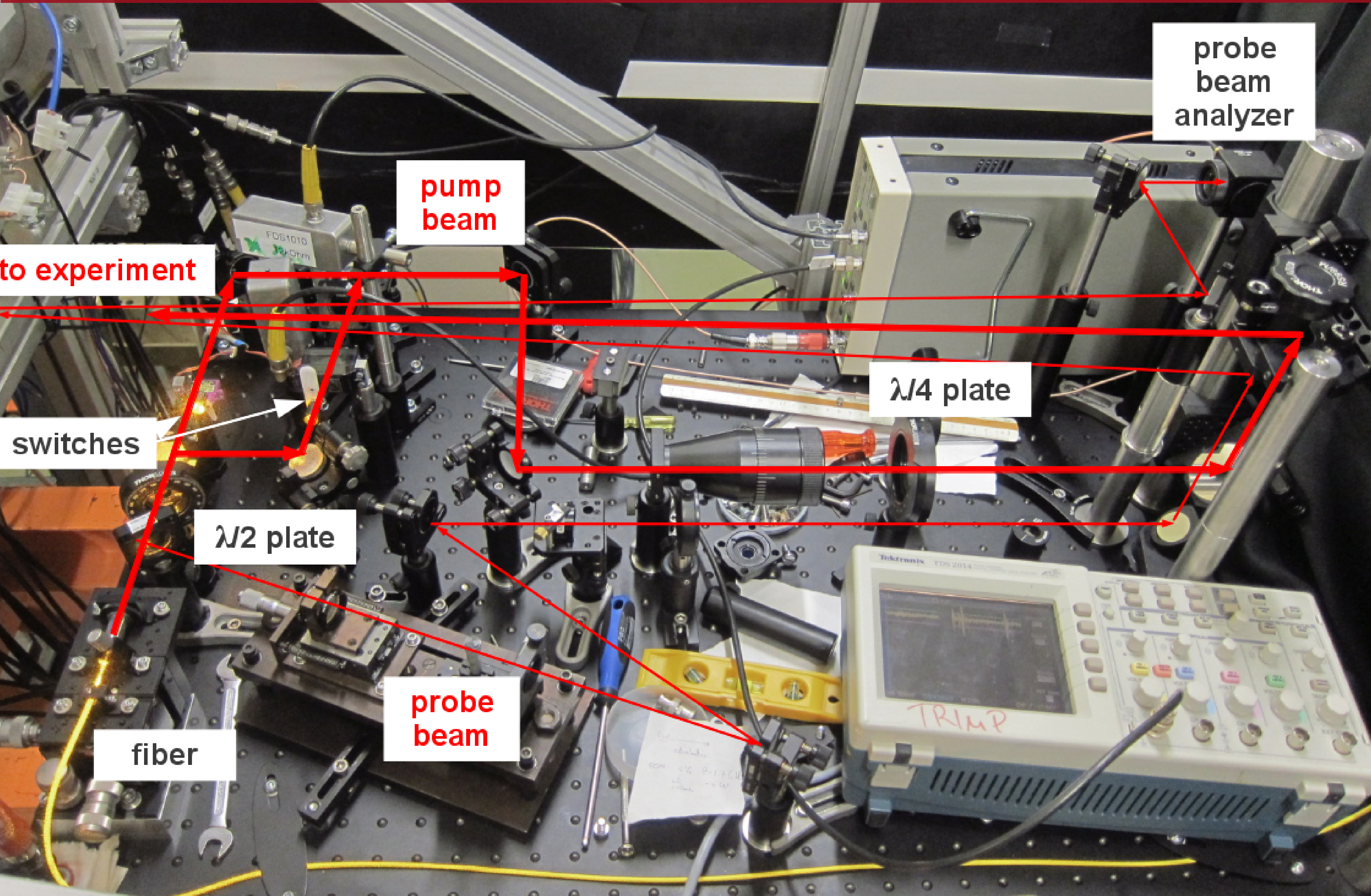
Experiment:

- **Isotope beam stopped** in buffer gas cell
  - Aluminum foil degraders & buffer gas pressure (noble gas, 2atm)

- **Polarized nuclei** via optical pumping:
  - Switching polarization:



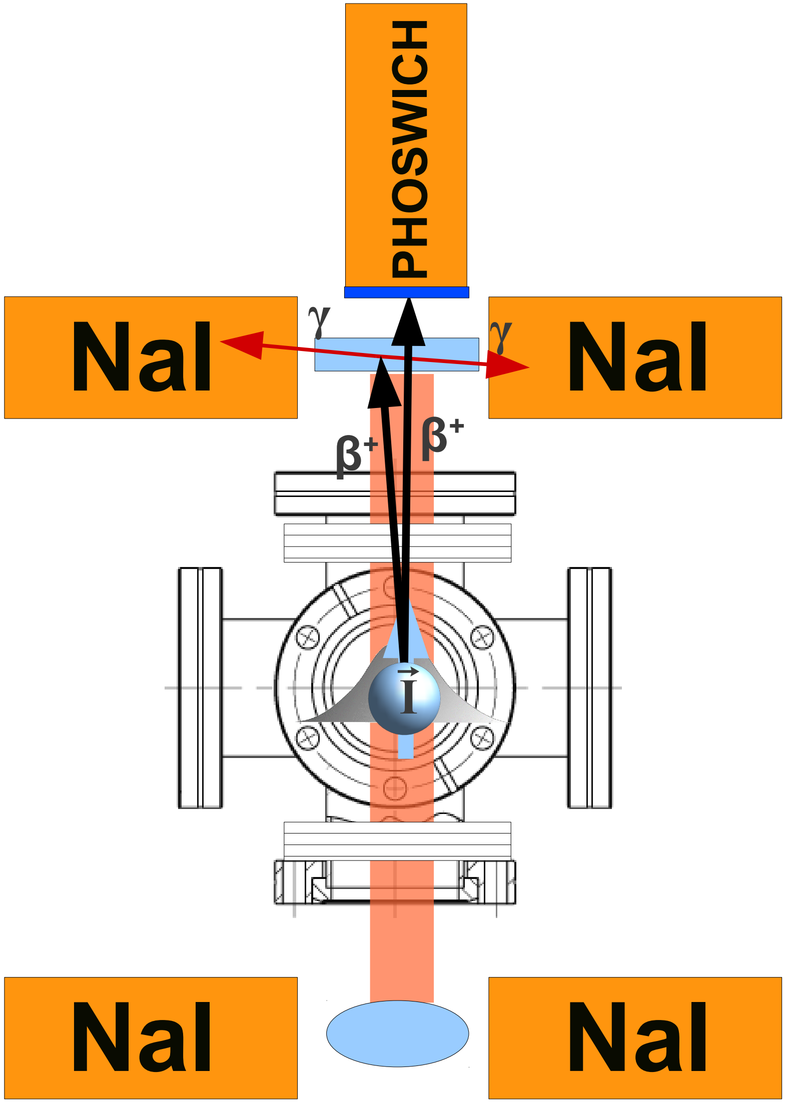
Experiment:


probe beam analyzer
pump beam
to experiment
λ/4 plate
switches
λ/2 plate
probe beam
fiber

Measurement of polarization:

- **PHOSWICH detector** above target cell to detect β^+
- **Two pairs of NaI detectors** to measure 511 keV coincidences from β^+ particles stopped in mirrors above and below target cell

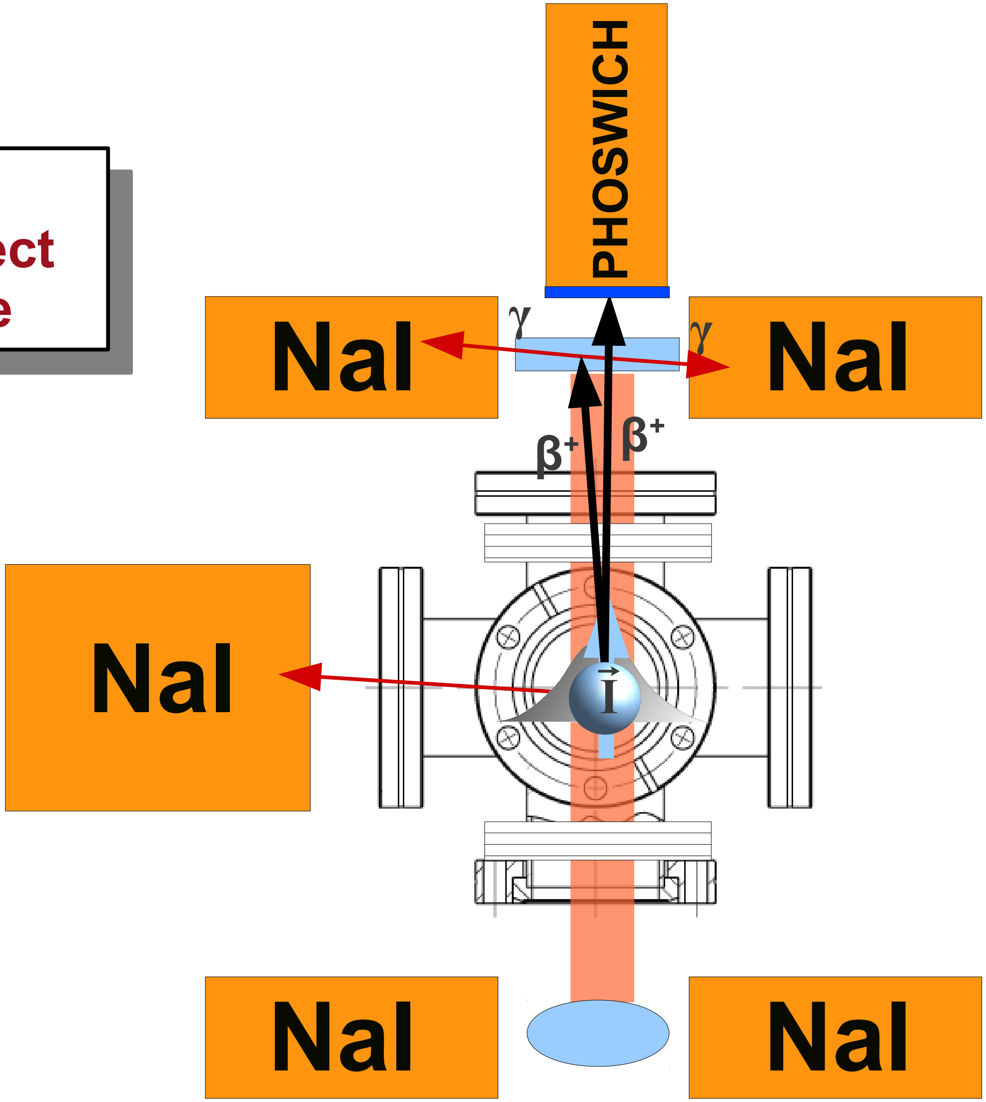
Use parity violating decay asymmetry of weak interaction to monitor nuclear polarization



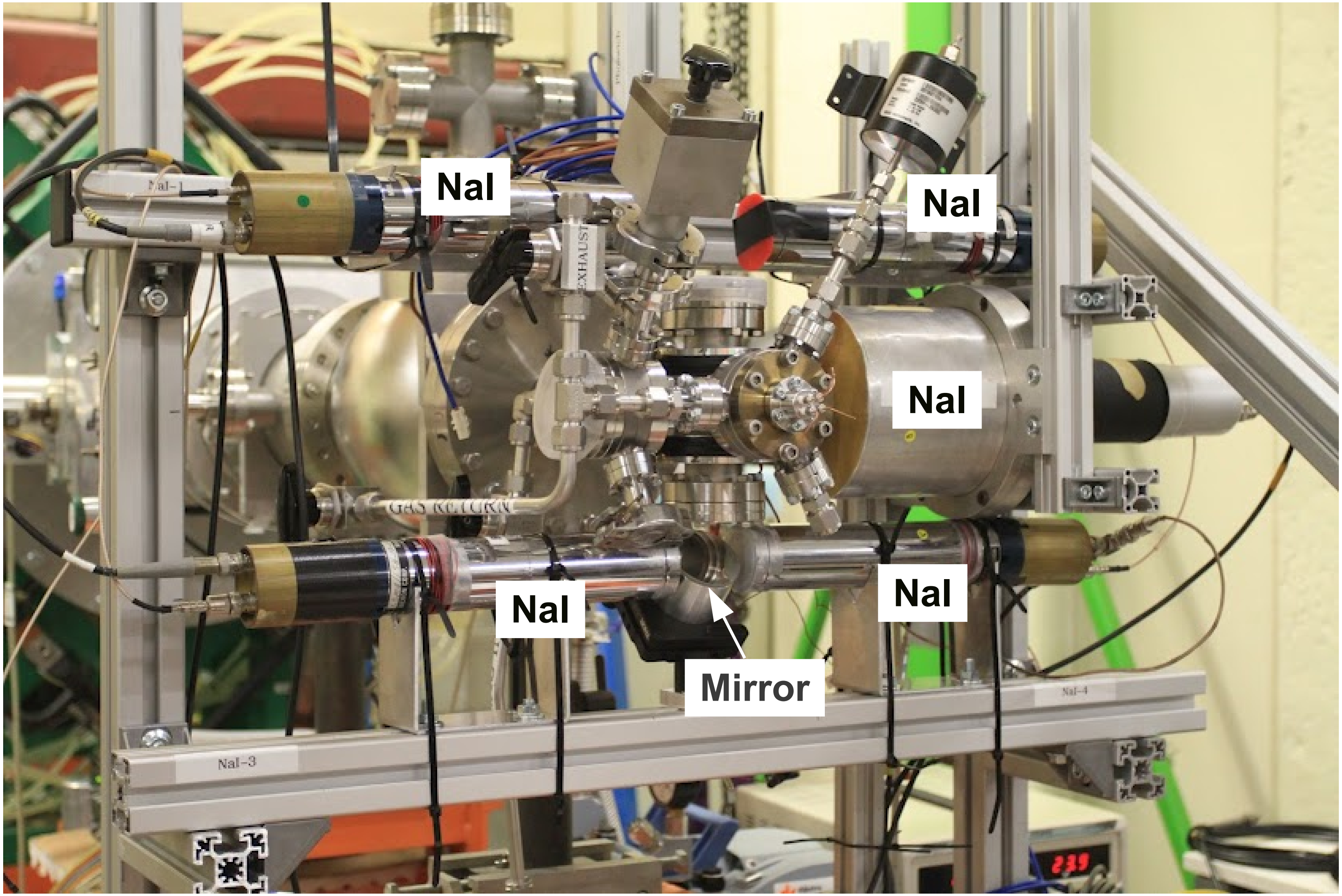
Measurement of lifetime:

- **Additional NaI detector** for daughter particles decay photons
  $2^+ \rightarrow 0^+$ EM-decay of ^{20}Ne, parity conserving, Lorentz invariant

Use EM decay of ^{20}Ne daughter nucleus to detect changes in ^{20}Na lifetime

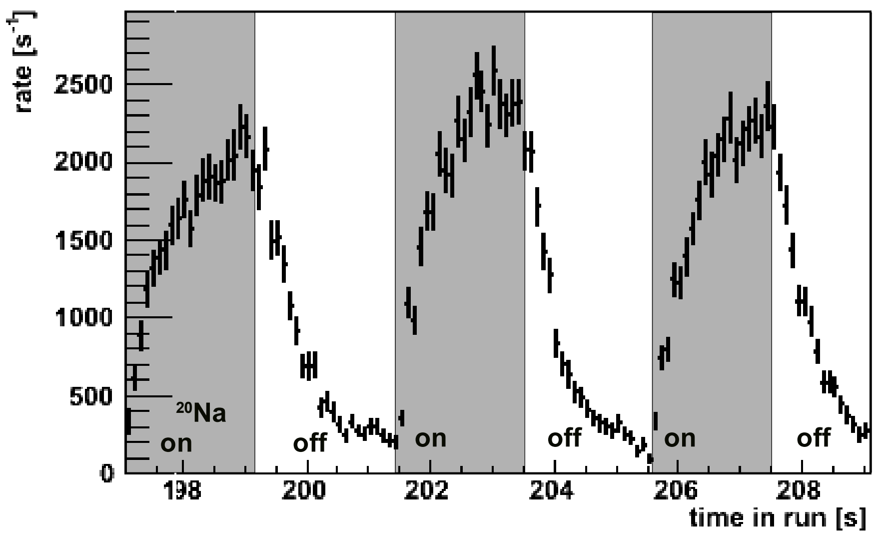


Experimental setup:



Polarization measurement:

- **β⁺ Rates** from PHOSWICH detector
  - 2s-on, 2s-off period of ^{20}Na beam:



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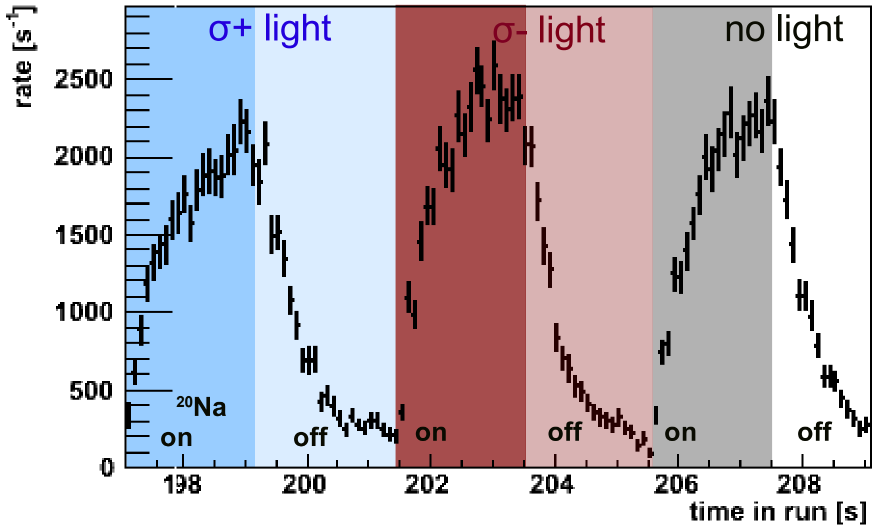

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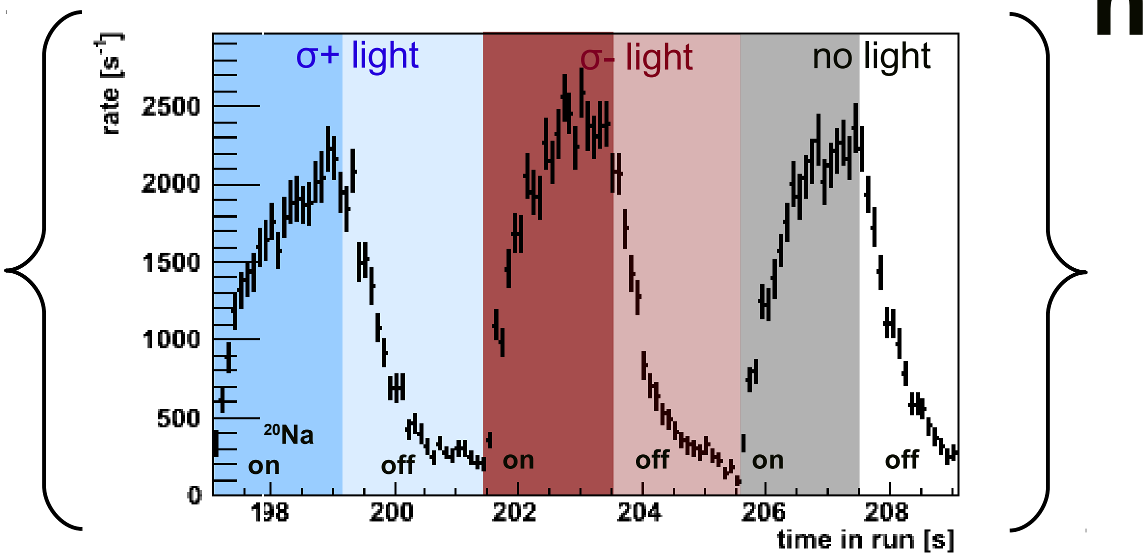
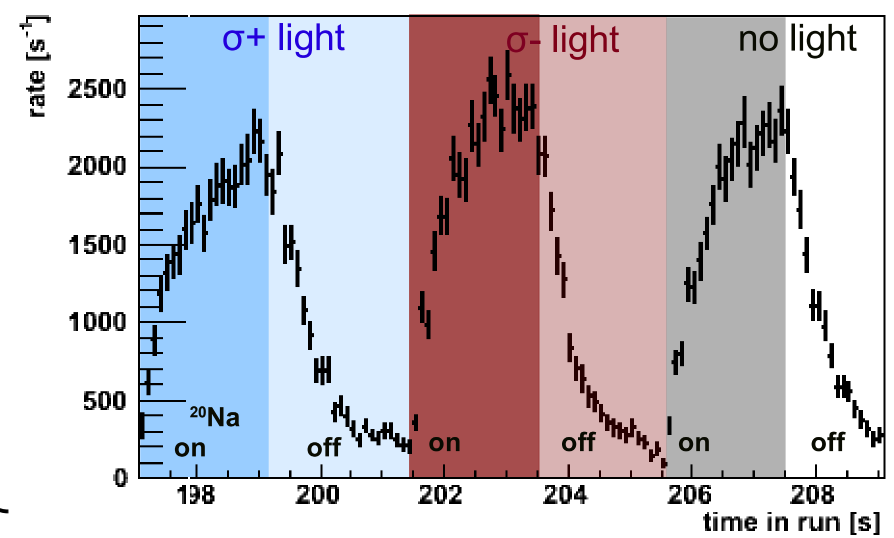
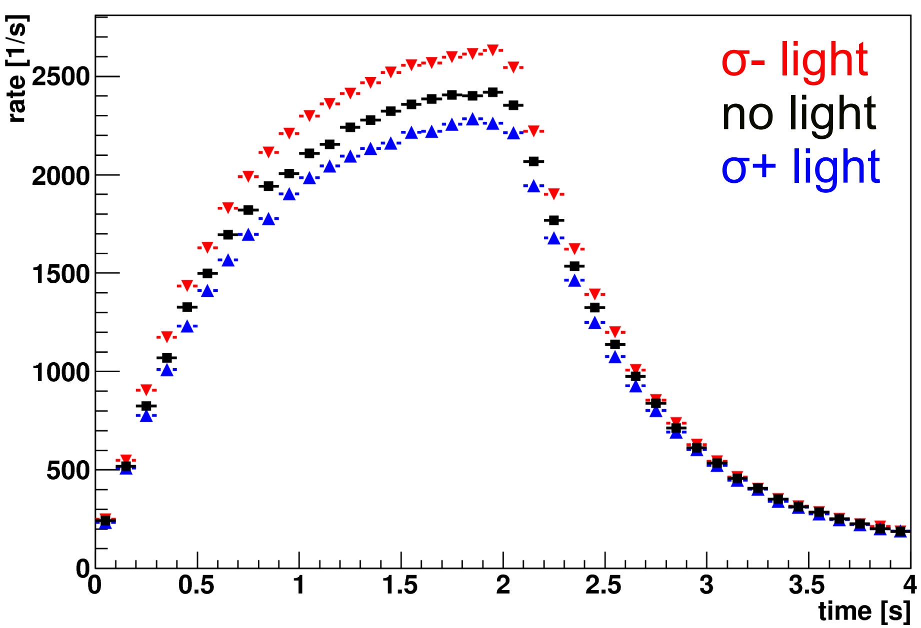


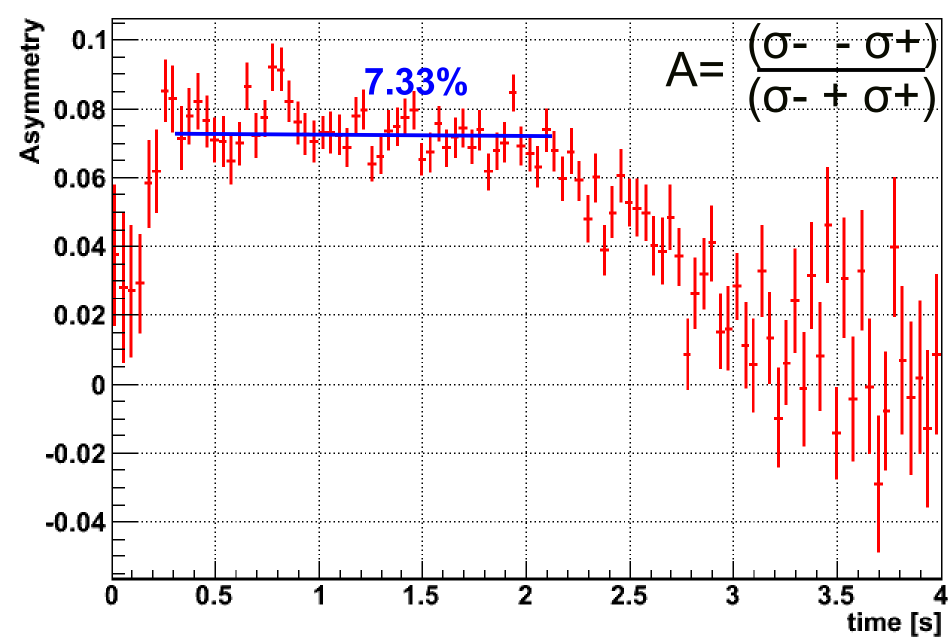
Polarization measurement:

- **β^+ Rates** from PHOSWICH detector
  - 2s-on, 2s-off period of ^{20}Na beam:

n

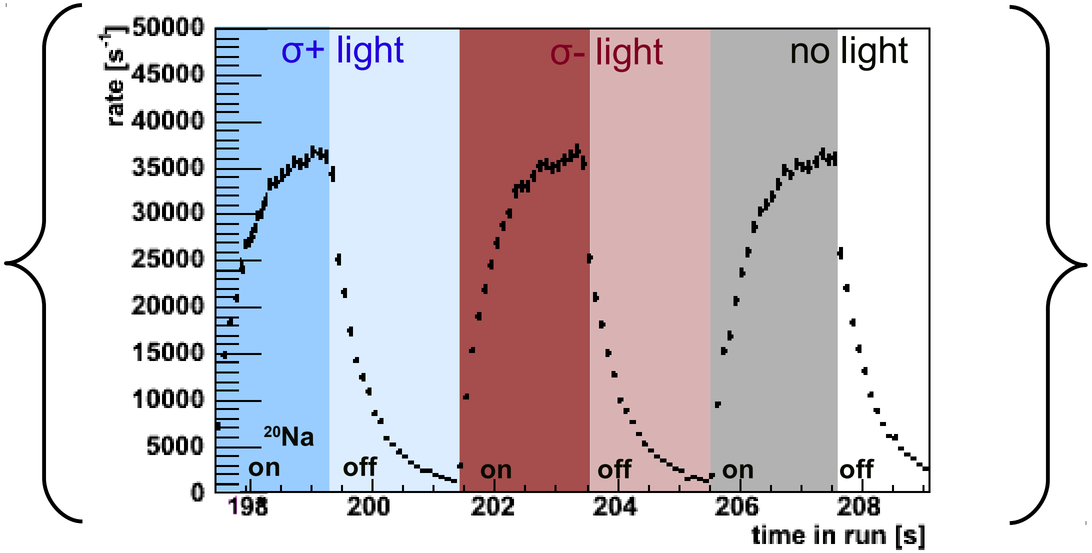






Lifetime measurement:

- γ **Rates** from NaI detector
  - 2s-on, 2s-off period of ^{20}Na beam



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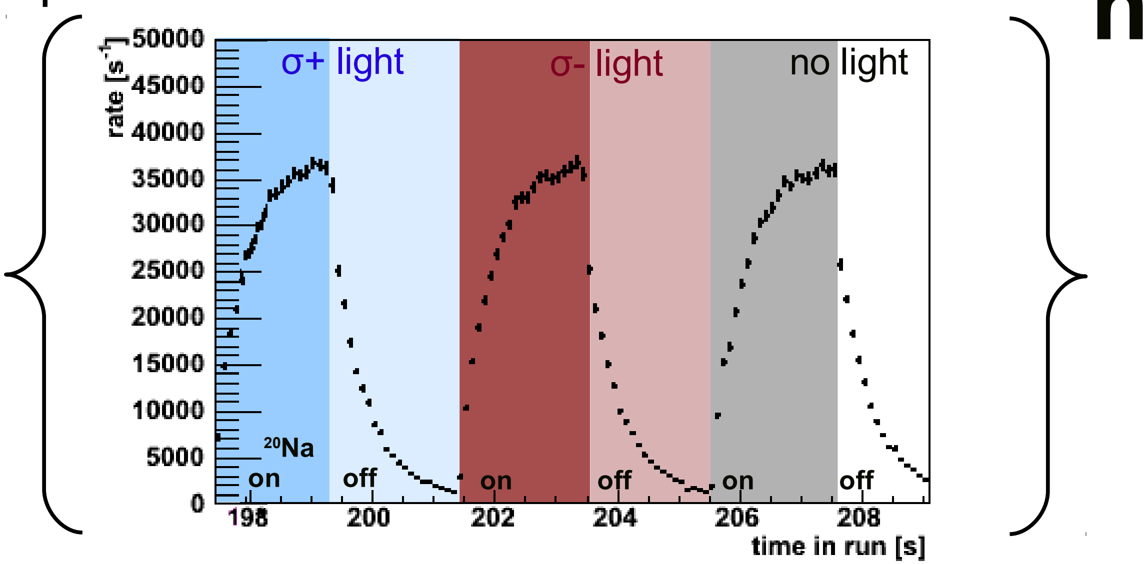
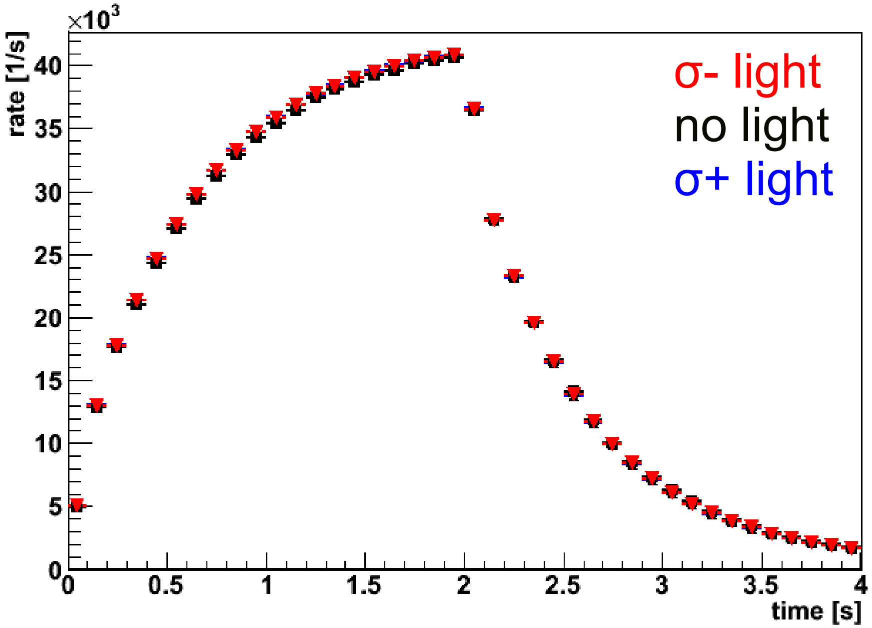
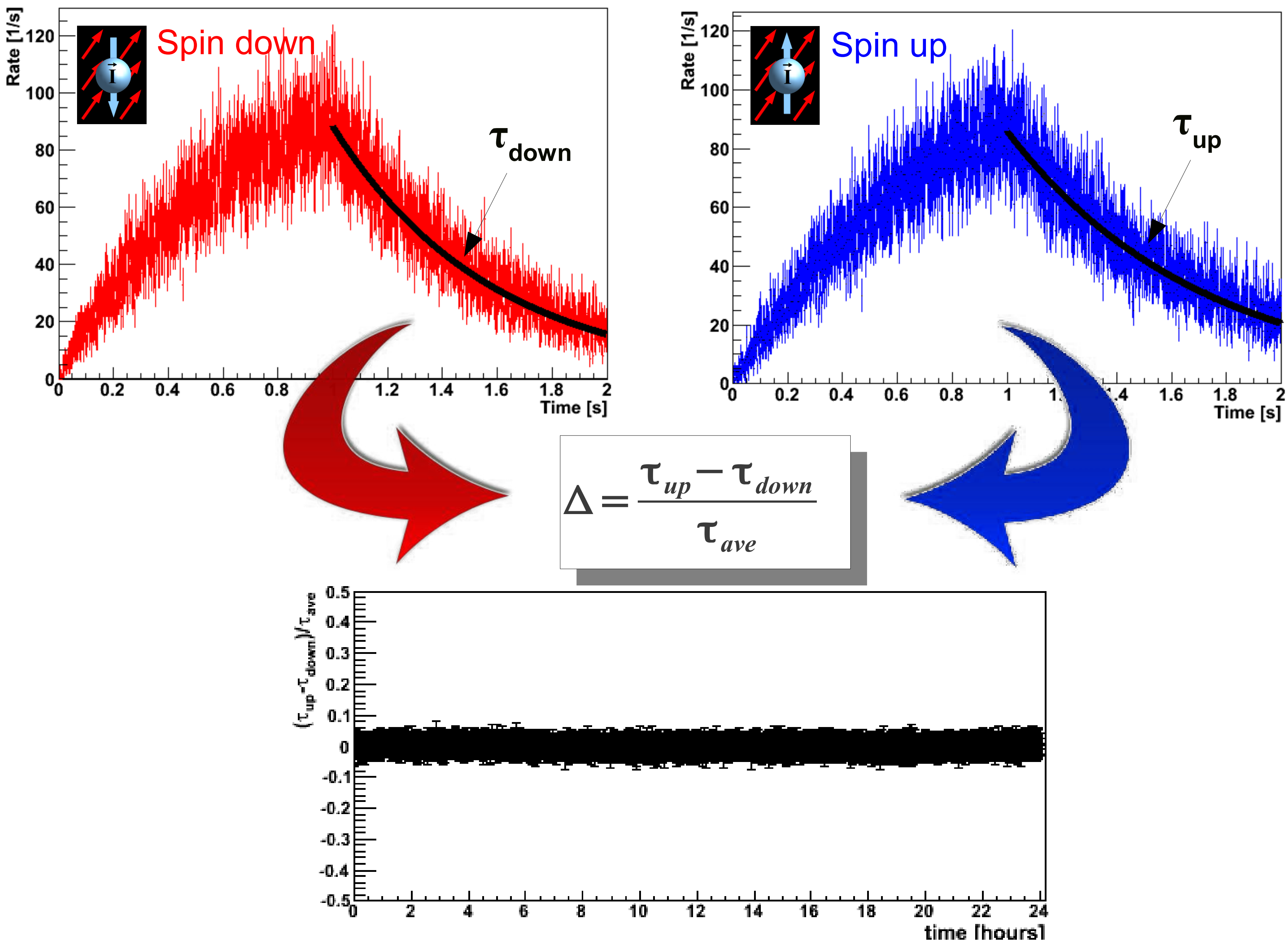




Lifetime-analysis:

- *compare lifetimes for σ+ and σ- case*
- *take into account time-dependence of polarization*
- *define and estimate systematic effects*
- *train algorithms on "no light" case*

Data Analysis (simulation):



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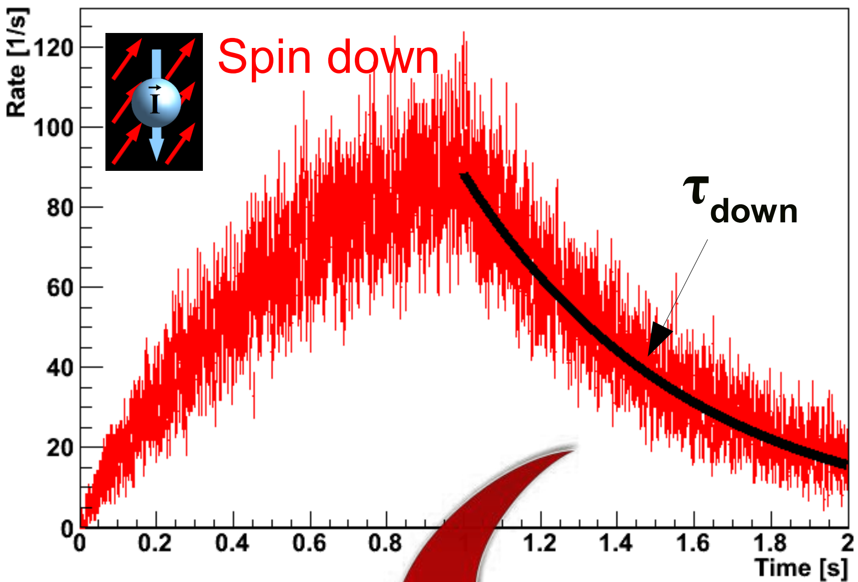
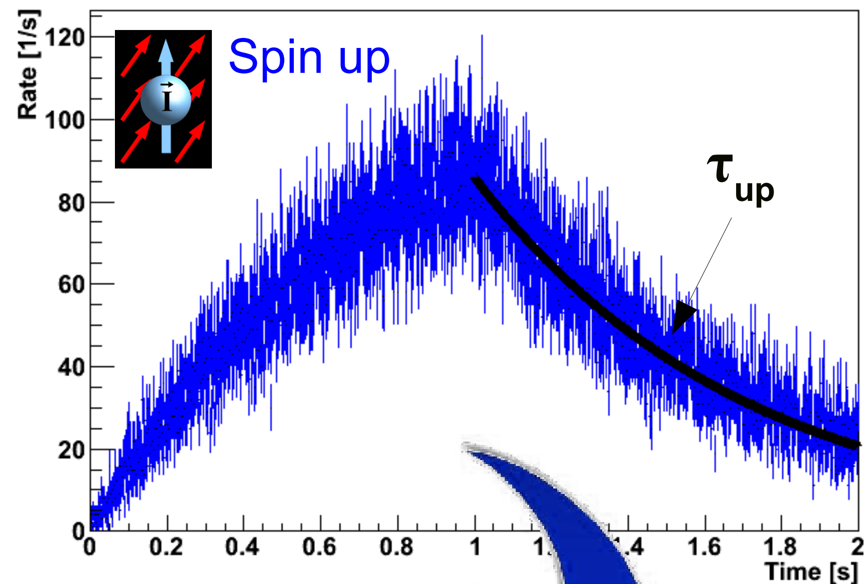


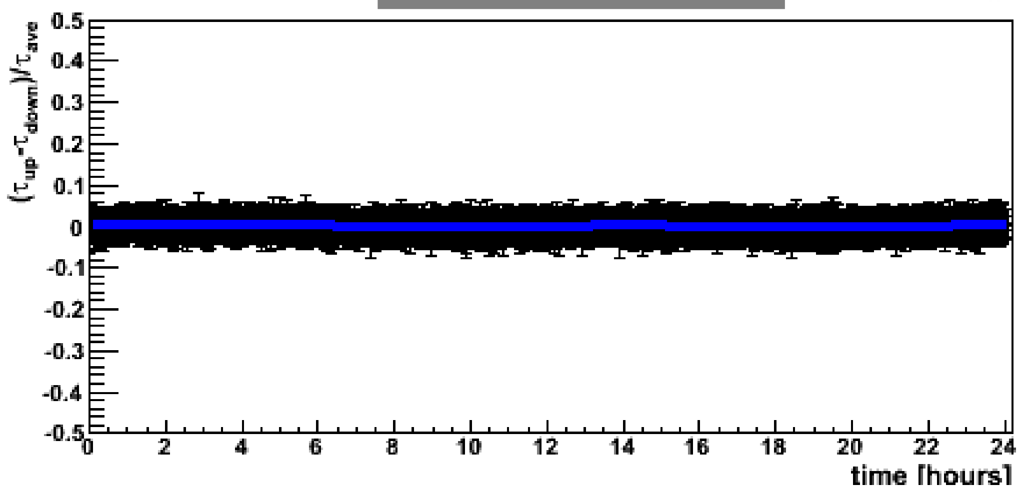


$$\Delta = \frac{\tau_{up} - \tau_{down}}{\tau_{ave}}$$

Fitfunction:

$$\Delta(t) = C + A_s \sin(\omega_\oplus t) + A_c \cos(\omega_\oplus t) + B_s \sin(2\omega_\oplus t) + B_c \cos(2\omega_\oplus t)$$

$$\omega_\oplus = 2\pi / T_{\text{sid. day}}$$



From fit:

$C = (0.84 \pm 1.31) \times 10^{-4}$

$A_S = (14.9 \pm 1.85) \times 10^{-4}$

$A_C = (13.6 \pm 1.85) \times 10^{-4}$

$B_S = (20.3 \pm 1.85) \times 10^{-4}$

$B_C = (0.69 \pm 1.85) \times 10^{-4}$

Data Analysis:

Analyzing 24h of non-polarized events:

- fit lifetimes of 2 consecutive "no-light"-periods

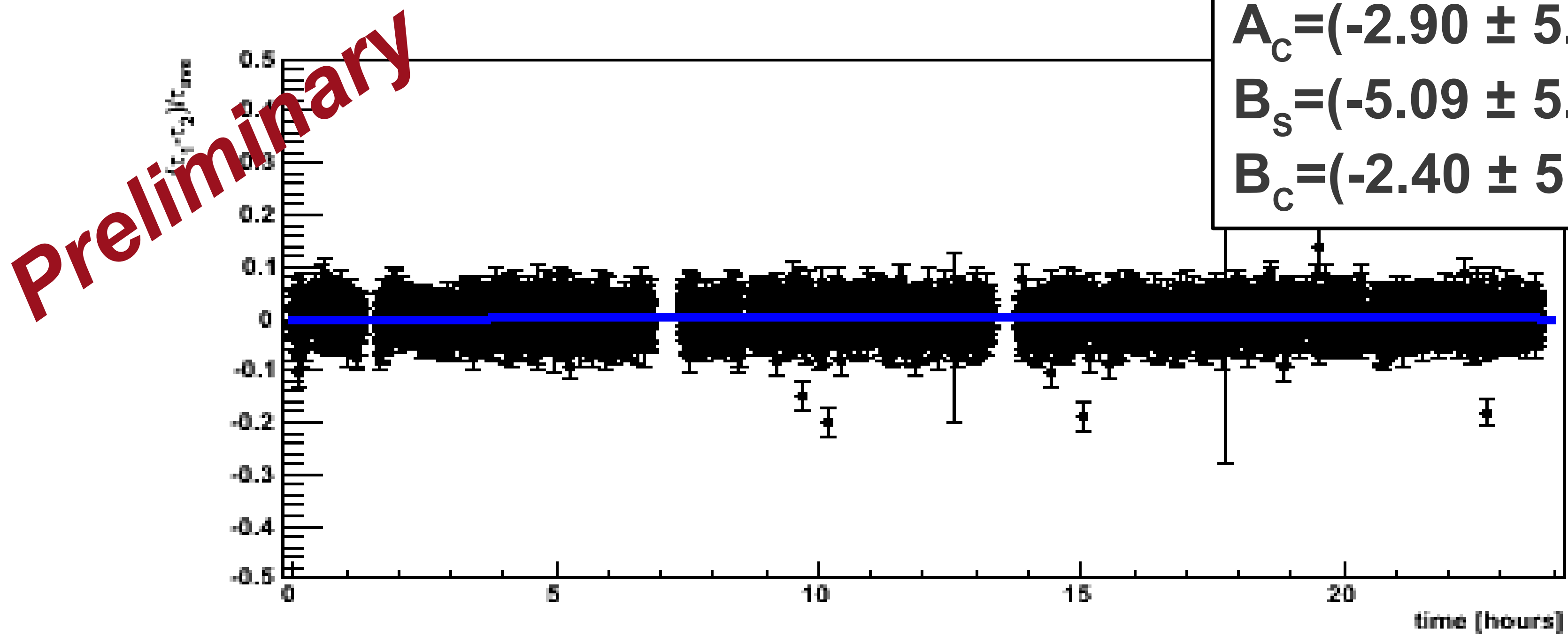
$C =(4.69 \pm 3.90)\times10^{-4}$

$A_S=(0.90 \pm 5.50)\times10^{-4}$

$A_C=(-2.90 \pm 5.55)\times10^{-4}$

$B_S=(-5.09 \pm 5.55)\times10^{-4}$

$B_C=(-2.40 \pm 5.56)\times10^{-4}$



Next steps:

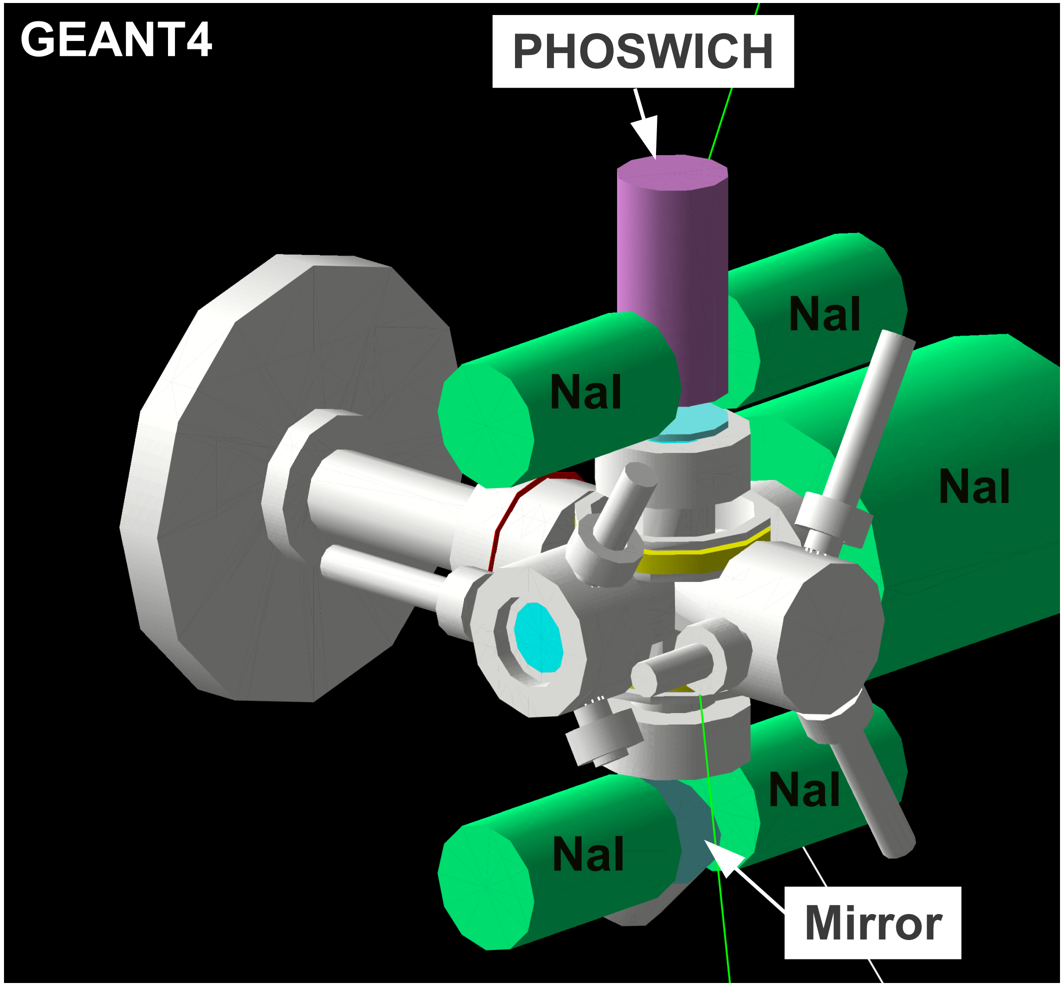
- determine polarization asymmetry

- analyze lifetimes for polarized nuclei

- evaluate and quantify systematic effects

GEANT4 simulation:

^{20}Na
Atoms



Simulations needed for:

- *detector acceptances*
- *study of systematic effects (stopping position of ^{20}Na atoms, detector alignment, etc.)*

Standard Model Extension (SME):

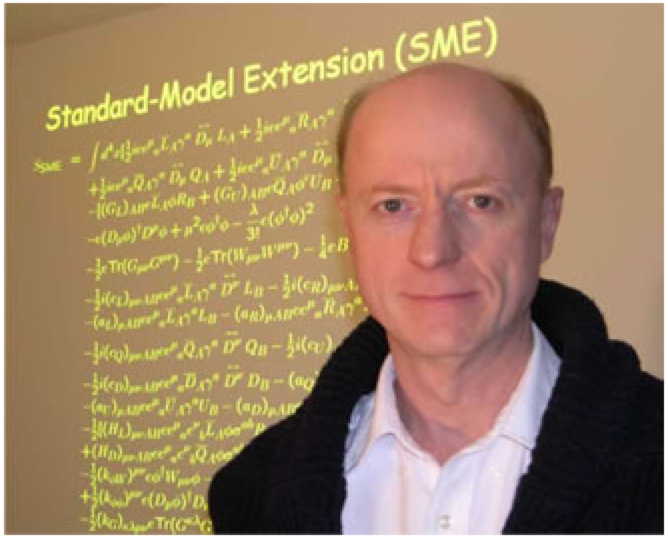
$$\frac{d\Gamma}{dE\,d\Omega} \sim \left(1 + A_0 \frac{\langle \vec{I} \rangle}{I} \cdot \frac{\vec{p}}{E}\right) + \xi_1 \left(1 + \xi_A \left(\hat{p} \cdot \frac{\langle \vec{I} \rangle}{I}\right)\right) \hat{p}\,\hat{n} + \xi_2 \frac{\langle \vec{I} \rangle}{I} \hat{n} + \xi_3\, \hat{p}_i \left(\frac{\langle \vec{I} \rangle}{I}\right)_j \rho^{ij}$$

Experiment at KVI probes ξ_2

More general framework to compare with other experiments:

Standard Model Extension (SME)

D. Colladay, A. Kostelecký, PRD58 (1998) 116002)

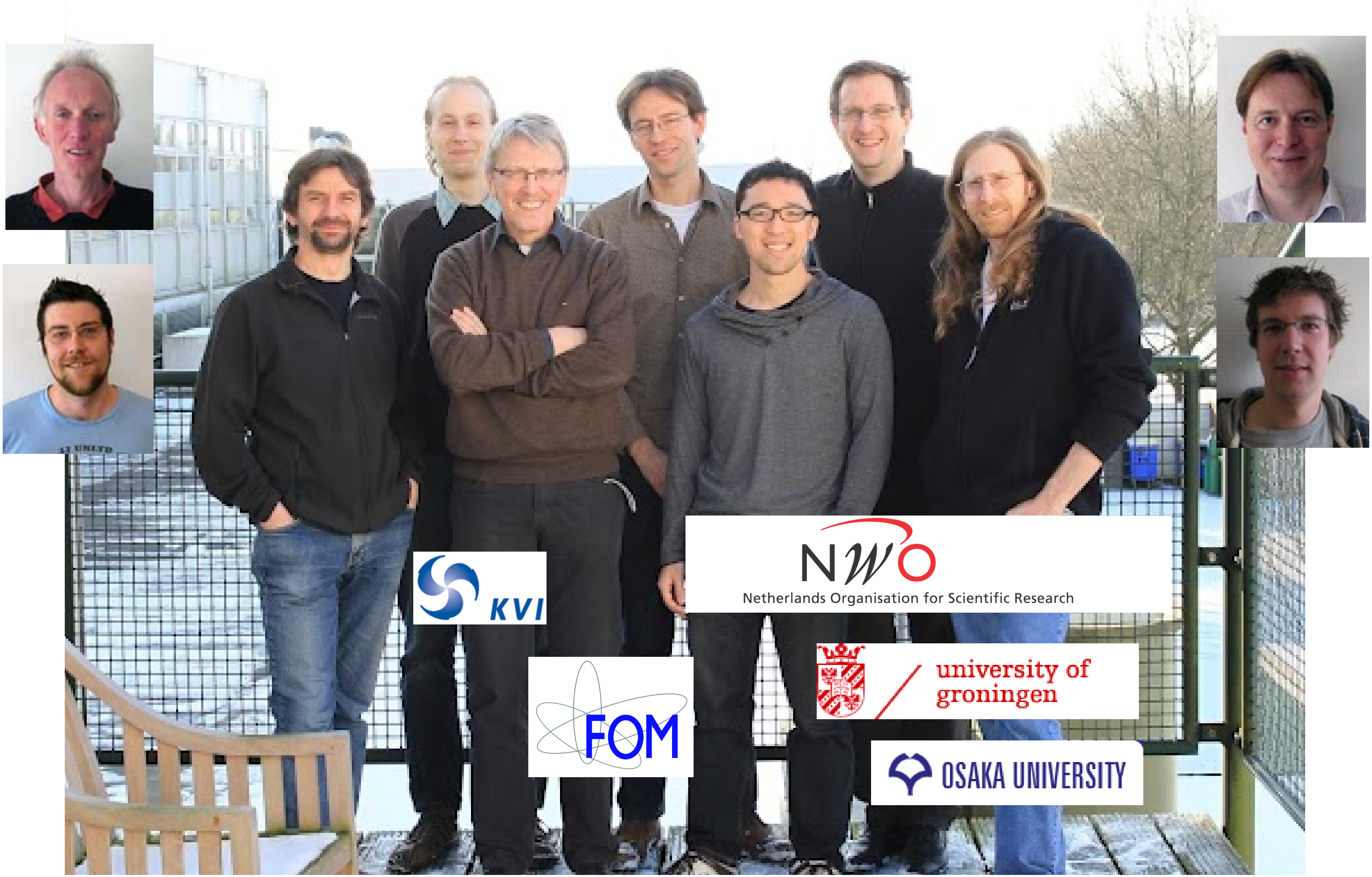


- relate ξ coefficients to SME parameters
- use galactical coordinates in sun-centered equatorial frame

Conclusions

- **Unique Test of LSB** using weak decay of polarized particles
  Probe muon, neutron, radioactive isotopes,...
- **Combined effort** from theorists and experimentalists at KVI
  Interpretation of observables in LSB framework (SME) underway
- **First dedicated experiment** studying LSB on polarized atoms
  Polarization of nuclei achieved, several 24h-periods of data on disk
- **Outlook**
  Lifetime analysis in progress, results expected soon

Thank you!


KVI
NWO
Netherlands Organisation for Scientific Research
FOM
university of groningen
OSAKA UNIVERSITY

Greenberg's theorem:

O. W. Greenberg, PRL89 (2002) 231602

"If CPT invariance is violated in an interacting theory, then that theory also violates Lorentz invariance"

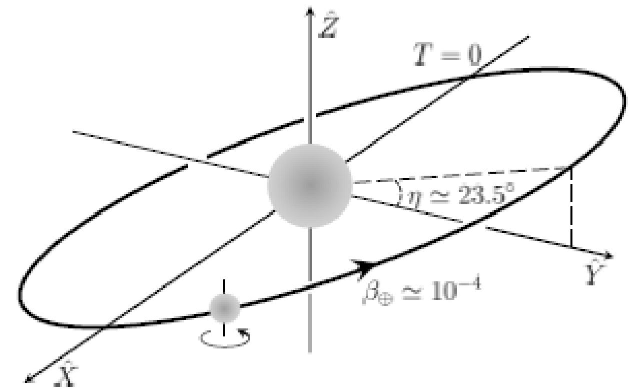
"Theories that violate CPT by having different particle and antiparticle masses must be nonlocal"

PDG2012 ("Tests of conservation laws", L. Wolfenstein and C.-J. Lin):

"The best test comes from the limit on the mass difference between K^0 and $\overline{K}^0$"

Relating measurement to SME parameters:

- ξ_2 measured in labframe for spin pointing in +z or -z direction - needs to be transformed into Standard Sun-Centered inertial reference frame



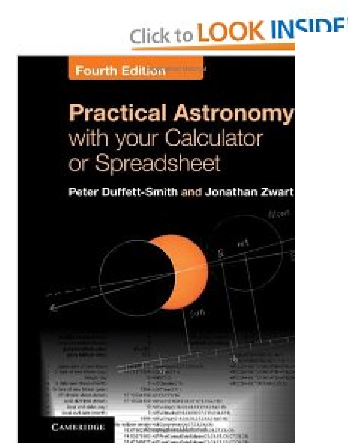
$$\xi_{2,LAB} \propto c^{z0}_{LAB} = c^{x0}_{SCF} \sin\chi \cos(\omega_\oplus t_\oplus) + c^{y0}_{SCF} \sin\chi \sin(\omega_\oplus t_\oplus) + c^{z0}_{SCF} \cos\chi$$

χ = KVI colatitude (90^0 - 53.25^0)

$\omega_\oplus = 2\pi/T_{\text{sid. day}} = 2\pi/(23\text{h}56\text{m}04\text{s})$

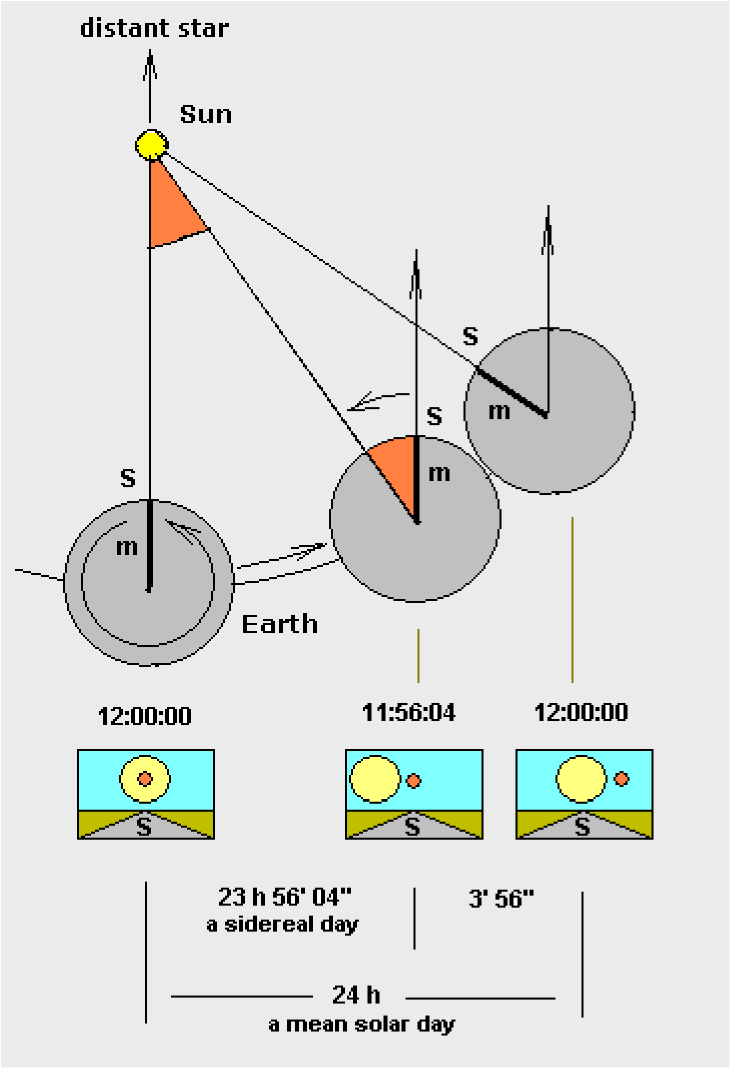
$t_\oplus$ = sidereal time

- need to express UNIX time (~UTC ~UT) in sidereal time:
  - J. Meeus - Astronomical Formulae for calculators
  - P. Buffet-Smith, Practical Astronomy with your calculator
  - S. Aoki et al., Astron. Astrophys. 105 (1982) 359



Sidereal time:

- We consider the Lorentz-Violating fields constant and "fixed to a galactical reference frame"
  earth moves while rotating→ "Solar time" is not useful, need time independent of position of sun



from Wikipedia

Sidereal time:

- We consider the Lorentz-Violating fields constant and "fixed to a galactical reference frame" earth moves while rotating→ "Solar time" is not useful, need time independent of position of sun

Algorithm:

- get universal days elapsed since 01-01-2000 12h UT1 (Julian Day Number since JD 2451545)
- divide by 36525 to get fractional centuries:

$$T_U' = \frac{d_U'}{36525}$$

- Use this to obtain Greenwich Mean Sidereal Time (GMT) at 0h UT1 in sidereal seconds:

$$\text{GMST1 of } 0^h \text{ UT1} = 24110^s.54841 + 8640184^s.812866\, T_U' + 0^s.093104\, T_U'^2 - 6^s.2\, 10^{-6}\, T_U'^3 .$$

- divide by 3600 to get sidereal hours
- add longitudinal term $(\eta/360)\cdot 24$ with η **KVI long. (6.53^0 E)**
- convert fraction of hours since 0h to sidereal hours and add

1 sid. hour = 1 h ·(364.25/365.25)

- reduce result to 24 hours