# Double-Quantum NMR Spectroscopy: Investigating Structure and Dynamics of Abundant Spin Systems.

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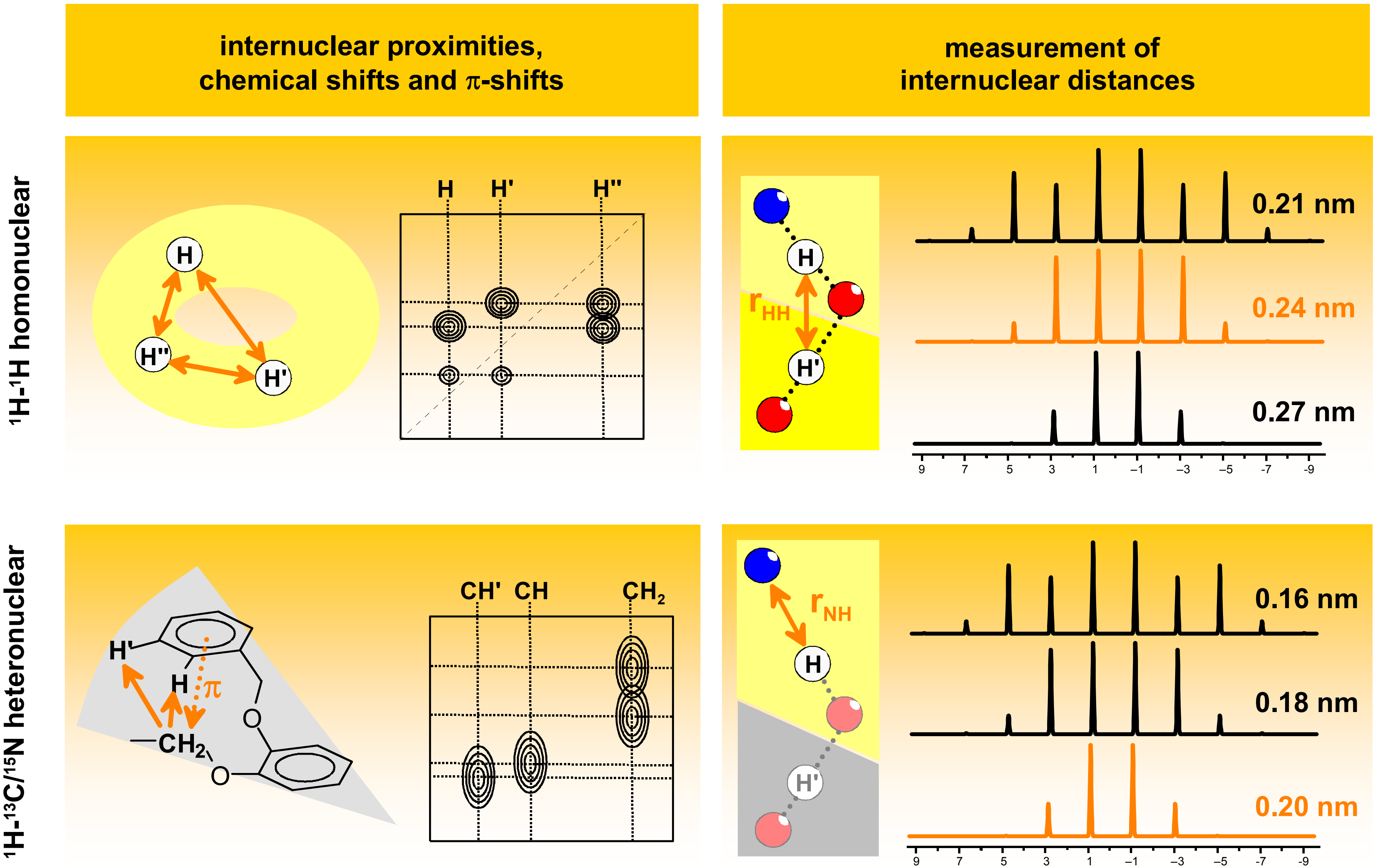
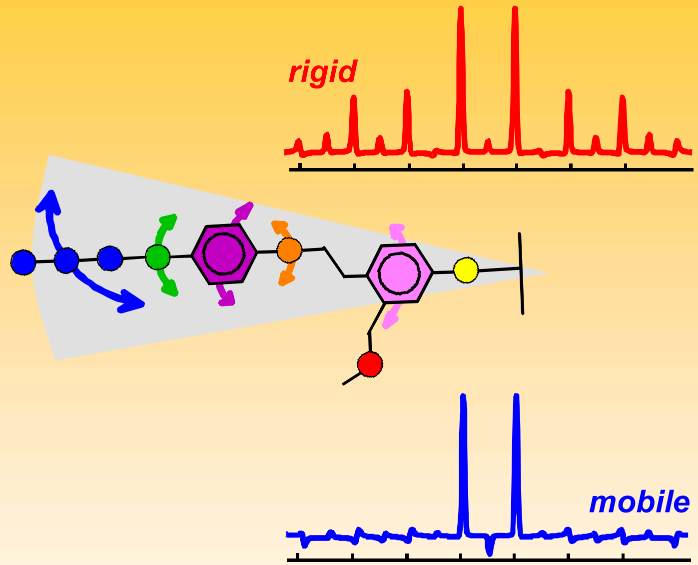
# Double-quantum NMR methods: investigating (supra) molecular structure



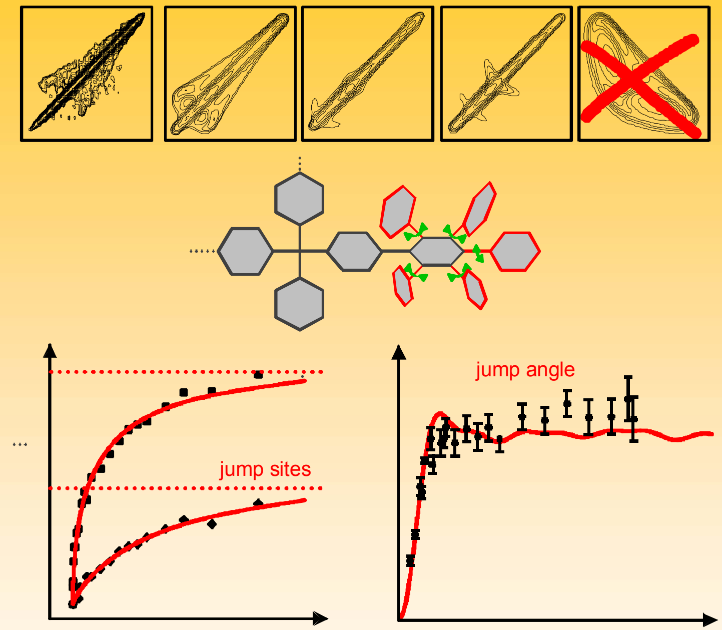
# NMR methods: investigating molecular dynamics

## fast local dynamics




Averaging of dipolar couplings

## slow reorientations




**loss** of NMR signal

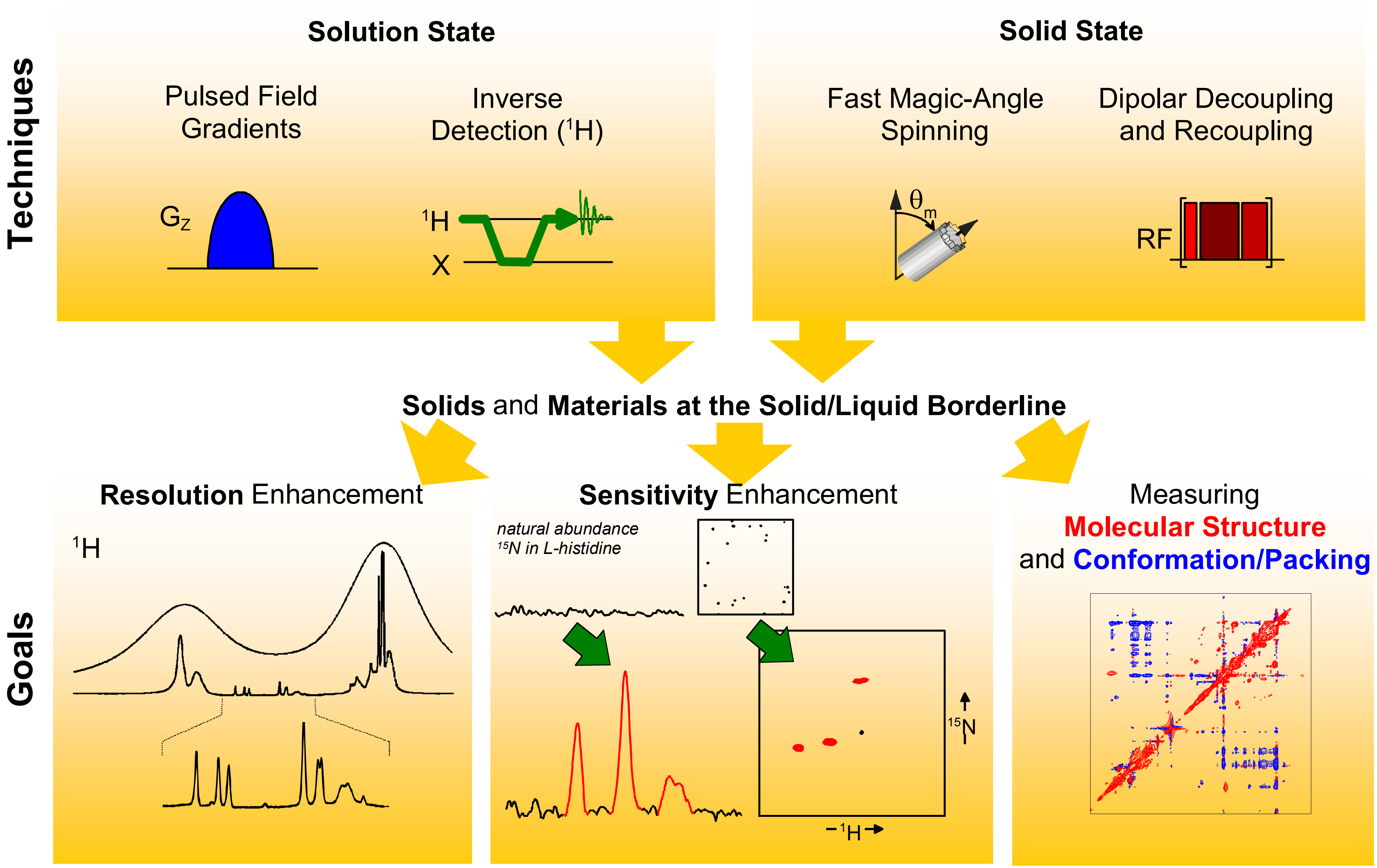
**exchange NMR** experiments

fast | intermediate | slow | static

$10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $10^{0}$ $10^{1}$ $10^{2}$

motional correlation time [seconds]

# Merging solid-state and solution-state NMR methods



# Outline of the Talk

- Homonuclear DQ NMR spectroscopy under fast MAS
- Residual dipolar couplings and order parameters in nematic LC
- Multi-Spin Effects in abundant spin systems
  - two spin approximation and it's limits
  - double-quantum relay in dipolar systems
  - multi-spin coherences envolving more than 2 spins
- Conclusions for homonuclear DQ NMR in dense spin systems

- Heteronuclear MQ NMR spectroscopy and REDOR
- Shape persistent polymers with dentritic sidegroups
- Inverse detection of $^{15}N$ in natural abundance
- Conclusions

# High Resolution Double-Quantum NMR in Solids

properties of double-quantum coherences :

- $\omega_{DQ} = \sum_i \omega_{SQ,i}$
- $I_{DQ,ij} = f(D_{ij} \cdot t)$
- $\frac{dM}{dt} \approx 0$

high resolution solid-state NMR spectroscopy: ☞ average out dipolar coupling via

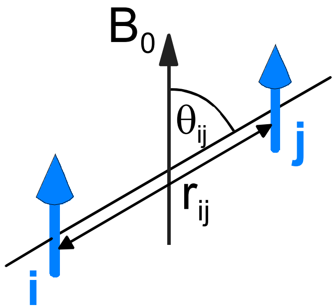
- Multi pulse sequence (WAHUHA, MREV-8)
- Magic Angle Spining (MAS)

Problem: Coupling between the spins is needed for double-quantum excitation !

| excitation | evolution $t_1$ | reconversion | detection $t_2$ |
| --- | --- | --- | --- |
| $\omega_R \approx 0$ | $\omega_R > D_{ij}$ | $\omega_R \approx 0$ | $\omega_R > D_{ij}$ |

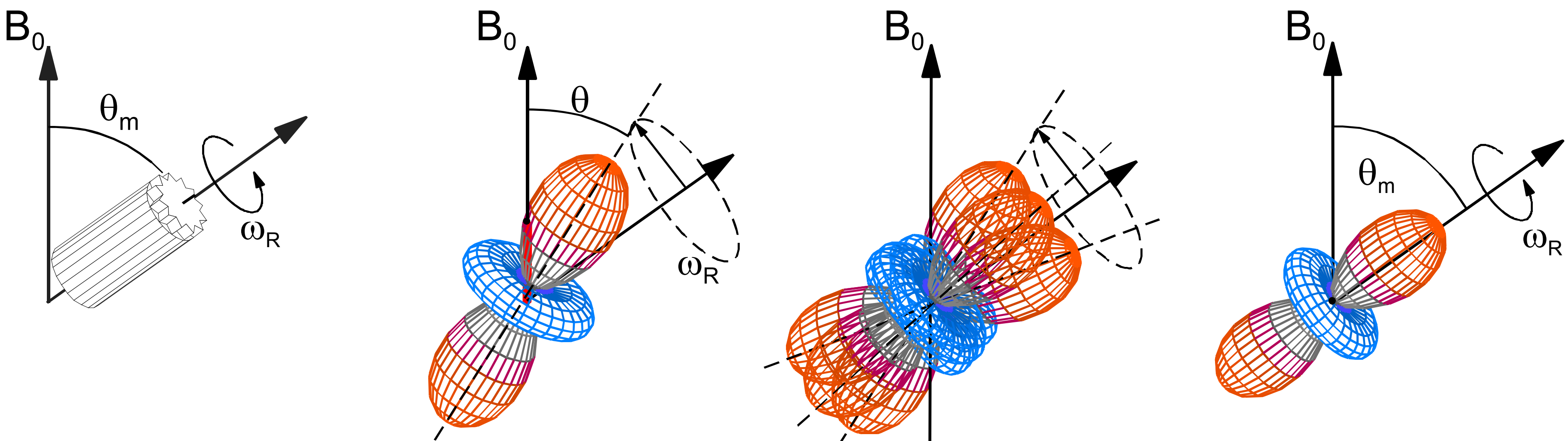
# Dipolar Couplings and Sample Rotation at the Magic Angle

Dipole Dipole Coupling:




| spatial part | spin part |
|---|---|
| $\hat{H} \propto \frac{1}{r_{ij}^3}\cdot\frac{1}{2}(3\cos^2\theta_{ij} - 1)$ | $\gamma_i\gamma_j(2\hat{I}_{Z,i}\hat{I}_{Z,j} + \hat{I}_{+,i}\hat{I}_{-,j} + \hat{I}_{-,i}\hat{I}_{+,j})$ |
| $\longrightarrow$ **0** | unchanged |

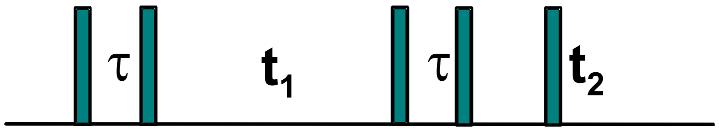
Magic Angle Spinning:



# Excitation of Double-Quantum Coherences under MAS

## Direct Excitation

$D_{ij} > \omega_R$



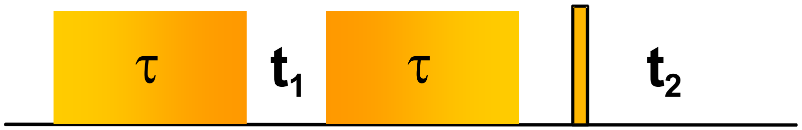

$\tau < 0.5 \cdot \tau_R$

**no synchronization**

- **3 Pulse Sequence**
  (+ z-filter)

## Recoupling

$D_{ij} < \omega_R$




$\tau = n \cdot \tau_R$

**rotor synchronization**

- **DRAMA**
- **BABA**
- **C7**

In the regime of fast MAS only recoupling techniques are applicable.

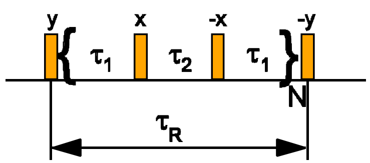
# Recoupling Pulse Sequences

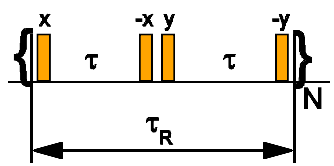
Average Hamiltonian of Pulse Sequences :

$$H_{av}^{0} = \sum_{i<j} \omega_{PF} I_i^{+} I_j^{+} + \omega_{PF}^{*} I_i^{-} I_j^{-}$$

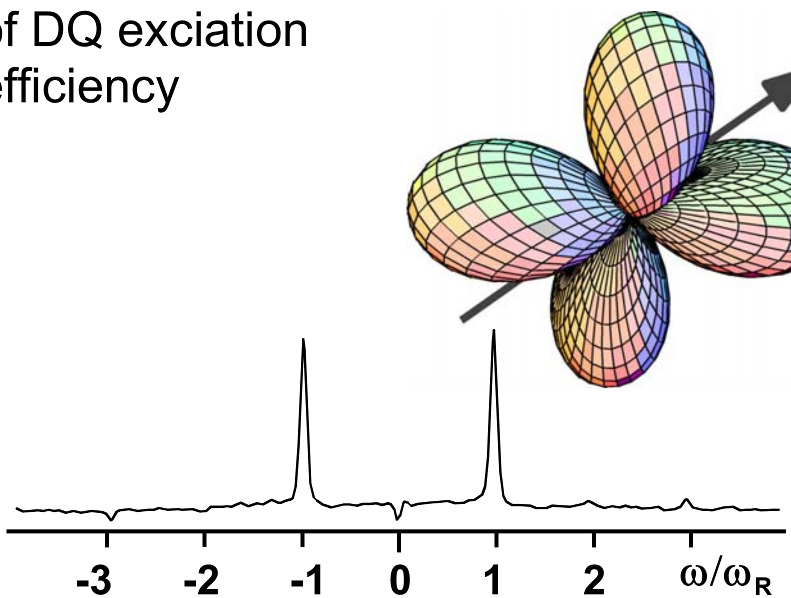
## Laboratory-System Pulse Sequences

examples: DRAMA, Back-to-Back, REDOR...



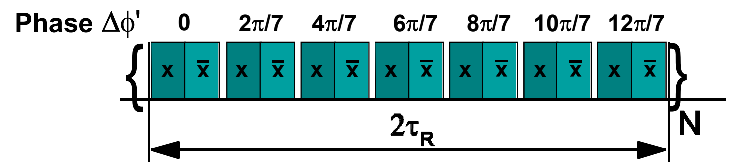




orientation dependence of DQ exciation efficiency

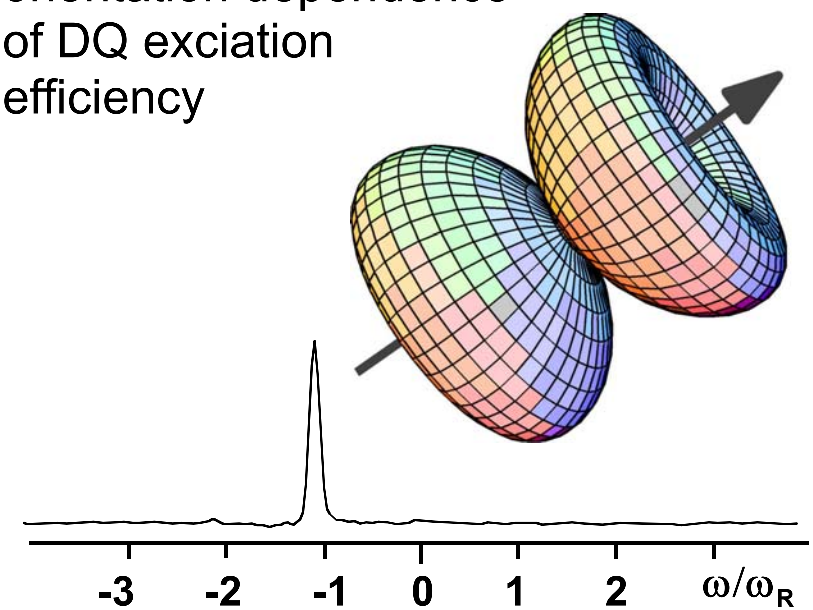



## Rotor-System Pulse Sequences

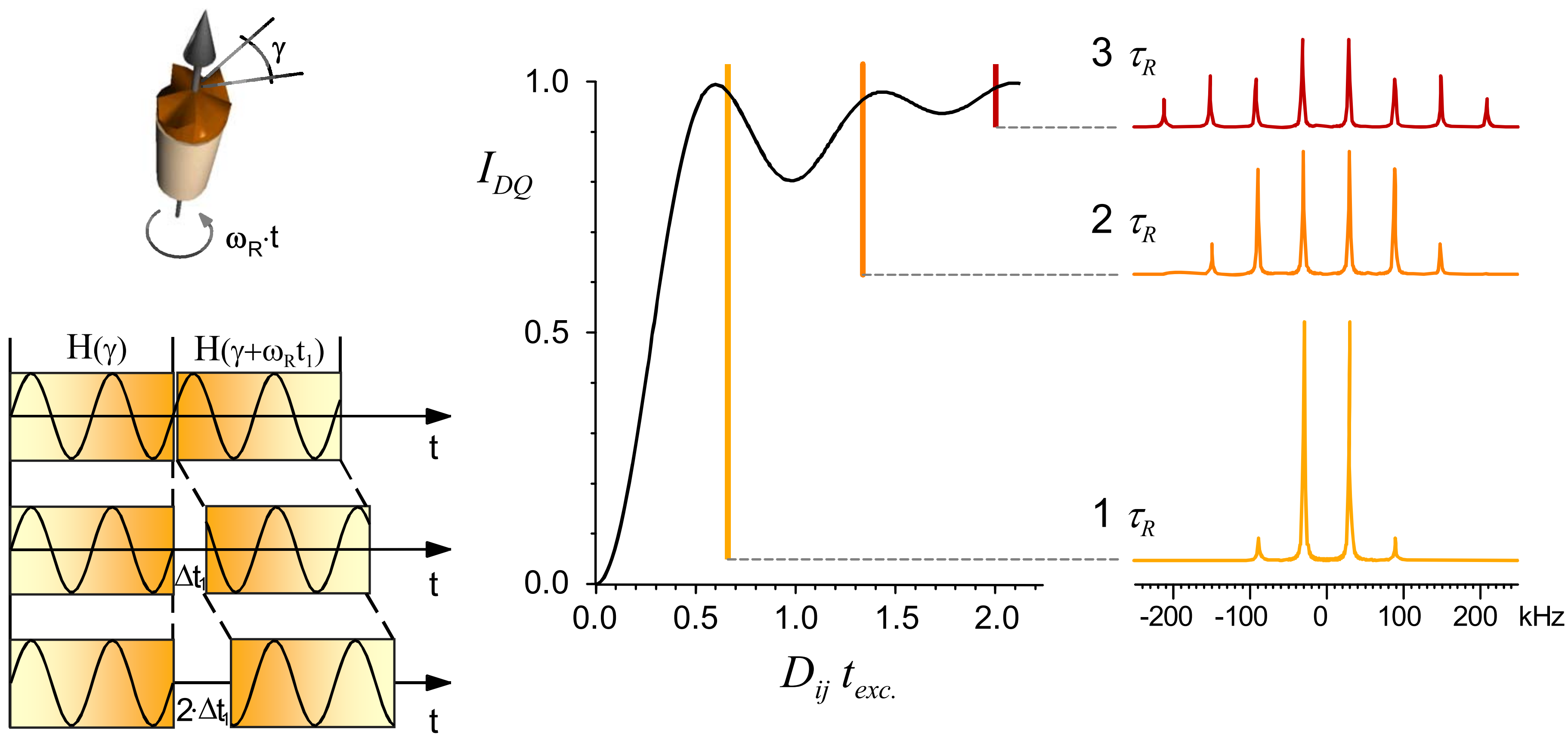
examples: $C_7$, POST $C_7$, MELODRAMA ...




orientation dependence of DQ exciation efficiency

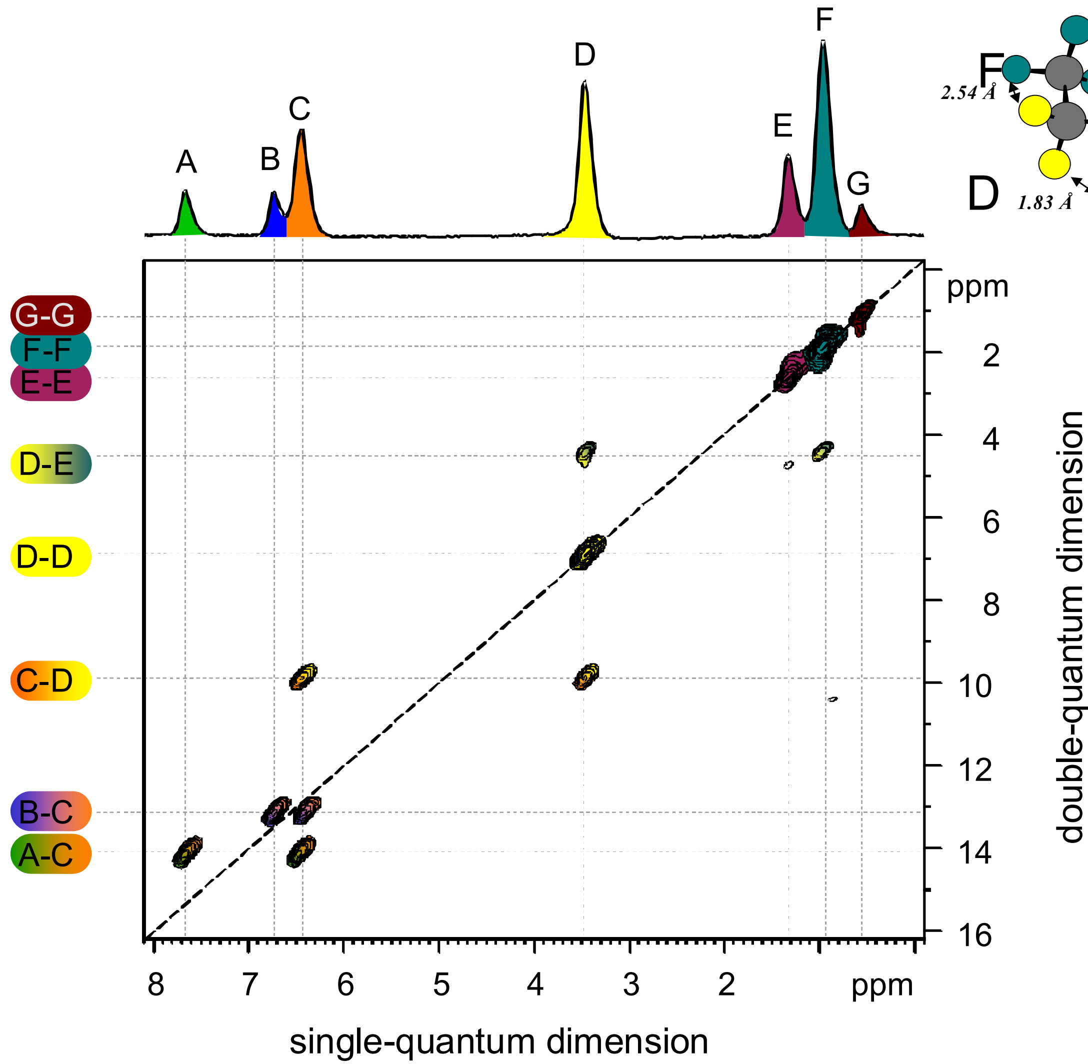


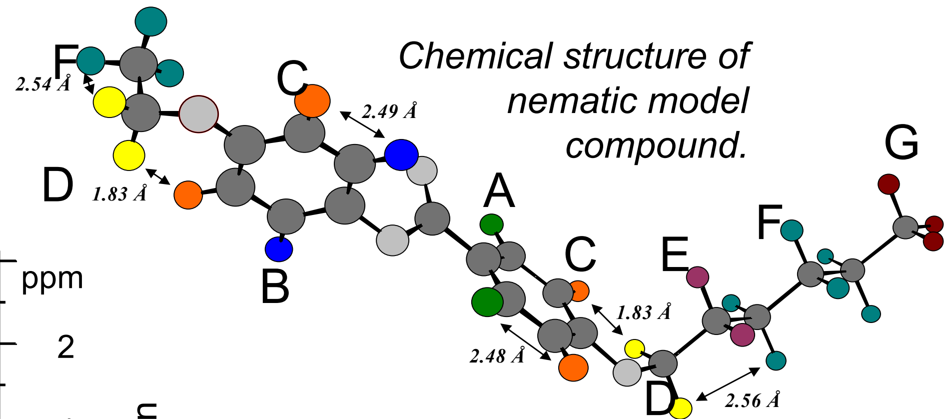
# Double Quantum Spectroscopy under fast MAS




The rotor modulation of the recoupled dipolar Hamiltonian due to $t_1$-increments $\Delta t_1 \neq \tau_R$ leads to MAS sideband pattern in the $t_1$ dimension, which depend on the recoupling time and the dipolar coupling only.

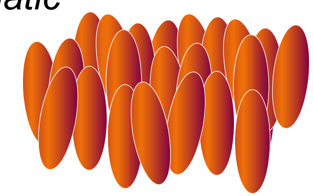
# Local Order in Nematic Liquid Crystals




*Chemical structure of nematic model compound.*

*Structure of a nematic liquid crystal*



DQ build-up behaviour

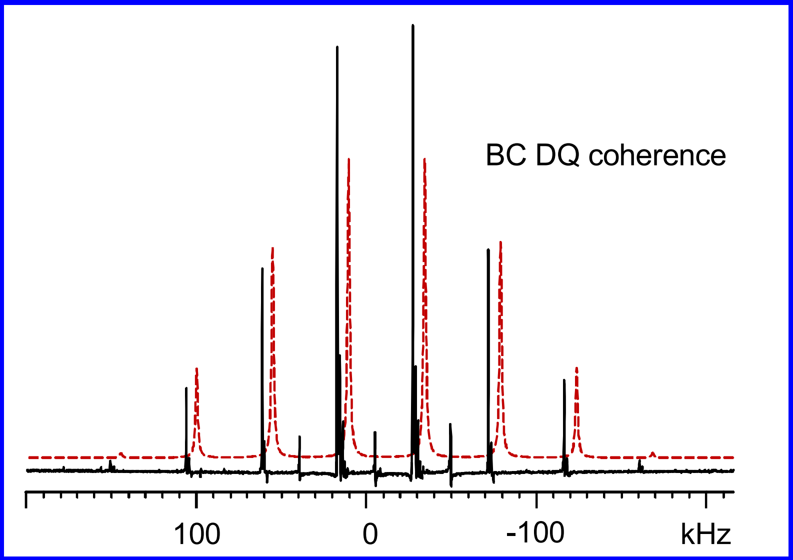
DQ sideband pattern

$\Rightarrow$ local order parameter

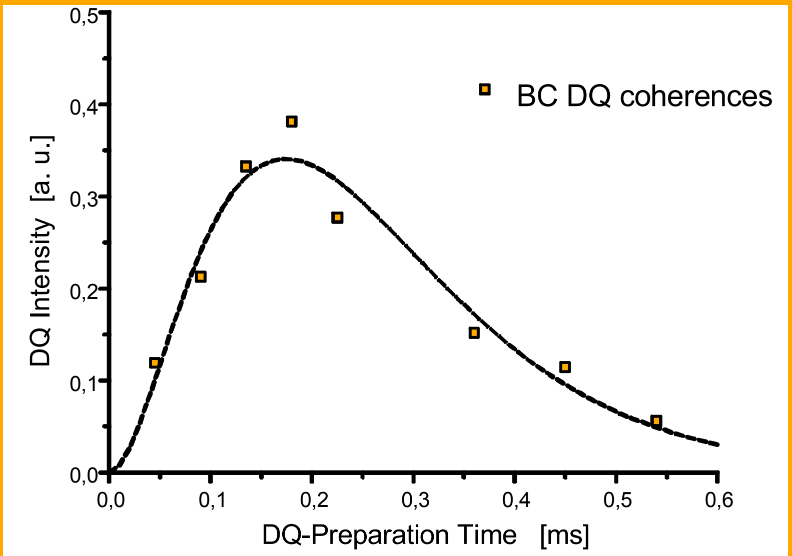
$$S = \left\langle {}^{1}/_{2}(3\cos^2\theta - 1) \right\rangle = 0.6$$

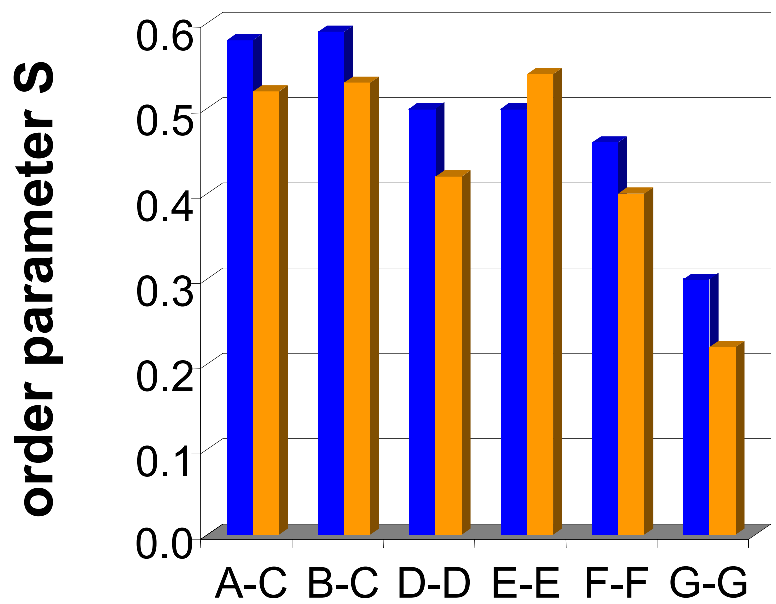
Double-quantum measurements are in good agreement with $^2H$ experiments

# Dipolar Coupling and Order Parameters

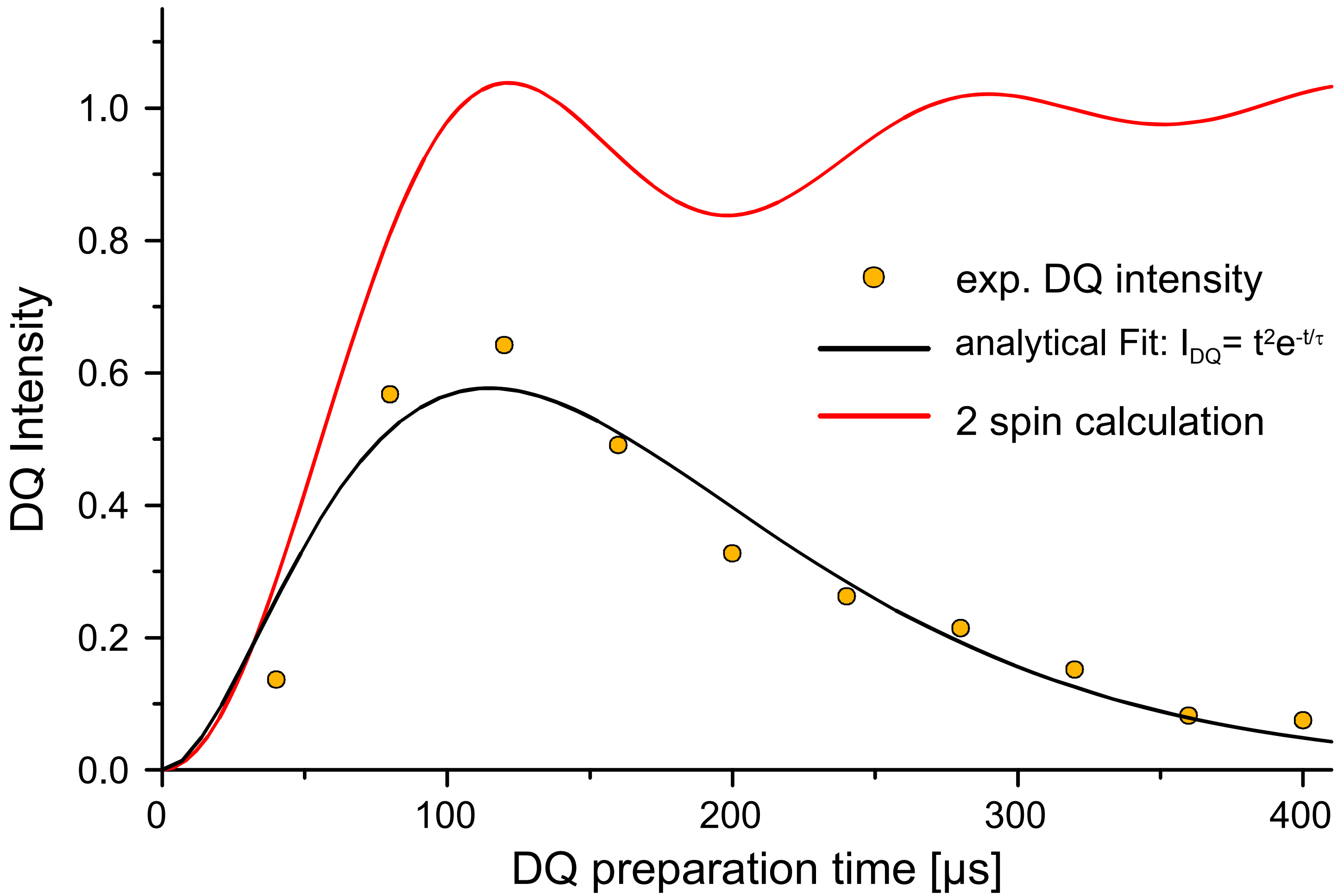



| DQ coherence | | A-C | B-C | D-D | E-E | F-F | G-G |
|---|---|---|---|---|---|---|---|
| $D_{ij,eff.}$ [kHz] | SBP | 4.8 | 4.9 | 5.2 | 5.2 | 4.8 | 3.1 |
| | Build-up | 4.4 | 4.3 | 4.5 | 5.6 | 4.3 | 2.4 |
| $S_{ij}$ | SBP | 0.58 | 0.59 | 0.50 | 0.50 | 0.46 | 0.30 |
| | Build-up | 0.52 | 0.53 | 0.42 | 0.54 | 0.40 | 0.22 |



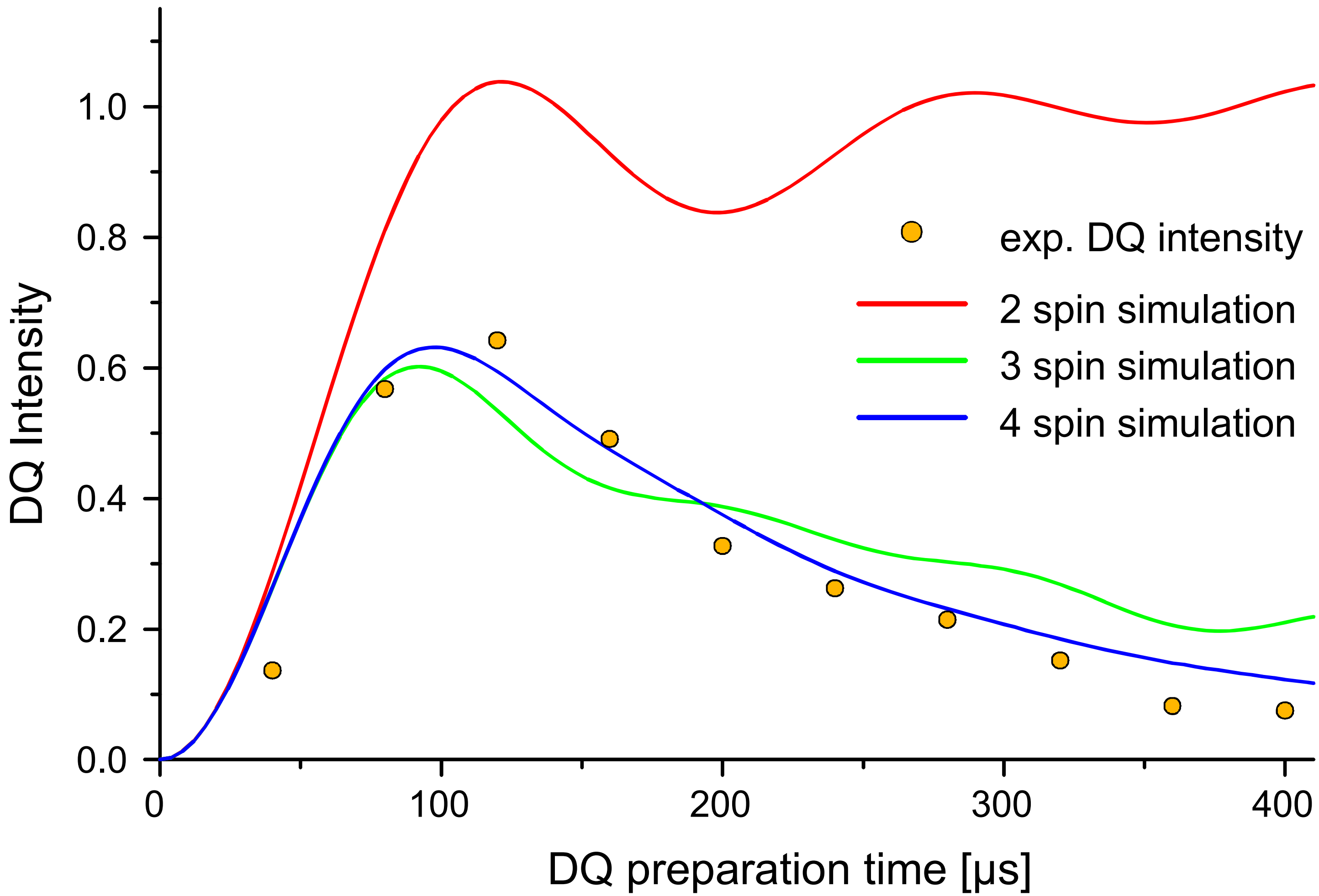



# Multi-Spin Effects in Double-Quantum Build-Up



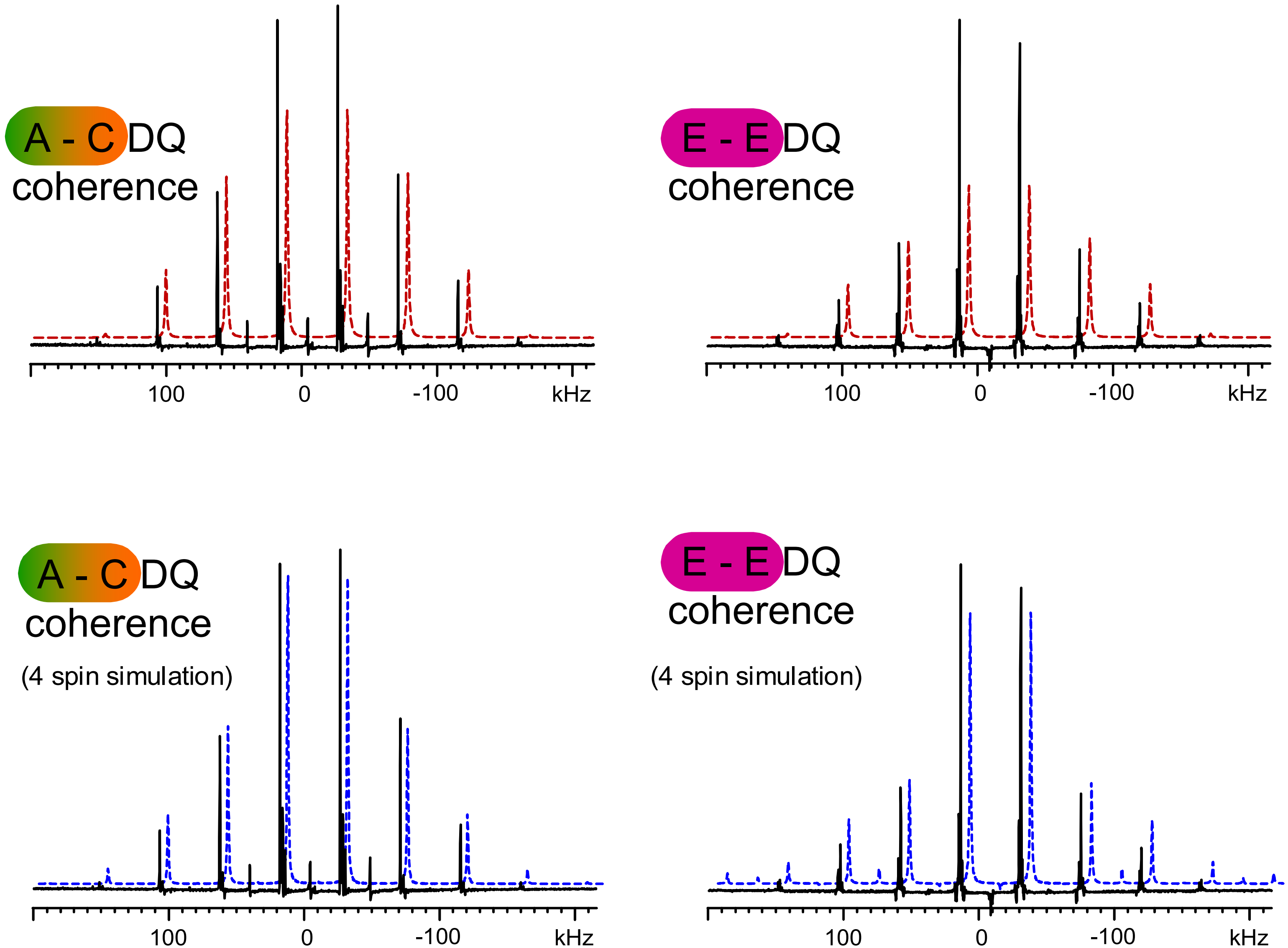

2-spin approximation discribes only the initial behavior.

# Multi-Spin Effects in Double-Quantum Build-Up




Multi-spin effects lead to exponential decay of the DQ intensities

# Multi-Spin Effects in DQ Sideband Pattern

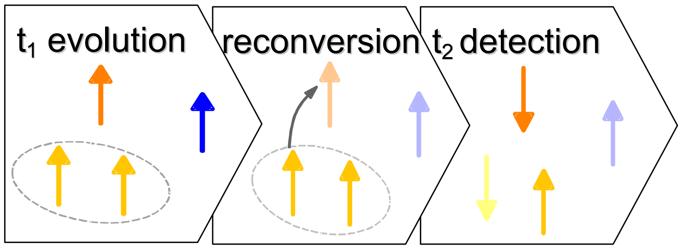


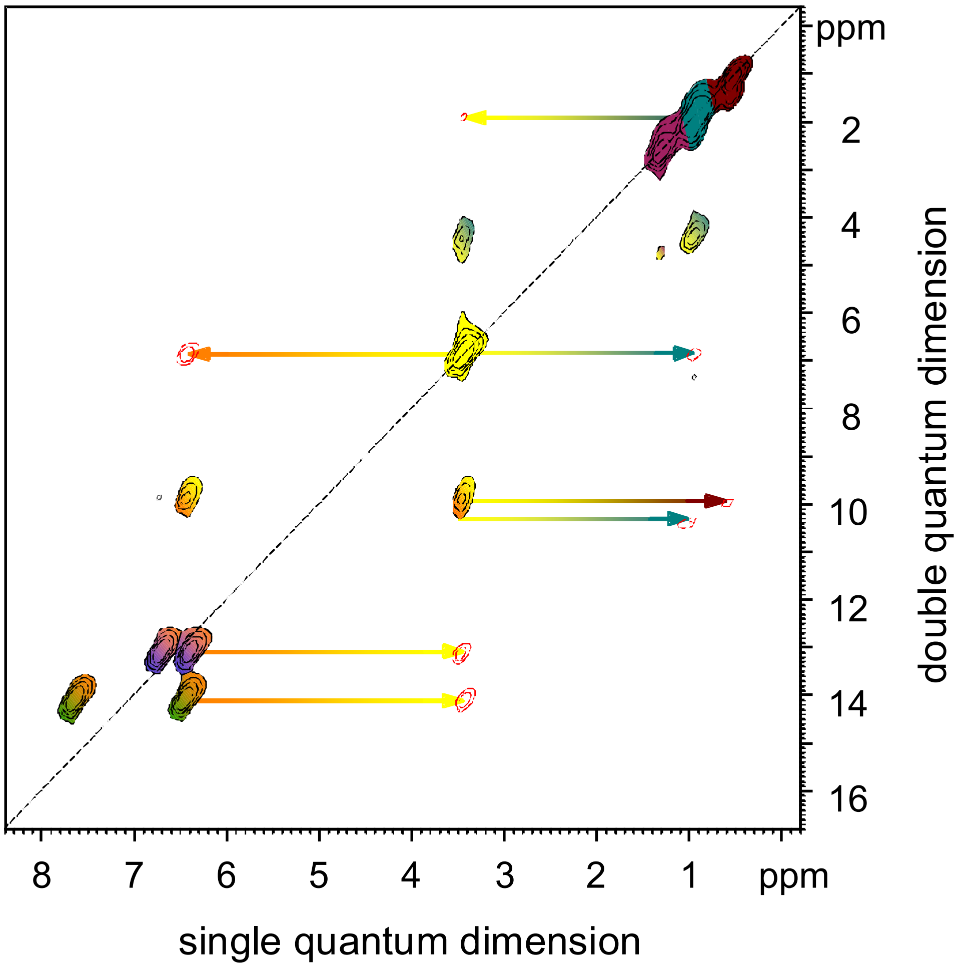

1st order sidebands are under estimated by 2-spin approximation

# DQ Polarisation Transfer: 1. Order Relay

double-quantum experiment :


1. Order DQ relay



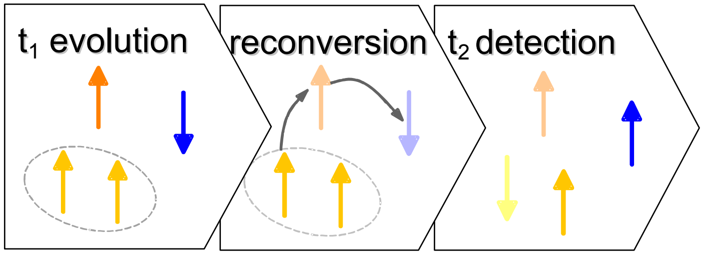



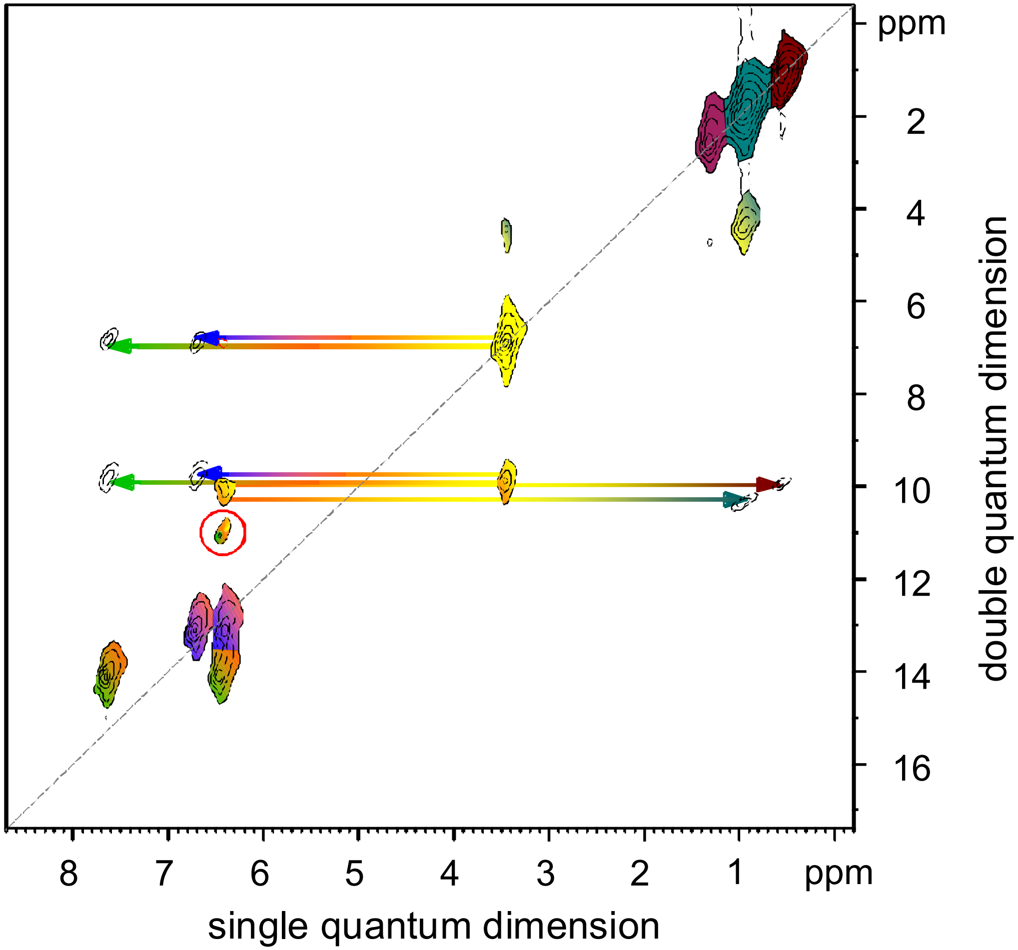

Double-quantum polarisation transfer leads to negative signal intensities

# DQ Polarisation Transfer: 2. Order Relay

double-quantum experiment :

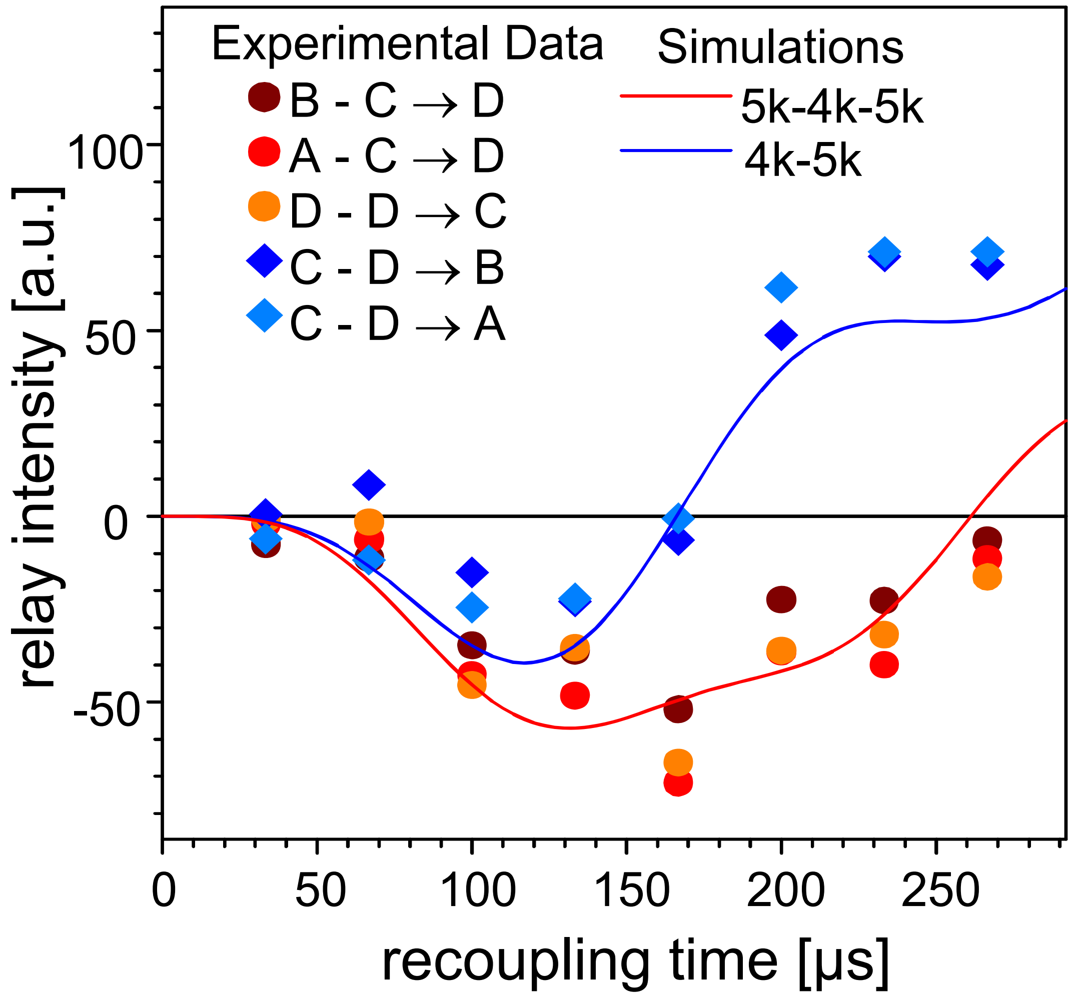

## 2. order double-quantum relay




For longer double-quantum recoupling times coherences get delocalised and can obscure the double-quantum spectrum

# Time Dependence of Dipolar DQ Relay Intensities



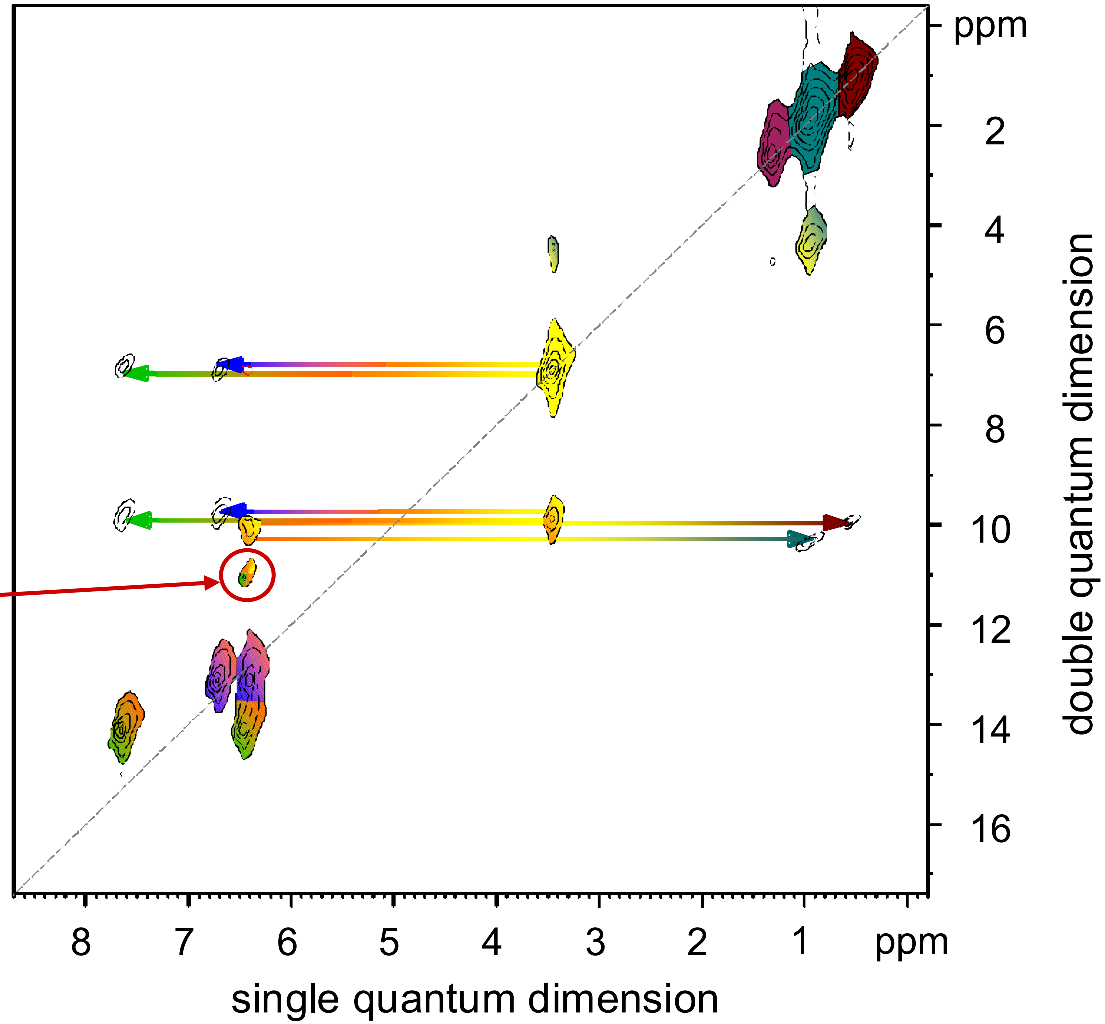

Dipolar couplings lead to more complicated realy behavior than J-coupling

# Multi-Spin Coherences: 4 Spin 2 Quantum

## 4 spin 2 quantum coherences

$$H_{4S2Q} = a_{ijkl} I_i^+ I_j^+ I_k^+ I_l^- + a_{ijkl}^* I_i^- I_j^- I_k^- I_l^+$$

$(I_A^+ I_C^- I_C^+ I_D^+ + I_A^- I_C^+ I_C^- I_D^-)$ – coherence

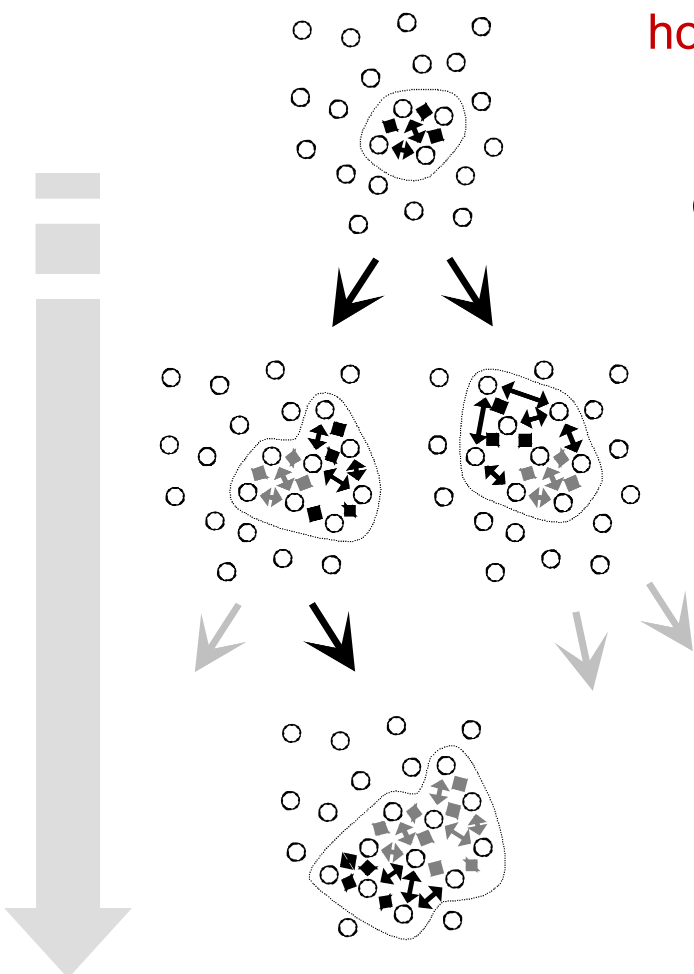



Multi-spin DQ coherences can be observed, but are hard to analyse.

# Conclusions for $^{1}H$ DQ NMR Spectroscopy

- High resolution DQ spectra under fast MAS can be obtained using appropriate recoupling sequences.
- DQ build-up behavior and DQ spinning sideband pattern provide quantitative information about dipolar couplings.
- Even though, multi-spin effects are observed, a carefull 2-spin analysis provides reasonable dipolar coupling values.
- In favorable cases, multi-spin effects can be analyzed and additional information can be obtained.
- DQ relay intensities due to dipolar couplings are harder to analyze than those due to J-couplings.

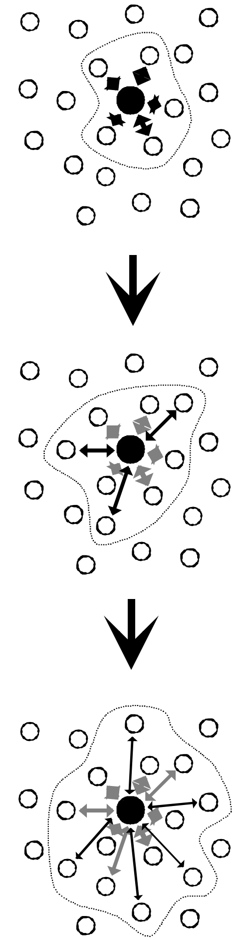
# How dipolar interactions "explore" space



approaching incoherent diffusive processes

homonuclear case:

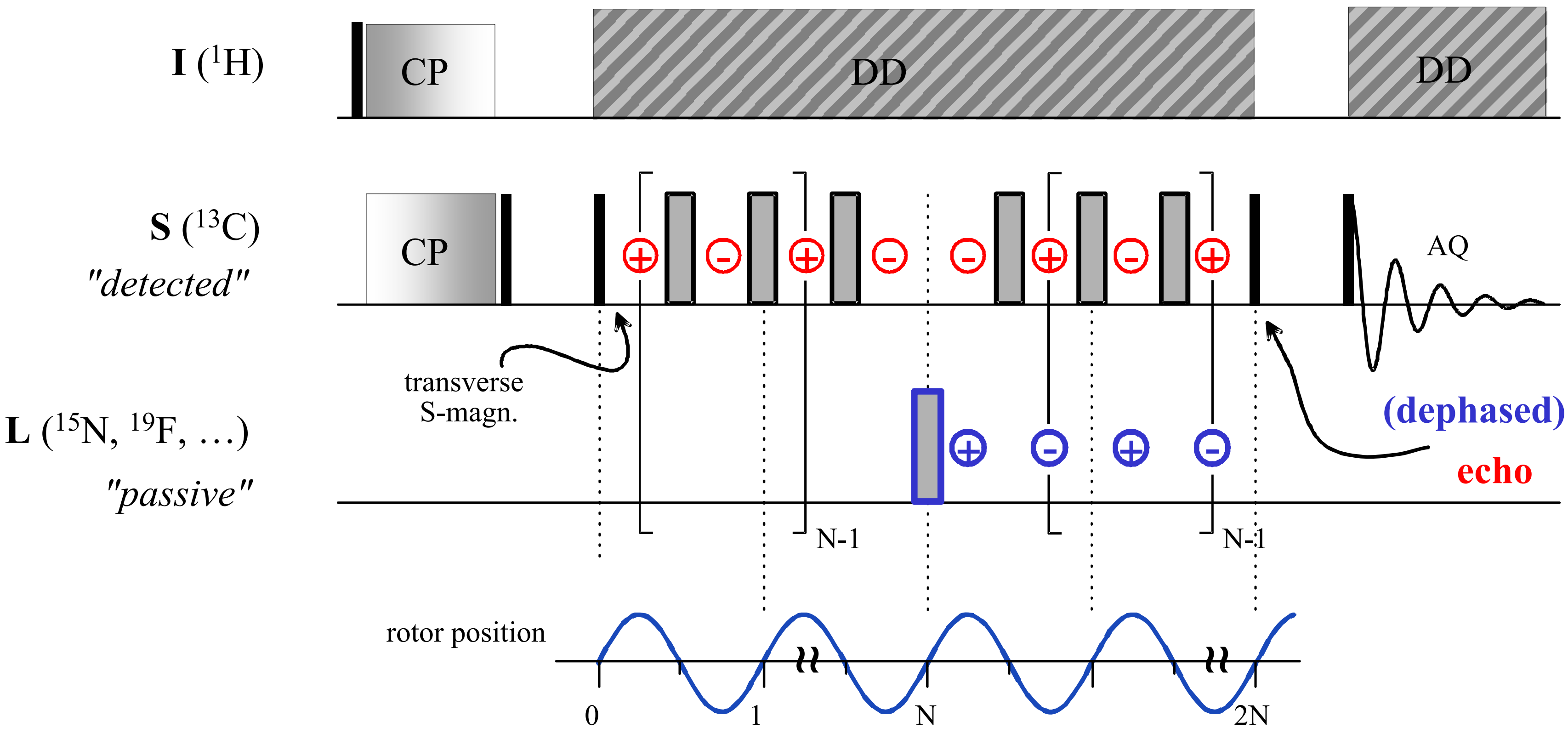
random walk characteristics, delocalized



heteronuclear case:

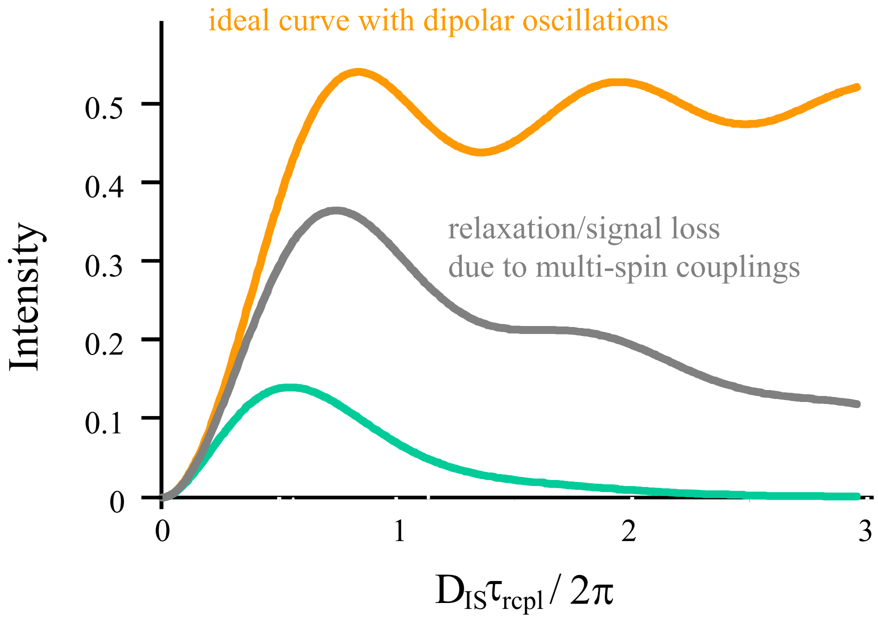
well-localized probing of the $^{13}C$ environment

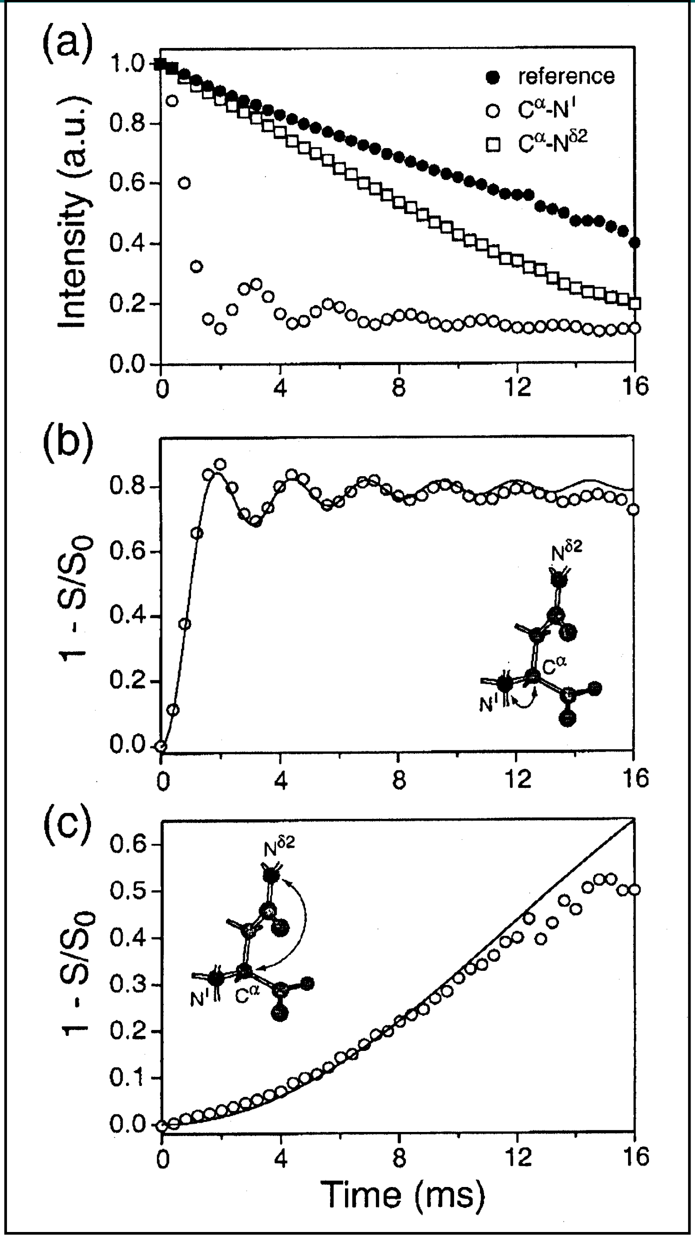
# Rotational Echo Double Resonance (REDOR)




$$\mathbf{S}_Y \xrightarrow[2N\tau_R \cdot \mathbf{S}_Z\mathbf{L}_Z]{1^{st}\text{ half:}} \begin{matrix} \mathbf{S}_Y \cos(N\Phi) \\ -2\mathbf{S}_X\mathbf{L}_Z \sin(N\Phi) \end{matrix} \xrightarrow[2N\tau_R \cdot \mathbf{S}_Z\mathbf{L}_Z]{2^{nd}\text{ half:}} \mathbf{S}_Y\left[\cos^2(N\Phi) \pm \sin^2(N\Phi)\right] = \begin{cases} \mathbf{S}_Y \\ \mathbf{S}_Y \cos(2N\Phi) \end{cases}$$

# Internuclear distances from REDOR curves




Experiments in Asparagine

**Table 1.** Internuclear Distances in [U-$^{13}$C,$^{15}$N]Asparagine

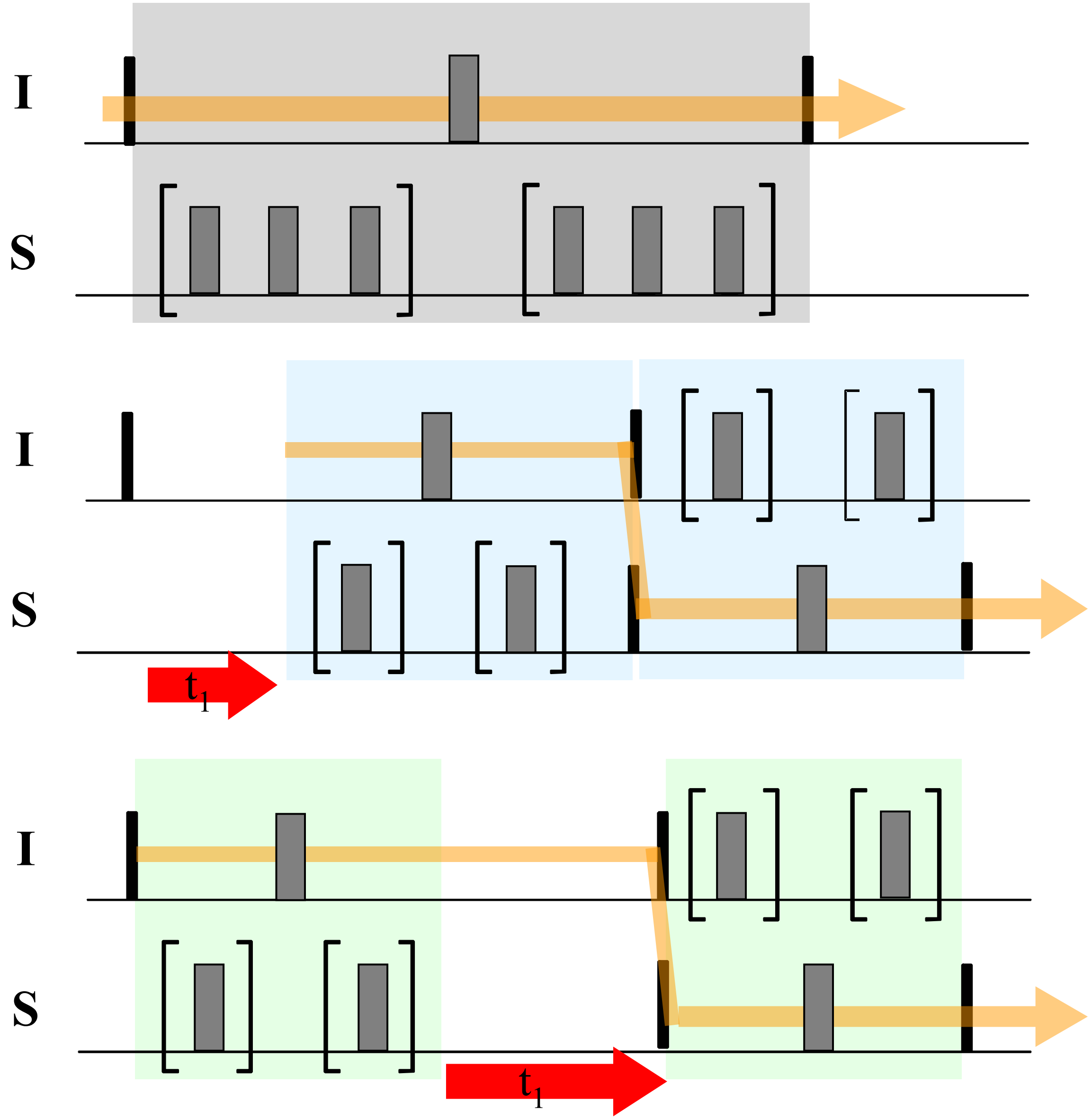
| atoms[a] | | $r_{C-N}$ (Å) NMR[b] | $r_{C-N}$ (Å) neutron[c] |
|---|---|---|---|
| N′ | $C^{\alpha}$ | 1.50 ± 0.02 | 1.49 |
| | $C^{\beta}$ | 2.49 ± 0.02 | 2.48 |
| $N^{\delta 2}$ | $C^{\alpha}$ | 3.58 ± 0.20 | 3.75 |
| | $C^{\beta}$ | 2.44 ± 0.02 | 2.42 |

# Coherent polarisation transfer

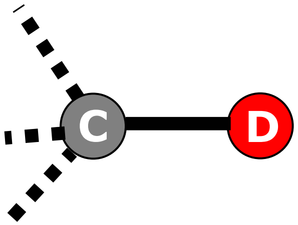
REDOR scheme

Heteronuclear correlation (SQ-SQ) via transferred echo double resonance (TEDOR)

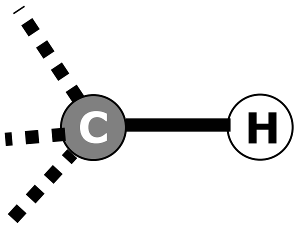
Heteronuclear single-quantum correlation (HSQC) via recoupled polarisation transfer (REPT)



# From deuterons to $CH_n$ groups

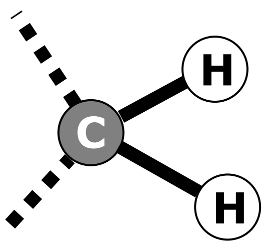


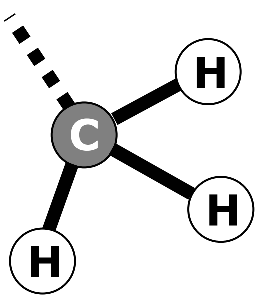

Selectively placed **deuterons**
as probes for molecular dynamics
(quadrupole coupling of spin-1 nucleus)




Regular **$CH_n$** groups

- use of dipole-dipole coupling between C and H
- no additional synthetic effort
  - ▶ no selective placement of probing nucleus
  - ▶ no isotopic enrichment
- assignment of dynamics by $^{13}C$ chemical shifts
- handling of CH, $CH_2$ and $CH_3$ groups
- interferences of multiple C-H couplings
- decoupling from surrounding $^1H$

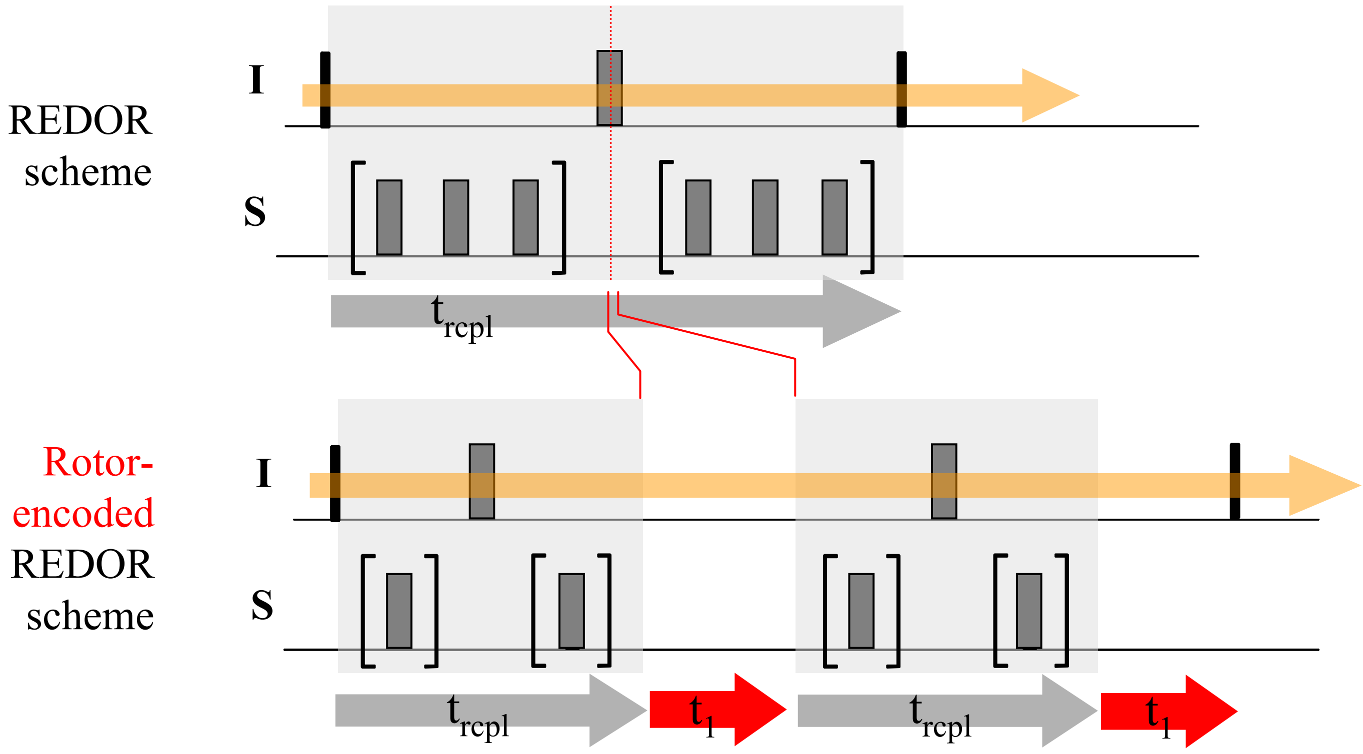


# Signal build-up versus rotor-encoding

Two alternative concepts for measuring recoupled interactions:

- following the signal intensity as a function of the recoupling time (resulting in build-up or dephasing curves)
- recording rotor-encoded signal (resulting in MAS sideband patterns)

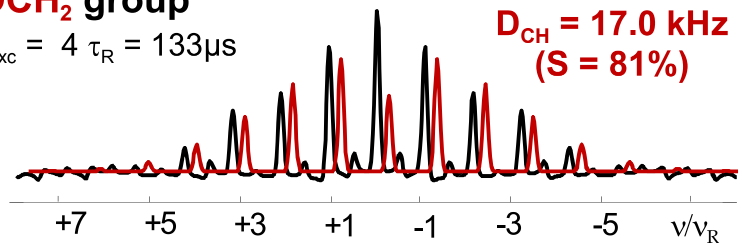


# Cylindrical self-assembly of dendritic sidegroups (I)

**REREDOR**

**$OCH_2$ group**

$\tau_{exc}$ = 4 $\tau_R$ = 133µs




**$OCH_2$ group**

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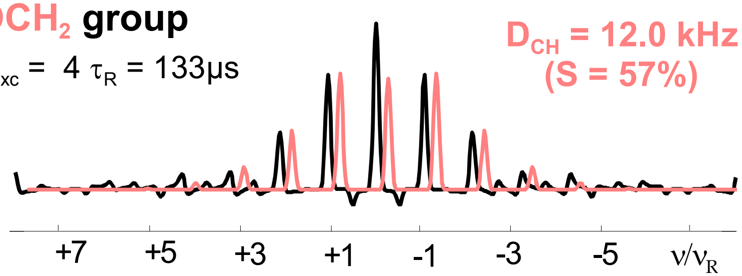
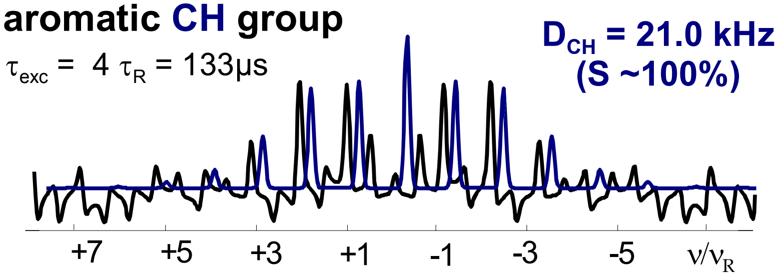
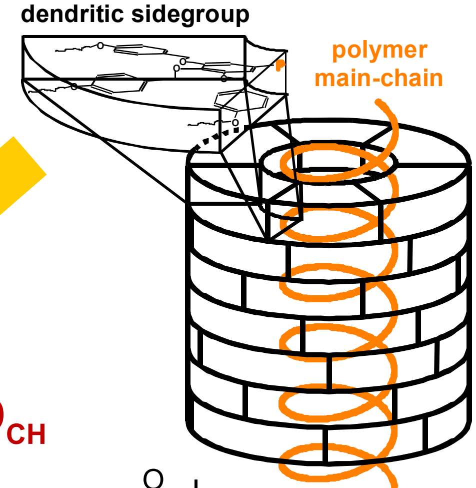


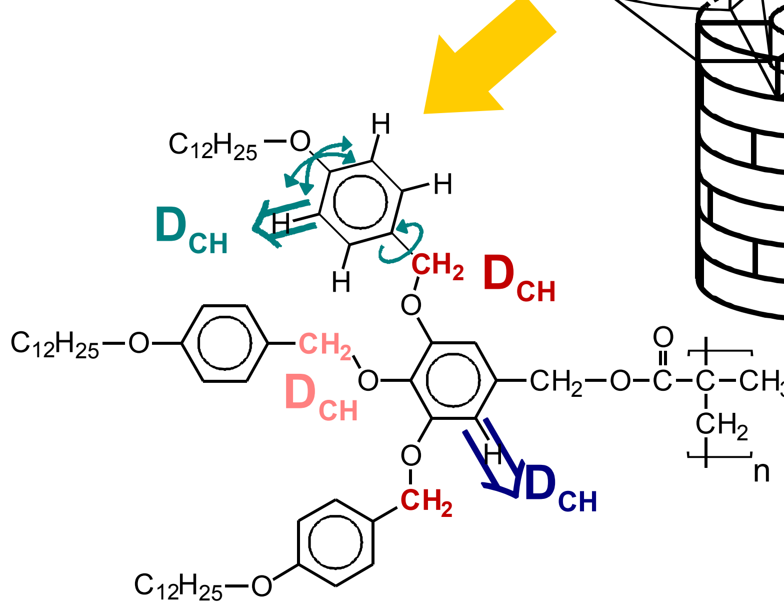

**aromatic CH group**

$\tau_{exc}$ = 4 $\tau_R$ = 133µs




Materials:
V. Percec

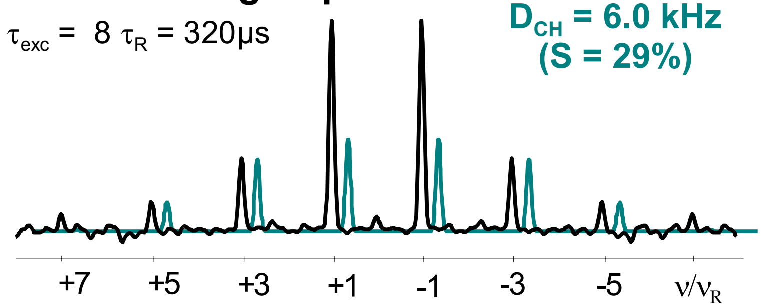


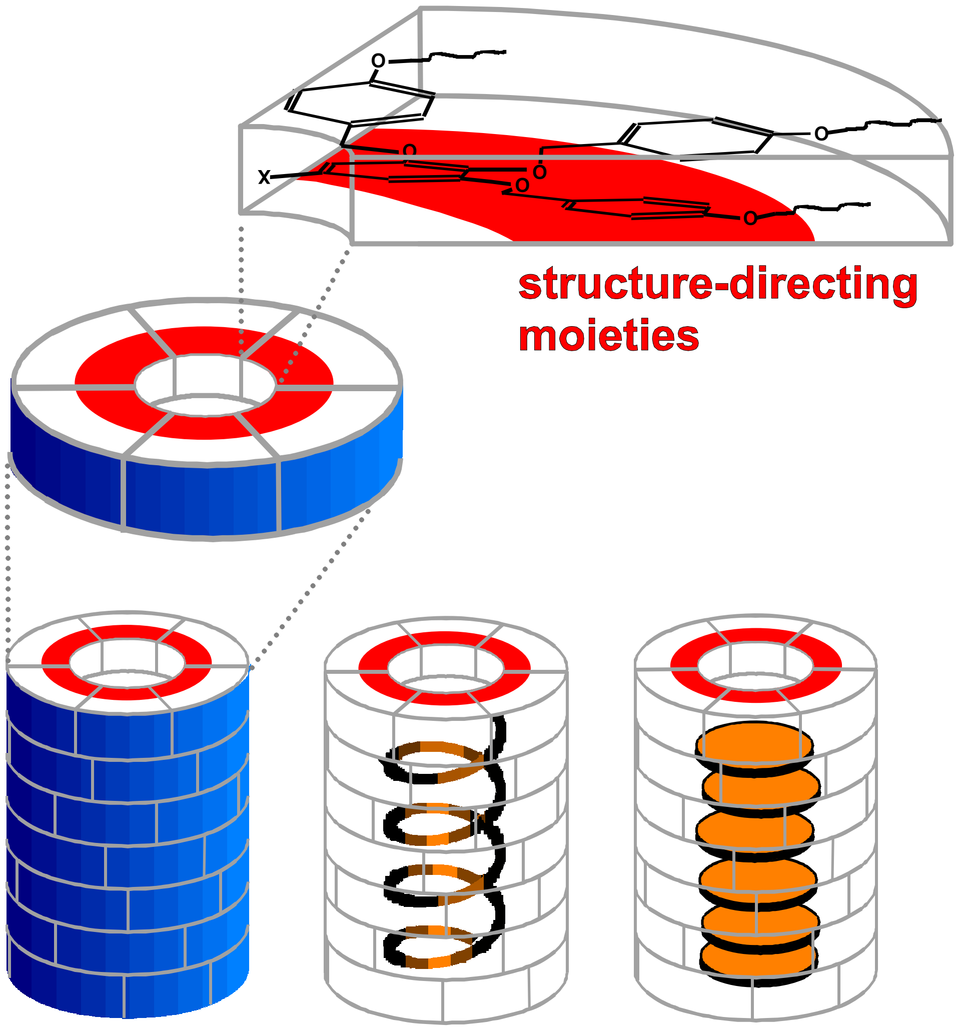

**REPT-HDOR**

**aromatic CH group**

$\tau_{exc}$ = 8 $\tau_R$ = 320µs



# Cylindrical self-assembly of dendritic sidegroups (II)




dendritic
sidegroup

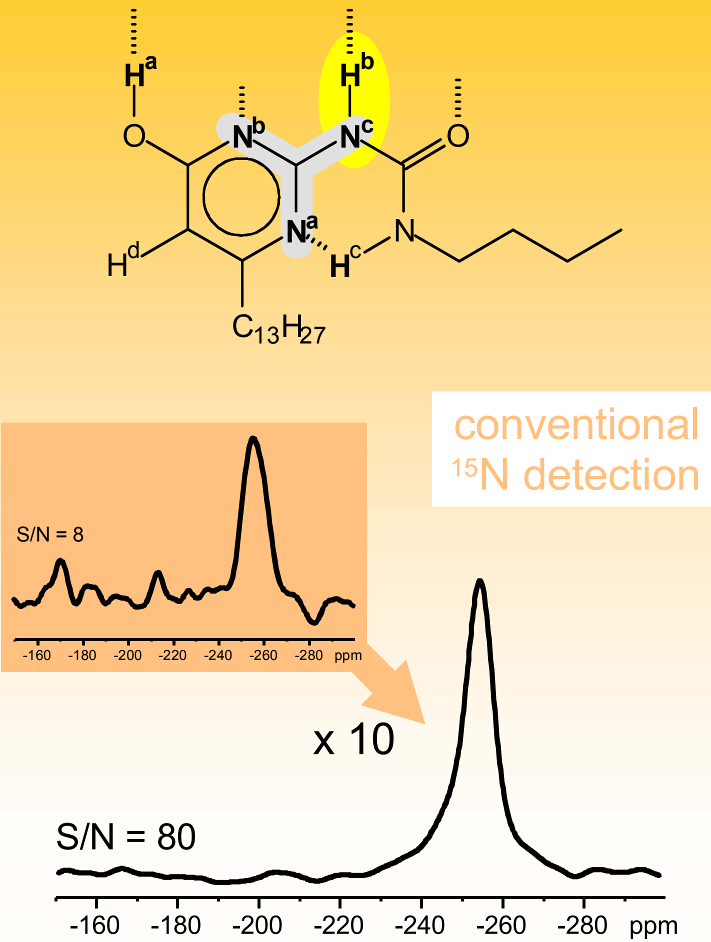
cylindrical assembly
independent of molecule
in the center (chain, discs)

polymer chain

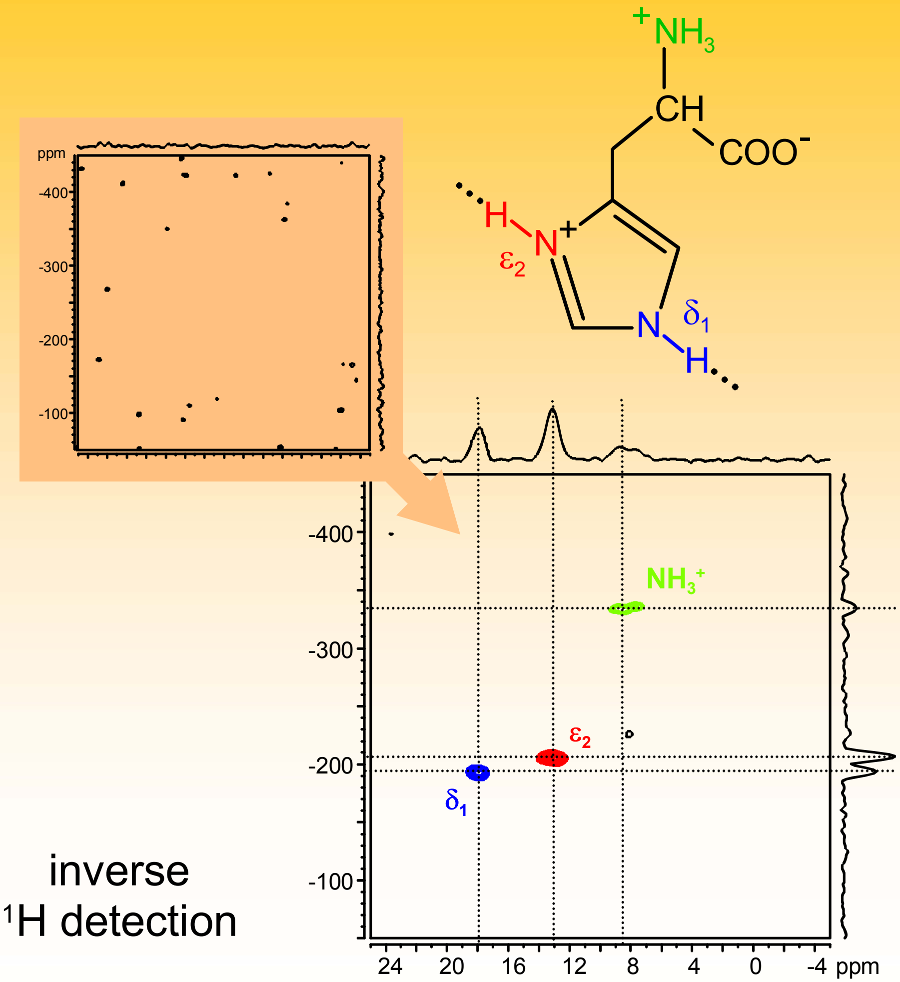
stack of
aromatic molecules

# Sensitivity enhancement by inverse ($^{1}H$) detection

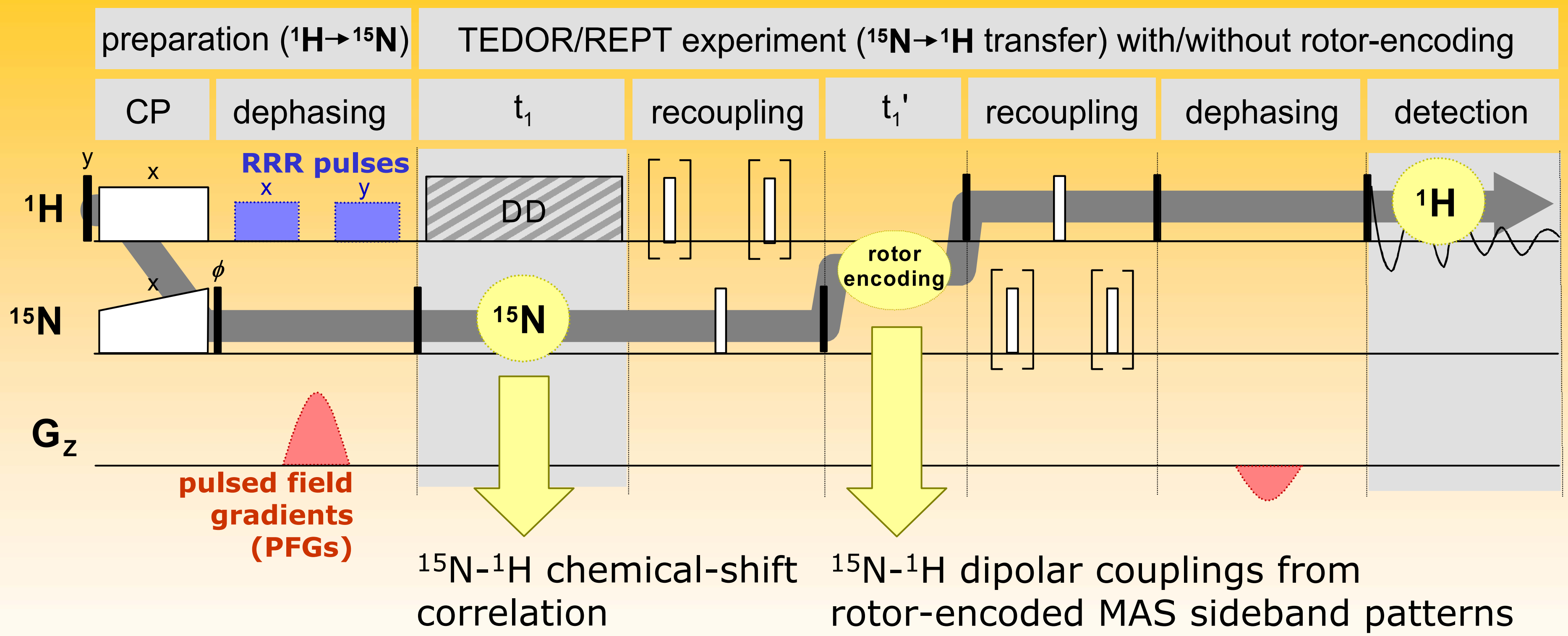
33% $^{15}N$-enriched




0.35% $^{15}N$ (natural abundance)



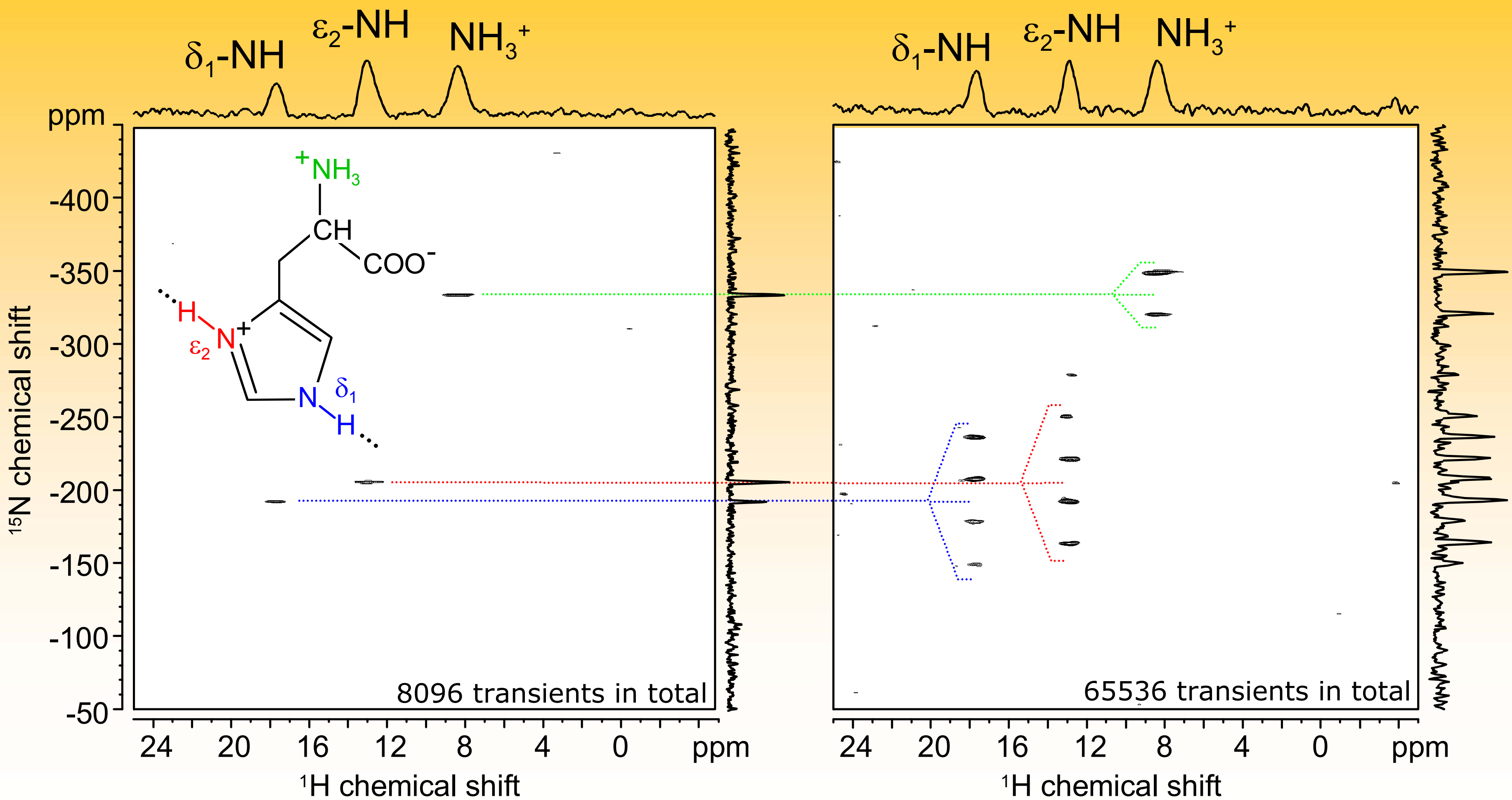
# Natural-abundance $^{15}N$-$^{1}H$ correlation NMR



# NH···O hydrogen bonds in L-histidine

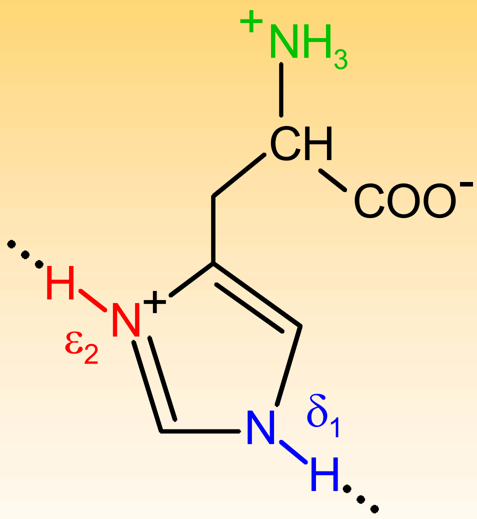
2D chemical shift correlation:

2D chemical shift correlation plus NH coupling information:

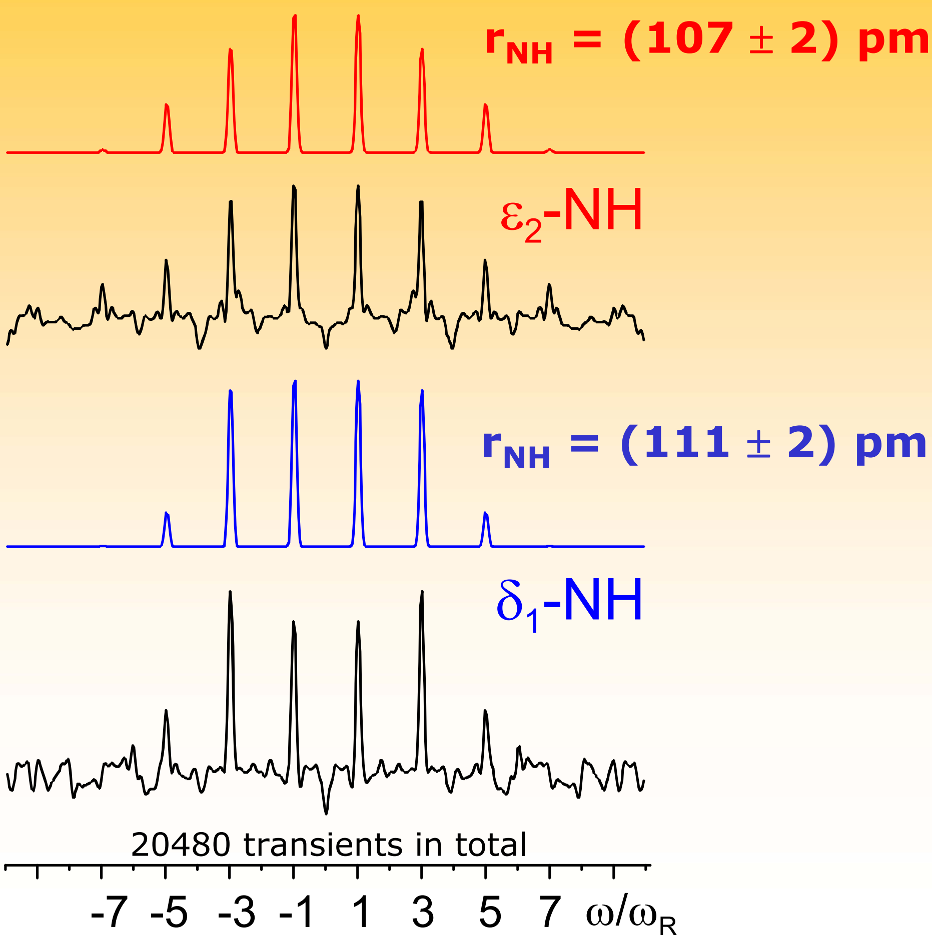



700 MHz $^{1}H$ frequency, 30 kHz MAS, ~ 15 mg sample.

# N-H bond stretching due to hydrogen bonding




NH dipolar coupling from rotor-encoded spinning sideband pattern:



# Conclusions for heteronuclear methods

- Similarities of homo- and heteronuclear are sufficient to pursue the strategies known form $^{1}$H DQ NMR.
- Rotor encoding can be used to measure heteronuclear dipolar couplings with REDOR based techniques.
- The larger spread of chemical shifts of rare low $\gamma$ nuclei provides site selective information about molecular dynamics.
- $^{1}$H detection of low $\gamma$ nuclei can increase the sensitivity and NMR measurements in natural abundance become feasible.

# NMR on supramolecular systems

**Homonuclear double-quantum measurements**

- Dipolar couplings and order parameters in LC system — *Michael Neidhöfer*
- Analysis of $^{1}H$ DQ relay — *Robert Graf*

**Heteronuclear method development in solid-state NMR**

- $^{13}C$ site-resolved dynamics of $CH_n$ groups — *Kay Saalwächter*
- natural abundance $^{15}N$-$^{1}H$ correlation spectroscopy — *Ingo Schnell*
- N-H distance measurements

**Investigations of complex systems**

- Dynamics and self-assembly of dendritic sidegroups — *Almut Rapp*