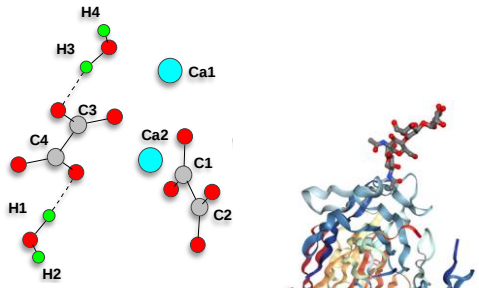
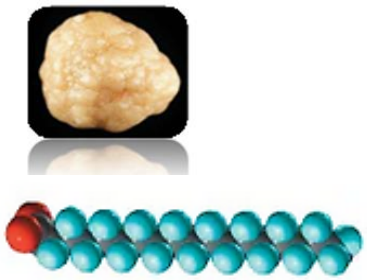
3D MAS MRI of Solid State Pathological Natural Samples

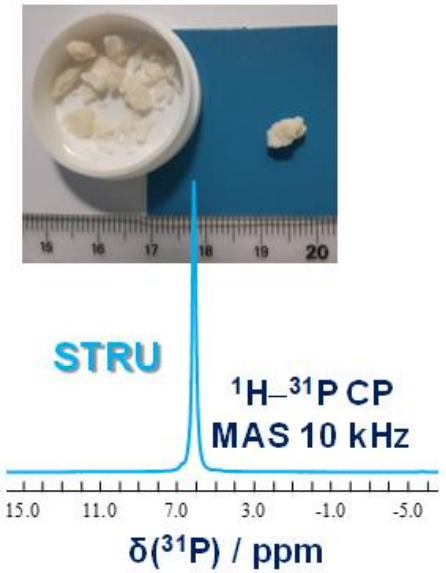
Y. Hammami[1], W.-C. Teh[1], V. Sarou-Kanian[2], F. Fayon[2], C. Bonhomme[1]

[1]Sorbonne Université, Paris, France

[2]CEMHTI, Orléans, France







Alpine Conference on Magnetic Resonance in Solids
14-18 September 2025, Chamonix-Mont-Blanc, France.

Pathological calcifications (kidney stones, KS)

Tenon hospital, Paris

Coll.: M. Daudon, E. Letavernier, D. Bazin

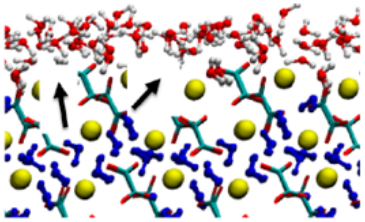
a major societal/health problem worldwide
(in France, related costs *per year* > 800 million €)

an intrinsic structural/chemical complexity

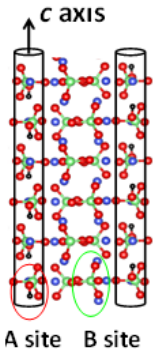
- minerals
- fatty acids, triglycerides, proteins
- … ↔ Hybrid organic/inorganic materials

Ca Oxalates (mono-, di-, tri-hydrate)
Ca Phosphates (hydroxyapatite, HAp)

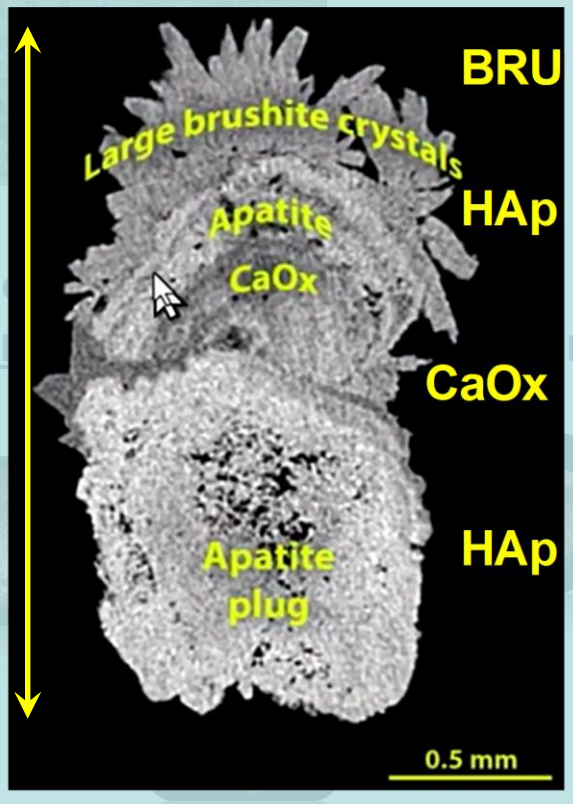
CaOx



HAp



Pathological calcifications (kidney stones, KS)



kidneystones.
uchicago.edu

strong structural / morphological *heterogeneity*:

BRU: $CaHPO_4$

HAp: $Ca_{10}(PO_4)_x(CO_3)_{(3x-y)/2}(OH)_y$

CaOx: $CaC_2O_4.H_2O$

Pathological calcifications (kidney stones, KS)

Tenon hospital, Paris

Coll.: M. Daudon, E. Letavernier, D. Bazin

towards new *ex vivo* characterization methods

- ► diagnosis
- ► prevention

a major societal/health problem worldwide
(in France, related costs *per year* > 800 millions €)

an intrinsic structural/chemical complexity

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- … ↔ Hybrid organic/inorganic materials

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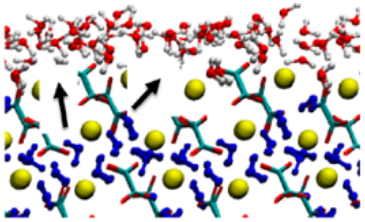
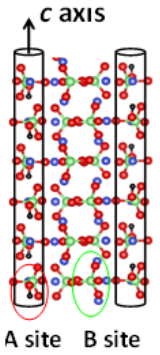
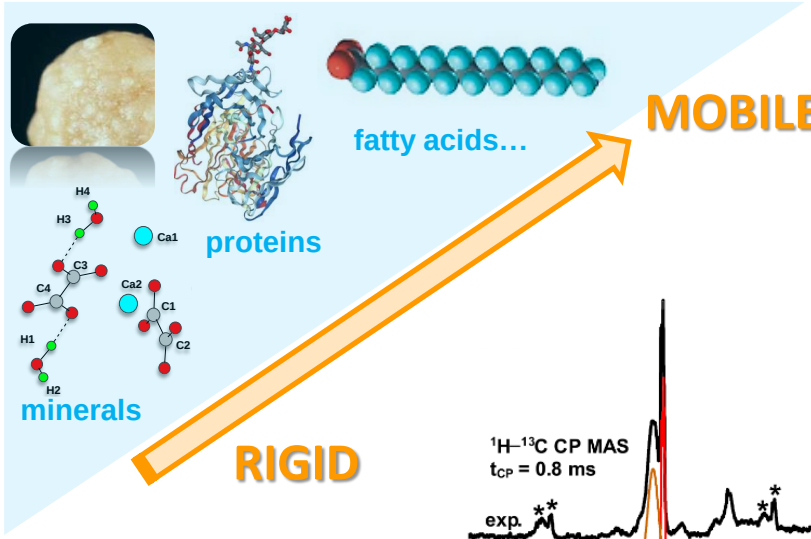


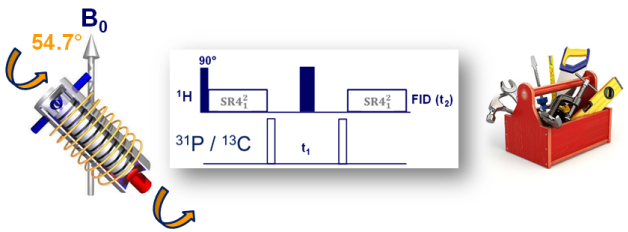
HAp



⟶ NMR / DNP / crystallography

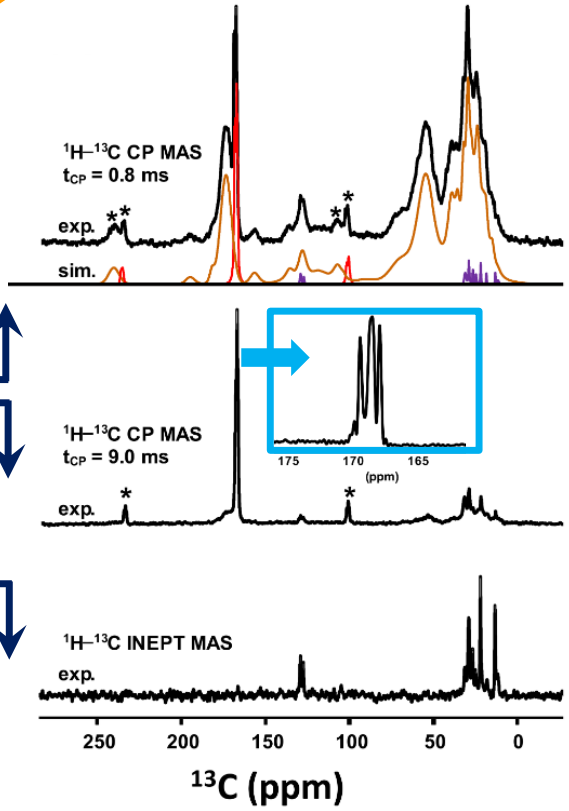
Structure, interfaces and local dynamics in KS



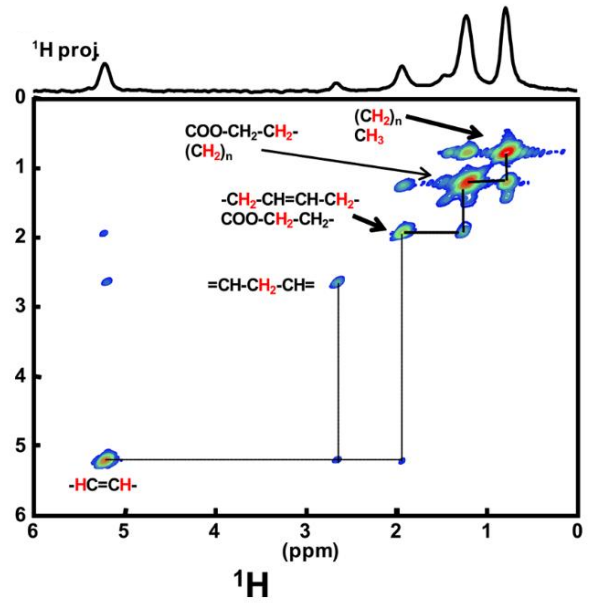


^{13}C CP MAS
through *space*

^{13}C INEPT MAS
through *bond*



^{1}H, *N.A.* ^{13}C NMR, ^{31}P, *N.A.* ^{43}Ca



^{1}H–^{1}H DQF COSY MAS NMR
through *bond*

C. Leroy, C. Gervais, D. Laurencin, C. Bonhomme *et al.*, *Magn. Reson.*, 2021

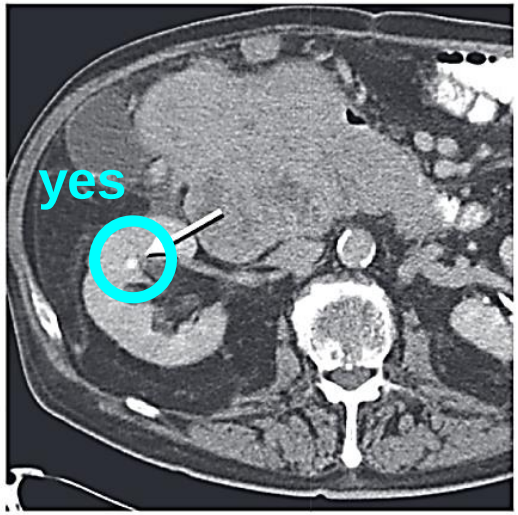
tribute Britannica, Sinobiol

Imaging of kidney stones?

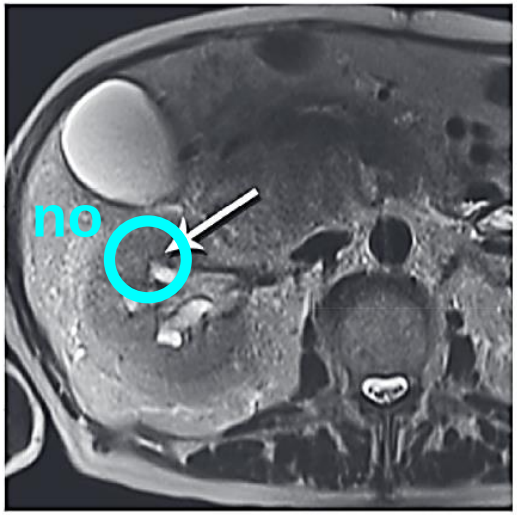
► **state of the art (@ hospitals):**
non-contrast & dual-energy μ–Computed Tomography (μ–CT)

► **what about (standard) MRI?**

"… Using standard MRI sequences, stones appear as a *non-specific void…*"
(Brisbane *et al.*, Nat. Rev. Urol., 2016)



μ–CT



MRI

► **μ–CT drawbacks:**

level of hydration of CaOx?

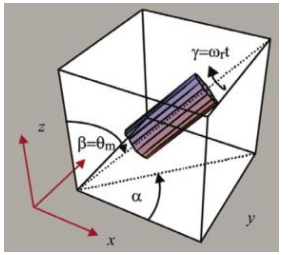
drug induced KS?

mobile gel phases?

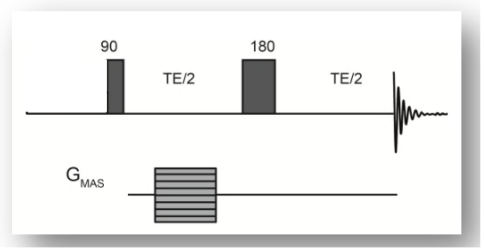
non-radio opaque phases?

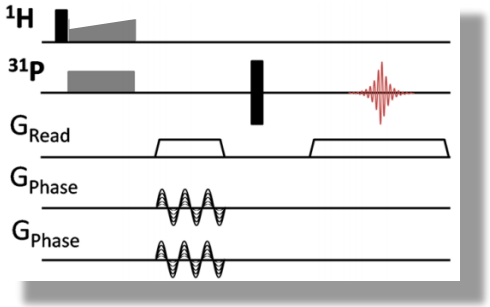
E.-S.H. Ibrahim, R.A. Poley, W.E. Haley, 2016

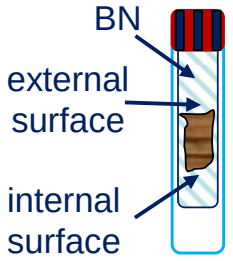
- **Magic Angle Spinning MRI (*ex vivo*)**



  - ↘ **Chemical Shift Imaging**
  - ↘ **3D ^{1}H & ^{31}P imaging**







- **Perspectives for kidney stones MAS MRI**

SOLID STATE MRI

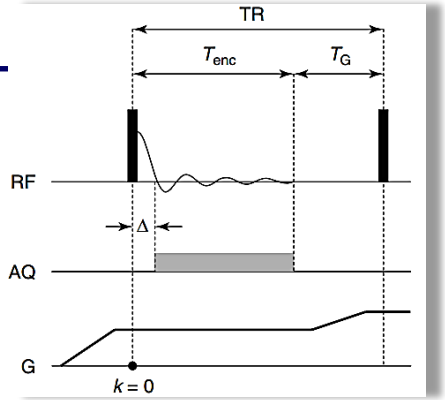
- strong anisotropies and magnetic susceptibility inhomogeneity
- "short" T_2* and T_2'
- loss of efficiency in spin and gradient echo sequences
- loss in sensitivity and resolution for *frequency* encoding (T_2*)

A first option: Zero Echo Time (ZTE)

SOLID STATE MRI

- strong anisotropies and magnetic susceptibility inhomogeneity
- "short" T_2* and T_2'
- loss of efficiency in spin and gradient echo sequences
- loss in sensitivity and resolution for frequency encoding (T_2*)

D.P. Madio, I.J. Lowe,
***Magn. Res. Med*., 1995**



"**BRUTE FORCE**" + **SHORT TIME acquisition** (ZTE, UTE, SWIFT…)

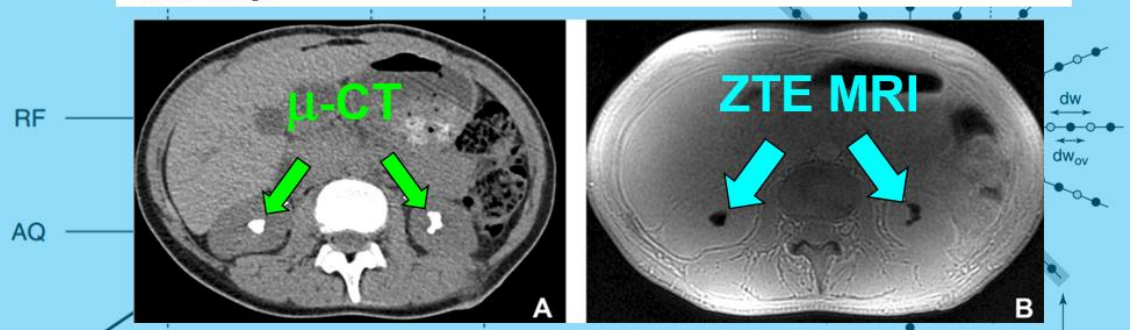
***ex vivo* & *in vivo* studies**

PAEDIATRIC

European Radiology

Zero-echo time MRI: an alternative method for the diagnosis of urinary stones in children **2025**

H. Nursun Ozcan[1*], Gozde Ozer[1], Hasan Serkan Dogan[2], Jale Karakaya[3], Berna Oguz[1], Serdar Tekgul[2] and Mithat Haliloglu[1]

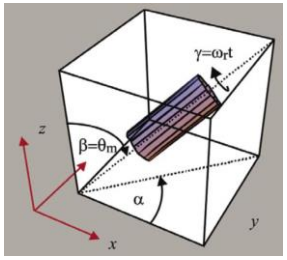


but: *large Gradient → large dispersion of signal…*

- **Magic Angle Spinning MRI (*ex vivo*)**

  - ↘ **Chemical Shift Imaging**

    - ↘ 3D ^{1}H & ^{31}P imaging



SOLID STATE MRI

- strong anisotropies and magnetic susceptibility inhomogeneity
- "short" T_2* and T_2'
- loss of efficiency in spin and gradient echo sequences
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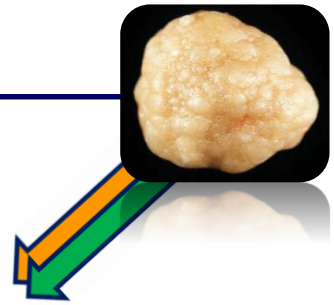
MAGIC ANGLE SPINNING + LINE NARROWING

- **Perspectives for kidney stones MAS MRI**



- **Magic Angle Spinning MRI (*ex vivo*)**

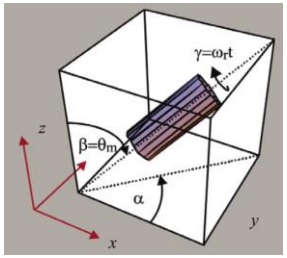
  - ↘ **Chemical Shift Imaging**

    - ↘ 3D ^{1}H & ^{31}P imaging

BRU + HAp **ORG**

SOLID STATE MRI

- ► strong anisotropies and magnetic susceptibility inhomogeneity
- ► "short" T_2* and T_2'
- ► loss of efficiency in spin and gradient echo sequences
- ► loss in sensitivity and resolution for frequency encoding (T_2*)



MAGIC ANGLE SPINNING + LINE NARROWING

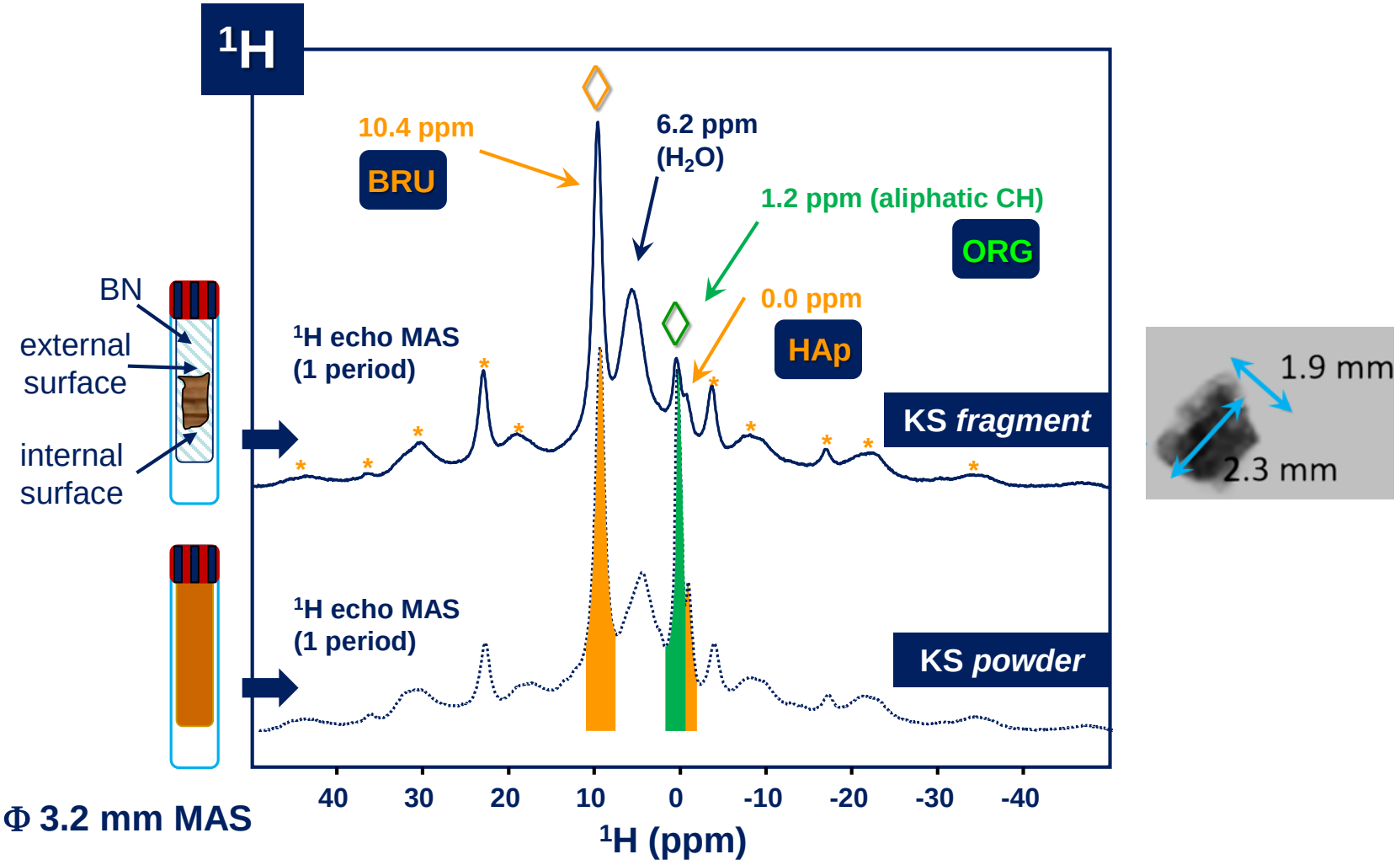
- **Perspectives for kidney stones MAS MRI**

Brushite and hydroxyapatite based kidney stones

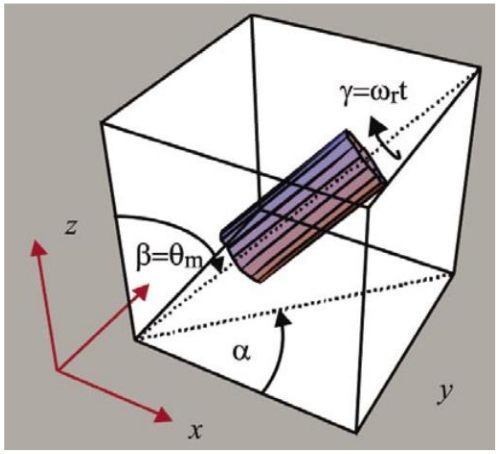
sample: N49888 **(Necker)** →

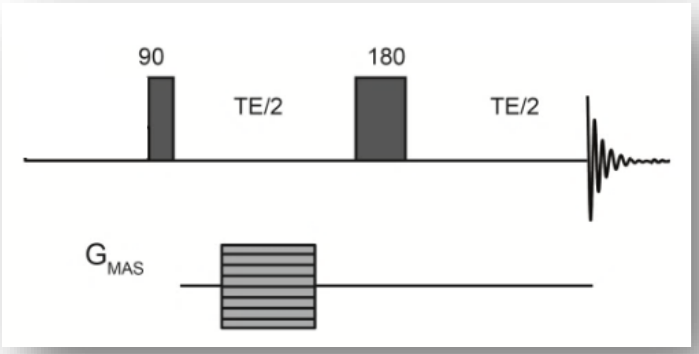
BRU: $CaHPO_4$ **HAp:** $Ca_{10}(PO_4)_x(CO_3)_{(3x-y)/2}(OH)_y$

ORG: organics



Chemical Shift Imaging (CSI)





see: Maudsley *et al*., 1983,
Pampel *et al*., 2006,
Sarou-Kanian, Fayon *et al*., 2015

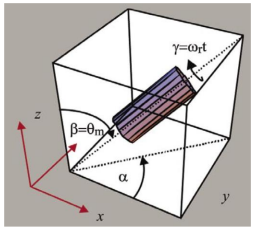
***spectral* dim.: direct**
***spatial* dim.: indirect**

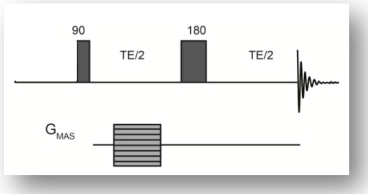
Bruker Micro-2.5 gradient
Φ 3.2 mm MAS

synchronization of gradients with MAS frequency

Coll.: V. Sarou-Kanian, F. Fayon, Orléans , France

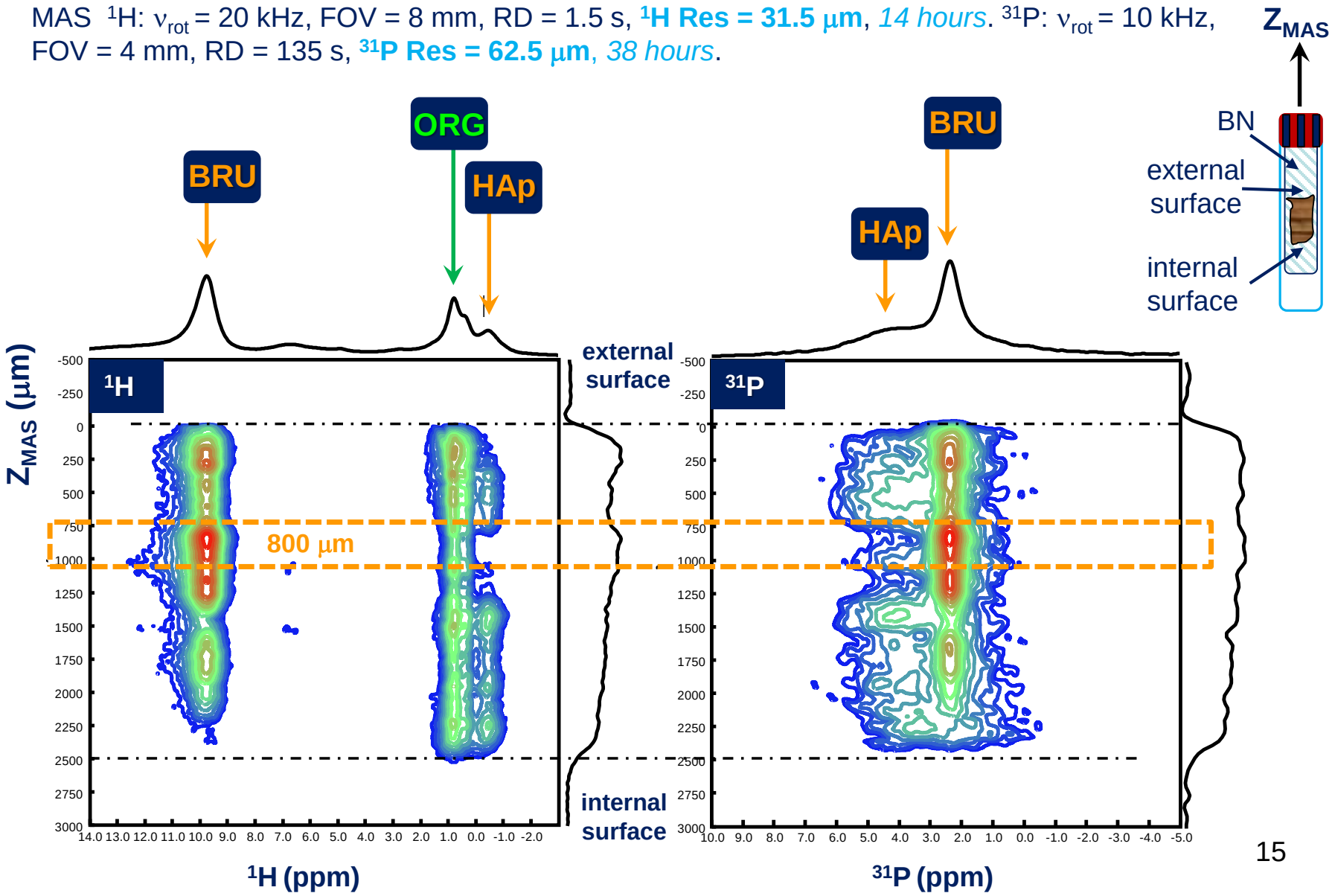
Chemical Shift Imaging (CSI)





First MAS images of kidney stones

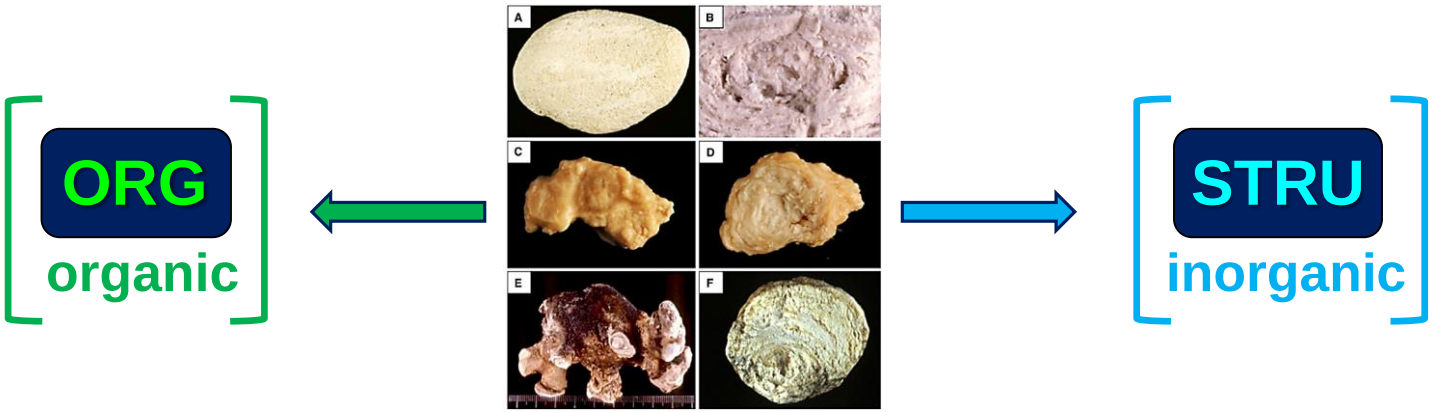
WB 750 MHz AVANCE III HD, 17.6 T. Bruker *Micro 2.5*. 2.5 G.cm^{-1}A^{-1} (60 A *per* axis). 3.2mm MAS ^{1}H: ν_{rot} = 20 kHz, FOV = 8 mm, RD = 1.5 s, **^{1}H Res = 31.5 µm**, *14 hours*. ^{31}P: ν_{rot} = 10 kHz, FOV = 4 mm, RD = 135 s, **^{31}P Res = 62.5 µm**, *38 hours*.



- **Magic Angle Spinning MRI (*ex vivo*)**

  ↘ Chemical Shift Imaging

  ↘ 3D ^{1}H & ^{31}P imaging



- Perspectives for kidney stones MAS MRI

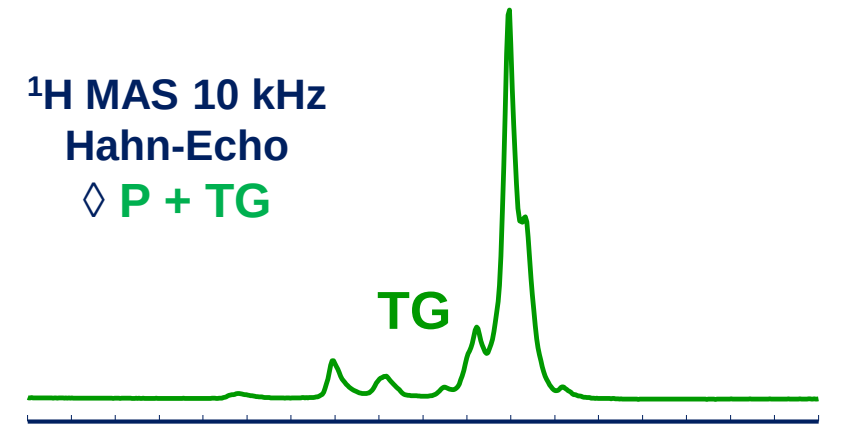
Organic based kidney stones

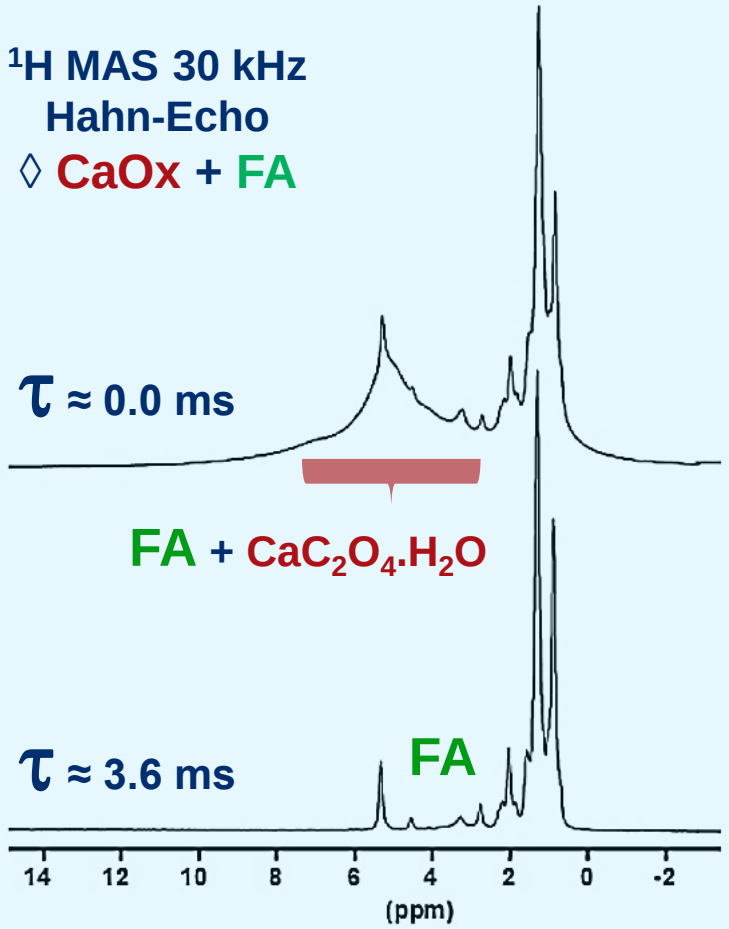
uric acid
ammonium urate
other urates
cystine
other purines (xantine…) + drugs + …

proteins (P)
triglycerides (TG)
fatty acids (FA)

→ a large range of MOBILITY (T_2')

organic sample : **T86891** (Tenon)
60% **proteins (P)** / 30% **triglycerides (TG)**
10% apatite (averaged FTIR data)





C. Leroy, C. Gervais, D. Laurencin, C. Bonhomme *et al.*, *Magnetic Reson.*, 2021

3D ^{1}H MAS images of organic based kidney stones

organic sample : **T86891** (Tenon)
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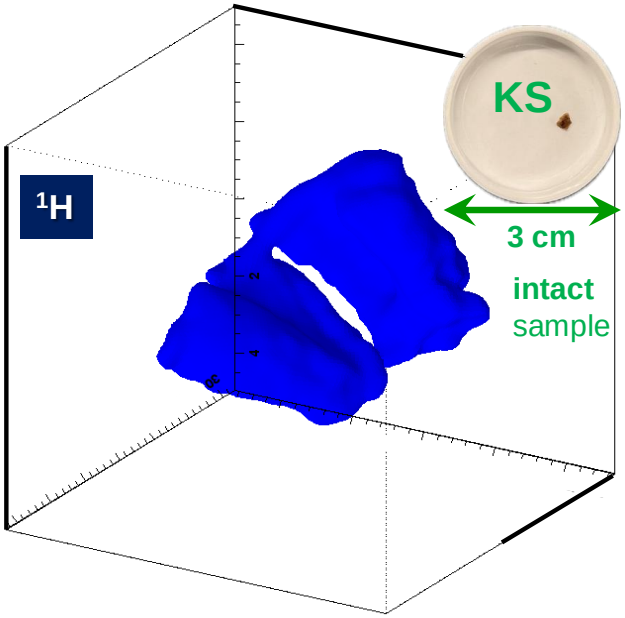
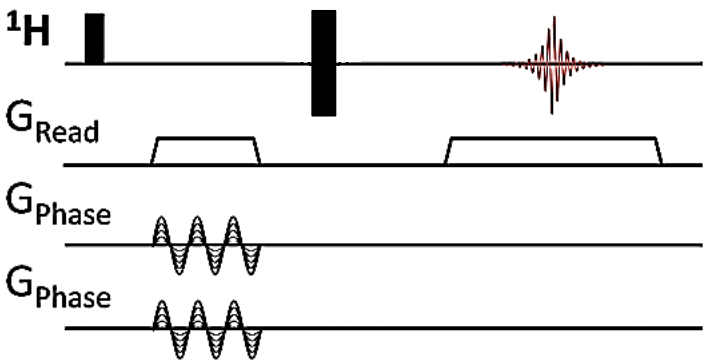
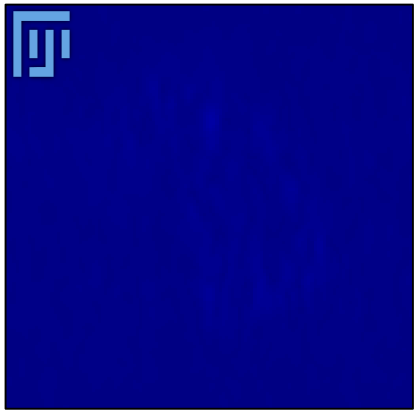
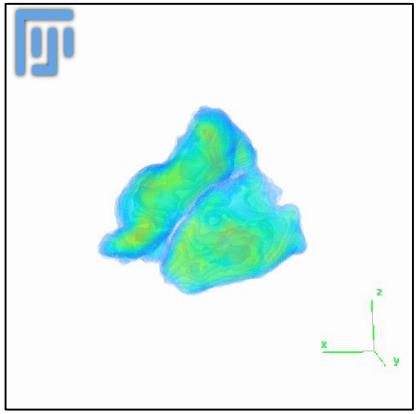


3D ^{1}H MAS MRI (10 kHz)
FOV *4x4x4 (mm)*
40x75x75 (µm)
15 hours



***in*: M. Yon, V. Sarou-Kanian, F. Fayon *et al*., *Sci. Rep*., 2017**

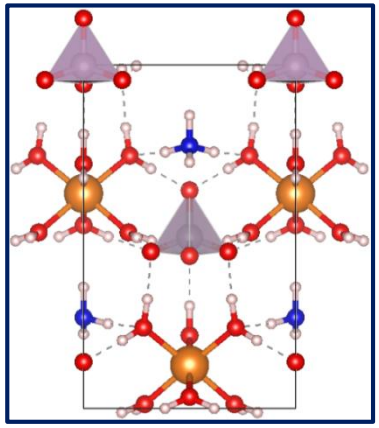




FIJI 3D reconstruction

Struvite based kidney stones

STRU: $NH_4MgPO_4.6H_2O$



► **urease-producing bacteria**

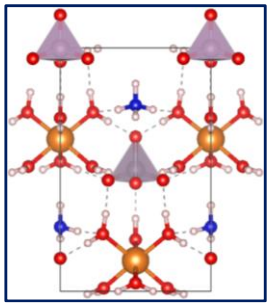
► **urinary tract infection**

25% of staghorn calculi (10% all types)

Flannigan *et al*., *Nat. Rev. Urol*., 2014 & *Can. Urol. Assoc*., 2018

Struvite based kidney stones

STRU: $NH_4MgPO_4.6H_2O$



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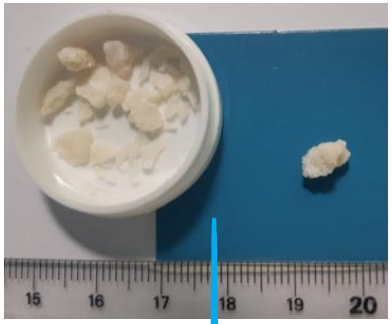
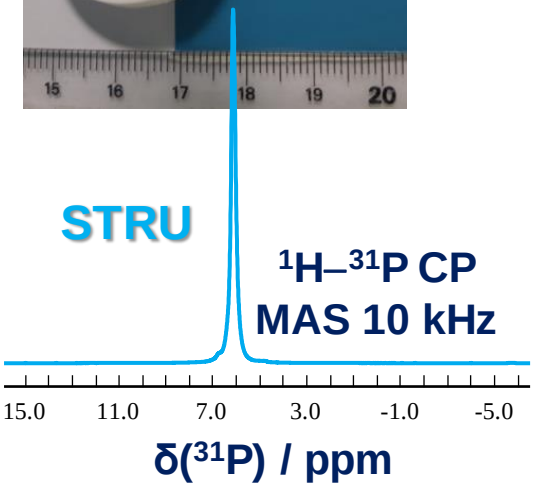
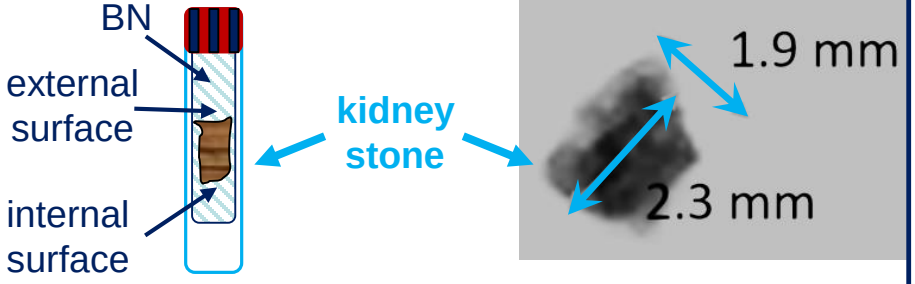




sample: **T83936 (Tenon)**
87% **struvite (STRU)** / 10% apatite / 3% proteins
(FTIR *averaged* data)

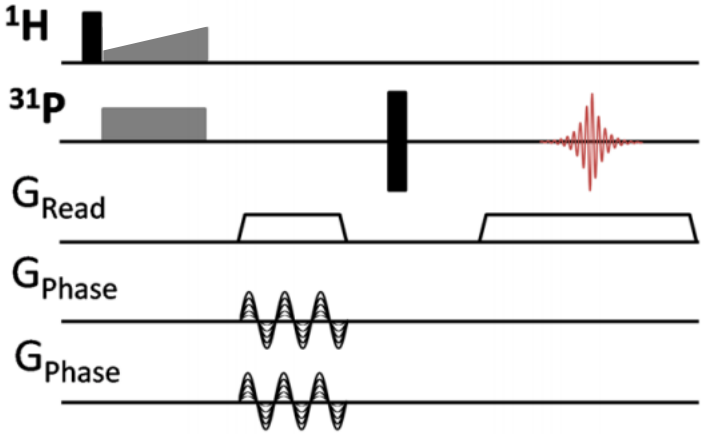


Φ 3.2 mm MAS

Bruker Micro-2.5 gradient

3D ^{31}P CP MAS images of struvite based kidney stones

mineral sample: **T83936 (Tenon)**
87% **struvite (STRU)** / 10% apatite / 3% proteins
(FTIR *averaged* data)



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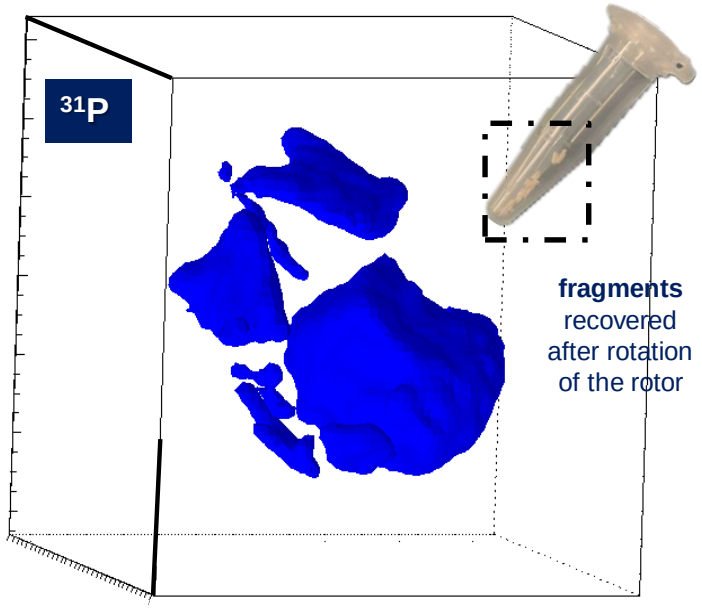
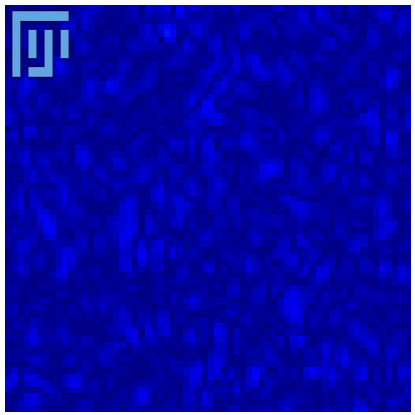
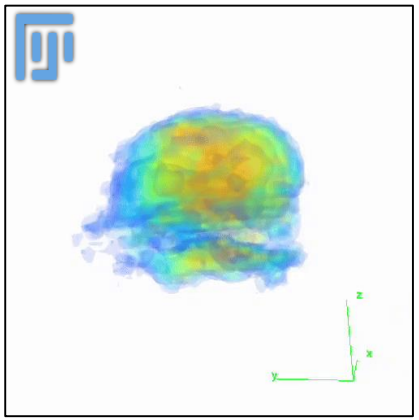


3D ^{1}H–^{31}P MAS MRI (10 kHz)
FOV *5x4x4mm*
50x150x150 (µm)
14 hours





FIJI 3D reconstruction

Conclusions and perspectives

- MAS MRI: a new tool for kidney stones imaging
- Numerous contrasts: T_1, T_2', T_2*, $T_1\rho$, t_{CP}…
- Access to localized chemical information in complex architectures

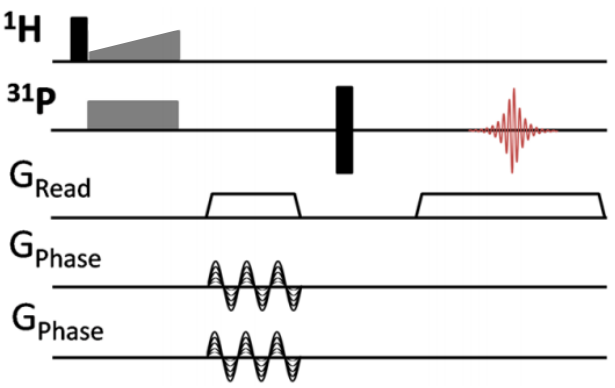
► μ–CT drawbacks:

level of hydration of CaOx?

drug induced KS?

mobile gel phases?

non-radio opaque phases?



2D-3D MAS MRI

Many thanks to:

Y. Hammami, W.-C Teh (Paris, France)

V. Sarou-Kanian, F. Fayon (Orléans, France)

M. Daudon, E. Letavernier, D. Bazin (Tenon Hospital, Paris, France)

Conclusions and perspectives

- **MAS MRI: a new tool for kidney stones imaging**
- **Numerous contrasts: T_1, T_2', T_2*, $T_1\rho$, t_{CP}…**
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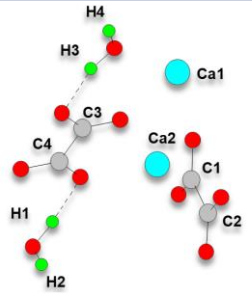
► **MRI *sensitivity* is key for *spatial resolution*…**

2025

Ultra-low Temperature DNP for Ultra-Fast NMR and High-Resolution Microimaging in Solids

Gaël DE PAËPE *(CEA, Grenoble)*

Franck FAYON *(CEMHTI, Orléans)*
Christian BONHOMME *(SU, Paris)*



towards N.A. ^{13}C NMR!