

# Cookies #4

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09-20-18



# QUARKS

u	s	t
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d	c	b
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# LEPTONS

e	$\mu$	$\tau$
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$\nu_e$	$\nu_\mu$	$\nu_\tau$
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# QUARKS

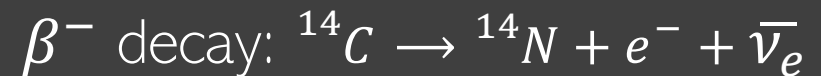
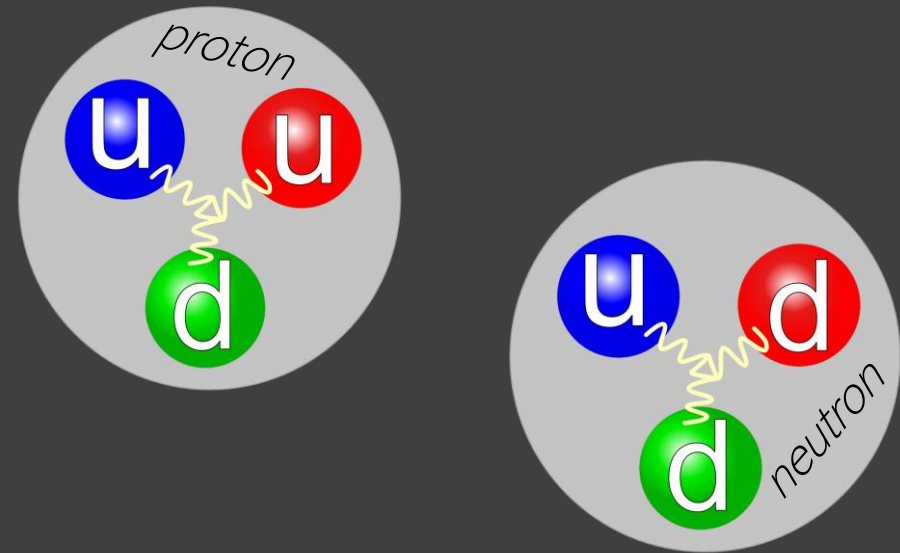
u	s	t
d	c	b

# LEPTONS

e	$\mu$	$\tau$
$\nu_e$	$\nu_\mu$	$\nu_\tau$

Everyday matter is made of  
1<sup>st</sup> generation particles

e.g.



# QUARKS

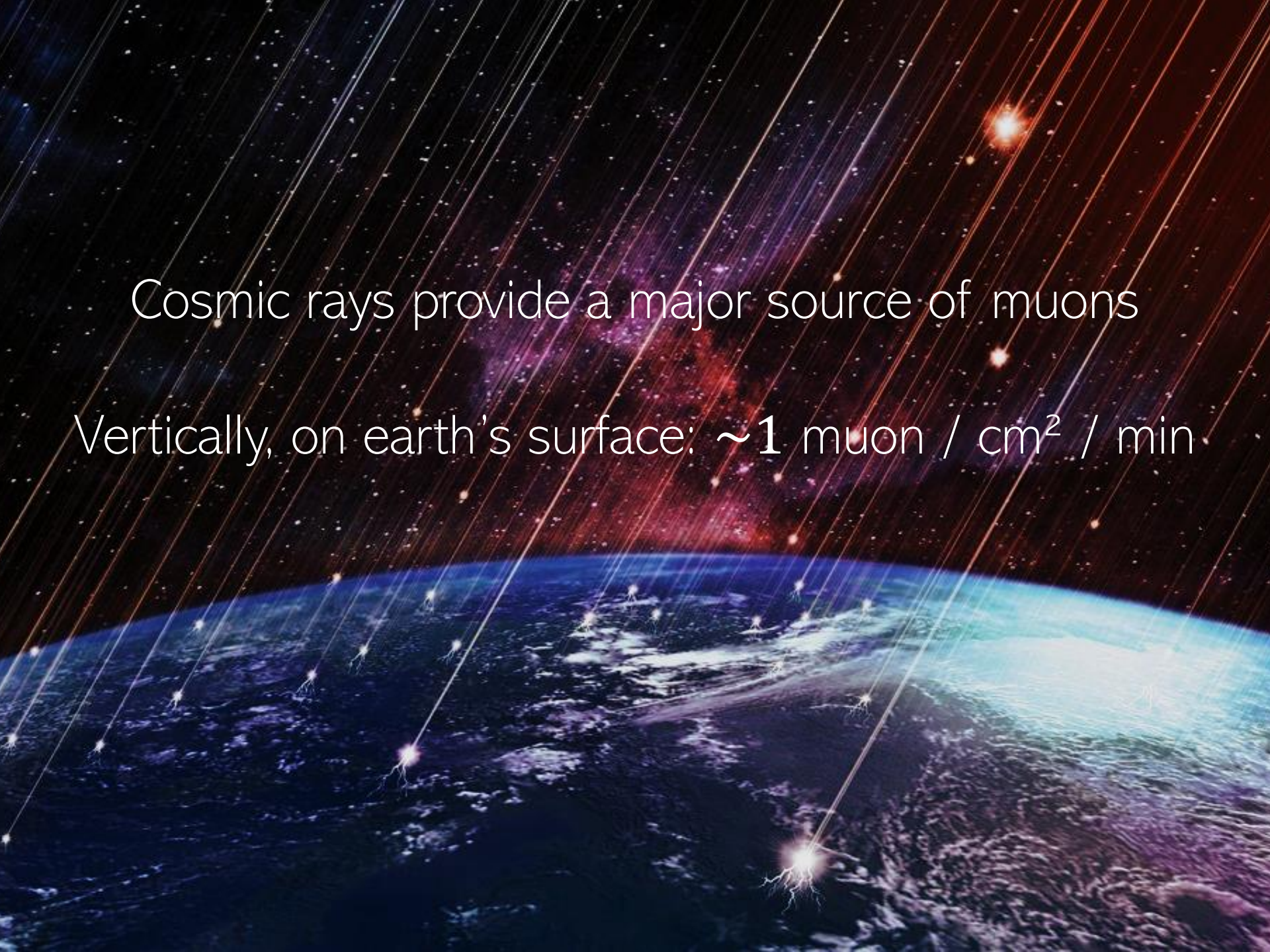
u	s	t
d	c	b

# LEPTONS

e	$\mu$	$\tau$
$\nu_e$	$\nu_\mu$	$\nu_\tau$

The 2<sup>nd</sup> generation exception:  
the **muon**

What can be learnt from  
firing these exotic particles  
into magnetic materials ?

A composite image of Earth from space, showing the blue and white horizon of the planet against a dark, starry background. Numerous bright, multi-colored streaks (representing cosmic rays) are shown falling from the top of the frame towards the Earth's surface. The streaks are primarily red, orange, and yellow, with some purple and blue hues. The Earth's surface is depicted with dark blue oceans and white clouds. The overall scene is set against a backdrop of a dense field of stars and a prominent, colorful nebula or galaxy structure in the upper center.

Cosmic rays provide a major source of muons  
Vertically, on earth's surface:  $\sim 1$  muon /  $\text{cm}^2$  / min

charge      spin      mass      moment       $\gamma / 2\pi$       lifetime  
 (kHz G<sup>-1</sup>)      ( $\mu$ s)

e	$\pm e$	1/2	$m_e$ = 0.51 MeV	657 $\mu_p$	2800	$\infty$
$\mu$	$\pm e$	1/2	207 $m_e$ = 105.7 MeV	3.18 $\mu_p$	13.5	2.19
p	$\pm e$	1/2	1836 $m_e$ = 938 MeV	$\mu_p$	4.26	$\infty$

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What happens when they arrive into dense matter ?

charge      spin      mass      moment       $\gamma / 2\pi$       lifetime  
 (kHz G<sup>-1</sup>)      ( $\mu$ s)

e	$\pm e$	1/2	$m_e$ = 0.51 MeV	657 $\mu_p$	2800	$\infty$
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They stop and then die

*Scattering is not involved*

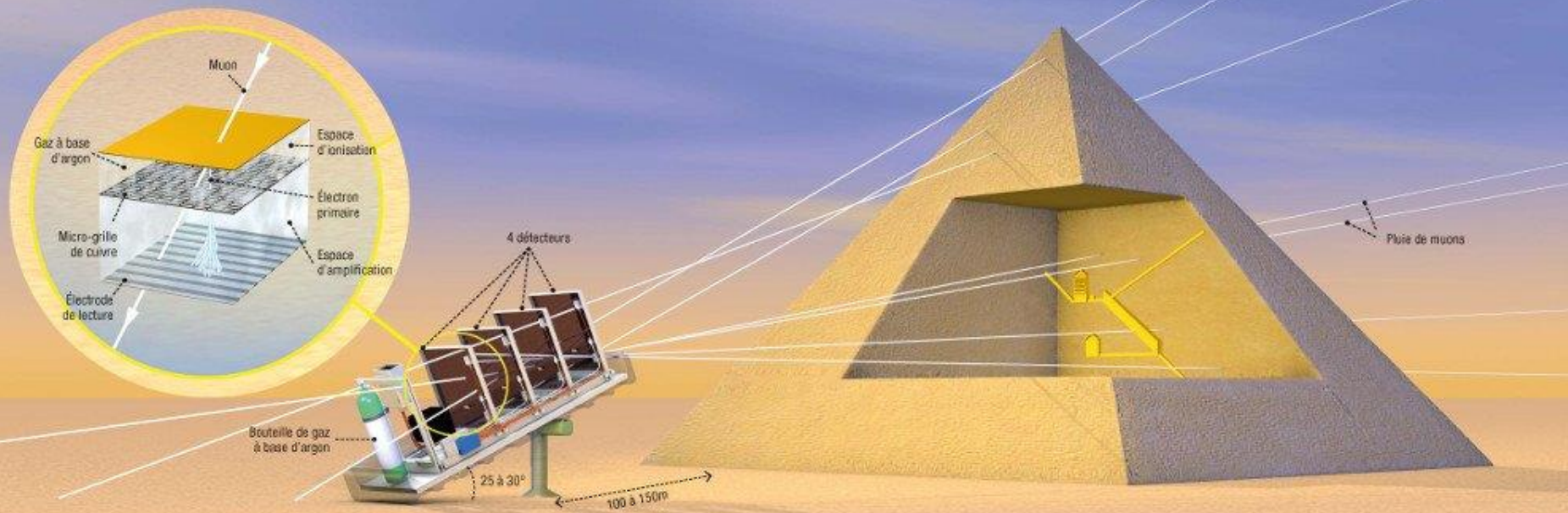




## Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons

Kunihiro Morishima<sup>1</sup>, Mitsuaki Kuno<sup>1</sup>, Akira Nishio<sup>1</sup>, Nobuko Kitagawa<sup>1</sup>, Yuta Manabe<sup>1</sup>, Masaki Moto<sup>1</sup>, Fumihiko Takasaki<sup>2</sup>, Hirofumi Fujii<sup>2</sup>, Kotaro Satoh<sup>2</sup>, Hideyo Kodama<sup>2</sup>, Kohei Hayashi<sup>2</sup>, Shigeru Odaka<sup>2</sup>, Sébastien Procureur<sup>3</sup>, David Attié<sup>3</sup>, Simon Bouteille<sup>3</sup>, Denis Calvet<sup>3</sup>, Christopher Filosa<sup>3</sup>, Patrick Magnier<sup>3</sup>, Irakli Mandjavidze<sup>3</sup>, Marc Riallot<sup>3</sup>, Benoit Marini<sup>4</sup>, Pierre Gable<sup>5</sup>, Yoshikatsu Date<sup>6</sup>, Makiko Sugiura<sup>7</sup>, Yasser Elshayeb<sup>8</sup>, Tamer Elnady<sup>9</sup>, Mustapha Ezzy<sup>8</sup>, Emmanuel Guerriero<sup>5</sup>, Vincent Steiger<sup>4</sup>, Nicolas Serikoff<sup>4</sup>, Jean-Baptiste Mouret<sup>10,11,12</sup>, Bernard Charlès<sup>13</sup>, Hany Helal<sup>4,8</sup> & Mehdi Tayoubi<sup>4,13</sup>

### The principle of muography



charge      spin      mass      moment       $\gamma / 2\pi$       lifetime  
 (kHz G<sup>-1</sup>)      ( $\mu$ s)

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Large gyromagnetic ratio  $\gamma$  ( $\sim 3 \times$  proton's)

Muons are very sensitive to magnetic fields

	charge	spin	mass	moment	$\gamma / 2\pi$ (kHz G <sup>-1</sup> )	lifetime ( $\mu$ s)
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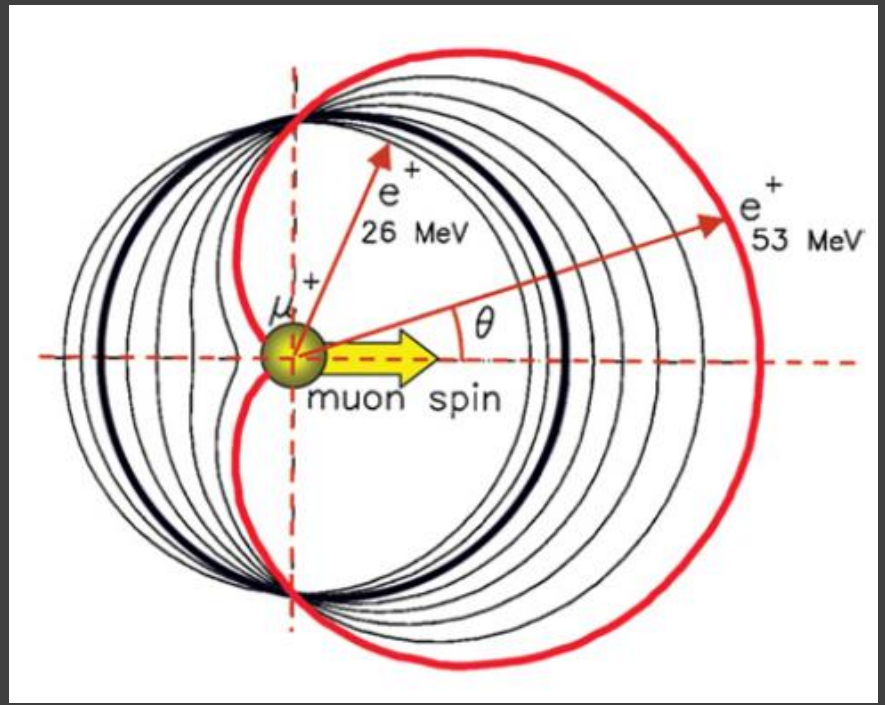
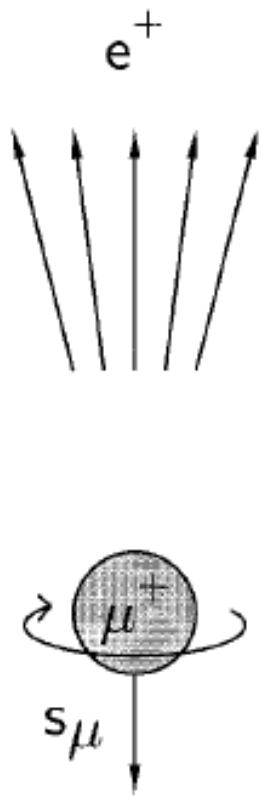
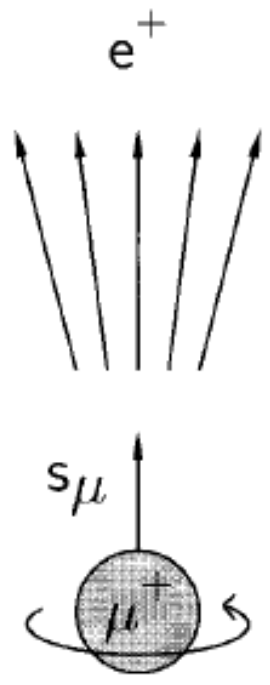
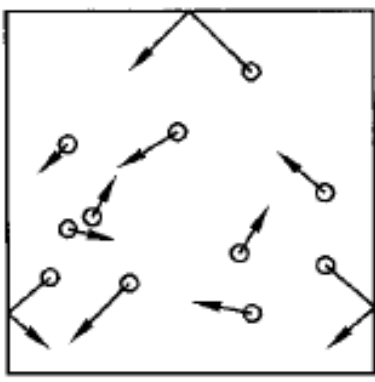
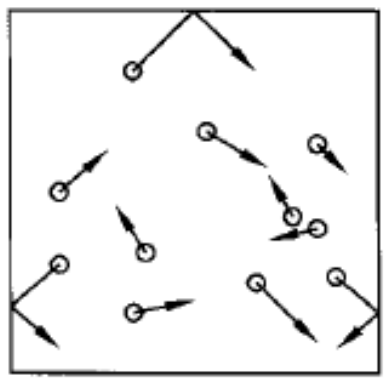


The muon decay is a 3 body process

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

The weak interaction do not conserve parity

The emitted positron emerges predominantly along the direction of the muon spin



No  $B_{\text{ext}}$  needed: non-perturbative technique

Probe of  $B_{\text{loc}}$  in a *local & bulk* way



A world map with four red circles marking the locations of muon spin rotation facilities. Each circle is accompanied by a text box. The text boxes for TRIUMF, ISIS, and PSI have a blue background, while the one for jPARC has a white background. The text in the boxes is white, except for the jPARC box which is black. The map shows the continents in light gray against a dark background.

TRIUMF  
continuous beam

ISIS  
pulsed beam (50 Hz)

PSI  
continuous beam

jPARC  
pulsed beam (25 Hz)

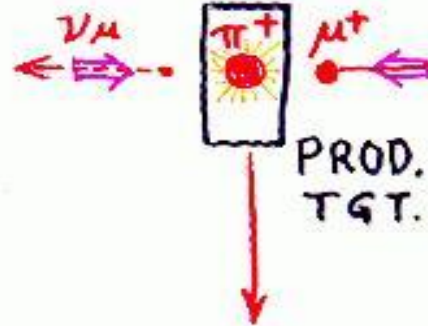
$\mu^+$ SR facilities world-wide

It stands for *positive Muon Spin Rotation & Relaxation*

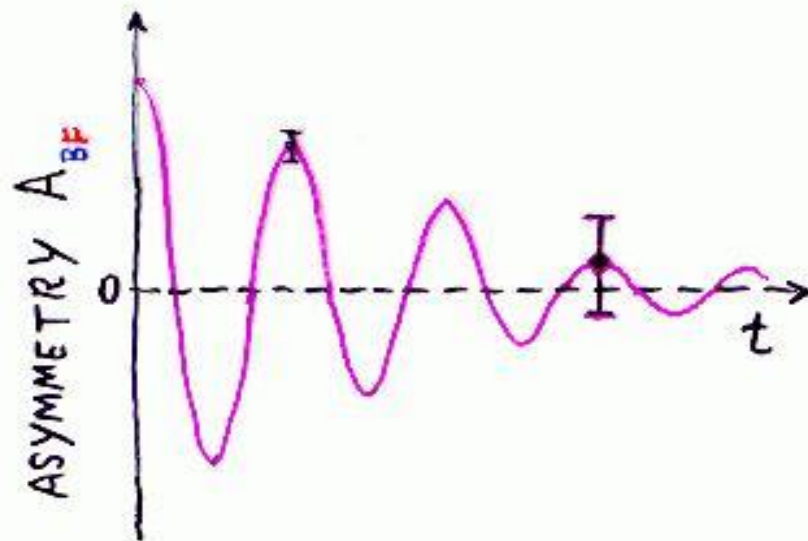
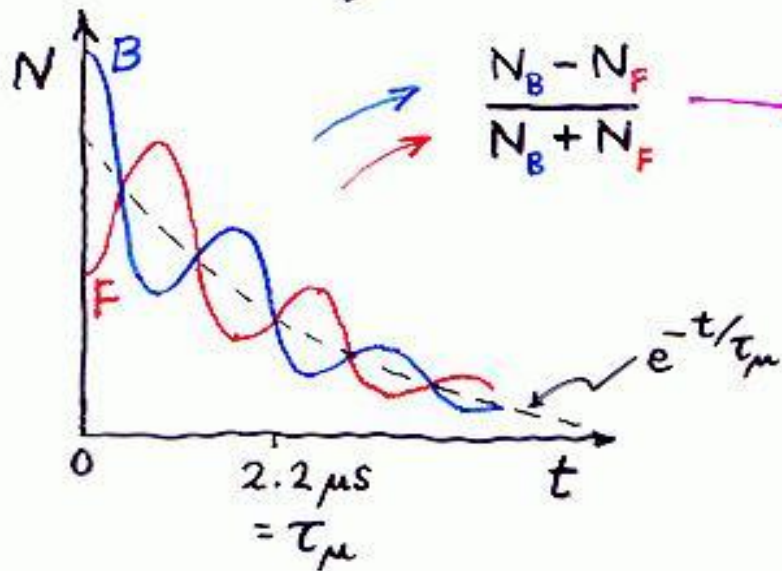
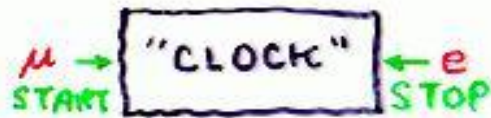
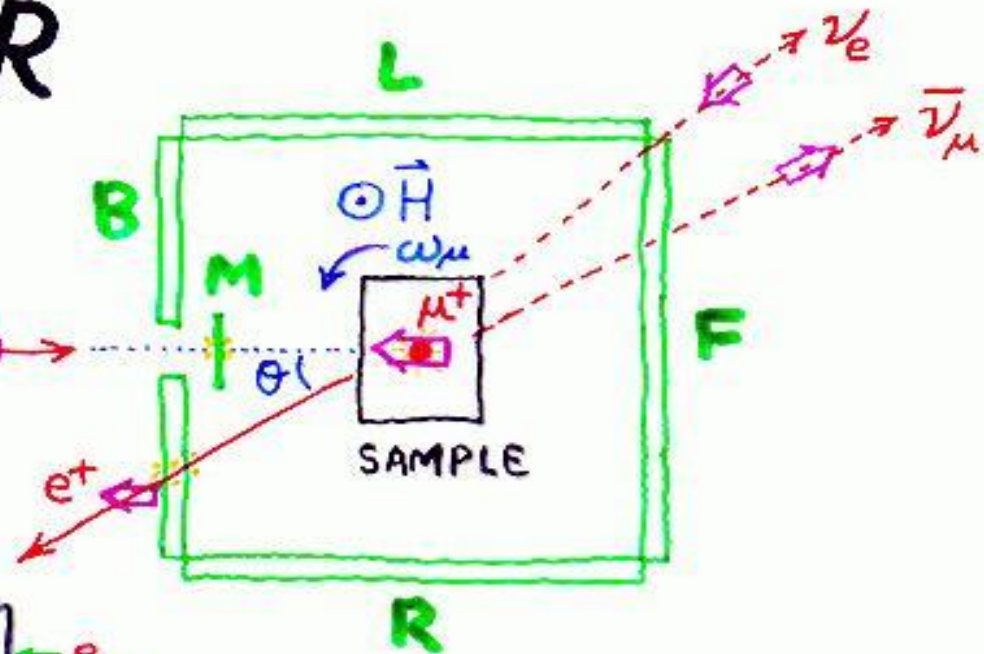
# $\mu^+SR$

CYCLOTRON

$\geq 500$  MeV protons



MUON  
BEAMLINE

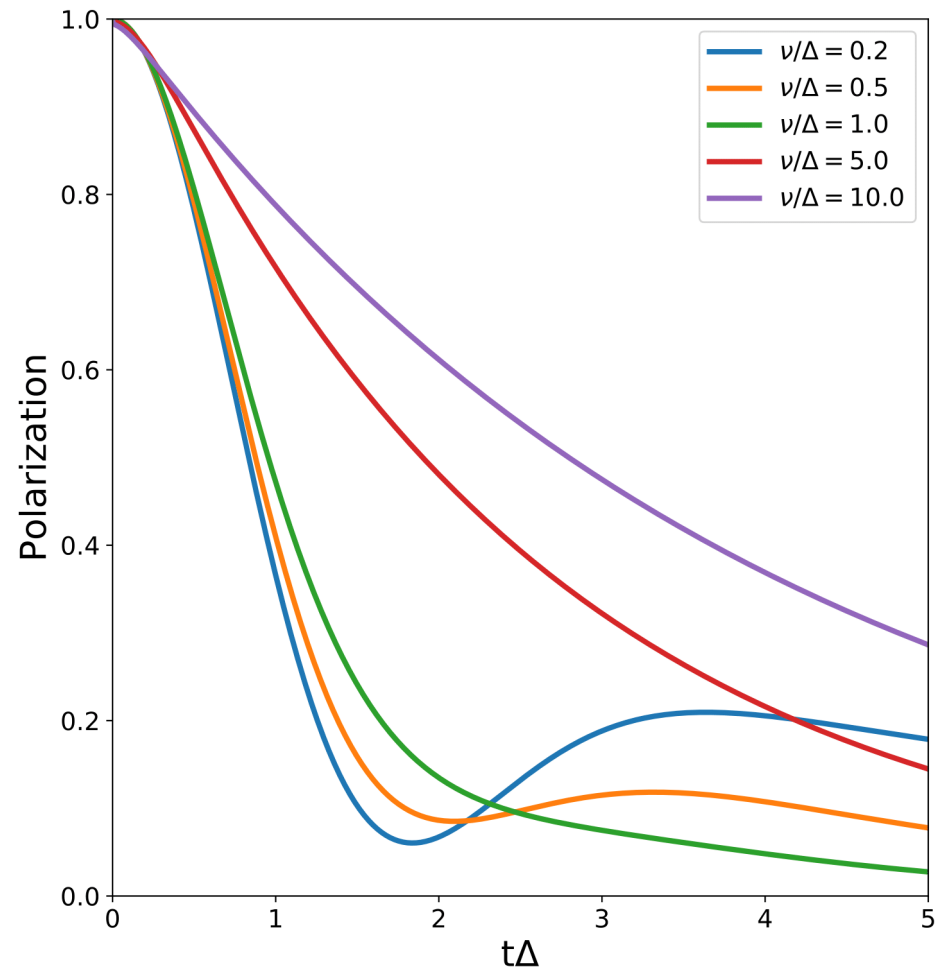
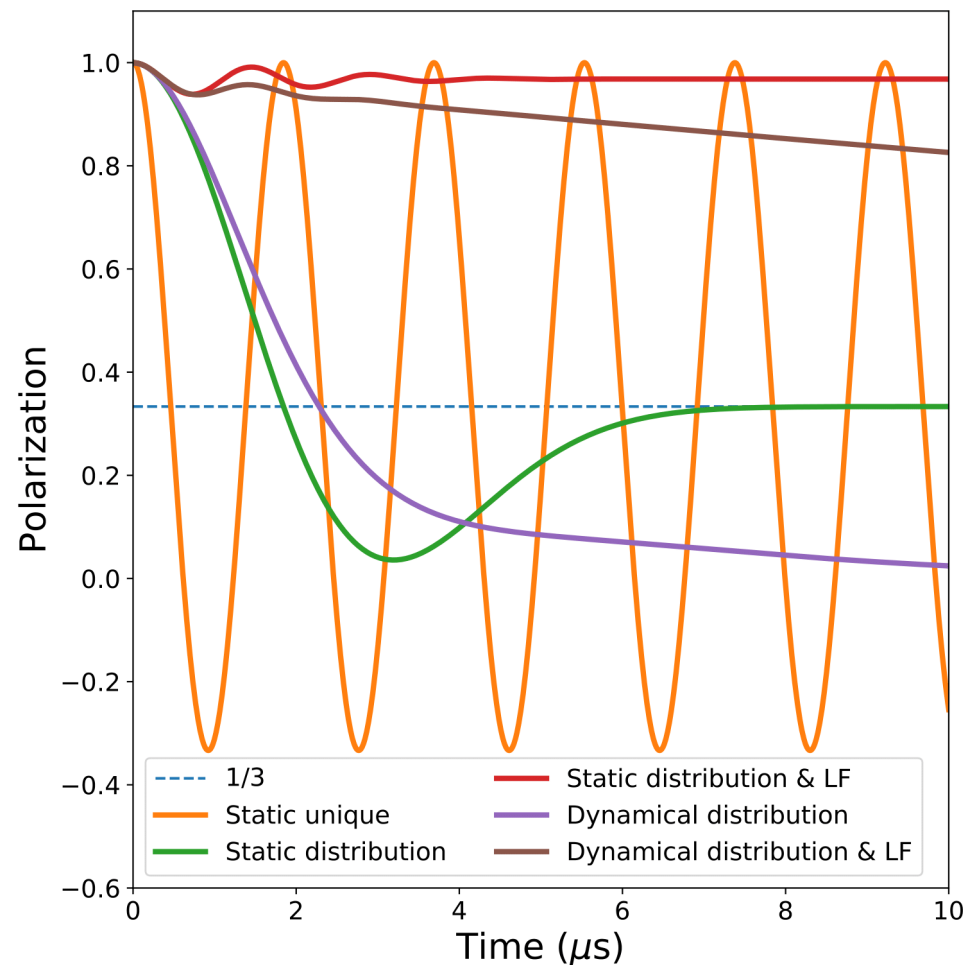




# What to expect ?

*The field distribution approach*

Kind of  $B_{\text{loc}}$   $\leftrightarrow$  kind of  $\mu^+$ SR spectrum



What to expect ? (Take home summary)

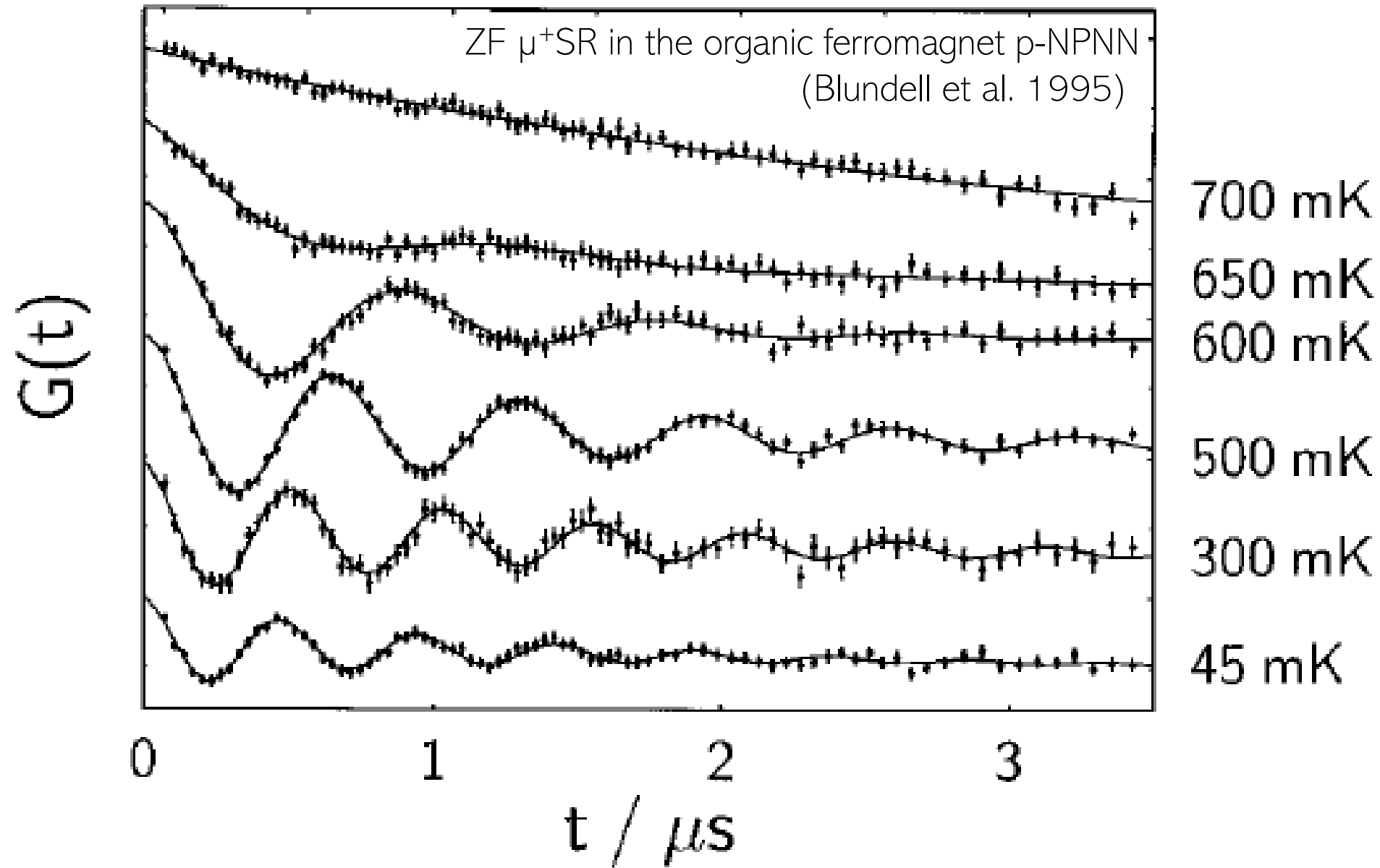
*Amplitude / Frequency / Damping*

Amplitude: magnetic volume fraction (hom./inhom.)

Frequency: average local (on-site) magnetic field

Damping: field distribution / magnetic fluctuations

# A (straightforward) first example

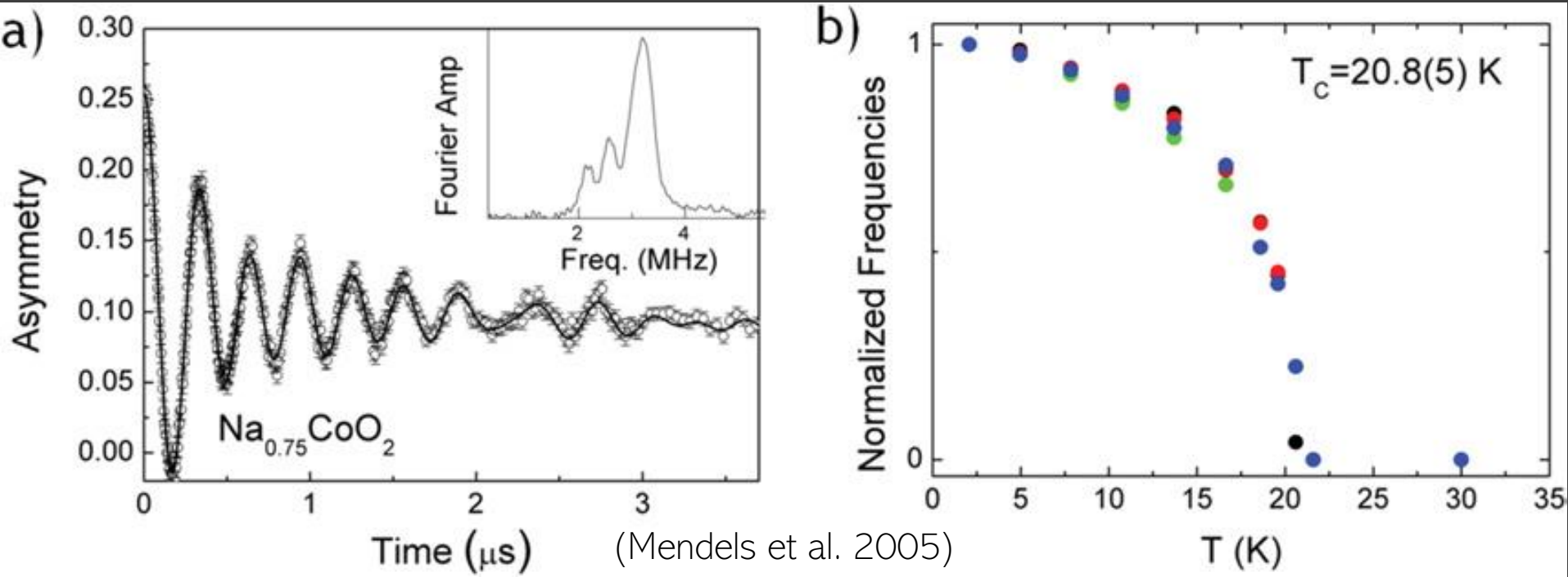


# A second example

A sodium cobaltate that undergoes an AF transition

4 frequencies  $\rightarrow$  4 stopping sites

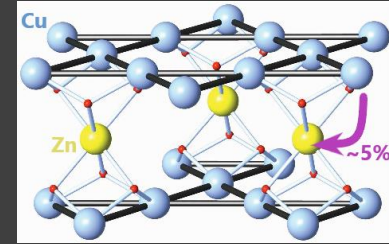
Long-time asymmetry  $\sim 1/3$  initial asymmetry  $\rightarrow$  fully static magnetism



# A third example: a Quantum Spin Liquid

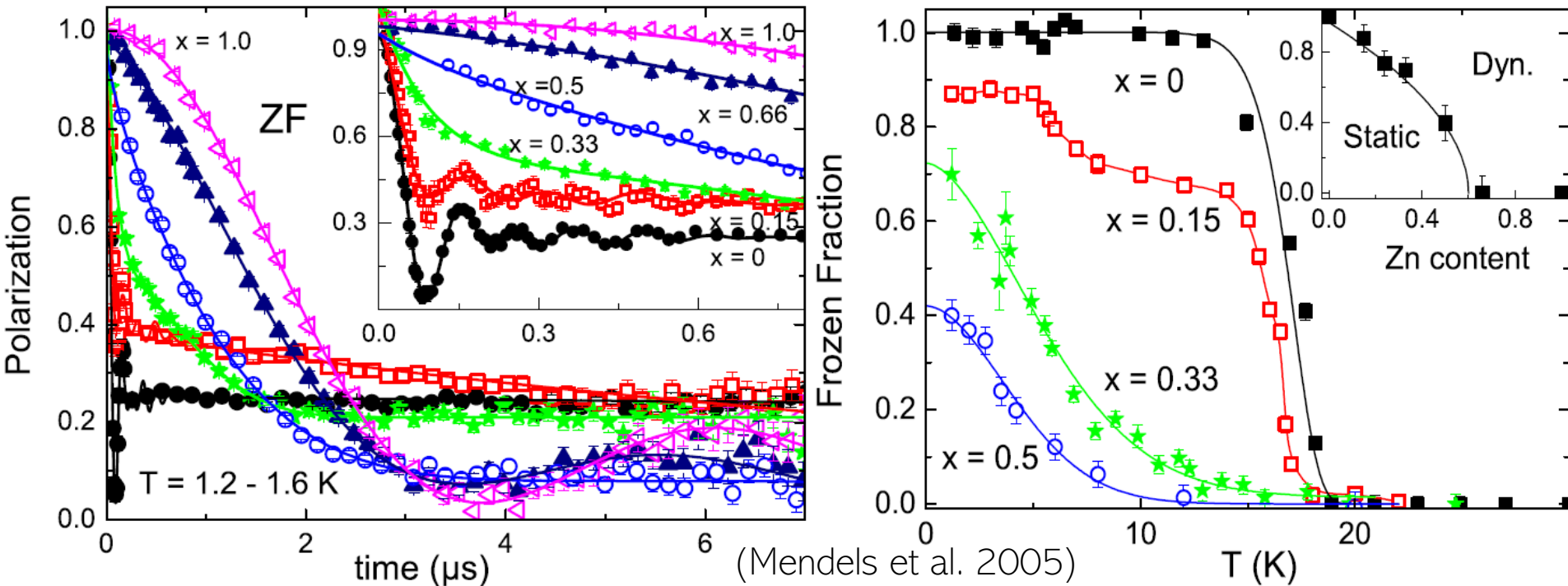
Paratacamites family:  $Zn_xCu_{1-x}(OH)_6Cl_2$

The end member ( $x = 1$ ) is the celebrated Herbertsmithite



First experimental realization of the Kagome Heisenberg AntiFerromagnet

First experimental evidence of a QSL ground state with ZF  $\mu^+$ SR



# SQM team «~~NMR~~» team

It stands for *Spectroscopies of Quantum Materials*.

Permanent



P. Mendels



F. Bert



V. Brouet



E. Kermarrec



H. Alloul

PhD, Post-doc



A. Louat



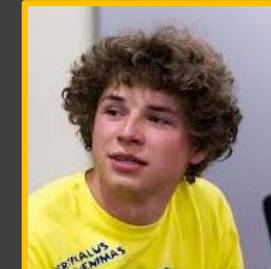
R. Sharma



B. Le Pennec



S. Bhattacharya



G. Simutis

October arrivals



Techniques

NMR

ARPES

INS

$\mu^+$ SR

Thank you !

