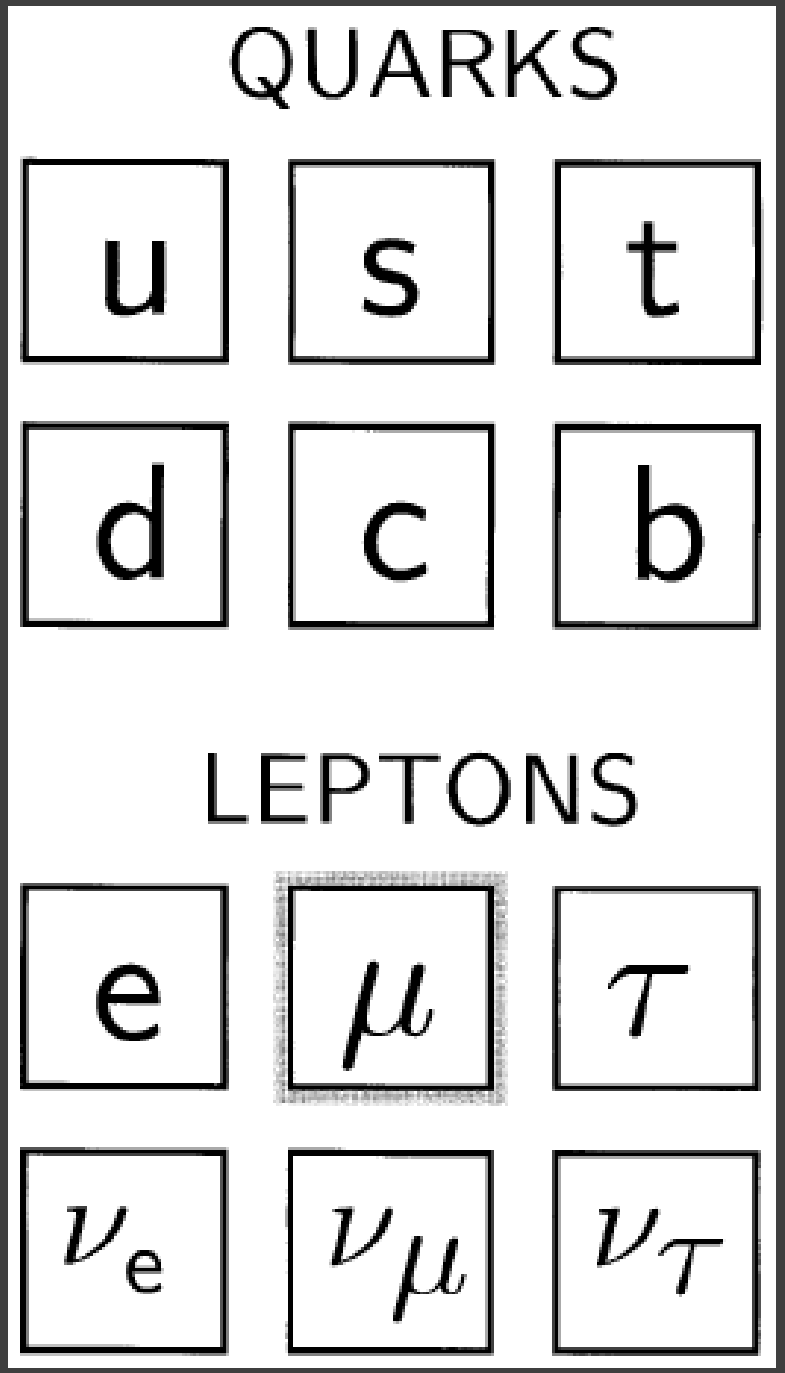
Cookies #4

Quentin Barthélemy

09-20-18


QUARKS
u
s
t
d
c
b
LEPTONS
e
μ
τ
ν_e
ν_μ
ν_τ

QUARKS

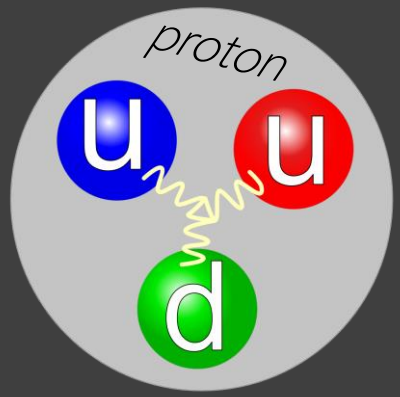
u	s	t
d	c	b

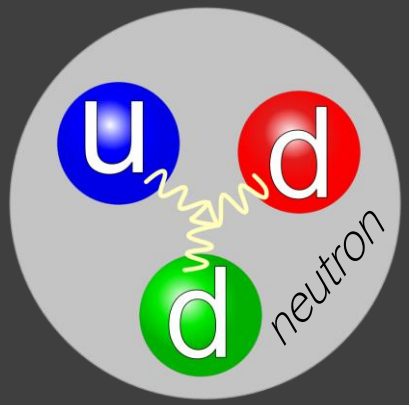
LEPTONS

e	μ	τ
ν_e	ν_μ	ν_τ

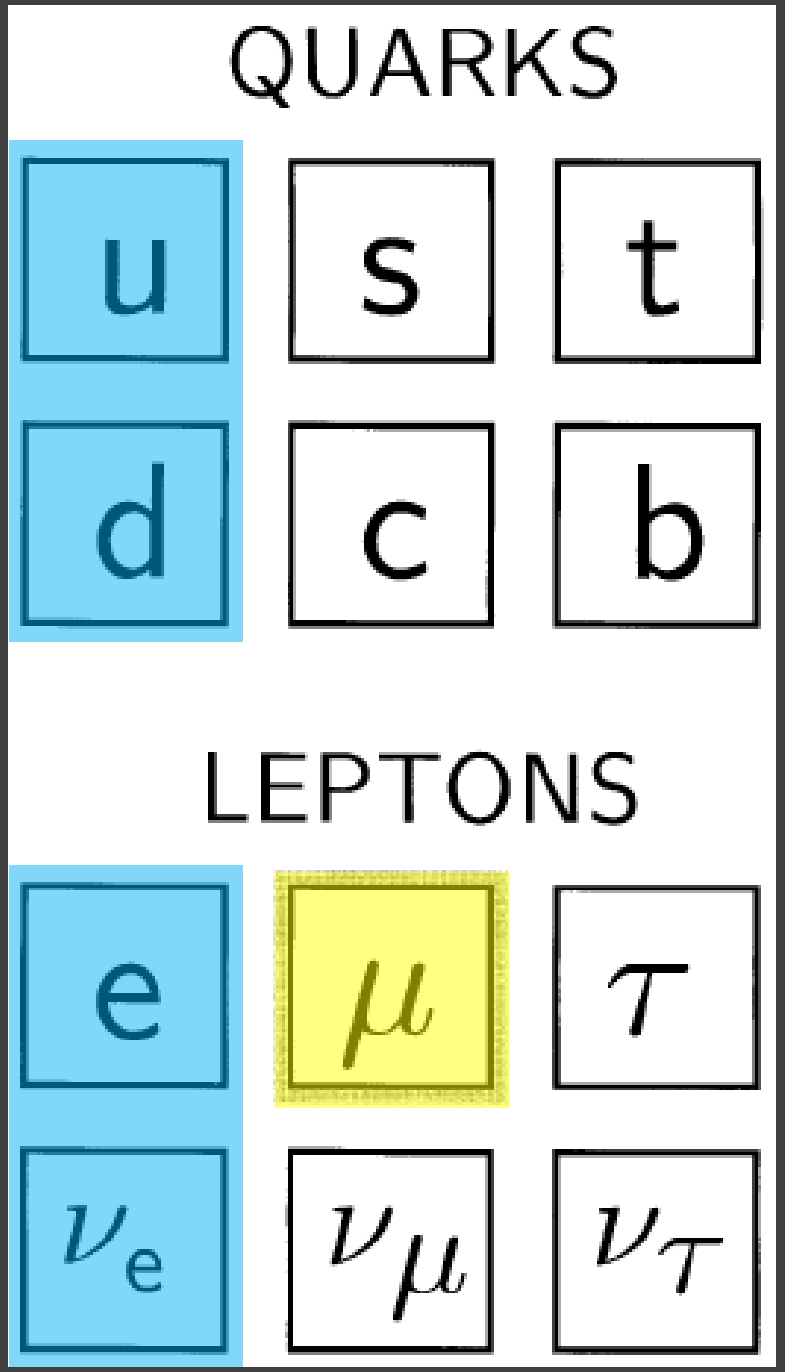
Everyday matter is made of 1st generation particles

e.g.



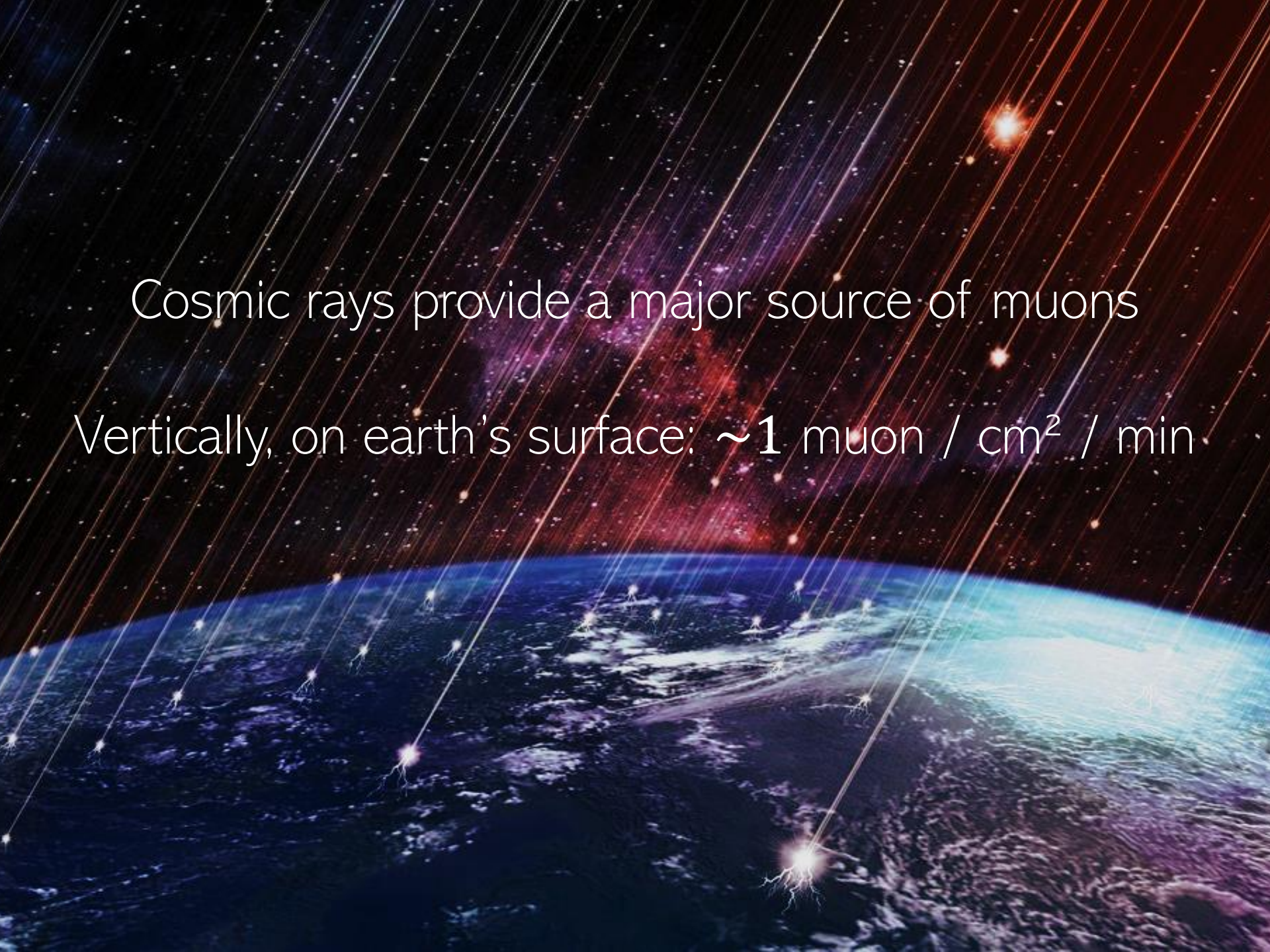


β^- decay: $^{14}C \longrightarrow {}^{14}N + e^- + \overline{\nu_e}$



The 2nd generation exception:
the **muon**

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


Cosmic rays provide a major source of muons
Vertically, on earth's surface: ~1 muon / cm² / min

	charge	spin	mass	moment	$\gamma / 2\pi$ (kHz G^{-1})	lifetime (μs)
e	$\pm$e	1/2	m_e = 0.51 MeV	657 μ_p	2800	∞
μ	$\pm$e	1/2	207 m_e = 105.7 MeV	3.18 μ_p	13.5	2.19
p	$\pm$e	1/2	1836 m_e = 938 MeV	μ_p	4.26	∞

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p	$\pm$e	1/2	1836 m_e = 938 MeV	μ_p	4.26	∞

What happens when they arrive into dense matter ?

	charge	spin	mass	moment	$\gamma / 2\pi$ (kHz G^{-1})	lifetime (μs)
e	$\pm$e	1/2	m_e = 0.51 MeV	657 μ_p	2800	∞
μ	$\pm$e	1/2	207 m_e = 105.7 MeV	3.18 μ_p	13.5	2.19
p	$\pm$e	1/2	1836 m_e = 938 MeV	μ_p	4.26	∞

They stop and then die

Scattering is not involved

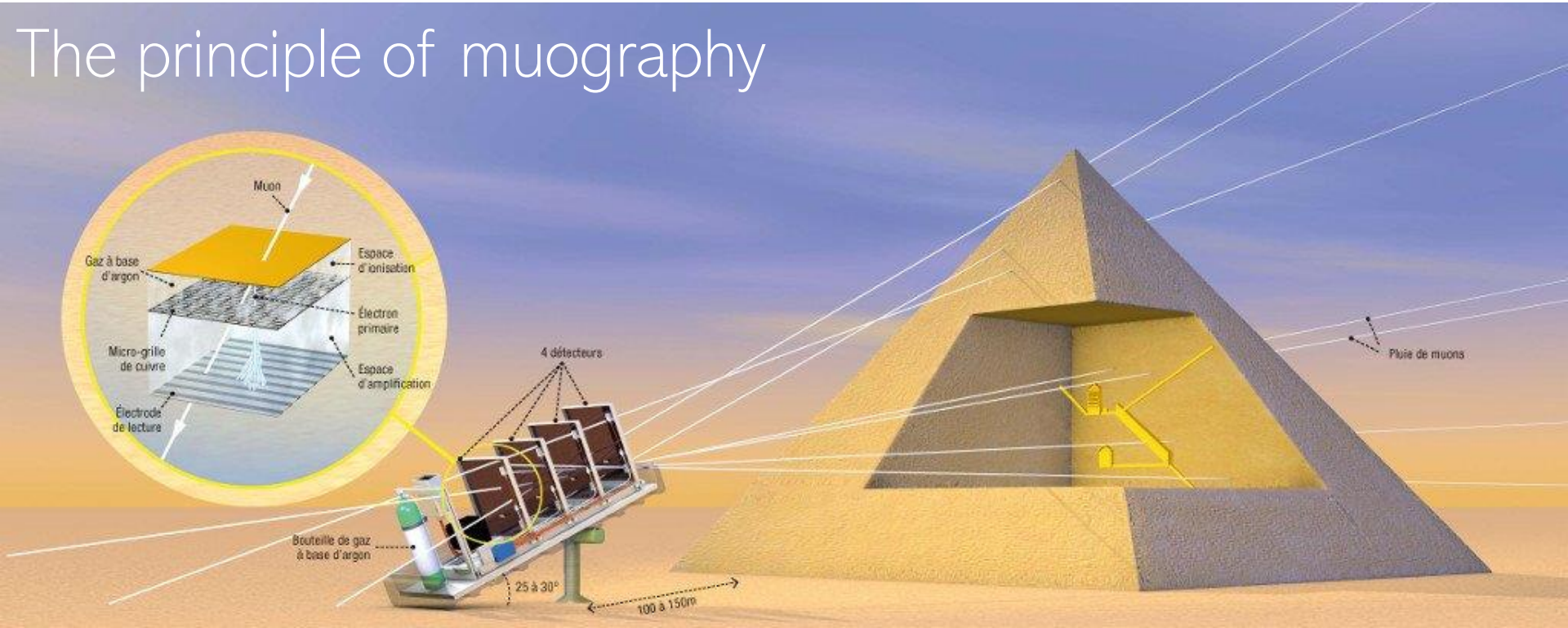
LETTER

21 December 2017

doi:10.1038/nature24647

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

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



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

Muons are very sensitive to magnetic fields

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e	$\pm$e	1/2	m_e = 0.51 MeV	657 μ_p	2800	∞
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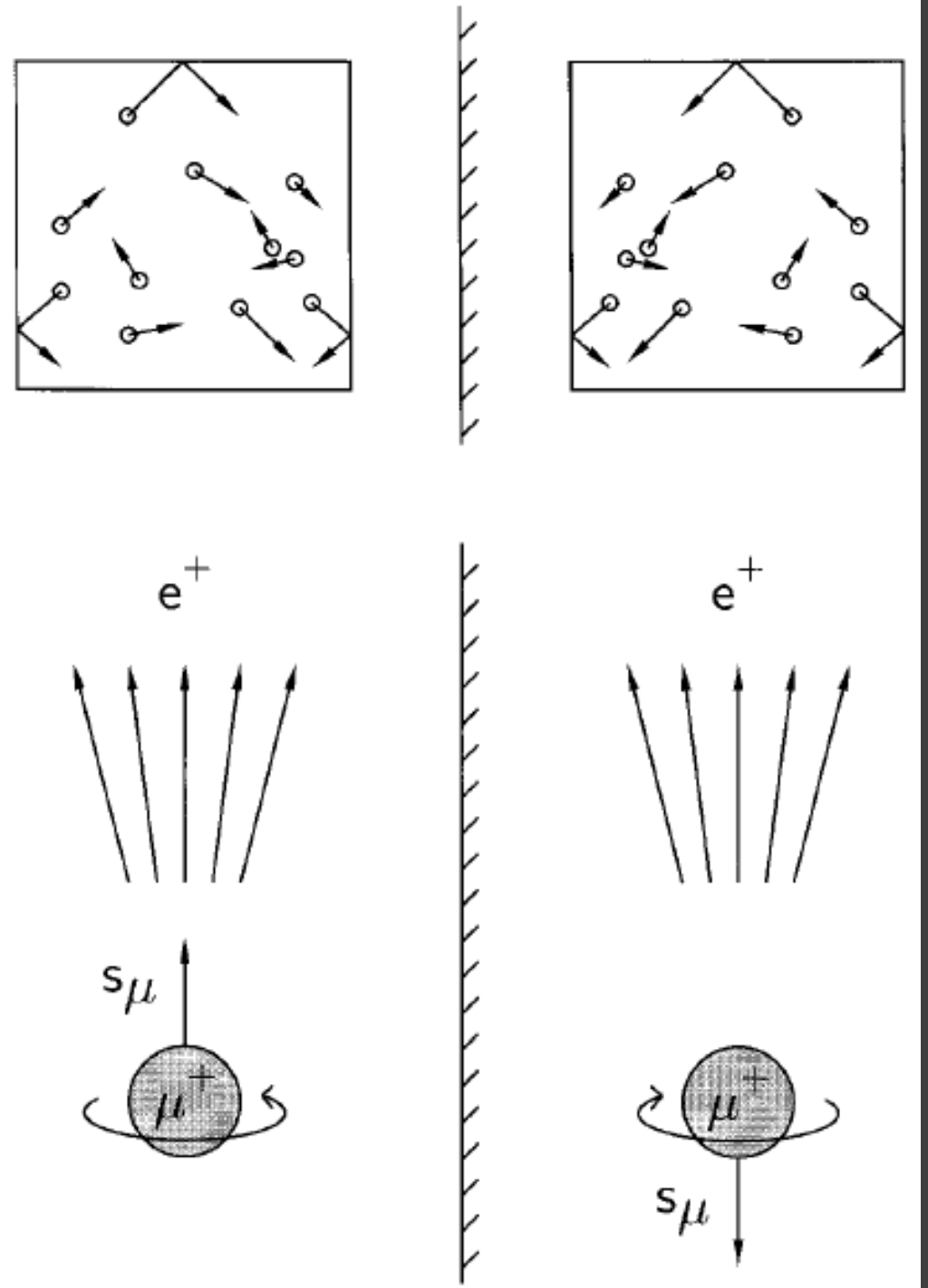
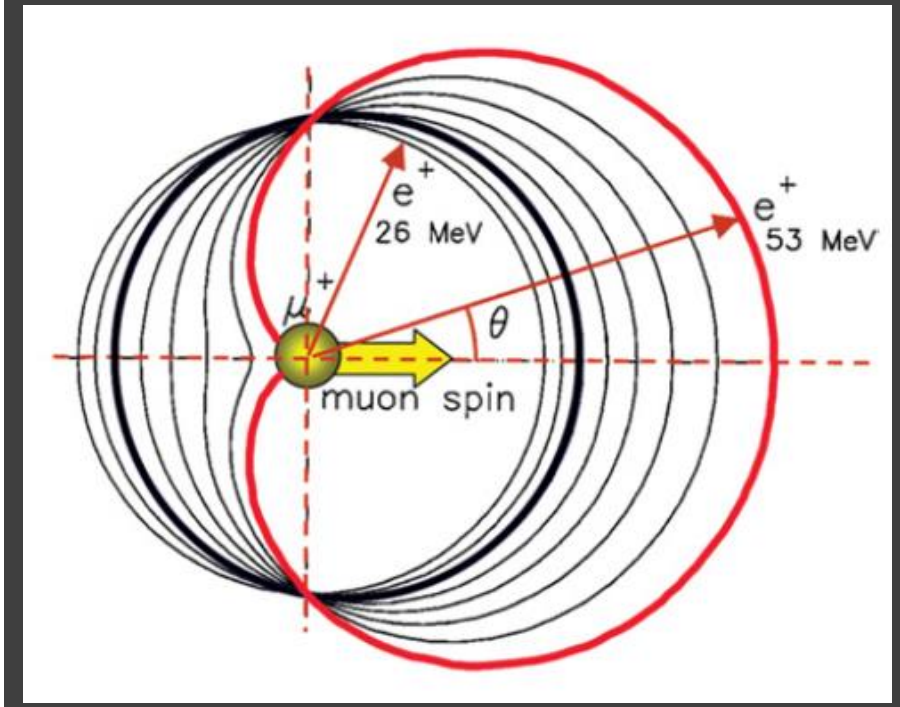
The muon decay is a 3 body process

$$\mu^+ \longrightarrow e^+ + \nu_e + \overline{\nu_\mu}$$



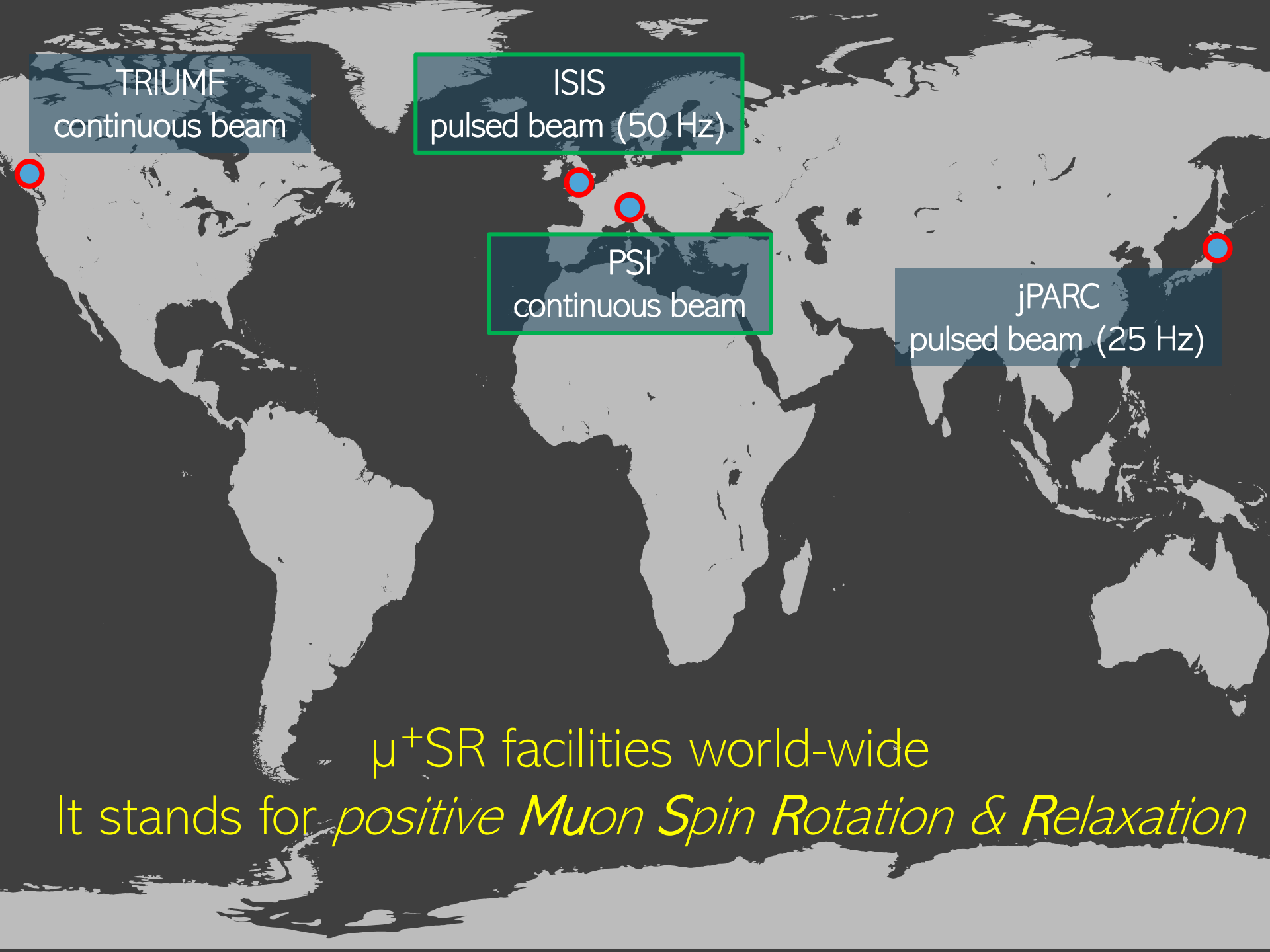
The weak interaction do not conserve parity

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



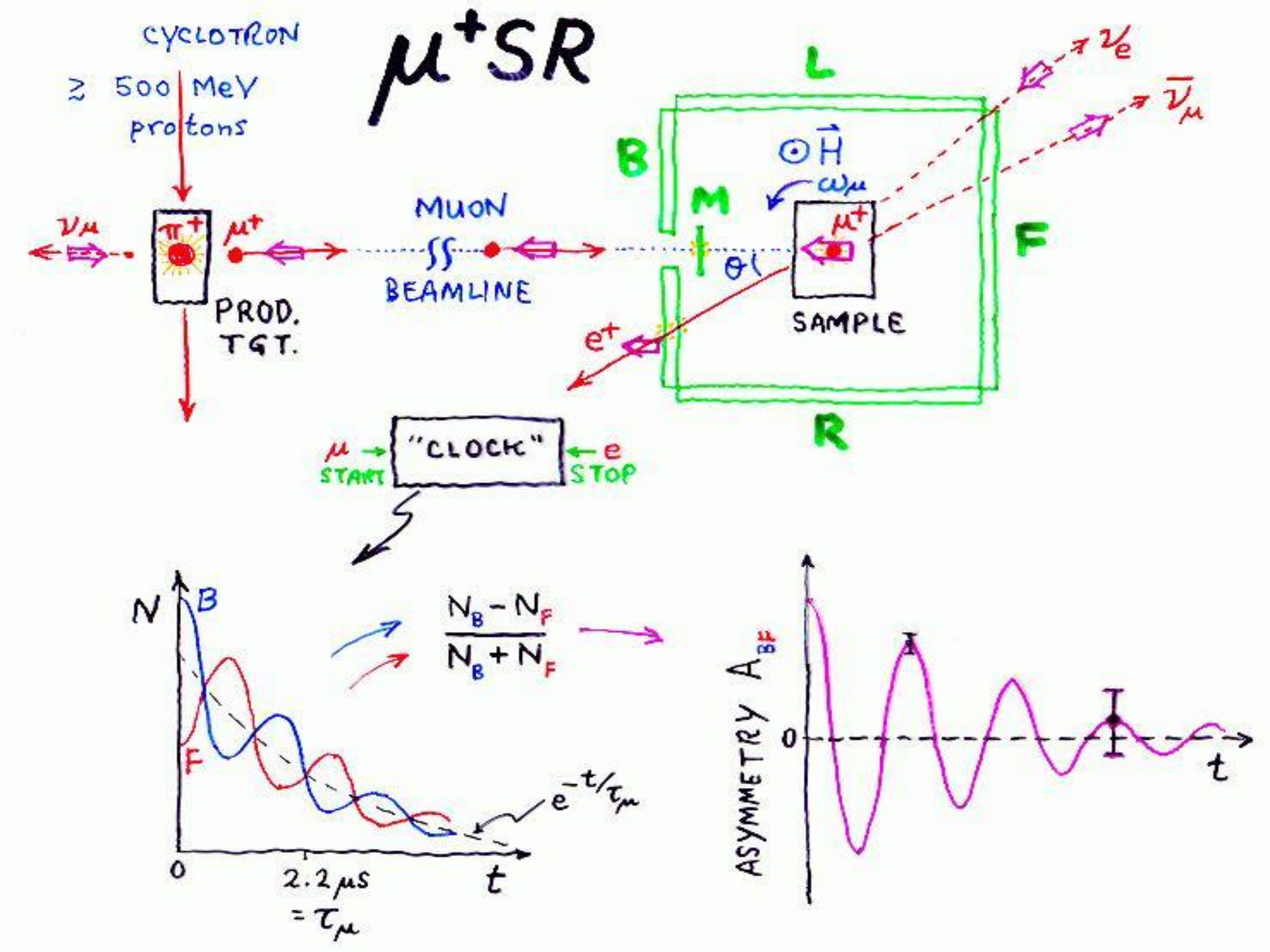
No B_{ext} needed: non-perturbative technique

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



μ⁺SR facilities world-wide

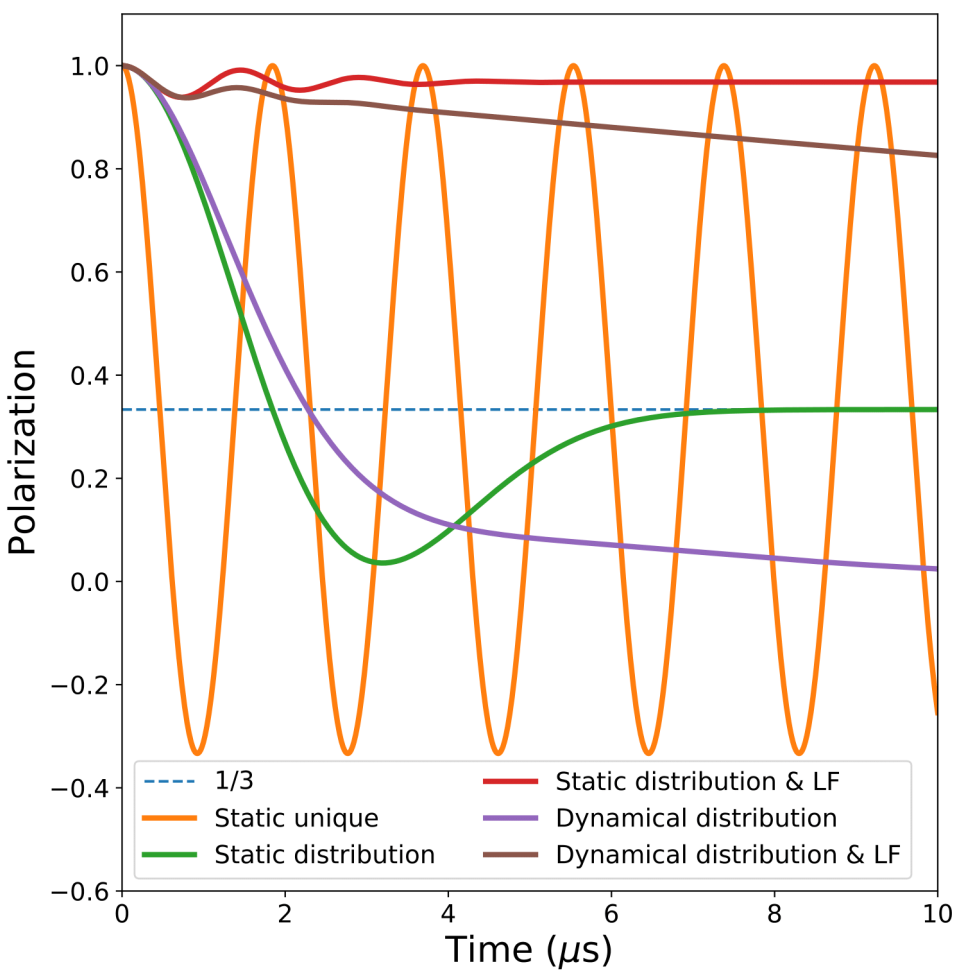
It stands for *positive **Mu**on **S**pin **R**otation & **R**elaxation*

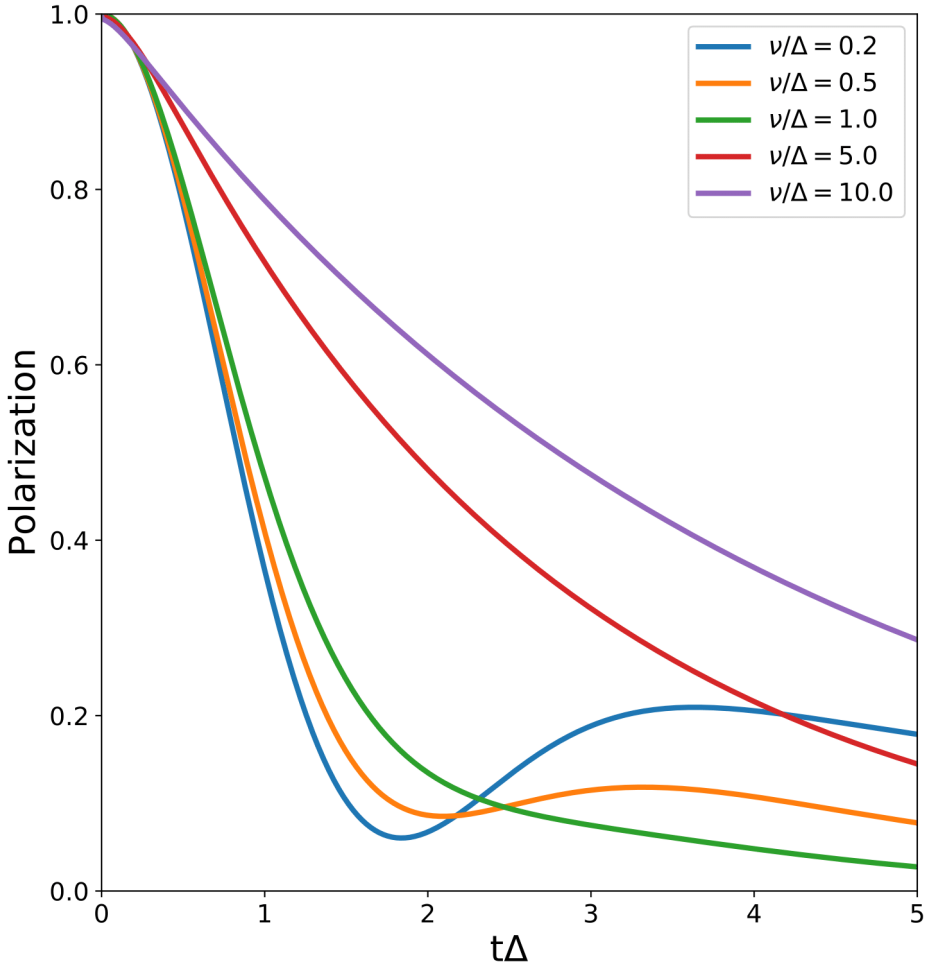

CYCLOTRON
≳ 500 MeV protons
μ+SR
L
B
M
F
R
ν_e
$\bar{\nu}_\mu$
$\odot \vec{H}$
ω_μ
ν_μ
π^+
μ^+
MUON
BEAMLINE
PROD. TGT.
SAMPLE
e^+
θ
μ START
"CLOCK"
e STOP
N
B
F
0
2.2 μs = τ_μ
t
e^{-t/τ_μ}
$\frac{N_B - N_F}{N_B + N_F}$
ASYMMETRY A_{BF}
0
t

What to expect ?

The field distribution approach

Kind of B_{loc} ↔ kind of μ^+SR spectrum





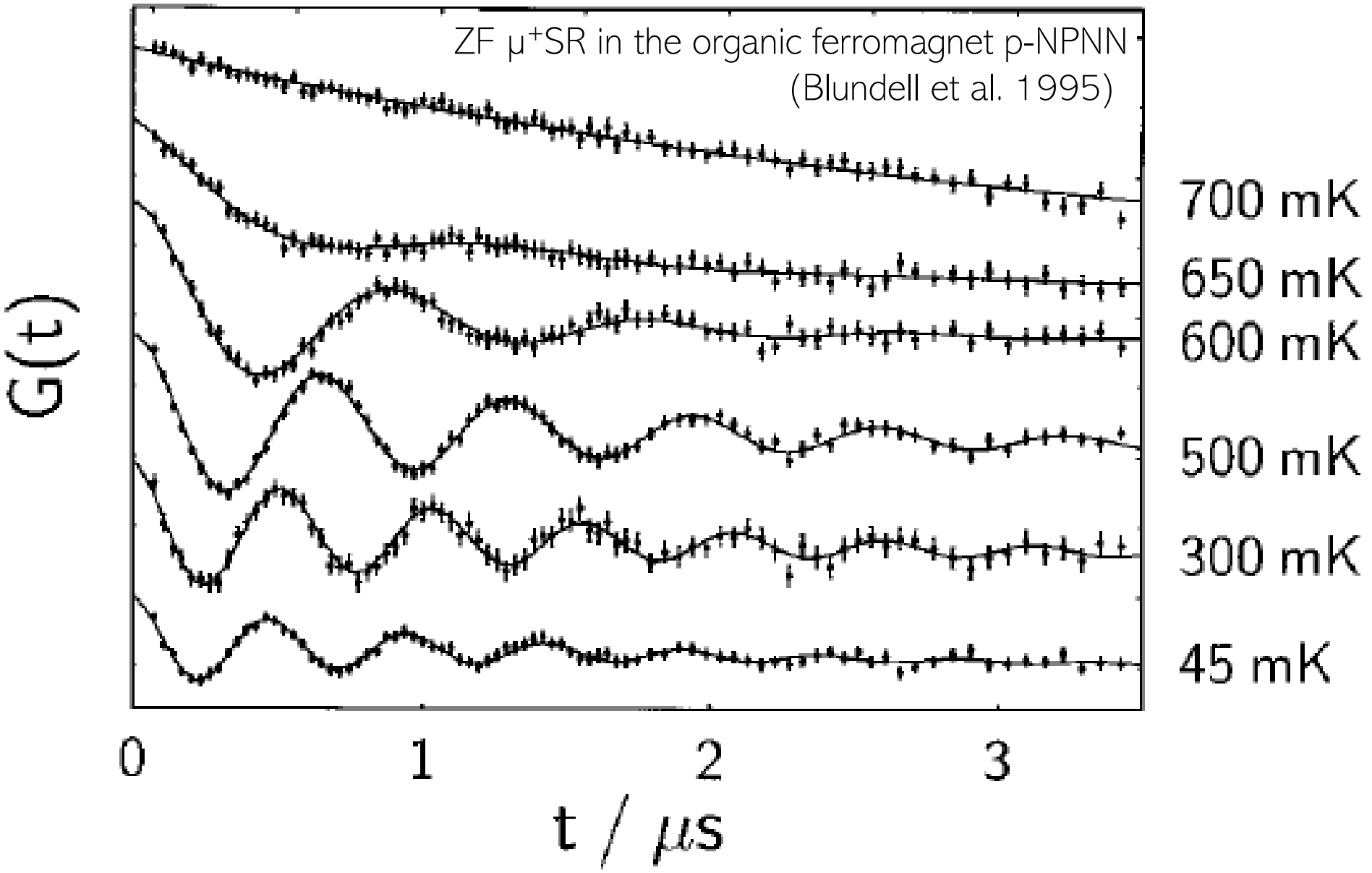
What to expect ? (Take home summary)
Amplitude / Frequency / Damping

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

Frequency: average local (on-site) magnetic field

Damping: field distribution / magnetic fluctuations

A (straightforward) fisrt example

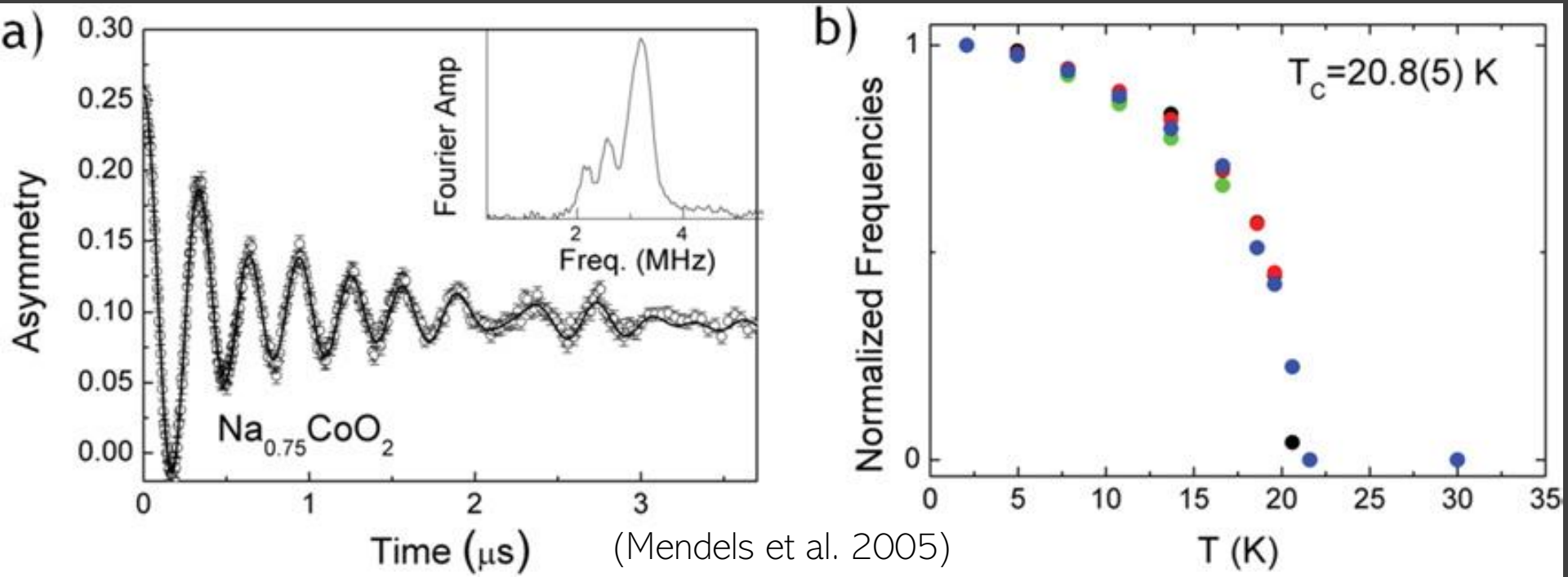


A second example

A sodium cobaltate that undergoes an AF transition

4 frequencies ⟶ 4 stopping sites

Long-time asymmetry ~ 1/3 initial asymmetry ⟶ fully static magnetism

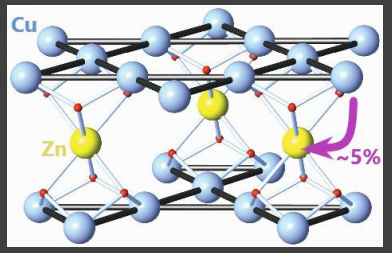


(Mendels et al. 2005)

A third example: a Quantum Spin Liquid

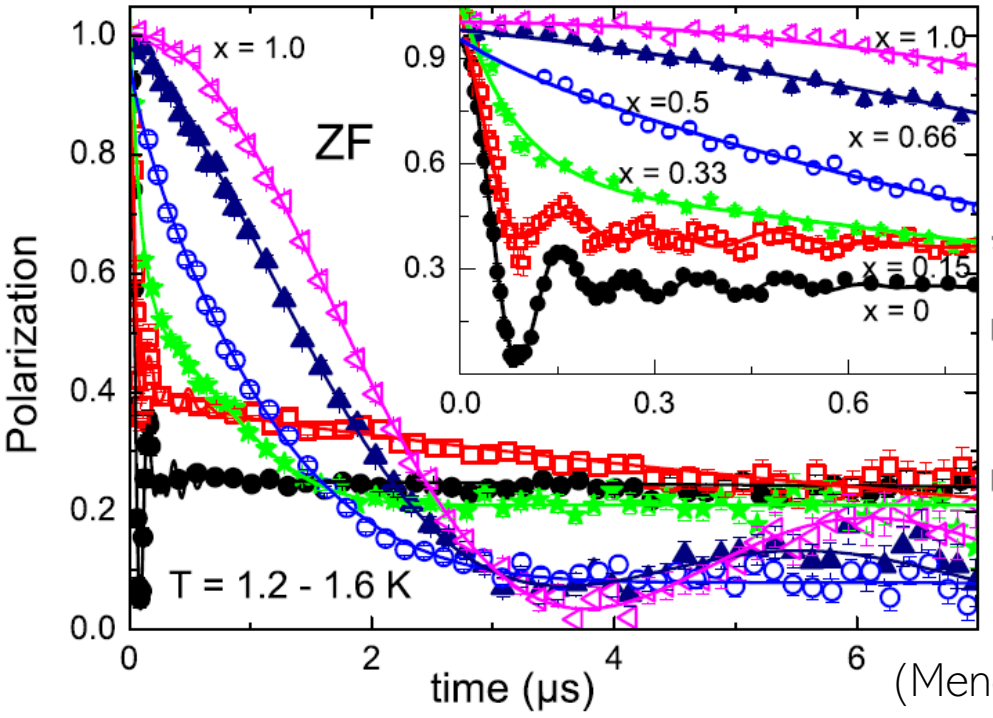
Paratacamites family: $Zn_xCu_{1-x}(OH)_6Cl_2$

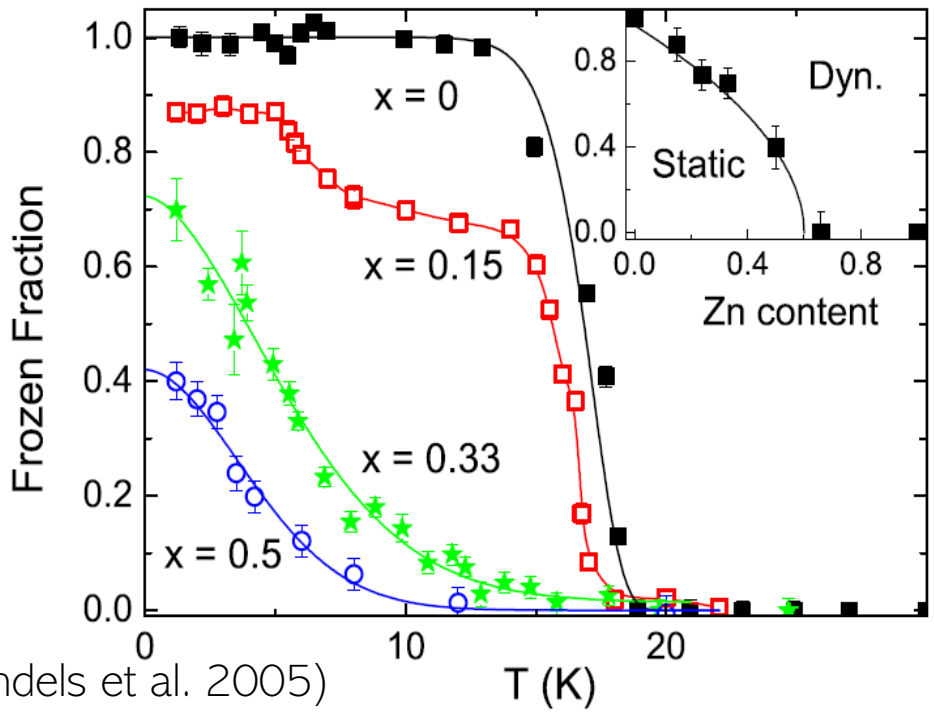
The end member (x = 1) is the celebrated Herbertsmithite



First experimental realization of the Kagome Heisenberg AntiFerromagnet

First experimental evidence of a QSL ground state with ZF μ^+SR





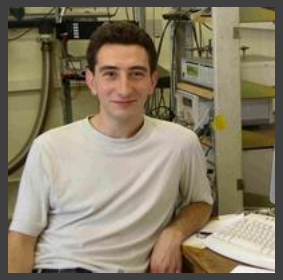
(Mendels et al. 2005)

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 | μ^+SR

Thank you !