Particle Physics
- Muon and FFAG -

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1st FFAG School
KURRI, Japan

Particles and Interactions

Building Blocks of Matter : Elementary Particles

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

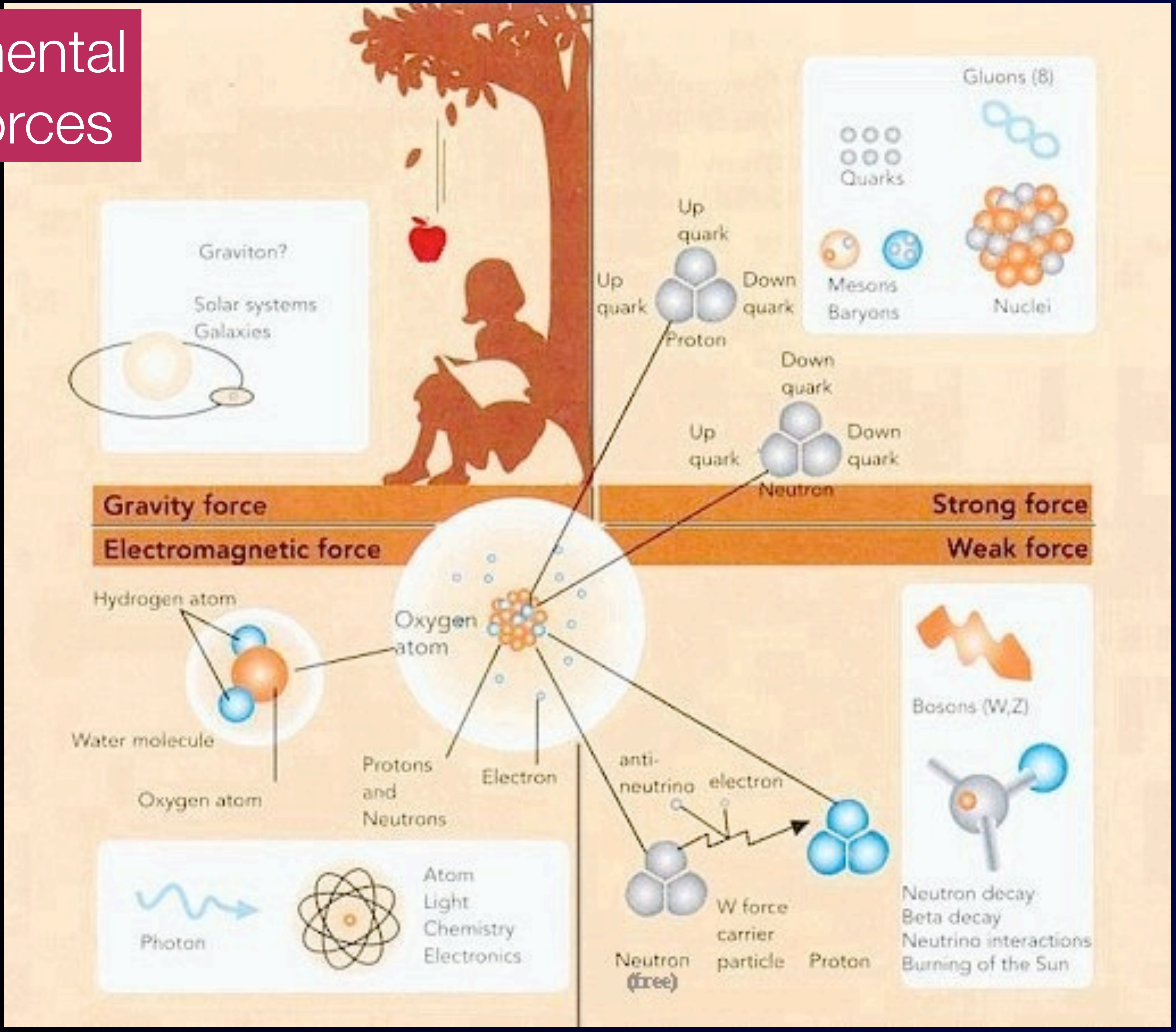
Leptons spin = 1/2

	Flavor	Mass GeV/c^2	Electric charge
1st generation	ν_e electron neutrino	$<1\times10^{-8}$	0
	e electron	0.000511	−1
2nd generation	ν_μ muon neutrino	<0.0002	0
	μ muon	0.106	−1
3rd generation	ν_τ tau neutrino	<0.02	0
	τ tau	1.7771	−1

Quarks spin = 1/2

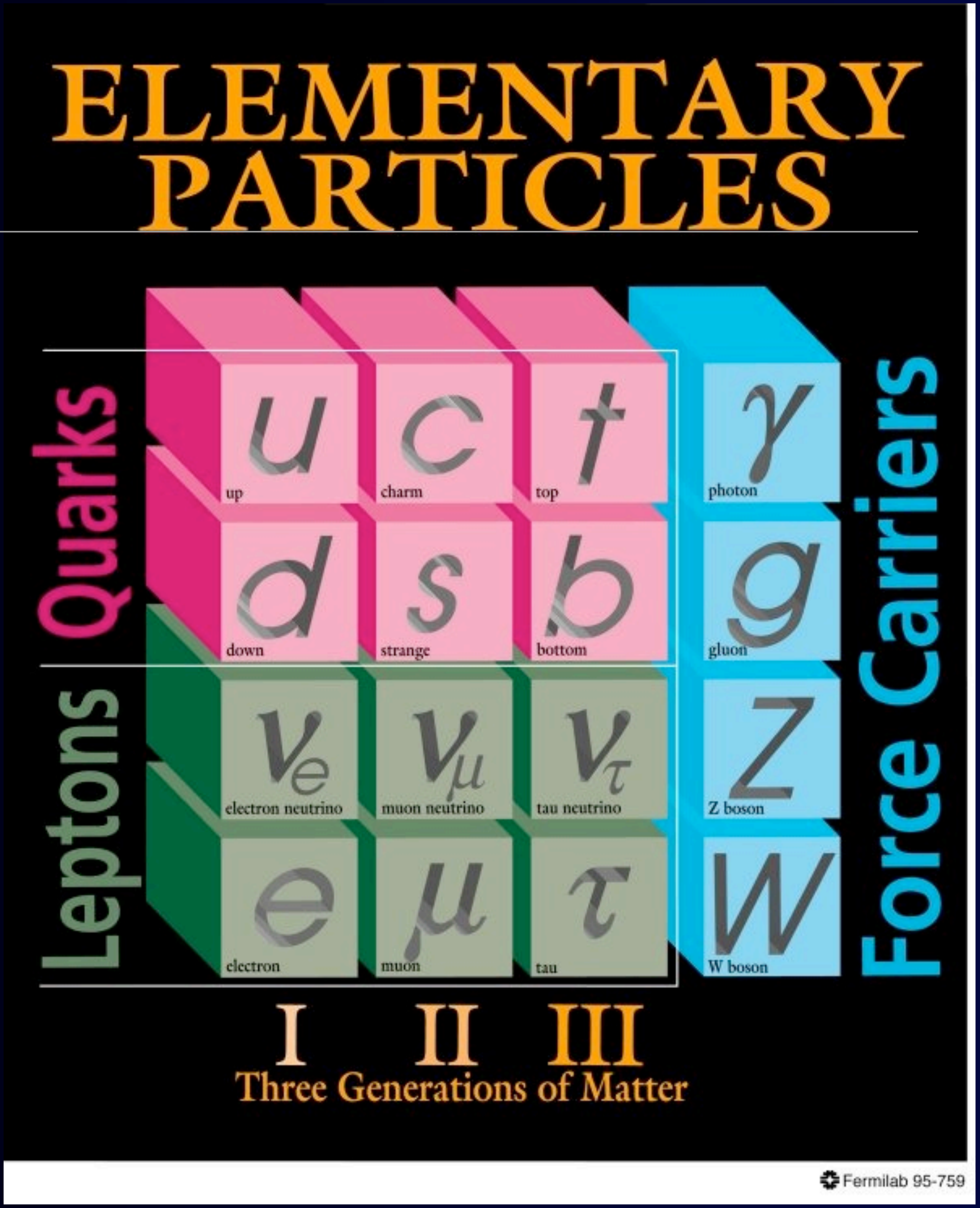
	Flavor	Approx. Mass GeV/c^2	Electric charge
1st generation	u up	0.003	2/3
	d down	0.006	−1/3
2nd generation	c charm	1.3	2/3
	s strange	0.1	−1/3
3rd generation	t top	175	2/3
	b bottom	4.3	−1/3

Fundamental Four Forces

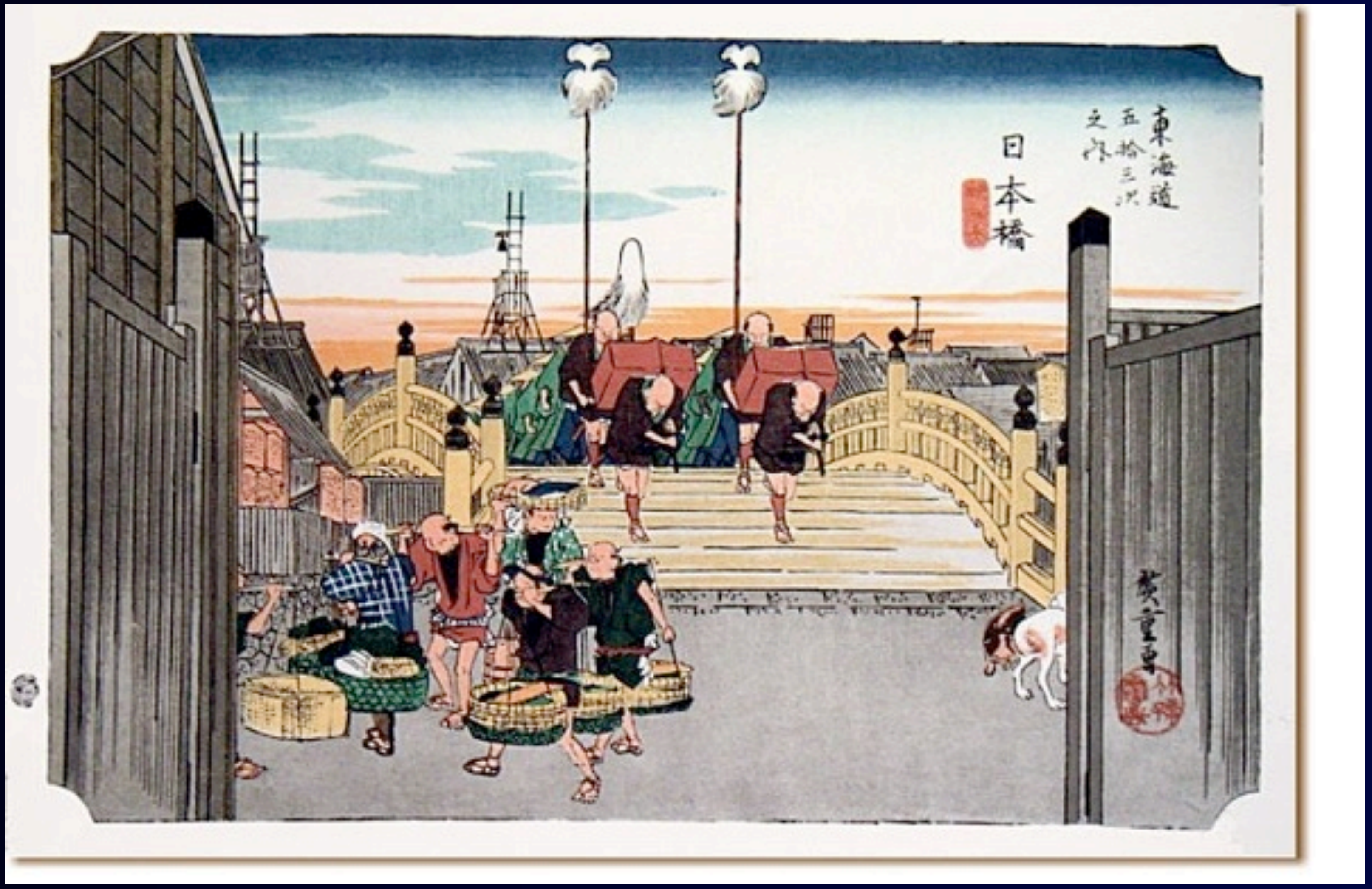


List of Elementary Particles

- A list of elementary particles of building blocks (quarks and leptons, fermions) and particles of force carriers (bosons).
- In particle physics, a field is treated as a particle.

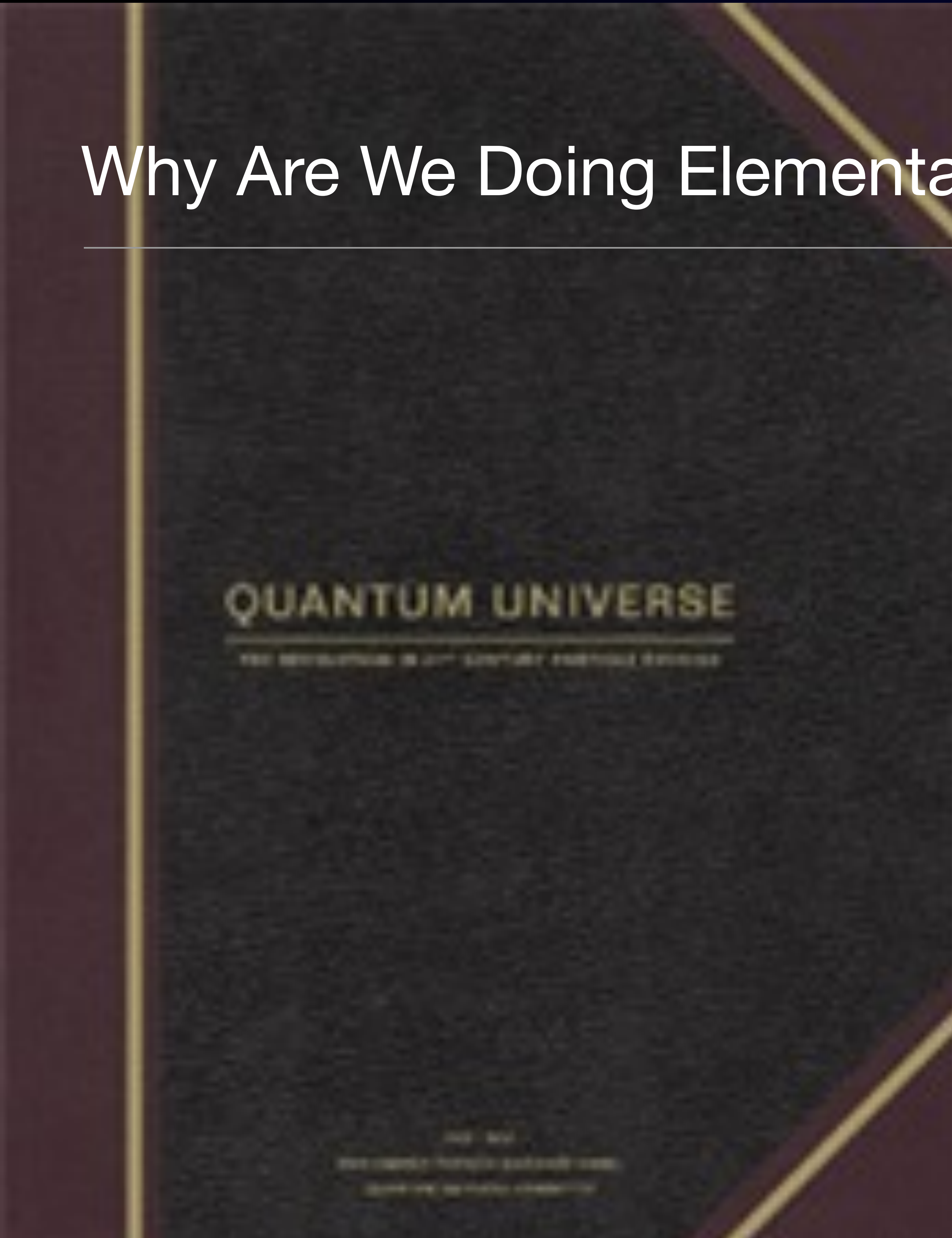


Big questions in Particle Physics



starting from Nihonbashi, Tokyo

Why Are We Doing Elementary Particle Physics ?



Why Are We Doing Elementary Particle Physics ?

from "Quantum Universe"
(The revolution of 21st Century Particle Physics)

(1) What is the origin of mass for fundamental particles?
(2) Are there undiscovered principles of nature?
(3) Are there extra dimensions of space?
(4) Do all the forces becomes one?
(5) Why are there so many kinds of particles?
(6) What happened to the antimatter?
(7) What is dark matter? How can we make it in the laboratory?
(8) How can we solve the mystery of dark energy?
(9) How did the universe come to be?
(10) What are neutrinos telling us?

SM cannot answer those questions.

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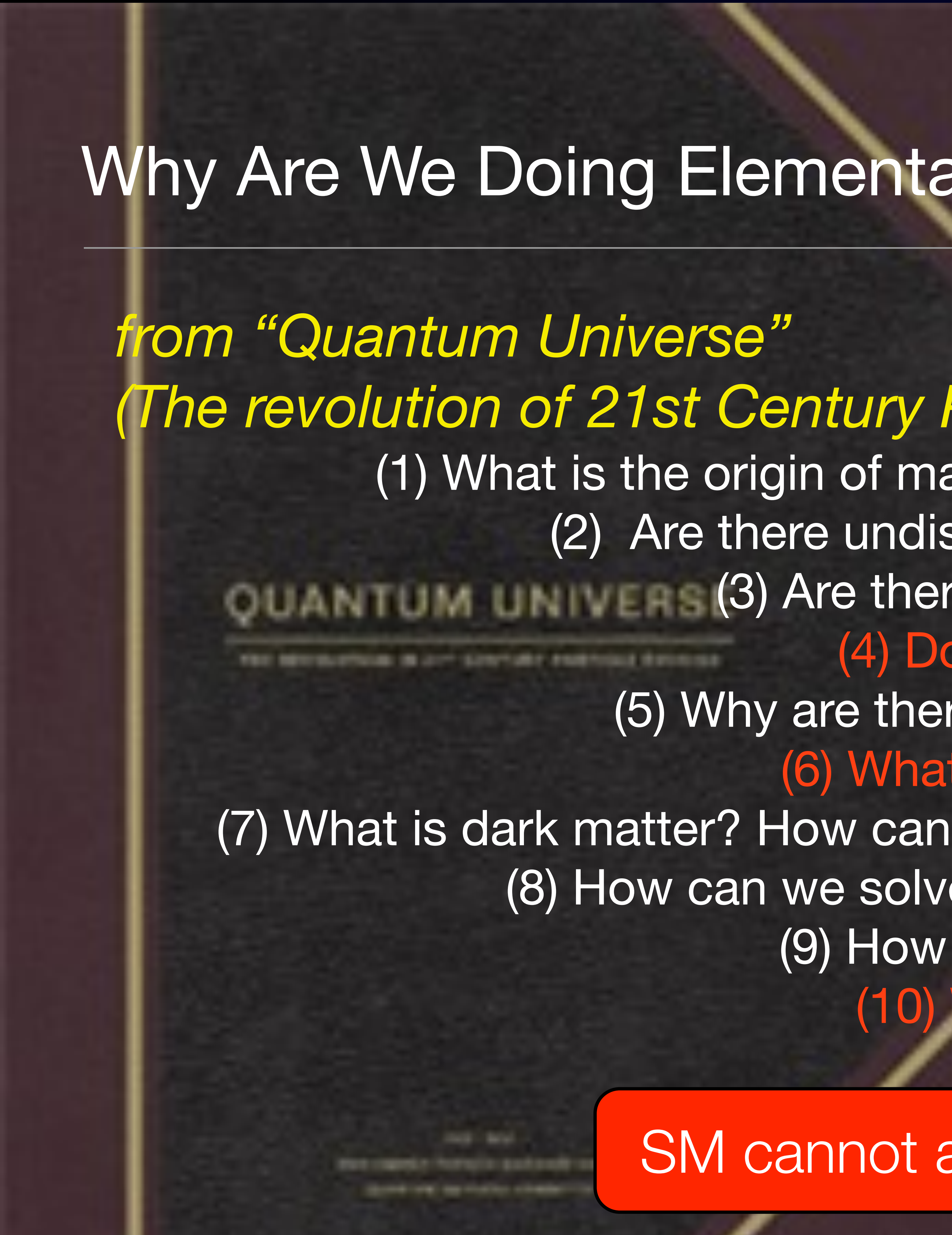

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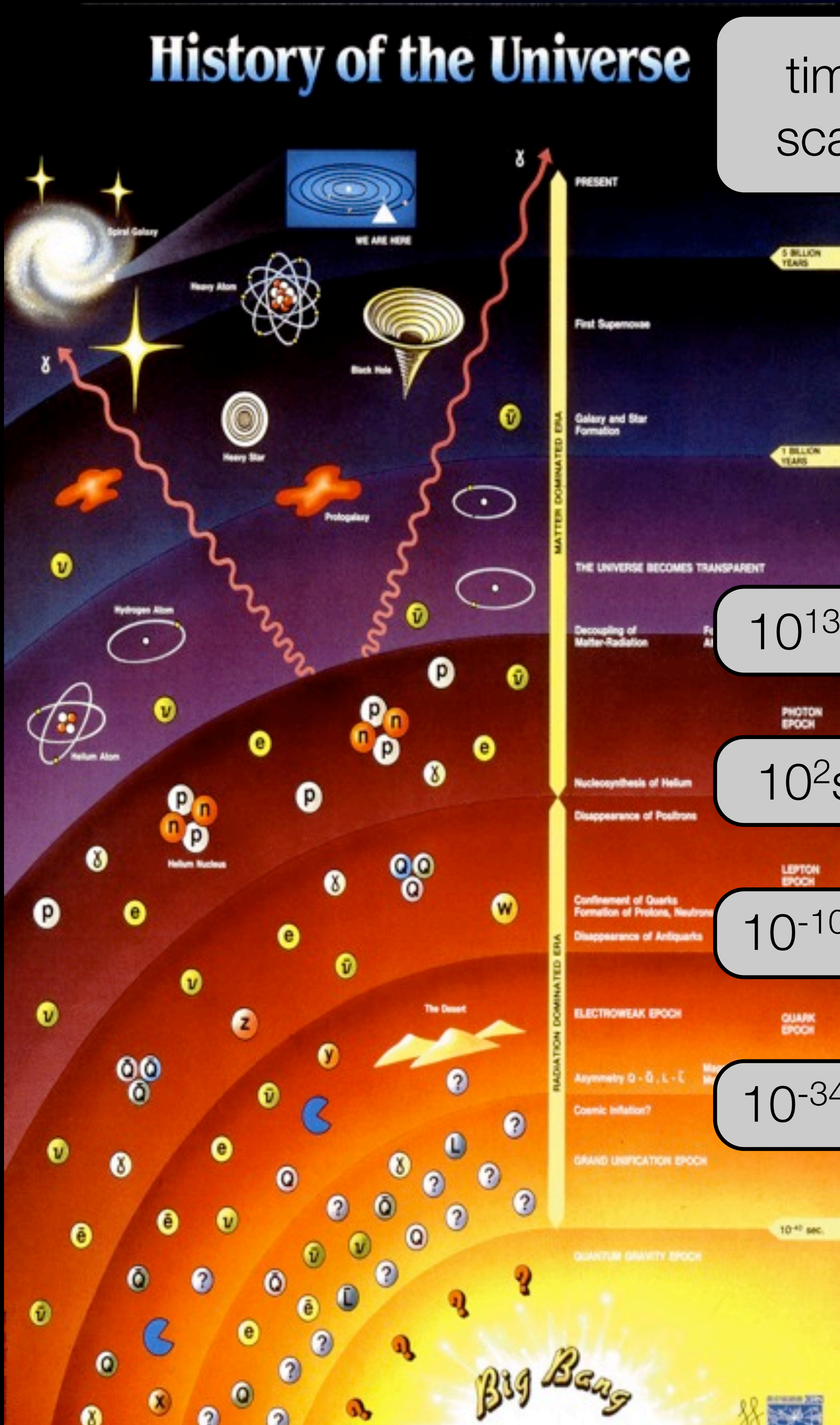
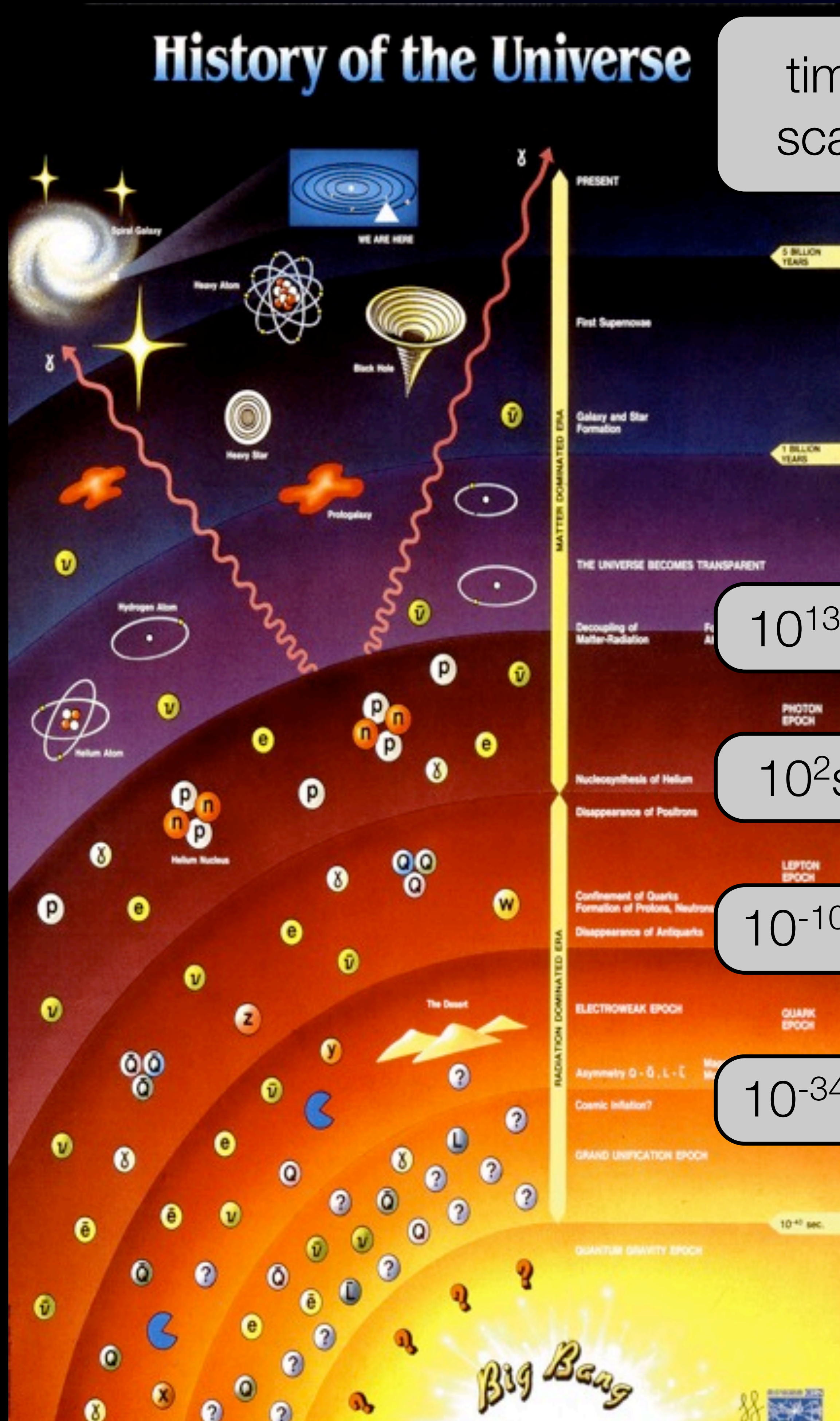


time scale	energy scale
10^{13}sec	10^{-9}GeV
10^{2}sec	10^{-3}GeV
10^{-10}sec	10^{2}GeV
10^{-34}sec	10^{16}GeV
	10^{19}GeV

Electroweak Epoch
- Higgs particles
- Supersymmetry

Unification Epoch
- Grand unification of fundamental forces
- Origin of Neutrino mass (RH neutrino)
- Leptogenesis (baryogenesis)

Quantum Gravity Epoch
- Superstrings



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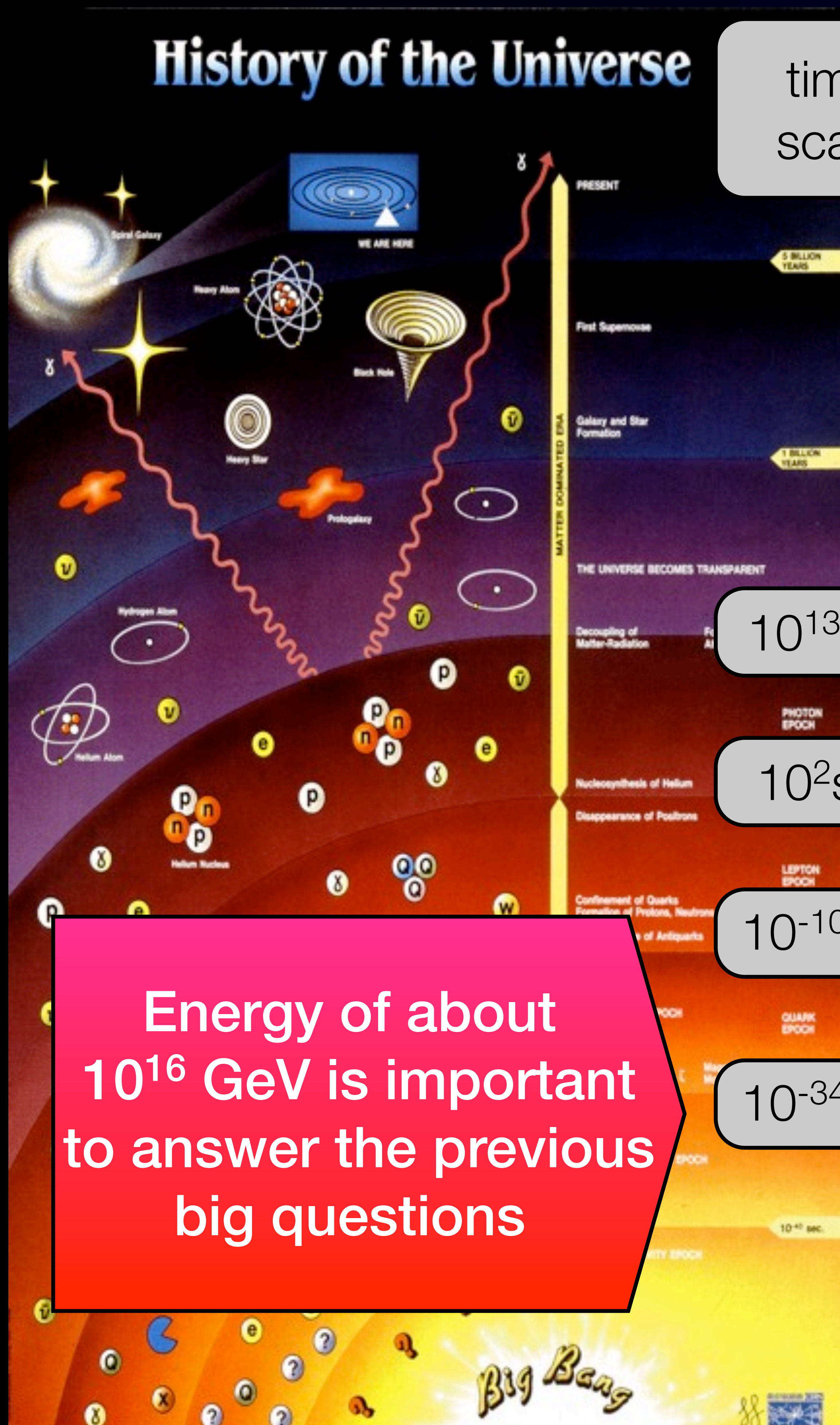

Energy of about 10^{16} GeV is important to answer the previous big questions

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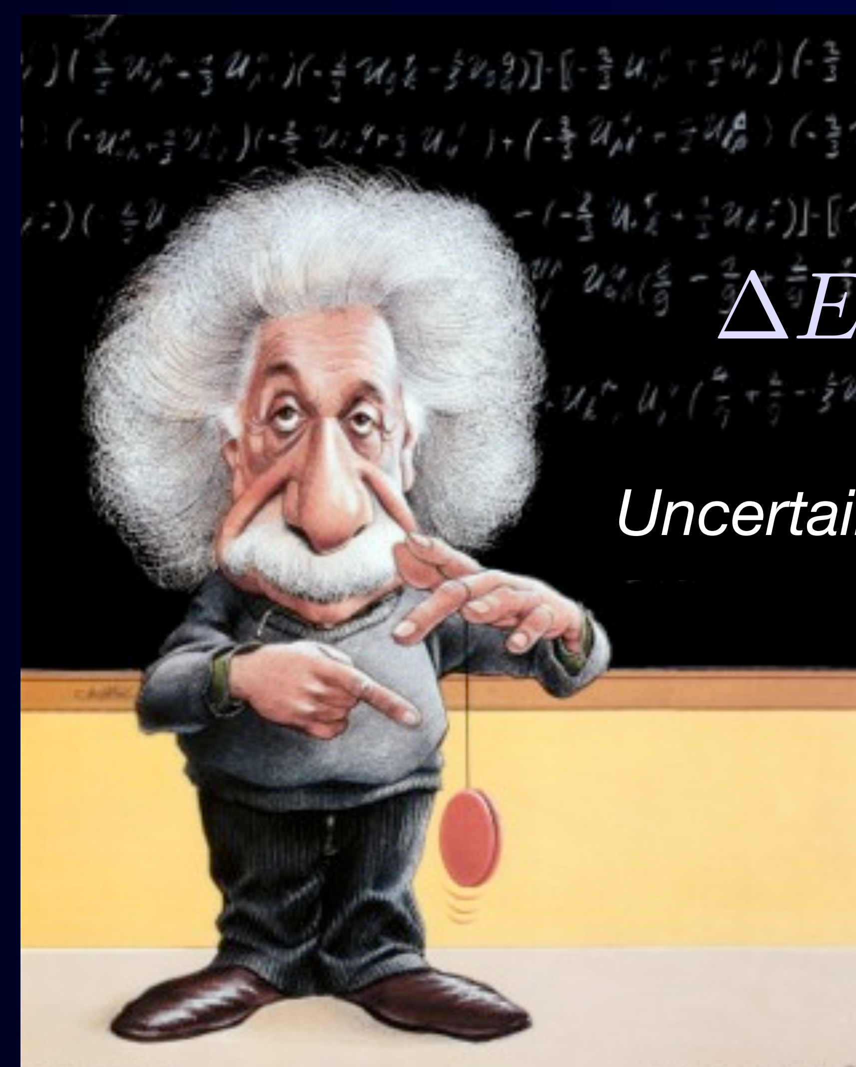
The Intensity Frontier is.....

- Energy scale reached by the intensity frontier would be much higher than that of accelerators of O(1 TeV) through quantum radiative corrections (renormalization equation group).

Quantum Corrections

- Effects are small.
  - Rare process searches
  - High precision measurements
- High intensity machine is needed.
- Indirect searches

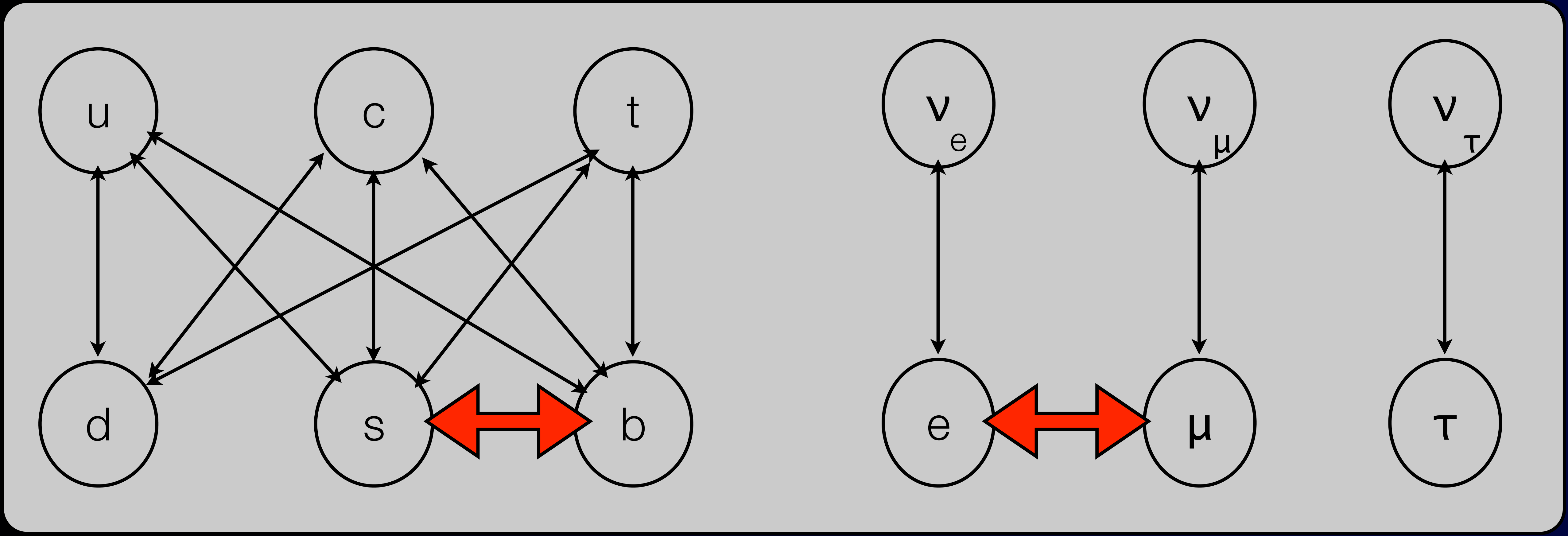


$$\Delta E \sim \frac{\hbar}{2\Delta t}$$

Uncertainty principle

Which Processes for New Physics in Low Energy ?

- Processes which are forbidden or highly suppressed in the Standard Model would be the best ones to search for new physics beyond the Standard Model.
- Flavor Changing Neutral Current Process (FCNC)



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- FCNC in the quark sector
  - $b \to s\gamma$, $K \to \pi\nu\nu$, etc.
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  - Need to study deviations from the SM predictions.
    - Uncertainty of more than a few % (from QCD) exists.

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  - Need to study deviations from the SM predictions.
    - Uncertainty of more than a few % (from QCD) exists.
- FCNC in the lepton sector
  - $\mu \to e\gamma$, $\mu+N \to e+N$, etc. (lepton flavor violation =LFV)
  - Not allowed in the Standard Model ($\sim 10^{-50}$ with neutrino mixing)
  - Need to study deviations from none
    - clear signature and high sensitivity

Why Muons for the Intensity Frontier ?

Guidelines for Rare Process Searches

(1) Many particles are needed

The muon is the lightest unstable particle and therefore given energy, more muons can be produced.

(2) Theoretical uncertainty should be small.

The muon does not have strong interaction, and therefore the processes with muons are theoretically clean.

Why Muons, not Taus for LFV Search ?

- A number of taus available at B factories are about 1-10 taus/sec. At super-B factories, about 100 taus/sec are considered. Also some of the decay modes are already background-limited.
  - intensity improvement factor of about O(10).

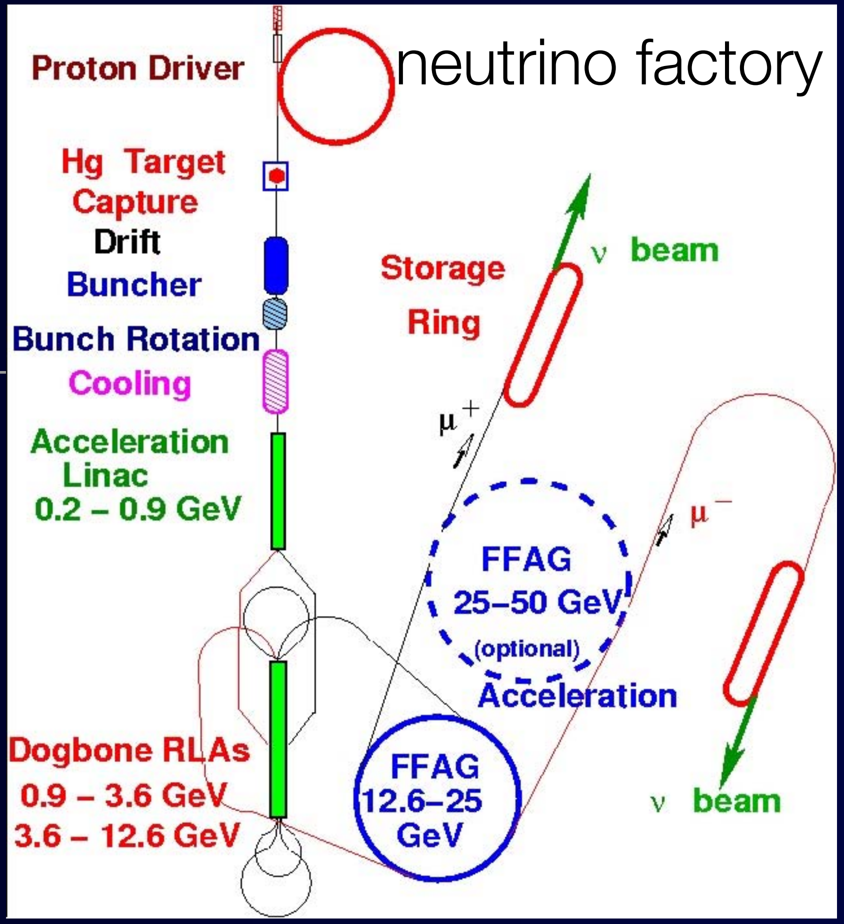
- The number of muons available now, which is about 10^{8} muons/sec at PSI, is the largest. Next generation experiments aim 10^{11}-10^{12} muons/sec. With the technology of the front end of muon colliders and/or neutrino factories, about 10^{13}-10^{14} muons/sec are considered.
  - intensity improvement factor of about O(1,000,000)

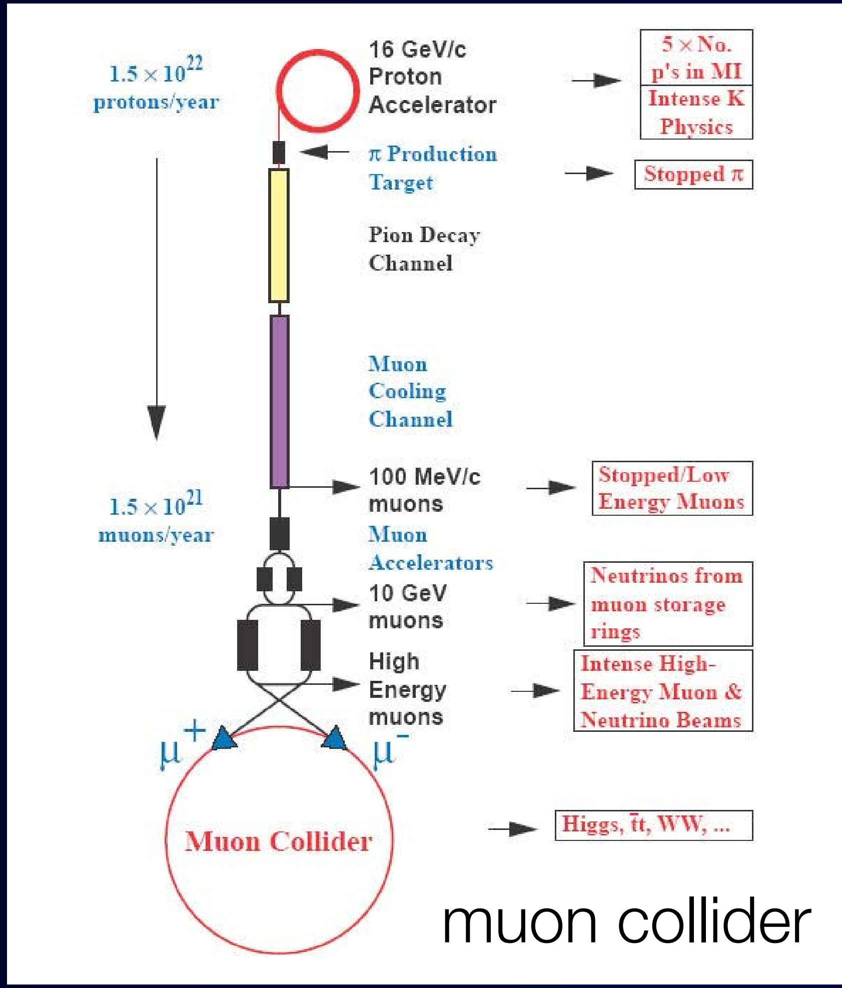
Synergy in Technology between Muon Physics and MCNF

How to make many muons ?

- Now, muon intensity of ~10^8 /sec at PSI.
- In future, the intensity can be 10^{11}-10^{14} / sec, with the technology developed for the front end R&D of muon colliders and/or neutrino factories (an improvement factor of up to about O(1,000,000).
- Technical ideas, which can be used for low-energy muon physics, are
    - pion solenoid capture
    - phase rotation / cooling

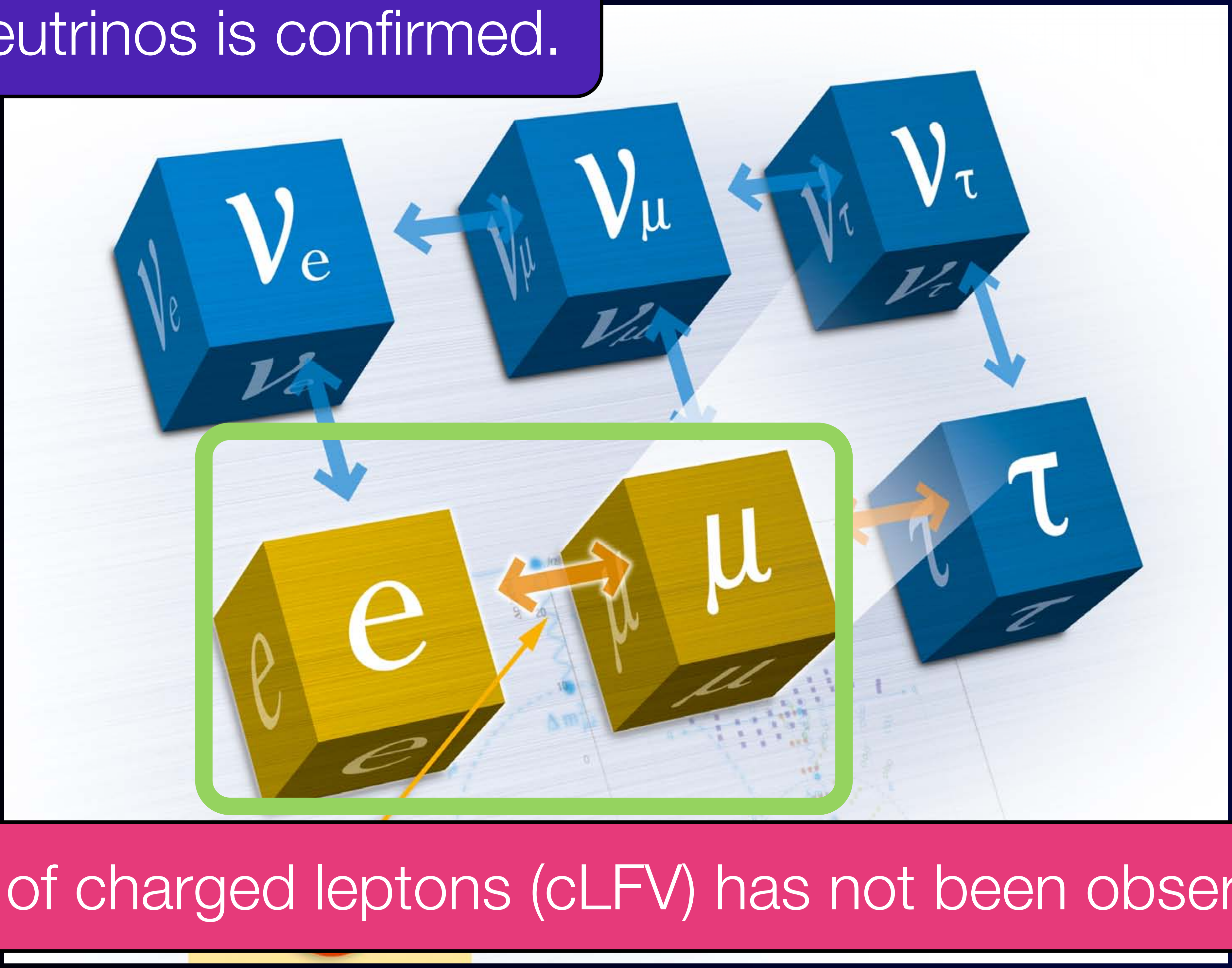
high power protons + new technology





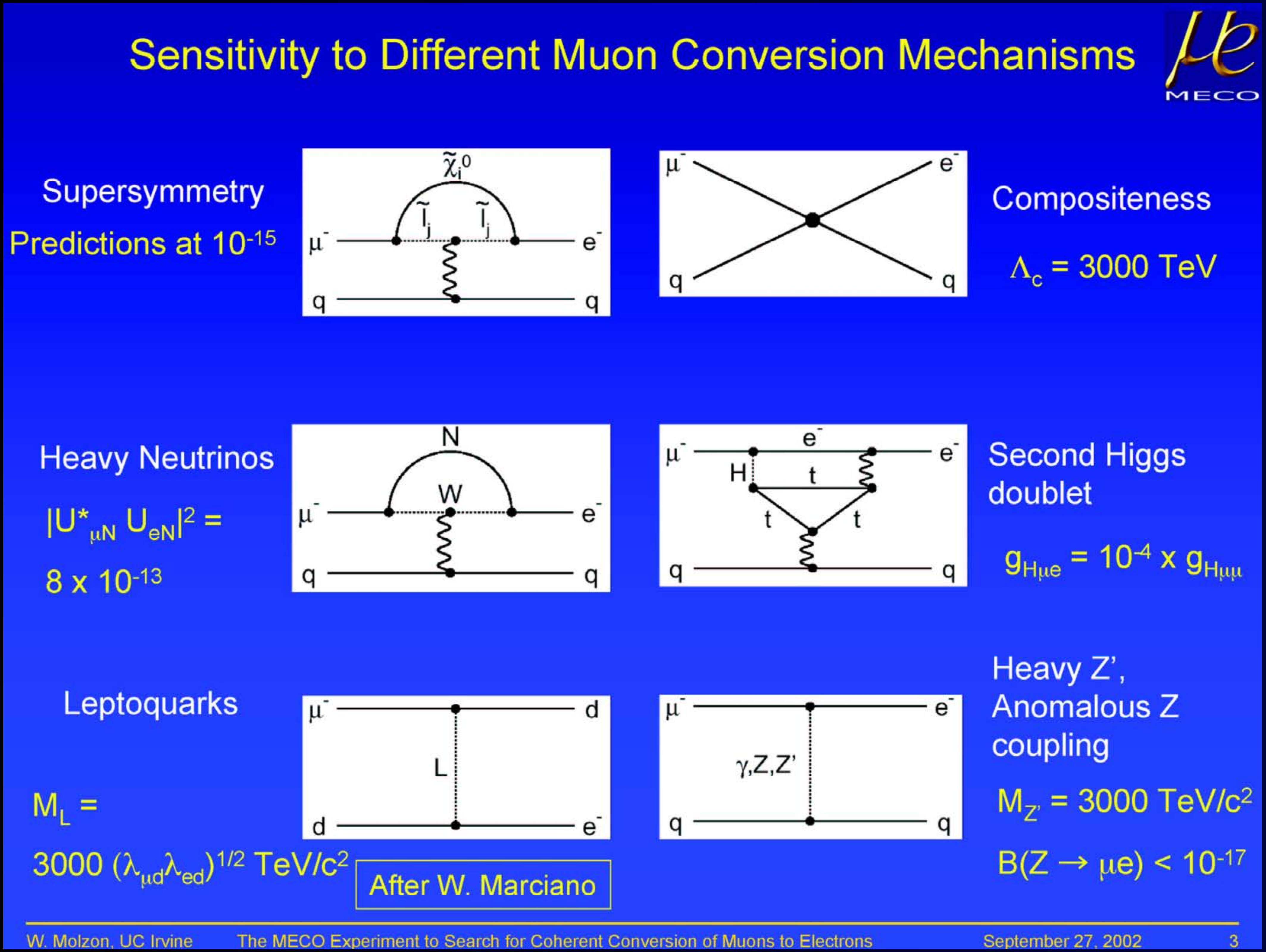
What is Lepton Flavor Violation of Charged Leptons (cLFV) ?

LFV of neutrinos is confirmed.



LFV of charged leptons (cLFV) has not been observed.

Various Models Predict Charged Lepton Mixing.



New Physics Search Rating (A. Buras)

W. Altmannshofer, A.J. Buras, S. Gori, P. Paradisi, D.M. Straub, . **Nucl.Phys.B830:17-94 ,2010**.

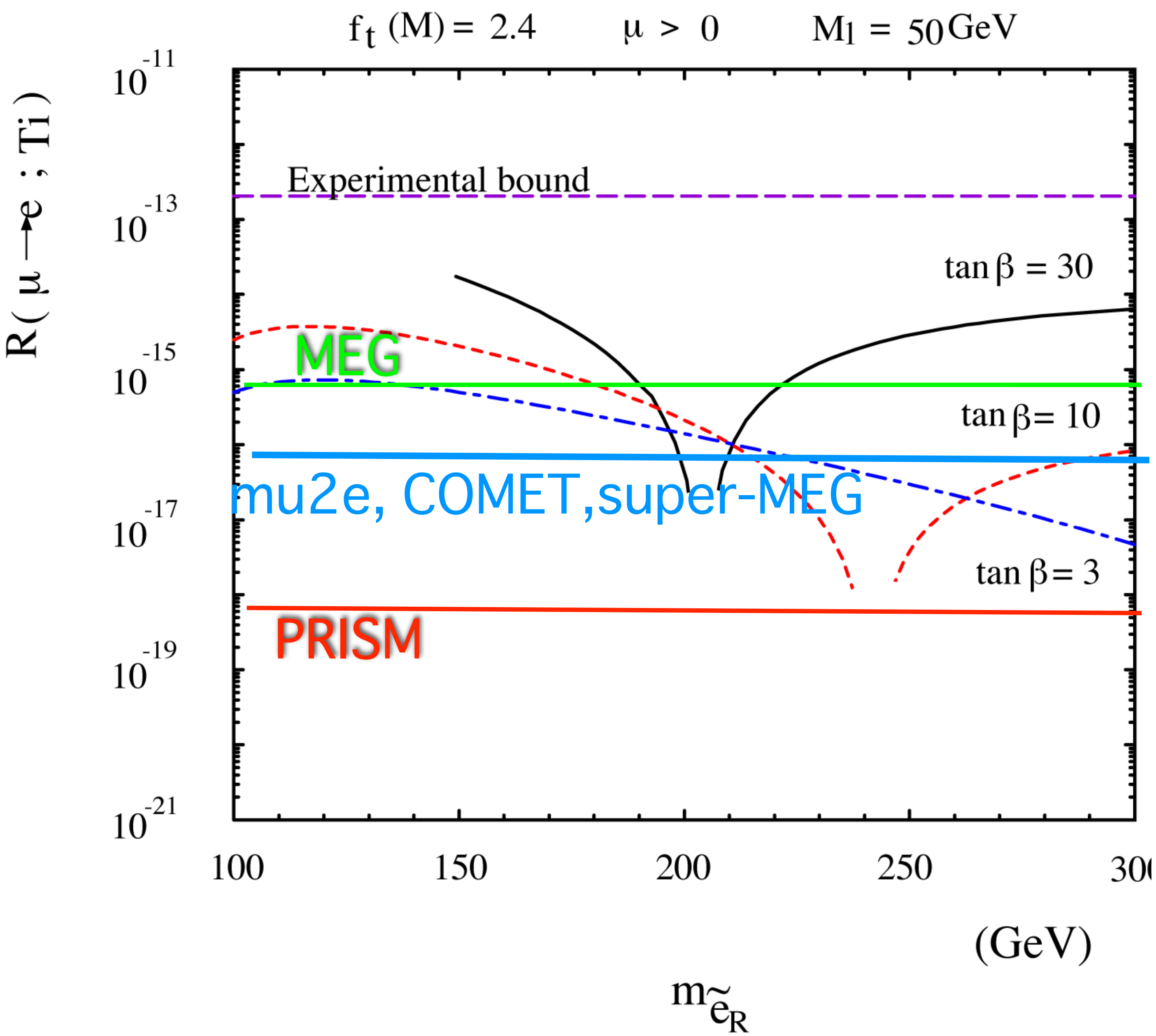
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}\,(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

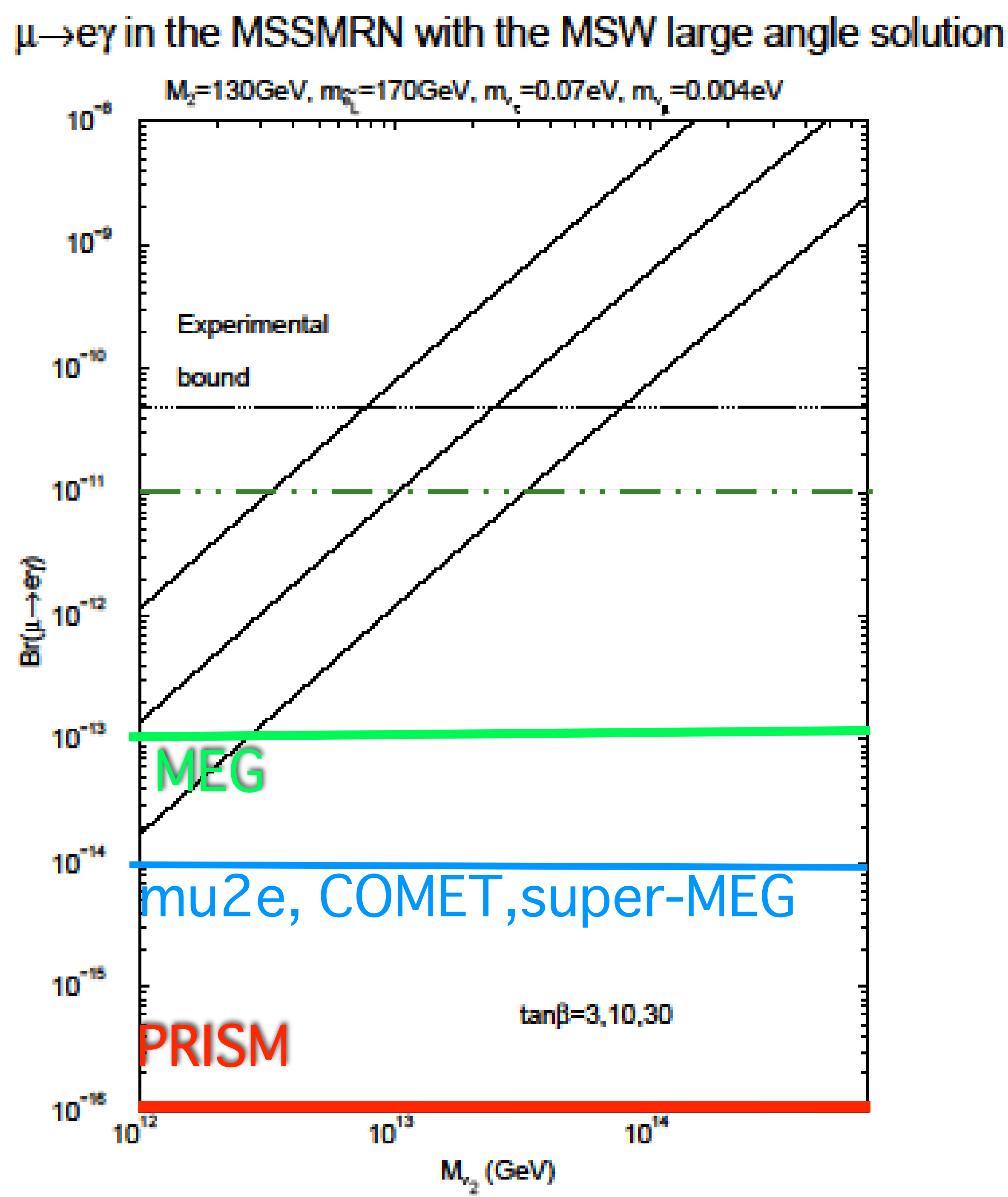
Different theoretical models

All three stars for "muon to electron conversion"

SUSY Predictions for cLFV

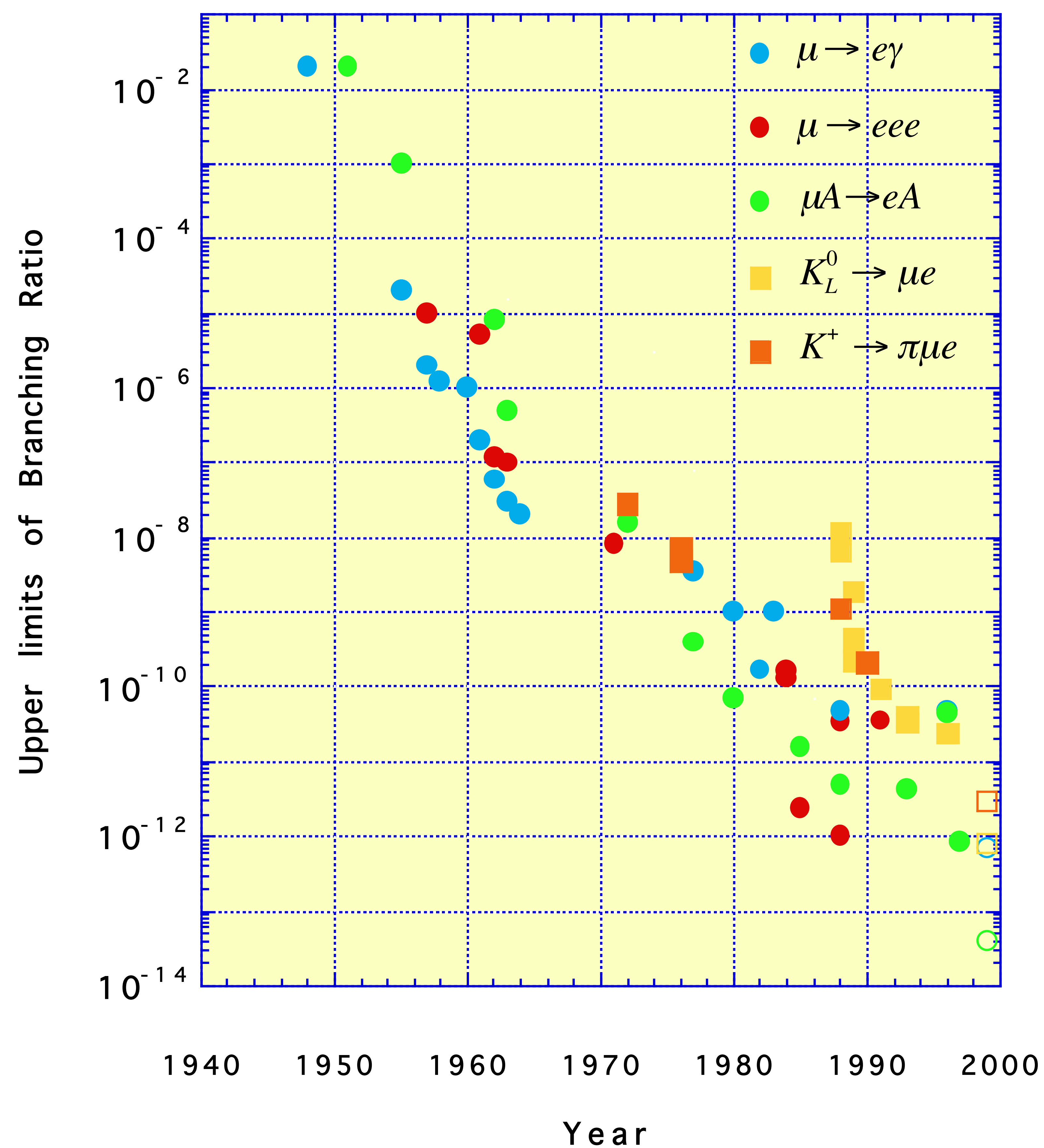


SU(5) SUSY GUT



SUSY Seesaw Model

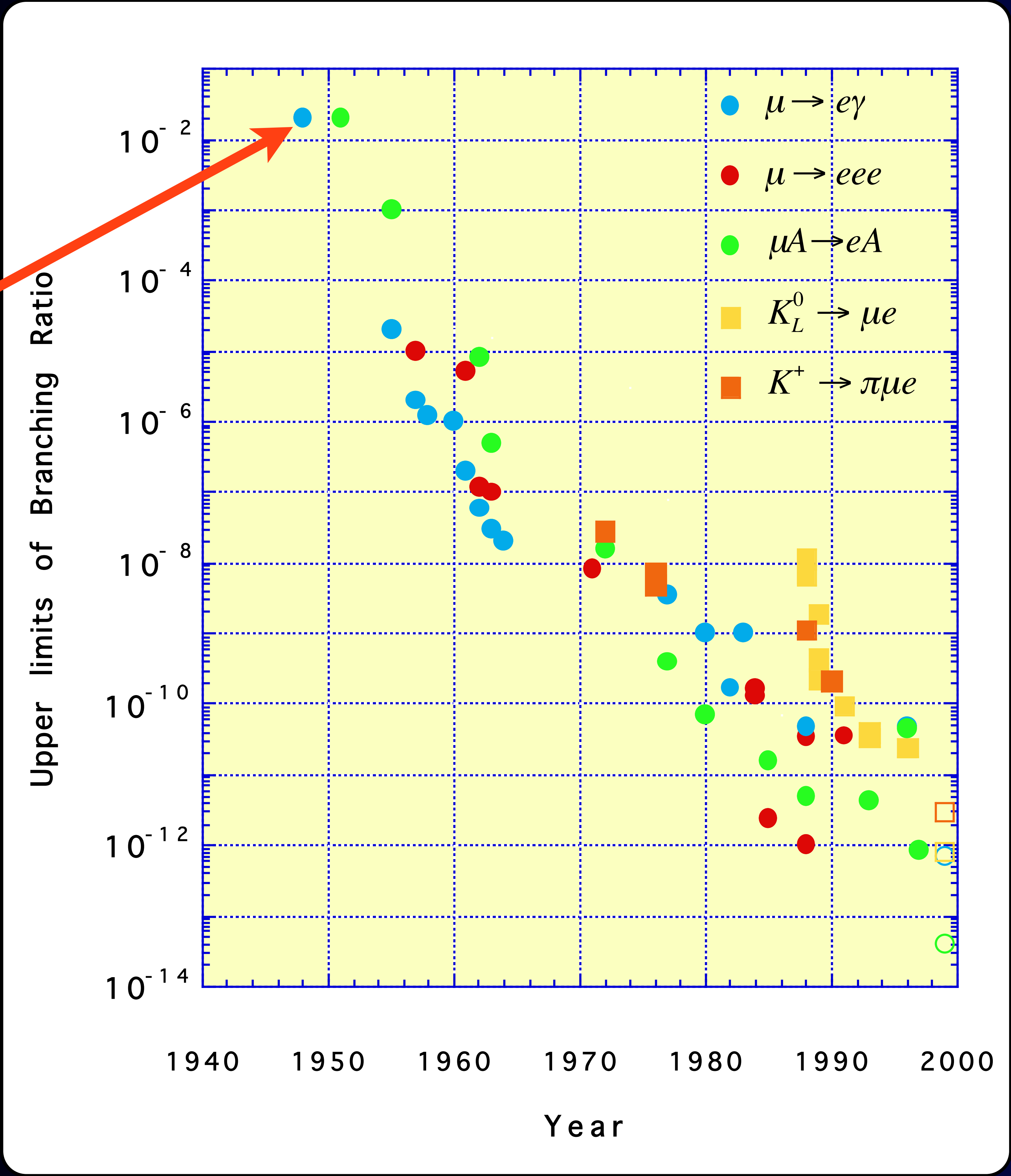
cLFV History



cLFV History

First cLFV search

Pontecorvo in 1947



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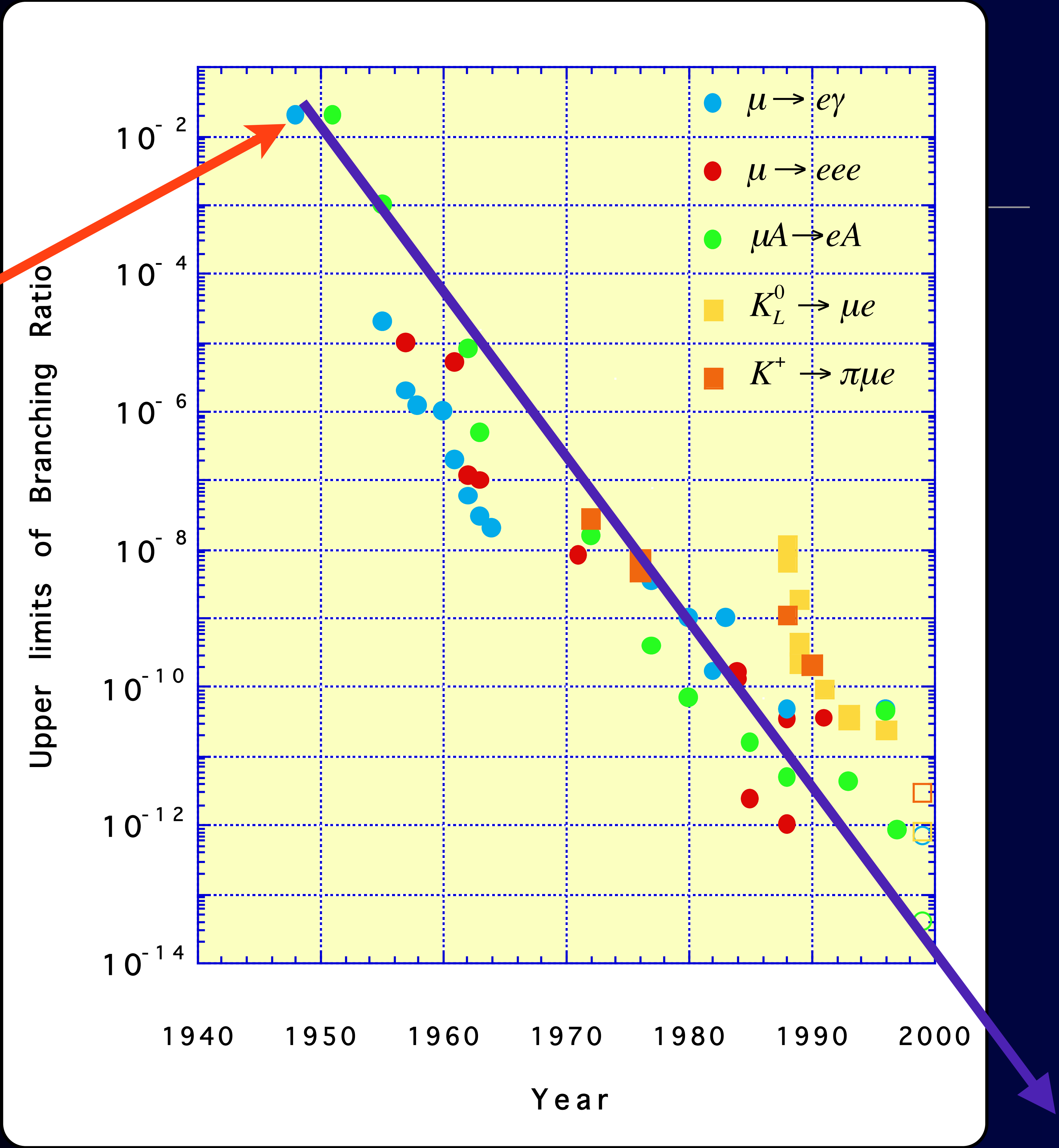
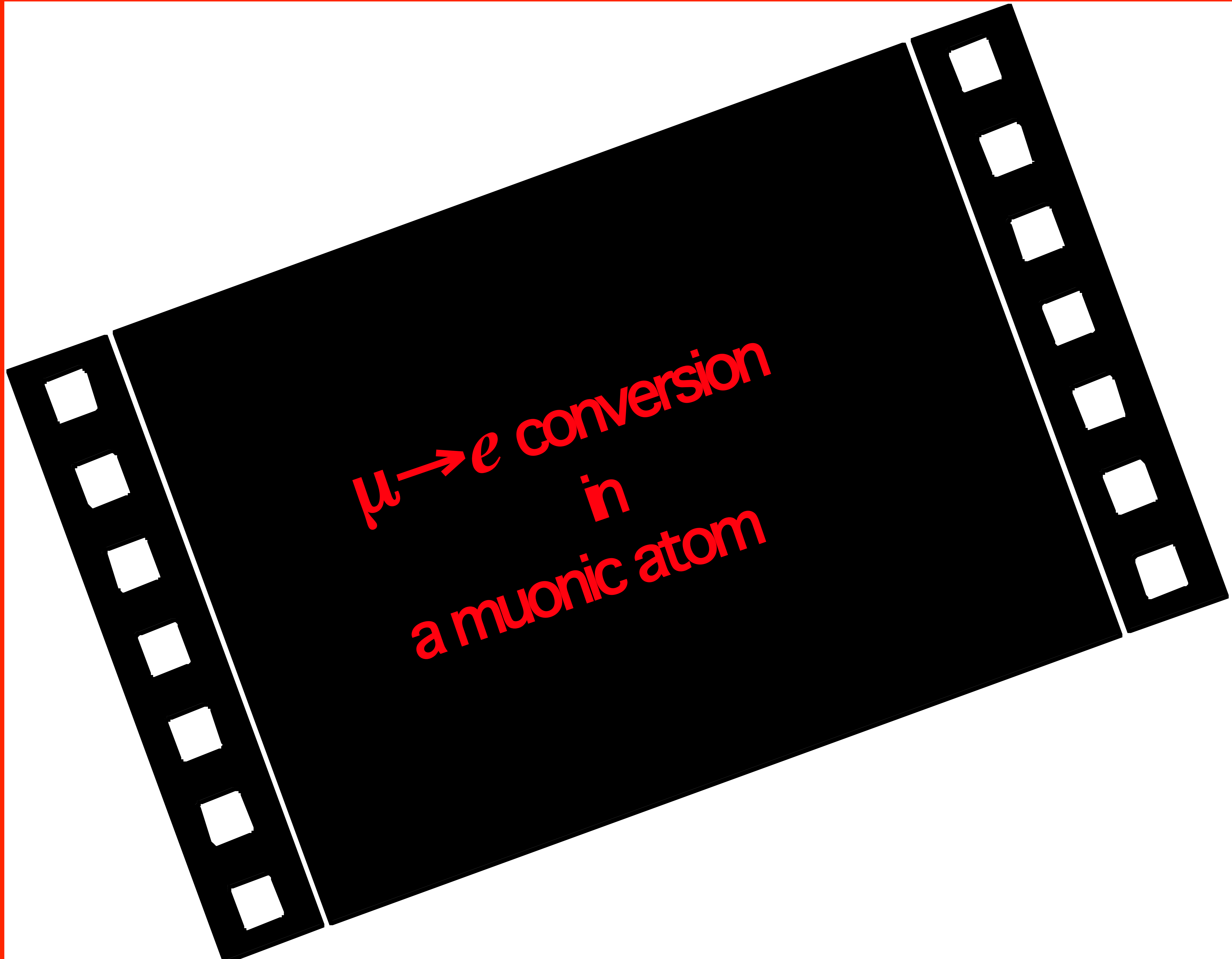


Present Limits and Expectations in Future

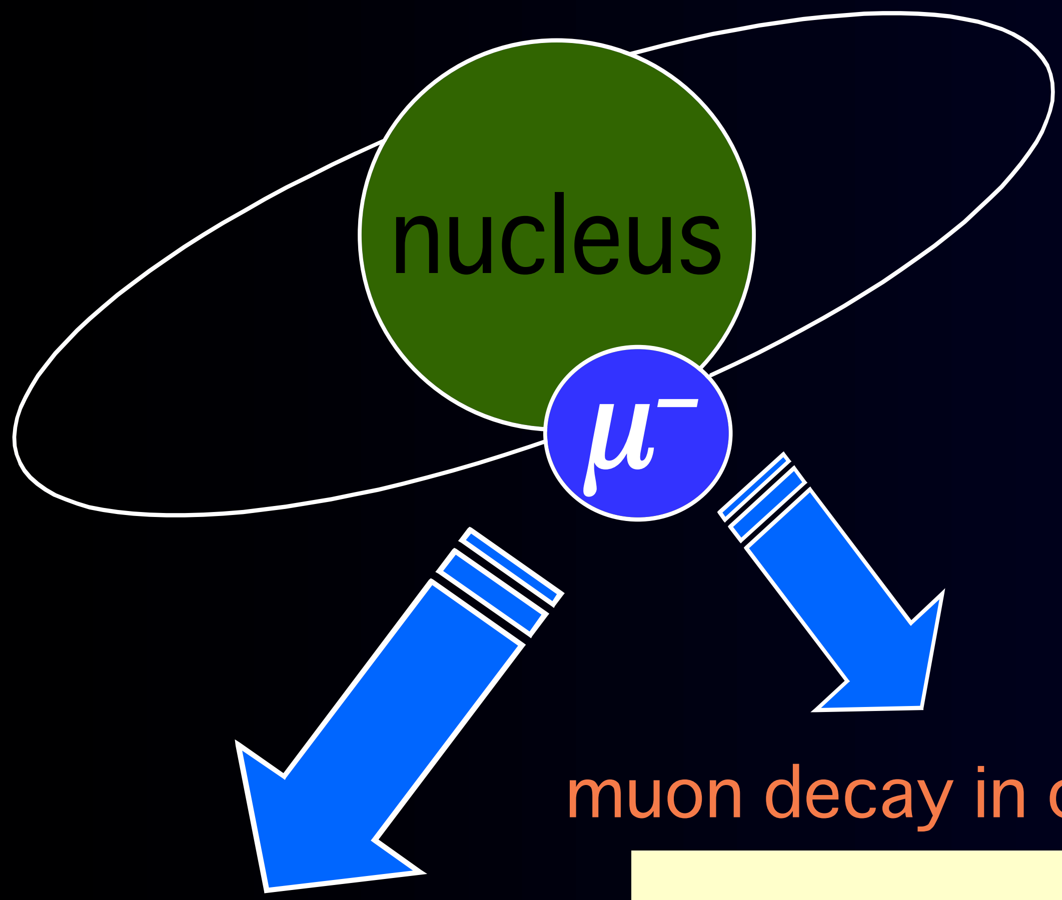
process	present limit	future	
$\mu \to e\gamma$	$<1.2 \times 10^{-11}$	$<10^{-13}$	MEG at PSI
$\mu \to eee$	$<1.0 \times 10^{-12}$	$<10^{-13} - 10^{-14}$	?
$\mu N \to eN$ (in Al)	none	$<10^{-16}$	Mu2e / COMET
$\mu N \to eN$ (in Ti)	$<4.3 \times 10^{-12}$	$<10^{-18}$	PRISM
$\tau \to e\gamma$	$<1.1 \times 10^{-7}$	$<10^{-9} - 10^{-10}$	super B factory
$\tau \to eee$	$<3.6 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	super B factory
$\tau \to \mu\gamma$	$<4.5 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	super B factory
$\tau \to \mu\mu\mu$	$<3.2 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	super B factory



$\mu \rightarrow e$ conversion
in
a muonic atom

What is a Muon to Electron Conversion ?

1s state in a muonic atom



muon decay in orbit

$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

nuclear muon capture

$$\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$$

Neutrino-less muon nuclear capture (=μ-e conversion)

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

lepton flavors changes by one unit.

$$B(\mu^- N \rightarrow e^- N) = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu N')}$$

μ-e Conversion Signal and Backgrounds

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

- Signal
  - single mono-energetic electron

$$m_\mu - B_\mu \sim 105 MeV$$

- The transition to the ground state is a coherent process, and enhanced by a number of nucleus.

$$\propto Z^5$$

- Backgrounds
  - Intrinsic physics background
    - muon decay in orbit (DIO)
  - beam-related background
    - radiative pion capture
    - muon decay in flight (DIF)
  - cosmic-ray background
  - tracking failure
  - etc....

Improvements for Signal Sensitivity

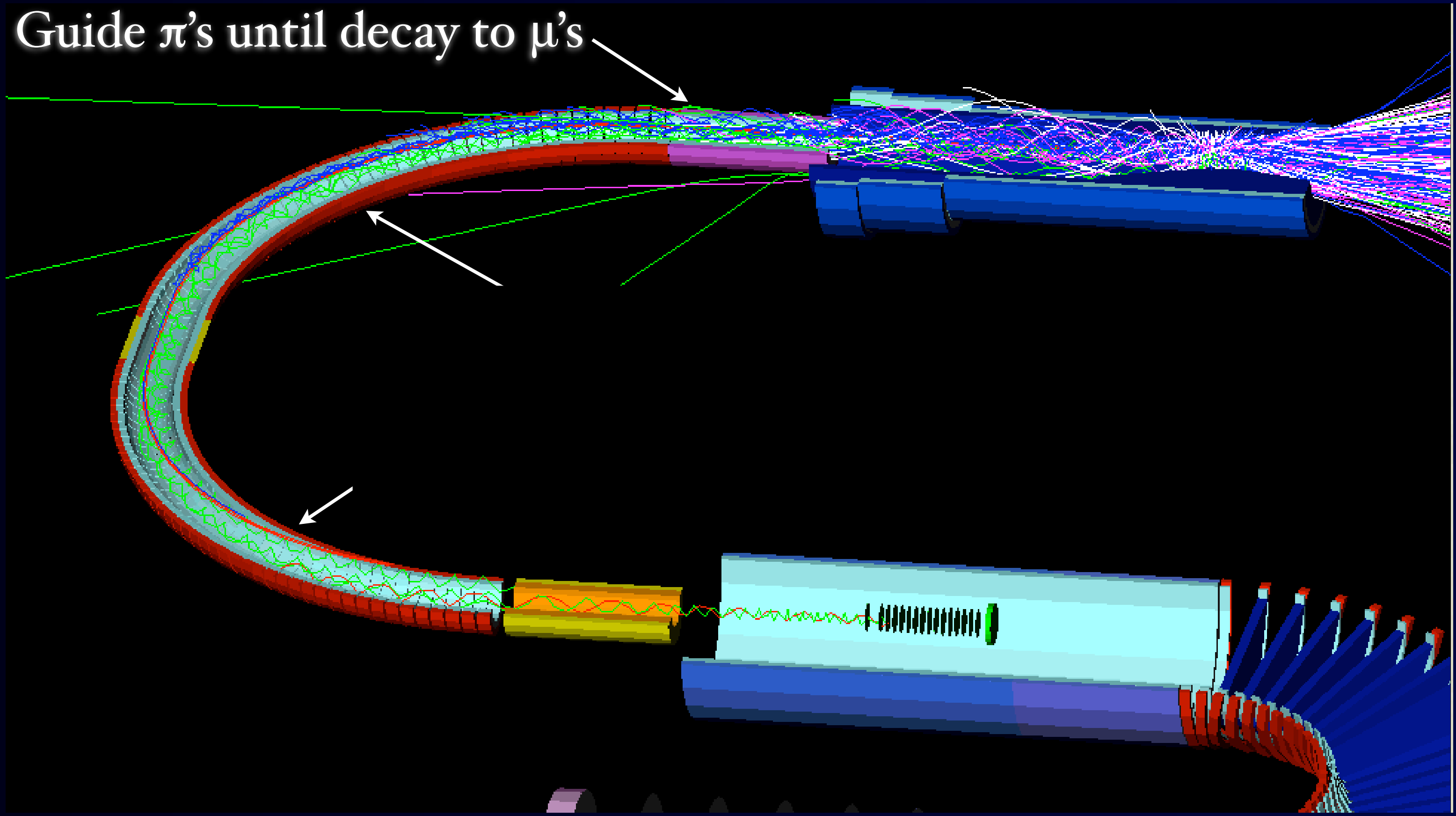
To achieve a single sensitivity of 10^{-16}, we need

10^{11} muons/sec (with 10^{7} sec running)

whereas the current highest intensity is 10^{8}/sec at PSI.

Pion Capture and Muon Transport by Superconducting Solenoid System

(10^{11} muons for 50 kW beam power)



Improvements for Background Rejection

Beam-related backgrounds → Beam pulsing with separation of 1μsec — measured between beam pulses

proton extinction = #protons between pulses/#protons in a pulse $< 10^{-9}$

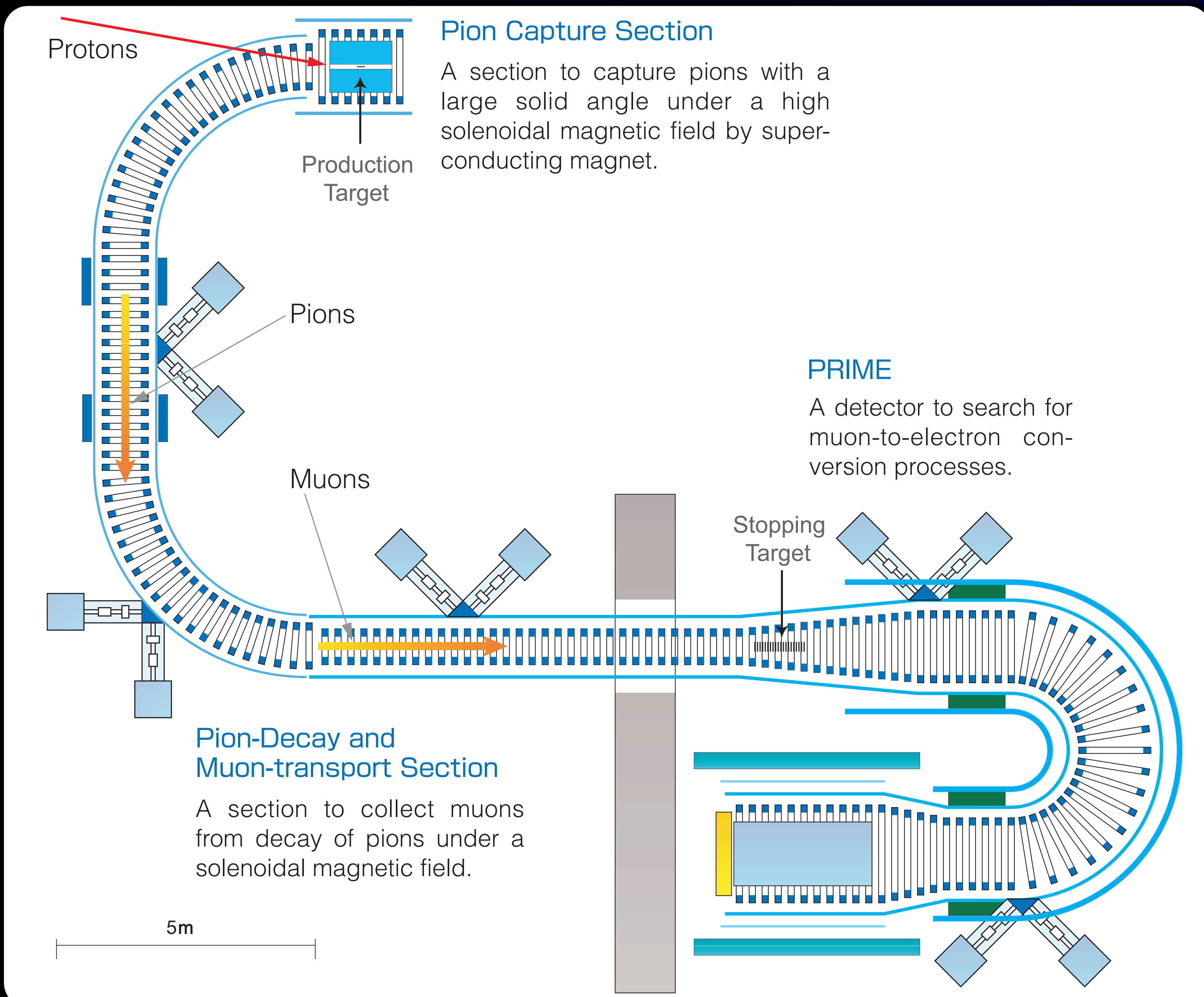
Muon DIO background → low-mass trackers in vacuum & thin target — improve electron energy resolution

Muon DIF background → curved solenoids for momentum selection — eliminate energetic muons (>75 MeV/c)

base on the MELC proposal at Moscow Meson Factory

COMET (COherent Muon to Electron Transition) in Japan

$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$$



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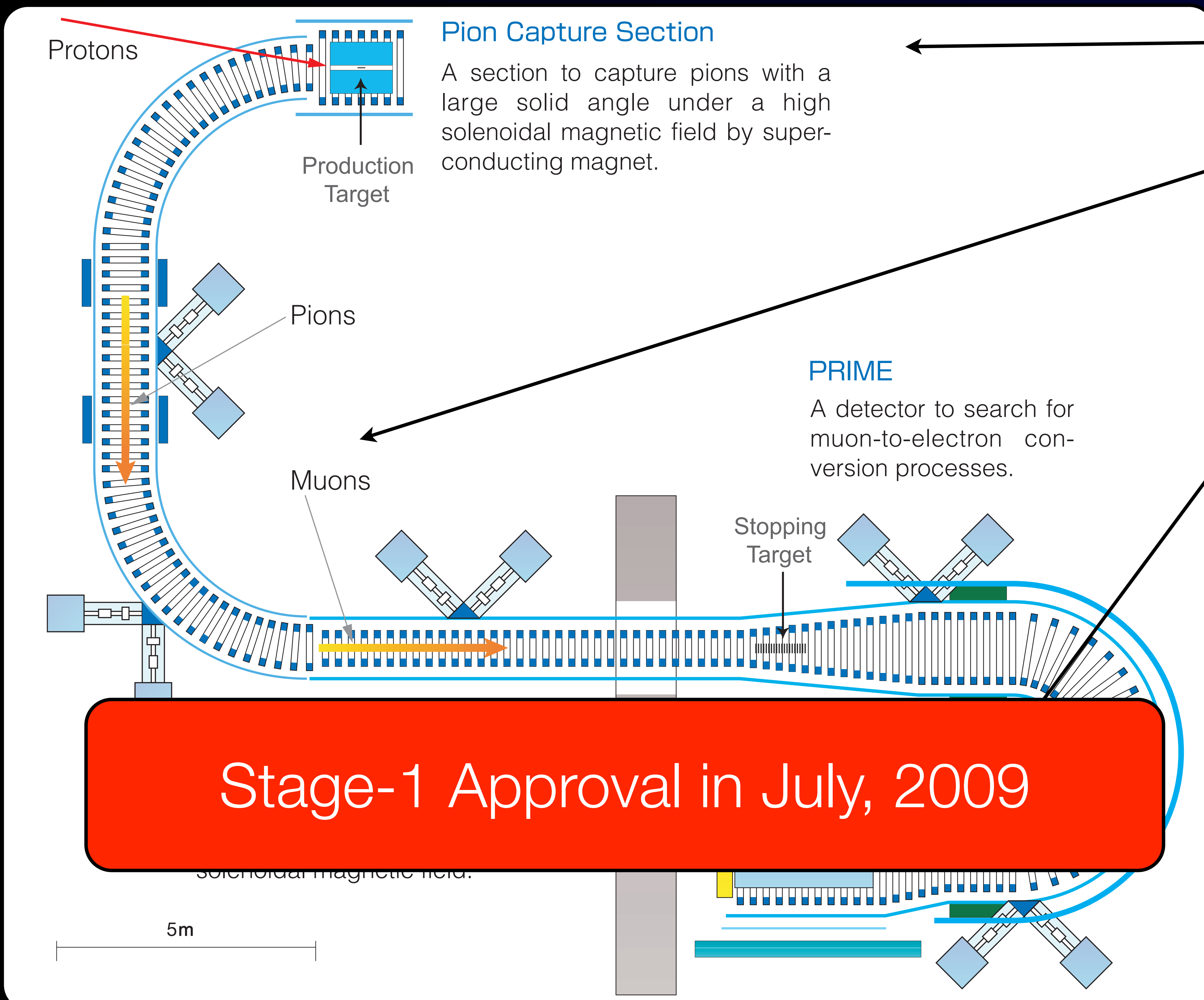

Stage-1 Approval in July, 2009

Proton Beam

The Muon Source
- Proton Target
- Pion Capture
- Muon Transport

The Detector
- Muon Stopping Target
- Electron Transport
- Electron Detection

proposed to J-PARC

COMET Collaboration List

49 people from 14 institutes (April 2010)

Imperial College London, UK
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University College London, UK
M. Wing, M. Lancaster, R. D'Arcy

University of Glasgow
P. Soler

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V. Kalinnikov, A. Moiseenko, D. Mzhavia, J. Pontecorvo, B. Sabirov, Z. Tsamaiaidze, and P. Evtukhouvich

BINP, Novosibirsk, Russia
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TRIUMF, Canada
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R. Palmer, Y. Cui

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Y. Arimoto, Y. Igarashi, S. Ishimoto, S. Mihara, H. Nishiguchi, T. Ogitsu, M. Tomizawa, A. Yamamoto, M. Yoshida and K. Yoshimura

Signal Sensitivity (preliminary) - 2×10^7 sec

- Single event sensitivity

$$B(\mu^- + Al \rightarrow e^- + Al) \sim \frac{1}{N_\mu \cdot f_{cap} \cdot A_e},$$

  - N_μ is a number of stopping muons in the muon stopping target. It is 2×10^{18} muons.
  - f_{cap} is a fraction of muon capture, which is 0.6 for aluminum.
  - A_e is the detector acceptance, which is 0.04.

total protons muon transport efficiency muon stopping efficiency	8.5×10^{20} 0.008 0.3
# of stopped muons	2.0×10^{18}

$$B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17}$$

$$B(\mu^- + Al \rightarrow e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)$$

Background Rates

Radiative Pion Capture	0.05
Beam Electrons	< 0.1[‡]
Muon Decay in Flight	< 0.0002
Pion Decay in Flight	< 0.0001
Neutron Induced	0.024
Delayed-Pion Radiative Capture	0.002
Anti-proton Induced	0.007
Muon Decay in Orbit	0.15
Radiative Muon Capture	< 0.001
μ^- Capt. w/ n Emission	< 0.001
μ^- Capt. w/ Charged Part. Emission	< 0.001
Cosmic Ray Muons	0.002
Electrons from Cosmic Ray Muons	0.002
Total	0.34

[‡] Monte Carlo statistics limited.

beam-related prompt backgrounds

beam-related delayed backgrounds

intrinsic physics backgrounds

cosmic-ray and other backgrounds

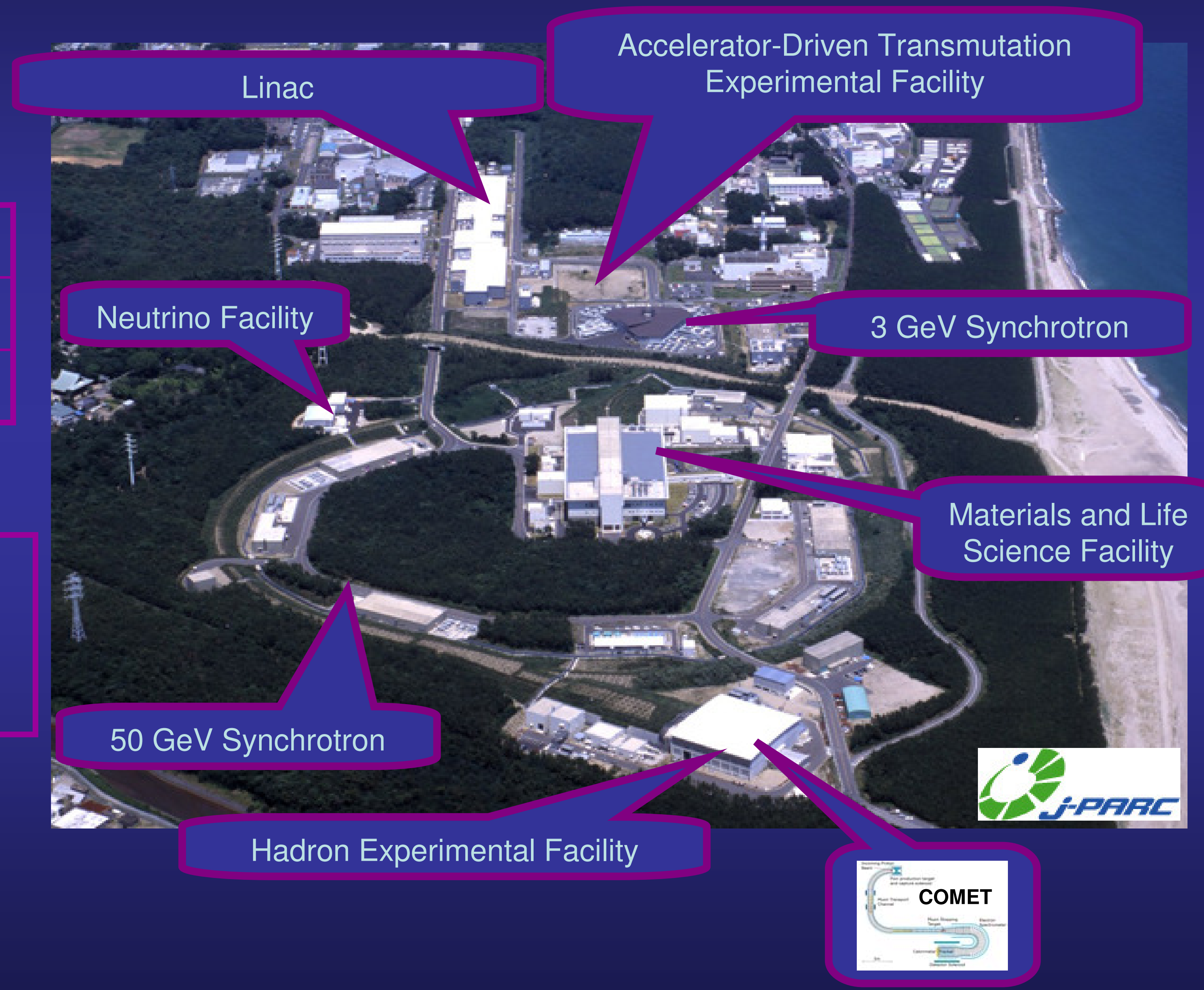
Expected background events are about 0.34.

COMET at J-PARC

Proton beam parameters

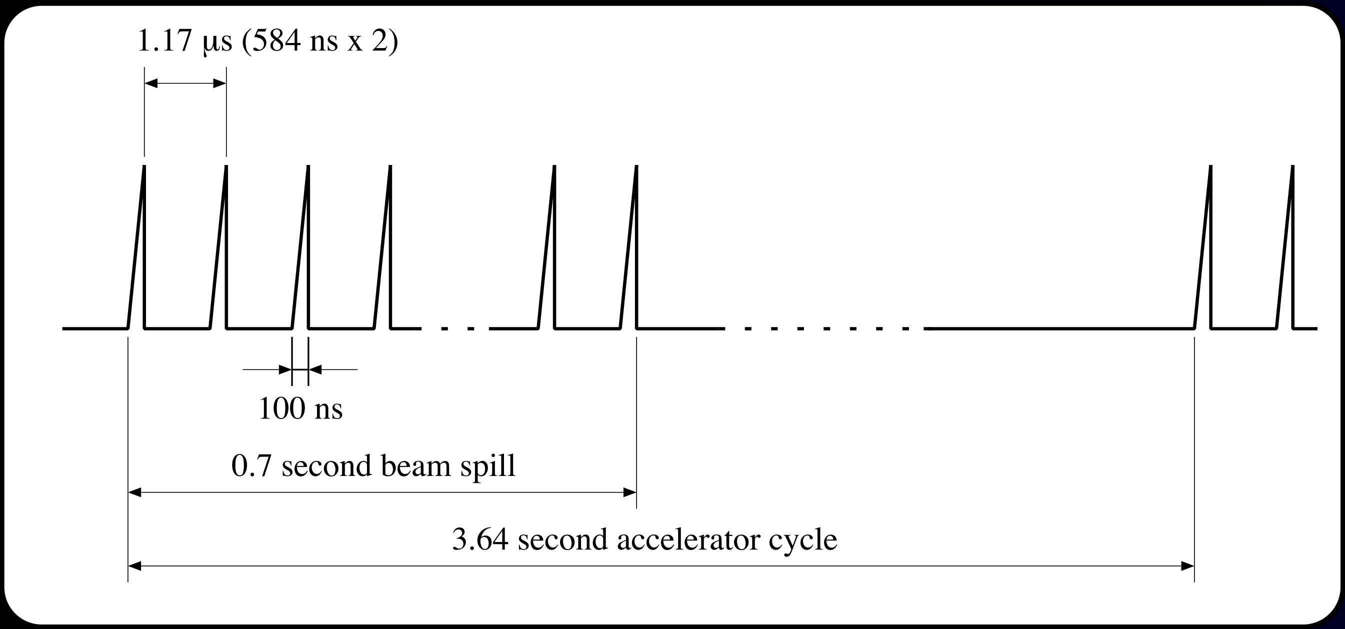
Beam Power	56 kW
Beam Energy	8 GeV
Average Current	7μA

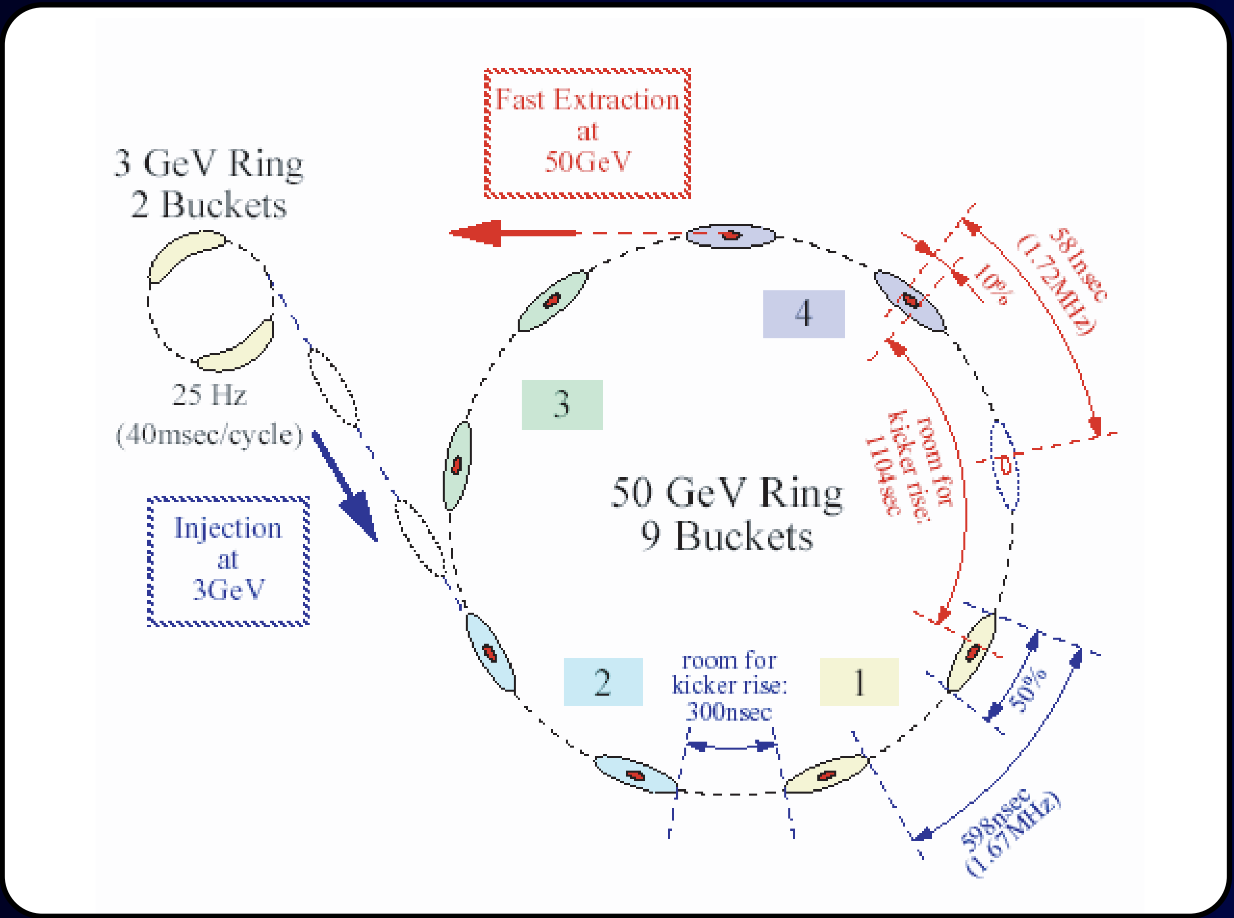
- Slow-extracted proton beam.
- 8 GeV to suppress anti-proton production.



Pulsed Proton Beam at J-PARC

- A pulsed proton beam is needed to reject beam-related prompt background.
- Time structure required for proton beams.
  - Pulse separation is ~ 1μsec or more (muon lifetime).
  - Narrow pulse width (<100 nsec)
- Pulsed beam from slow extraction.
  - fill every other rf buckets with protons and make slow extraction
  - spill length (flat top) ~ 0.7





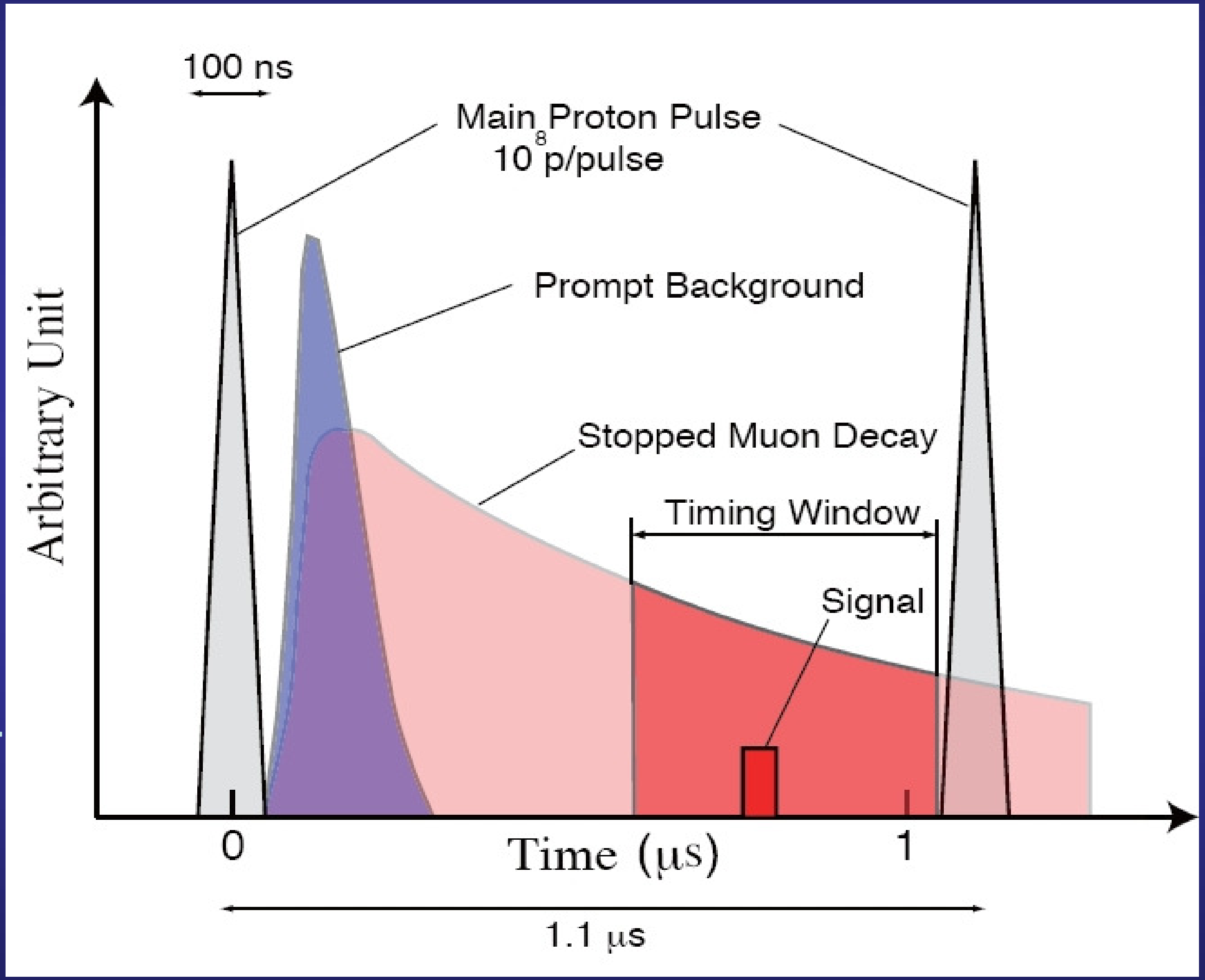
Proton Beam for COMET

- Muonic lifetime is dependent on target Z. For Al lifetime is 880ns.

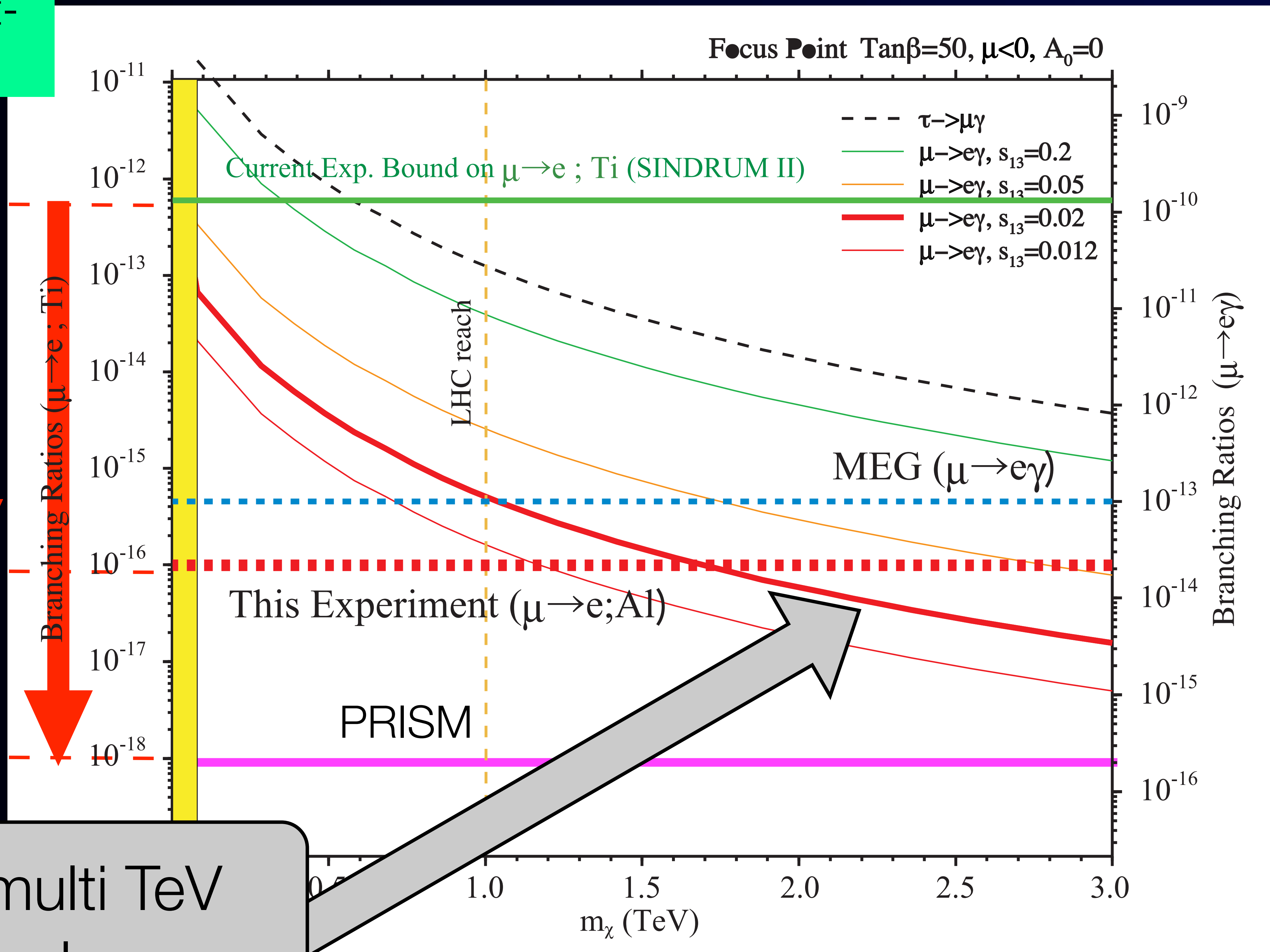
Bunch Structure

Bunch Separation	1.3 µs
Bunch Length	100ns
Protons per Bunch	1.2×10^{8}
Bunches per Spill	5.3×10^{5}
Spill time	0.7s
Extinction	10^{-9}

- Background rate needs to be low in order to achieve sensitivity of $<10^{-16}$.
- Extinction is very important.
  - Without sufficient extinction, all processes in prompt background category could become a problem.



mSUGRA with right-handed neutrinos



will be improved by a factor of 10,000.

will be improved by a factor of 1000,000.

sensitive to multi TeV energy scale.

Sensitivity Goals

$$B(\mu^- + Al \to e^- + Al) < 10^{-16}$$

$$B(\mu^- + Ti \to e^- + Ti) < 10^{-18}$$

Further Background Rejection to < 10^{-18}

mono-energetic muon beam

Muon DIO background → narrow muon beam spread — 1/10 thickness muon stopping target

pure muon beam

Pion background → long muon beam-line — muon storage ring

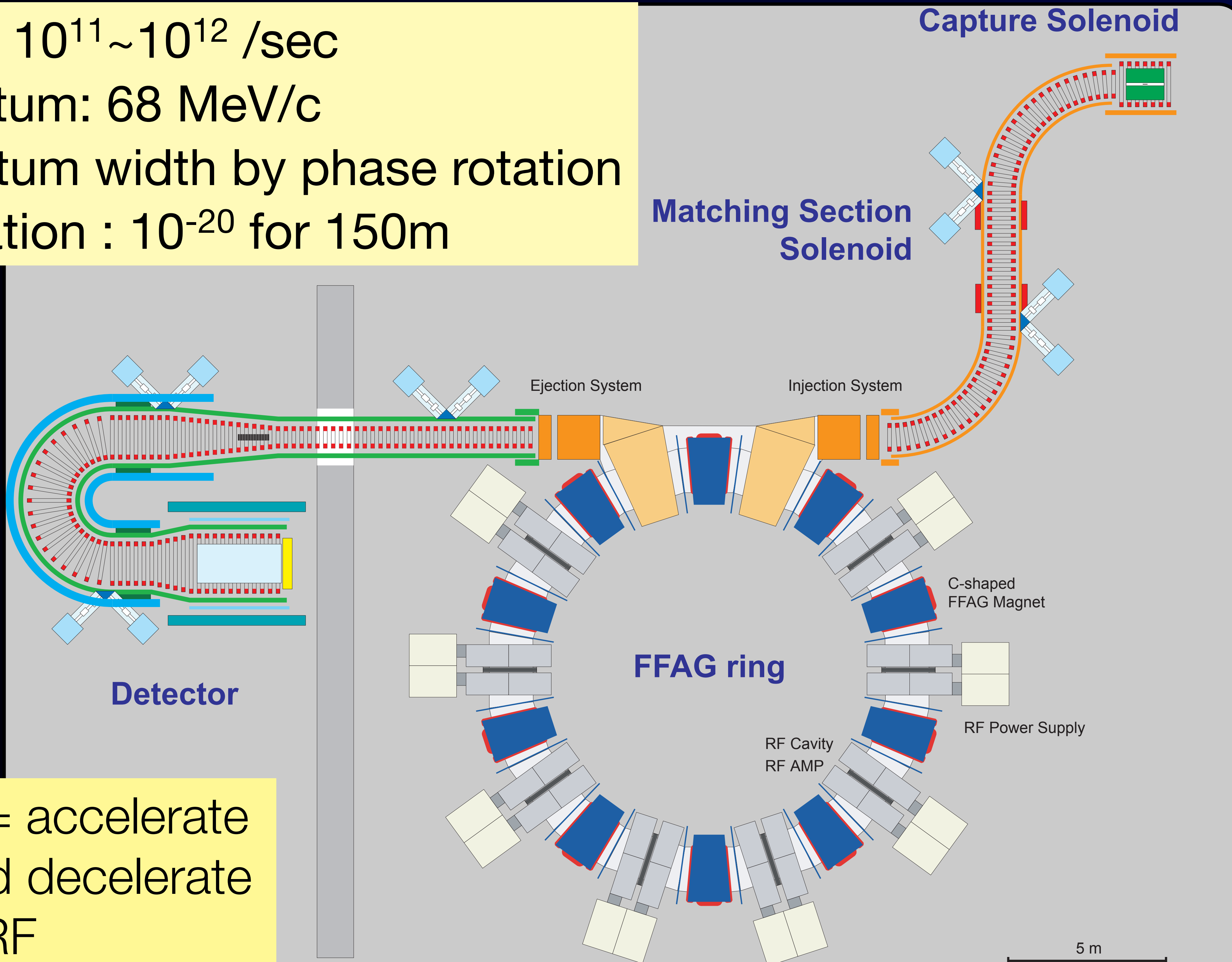
Beam-related Background → Extinction at muon beam — fast kickers

Cosmic-ray background → low-duty running — 100 Hz rather than 1 MHz

PRISM Muon Beam
PRIME Detector

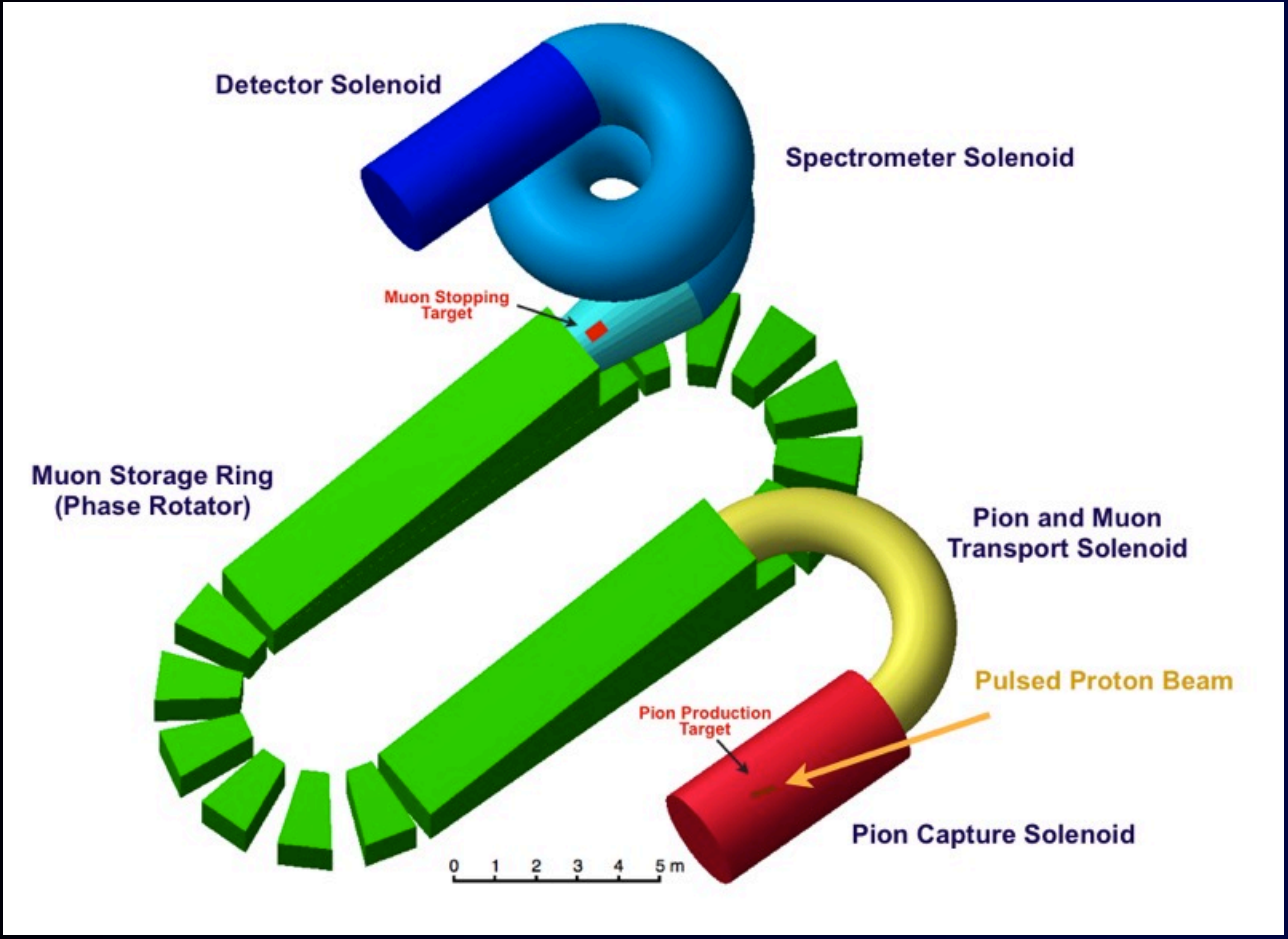
PRISM=Phase Rotated Intense Slow Muon source

muon intensity: $10^{11} \sim 10^{12}$ /sec
central momentum: 68 MeV/c
narrow momentum width by phase rotation
pion contamination : 10^{-20} for 150m



Phase rotation = accelerate slow muons and decelerate fast muons by RF

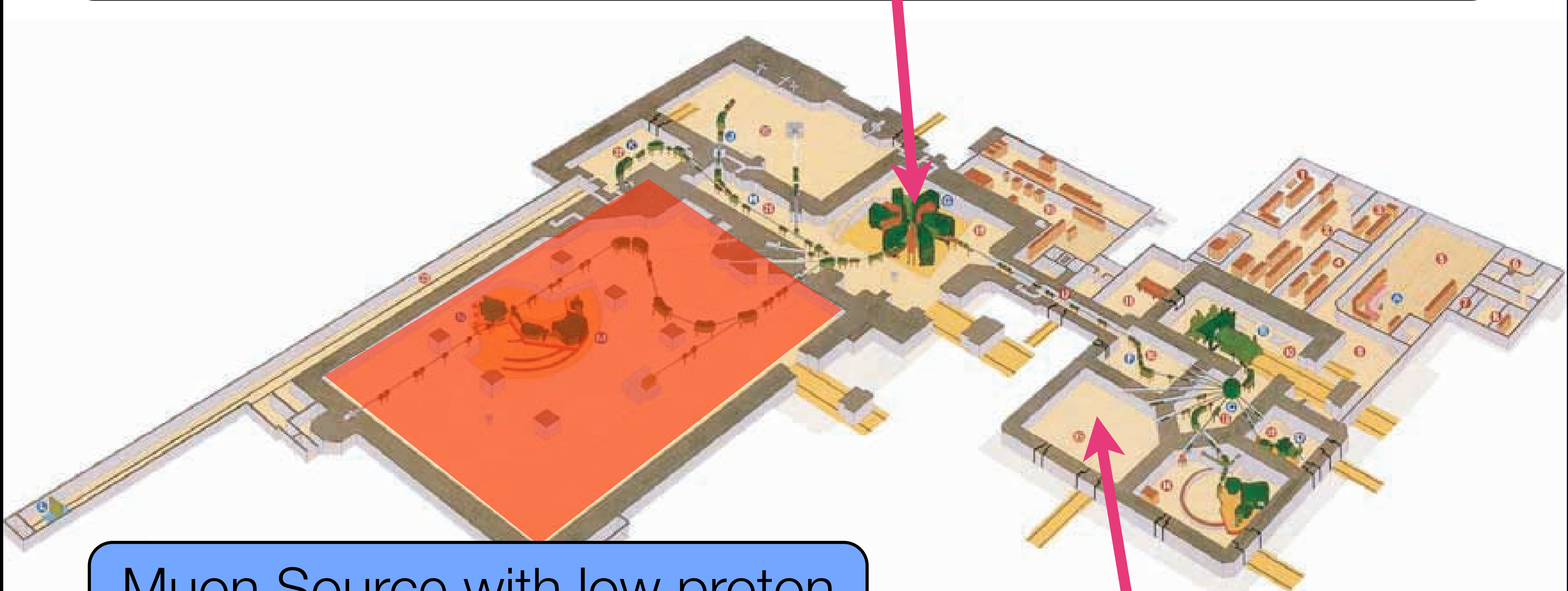
PRISM/PRIME
Detector Layout



R&D on the PRISM-FFAG Muon Storage Ring at Osaka University

Research Center for Nuclear Physics (RCNP), Osaka University

Research Center for Nuclear Physics (RCNP), Osaka University has a cyclotron of 400 MeV with 1 microA. The energy is above pion threshold.



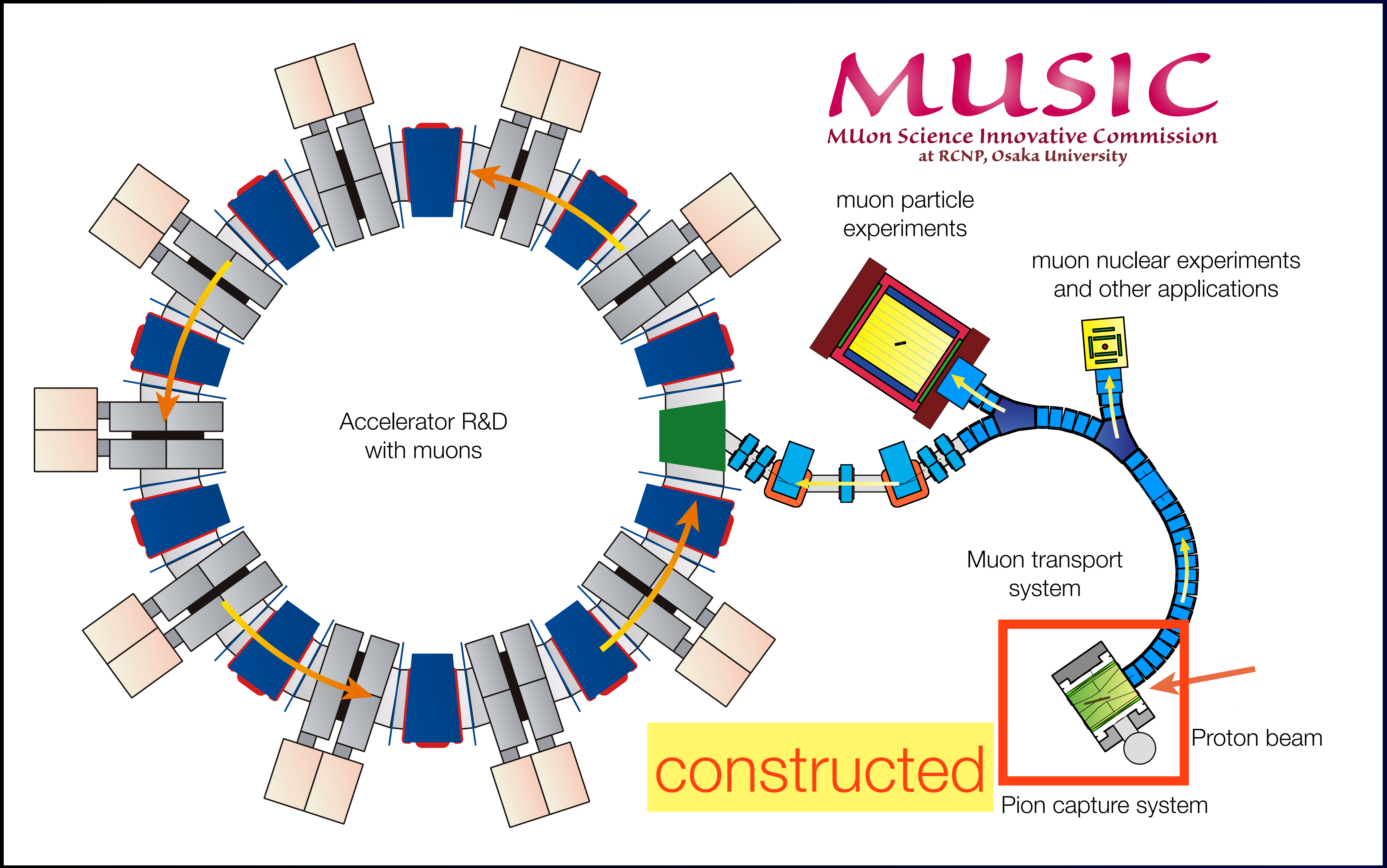
Muon Source with low proton power at Osaka U.?

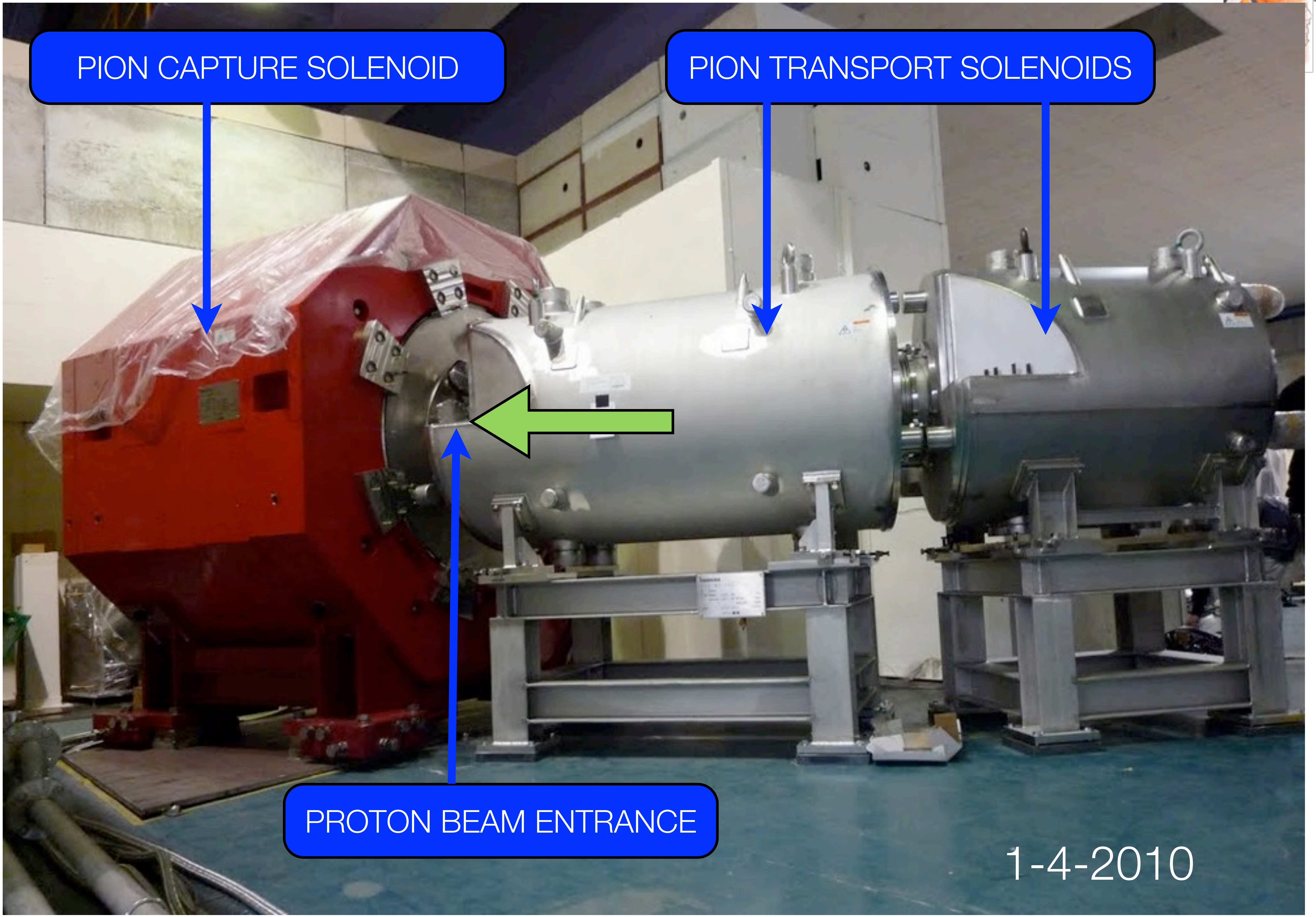
PRISM-FFAG R&D

muon yield estimation

50 kW : 10^{11} muons/sec (for COMET)

0.4 kW : 10^{9} muons/sec (for MUSIC)

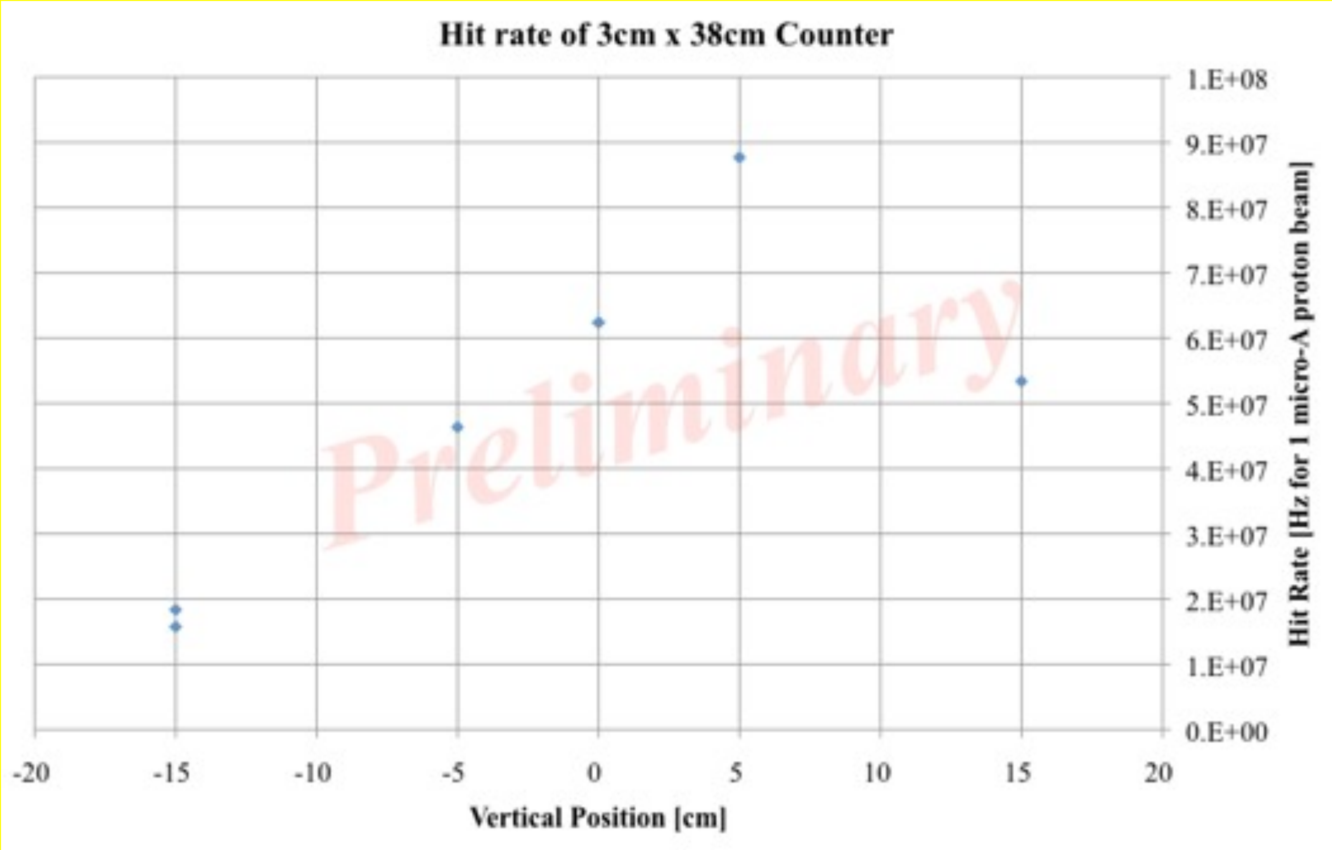



PION CAPTURE SOLENOID
PION TRANSPORT SOLENOIDS
PROTON BEAM ENTRANCE
1-4-2010

MuSIC First Beam from 29th and 30th, July, 2010

- A 36 hour beam time with 1 nA
- Measurements on
  - beam intensity and
  - beam spatial distribution
- Analysis is still being made.
- Preliminary results (right)
  - vertical beam distribution
  - integrated rate: 6×10^8 Hz/μA
  - some corrections further needed to get final numbers.
- Future works
  - particle ID
    - mixture of pions, muons and electrons
  - momentum distribution
  - dipole field correction

counting rates as a function of vertical position

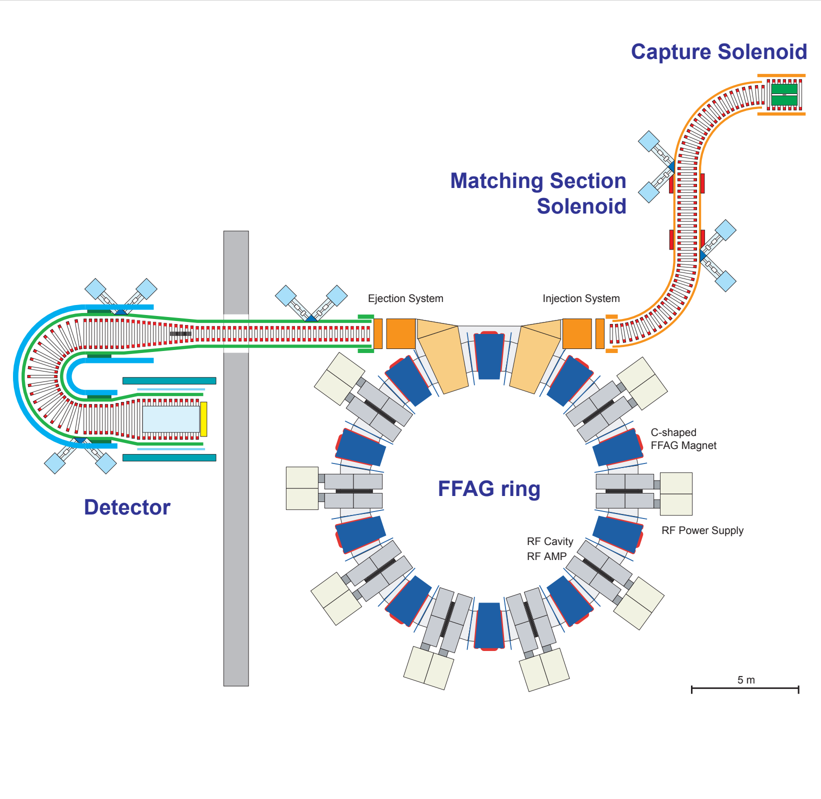


Roadmap of Particle Physics based on muons

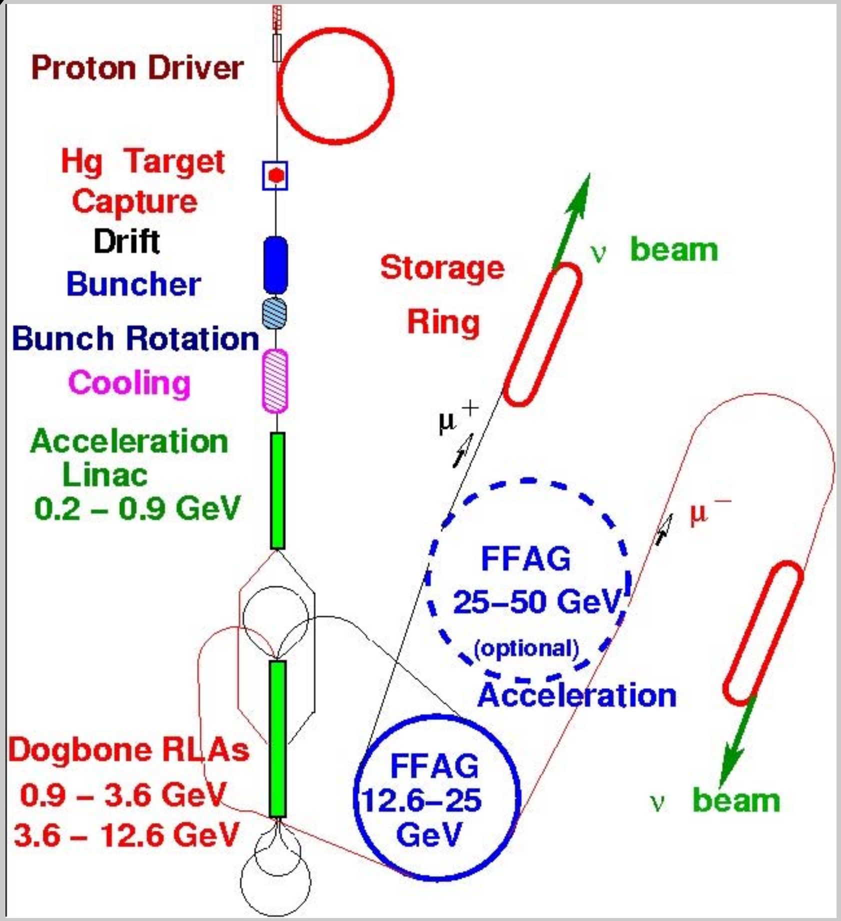
Based on common technologies

Muon Factory

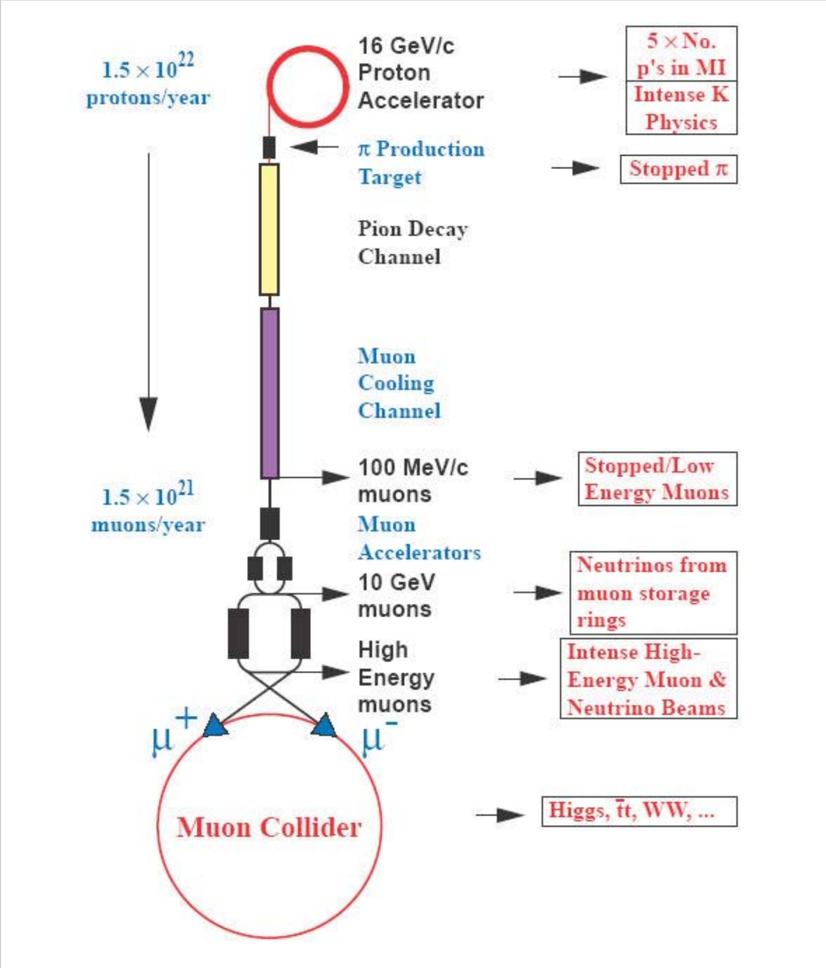
muon LFV,
muon g-2,
muon EDM
muon application



Neutrino Factory



Energy frontier Muon Collider - 2~4 TeV



Summary

- Physics motivation of cLFV processes would be significant and robust in 10-15 years from now.
- Among various muon cLFV processes, μ-e conversion might be the next step.
- The COMET experiment at J-PARC is aiming at a search for μ-e conversion for 2.6 x 10^{-17} single event sensitivity. The COMET has received stage-1 approval at the J-PARC PAC, aiming its start in around 2015.
- Further prospect aiming at better than 10^{-18} sensitivity, PRISM/PRIME has been considered.
- As R&D the MUSIC project for an intense muon source at Osaka University is undertaken.