J-PARC Overview
+ g-2/EDM@J-PARC

For the collaboration btwn IoP and J-PARC/KEK

May 15, 2017, Bhubaneswar, India

Naohito SAITO

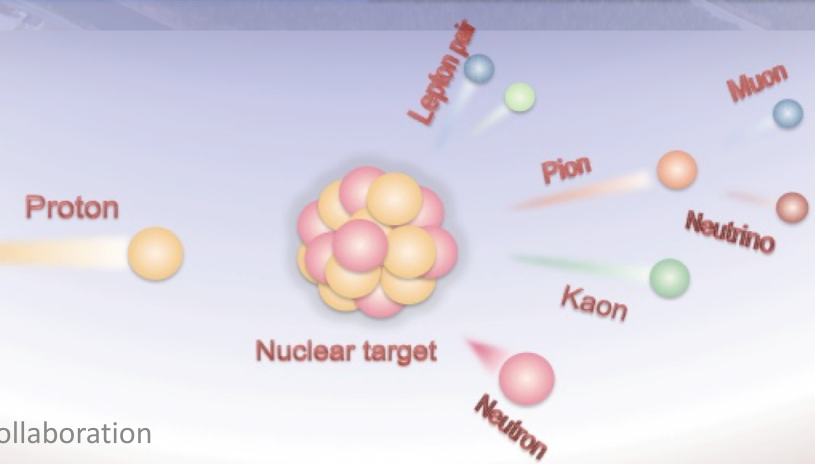
J-PARC

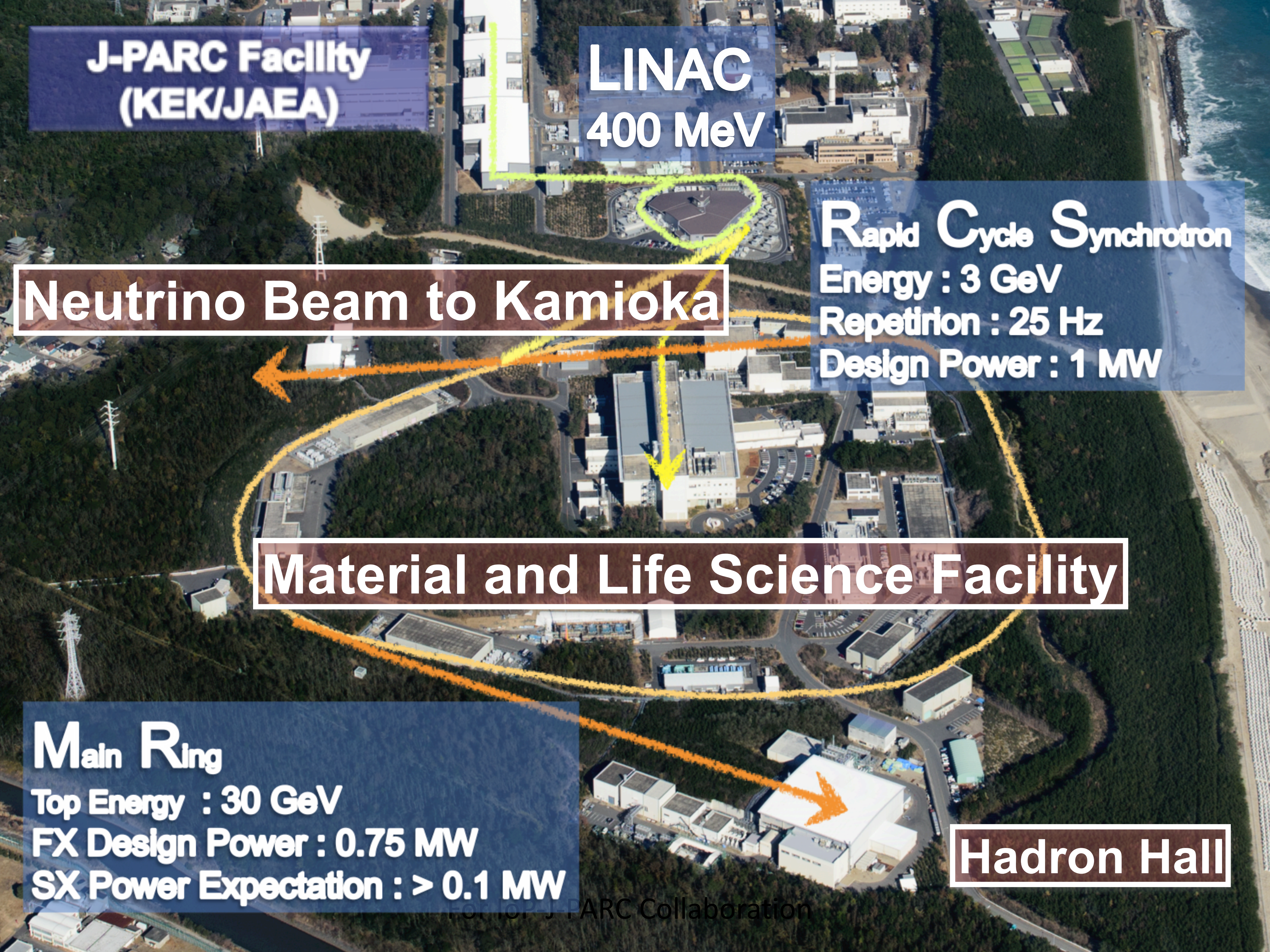
High Energy Accelerator Research Organization (KEK)

Japan Atomic Energy Agency (JAEA)

J-PARC Overview

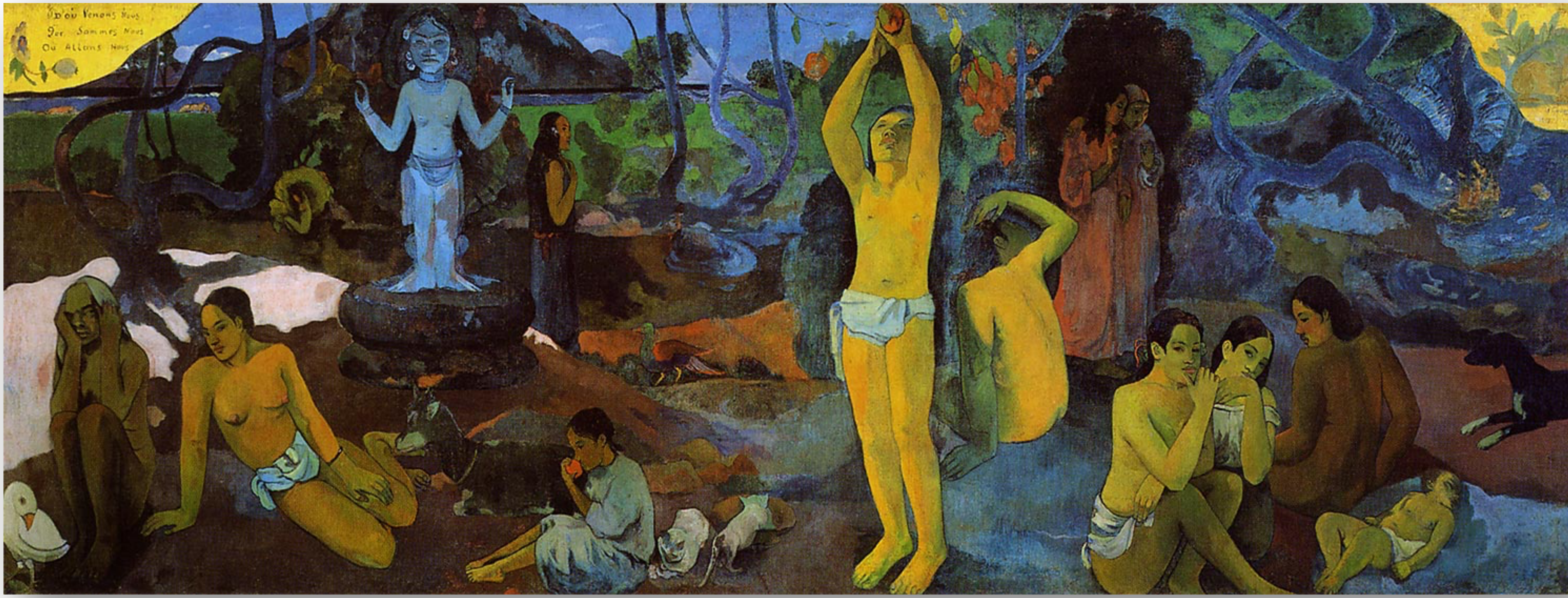
- Multi-purpose research facility with hi-intensity proton driver:
  - Material and Life Science
  - Particle and Nuclear Physics
  - ADS R&D
- Jointly operated by two organizations:
  - KEK, and
  - JAEA
- For origin of
  - Matter and Universe
  - Diversity of material and life




J-PARC Facility
(KEK/JAEA)
LINAC
400 MeV
Rapid Cycle Synchrotron
Energy : 3 GeV
Repetirion : 25 Hz
Design Power : 1 MW
Neutrino Beam to Kamioka
Material and Life Science Facility
Main Ring
Top Energy : 30 GeV
FX Design Power : 0.75 MW
SX Power Expectation : > 0.1 MW
Hadron Hall
J-PARC Collaboration

D'où venons-nous ? Que sommes-nous ? Où allons-nous ?

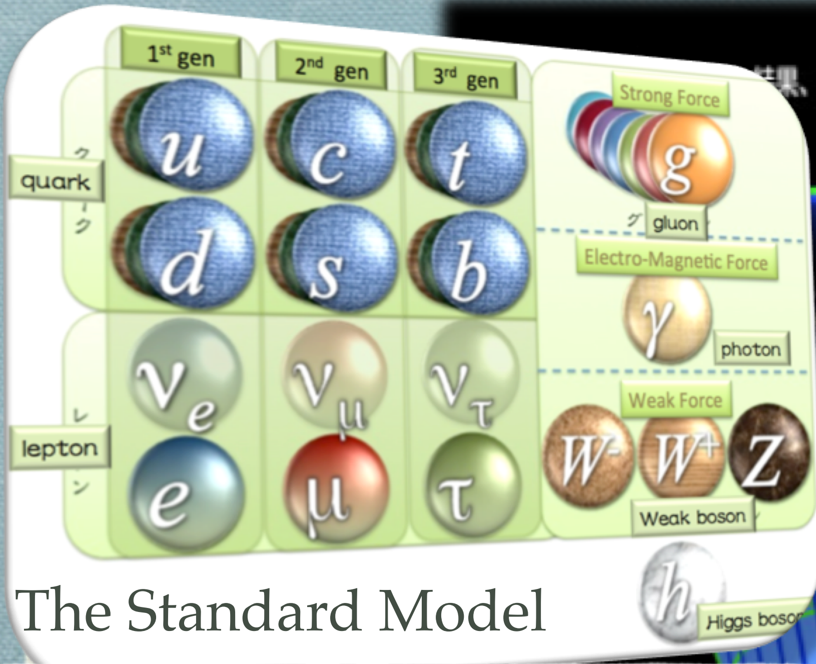
Where did we come from? What are we? Where do we go?

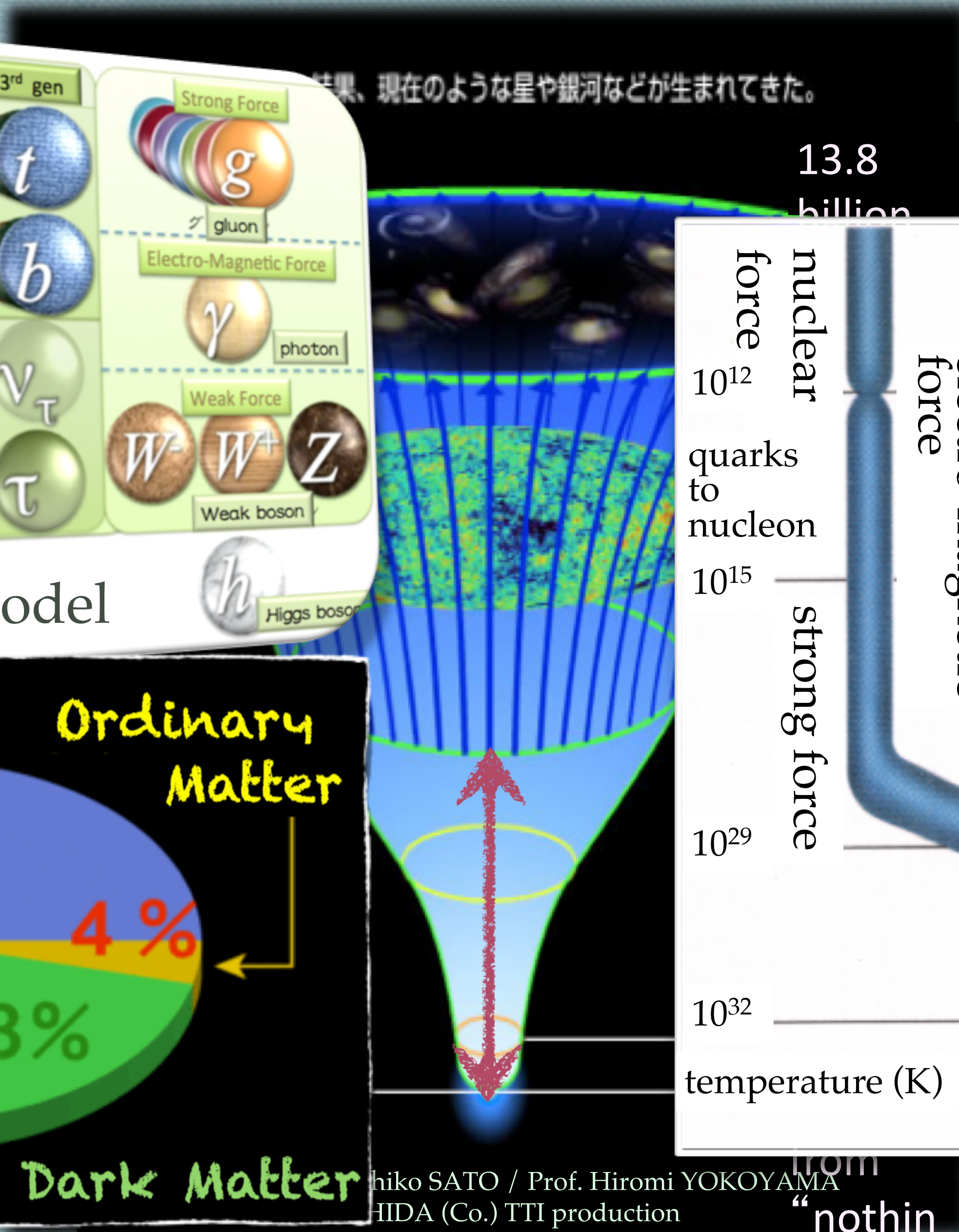


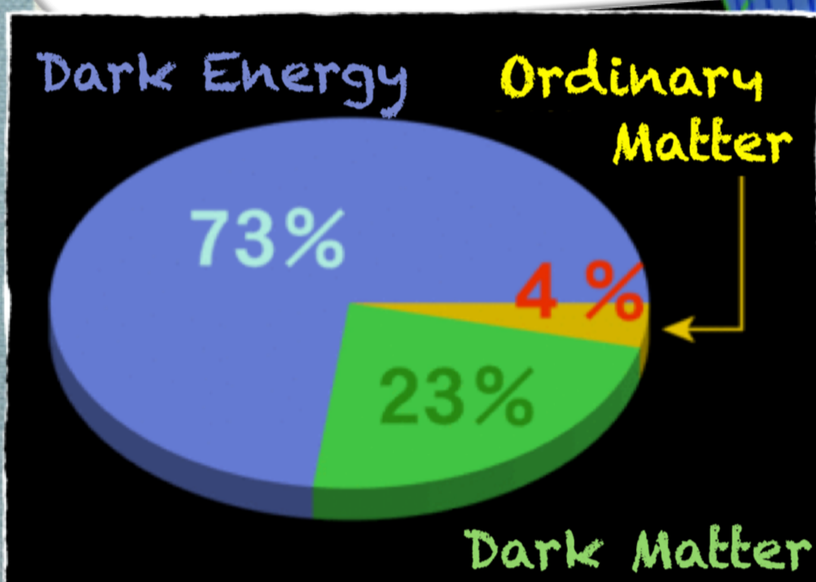
P. Gauguin 1897, Boston Museum

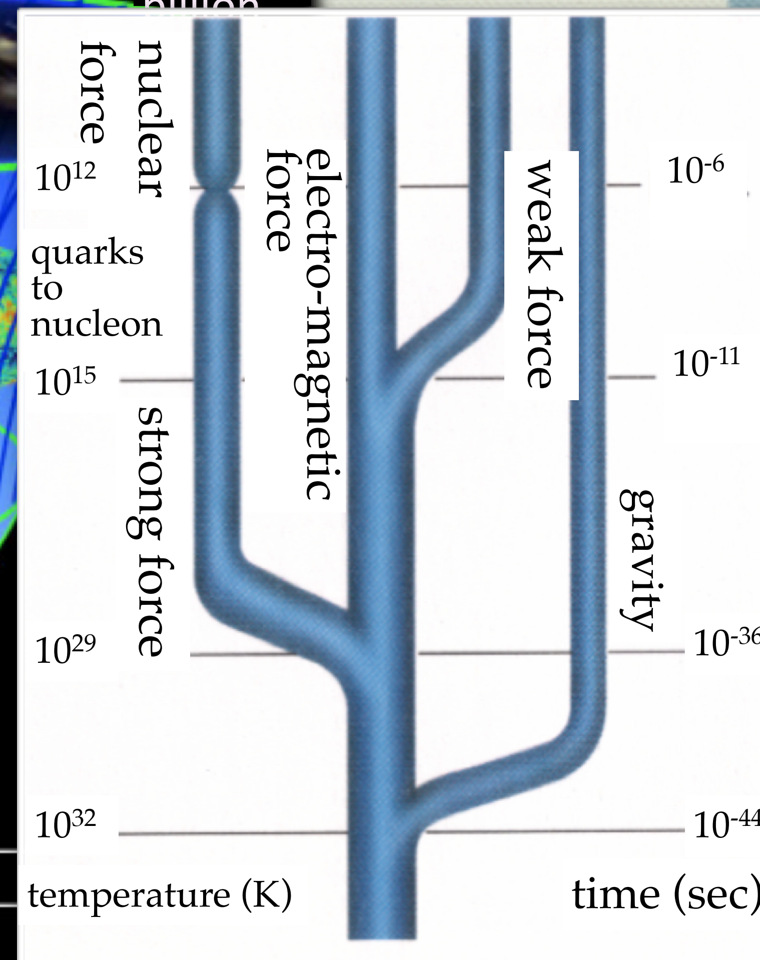
Quarks
Neutron
Hydrogen nucleus
Hydrogen atom
Protogalaxy
Electron
Proton
Helium nucleus
Helium atom
THE BIG BA
ORY
CUP NOODLE
カップヌードル
Galaxy
TIME BEGINS
ONE SECOND
PRESENT DAY
Time
Temperature
10-43 sec.
10-32 sec.
1027°C
10-6 sec.
1013°C
3 min.
108°C
300,000 yrs.
10,000°C
1 billion yrs.
-200°C
15 billion yrs.
-270°C
1 The cosmos goes through a superfast "inflation," expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second
2 Post-inflation, the universe is a seething, hot soup of electrons, quarks and other particles
3 A rapidly cooling cosmos permits quarks to clump into protons and neutrons
4 Still too hot to form into atoms, charged electrons and protons prevent light from shining; the universe is a superhot fog
5 Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine
6 Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars
7 As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets

History of Universe & the Standard Model





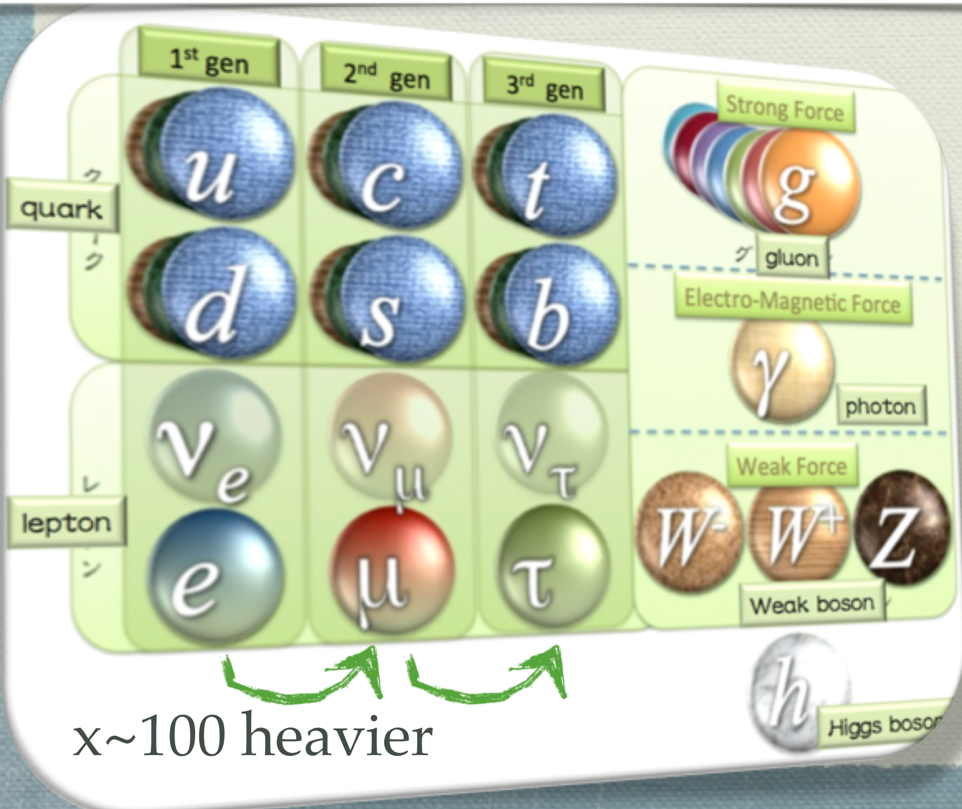




Many Remaining Questions

- Completion of the Standard Model

Beginning of New Physics Era



x~100 heavier

Why 3 generations?
Why CP violates? (particle-anti-particle asymmetry)
Why mass distributed this way?
Baryon number, Lepton number, Lepton flavor violated?
What is Dark Matter, Dark Energy?
Why our Universe is matter-dominant?
Is super-symmetry real?

Matter = Remnant of $1/10^9$ Asymmetry

Origin of Matter =

Matter-Antimatter Asym.

CPV and Flavor Mixing
CPV beyond CKM
Role of muon as a charged Lepton

+

Role of Strong Interaction

Strangeness and Charm

Explored with SuberKEKB and LHCb

Explored with J-PARC/PSI/Fermilab Intense Beams

Our Stable World

For IoP-J-PARC Collaboration

Hi-Energy Frontier

New phenomena may exist in the unprecedented energy region

→LHC, ILC and future colliders

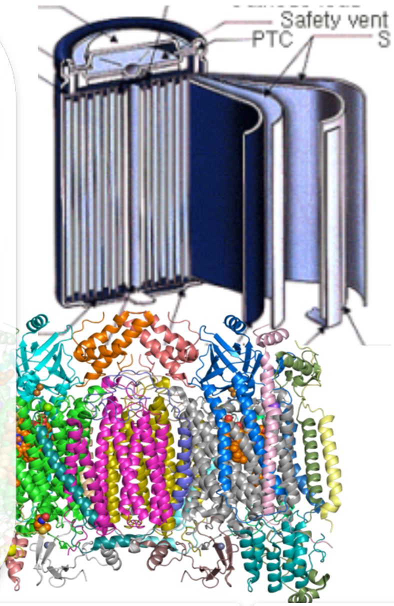
Astrophysics

Hi-Intensity Frontier

Ultra-precision measurements may provide a hint for New Physics!

→Hi-Luminosity lepton colliders, Hi-Intensity Proton Drivers

Hi-power Beams
for the Next Stage of Our Life

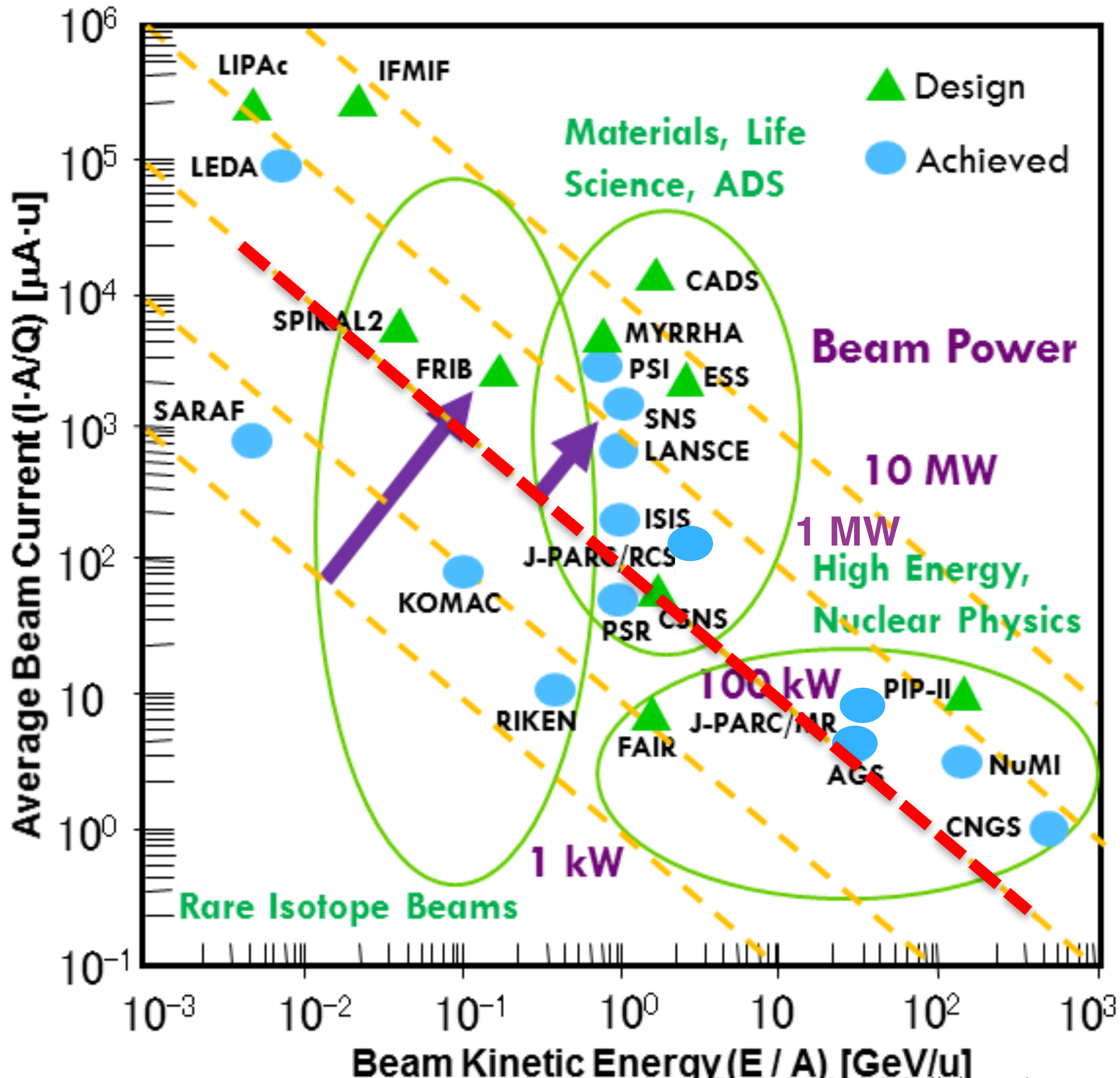


Why no anti-matter?
（matter and “anti-matter” are twin）
How a life emerged on the earth ?
（Anthropology）
How the diversity of the matter and life emerged?
（What a beautiful world!）

Our view is limited by
“what we can feel and touch”
To elucidate the truth in the nature, we need
”better eyes to investigate more fine structure
more precisely with more sensitivity”

Hi-power beams for the NEXT

A Quest for High Intensity



High Intensity

High Statistics

- More Precision
- More Rare Searches
- More Materials

Discovery!

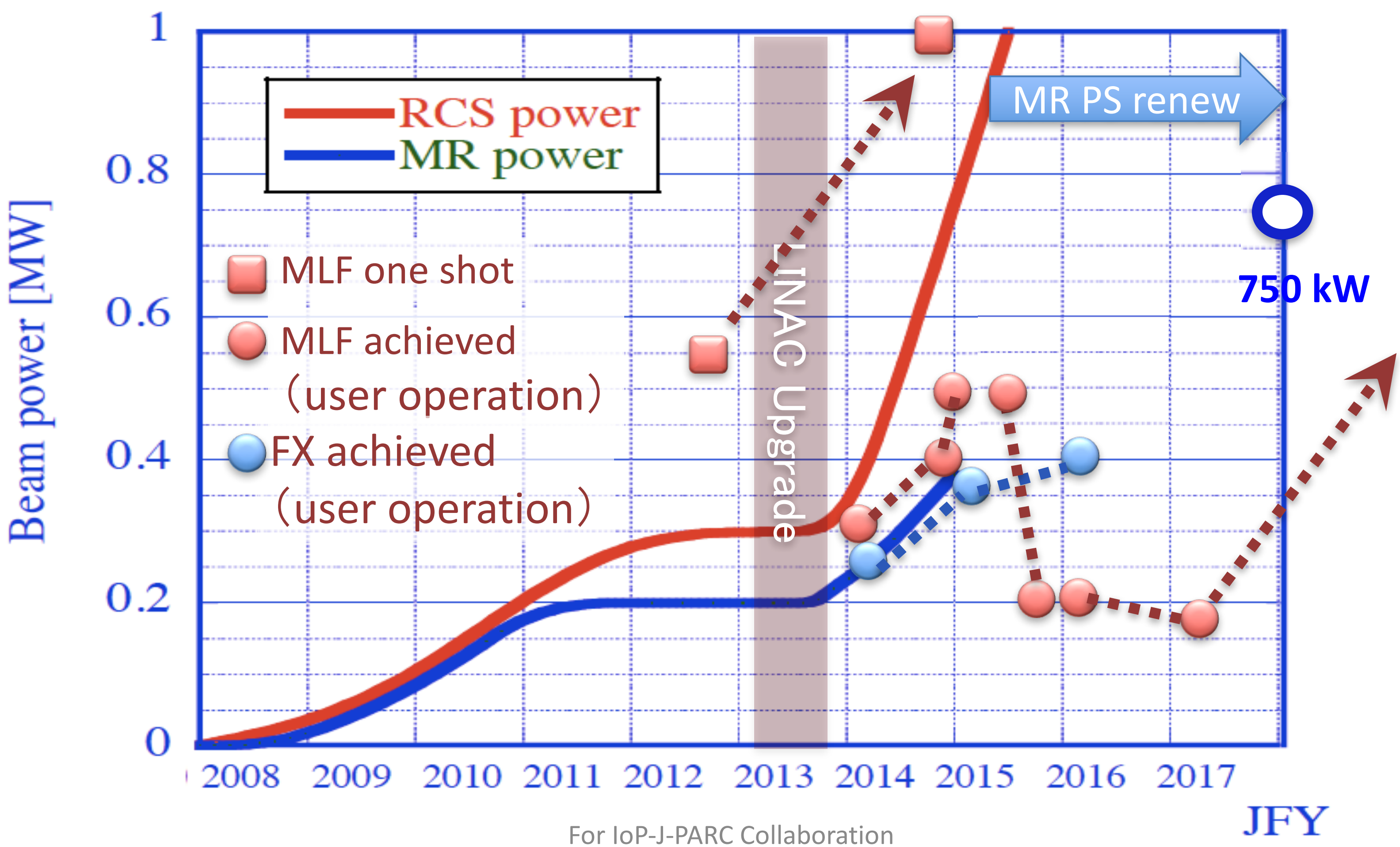
Jie Wei / Y. Yamazaki

Beam Power : Plan vs Reality

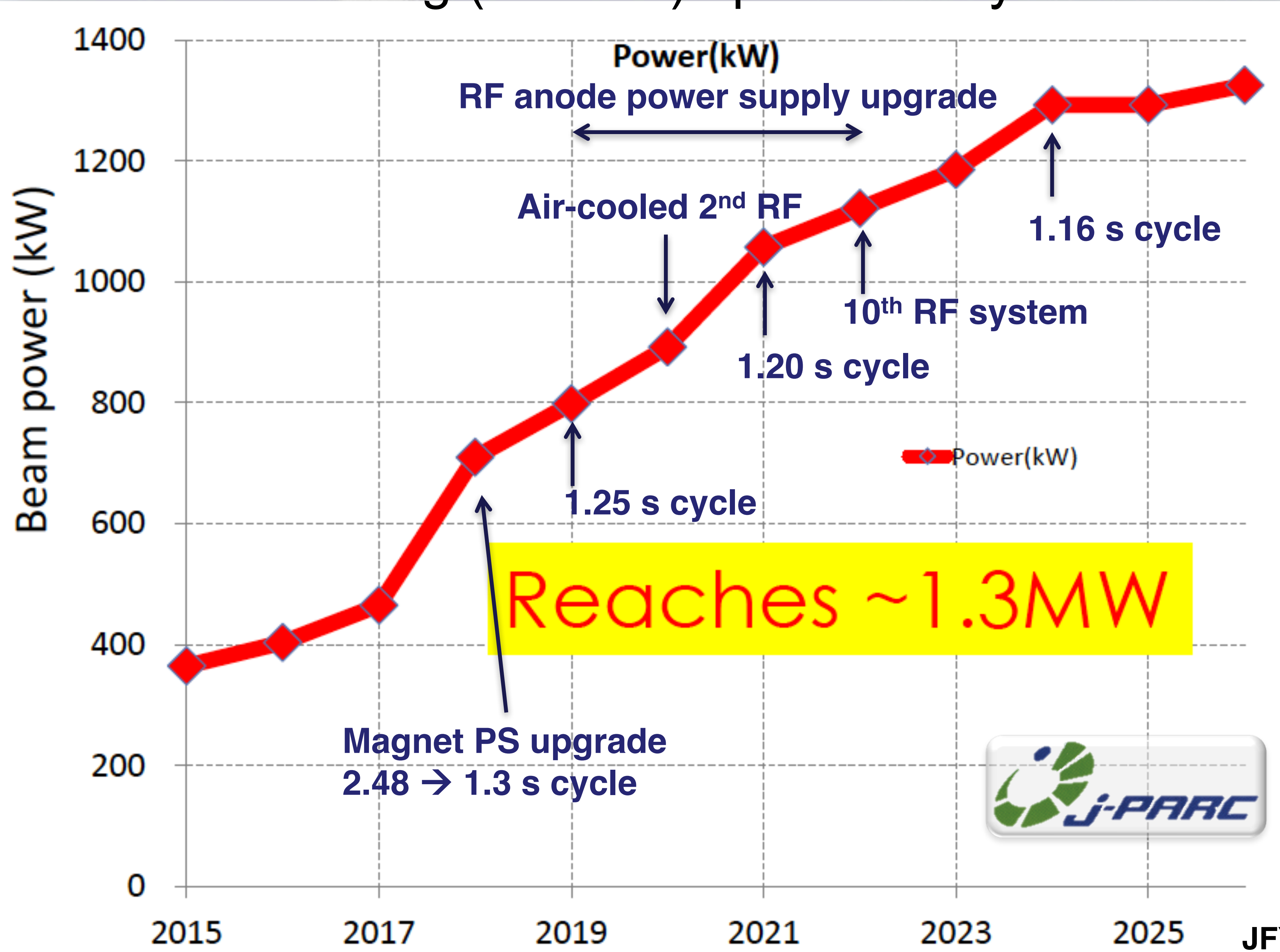
RCS ::1 MW achieved in Jan, 2015

Thanks to new working point!

MR::so far 0.38 MW for FX ; 0.9 MW reachable with new PS



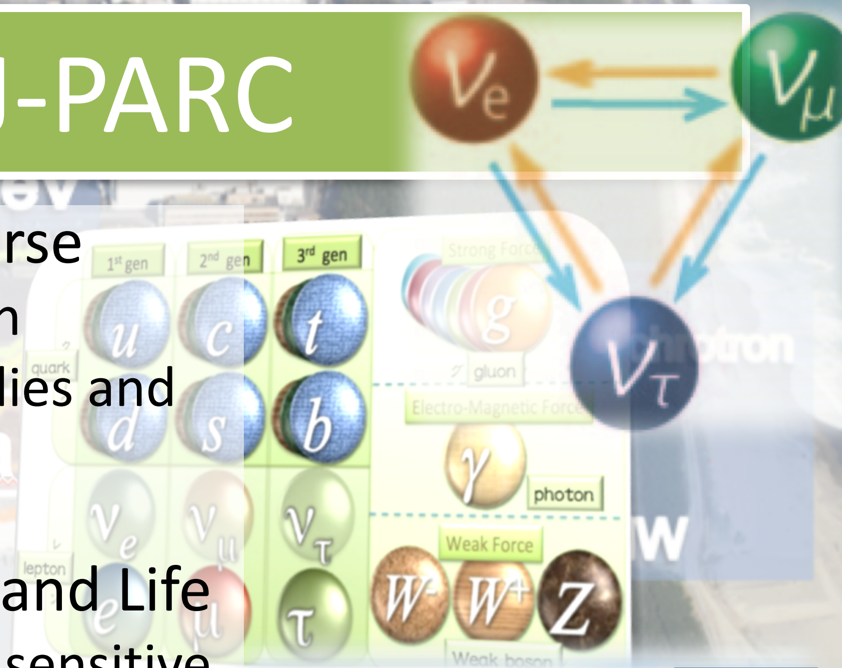
J-PARC Main Ring (30 GeV) operates beyond 1 MW

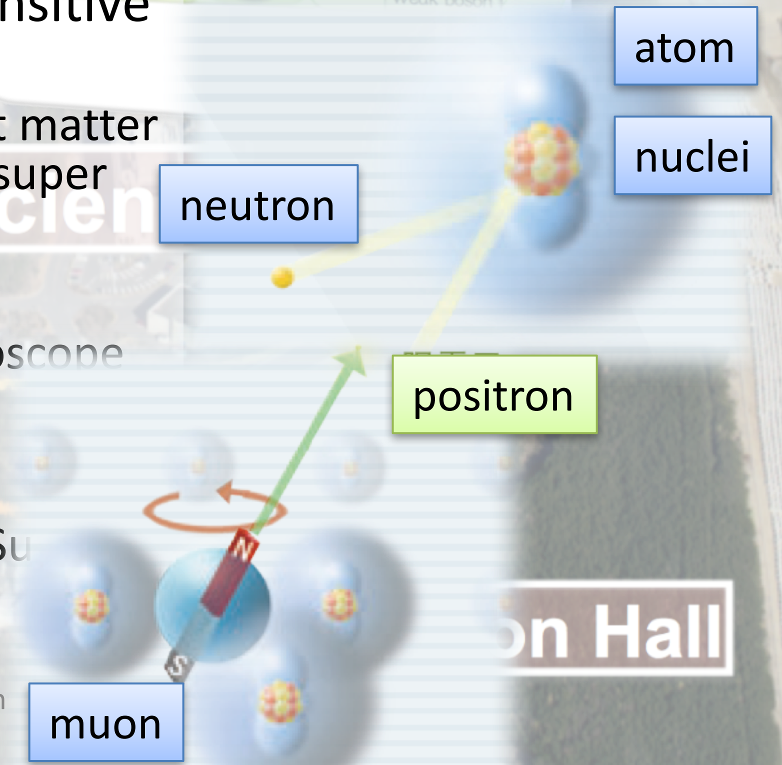


JFY

Science at J-PARC

- Elucidate Origin of Matter and Universe
  - Neutrino Oscillation and its CPV search
  - Charged Lepton and Quark Flavor studies and CPV search
  - Strong Interaction studies
- Explore Origin of Diversity in Matter and Life
  - Neutron as penetrating and hydrogen sensitive probe
    - Energy materials (e.g.bettery), Life and soft matter (e.g. proteins, polymer), Hard matter (e.g. super conductor)
  - Muon as a micro magnetic probe
    - mSR, X-ray from muonic atom, muon microscope
    - Fundamental physics
  - Industrial Application
    - Synergetic use of SPring-8/PF and J-PARC, Super Computer "Kei"
- R&D for Nuclear Transmutation





Multi-Probe Platform for

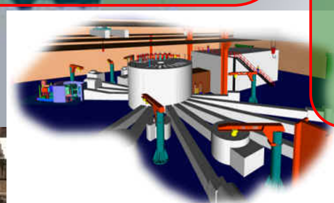
Material and Life Science

With Synergetic Use of Neutron, Muon, Photon and Positron

Accelerator Based Neutron Source in the World

ESS
(Sweden)
2019~
5MW

ISIS, RAL
(UK)
2nd target station
2008~
0.16MW
0.3MW



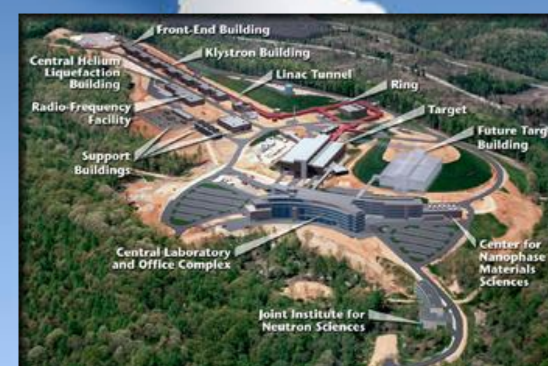
CSNS
(China),500kW
2019~

MLF, J-PARC
(Japan)
2008~
1MW

IPNS, ANL
@Illinois, USA
0.01MW

LANSCE, LANL
@Los Alamos, USA
0.06MW

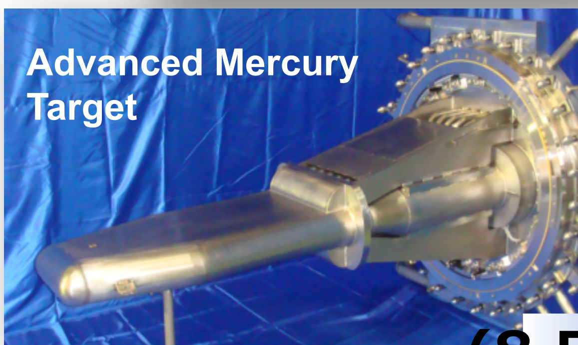
SNS, ORNL
(USA)
2006~
1.4MW



For IoP-J-PARC Collaboration

Material and Life Science Facility（MLF）

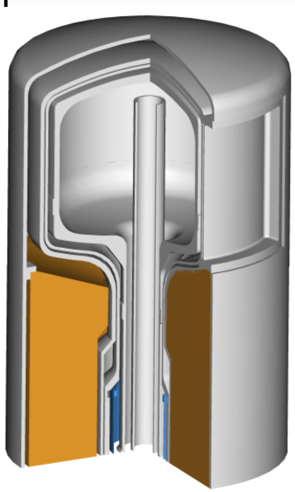
World Highest Intensity of Neutron Pulse Beam!

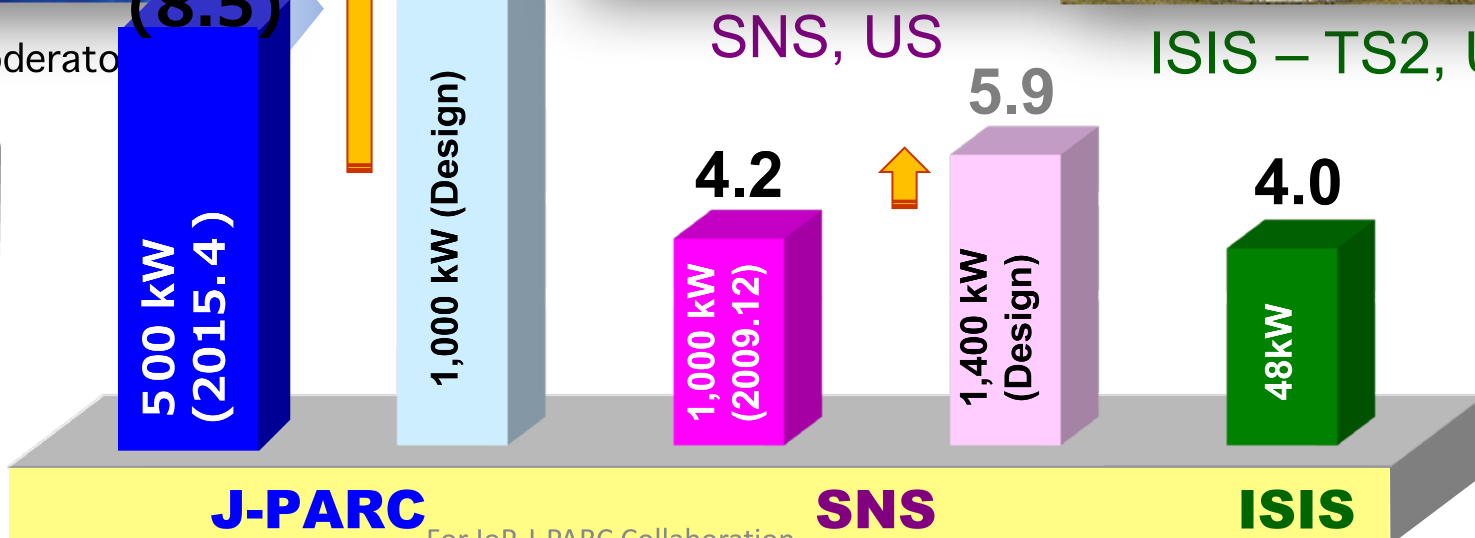


SNS, US

ISIS – TS2, UK

Hi-performance Moderato





For IoP-J-PARC Collaboration

Unit: 10^{12} n/(sr・pulse)

Hg-Target for

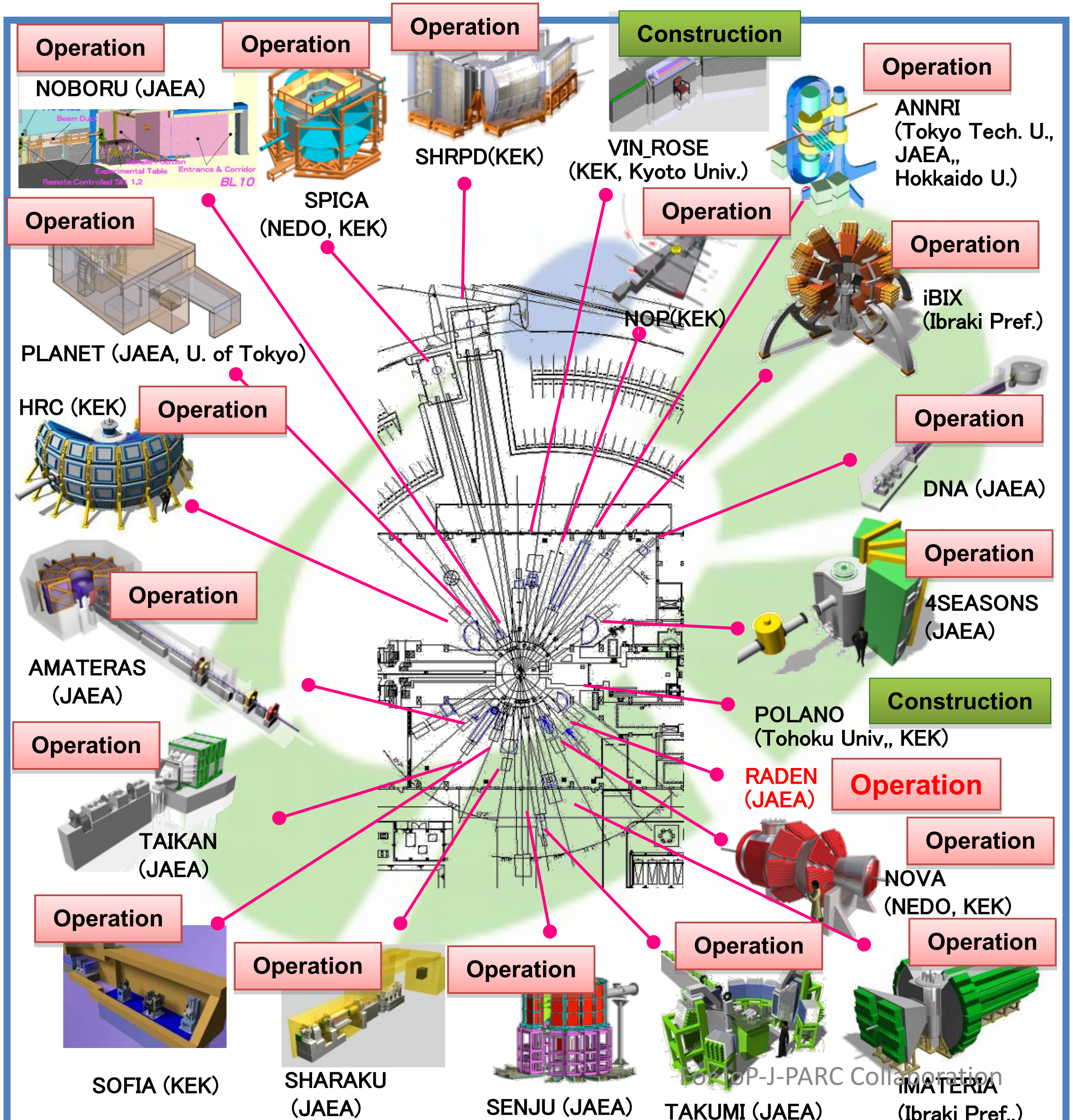
J-PARC MLF

(3 GeV – 1 MW)

Preparing the Hg-Target system for 1MW operation

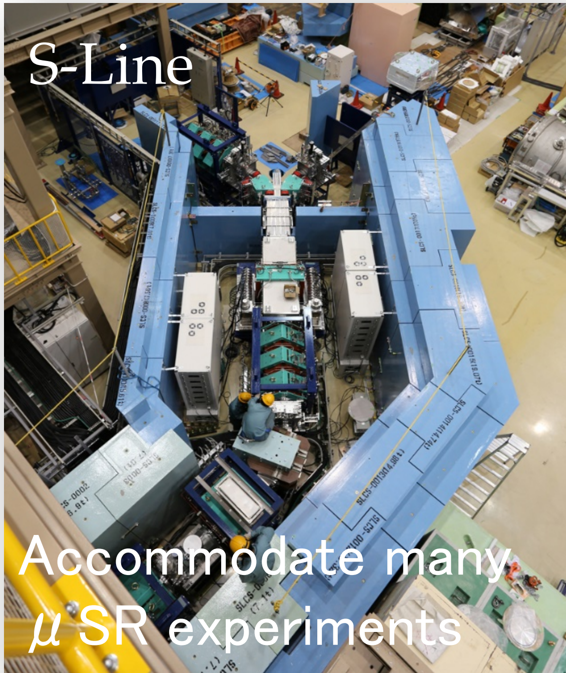
For IoP-J-PARC Collaboration

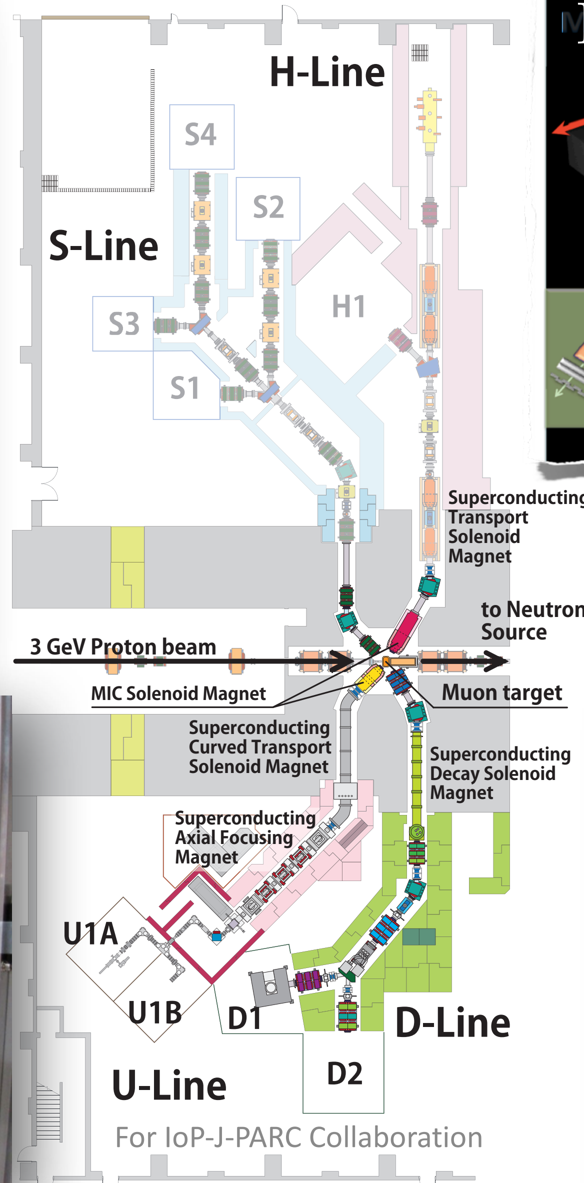
Neutron Instruments at MLF

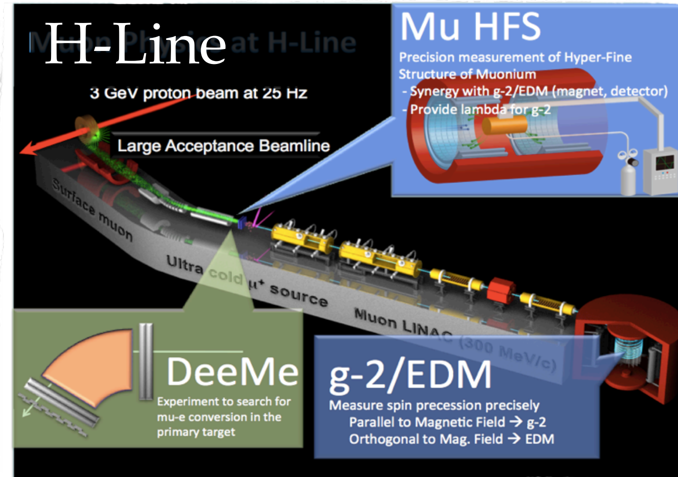


- The first neutron in May, 2008
- 23 Neutron Beam Ports
- From Fundamental Physics to Industrial Uses
- Operation: 19 (Apr., 2015)
  Construction/Commissioning:2
- Constructed by
  - KEK
  - JAEA
  - Ibaraki Prefecture
  - Universities, Institutes & Government organizations...
- Yearly Operation Days
  - ~180
- Yearly Guest Number
  - 731 (2014)

Muon Facility MUSE @ MLF







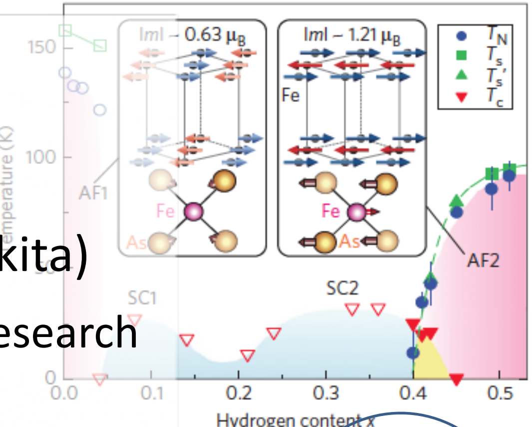
Fundamental Science with a large scale international coll.

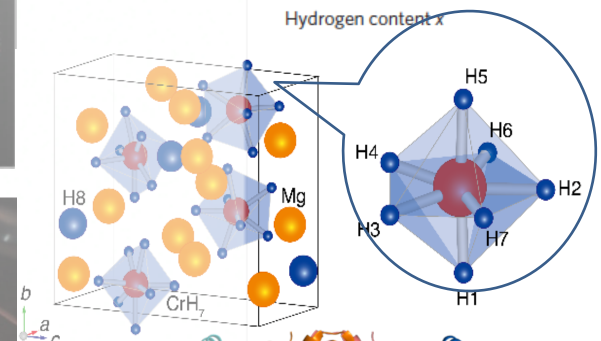
Industrial Use of MLF blooming

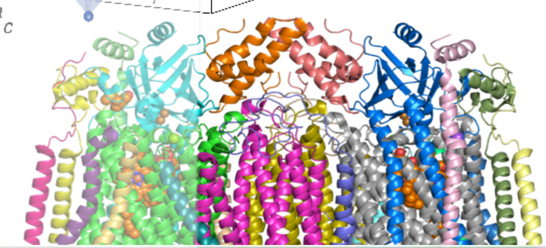
- A new framework for material development using J-PARC was press-released at Tokyo Motor Show by CEO of Sumitomo Rubber Industries.

Science Groups in MLF

- **Hard Matter** (K. Nakajima / S.Ito)
  - Strongly correlated maaterial / Quantum properties
- **Liquid & Soft Matter** (T. Kanaya / H. Seto / Y. Kawakita)
  - Polymer / Soft material / Liquid and Amorphous Materials Research
- **Energy Material** (T. Otomo / T. Kamiyama)
  - Hydrogen absorbing material / Battery
- **Engineering Material** (K. Aizawa / J. Suzuki)
  - Residual stress / Structure sensitive material
- **Muon Science** (Y. Miyake / R. Kadono)
  - Muon fundamental science / Muon application
- **Life Science**
- **Industrial Application**







Major Research Results 2016

- Thirteen press releases in 2016 (five in 2015)

MLF Solid electrolytes open doors to solid-state batteries

MLF Hydride-ion conduction makes its first appearance

MLF Development of whole-solid ceramics bettery with super-ion conductor

MLF Discover abnormal behavior of "pathological condition" protein molecule leading to the development of Parkinson's disease

MLF SEI coating that affects the characteristics of the battery ~ Develop method to approach its identity

MLF Observation of the quantum mechanical phase of the electronic state as a spin motion for the first time using metal ferromagnetic material $SrRuO_3$

MLF Successful analysis of internal behavior of charging /discharging lithium battery - realized by non-destructive and real-time observation using neutron beam –

MLF Discovering a new order condition on high-pressure ice - Solving one of the five unsolved problems of ice –

NU T2K Experiment took the first step to elucidate neutrino's "CP Symmetry breaking"

MLF Elucidation of the unique structure of ice containing large amounts of salt

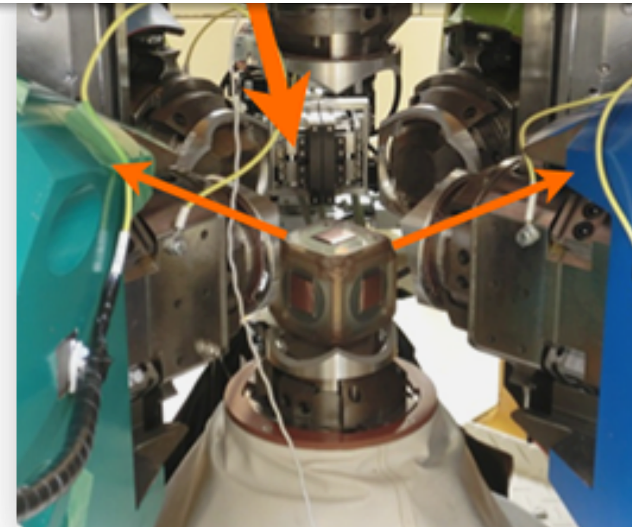
MLF Development of high-speed texture measurement system of metallic materials by neutron diffraction

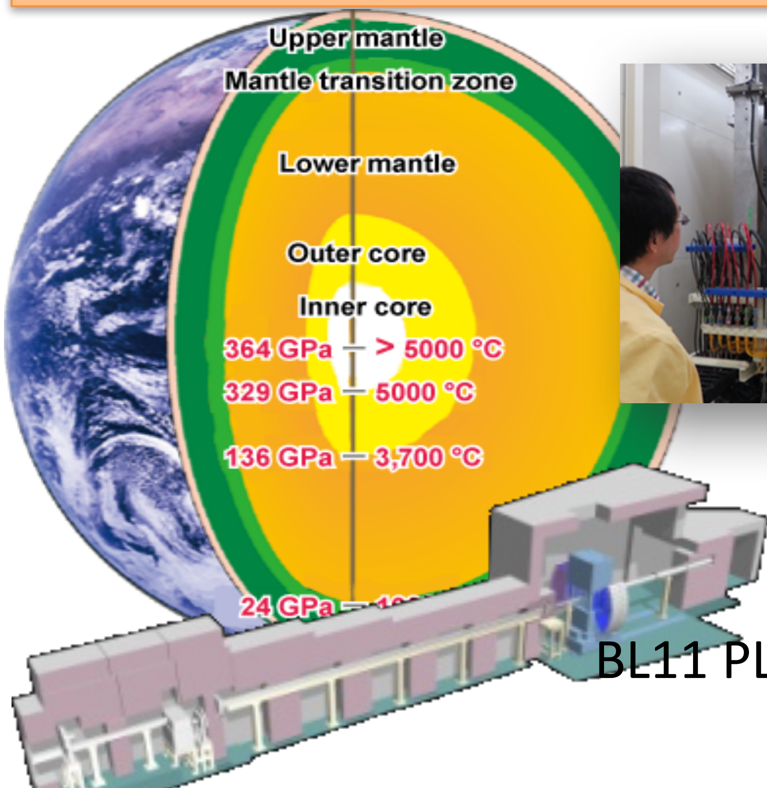
MLF MLF And, two more

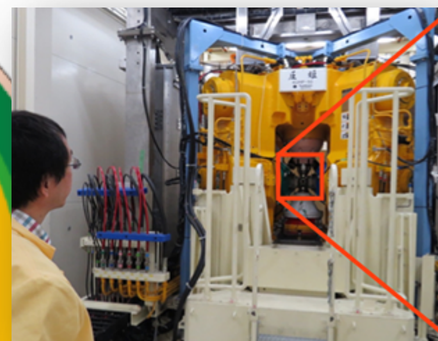
Geo-Science at J-PARC/MLF

Water in the inner-earth

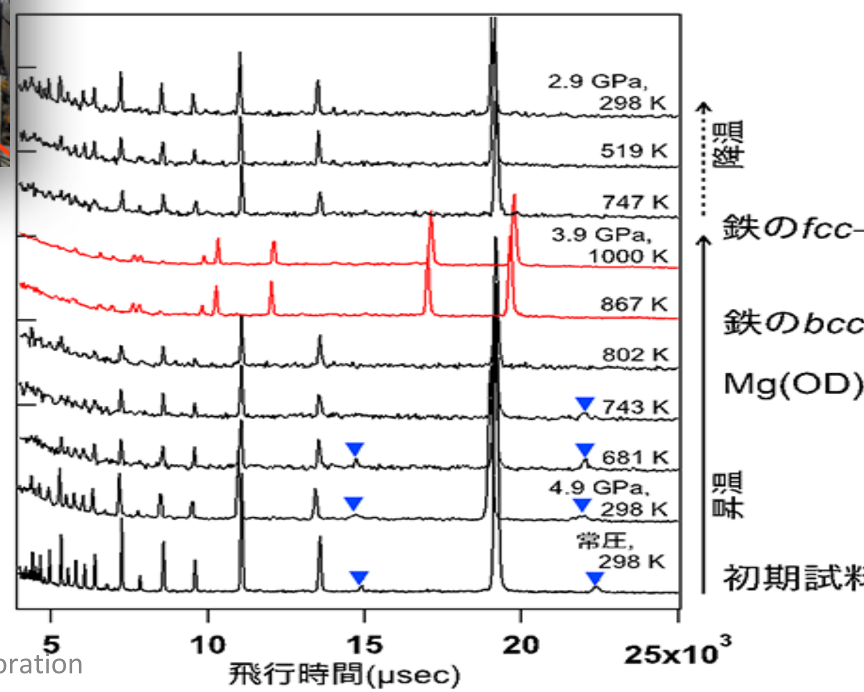
Investigate the mystery of light elements in the early history of the earth – hydrogen in the ferroic materials probed by pulsed neutron beam at J-PARC
- U. Tokyo, U. Ehime, U. Okayama, JAEA, J-PARC







BL11 PLANET



温度圧力の変化とともに含水鉱物Mg (OD) $_2$の脱水を経て、鉄が *bcc*相 (黒線 : 298-802K) から*fcc*相 (赤線 : 867-1000K) へ相転移する様子を示す回折パターンの時間変化。

For IoP-J-PARC Collaboration

物質・生命科学(MLF)(中性子利用系)

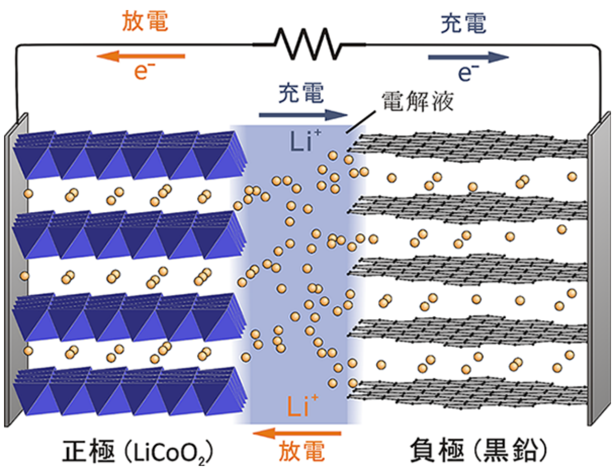
プレス発表

BL09 SPICA

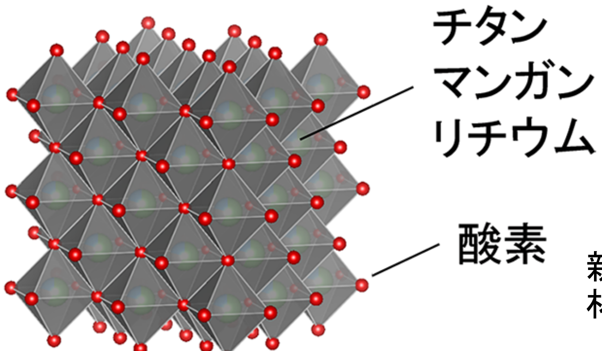
汎用元素からなる新規高容量電極材料の開発に成功:リチウムイオン蓄電池の高容量化実現につながる正極材料の発見～ 次世代の蓄電池の実現により、電気自動車の高性能化などに期待 ～(2016年12月23日プレス発表)

東京電機大学、高エネルギー加速器研究機構、J-PARCセンター

空気中の酸素分子を利用するリチウム・空気電池はエネルギー密度が高い。酸素を固体である「酸化物イオン」として用いることで、従来のリチウムイオン電池と全く同じ構造のまま、空気電池に匹敵するエネルギー密度をめざし研究が進められているが、高価なニオブを用いる必要があった。ニオブをチタンに代替したチタン・マンガン系を合成したところ、ニオブ系材料以上の高エネルギー密度が得られることが確認できた。J-PARCにおいては、BL09にてその結晶構造を決定した。



リチウムイオン電池の動作原理模式図



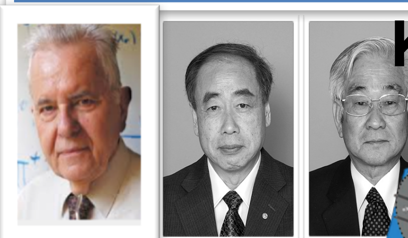
新しく発見したチタン系材料の結晶構造

ADS Test Facility for Nuclear Transmutation

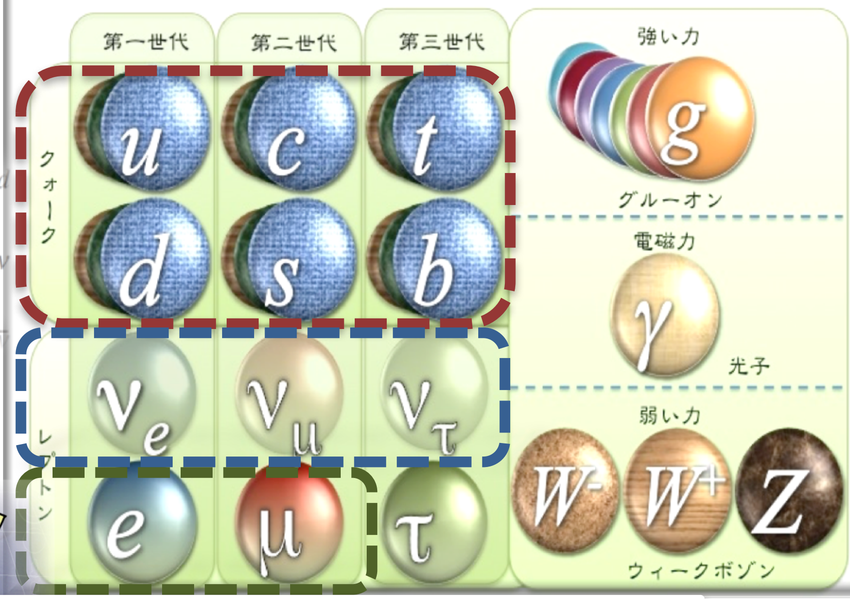
TDR being developed for construction start in JFY 2018

Particle-Nuclear Physics explored at J-PARC

Search for CPV beyond CKM theory



NA62, LHCb at CERN



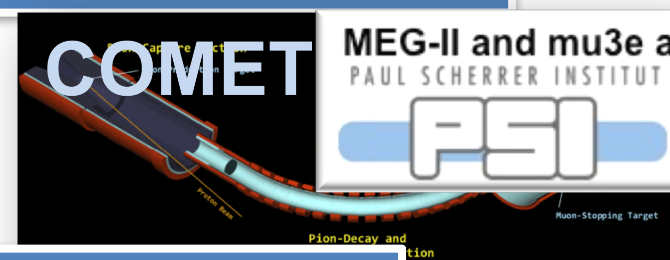
Neutrino Mixing thru PMNS matrix

T2K Exp.

CPV in neutrin sector?

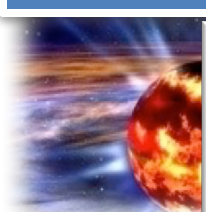
NOvA and more at Fermilab

Charged Lepton Flavor violated?



MEG-II and mu3e at PAUL SCHERRER INSTITUT PSI

Explore role of strangeness in neutron stars



Hadron Physics at GSI FAIR

y play an
an extreme high
neutron star.

CPV in Charged L

mu2e and g-2 at Fermilab

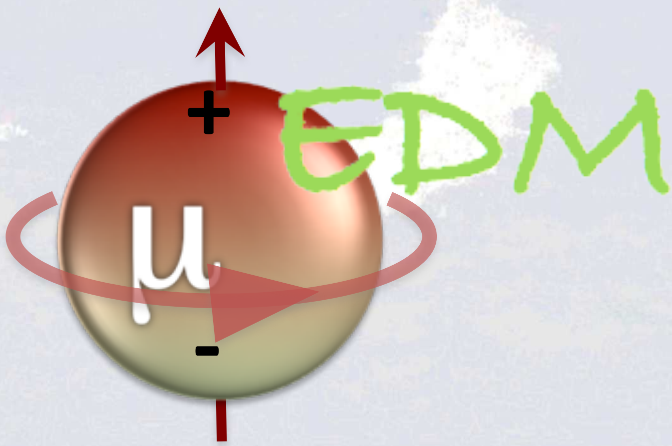
g_μ-2/μEDM

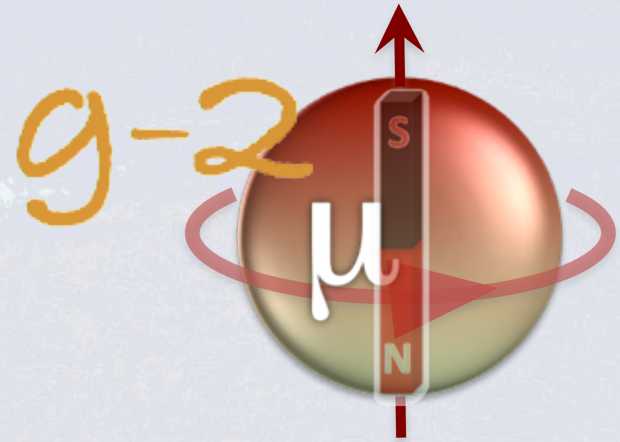
Neutrino is more Popular than ever

- Kajita-san and Murayama-san gave a lectures to 700 audience
- 200 primary and Junior-hi students actively involved
  - “What is the origin of mass?”
- Neutrino is now recognized as the special product beside sweet potato.

Pictures from

広報 とうかい 2016 8 10日号 No. 858





Muon Spin

Lepton and EDM Physics at Intensity Frontier Machine : J-PARC

cLFV

Improve by x 100 and more (10^{-12}--> $10^{-14; -16}$)

Search for Charged Lepton Flavor Mixing

Charged Lepton Flavor Mixing and Origin of Matter

g−2

Improve by x 5 (0.1 ppm)

Precision Measurement of Anomalous Magnetic Moment

Muon Precision Experiment to search for New Physics

μEDM

Improve by x 100 and more ($1\times10^{-21; -24}$ e cm)

Search for Electric Dipole Moment

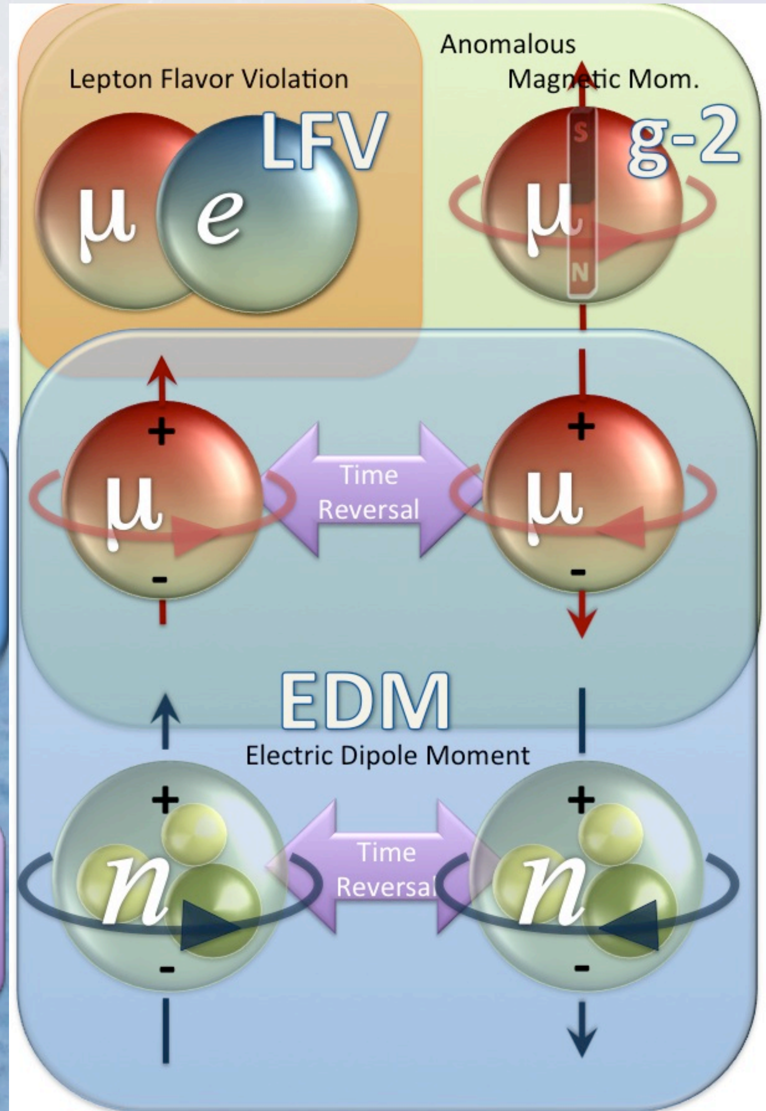
Space-time Symmetry and Origin of Matter

nEDM

Improve by 100 and more ($1\times10^{-28; -29}$ e cm)

Search for Electric Dipole Moment

Space-time Symmetry and Origin of Matter



$$\mathrm{EDM} \propto \mathrm{Im}(m^2_{\tilde\mu\tilde\mu})$$

$$\mathrm{cLFV} \propto \Delta m^2_{\tilde e\tilde\mu} + \Delta m^2_{\tilde\mu\tilde e}$$

$$g-2 \propto \mathrm{Re}(m^2_{\tilde\mu\tilde\mu})$$

$$M^2_{\tilde l\tilde l'} = \begin{pmatrix} m^2_{\tilde e\tilde e} & \Delta m^2_{\tilde e\tilde\mu} & \Delta m^2_{\tilde e\tilde\tau} \\ \Delta m^2_{\tilde\mu\tilde e} & m^2_{\tilde\mu\tilde\mu} & \Delta m^2_{\tilde\mu\tilde\tau} \\ \Delta m^2_{\tilde\tau\tilde e} & \Delta m^2_{\tilde\tau\tilde\mu} & m^2_{\tilde\tau\tilde\tau} \end{pmatrix}$$

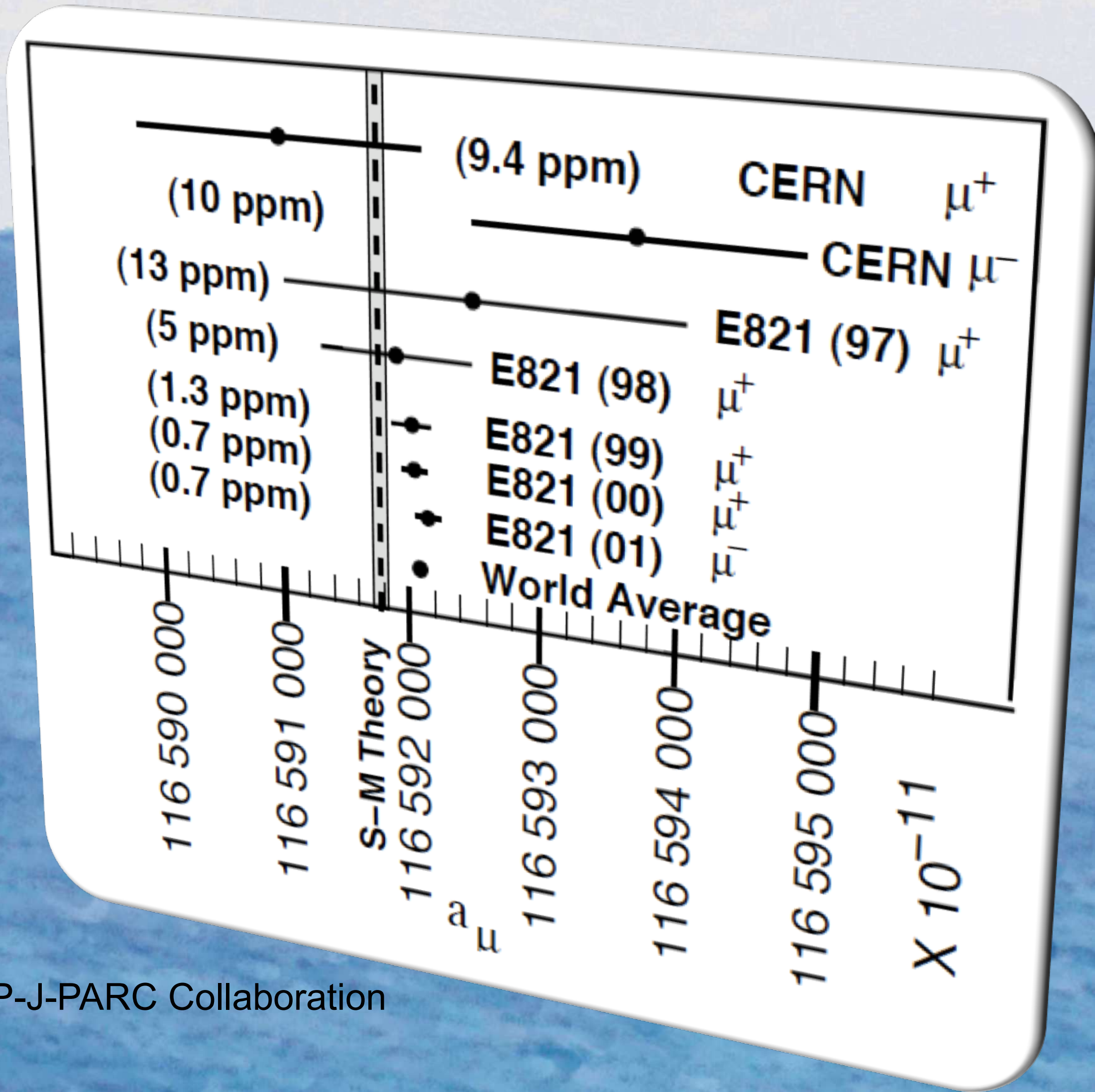
SUSY Mass Matrix

“Final Report” from BNL E821

$$\Delta a_{m}^{(\text{today})} = a_{m}^{(\text{Exp})} - a_{m}^{(\text{SM})} = (295 \pm 88) \times 10^{-11}$$

- E821 at BNL-AGS measured down to 0.7 ppm for both μ+ and μ–
- 3.4 sigma deviation from the SM
  - SM prediction OK?
  - New Physics?
- Need to explore further
- Preferably

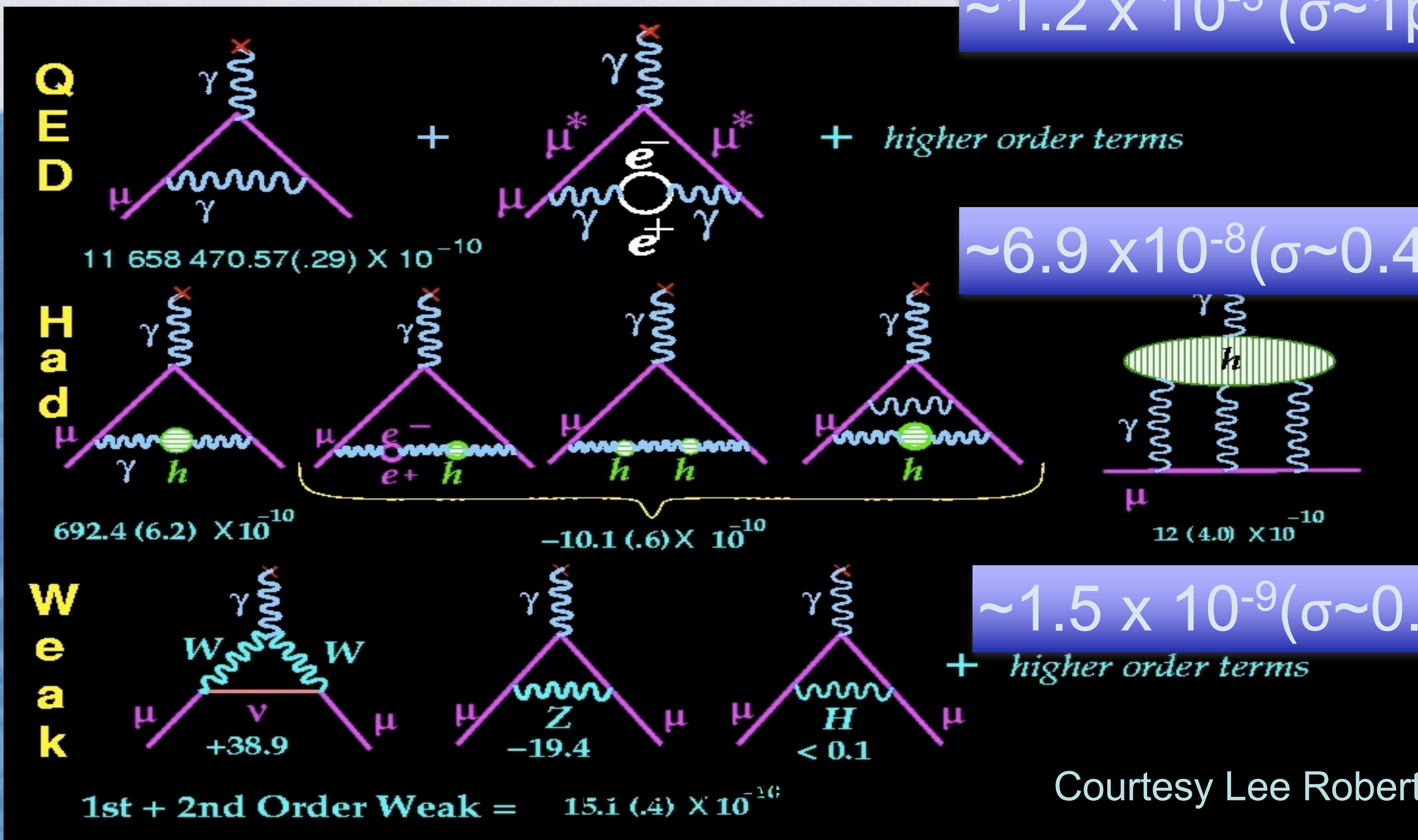
NEW METHOD!



For IoP-J-PARC Collaboration

SM Contribution to a≠0

- **Any particle which couples to muon/photon would contribute : QED >> Hadron > Weak**



~1.2 x 10^{-3} (σ~1ppb)

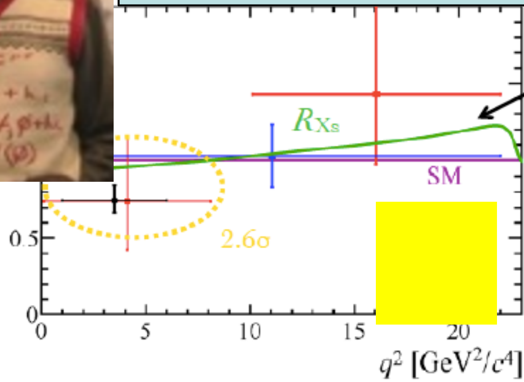
~6.9 x10^{-8}(σ~0.41ppm)

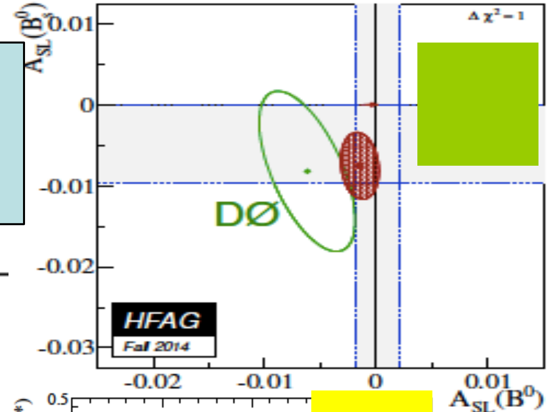
~1.5 x 10^{-9}(σ~0.02ppm)

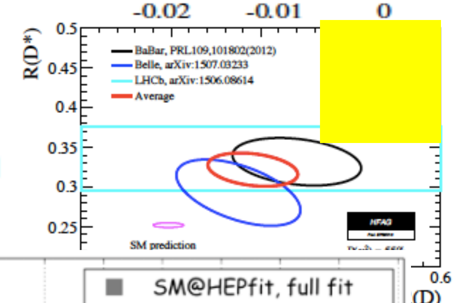
Courtesy Lee Roberts

John Ellis, March 14, 2016 (Nagoya)

Flavour Anomalies





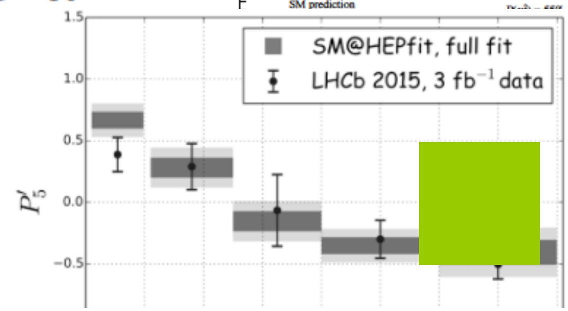


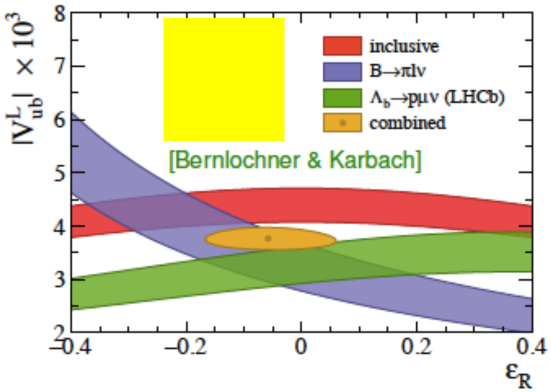
$h \to \tau\mu$

$B \to K e^+ e^- / B \to K \mu^+ \mu^-$

dimuon CP asym

$B \to D^{(*)} \tau\nu$





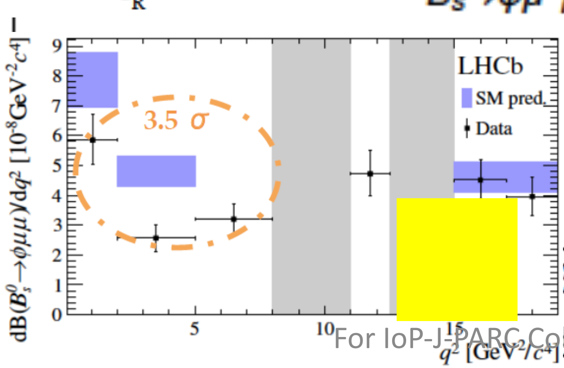
$B \to K^* \mu^+ \mu^-$ angular

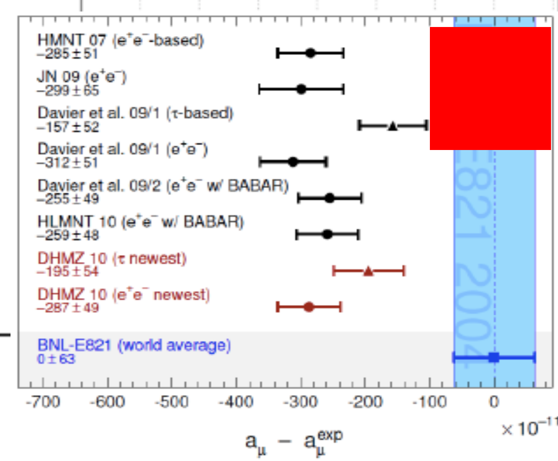
$|V_{cb}|$ incl/excl

$|V_{ub}|$ incl/excl

$B_s \to \phi \mu^+ \mu^-$

g−2





No worries

Wait & See

Serious?

muon *g*-2/EDM

BNL E821 measured the muon *g*-2 with 0.54 ppm precision.
More than 3σ deviation from the SM.

FNAL E989

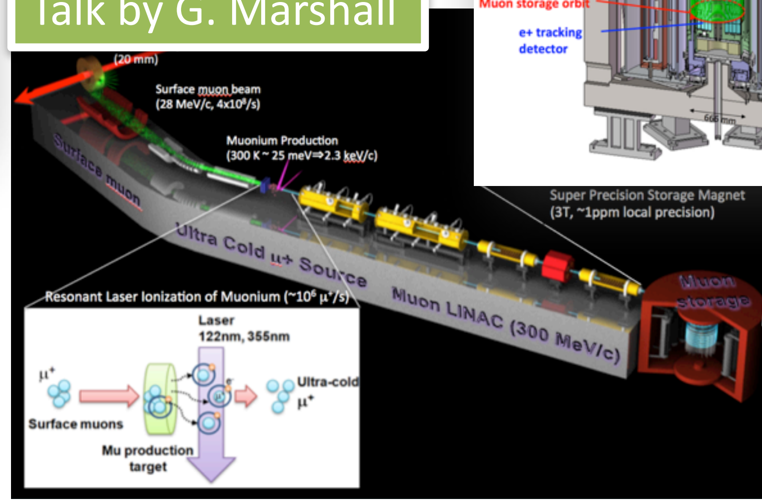
Talk by D. Herzog

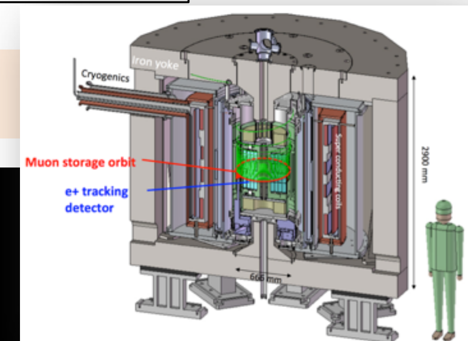
Photos from G. Venanzoni, EPS 2015

- Higher precision with the **magic momentum technique** established by BNL E821
- Muon storage magnet was moved from BNL. **Now cooling down.**
- Data taking expected in 2017

J-PARC E34

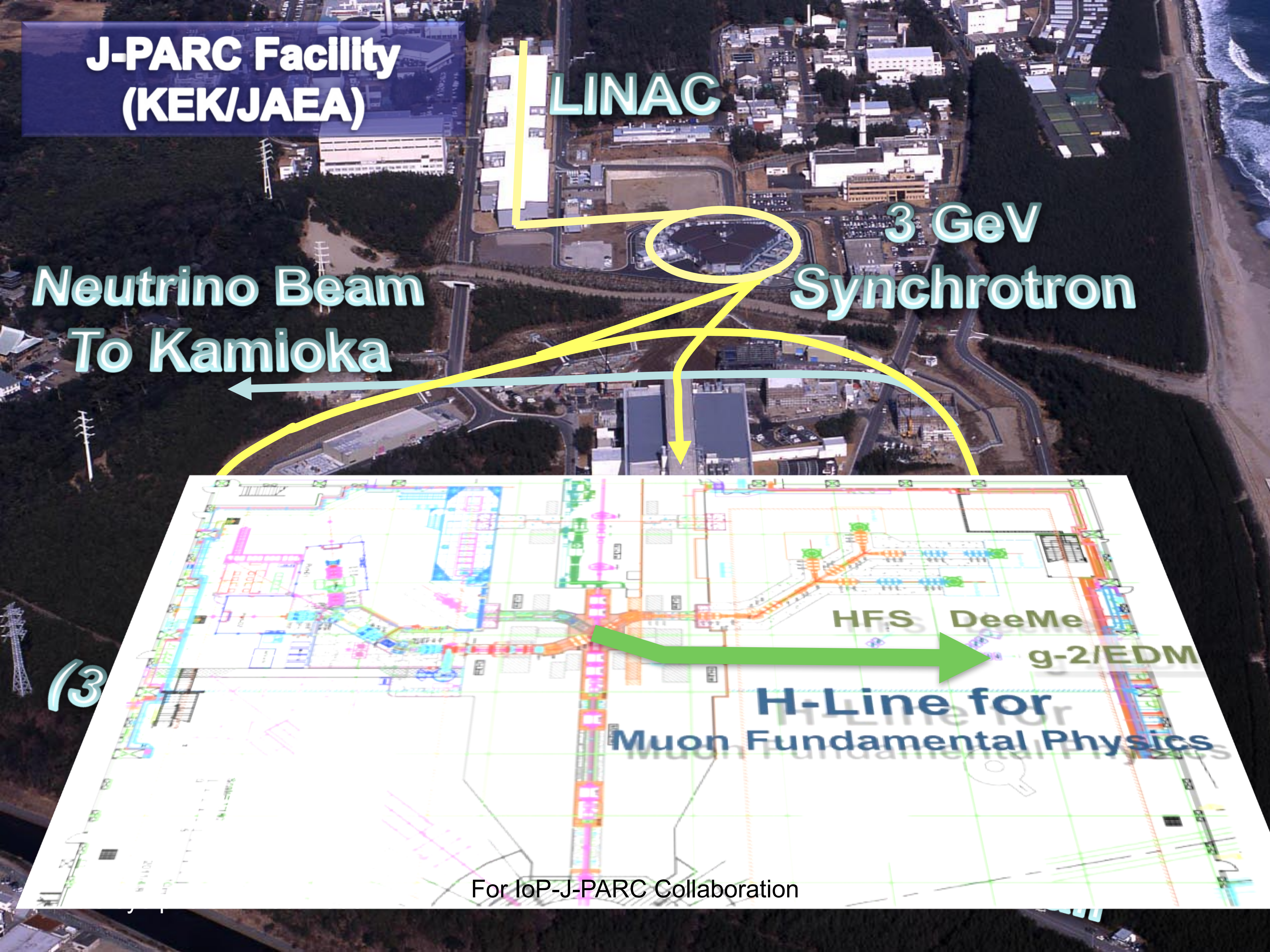
Talk by G. Marshall

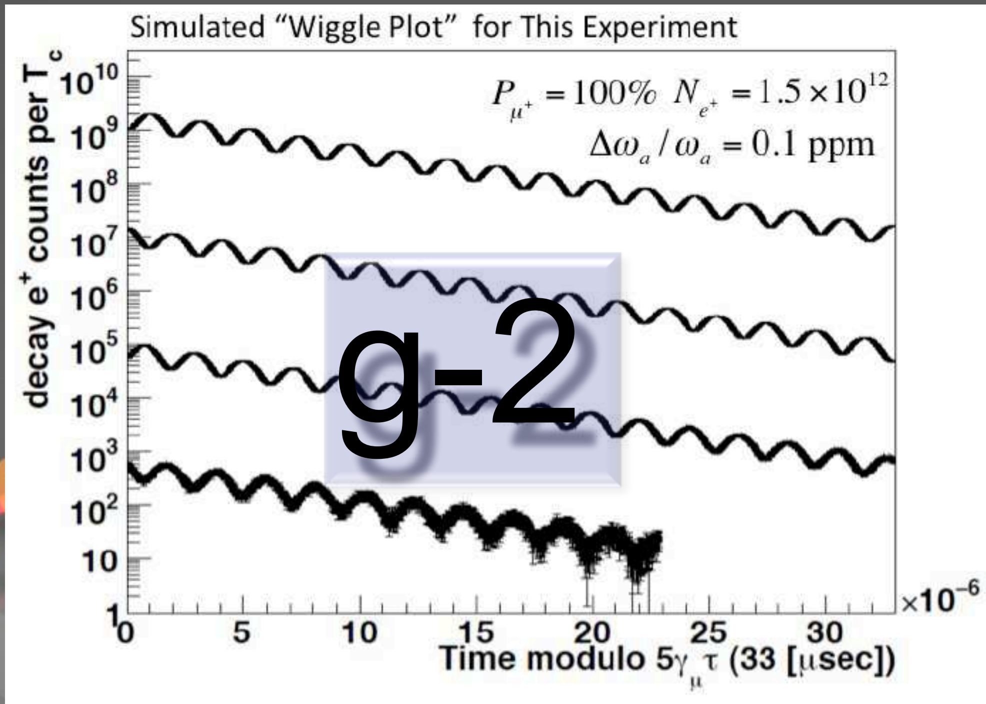


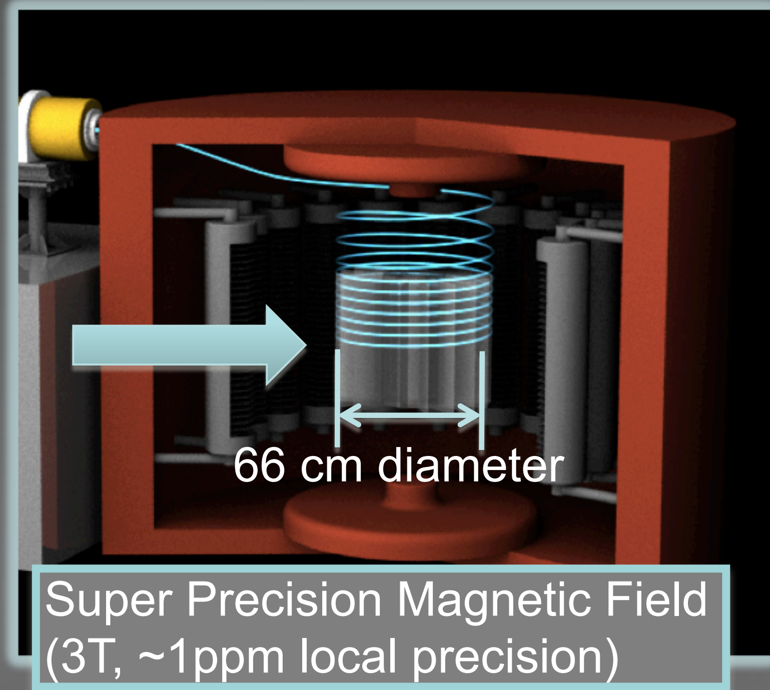


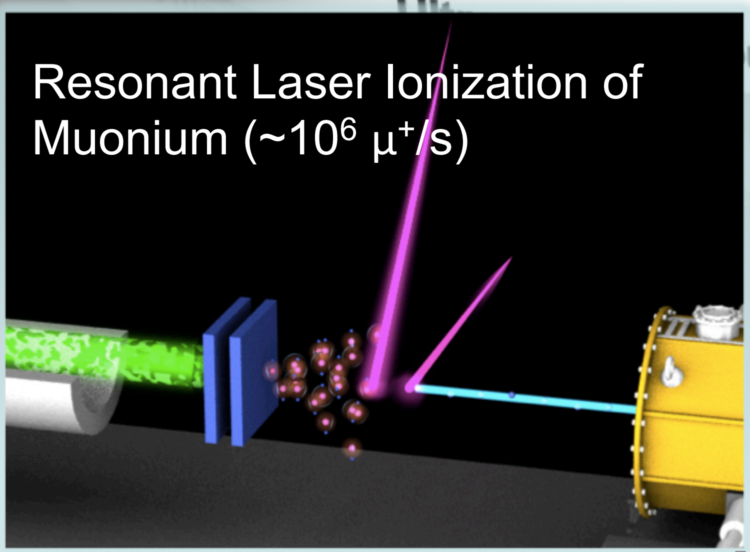
- Completely different technique with **ultra-cold muon beam**
  (compact storage ring, spin flip)
- **Independent test of BNL E821**
- TDR under review
- Also, prepares to measure Mu-HFS and μ_{μ}/μ_{p} (MuSEUM exp).

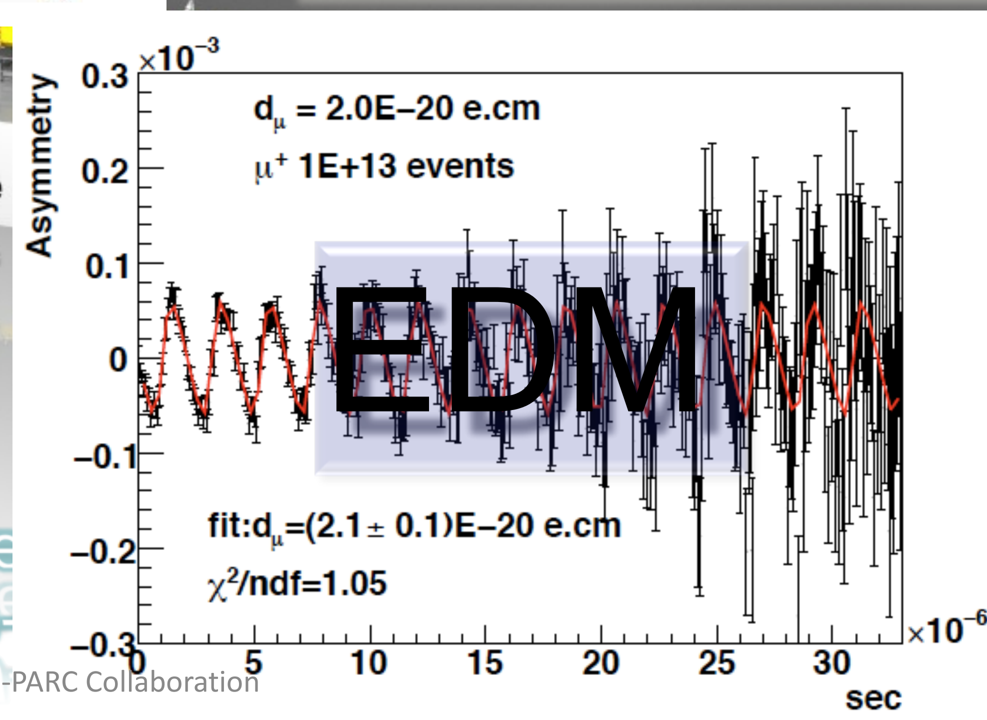
For IoP-J-PARC Collaboration
Slide by Tsutomu MIBE


J-PARC Facility
(KEK/JAEA)
LINAC
3 GeV
Synchrotron
Neutrino Beam
To Kamioka
HFS
DeeMe
g-2/EDM
H-Line for
Muon Fundamental Physics
For IoP-J-PARC Collaboration









talk by G. Marshall

Magic vs "New Magic"

- **Complimentary!**

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

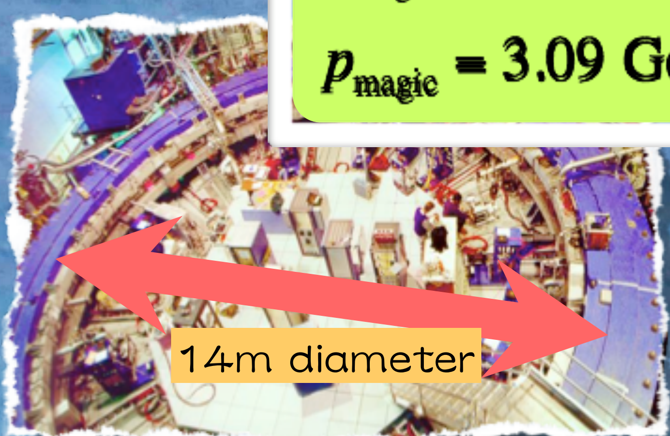
BNL/Fermilab Approach

$$a_\mu - \frac{1}{\gamma^2 - 1} = 0$$

$$\eta \approx 0$$

$$\gamma_{\text{magic}} = 29.3$$

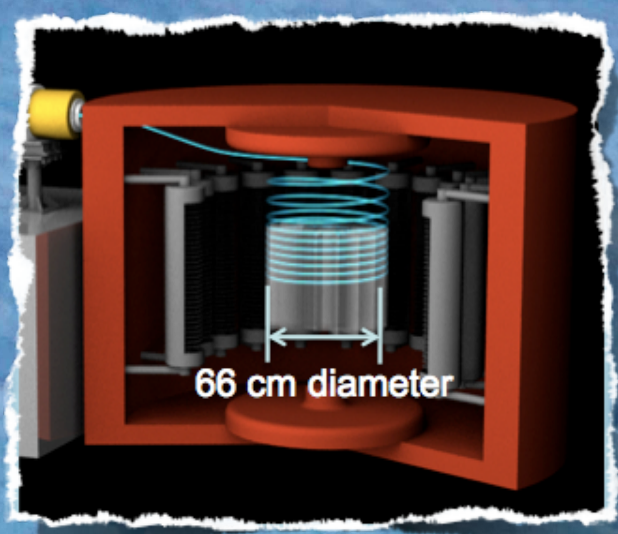
$$p_{\text{magic}} = 3.09\ \text{GeV}/c$$



J-PARC Approach

$$\vec{E} = 0$$

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$$



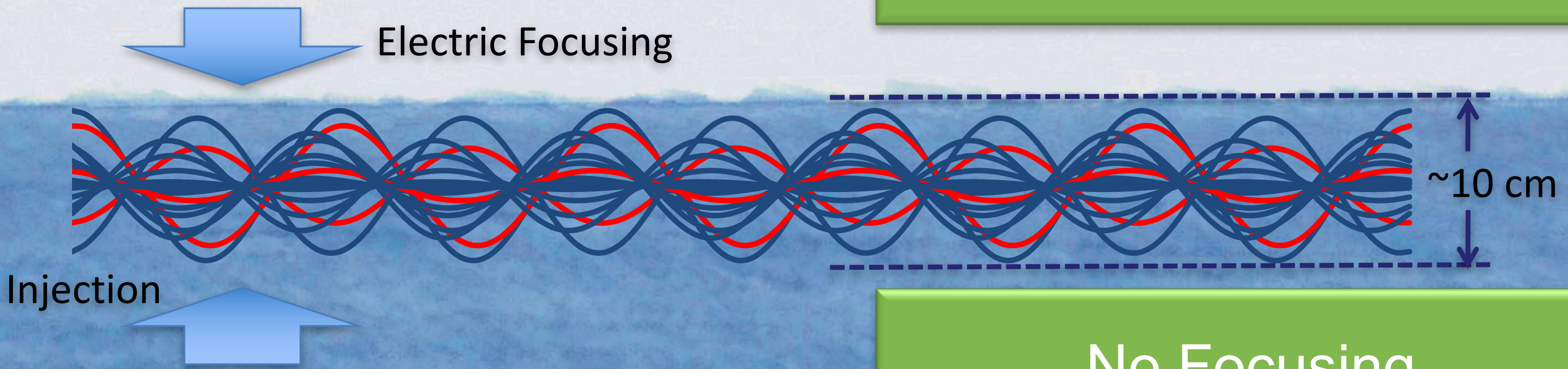
$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

For IoP-J-PARC Collaboration

Off Magic Momentum?

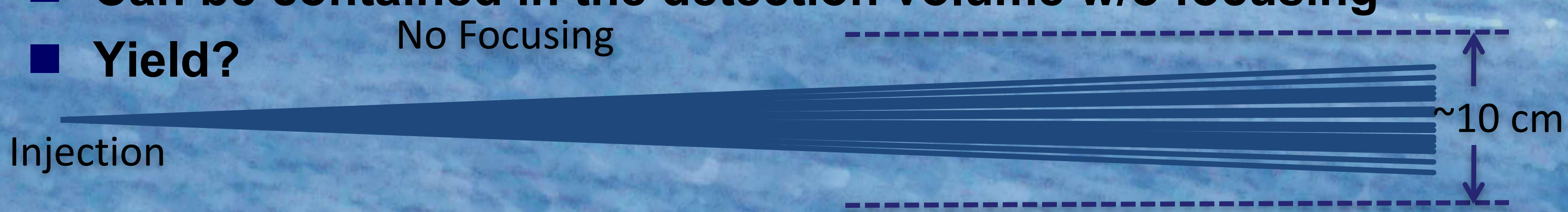
- **Tertiary Muon Beam**
  - **Widely spread over phase space**
  - **Contamination of pion**

Electric Field for Focusing
⇒ Magic Momentum



No Focusing
⇒ Any Momentum

- **Ultra-Cold Muon Beam**
  - **Can be contained in the detection volume w/o focusing**
  - **Yield?**

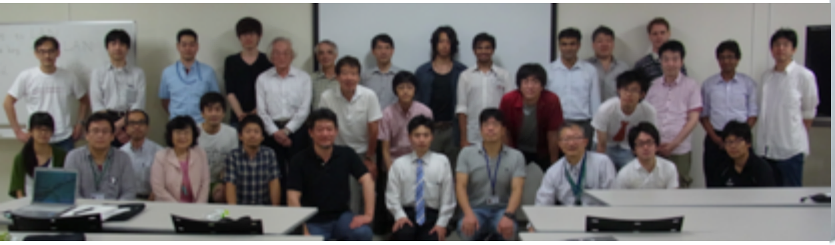


$s(p_T)/p_L \le 10^{-5}$ ⇒ < 10 cm spread over 10 km travel

The collaboration

- Collaborators
  - Proposal (2009) 72
  - Conceptual Design Report (2011) 92
  - Technical Design Report (2015) 136 (16 graduate students) (27 also in COMET)
- 9 countries, 49 institutions
  - Canada, China, Czech, France, Japan, Korea, Russia, UK, USA (in alphabetical order)

J-PARC 2014.9



KAIST (Korea) 2014.11

J-PARC 2015.6

The TDR

Technical Design Report
for
the Measurement of the Muon Anomalous Magnetic Moment $g-2$ and Electric Dipole Moment at J-PARC

May 15, 2015

prepared by 136 authors

Summary

In summary, this experiment intends to reach statistical uncertainties for muon $g-2$ of 0.37 ppm and for muon EDM of $1.3 \times 10^{-21} e \cdot \mathrm{cm}$, during an acquisition time of 2×10^7 seconds of high-quality data, with a completely new experimental technique based on an ultra-cold muon beam and a compact storage ring. We will show in this document that our current understanding of the available beam power, the efficiency of the ultra-cold muon source, the muon acceleration, injection, and storage, and decay detection, all indicate that this is achievable. The statistical reach in the quoted running time is lower than we originally proposed. However, the $g-2$ sensitivity, even at this level, should exceed that of BNL E821 and provide an independent test of the three to four sigma discrepancy with the Standard Model prediction. Moreover, it would reduce the existing upper limit for the muon EDM by a factor of about 70. In the process of achieving these important goals, we would also be able to identify and understand any systematic uncertainties that may have to be reduced before attaining the final goal as originally proposed. In parallel, we will continue R&D, especially on the ultra-cold muon source intensity, to further improve the sensitivity to the final goal of 0.1 ppm for $g-2$.

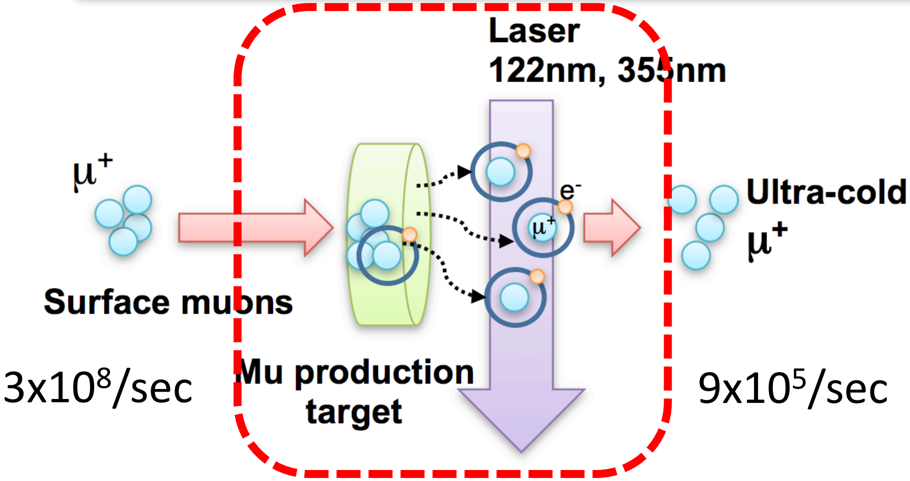
- TDR describes a technical design to achieve measurement of muon g-2 and EDM beyond BNL E821 precision.

	BNL E821		J-PARC E34
g-2:	0.46 ppm	→	0.37 ppm (→0.1ppm)
EDM:	0.9×10^{-19} ecm	→	1.3×10^{-21} ecm

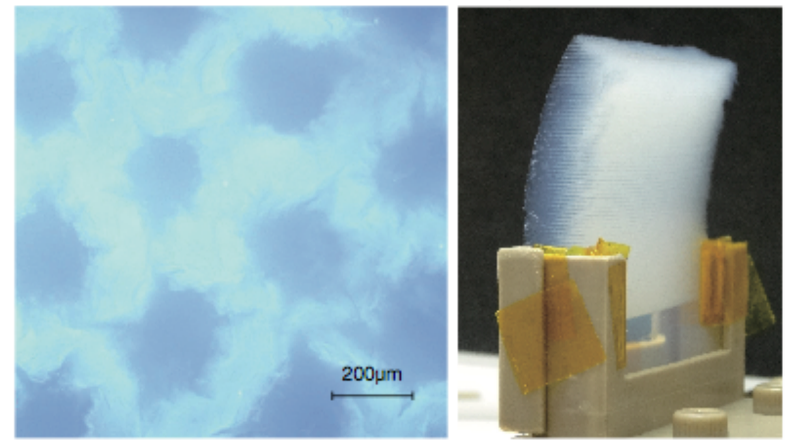
- Discussions with the lab and PAC (IPNS,IMSS) are in progress.

Muonium Production

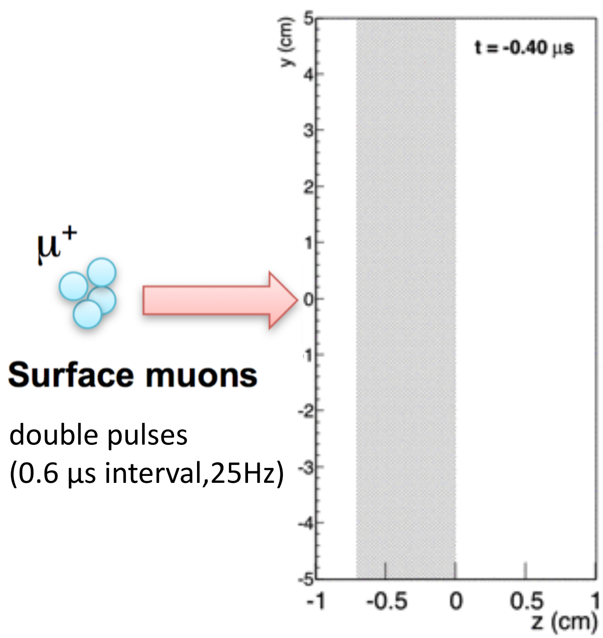
RIKEN, TRIUMF, UVic, Chiba, Korea U, KEK

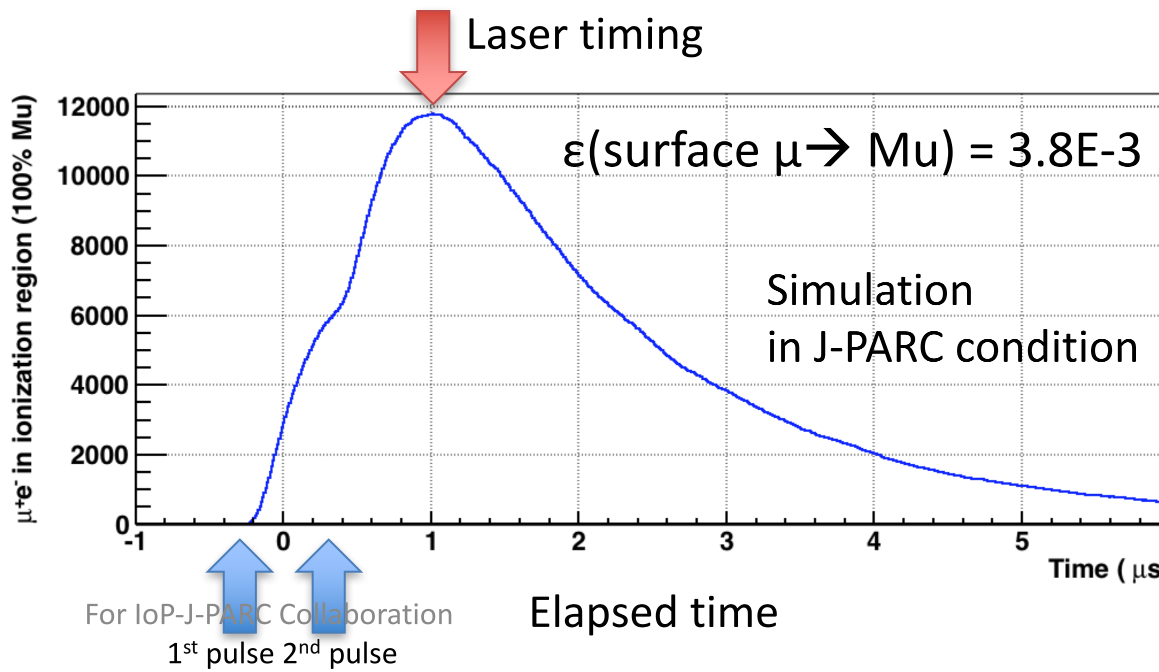


Mu production target
(laser-ablated silica aerogel)



G. Beer et al., Prog.Theor.Exp.Phys. (2014)091C01

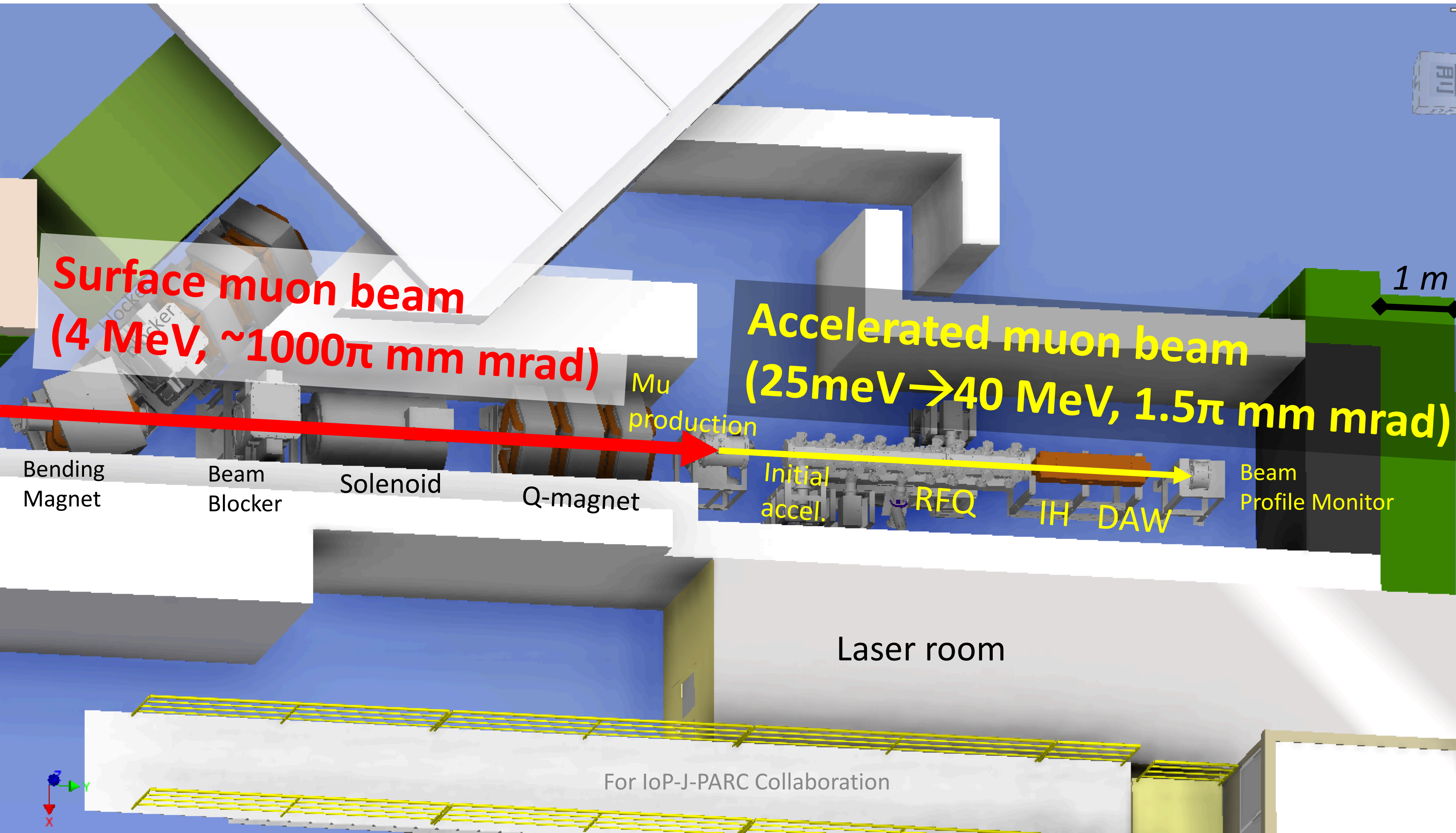




For IoP-J-PARC Collaboration

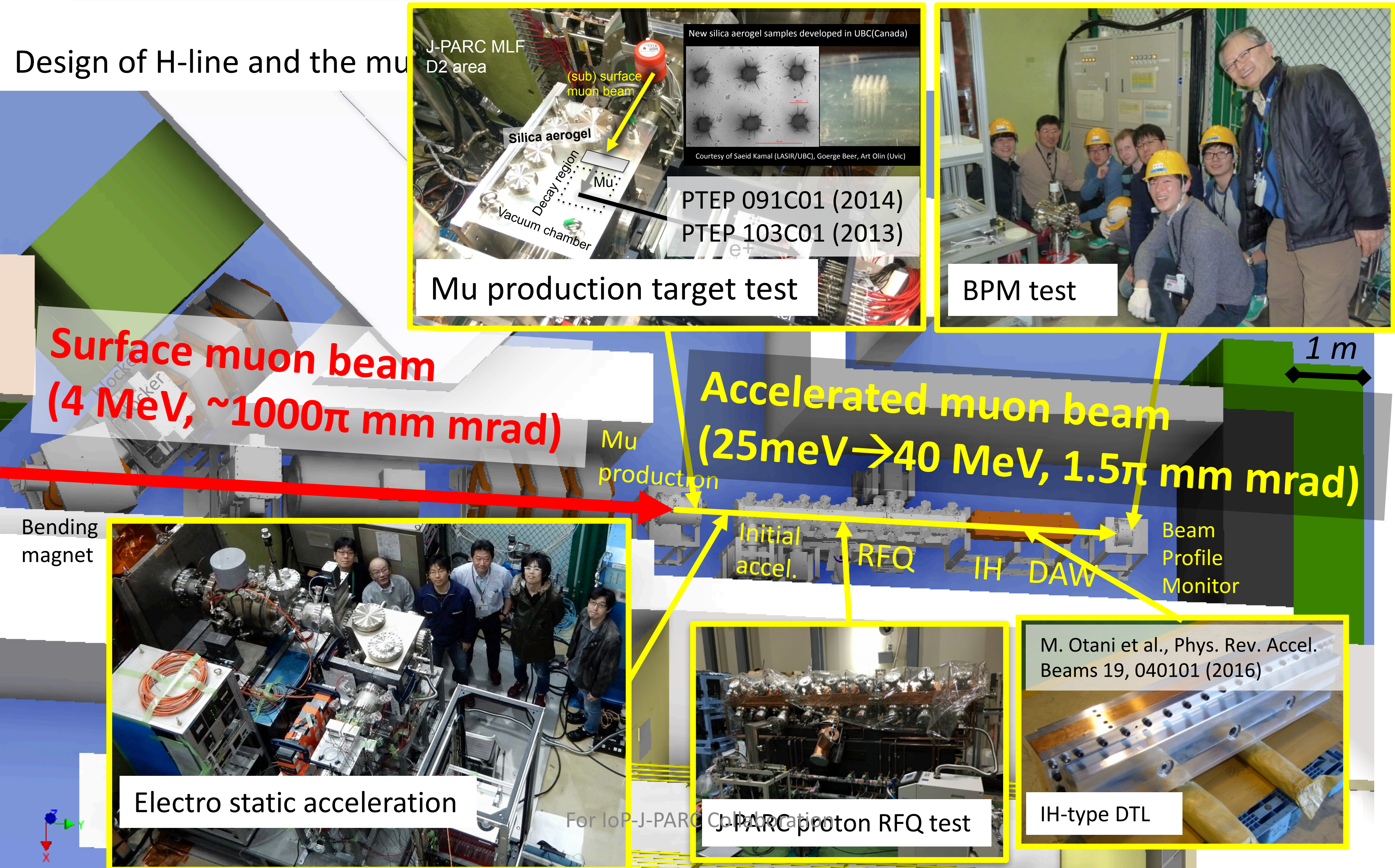
Ultra-cold Muon Beam at H-line

Design of H-line and the muon acceleration test



Ultra-cold Muon Beam at H-line

Design of H-line and the mu



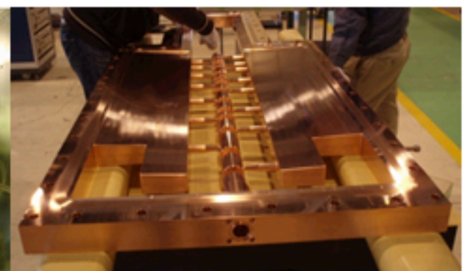
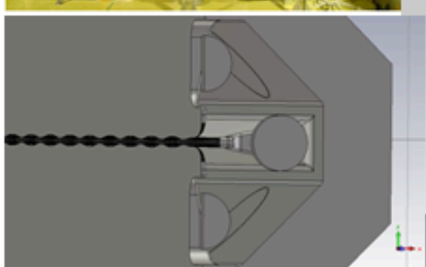
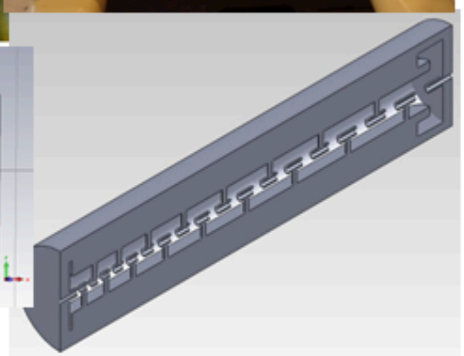
World First Muon Acceleration to 200 MeV

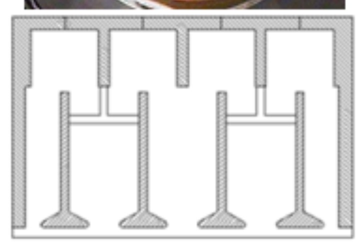
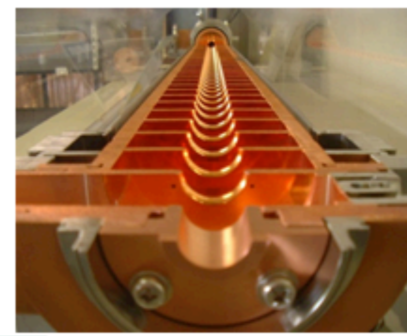
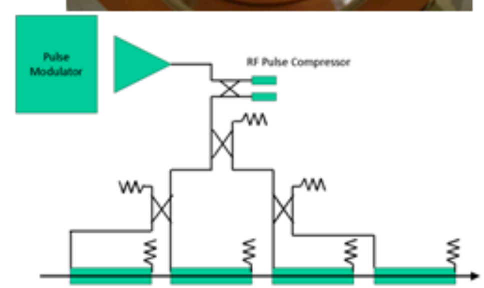
5.6 keV	0.34 MeV	5.1 MeV	42.3 MeV	200 MeV
β≈0.01	β≈0.08	β≈0.3	β≈0.7	β≈0.94

Bunching Section | Low-β | Middle-β | High-β

μe^-

RFQ (324 MHz) High capture efficiency	Interdigita-H (324 MHz) High shunt impedance	DAW (1300 MHz) External coupling structure for Middle-β	Disk loaded structure (1300 MHz) High gradient (4 structures)

Bunching Section

High hunt impedance

External coupling structure for low-β

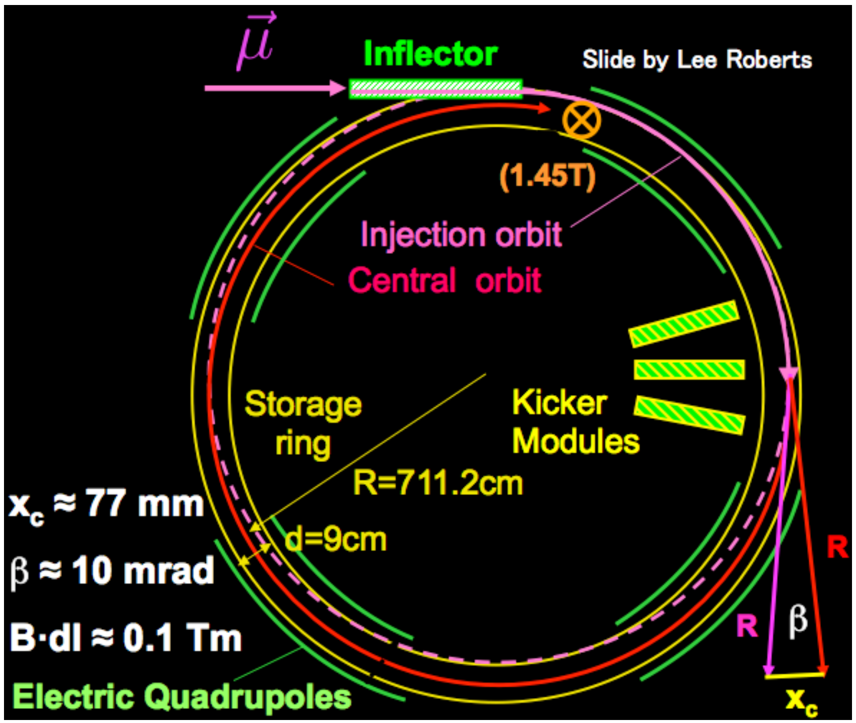
Similar to electron accelerator to obtain high gradient.

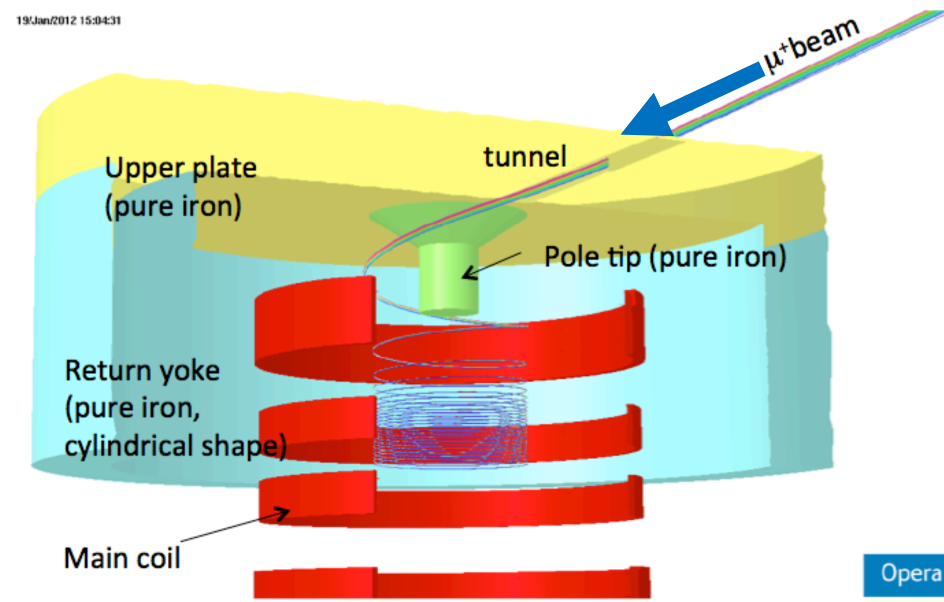
M. Otani et al., Phys. Rev. Accel. Beams 19, 040101 (2016)

Muon Beam Injection and Storage

Horizontal injection + kicker (BNL E821, FNAL E989)

3D spiral injection + kicker (J-PARC E34)





Injection efficiency : 3-5%(*)

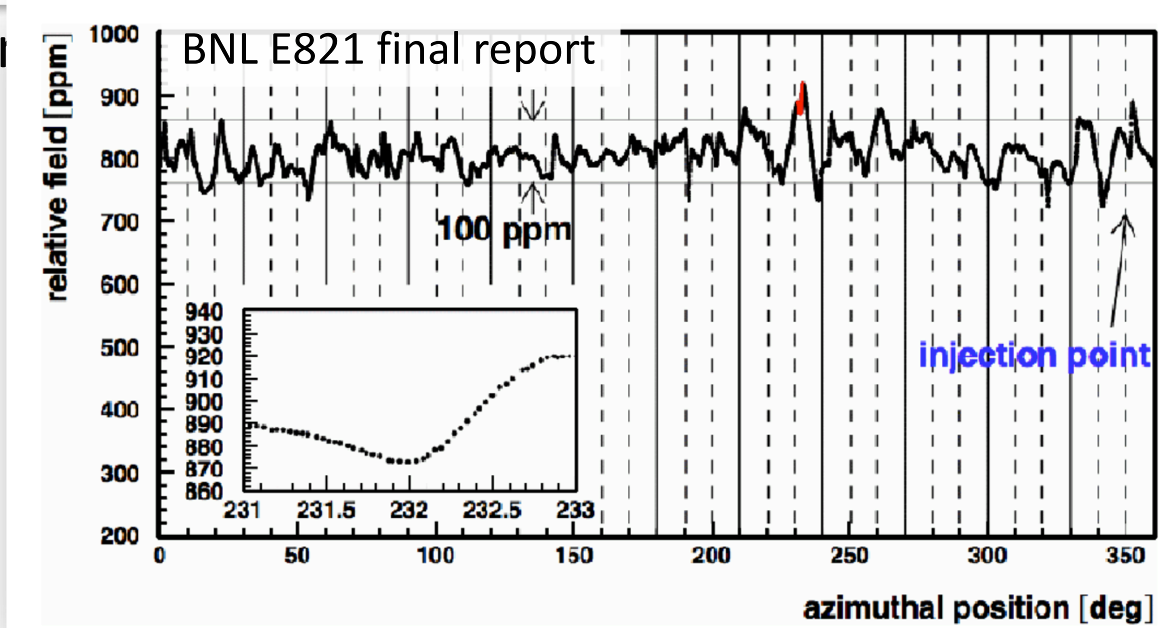
Injection efficiency : ~90%

(*) PRD73,072003 (2006)

A paper was submitted to NIMA in Oct 2015 by H. Iinuma et al.

B-field uniformity

Before shimming

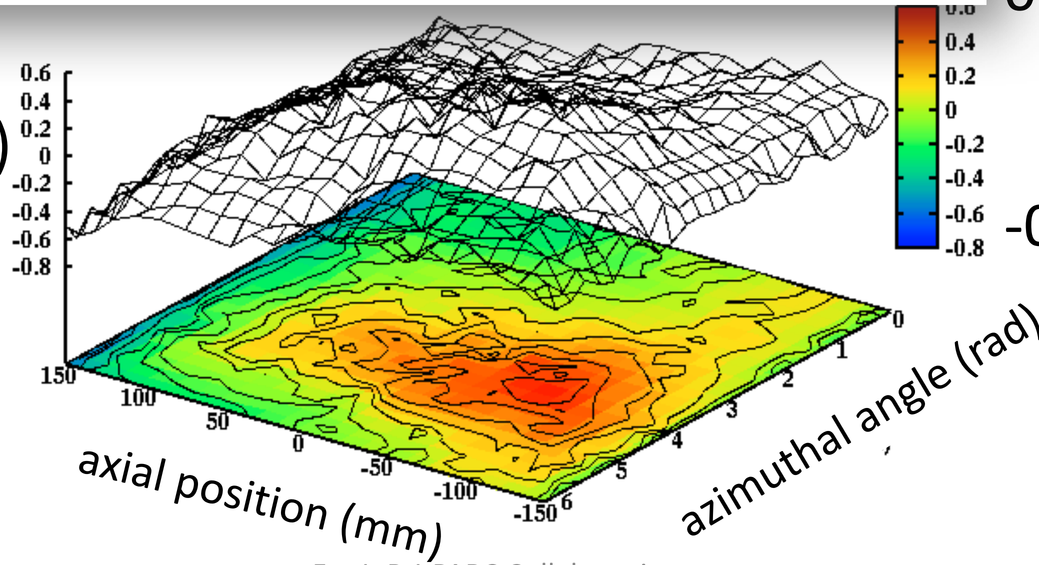


370 ppm

-630 ppm

After shimming

B(μT)



0.4 ppm

-0.5 ppm

r = 140 mm

Submitted to IEEE Transactions of Applied Superconductivity, by K. Sasaki et al. (2016)

Muon storage magnet and detector

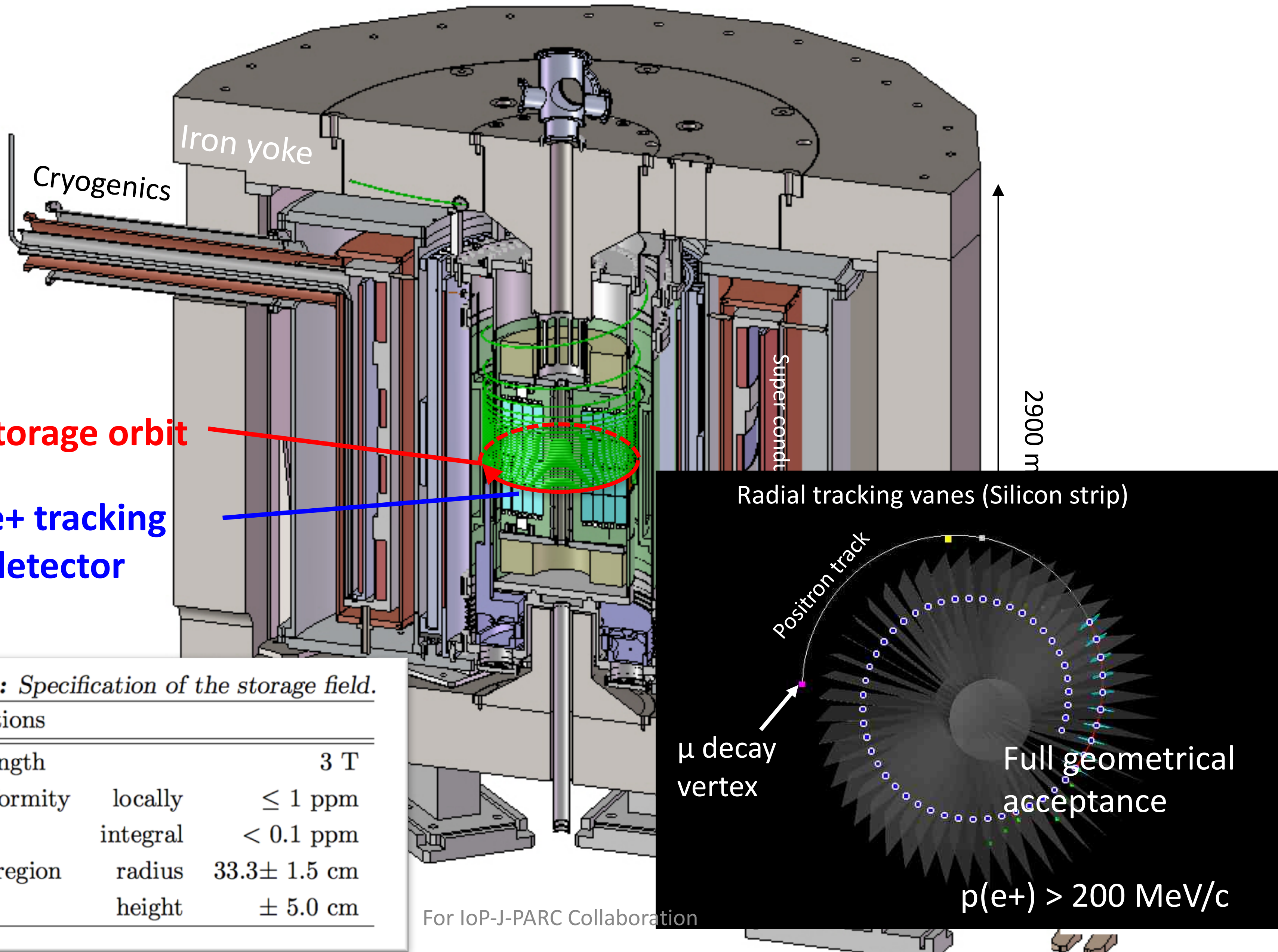
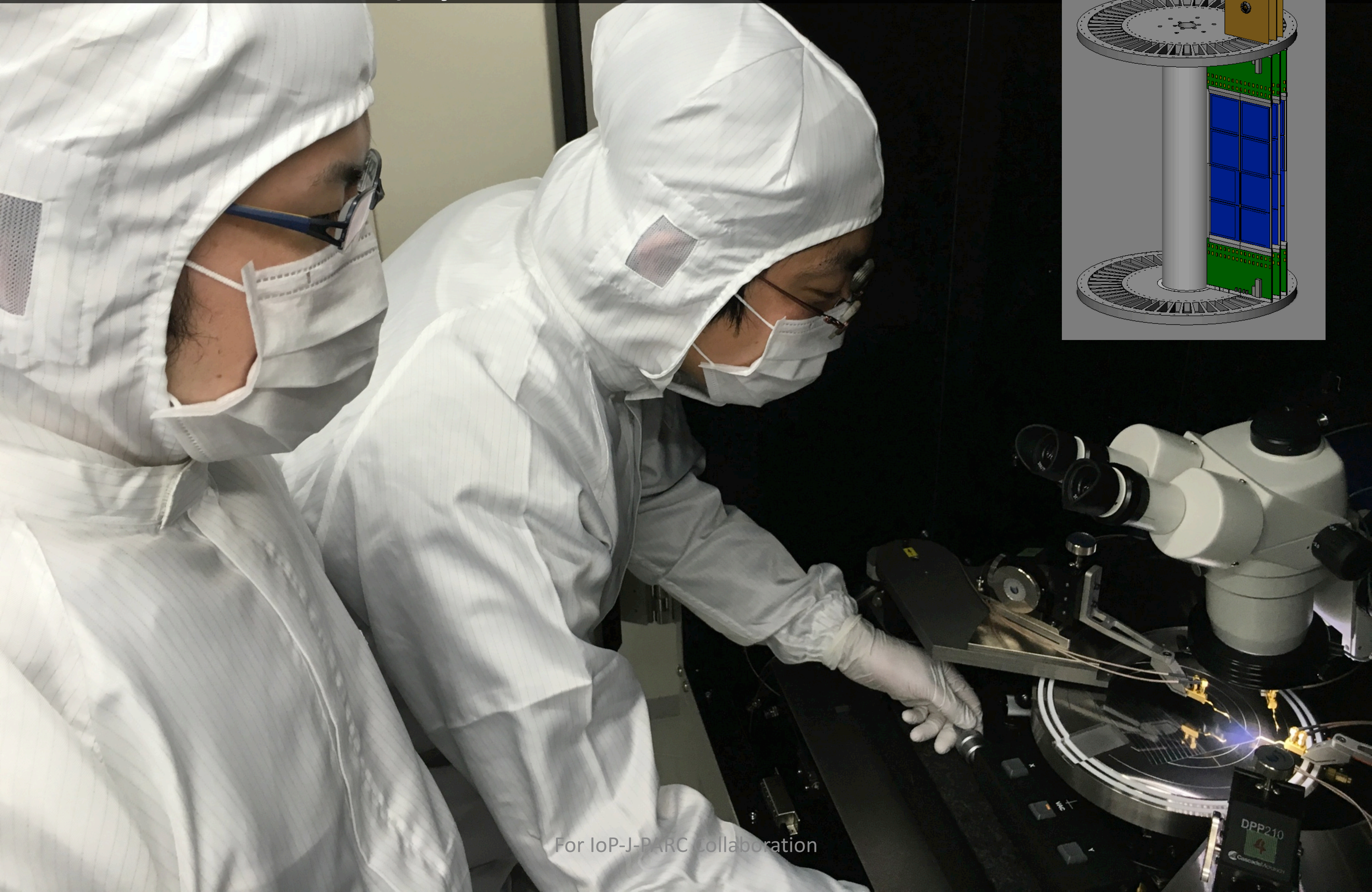


Table 1.2: *Specification of the storage field.*

specifications		
field strength		3 T
field uniformity	locally	≤ 1 ppm
	integral	< 0.1 ppm
uniform region	radius	33.3 ± 1.5 cm
	height	± 5.0 cm

Construction of Silicon strip tracker in progress (Kyushu Univ./KEK-IPNS)



Join us!


The 9th J-PARC g-2/EDM Open Collaboration Meeting & Training Sc ol
ibs
2014.11.5 (Wed) ~ 8(Sat), KAIST, Daejeo
http://capp.kaist.ac.kr/CM9

J-PARC: Next 5 Years

- Achieve Design Intensity
- More Science Outputs
- Explore Intensity Frontier

Accelerator

- RCS:1 MW achieved
- MR 0.75 MW → 1.3 MW
- Explore Multi-MW Possibility

Neutrino

- Established non-zero θ_{13}
- Constrain CPV. Hierachy?
- Prepare next gen. of Exp.

ADS (Acc. Driven System)

Staged R&D approach from ADS Target Test Facility to Transmutation Exp. Facility

Hadron

- Restarted Physics Production
: Hyper-nucl/hadron physics, K-rare decays
- Complete new beam line for COMET/Hi-p BL and 1st results

MLF

Stability and Intensity

- Neutron and Muon: Diverse Material and Life Science
- Enhance Industrial Usage
- New beam lines to extend Science Frontier (g-2/EDM/HFS/DeeMe)

Collaboration with Academia & Industry

Domestic University

New Graduate Course Established to include J-PARC science

Univ. branch at J-PARC

Education and training of students and young researchers at the very front of J-PARC operation, especially to raise the next generation who can create a future cutting edge facilities

Oversea Institutions

Collaboration with TRIUMF

Experimental Collaboration and exchange program of researchers; share the know-how on facility and safety management

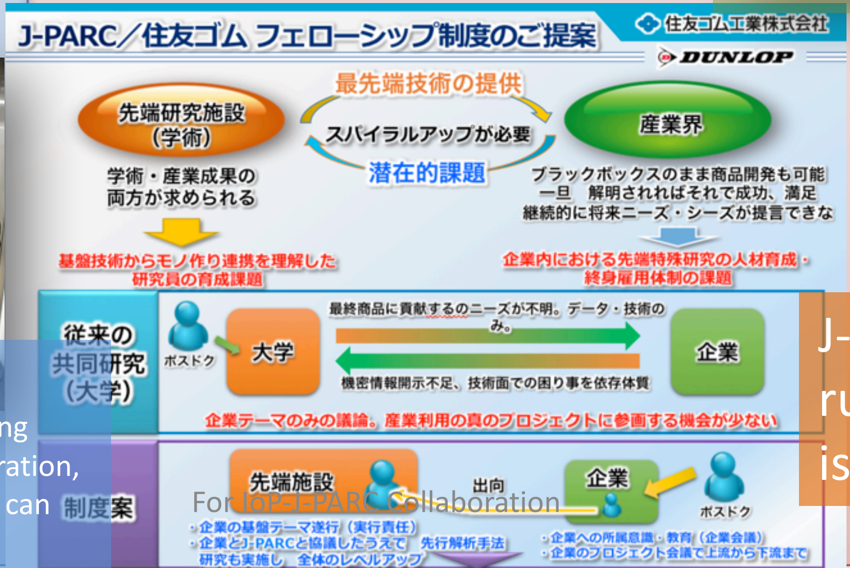
Collaboration with ANSTO

For improving user environment, sample environment, e.g. deuterization lab, and exchange program for researchers.

Collaboration with ESS

Contribute to the newly constructed major facility based on the experience of J-PARC construction.

Industrial Sector



J-PARC/Sumitomo rubber Inc. Fellowship is established

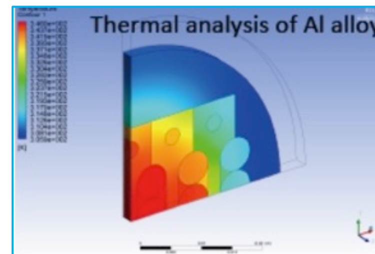
RaDIATE

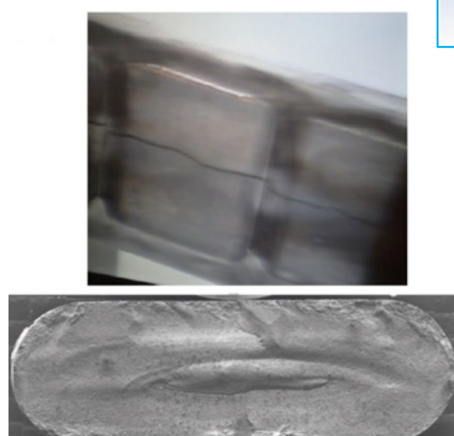
Radiation Damage In Accelerator Target Environments

radiate.fnal.gov

- High Intensity Accelerator requires investigation of radiation damage of target and beam window
- RaDIATE: an internat'l collab. of scientists and engineers from acc. and reactor facilities to solve the problems
- J-PARC has joined the team since 2014. MOU is in preparation.

Neutrino Beam Window
Ti Alloy ~1x10^{21} pot
~1 Displacement Per Atom
(Existing data up to ~0.3DPA)





2016~...(予定)

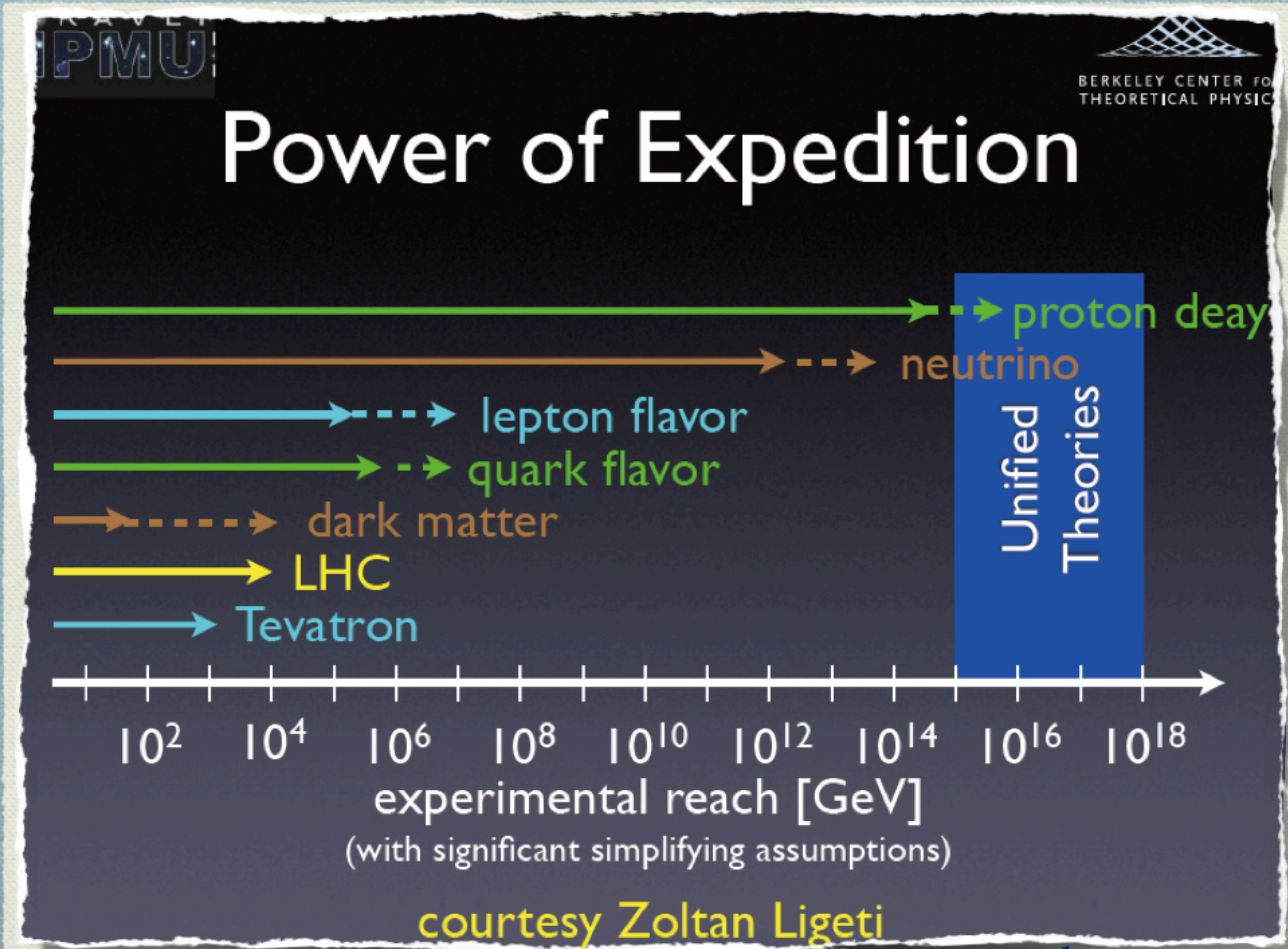
NuMI graphite broken target
Post-Irradiation Examination (PIE)
at PNNL: Swelling effect observed

New Irradiation Run at
BNL (2017 February ~)

Summary

- J-PARC is a multi-purpose facility with the high-intensity proton driver
  - Particle and Nuclear physics
  - Material and Life Science
  - R&D for nuclear transmutation
- High power scenario is refined based on REAL DATA : MR 0.75 MW → 1.3 MW
- Multi-MW proposals are being developed
- We invite YOUNG scientists to share more excitements!

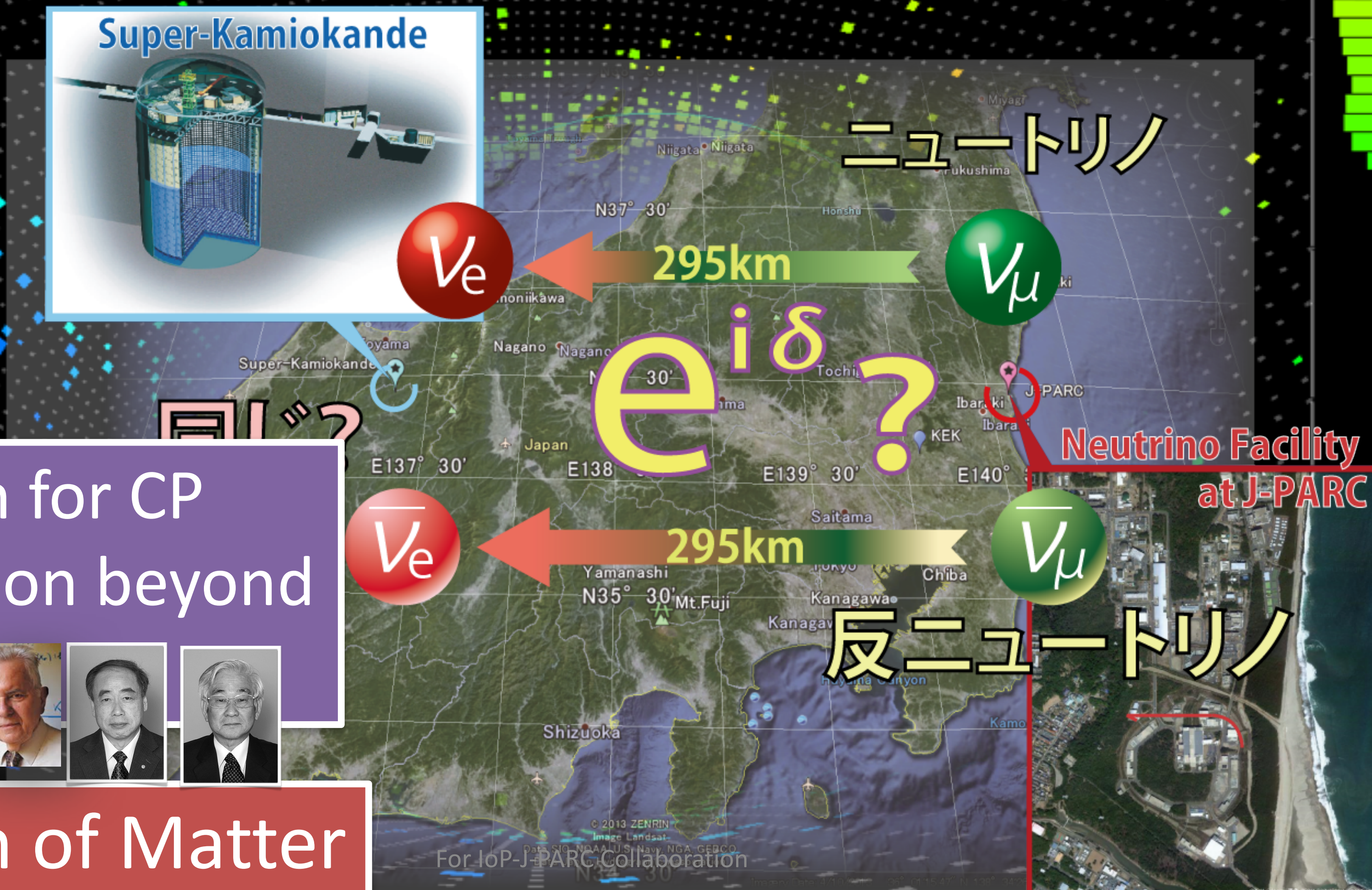
Including Young at Heart!



a slide by Hitoshi Murayama

Goal of T2K

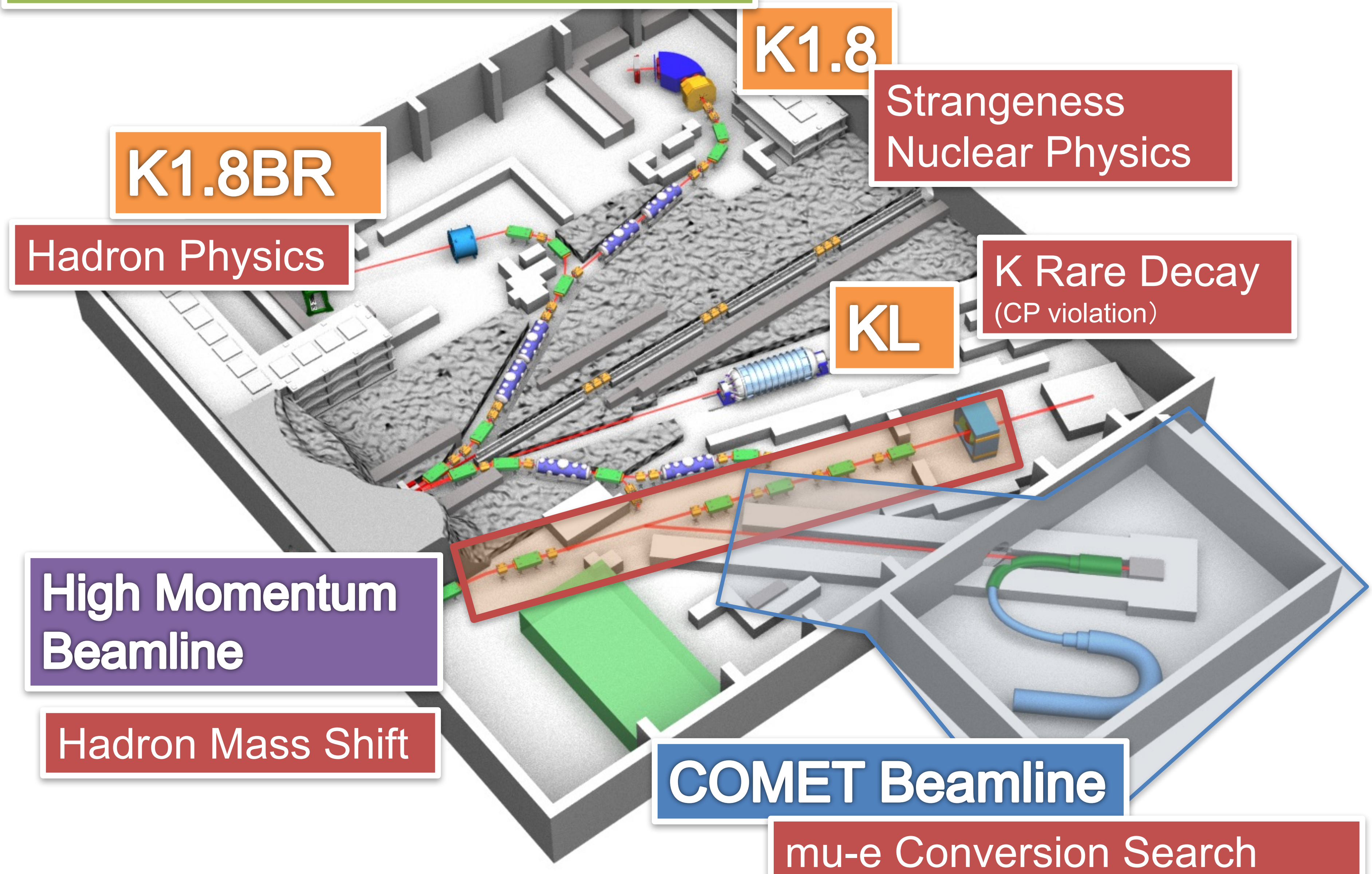
Neutrino and anti-neutrino behave same?



Search for CP Violation beyond CKM

Origin of Matter

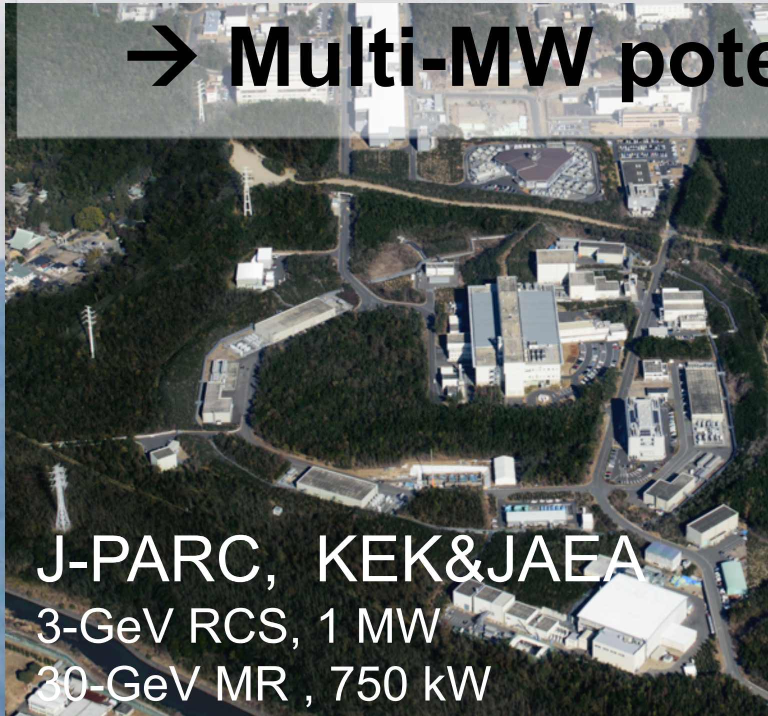
Hadron Hall in 2016



Hi-Intensity P-driver

- 1 MW class
  → Multi-MW potential


SPS, CERN
450-GeV Synchrotron


J-PARC, KEK&JAEA
3-GeV RCS, 1 MW
30-GeV MR , 750 kW


Main Injector, FNAL
120-GeV Synchrotron, 700 kW

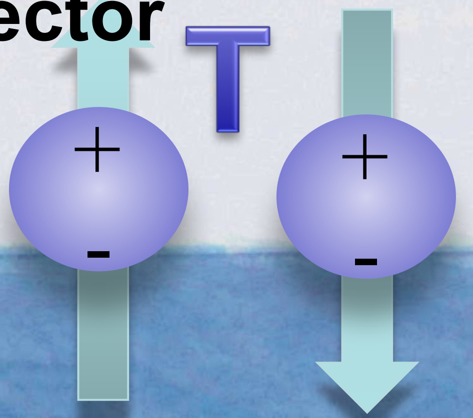

Spallation Neutron Source, ORNL
1-GeV AR, 1.4 MW


HIPA, PSI
590 MeV/u cyclotron, 1.4 MW

Particle Dipole Moments

- **Magnetic and Electric Dipole Moments are related to Spin of the Particle: axial vector**

$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s} \qquad \vec{d} = \eta\left(\frac{e}{2mc}\right)\vec{s}$$



$$a = \frac{g-2}{2}$$

$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

MDM (Magnetic Dipole Moment)
Contains contributions from ALL PHYSICS!
- EW, QCD, and New Physics
⇒ precision test of the SM
⇒ the most precise determination of α_{EM} from electron g-2 (0.37 ppb)

EDM (Electric Dipole Moment)
If EDM nonzero, T is violated
⇒ CP violation in the lepton sector (under CPT)
⇒ leptogenesis?
⇒ Baryon Asymmetry in the Universe

KEK-wide contributions

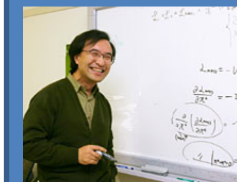
Institute of Materials and Structure Science (IMSS)

Beamline design,
construction,
and operation
Infrastructure

Institute of Particle and Nuclear Studies (IPNS)

Muon source
Muon LINAC
Detector

Theory Center



Precise SM prediction

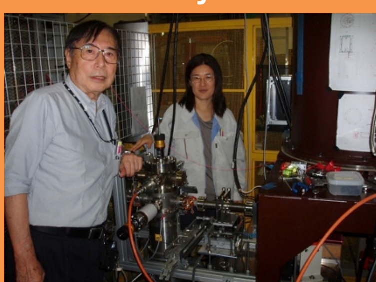
muon g-2/EDM at J-PARC

Cryogenics Science Center

Storage magnet
Field measurement

Accelerator Laboratory

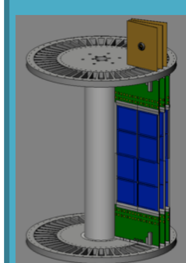
Muon LINAC design
Beam Injection



J-PARC Center

Muon LINAC

Mechanical Engineering Center



Detector mechanical support, cooling
Precision alignment

Expected impacts to the Lab (and communities)

Institute of Materials and Structure Science (IMSS)

esign,

n,

on

re

muon microscope

Institute of Particle and Nuclear Studies (IPNS)

Muon source

Muon LINAC

Detector

Theory Center

Established BSM evidence (or limit)

Precise SM prediction

muon g-2/EDM at J-PARC

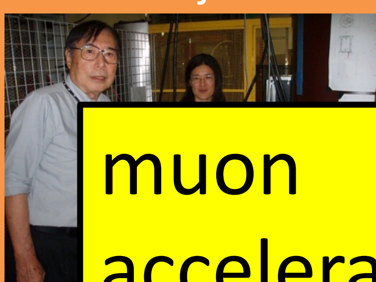
Cryogenics Science Center

Storage magnet

Accelerator Laboratory

Muon LINAC design

Beam Injection



muon acceleration technologies

J-PARC Center

Muon LINAC

Mecha

Technologies for high-precision engineering

support, cooling

Precision alignment

Direct Access to J-PARC

- Local community fully understands the need
- Nuclear security is also compromised due to many open users who would just go through JAEA campus to go to J-PARC
- Discussion with Tokai Village is resumed
- Funding is an issue.

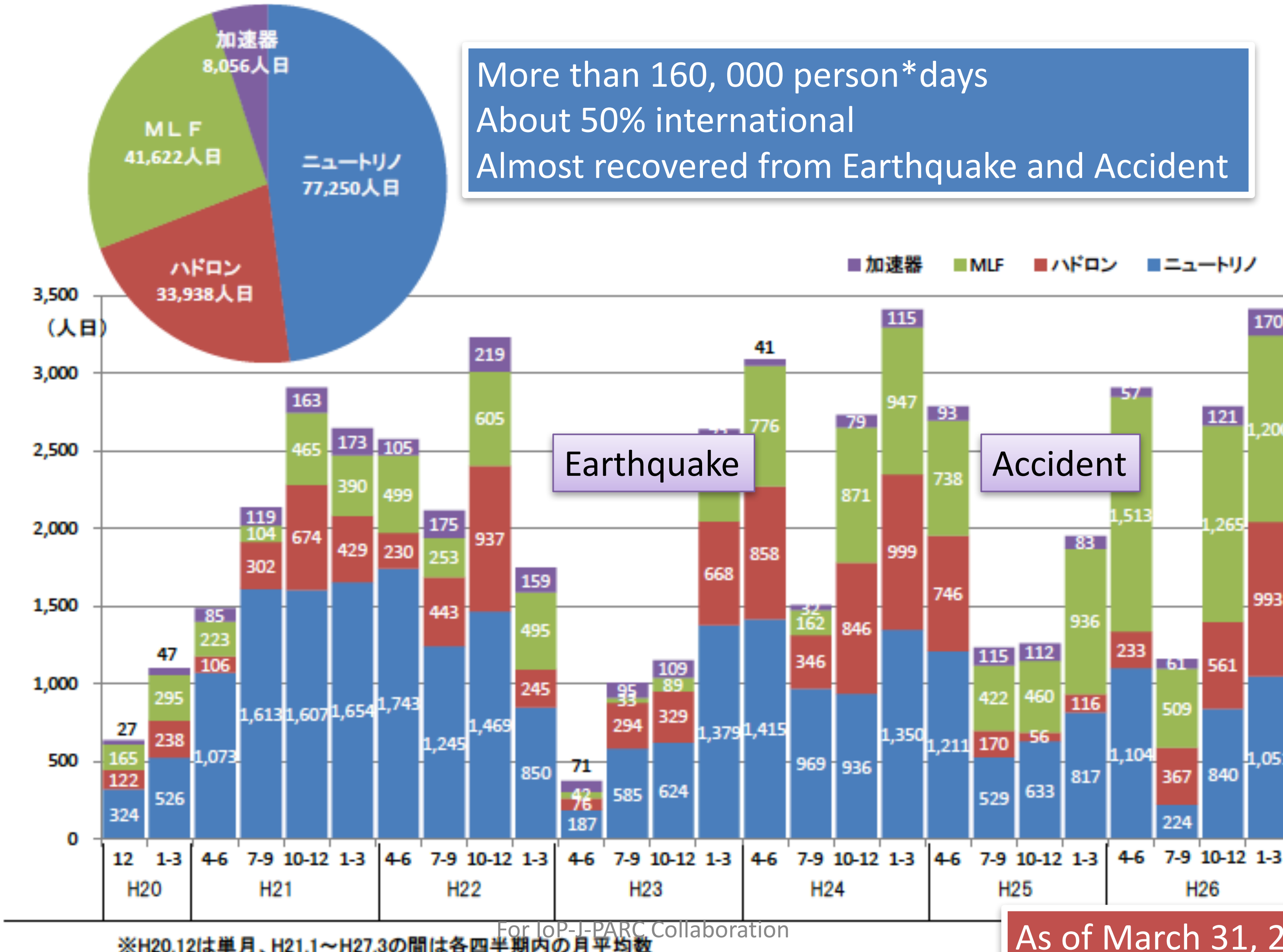
Summary

- J-PARC is improving operation efficiencies!
  - MLF is recovered from neutron target troubles and runs at eff >90%
  - We intend to bring MLF power towards 1 MW with keeping the efficiency > 90% ; Muon will be benefited from that.
  - MR needs improvements
- High power frontier will be further explored
  - MLF would reach 600 kW in a year starting form the next summer
  - MR-FX reached 470 kW! SX will be pushed to 50 kW soon.
  - Targetry will be carefully strengthened (cf. RaDIATE)
- Limits of our progress
  - Budget
    - Operation fund (KEK side is more severe)
    - Upgrade (MR-new PS; MLF-POLANO; MUSE-H-Line ; new BL at MLF-n)
    - ADS R&D -> TEF construction
  - Environmental and Organizational
    - A lack of open research atmosphere : Direct Access Road
    - More uniform operation of MLF by JAEA / KEK / CROSS
- Stronger ties with Universities / Oversea institutions / Industries form more results and fostering the next generation

Hi-Power Beams for the next stage of our life!

of User Visits

More than 160, 000 person*days
About 50% international
Almost recovered from Earthquake and Accident



As of March 31, 2016

Future of Intensity Frontier

There will be more excitements to come! With

- More beam power
- More robust targetry
  with
- Nicely "crafted" experiments
- Enhanced support from theorists
- … and
- Ambitious YOUNG Scientists!

A hint of
New Physics?

Including Young at Heart!

muon-to-electron conversion search

FNAL mu2e

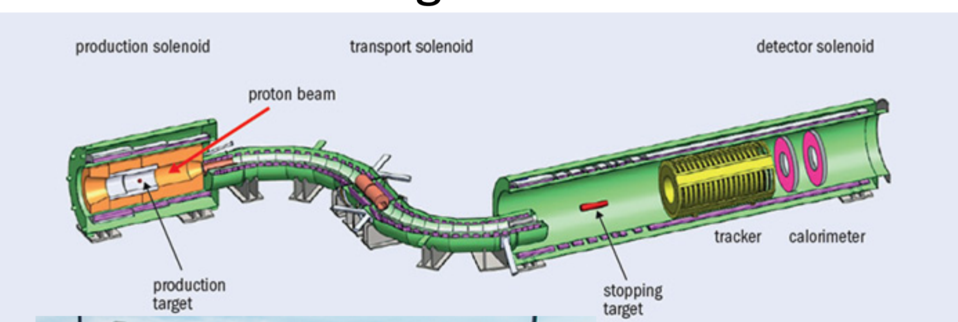
Talk by A. Gaponenko

- E_{proton}=8GeV 8 kW beam
  - Sensitivity < 10^{-16} @ 90% C.L.
- S-shape solenoid to transport and momentum-separate muons
- Ground-breaking in Apr.2015
- Detector & beamline commissioning scheduled in 2020

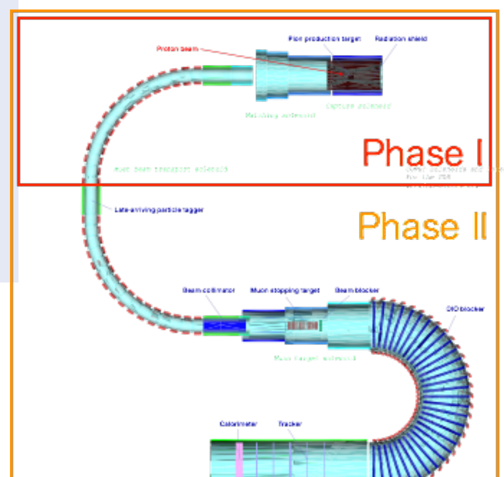
J-PARC COMET

Talk by S. Mihara

- E_{proton} = 8GeV, 3.2-56kW beam
  - Sensitivity @ 90 % C.L
  - Phase I: < 10^{-14} (3.2kW)
  - Phase II: <10^{-16} (56kW)
- U-shape solenoid to transport and momentum-separate muons in Phase I
  - Additional U-shape solenoid in Phase II
- Building const. completed in 2015
- Data taking (Phase-I) expected in 2018-2019



CERN Courier & mu2e homepage



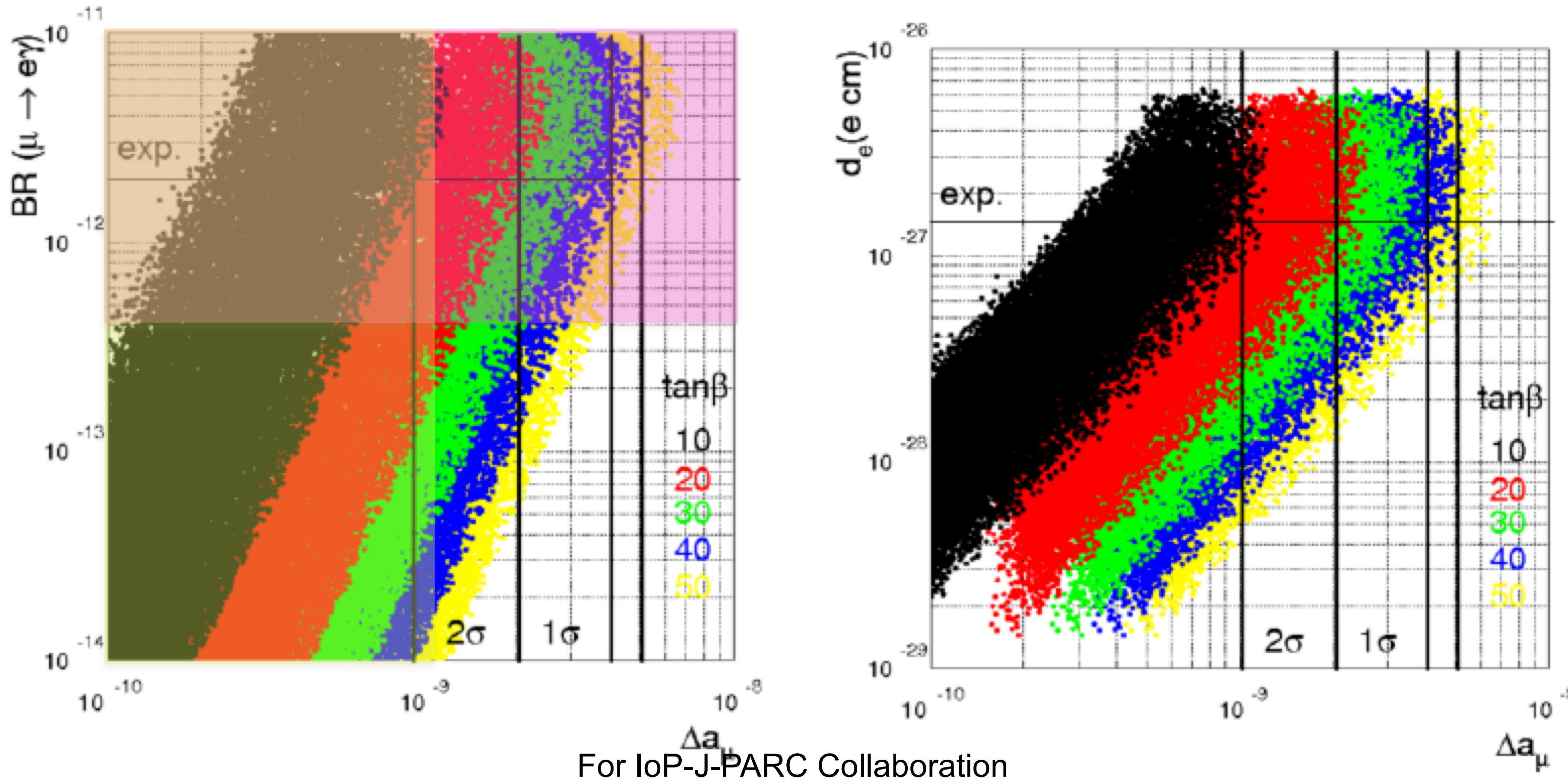
For IoP J-PARC Collaboration

Slide by Satoshi MIHARA

curved solenoid installation

Updates on g-2, cLFV, and EDM

- **P. Paradisi,** NP Proc. Volumes 248–250, March–May 2014, Pages 8–12

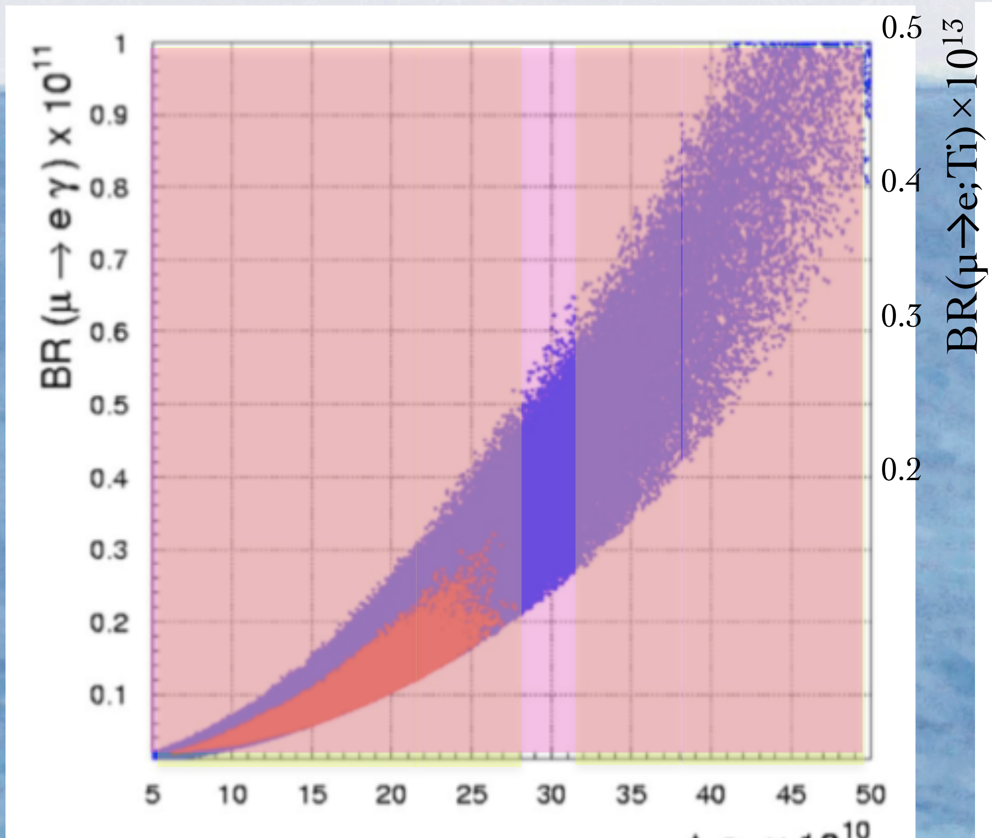


For IoP-J-PARC Collaboration

g-2, EDM and cLFV

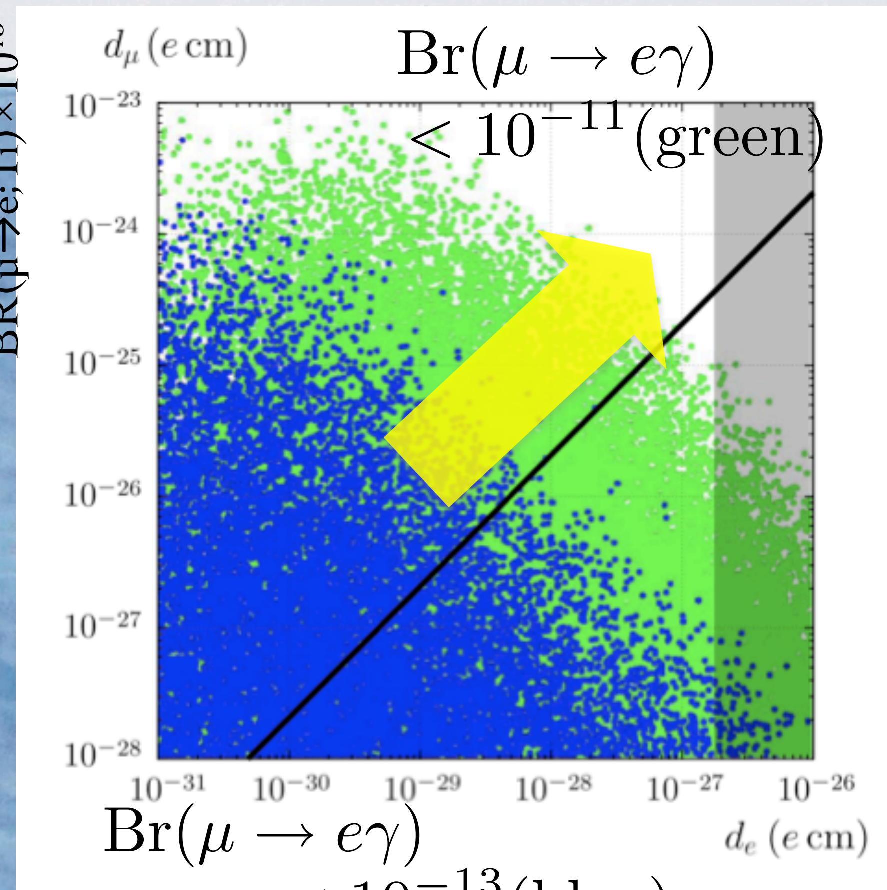
- **Large g-2 → Large cLFV → Large EDM**

G. Isidori, F. Mescia, P. Paradisi, and D. Temes, PRD 75 (2007) 115019



Limit by MEG Full Data Set 4.2 x 10^{-13} (arXiv:1605.05081)

J. Hisano, Nagai, Paradisi



Muon magnetic moment

- **Magnetic moment and spin can be related as**

$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s}$$

$\vec{\mu}$: magnetic moment

$\vec{s}$: spin

g : gyromagnetic ratio

- **Dirac equation predicts g=2** → a=0

$$\mu = (1+a)\left(\frac{e\hbar}{2m}\right) \qquad a = \frac{g-2}{2}$$

a=1.2e-3 for e, μ, …

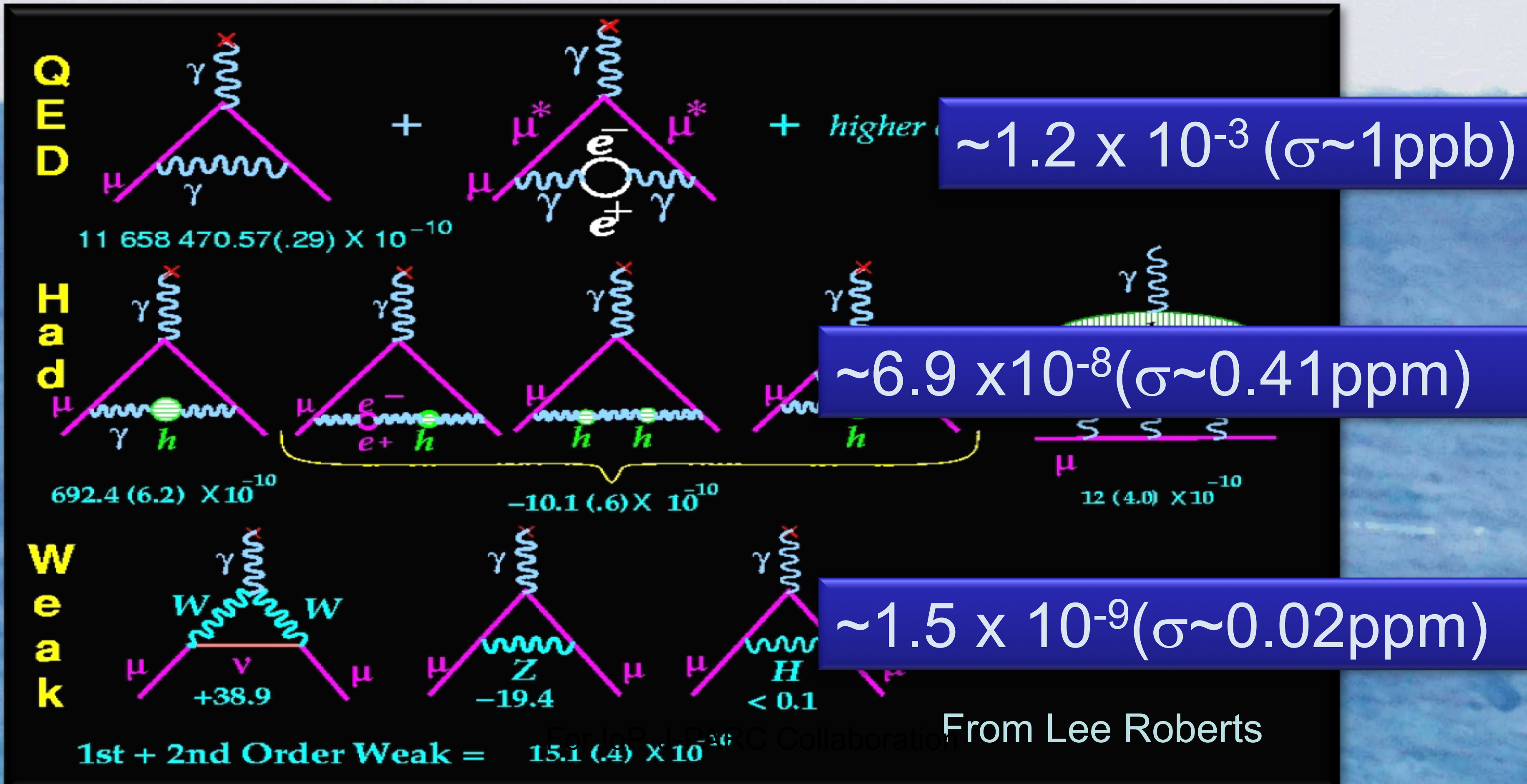
a=1.8 for proton

- **Radiative corrections (including NEW PHYSICS) would make g≠2** → a≠0

$$\left(\frac{m_\mu}{m_e}\right)^2 \sim 40{,}000 \qquad \left(\frac{m_\tau}{m_\mu}\right)^2 \sim 290$$

SM Contribution to a≠0

- **Any particle which couples to muon/photon would contribute : QED >> Hadron > Weak**



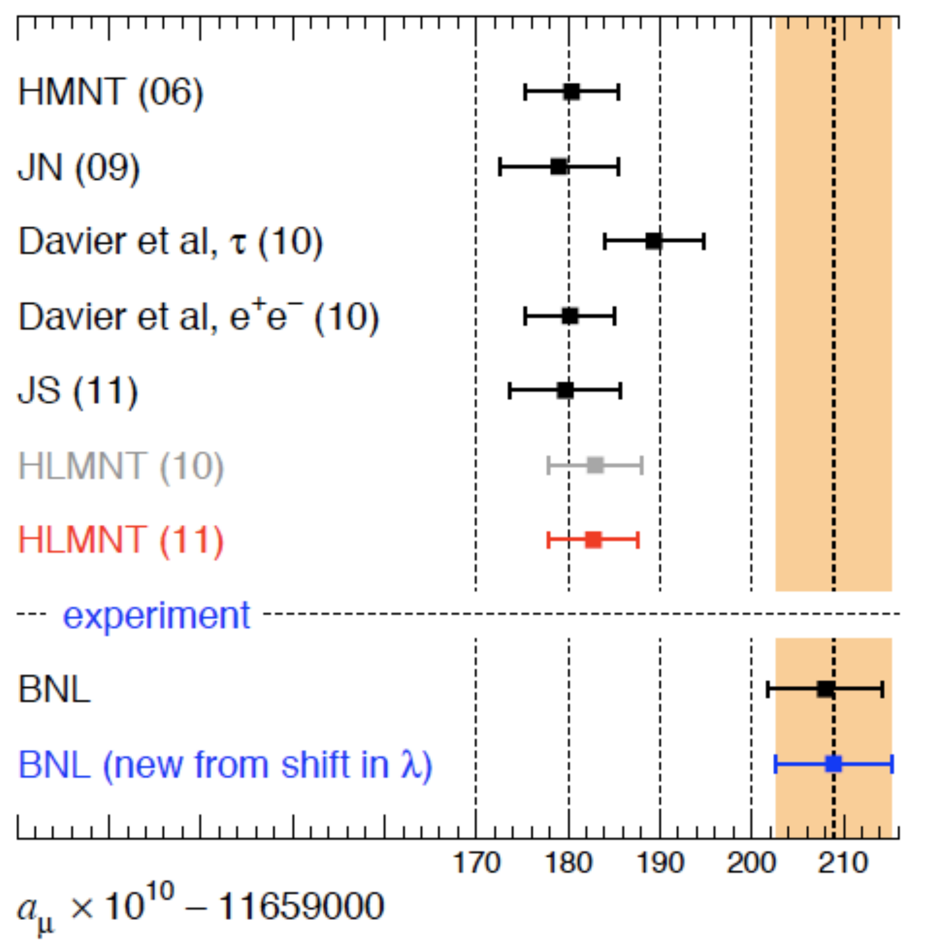
Updates on the SM Prediction

- Anomaly still alive!

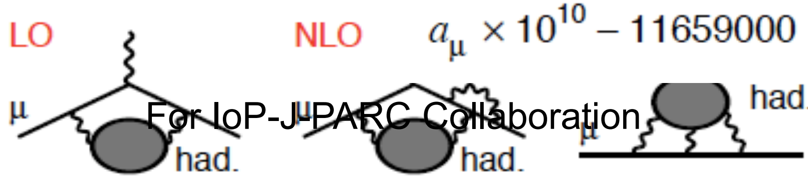
Summary: Standard Mode

QED contribution	11 658 471.808 (0.
EW contribution	15.4 (0.2)
Hadronic contribution	
LO hadronic	**694.9 (4.3**
NLO hadronic	−9.8 (0.1)
light-by-light	10.5 (2.6)
Theory TOTAL	**11 659 182.8 (4.9**
Experiment	**11 659 208.9 (6.3**
Exp − Theory	**26.1 (8.0)**

(Number



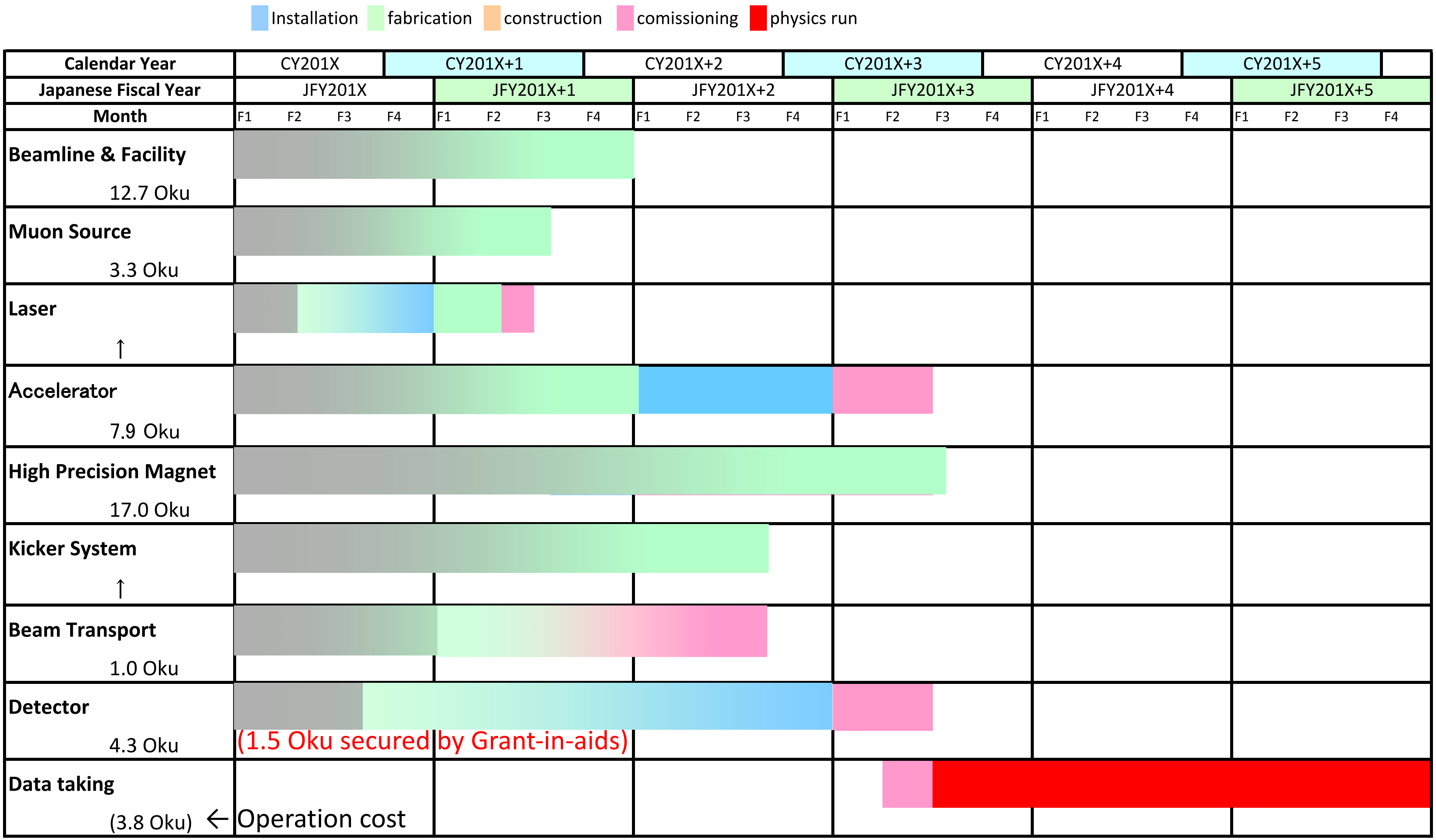
n.b.: hadronic contributions:



For IoP-J-PARC Collaboration

Technically-driven schedule and cost

Assumption : Major construction fund becomes available in JFY201X



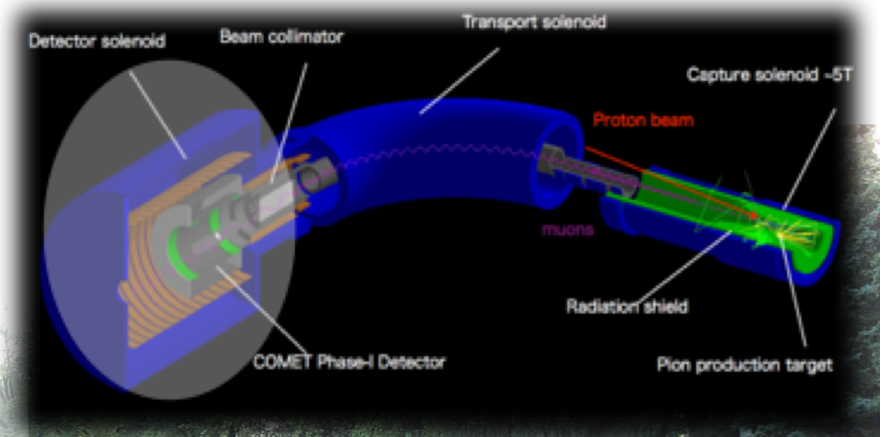
Unit: Oku (10^8) yen

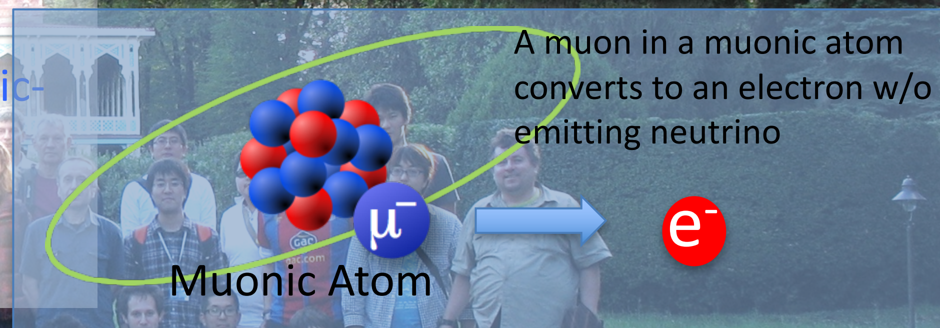
For IoP-J-PARC Collaboration

BACKUP

Search for Lepton Flavor Violation using J-PARC high-intensity pulsed muon beam
the COMET Experiment

- International collaboration composed of 175 researchers of 33 institutes (including JINR) from 15 countries
- Search for the μ-e conversion process violating lepton flavor number conservation
  - $< 10^{-14}$ sensitivity in Phase I（2018-2021）
  - $< 10^{-16}$ sensitivity in Phase II (2022 -)
  - Current upper limit: 7×10^{-13}
- Georgian contribution in Calorimeter, Cosmic-ray veto, tracking
  - Tbilisi State University
  - Georgian Technical University





For IoP-J-PARC Collaboration

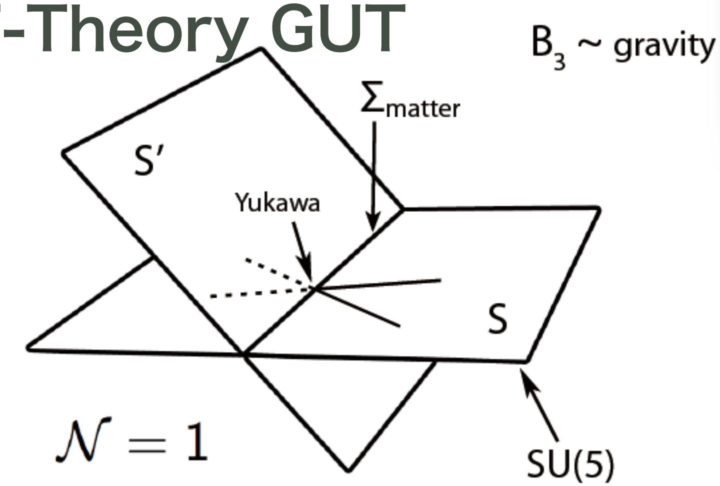
CM 14 hosted by Tbilisi State University

Flavor and Space-Time

J.J. Heckman, C.Vafa, Phys.Lett. B694 (2011) 482-484

- **CPV and Flavor Structure can be explained from higher dimensions / higher energies?**

F-Theory GUT



dim.	internal dim.	feature
10	$6=\dim(B_3)$	gravity
8	$4=\dim(S)$	gauge fields
6	$2=\dim(S\cap S')$	matter
4	$0=\dim(S\cap S'\cap S'')$	interactions

$$|V_{CKM}^{F-th}| \sim \begin{pmatrix} 1 & \alpha_{GUT}^{1/2} & \alpha_{GUT}^{3/2} \\ \alpha_{GUT}^{1/2} & 1 & \alpha_{GUT} \\ \alpha_{GUT}^{3/2} & \alpha_{GUT} & 1 \end{pmatrix} \sim \begin{pmatrix} 1 & 0.2 & 0.008 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

$$|V_{CKM}^{\text{obs}}| \sim \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 0.99 \end{pmatrix}$$

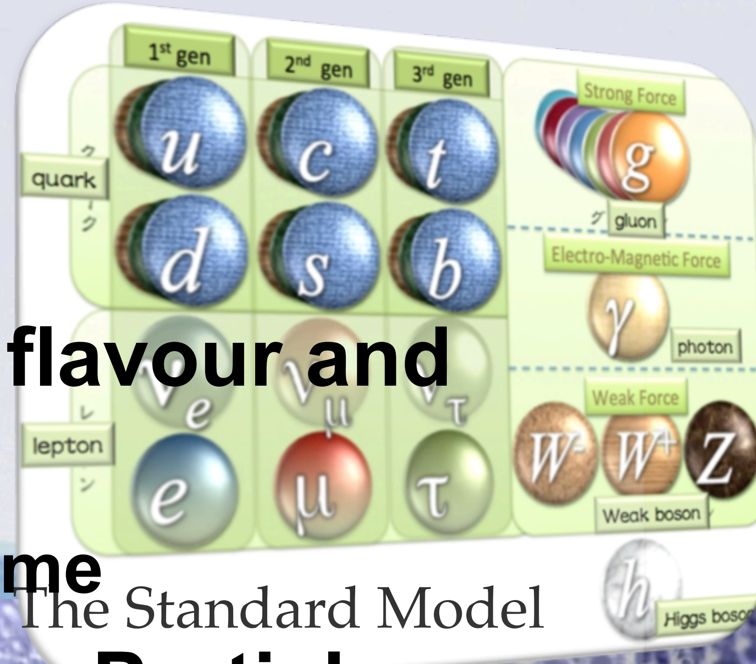
$$|V_{PMNS}^{F-th}| \sim \begin{pmatrix} U_{e1} & \alpha_{GUT}^{1/4} & \alpha_{GUT}^{1/2} \\ \alpha_{GUT}^{1/4} & U_{\mu 2} & \alpha_{GUT}^{1/4} \\ \alpha_{GUT}^{1/2} & \alpha_{GUT}^{1/4} & U_{\tau 3} \end{pmatrix} \sim \begin{pmatrix} 0.87 & 0.45 & 0.2 \\ 0.45 & 0.77 & 0.45 \\ 0.2 & 0.45 & 0.87 \end{pmatrix}$$

$$|V_{PMNS}^{\text{obs}}| \sim \begin{pmatrix} 0.77-0.86 & 0.50-0.63 & 0-0.22 \\ 0.22-0.56 & 0.44-0.73 & 0.57-0.80 \\ 0.21-0.55 & 0.4-0.71 & 0.59-0.82 \end{pmatrix}$$

$$\left|J_{\text{quark}}^{F-th}\right| \sim \alpha_{GUT}^3 \sim 6\times 10^{-5}$$

$$\left|J_{\text{lepton}}^{F-th}\right| \sim \alpha_{GUT} \sim 4\times 10^{-2}.$$

Just a Dream of an Experimentalist



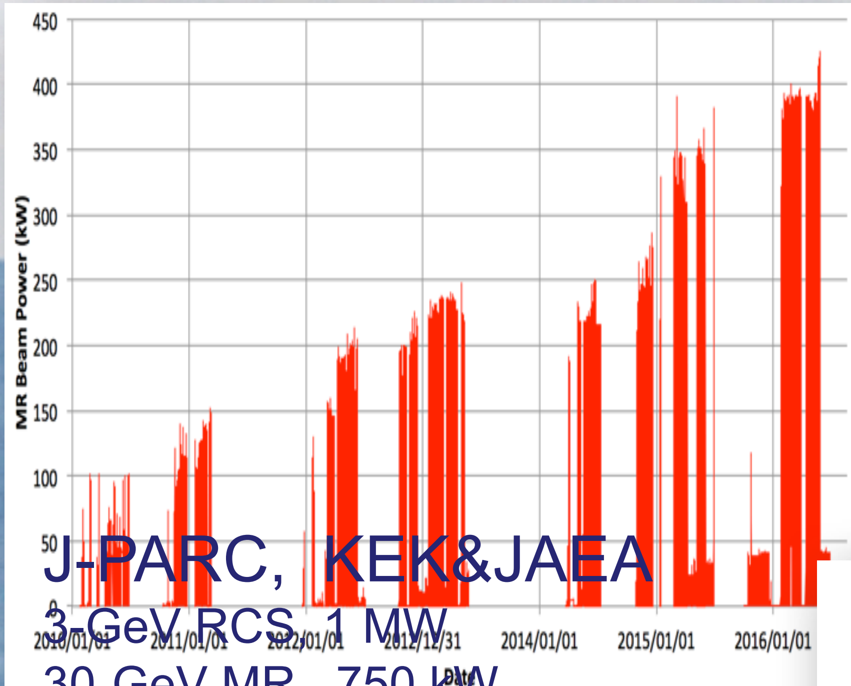
The Standard Model

- **Elucidate the relation btw flavour and space-time structure**
  - **Particle, Force, and Space-time**
- **Comments at the 2nd WS on Particle Physics of Dark Universe**

  http://kds.kek.jp/conferenceTimeTable.py?confId=11916#20130404.detailed
  - ***"Certainly flavor physics could provide some constraints for compactification … but not enough"***
  - ***"Need to combine accelerator based results and gravity, cosmology"***

High Intensity Proton Facilities

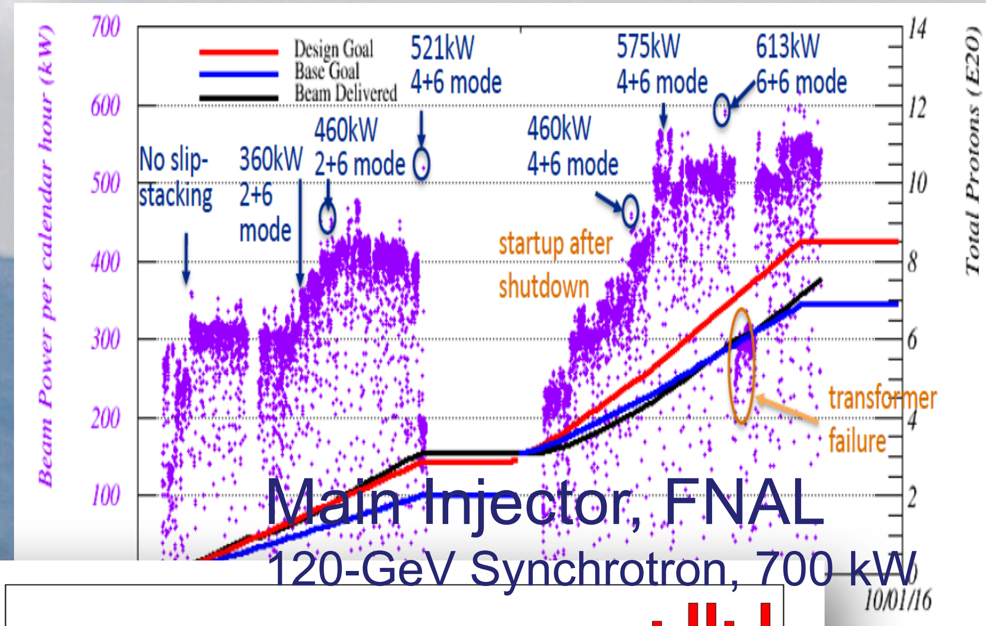
- 1 MW class → Multi-MW potential



J-PARC, KEK&JAEA

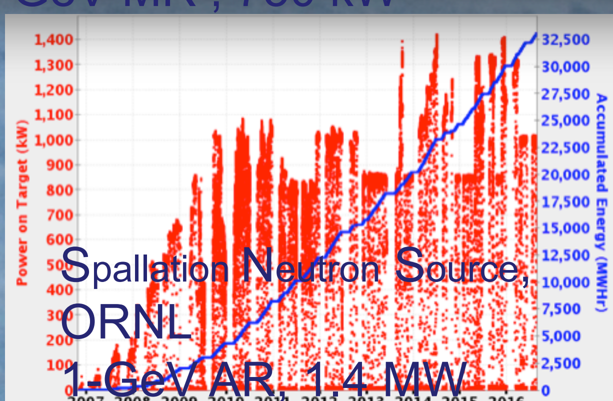
3-GeV RCS, 1 MW

30-GeV MR , 750 kW



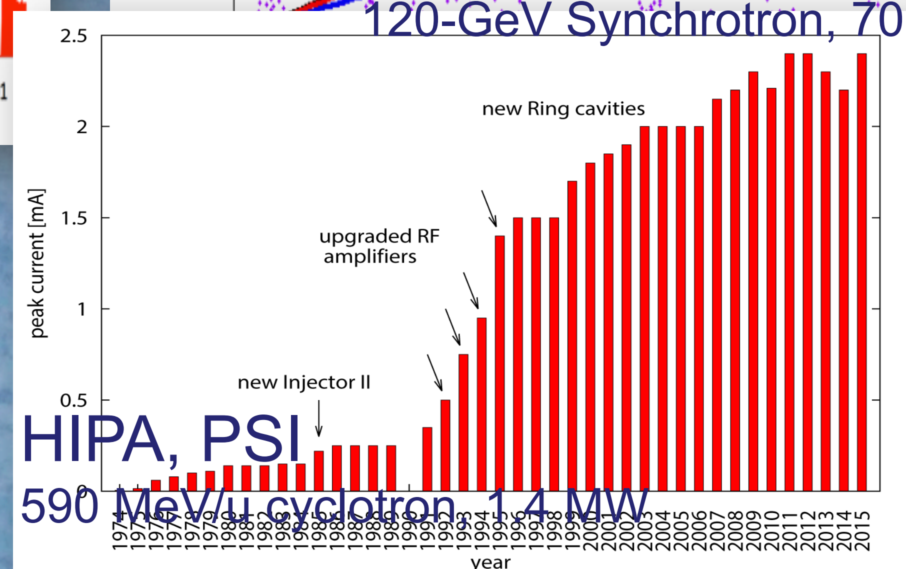
Main Injector, FNAL

120-GeV Synchrotron, 700 kW



Spallation Neutron Source, ORNL

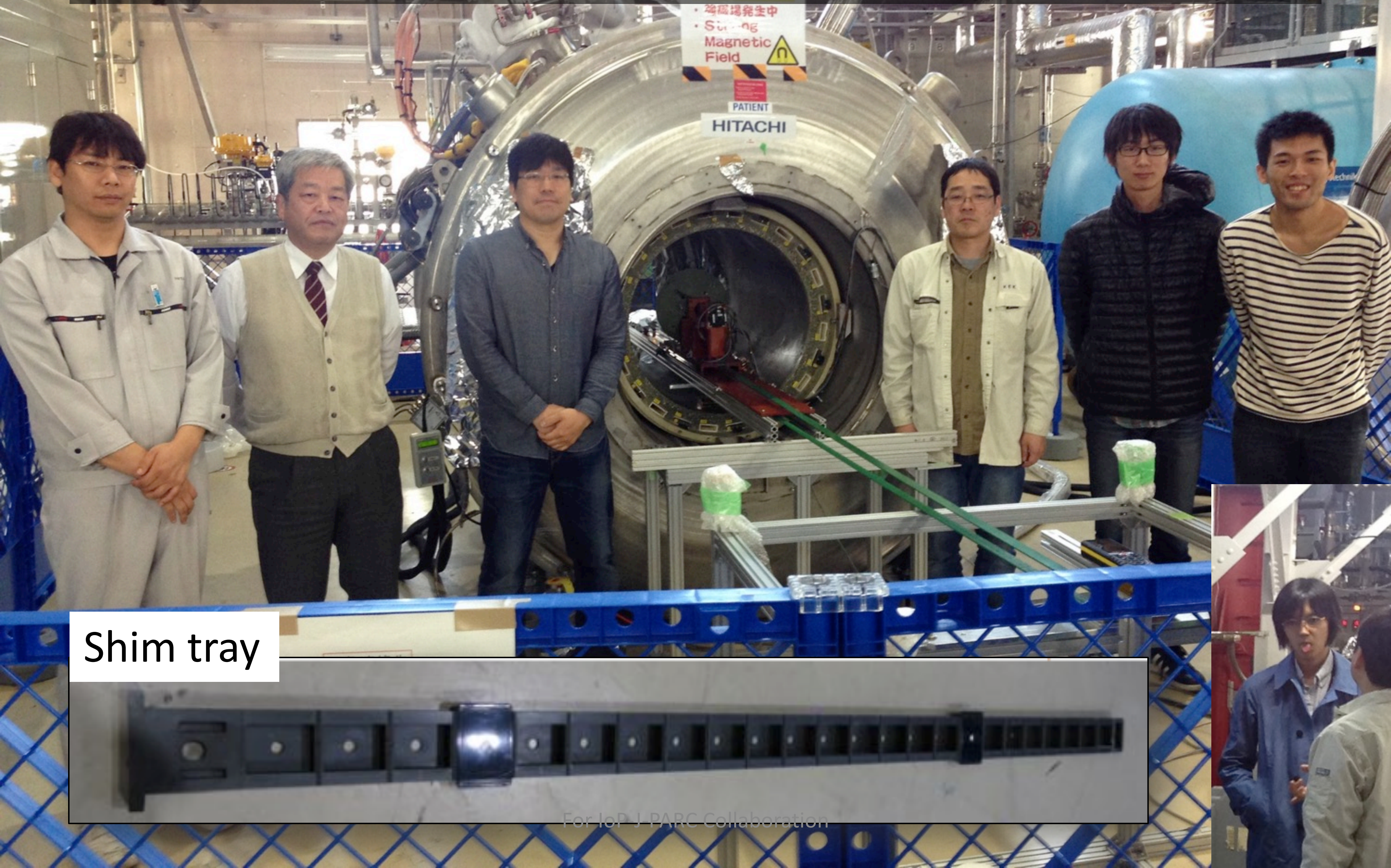
1-GeV AR, 1.4 MW



HIPA, PSI

590 MeV/u cyclotron, 1.4 MW

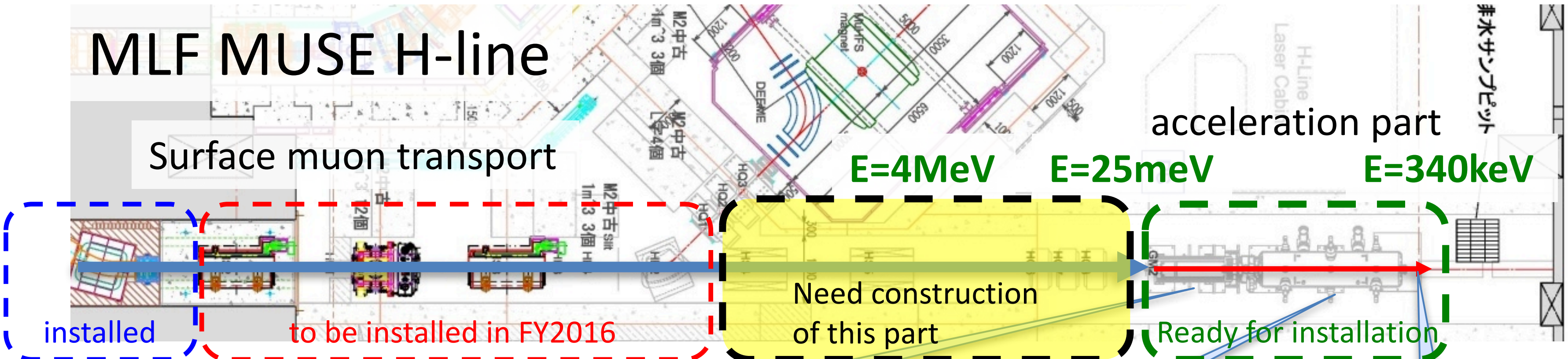
B-field shimming test with a medical MRI magnet (1.7 T) at J-PARC

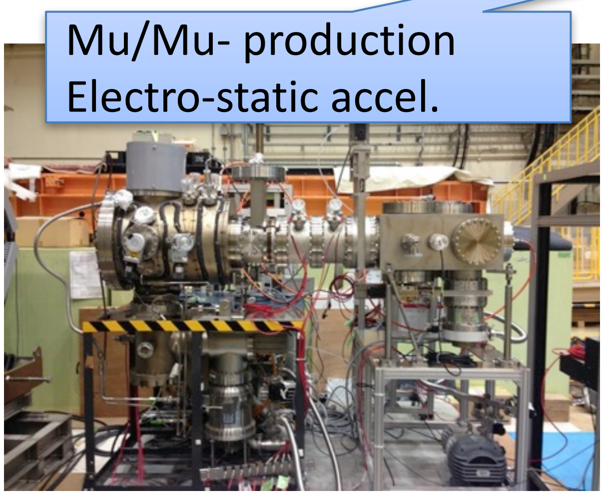


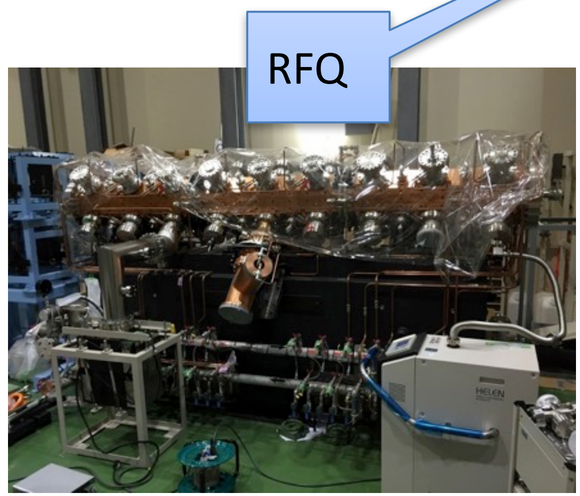
Shim tray

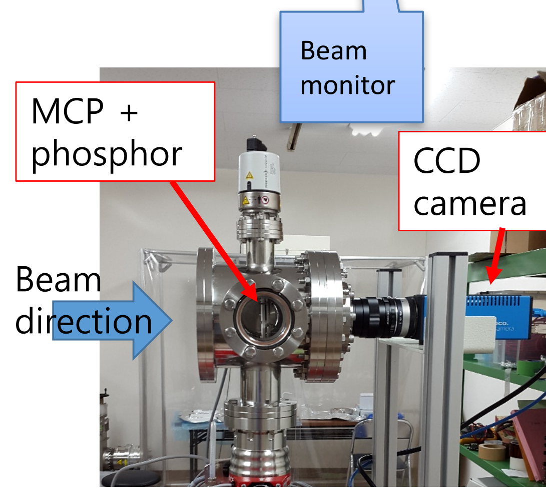
Muon acceleration test

- World first muon accelerator!









A short extension of muon transport line + shield will make this possible.

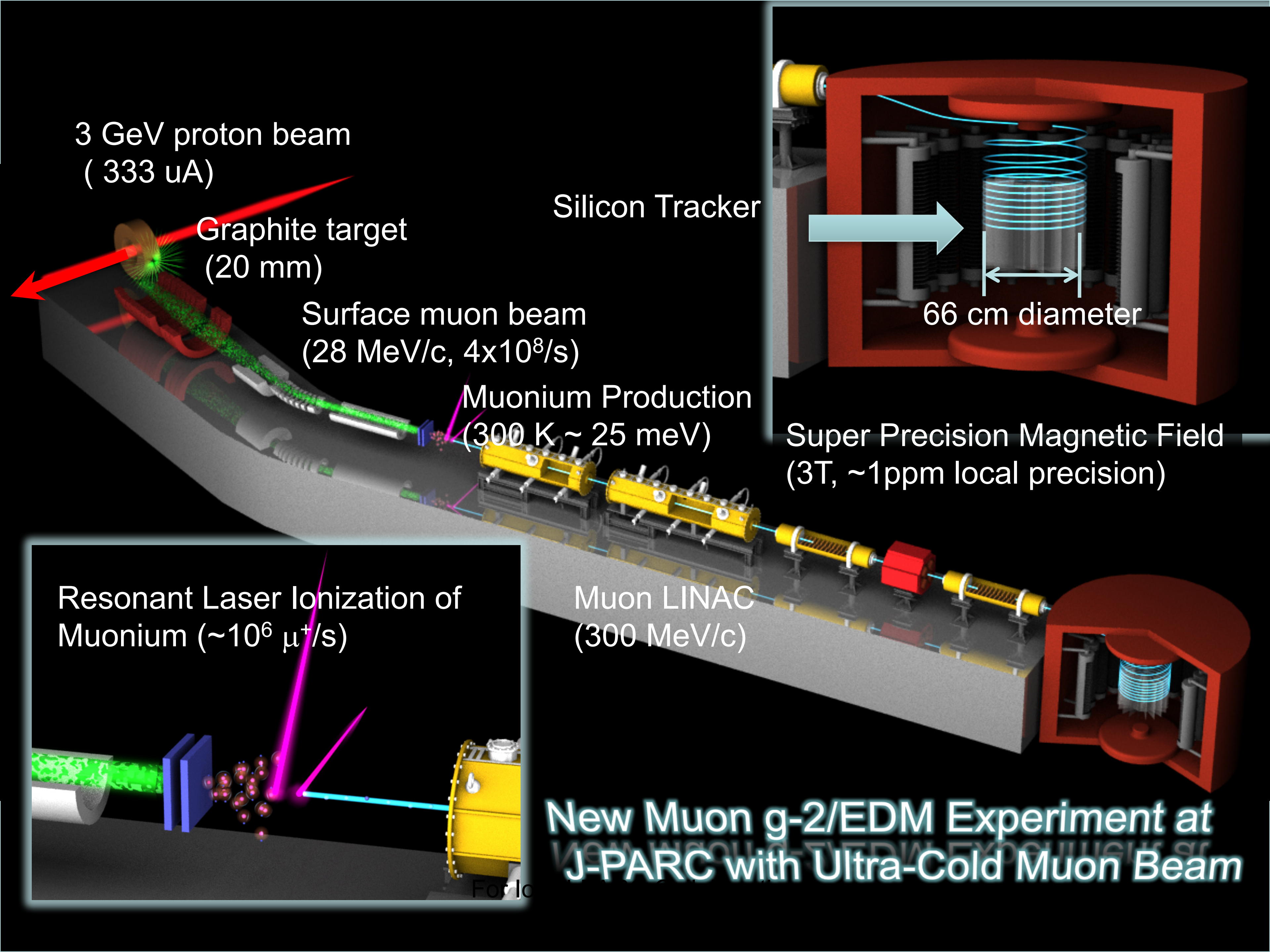
Focused Review

November 15-18, 2016 @ J-PARC

For IoP-J-PARC Collaboration

Industrial Use of MLF blooming

- A new framework for material development using J-PARC was press-released at Tokyo Motor Show by CEO of Sumitomo Rubber Industries.


3 GeV proton beam
(333 uA)
Graphite target
(20 mm)
Surface muon beam
(28 MeV/c, 4x10^8/s)
Muonium Production
(300 K ~ 25 meV)
Silicon Tracker
66 cm diameter
Super Precision Magnetic Field
(3T, ~1ppm local precision)
Resonant Laser Ionization of
Muonium (~10^6 μ+/s)
Muon LINAC
(300 MeV/c)
New Muon g-2/EDM Experiment at
J-PARC with Ultra-Cold Muon Beam

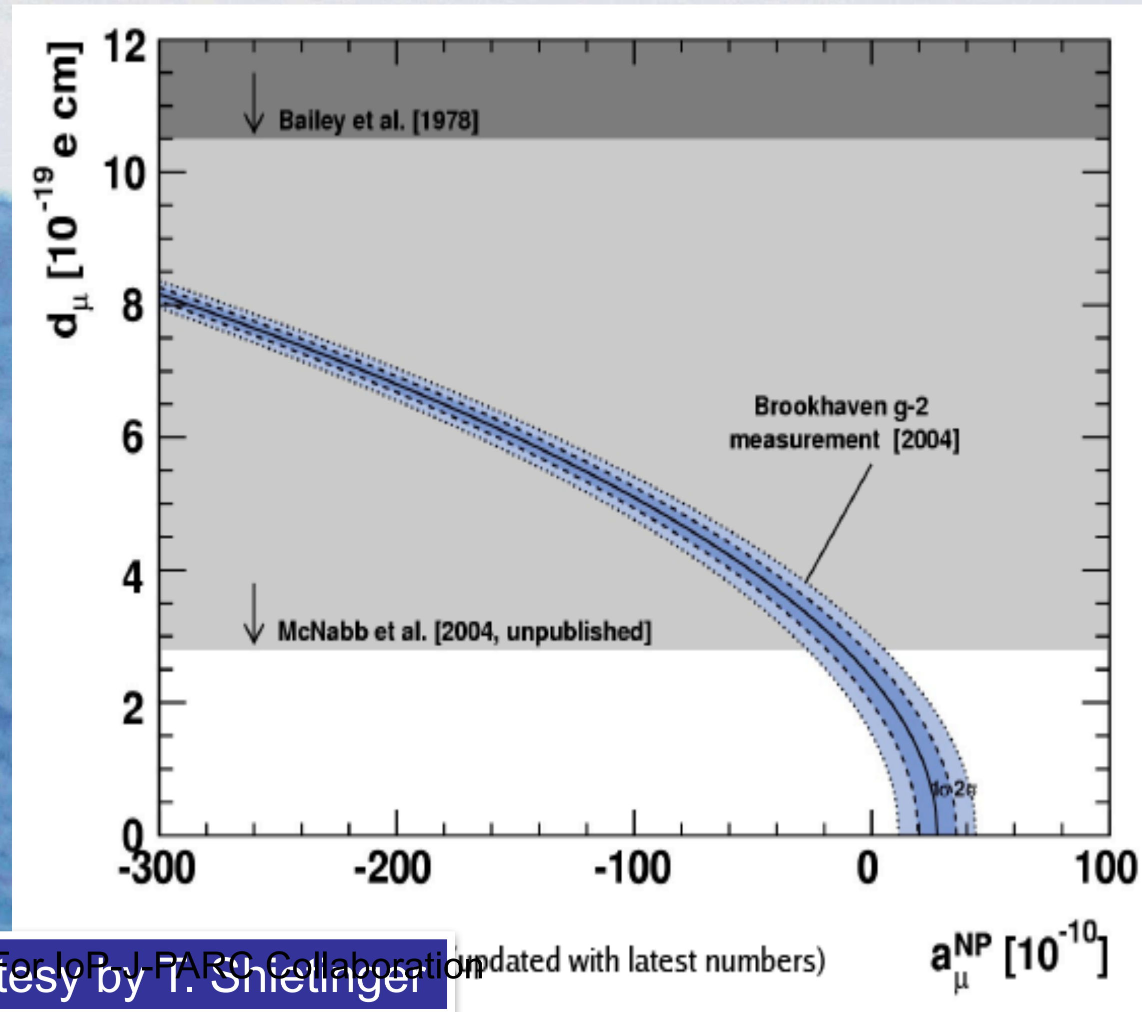
Measured in g-2 experiment

- "Inclusive" precession frequency

$$w = \sqrt{w_a^2 + w_h^2}$$

$$\Leftrightarrow \quad \vec{w}_a = -\frac{e}{m} a_m \vec{B}$$

- **Experimental limit of EDM is in the similar range!**

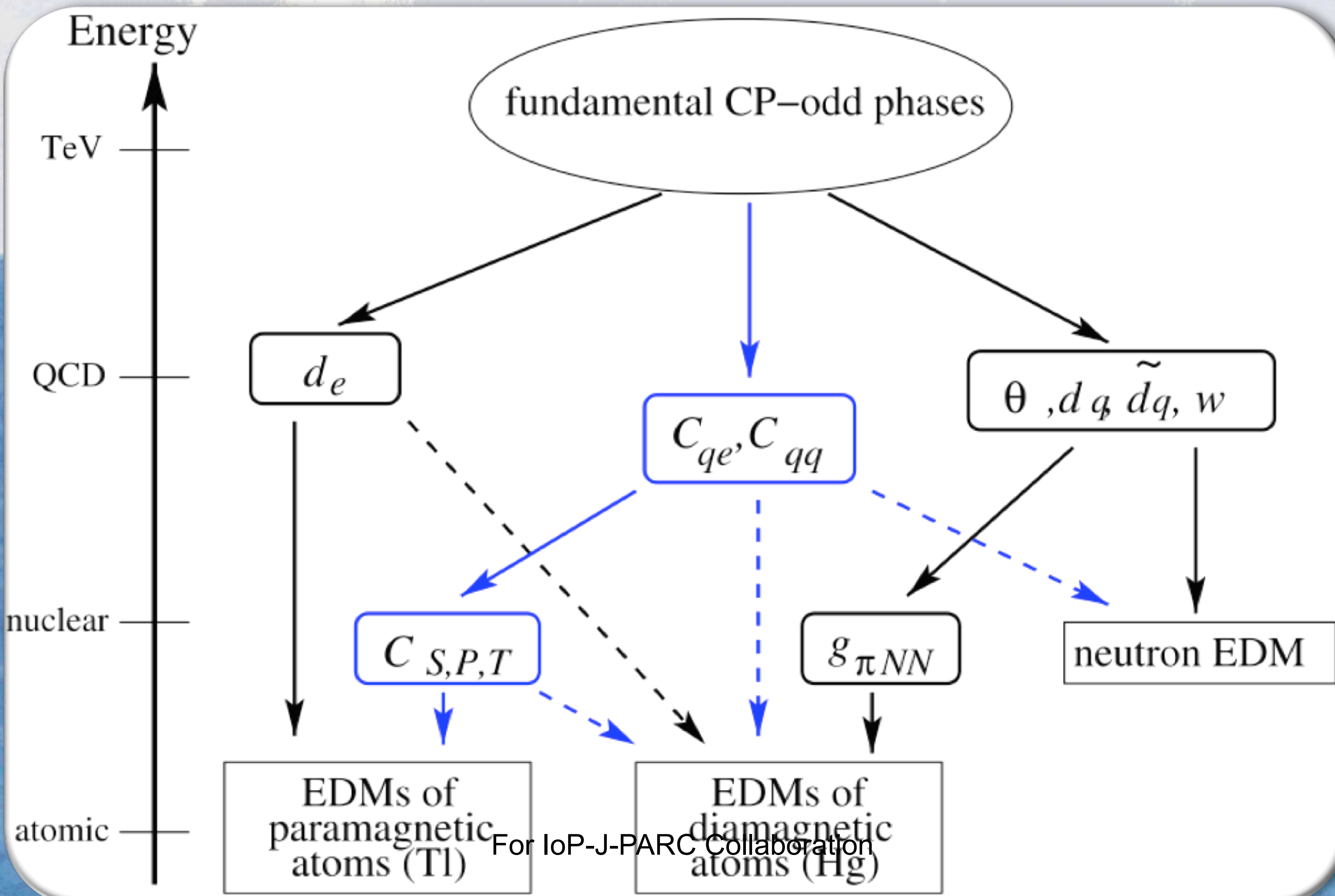


Courtesy by T. Shietinger

For JoP-J-PARC Collaboration

Origin of EDM

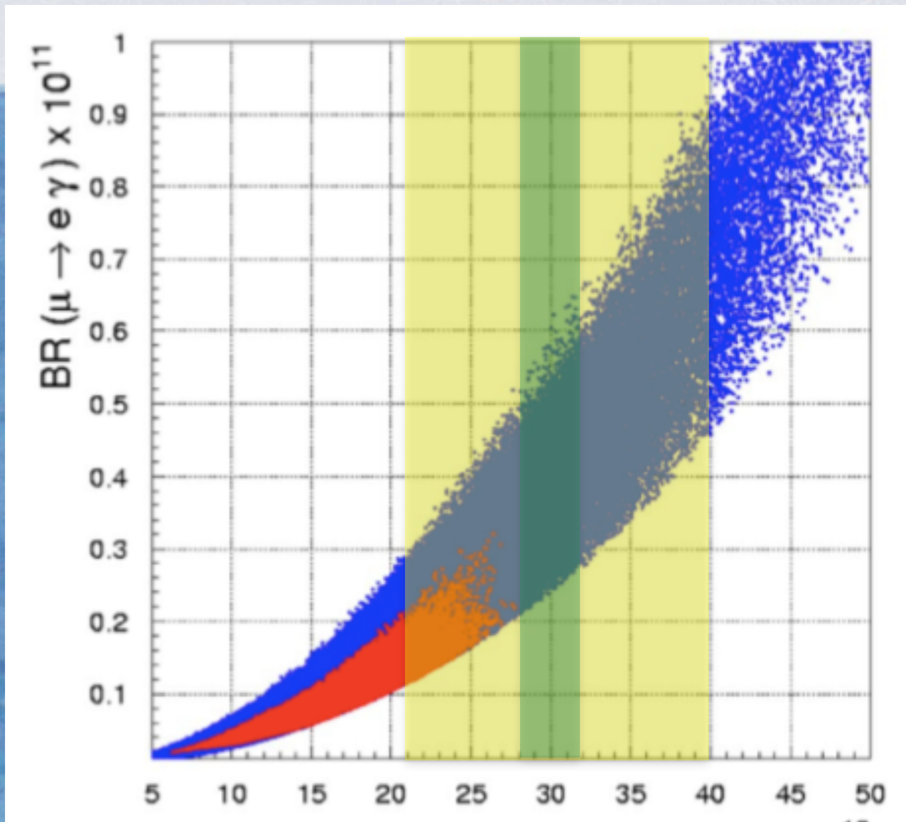
M.Pospelov and A.Ritz, Ann.Phys. 318 (2005) 119



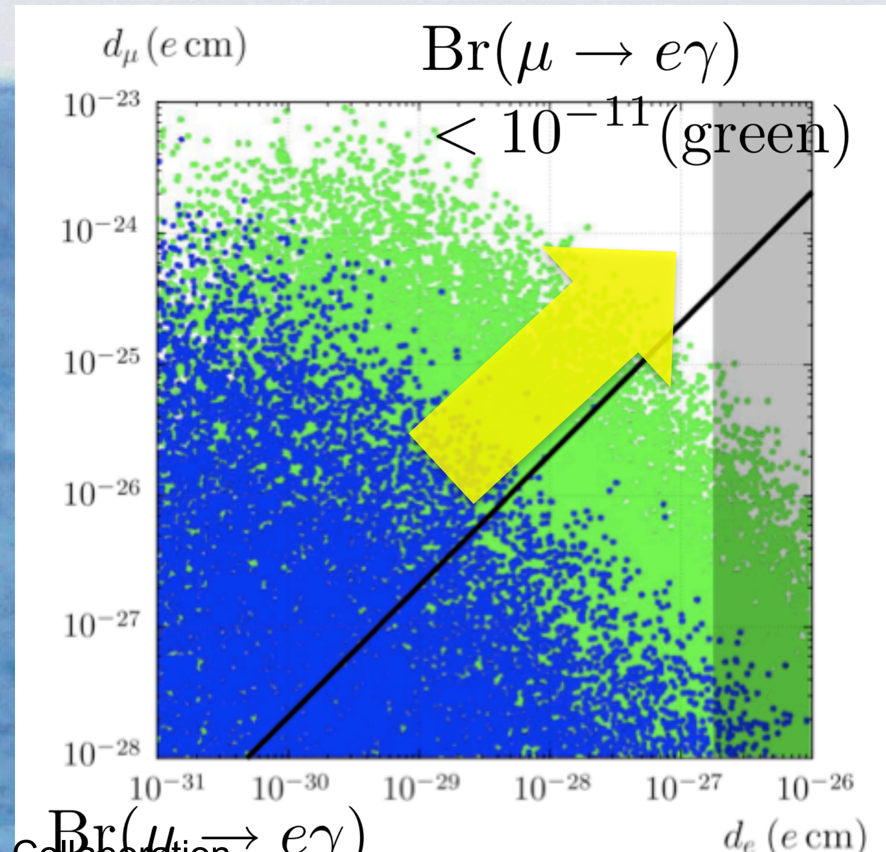
g-2, EDM and cLFV

- Large g-2 → Large cLFV → Large EDM

G. Isidori, F. Mescia, P. Paradisi, and D. Temes, PRD 75 (2007) 115019



J. Hisano, Nagai, Paradisi



$\mathrm{Br}(\mu \to e\gamma)$
$< 10^{-13}$ (blue)

Current limit by MEGA 1.2 x 10^{-11}

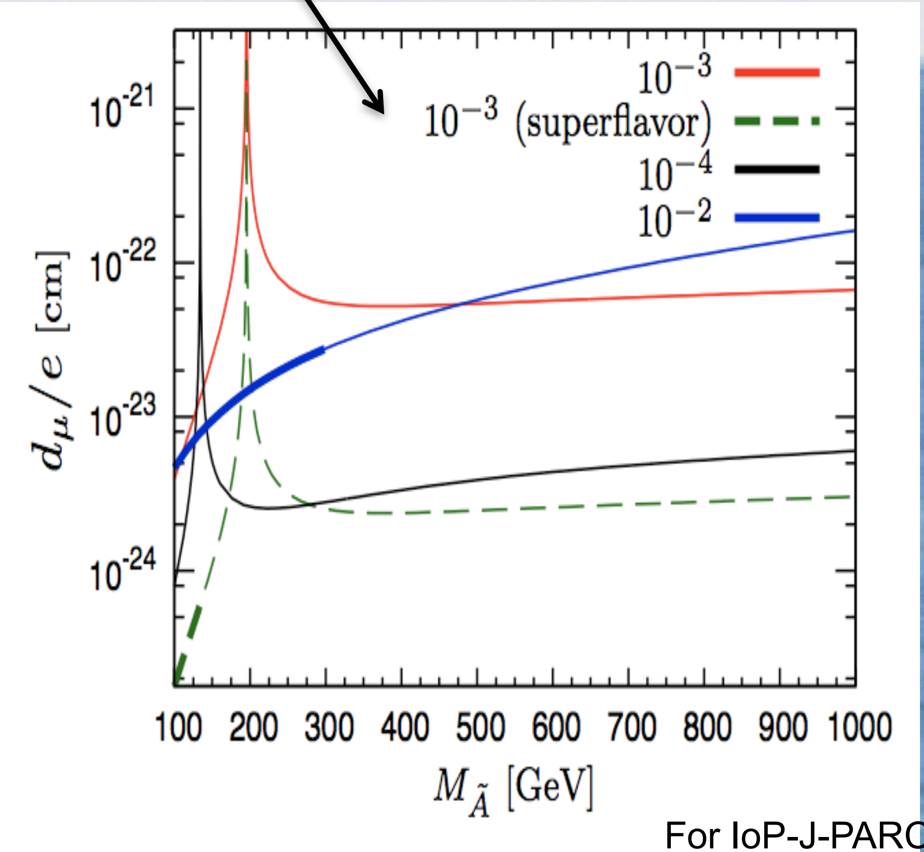
To be superseded by MEG soon

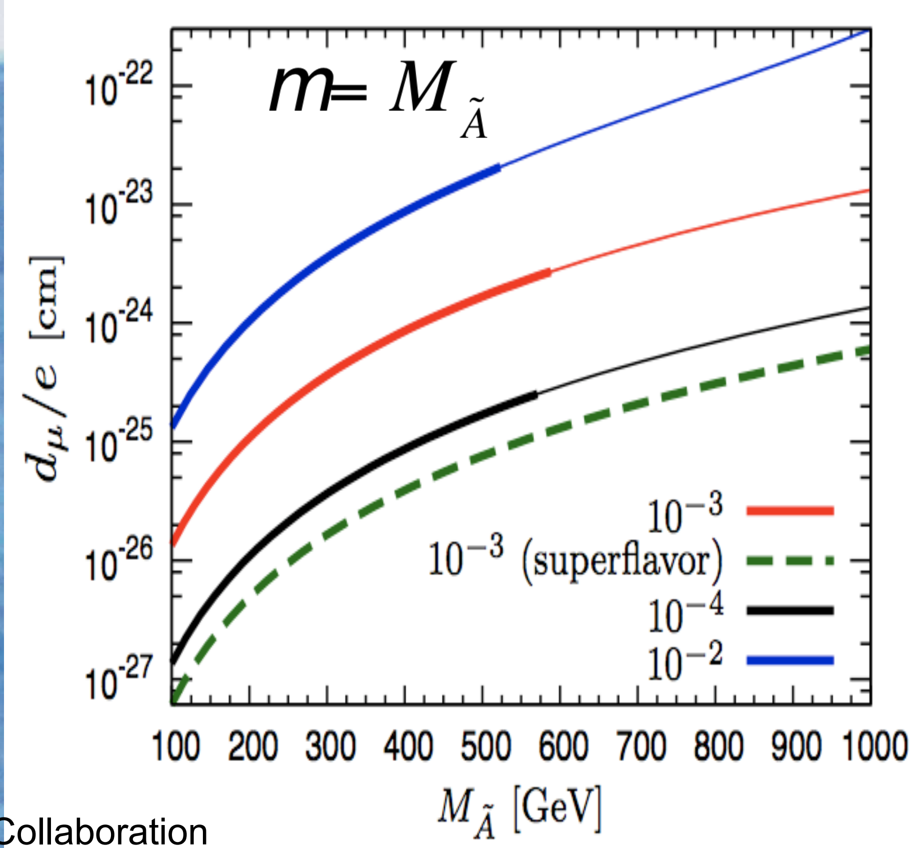
A Large Muon EDM from Flavor?

Gudrun Hiller, (CERN & Dortmund U.) , Katri Huitu, Timo Ruppell, (Helsinki U. & Helsinki Inst. of Phys.) , Jari Laamanen, (Nijmegen U.) . e-Print: arXiv:1008.5091 [hep-ph]

- **Muon EDM is enhanced due to LFV**

Parameter to describe the Flavor mixing in the Slepton sector



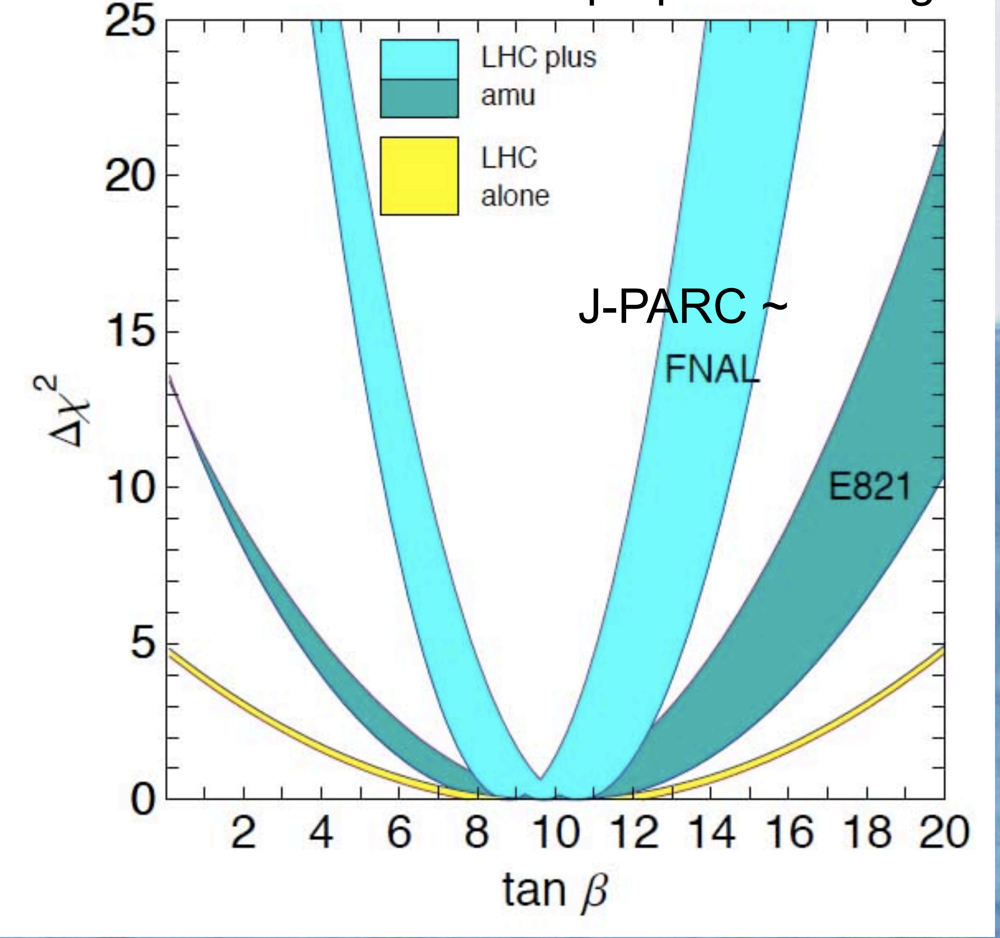


Muon g-2 in the LHC era

- **Even the first SUSY discovery was made at LHC, the muon g-2 measurement remains unique to determine SUSY parameters:**

  μ and tan β

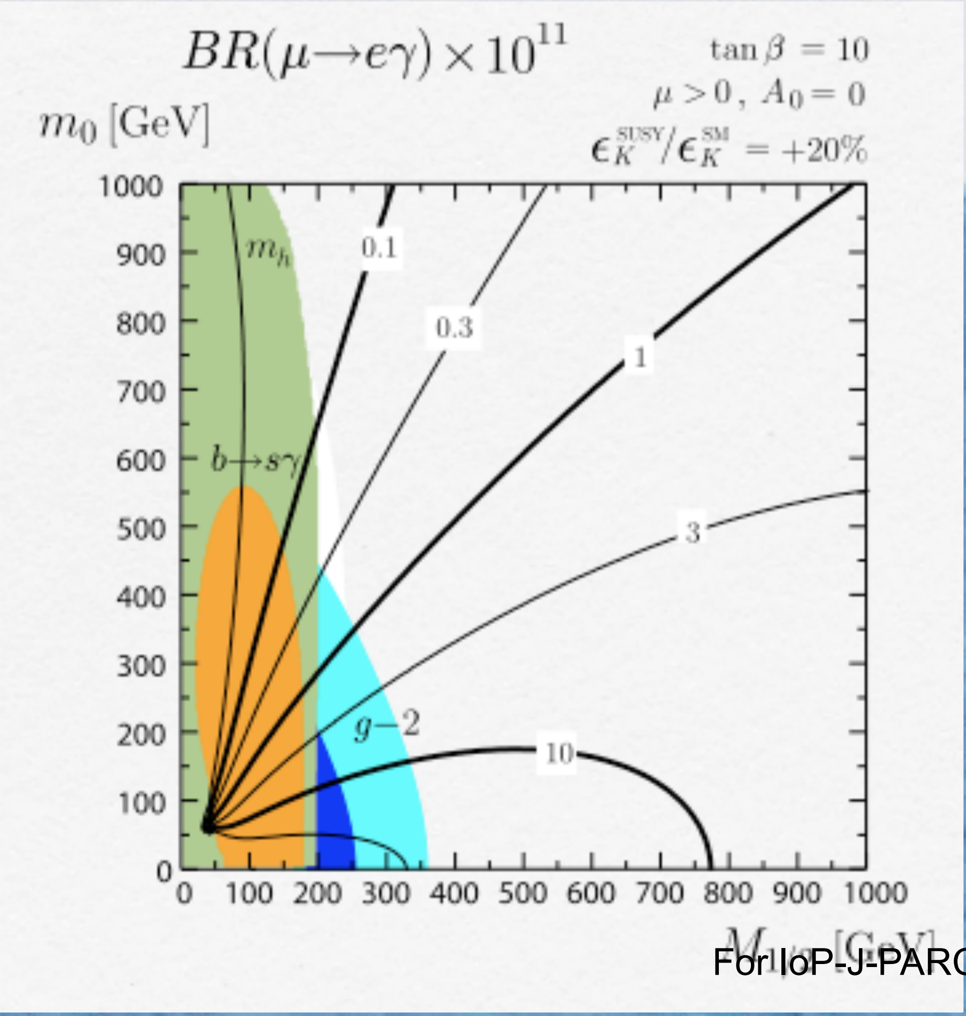
Form Fermilab proposal “New g-2”

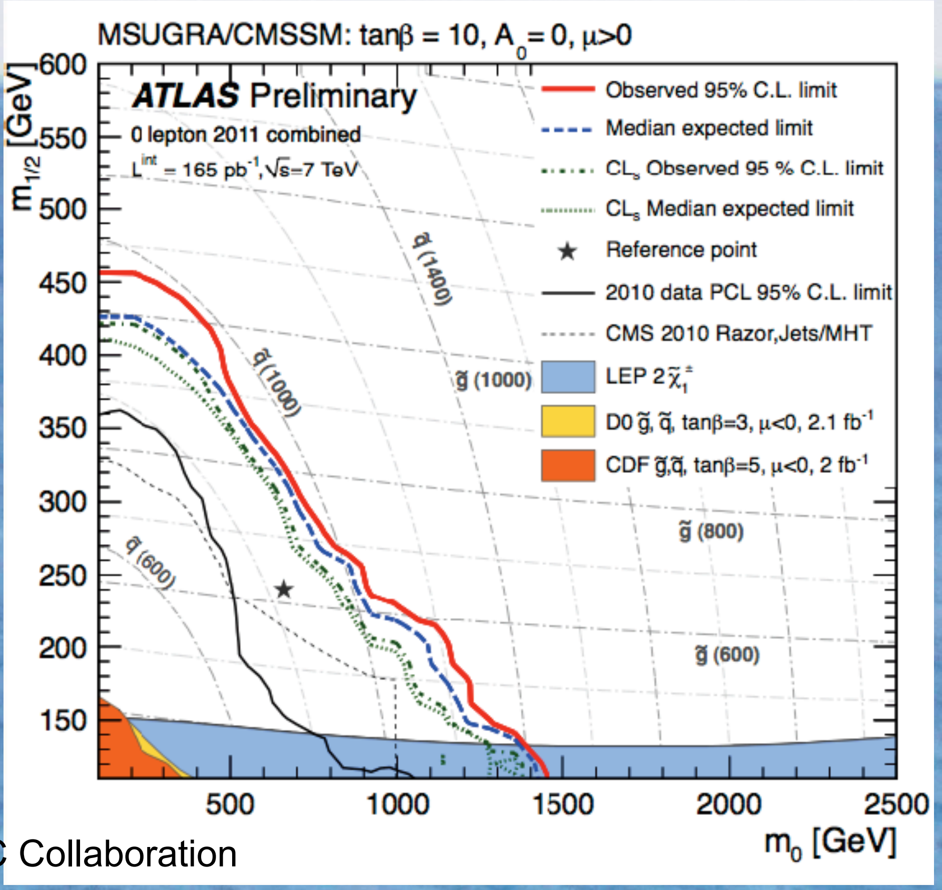


$$a_m(\mathrm{SUSY}) \approx (\mathrm{sgn}\, m) 13 \times 10^{-10} \tan b \left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)^2$$

LHC Results and Muon Physics

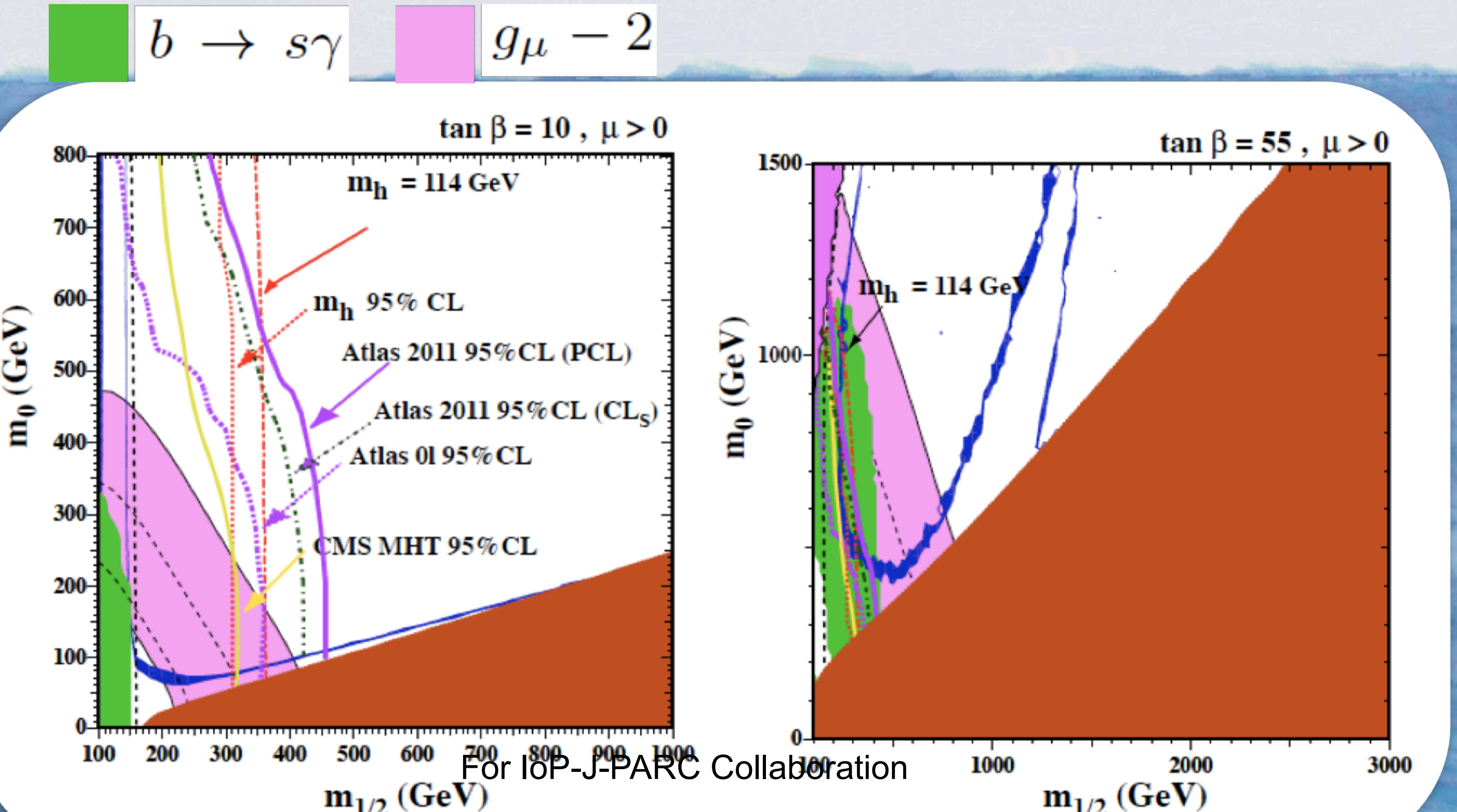
- Large tanβ?

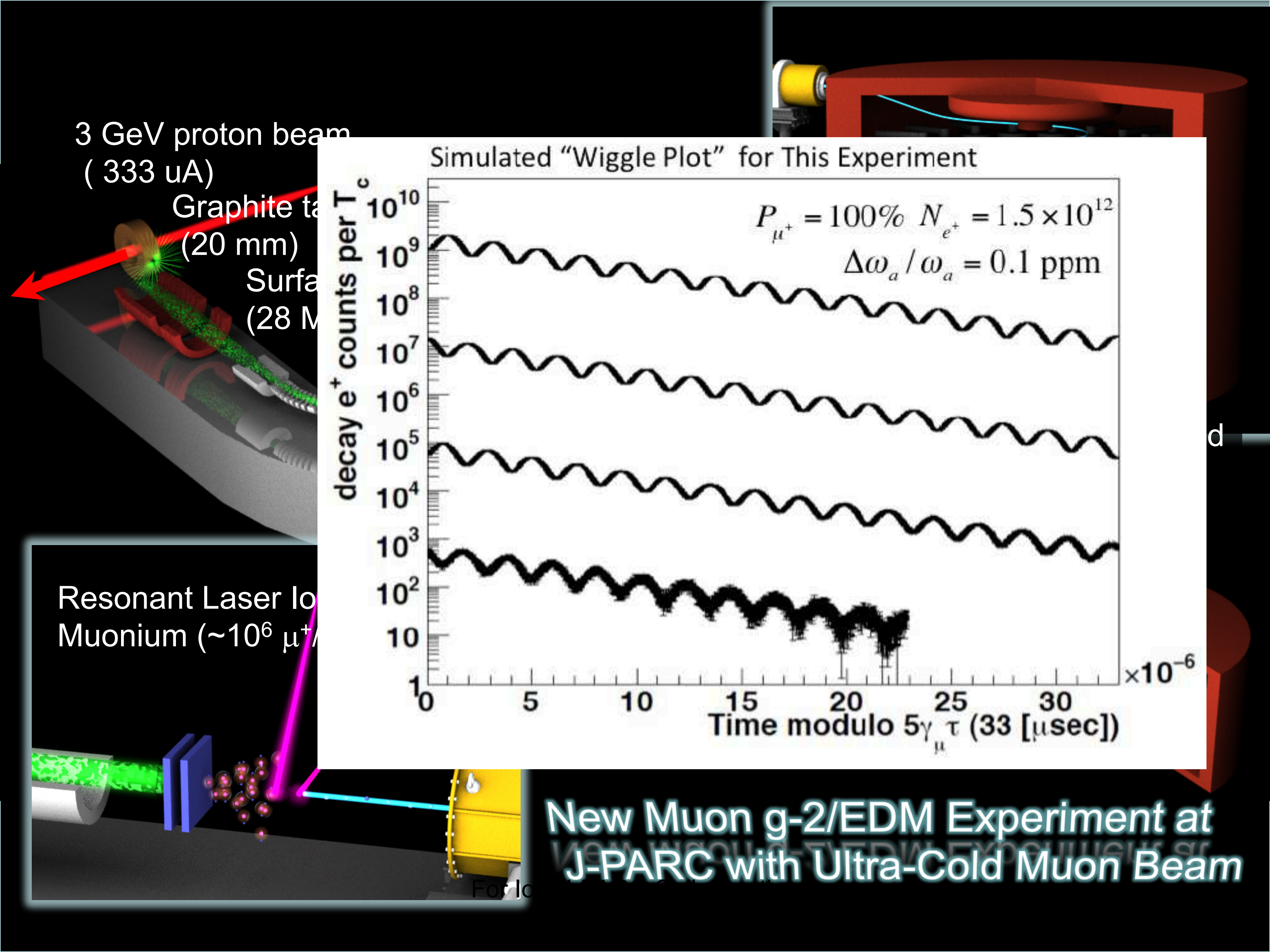




LHC Excluding “Hinted region”

- Precision frontier has its own value
- Connection with other physics is also important





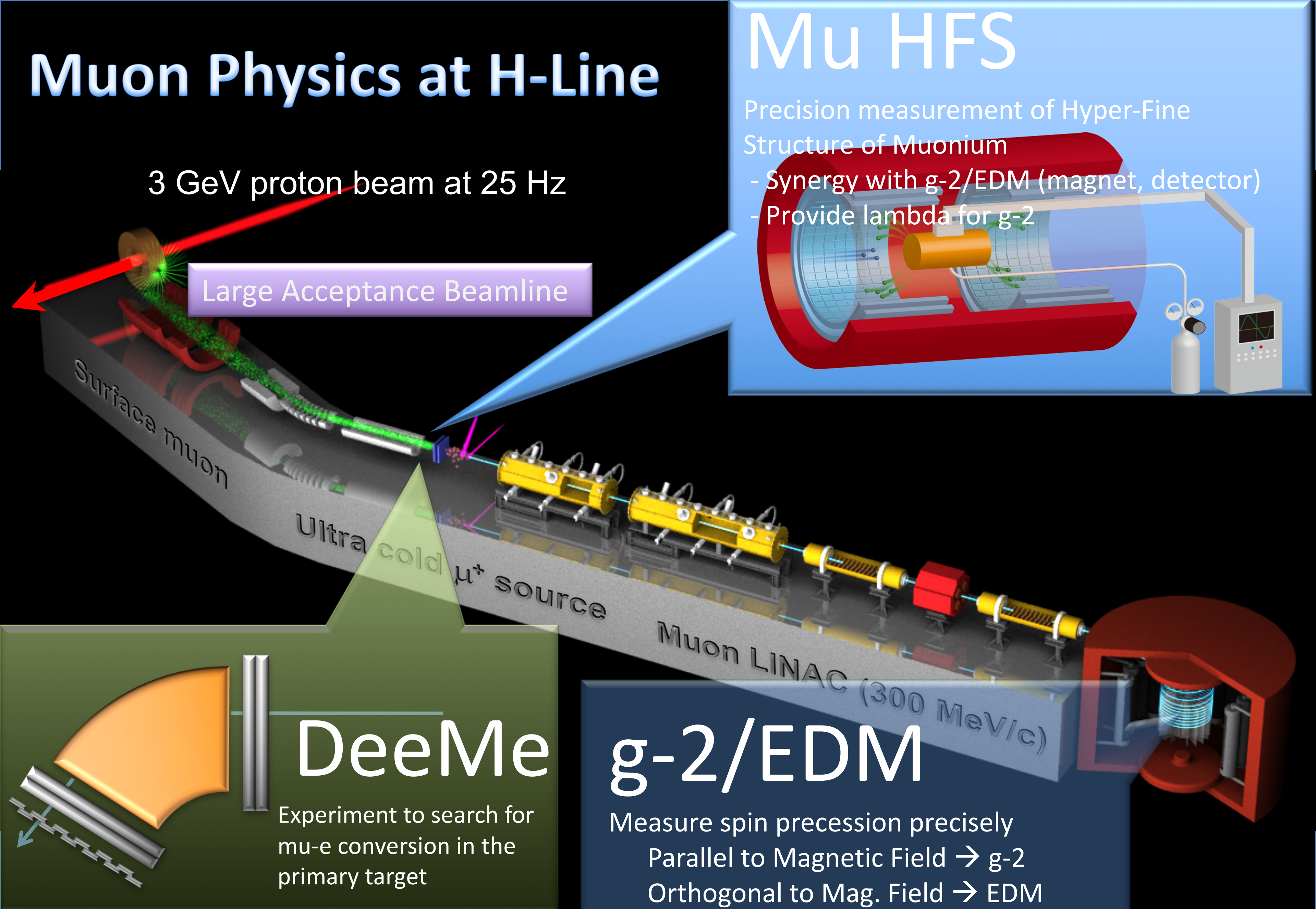
3 GeV proton beam
(333 uA)
Graphite ta
(20 mm)
Surfa
(28 M
Resonant Laser Io
Muonium (~10^6 μ+/
Simulated "Wiggle Plot" for This Experiment
$P_{\mu^+} = 100\%$ $N_{e^+} = 1.5 \times 10^{12}$
$\Delta\omega_a / \omega_a = 0.1$ ppm
decay e+ counts per T_c
1 10 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^10
0 5 10 15 20 25 30 ×10^-6
Time modulo $5\gamma_\mu\tau$ (33 [μsec])
New Muon g-2/EDM Experiment at
J-PARC with Ultra-Cold Muon Beam

BNL, FNAL, and J-PARC

- **complimentary**

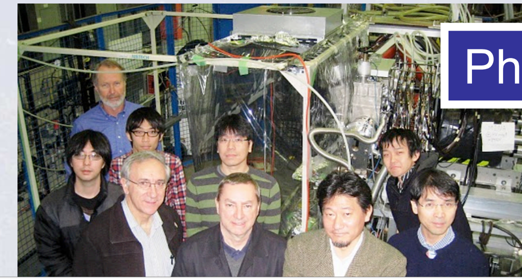
	BNL-E821	Fermilab	J-PARC
Muon momentum	3.09 GeV/c		0.3 GeV/c
gamma	29.3		3
Storage field	B=1.45 T		3.0 T
Focusing field	Electric quad		None
# of detected μ+ decays	5.0E9	1.8E11	1.5E12
# of detected μ- decays	3.6E9	-	-
Precision (stat)	0.46 ppm	0.1 ppm	0.1 ppm

Muon Physics at H-Line

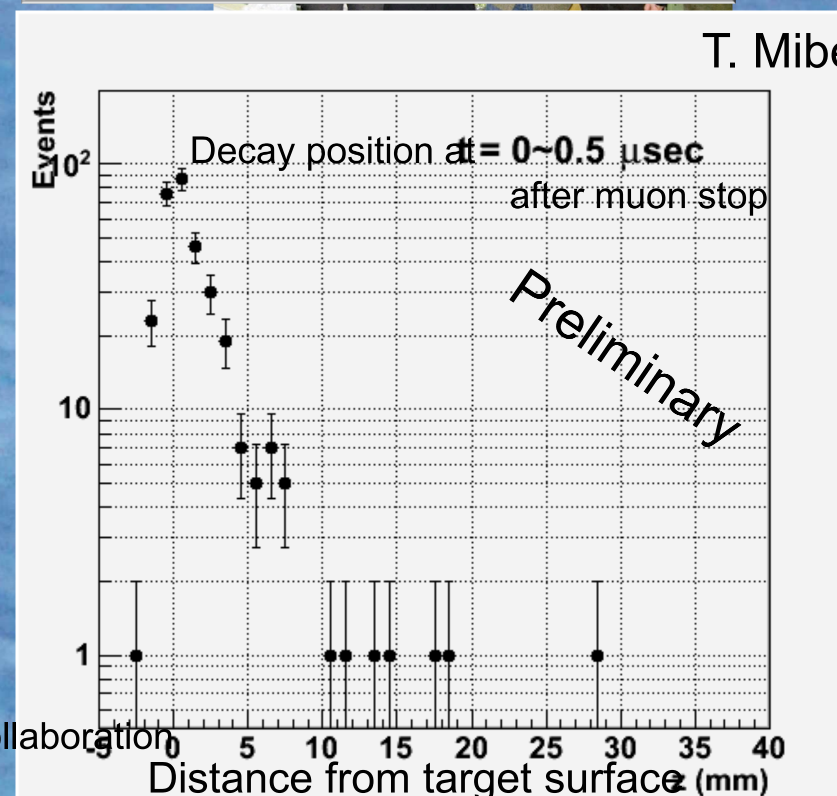


For IoP-J-PARC Collaboration

Mu Target R&D S-1249 :
preliminary conclusions and outlook



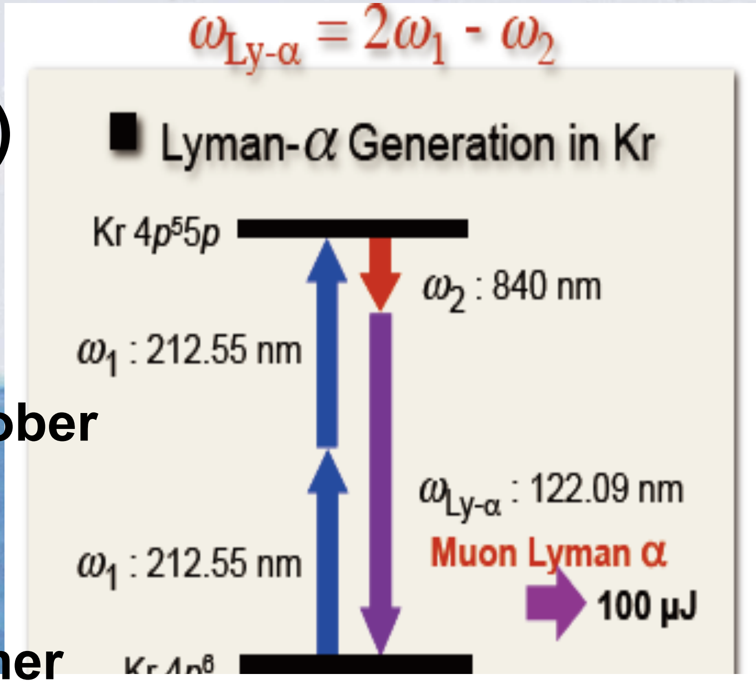
Silica aerogel (27mg/cm^3)



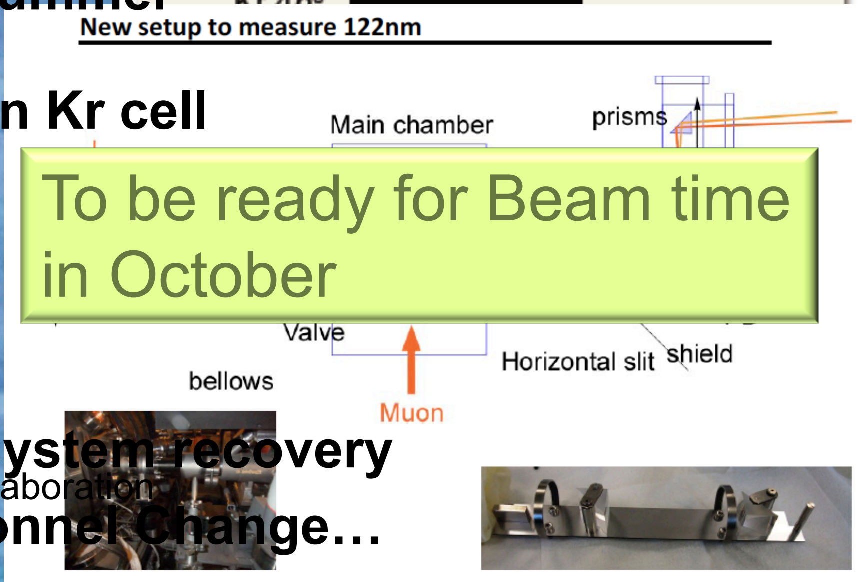
- **Experimental apparatus with MCP(new!) worked very well.**
- **The first data with aerogel (27mg/cm^3) already indicates that Mu production rate is similar to that of hot-W (2% at 27MeV/c) .**
- **The first beam time was canceled in the middle. But, we have more samples to study the density and structure dependence.**
- **Will continue this fall. (Additional 2 weeks has been approved by TRIUMF EEC.)**

Laser R&D and Ionization Test

N.F. Saito, O. Louchev, S. Wada, K. Yokoyama, K. Ishida, M. Iwasaki, P. Bakule, D. Tomono



- **Laser Development at RIKEN (x100)**
  - **Omega-1**
    - **Fiber Laser System** ✓
    - **Solid State Amplifier** ✓
    - **Non-linear frequency converter ~ October**
  - **Omega-2**
    - **SLM Seeder**
    - **1st and 2nd Non-linear amplification** } **~ This summer**
  - **2-photon resonant 4-wave mixing in Kr cell ~ October**
- **Ionization Test at RAL (x10)**
  - **X10 higher power, planned**
  - **April beam time, mostly spent on system recovery**
  - **Delays due to VISA problem, Personnel Change…**



To be ready for Beam time in October