PROBES of new physics and technological advancements from particle and gravitational wave physics experiments. A cooperative Europe – United States – Asia effort

Simone Donati

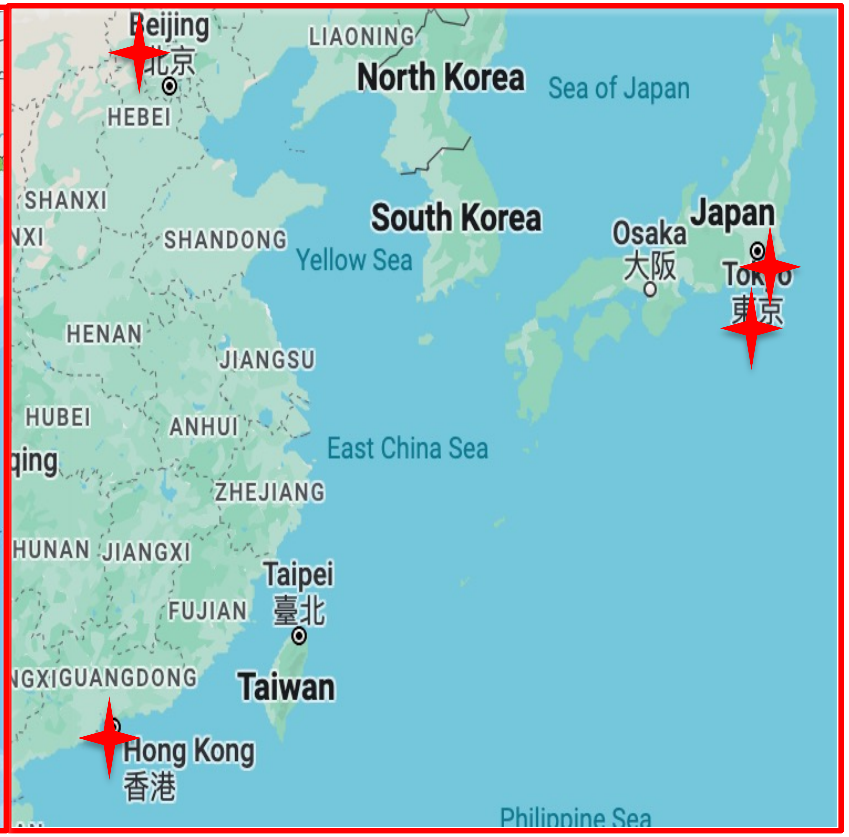
February 27th, 2024, Pisa

H2020 MSCA RISE 2020
GA 101003460

A cooperative Europe – United States – Asia effort (I)

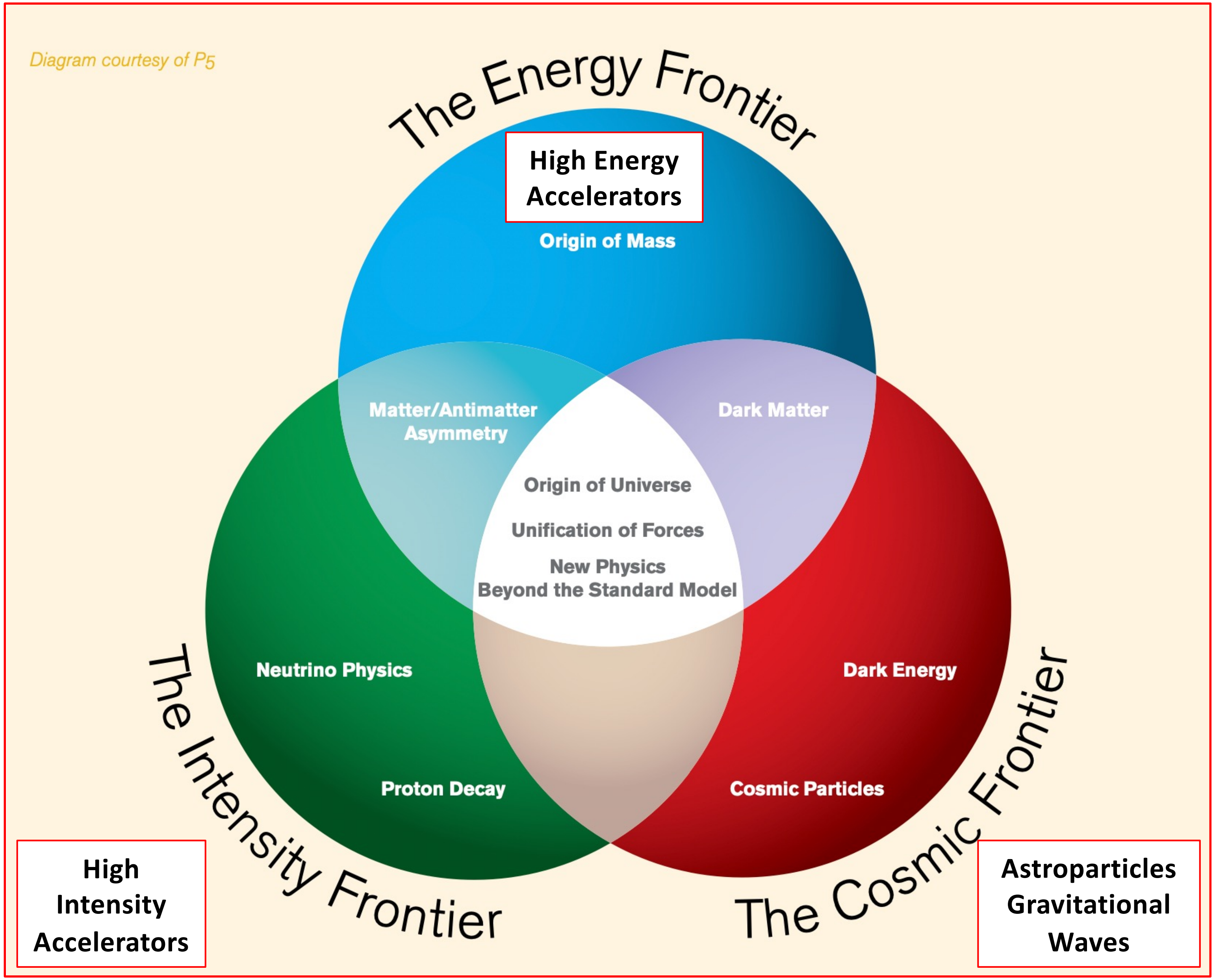
PROBES BENEFICIARIES	
INFN	IT
CAEN Spa	IT
CERN	CH
Clever Operation	FR
University of Bern	CH
Paul Scherrer Institut	CH
Imperial College	UK
CNRS	FR
Georgian Technical University	GE
Technical University Dresden	DE
University of Glasgow	UK
CEA	FR
University of Pisa	IT
European Gravitational Observatory	IT
IFAE	ES
ASTROCENT	PL
Karlsruher Institute of Technology	DE
University of Liverpool	UK
Scuola Suoeriore Sant'Anna	IT
SEEMS IKE	EL

A cooperative Europe – United States – Asia effort (II)



PROBES PARTNERS			
Fermi National Accelerator Laboratory	US	KEK	JP
Jefferson Laboratory	US	University of Tokyo	JP
California Institute of Technology	US	Chinese Ac. Science	CN
Massachusetts Institute of Technology	US	University of Hong Kong	HK
University of California	US		
Princeton University	US		
Johns Hopkins University	US		

PROBES: Exploring the Intensity and Cosmic Frontiers



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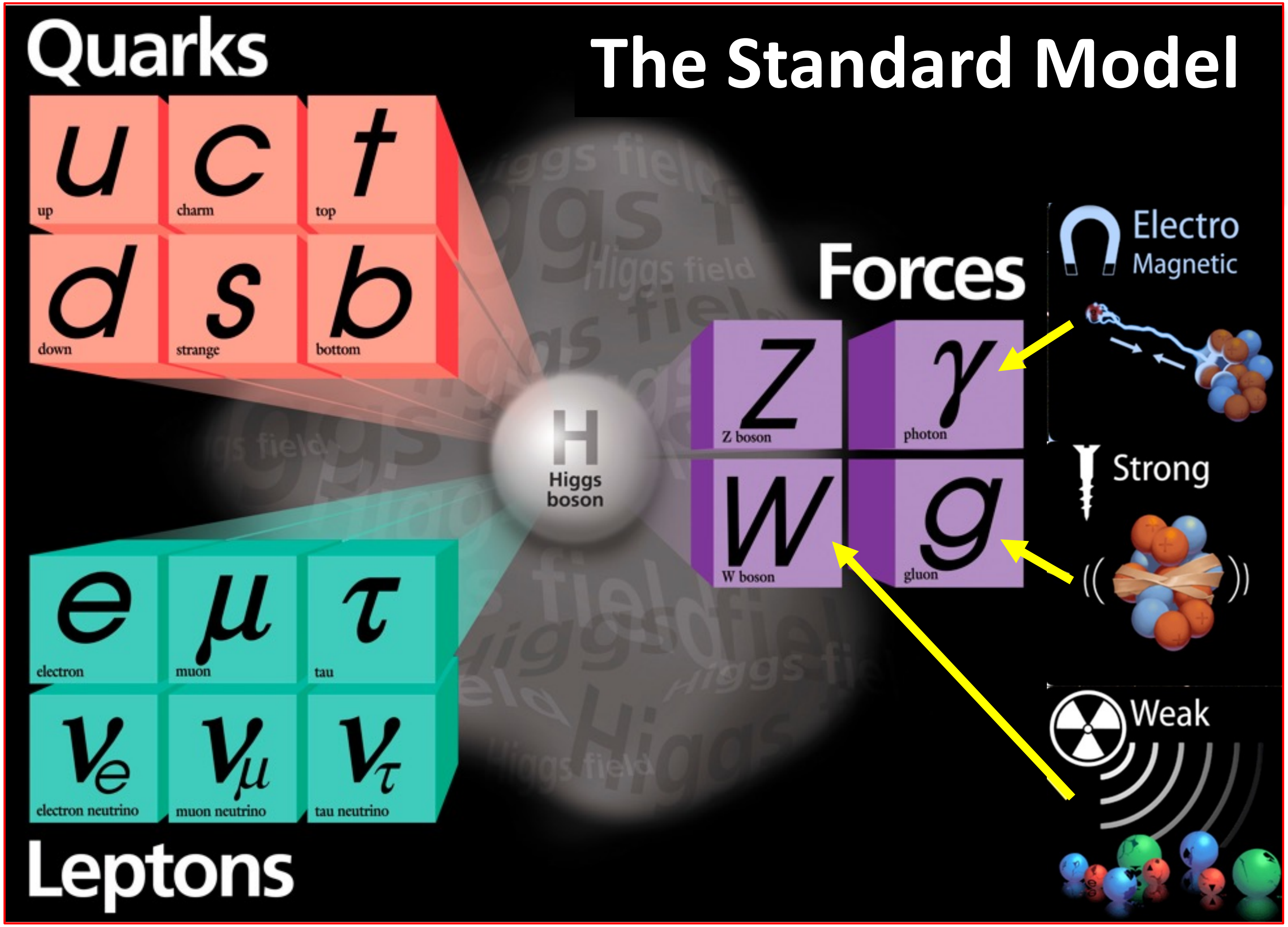
Elementary particles & fundamental interactions



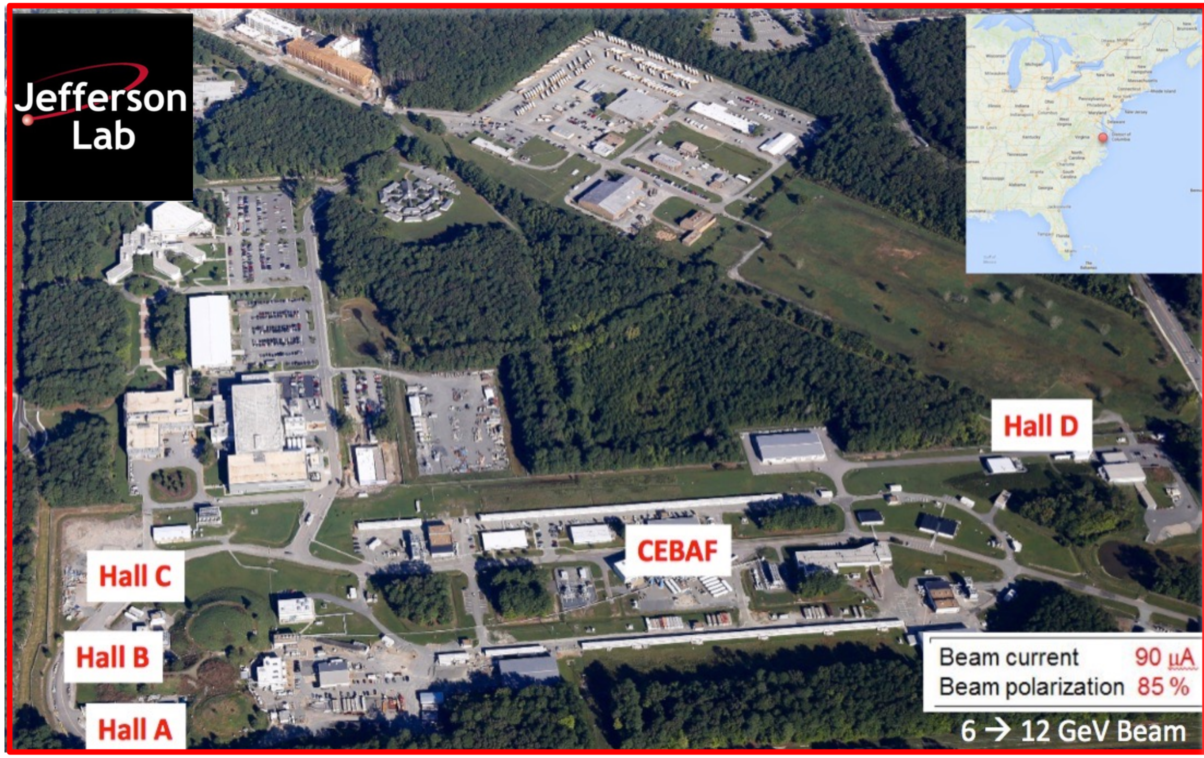
Hadron Physics: Jefferson Laboratory (US)

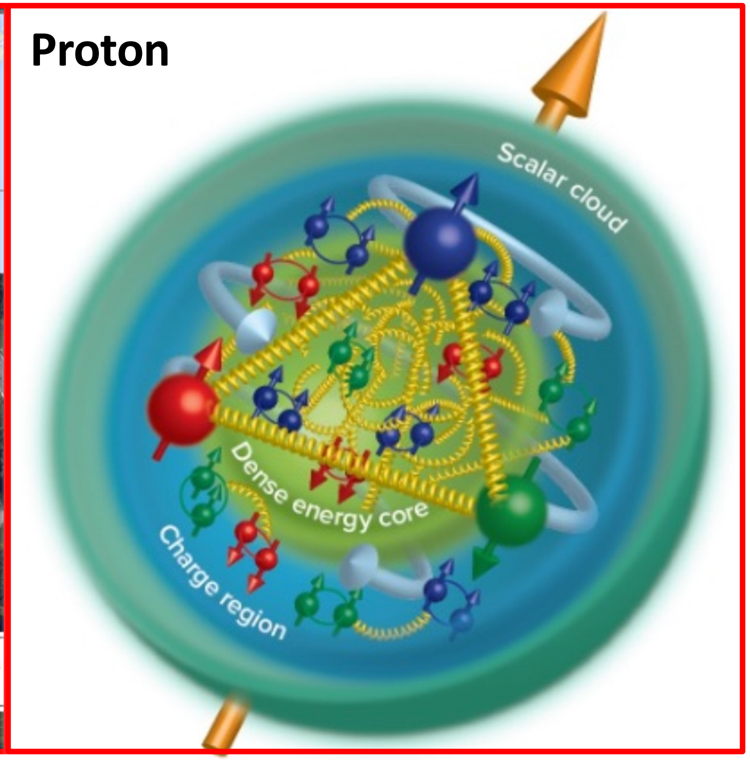
(WP1 "Hadron Physics: Detectors" - WP2 "Hadron Physics: Data Analysis")

JLAB Participants: >1500 scientists, > 230 Institutions, >30 countries

PROBES: INFN, CNRS, CEA, University of Glasgow

Hadron Physics: Jefferson Laboratory (US)

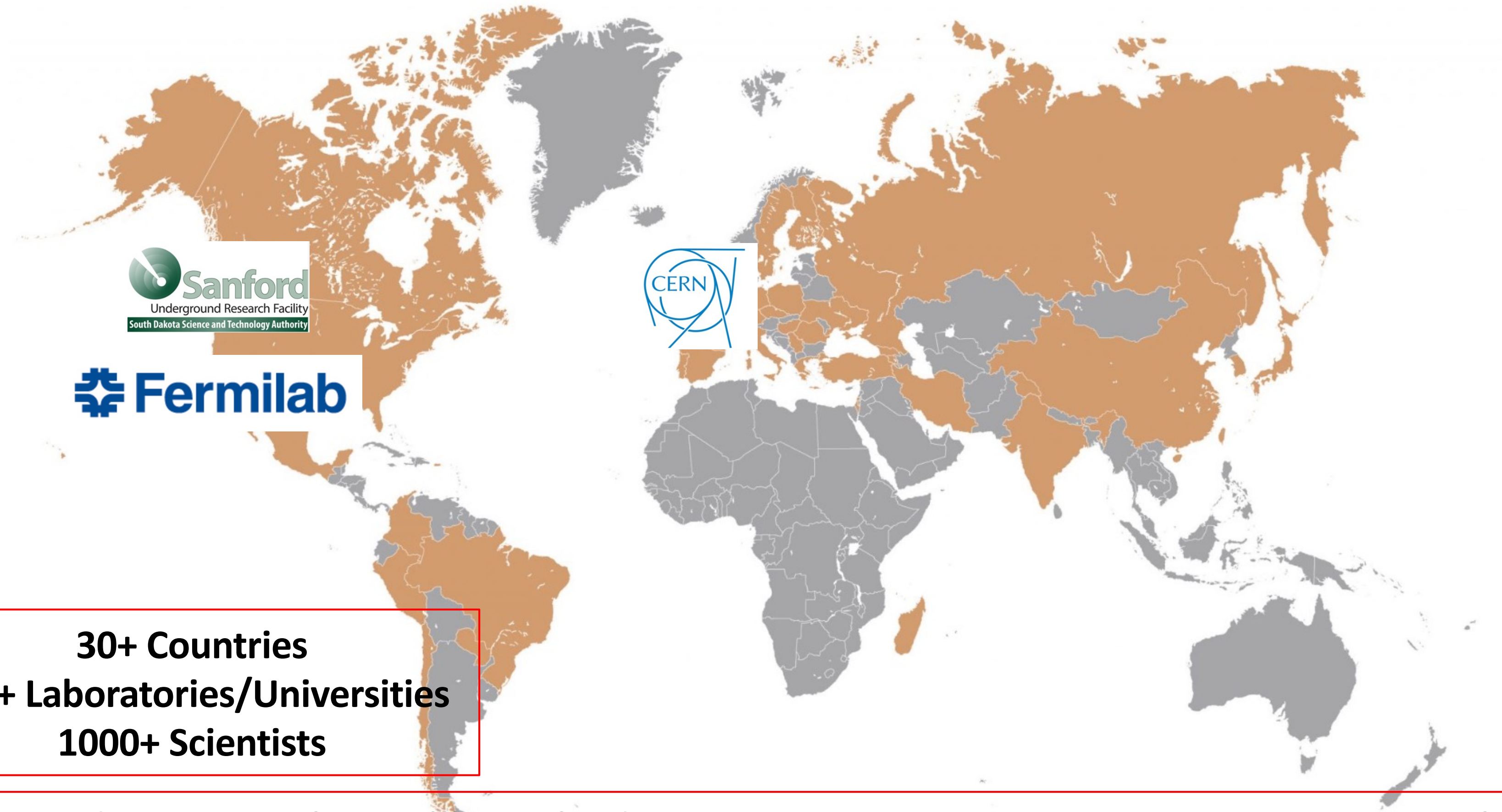




Of the four fundamental forces, the strong force is perhaps the least understood.
Quarks confinement within the proton: one of the great mysteries of modern physics.
JLAB exploits high-intensity electron beams to study the strong-force dynamics inside confined objects and "see" inside the proton (nucleon tomography at femto-scale).
+ Search for Light Dark Matter candidates (dark photon).
+ Study Equation of State of matter in extreme conditions of pressure and density (also interesting for neutron stars and Gravitational Waves Physics).

Short Baseline Neutrino Program (SBN) and DUNE

(WP3 “LFV Experiments: Detectors” – WP4 “LFV Experiments: Data Analysis”)



30+ Countries
200+ Laboratories/Universities
1000+ Scientists

United States, Czech Republic, Finland, France, Georgia, Germany, Greece, Hungary, Israel, Italy, Netherlands, Poland, Portugal, Romania, Russia, Serbia, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom

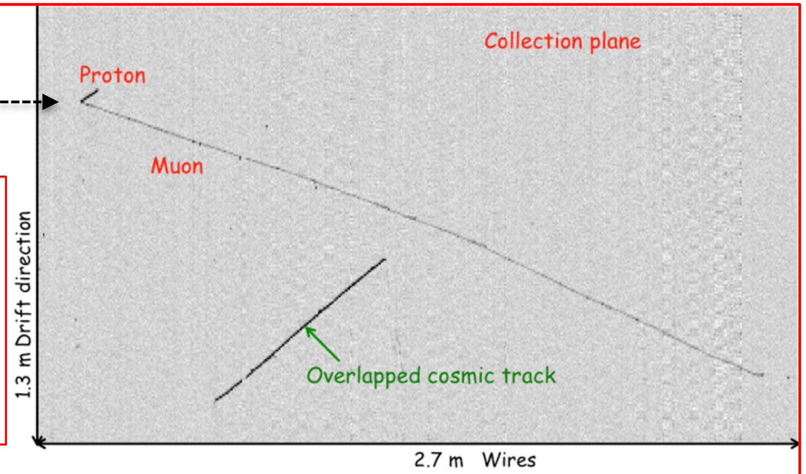
PROBES: INFN, CAEN, CERN, CLEVER, University of Bern, University of Pisa, University of Liverpool, SSSA

Exploiting a European (Lar-TPC) Technology at Fermilab
To solve neutrino mysteries

Liquid Argon -TPC

Ideal technology for neutrino physics

- **3D reconstruction with mm spatial resolution**
- **Precise calorimetry (energy measurement)**
- **Fast scintillation light (trigger signal).**



INFN LABORATORI NAZIONALI DEL GRAN SASSO

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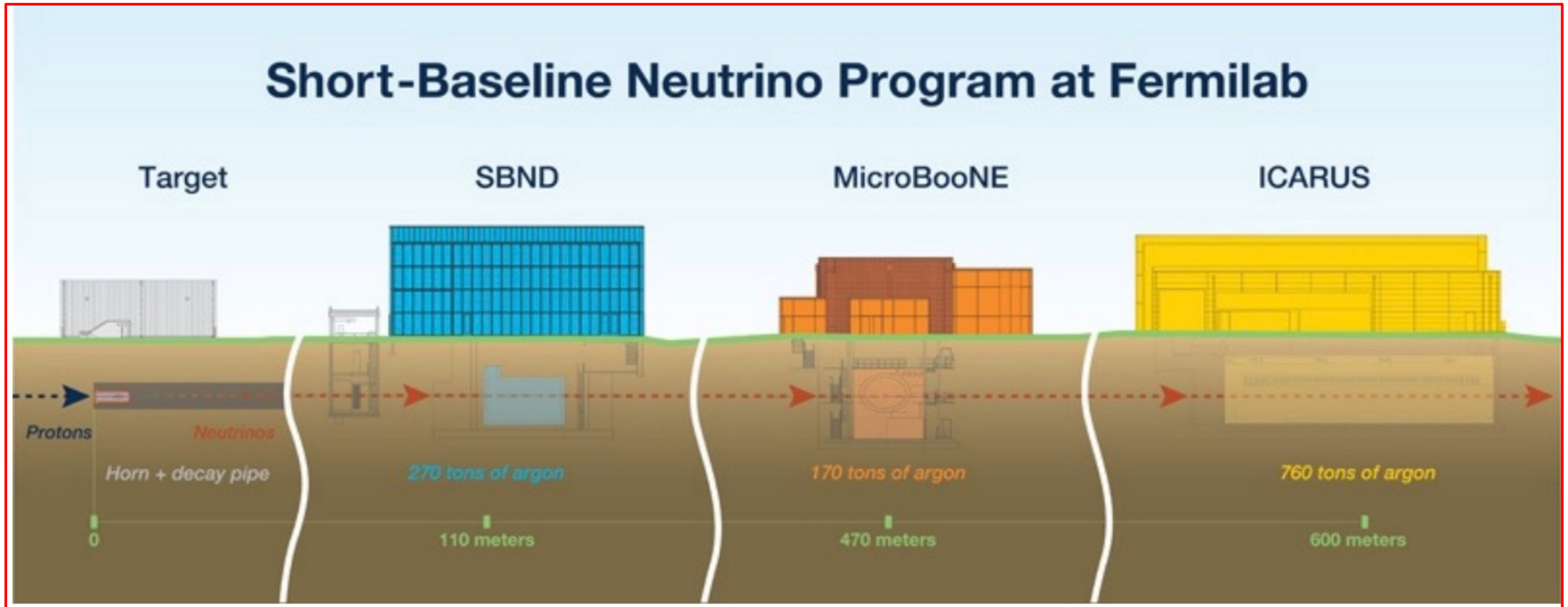
Follow the fantastic voyage of the ICARUS neutrino detector

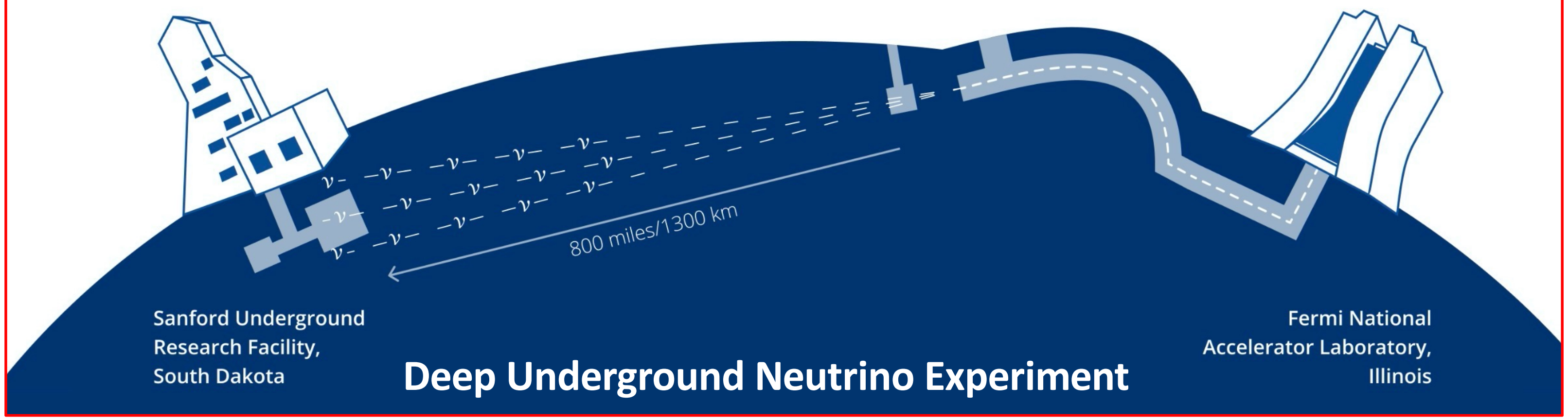
The world's largest particle hunter of its kind will travel across the ocean from CERN to Fermilab this summer to become an integral part of neutrino research in the United States

It's lived in two different countries and it's about to make its way to a third. It's the largest machine of its kind, designed to find extremely elusive particles and tell us more about them. Its pioneering technology is the blueprint for some of the most advanced science experiments in the world. And this summer, it will travel across the Atlantic Ocean to its new home (and its new mission) at the U.S. Department of Energy's Fermi National Accelerator Laboratory. It's called ICARUS, and you can follow its journey over land and sea with the help of an interactive map on Fermilab's website.

Short-Baseline Neutrino Program (SBN) and DUNE

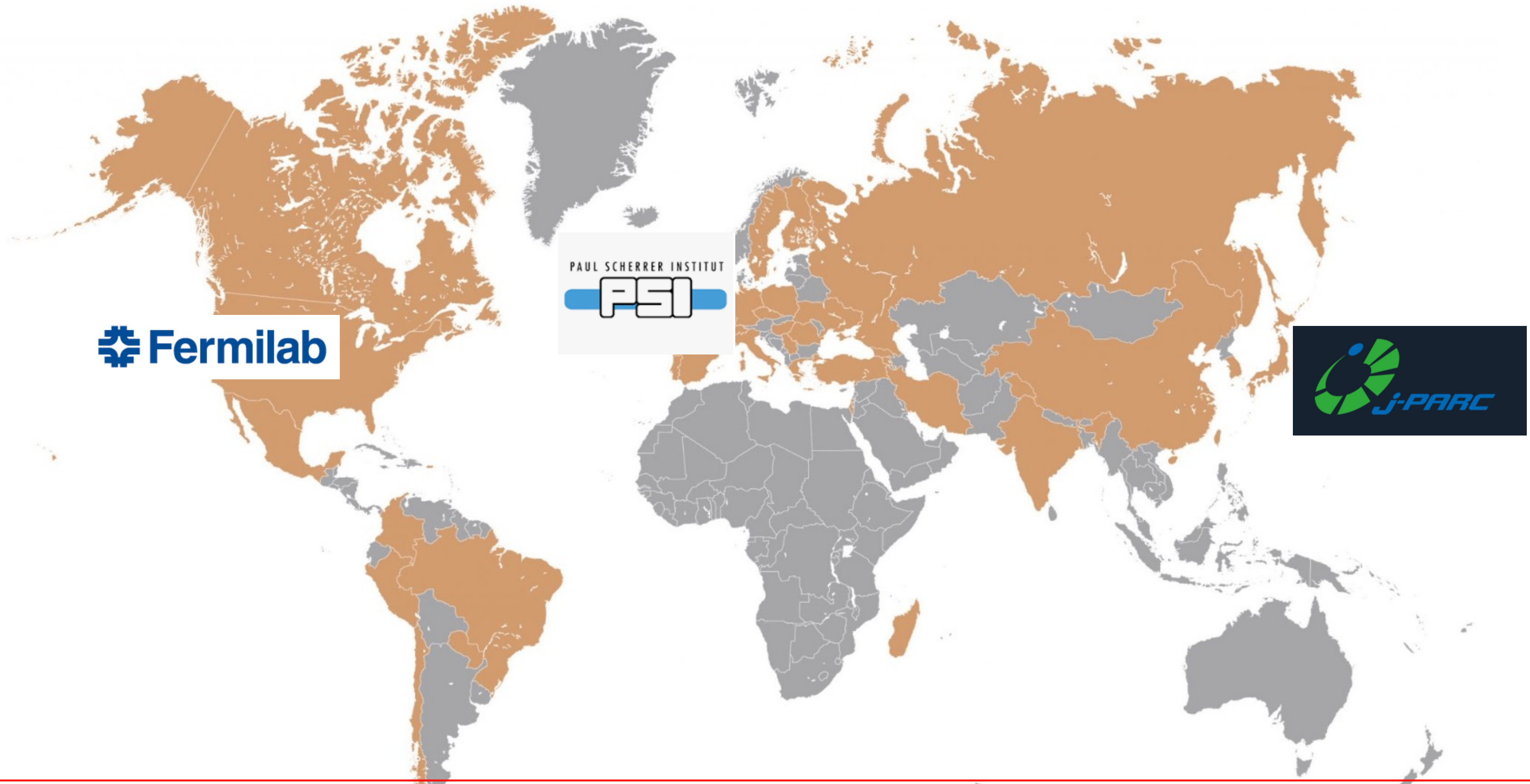
<u>SBN Physics goal</u>: solve sterile neutrino puzzle, measure oscillations and ν-Ar cross sections, understand nuclear effects/final states, develop technology for DUNE.





CLFV Experiments: FNAL (US) - PSI (CH) - J-PARC (JP)

(WP3 “LFV Experiments: Detectors” – WP4 “LFV Experiments: Data Analysis”)



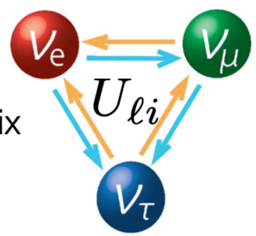
United States, Germany, Italy, United Kingdom, Switzerland, Japan, Czech Republic, France, Georgia
(Russia, Belarus, India, S.Korea, China, Saudi Arabia, Thailand, Australia, Malaysia, Canada, Vietnam)

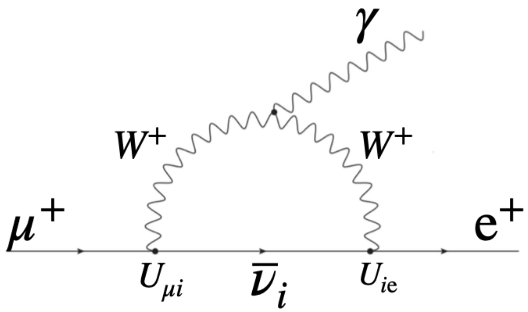
PROBES: INFN, University of Pisa, PSI. Imperial College, Georgian Technical University, Technical University Dresden

Neutrino oscillations and Charged Lepton Flavour Violation (CLFV)

Evidence of neutrino oscillation explicitly violates Lepton Flavor (LFV processes)

PMNS Matrix





But the neutrino-mediated contribution is **negligibly small**

$$\mathrm{BR}(\mu \to \mathrm{e} + \gamma) = \frac{\Gamma_{\mu \to \mathrm{e}+\gamma}}{\Gamma_{TOT}} = \frac{3\alpha}{32\pi} \left| \sum_{i=1}^{3} U_{\mu i} U^{*}_{\mathrm{e}i} \frac{m_i^2}{m_W^2} \right|^2 \approx 10^{-55 \leftrightarrow -50}$$

https://doi.org/10.1393/ncr/i2018-10144-0

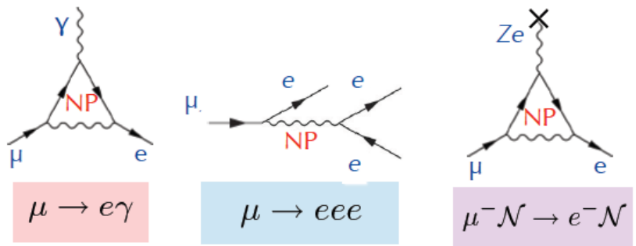
(C)LFV Golden channel for Beyond SM physics:

- not forbidden by other conservation laws
- SM contribution is beyond reach
- Model agnostic

"Null" SM background

Any observable effect is a direct sign of new physics

Interplay between measurements
In particular within the muon sector
but also with τ and meson decays

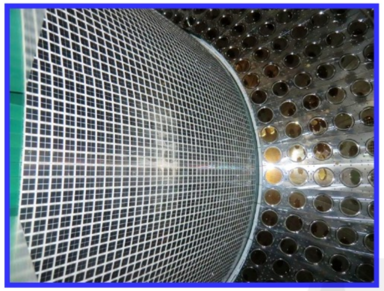


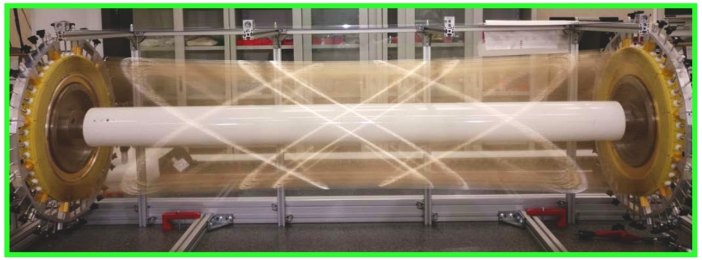
MEG   Mu3e   Mu2e, COMET

MEG-II Experiment at Paul Scherrer Institute (CH)

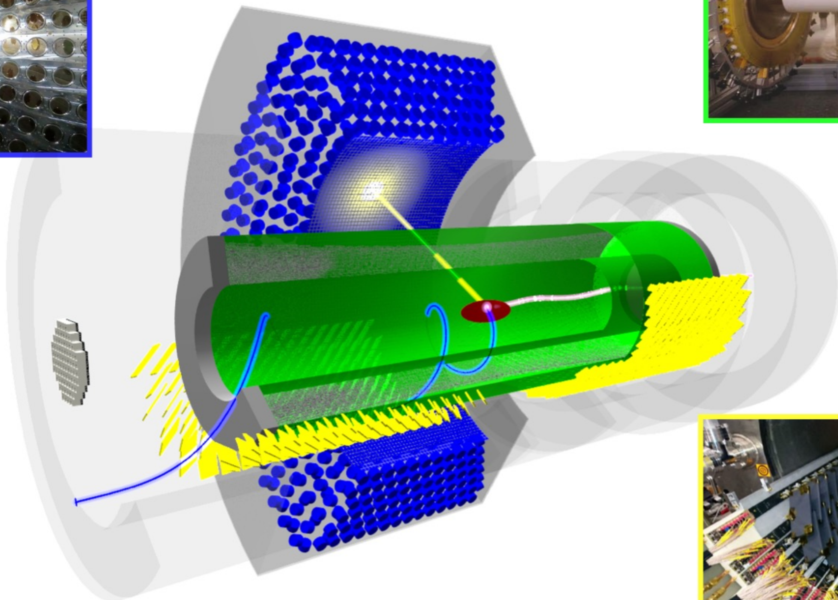
Detection strategy is the same of MEG
"Thin, Fast, Stable" detectors

LXe
Scintillation Detector
4092 **SiPMs** + 668 **PMTs**
$E_\gamma, \Theta_\gamma, T_\gamma$

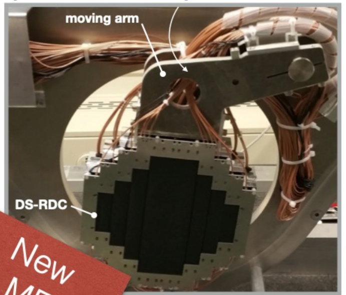




Drift Chamber
1728 square **drift cells**
More than 60 hits per track
Θ_e, P_e

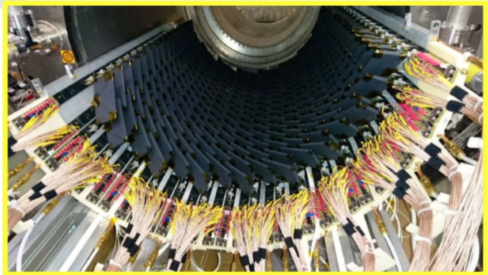


RDC
Tag e^+ with low momentum from $\mu^+ \to e^+ \nu \bar{\nu} \gamma$



New for MEG II

Timing Counter



512 **plastic scintillator** tiles with SiPMs.
T_e

MEG II final Sensitivity
$$\mathrm{BR}(\mu^+ \to e^+ + \gamma) \le 6 \cdot 10^{-14} \; (@\ 90\,\%\ C.L.)$$

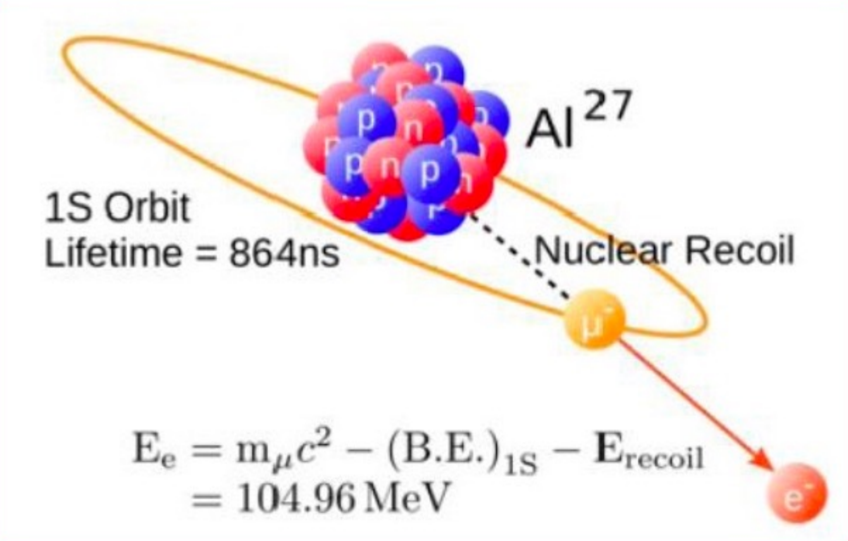
MEG-II construction and commissioning successfully completed in 2021
Data taking progressing well: 2021-2023 Runs largely surpassed previous MEG-I statistics
First physics results published in 2023

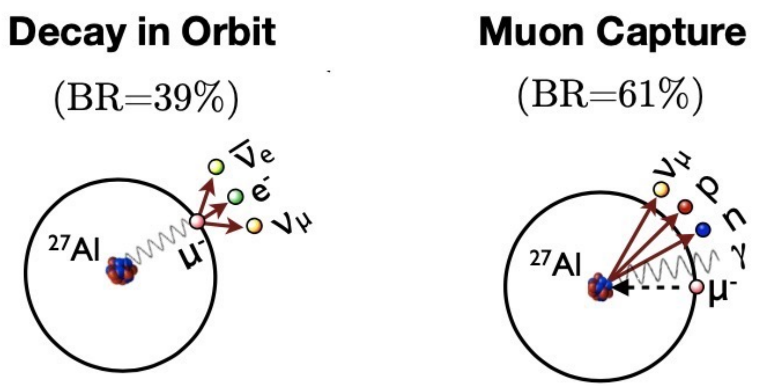
Neutrinoless coherent muon-to-electron conversion

Search for Charged Lepton Flavor Violation (CLFV) through the coherent conversion:

$$\mu^- + Al \rightarrow e^- + Al$$

- **Low momentum μ^- beam (< 100 MeV/c)**
- **High intensity pulsed rate**
  - **10^{10} μ^-/s stopped on Al target**
- **Stopped μ^- captured in atomic orbits**
  - **Cascade in the 1s state (fs)**





Background **Normalization**

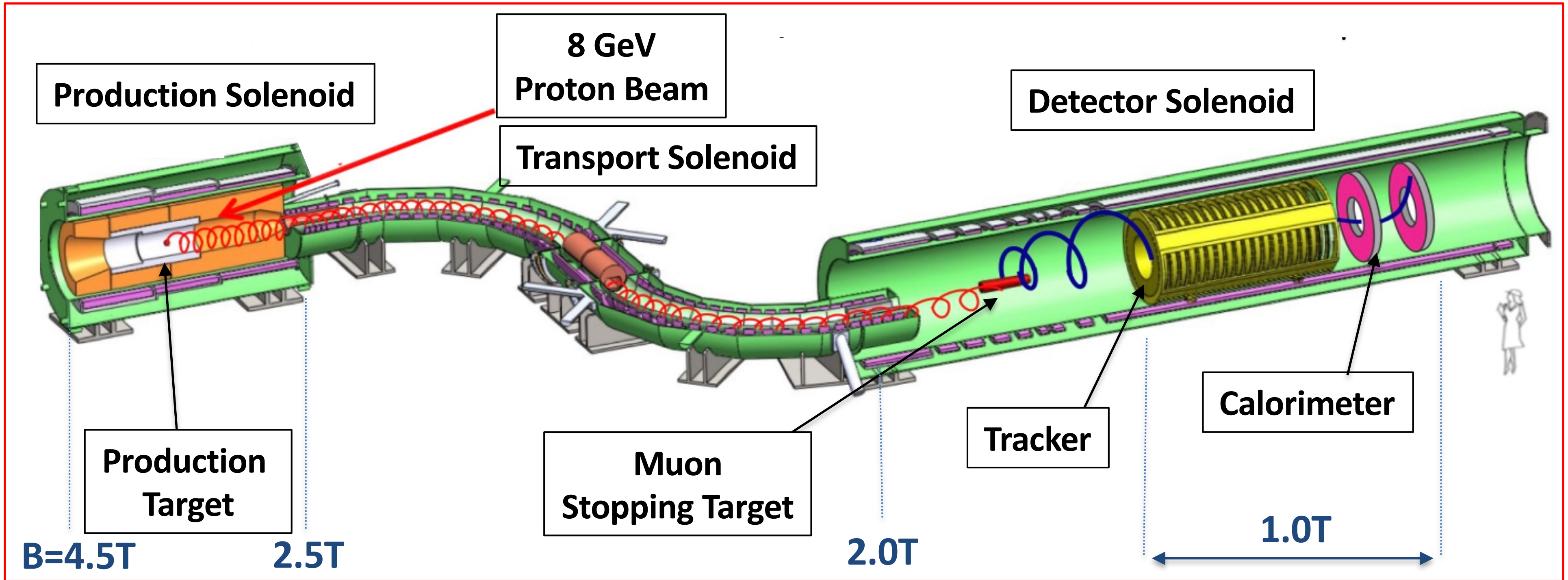
<u>Mu2e goal:</u> improve by a factor 10^4 the world's best sensitivity (SINDRUM II*) on:

$$R_{\mu e} = \frac{\Gamma(\mu^- + N \rightarrow e^- + N)}{\Gamma(\mu^- + N \rightarrow \text{all captures})}$$

down to a Single Event Sensitivity of 3 x 10^{-17}. SM prediction < 10^{-49} – 10^{-52}, any observation would be a clear evidence of New Physics.

***W. Bertl et al., Eur. Phys. J. C47, 337 (2006)**

Mu2e experiment at Fermilab (US)



Production Solenoid:

8 GeV protons strike tungsten target producing mostly pions

Graded B field reflects low momentum particles downstream

Transport Solenoid:

Select low momentum negative muons (+antiproton absorber)

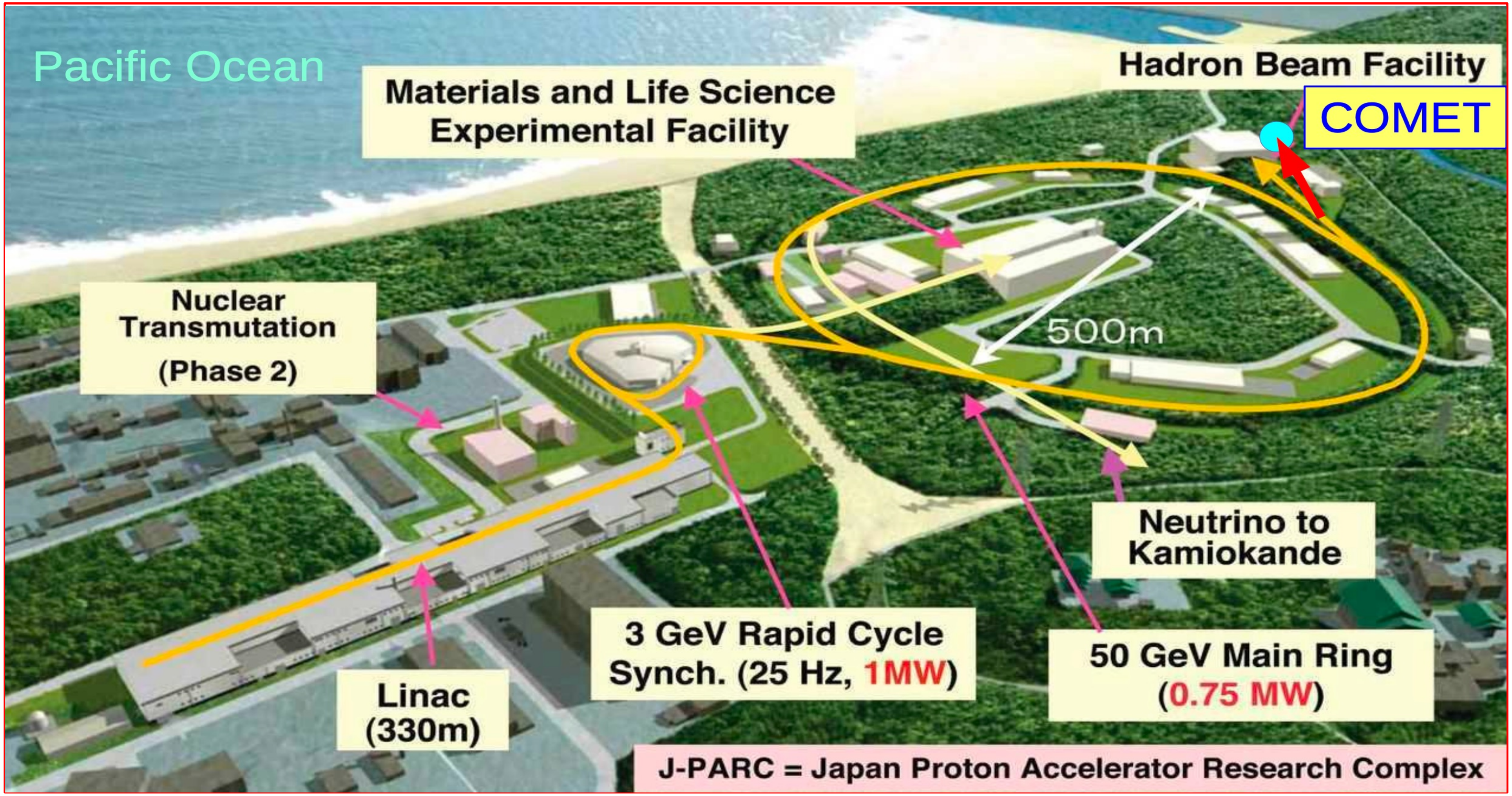
Detector Solenoid:

Capture muons on Al target, absorber reduces proton background

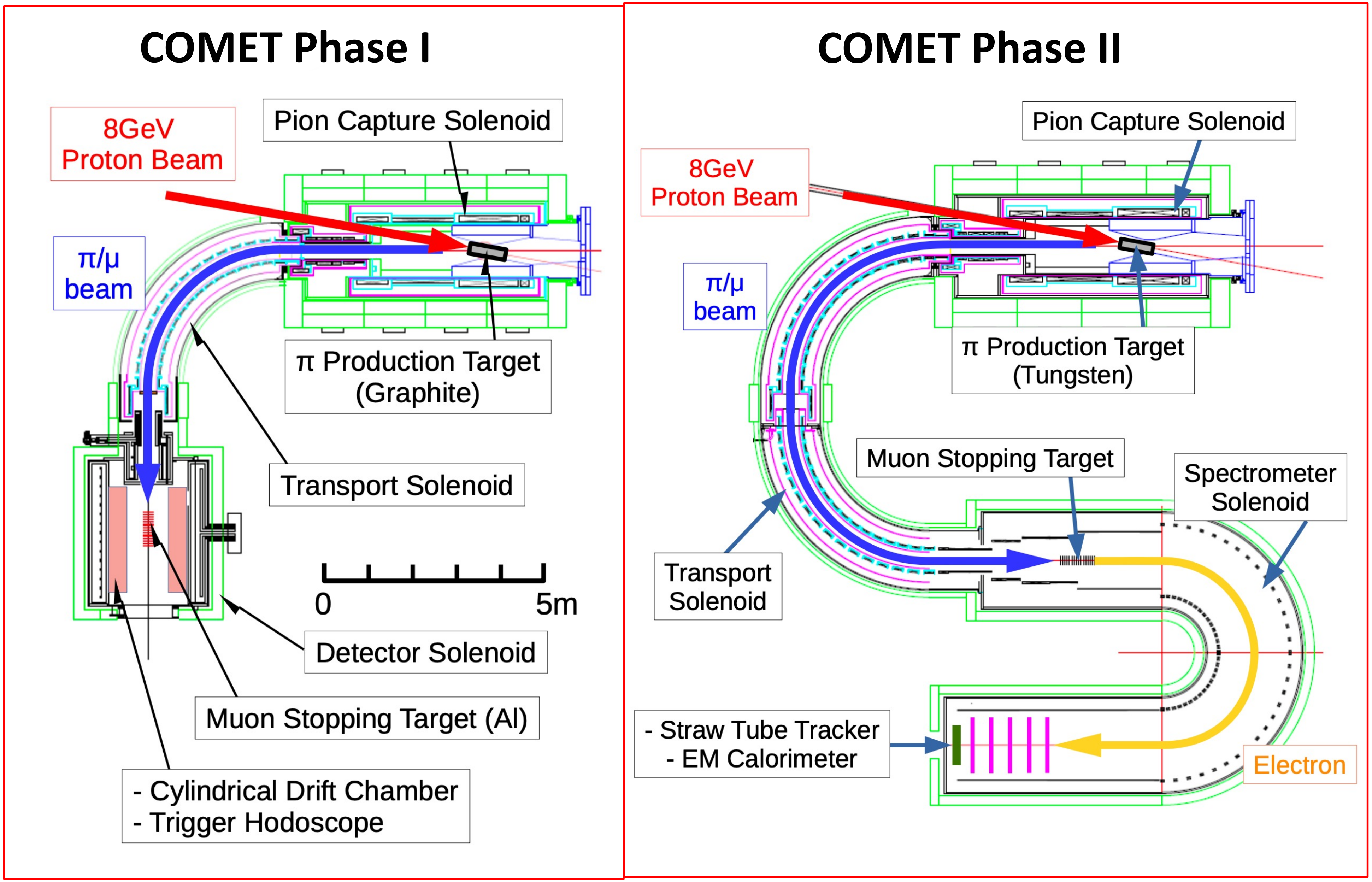
Graded B field focuses electrons in tracker fiducial volume

Tracker/Calorimeter measure particles momentum/energy

COMET Experiment at J-PARC (JP)



COMET Experiment at J-PARC: a staged approach



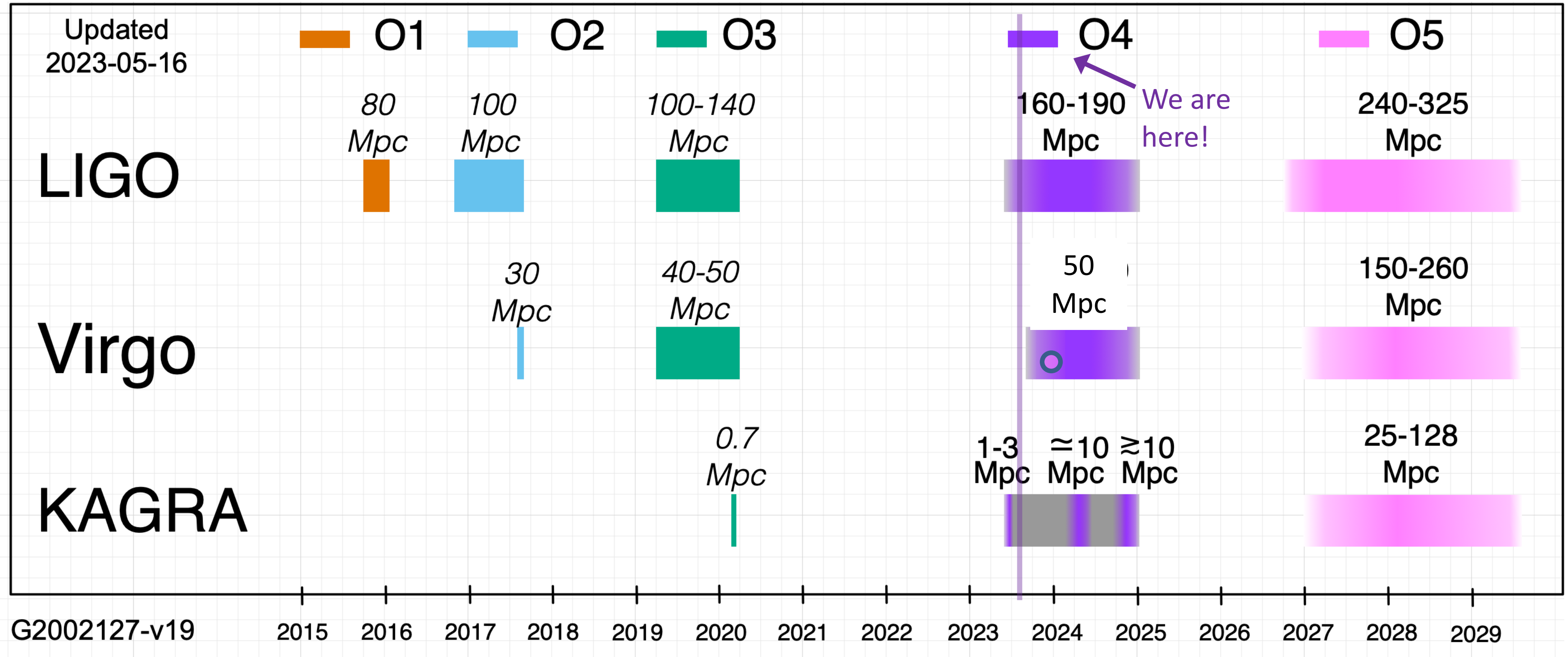
Gravitational Waves Experiments

(WP5 “Gravitational Waves: Detectors” - WP6 “Multi-Messenger Physics”)

LIGO-Virgo-KAGRA (LVK) Collaboration: Global Effort, 200+ Laboratories/Universities, 2000+ Scientists

PROBES: INFN, CNRS, University of Pisa, EGO, IFAE, ASTROCENT, NIKHEF, KIT, SEEMS

International Gravitational-Wave Observatory Network (IGWN)



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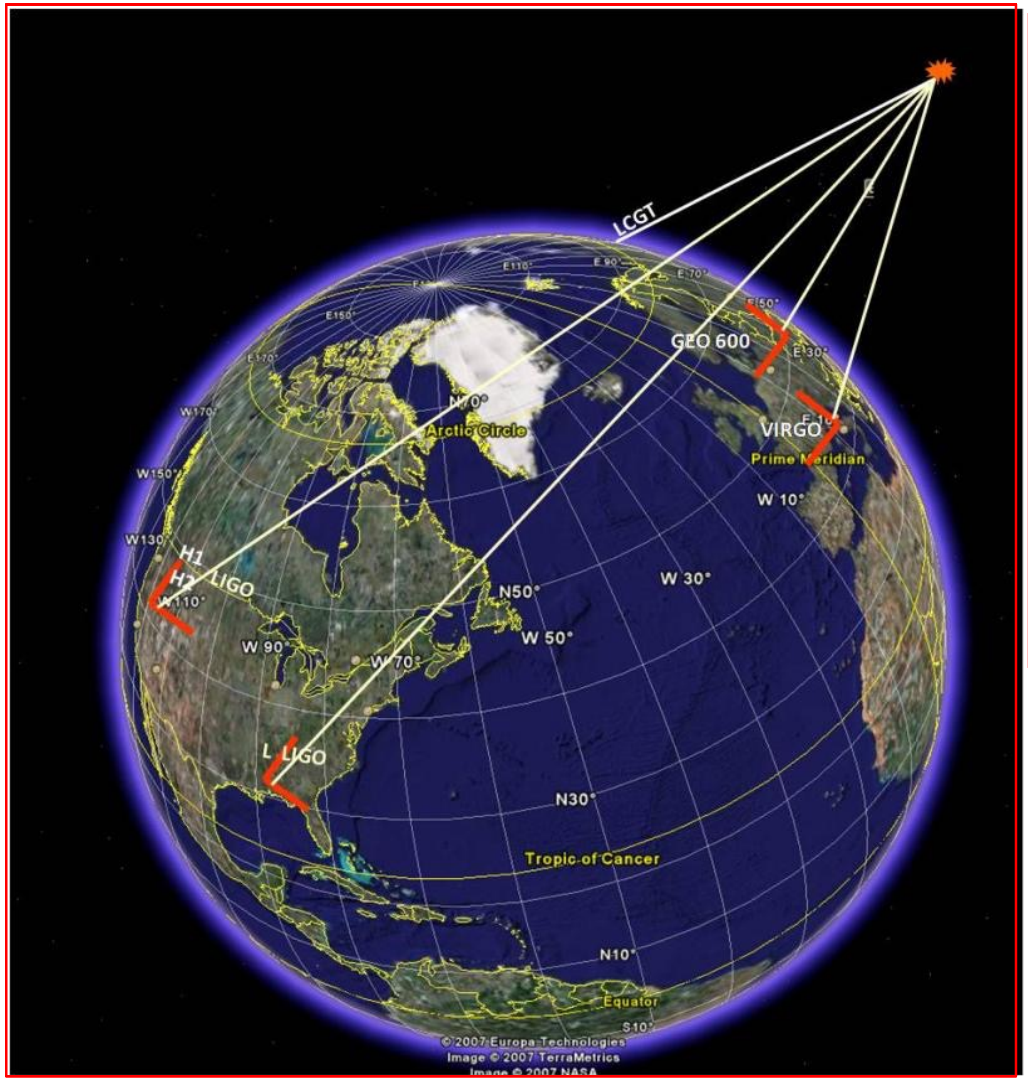
A Network of ground-based GW detectors



Advantages:

Improve event reconstruction

Increase detection probability

Increase significance of each detected event

Increase sky coverage

Search for EM Counterparts and set constraints on fundamental physics

PROBES Network Organization: Management Board/Scientific Board

MANAGEMENT BOARD			
Simone Donati	INFN	Maxime Defrune	CEA
Ferdinando Giordano	CAEN	Angela Papa	UNIPI
Francesco Lanni	CERN	Vincenzo Dattilo	EGO
Radia Sia	CLEVER	Mario Martinez	IFAE
Michel Weber	UBERN	Leszek Roskowski	ASTROCENT
Andreas Knecht	PSI	Johannes van den Brand	NIKHEF
Yoshi Uchida	IMPERIAL	Andreas Haungs	KIT
Silvia Niccolai	CNRS	Constantinos Andreopoulos	UNILIV
David Lomitze	GTU	Cesare Stefanini	SSSA
Kai Zuber	TUD	Amanda Soukoulia	SEEMS
David Ireland	UGLASGOW		
Chair: Simone Donati			

	WORK PACKAGE	LEAD BENEFICIARY	SCIENTIFIC BOARD
WP1	Hadron Physics: Detectors	INFN	M.Contalbrigo (INFN), M.Defurne (CEA), C.Carloganu (CNRS)
WP2	Hadron Physics: Data Analysis	UGLASGOW	D.Ireland (UGLASGOW), S.Niccolai (CNRS)
WP3	LFV Experiments: Detectors	IMPERIAL	Y.Uchida (IMPERIAL), A.Papa (UNIPI), A.Knecht (PSI)
WP4	LFV Experiments: Data Analysis	PSI	W.Weber (UBERN), C.Farnese (INFN), D.Lomitze (GTU)
WP5	Gravitational Waves: Detectors	EGO	V.Dattilo (EGO), M.Barsuglia (CNRS), H.Vocca (INFN)
WP6	Multi-Messenger Physics	CNRS	M.Razzano (INFN), B.Patricelli (UNIPI), M.Martinez (IFAE)
WP7	Dissemination and Outreach	IFAE	V.Boschi (INFN), V.Napolano (EGO)
WP8	Transfer of Knowledge	CERN	F.Varanini (INFN), D.Lomitze (GTU), R.Sia (CLEVER), F.Giordano (CAEN)
WP9	Management	INFN	S.Donati (INFN)
			Chair: Simone Donati

PROBES MidTerm Review Meeting - Agenda

	Welcome - Introduction	
WP9	Management	Simone Donati
WP5	Gravitational Waves: Detectors	Matteo Barsuglia
WP6	Multi-Messenger Physics	Barbara Patricelli
WP3+WP4	Neutrino Experiments, Detectors and Data Analysis	Alessandro Menegolli
WP3+WP4	CLFV Experiments, Detectors and Data Analysis	Angela Papa
WP1	Hadron Physics: Detectors	Marco Contalbrigo
WP2	Hadron Physics: Data Analysis	Mariangela Bondi
WP7	Dissemination and Outreach	Vincenzo Napolano
WP8	Transfer of Knowledge	Filippo Varanini
	Reports from Seconded Researchers	Juan Sebastian Alvarado
	Reports from Seconded Researchers	Livio Calivers
	Reports from Seconded Researchers	Oliver Jeremy
	Conclusions	

Implementation

		Planned MP	Started MP	Executed MP	Started/Planned	Executed/Planned %	Work Package	Destination
INFN	IT	158	56	34.62	35%	22%	1,2,3,4,5,6	US, JP
CAEN	IT	6					3,4	US
CERN	CH	16	3	1.97	19%	12%	3,4	US
CLEVER	FR	6					3,4	US
UBERN	CH	8	3	2.16	38%	27%	3,4	US
PSI	CH	12					3,4	JP
IMPERIAL	UK	18	4	1.36	22%	8%	3,4	JP
CNRS	FR	46	20	17.73	43%	39%	1,2,3,4,5,6	US, JP
GTU	GE	34	15	13.63	44%	40%	3,4	JP
TUD	DE	8					3,4	JP
UGLS	UK	16	7	5.53	44%	35%	1,2	US
CEA	FR	12	8	5.83	67%	49%	1,2	US
UNIPI	IT	25	2	1.13	8%	5%	3,4,5,6	US, JP
EGO	IT	20	3	0.67	15%	3%	5,6	US, JP
IFAE	ES	12	4	2.00	33%	17%	5,6	US, JP
ASTROCENT	PL	7					5,6	US, JP
NIKHEF	NL	10					5,6	US
KIT	DE	10					5,6	US
UNILIV	UK	12					3,4	US
SSSA	IT	6					3,4	US
SEEMS	GR	10					5,6	US
		452	126	86,63	28%	19%		

WP1 "Hadron Physics: Datectors"	Running Smoothly, Stable
WP2 "Hadron Physics: Data Analysis"	Running Smoothly, Stable
WP3 "LFV Experiments: Detectors"	Running Smoothly, Increasing Rapidly
WP4 "LFV Experiments: Data Analysis"	Running Smoothly, Increasing Rapidly
WP5 "Gravitational Waves: Detectors"	Beginning Now (Virgo O4)
WP6 "Multi-Messenger Physics"	Beginning Now (Virgo O4)