Fermilab Plan

with Project X

IPMU Seminar
August 19, 2009

Young-Kee Kim
Fermilab and University of Chicago

U.S. DEPARTMENT OF ENERGY

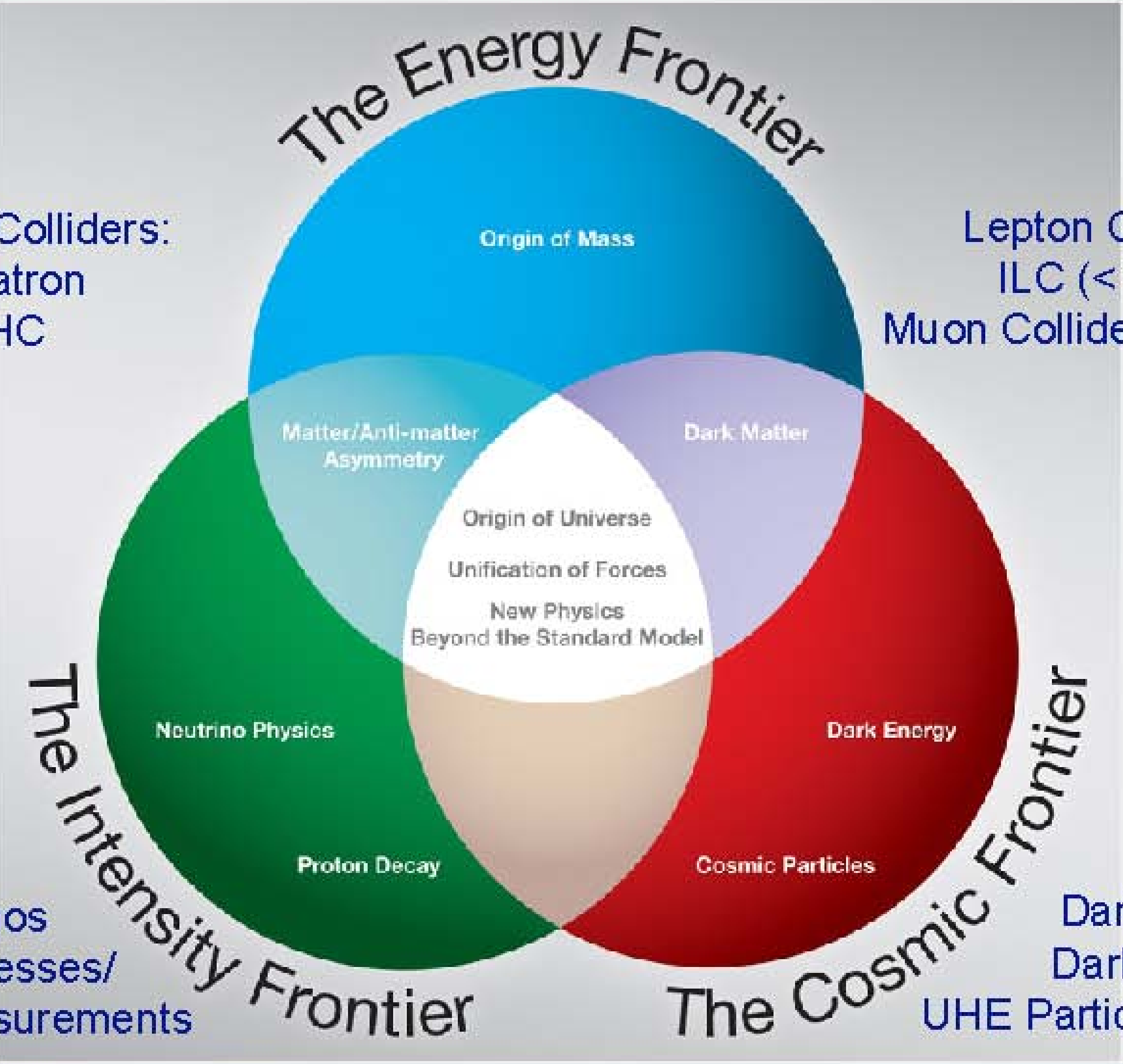
Fermilab

Fermilab Programs at The Three Frontiers

http://www.fnal.gov/pub/science/frontiers/

Hadron Colliders:
Tevatron
LHC

Lepton Colliders:
ILC (< 1 TeV)
Muon Collider (1 – 4 TeV)



Neutrinos
Rare Processes/
Precision Measurements

Dark Matter
Dark Energy
UHE Particles from Space

Fermilab: characteristics

- 1850 employees, 2300 users
- > 100 Ph.D.s per year
- 75,000 teachers
- 336,000 students (STEM)
- 6800 acres, park-like site

- Highest energy collider in the world: Tevatron
- Highest intensity neutrino beams (low and high energy)
- Particle astrophysics expts.
- Particle / particle-astro Theory
- Computing, Det./Accel. R&D

The national particle physics lab

- US: Transition from multi labs to Fermilab
- Principal HEP world laboratories:
  - CERN, Switzerland
  - Fermilab, US
  - KEK, Japan
  - IHEP, China
- Particle physics is a fully global enterprise

(proton mass = ●)

Particle Discoveries at Fermilab

The Energy Frontier: The Tevatron

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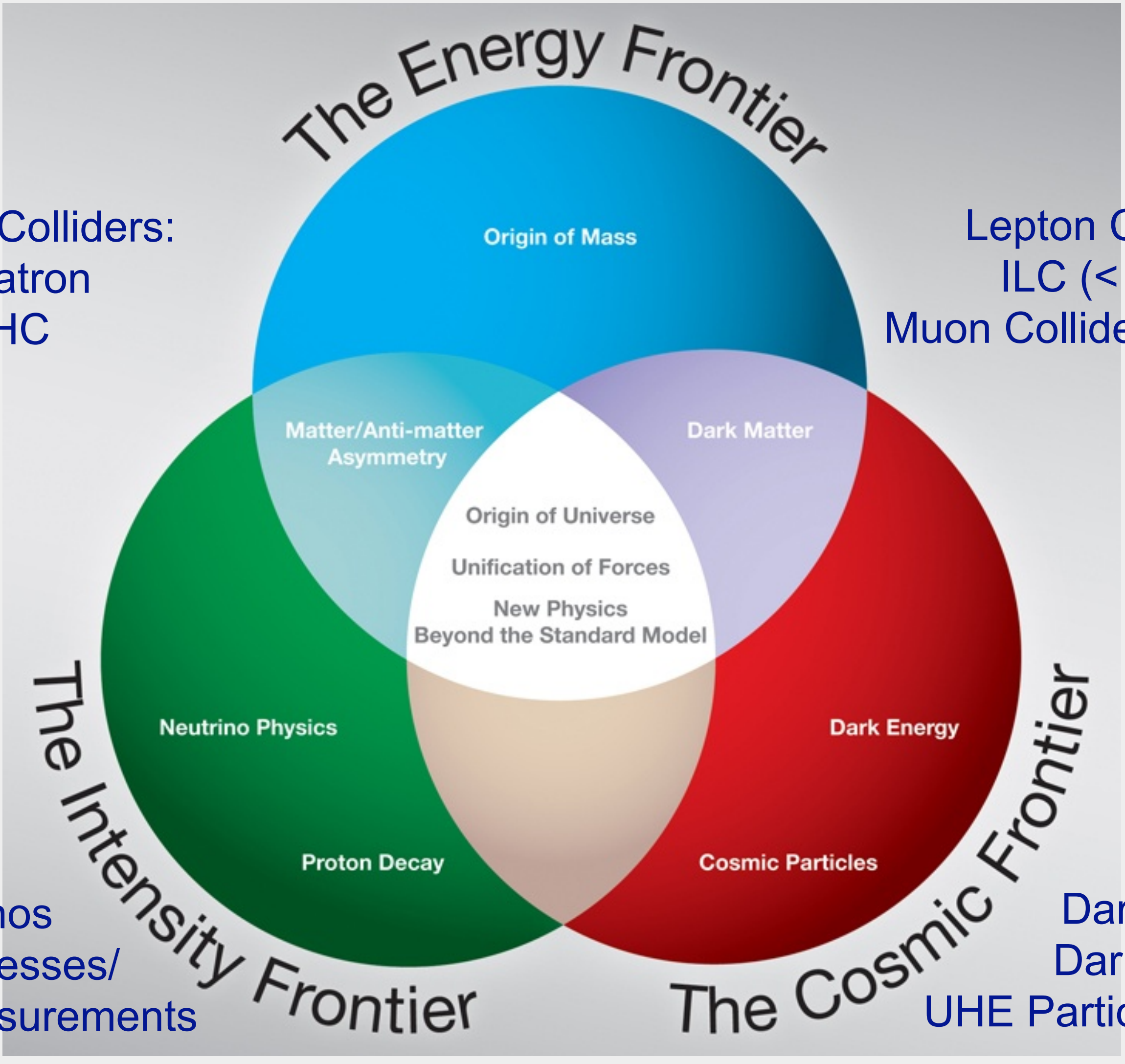

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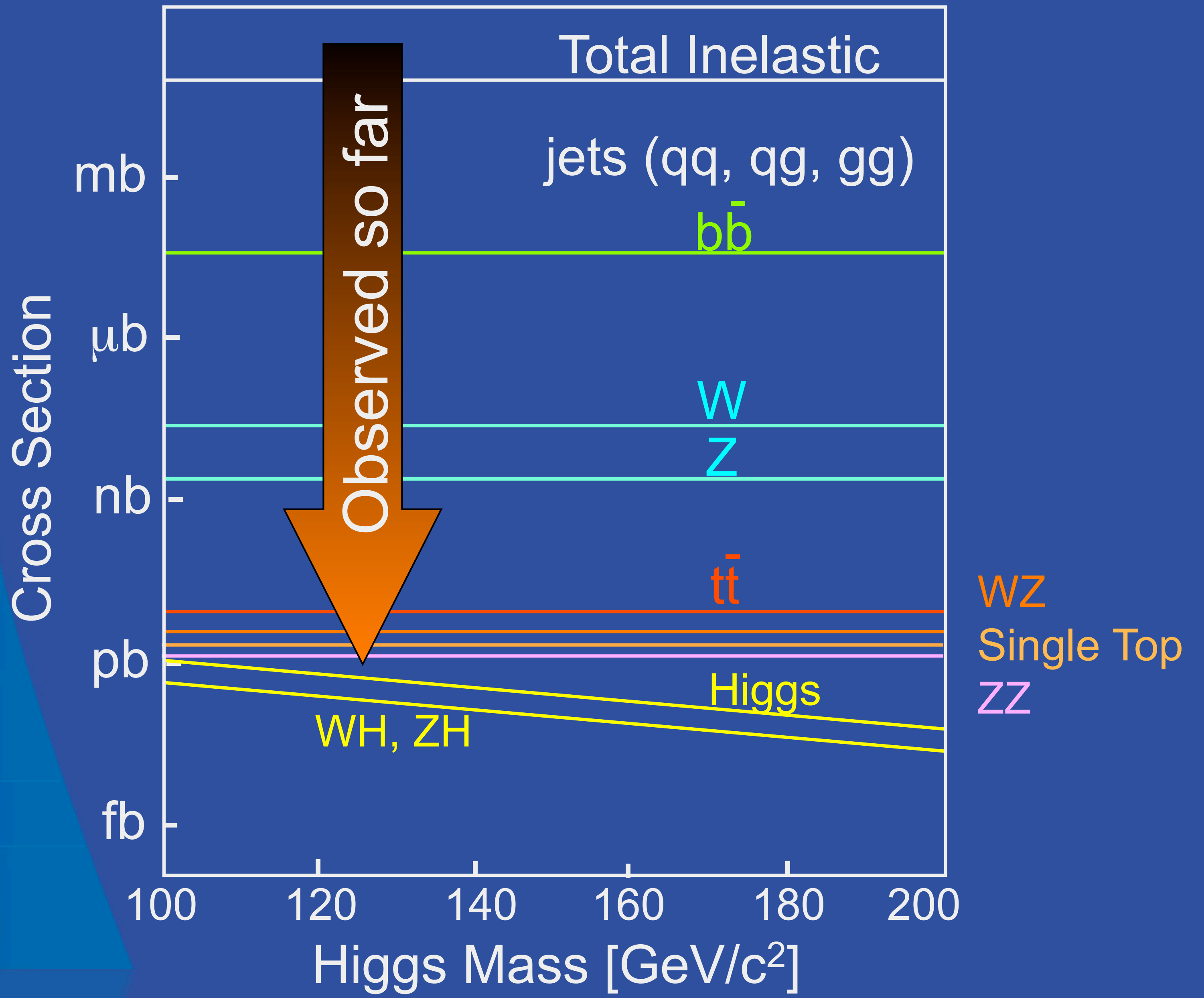
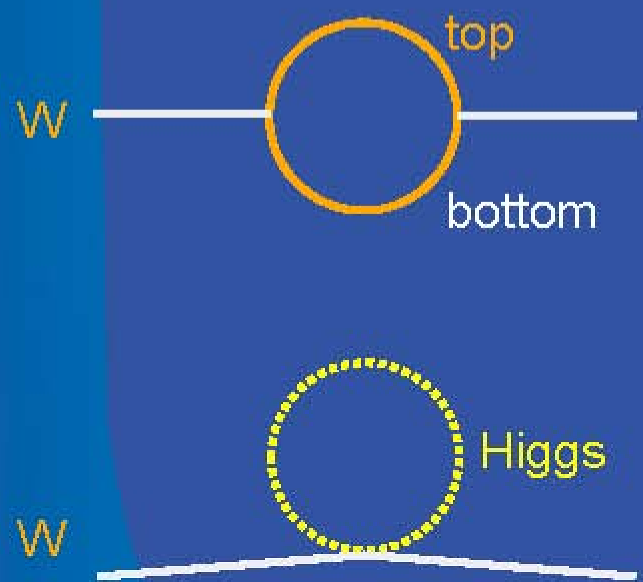
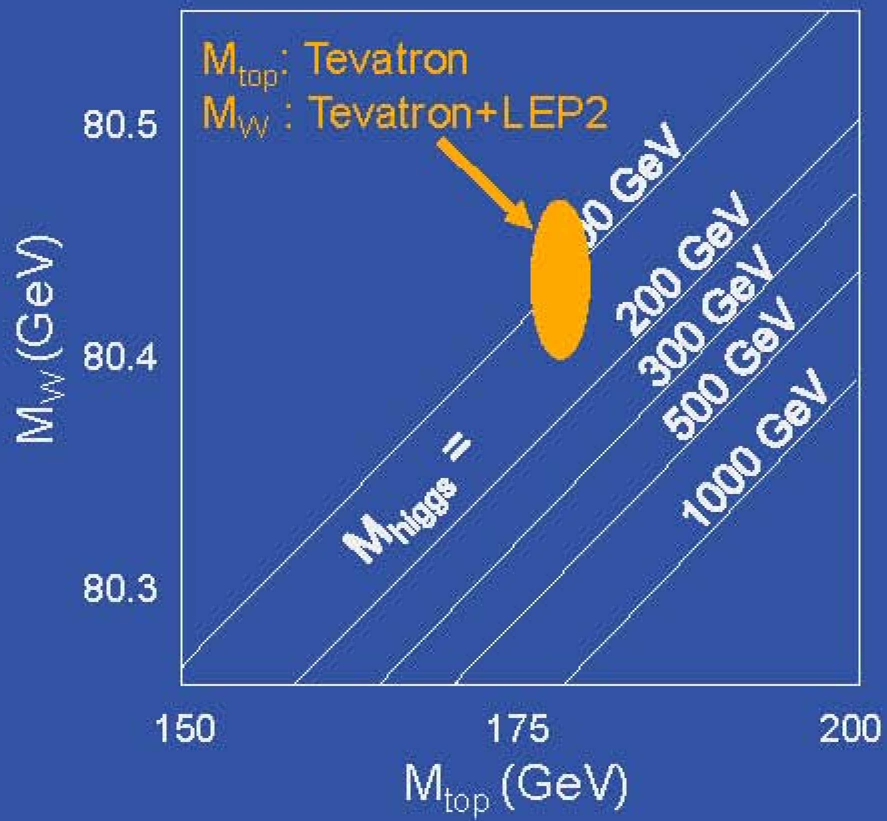
Physics at the Tevatron



The Tevatron Predicts Higgs Mass via Quantum Corrections

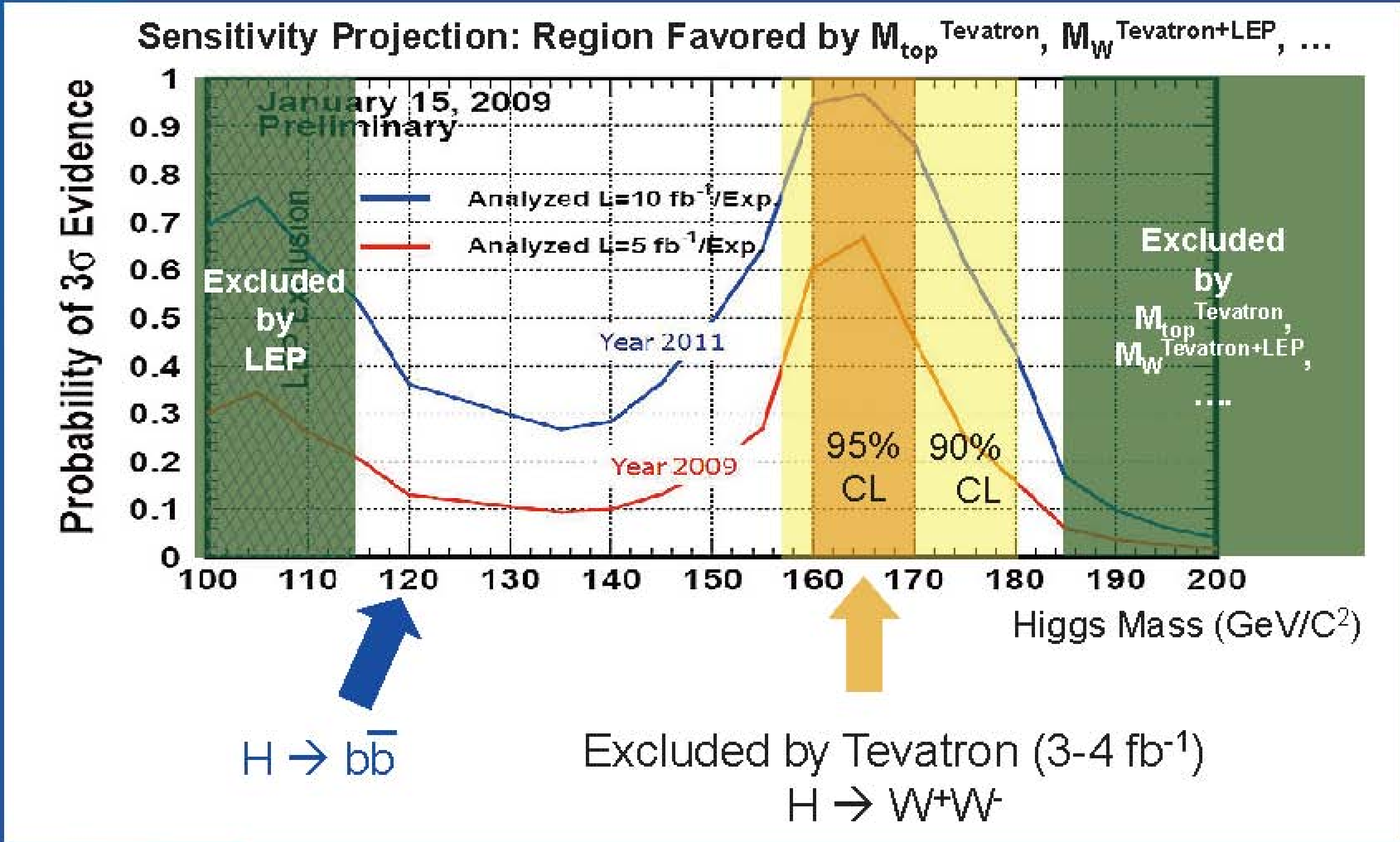




Favors Higgs mass range (114 – 180 GeV) at 95% CL.
In this range, Tevatron has good potential.

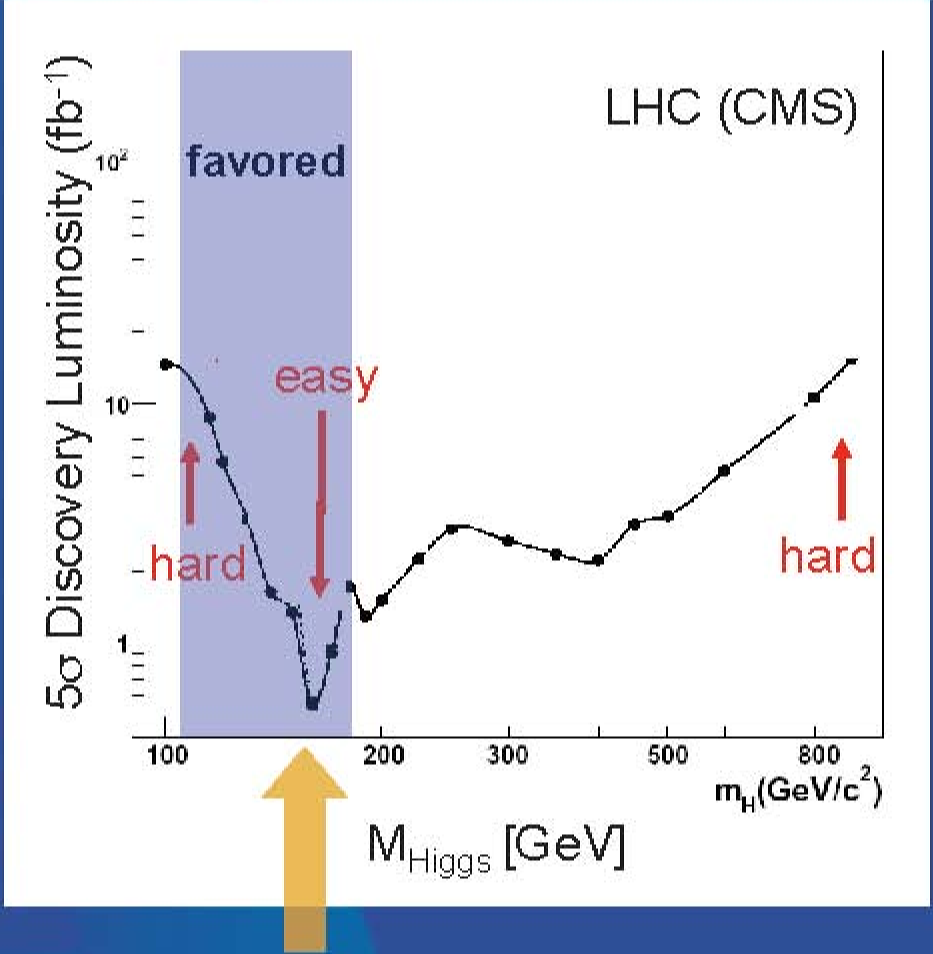
 Fermilab

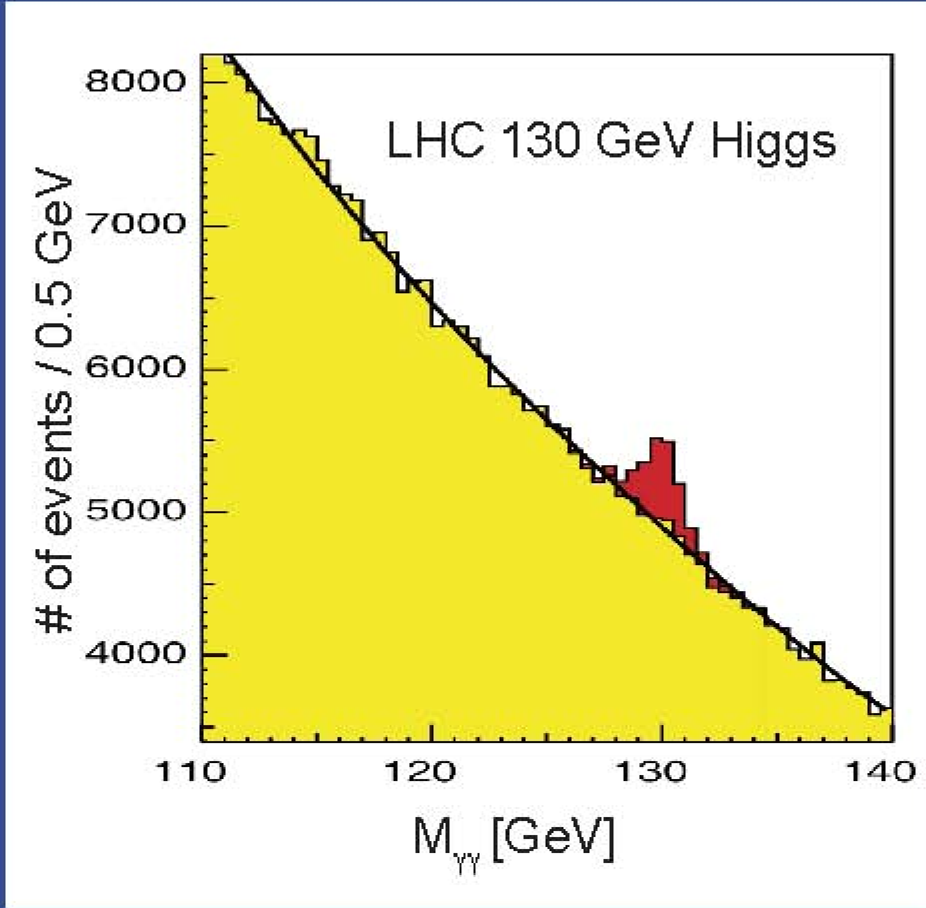
Tevatron Sensitivity on Standard Model Higgs



Update the results with 5 fb^{-1} data soon

Higgs at LHC and Tevatron





160 – 170 GeV
Excluded by Tevatron (3-4 fb^{-1})

Low Mass Higgs
(LHC: H → γγ, ττ) vs. (Tevatron: H → bb)

LHC's Window on the World

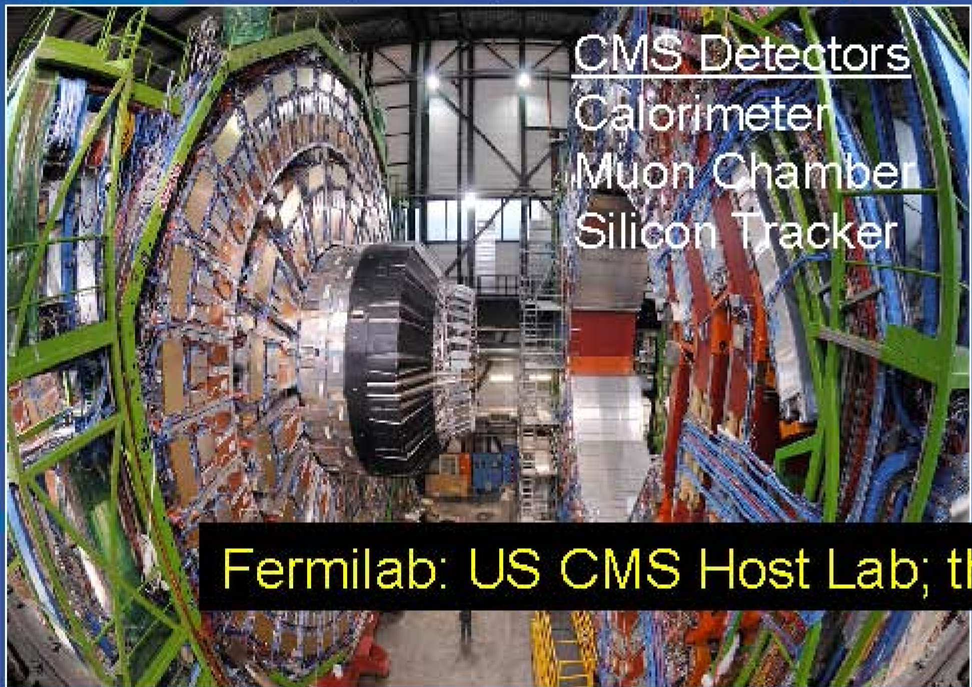
> 2,000 Physicists at ATLAS and CMS each

- Higgs
  - Standard Model
  - Beyond SM: Higgs sector may be very complex
- Supersymmetric Partners
- Dark Matter
- Another Force Carrier
- Large Extra Dimensions
- Unexpected
- ....

These are topics for the Tevatron as well
but at lower energies.

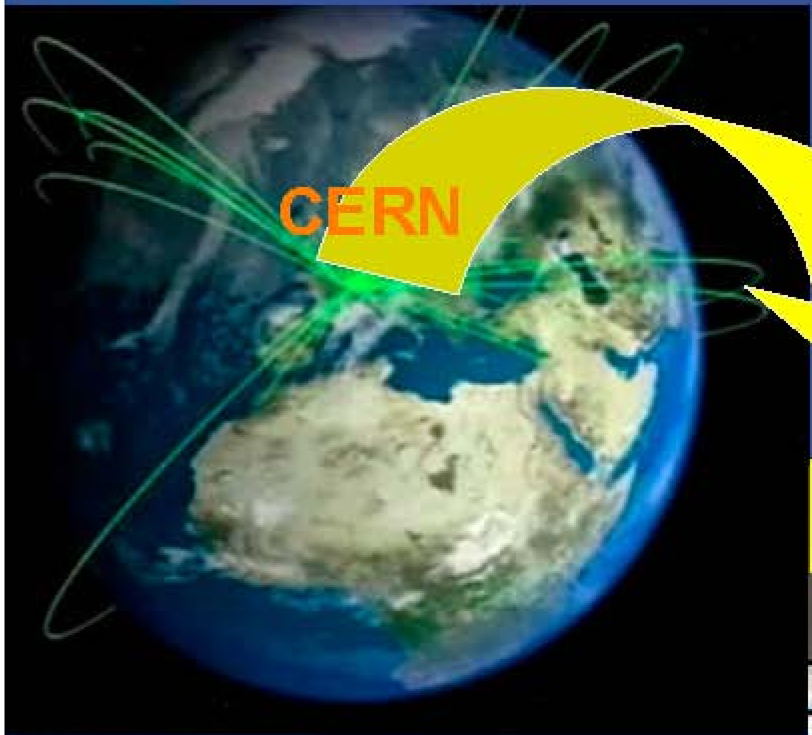
Fermilab and LHC:

Accelerator and Detector Design/Engineering/Construction and Upgrades



Fermilab: US CMS Host Lab; the only US CMS Lab

Fermilab and LHC



US CMS Host Lab; the only US CMS Lab

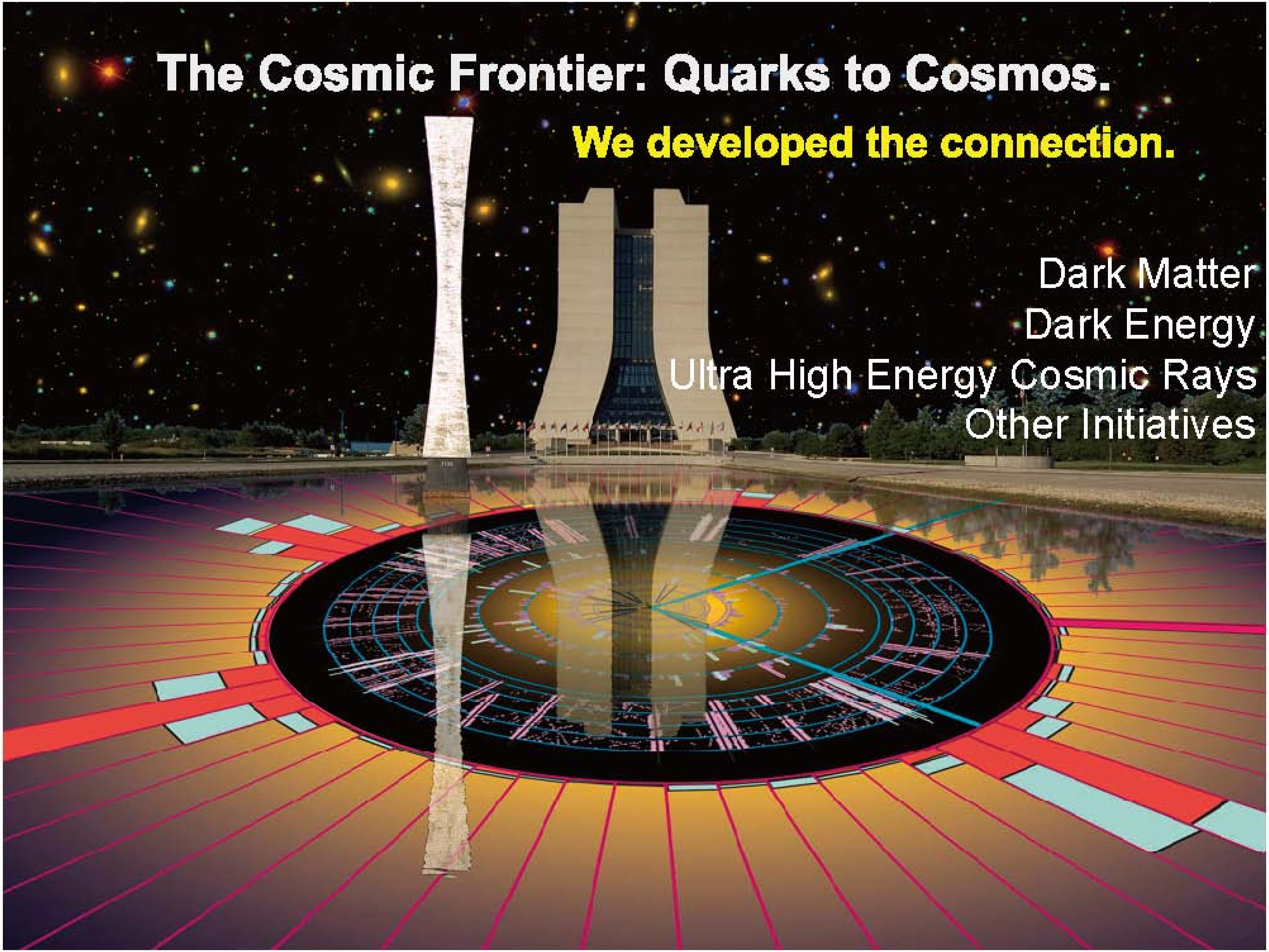
CMS Tier-1 Computing Center
LHC Physics Center
Support US CMS Community

To make being at Fermilab as good as being at CERN.
Requires critical mass (~100 Fermilab + University Scientists at Fermilab).

Supporting the LHC Community

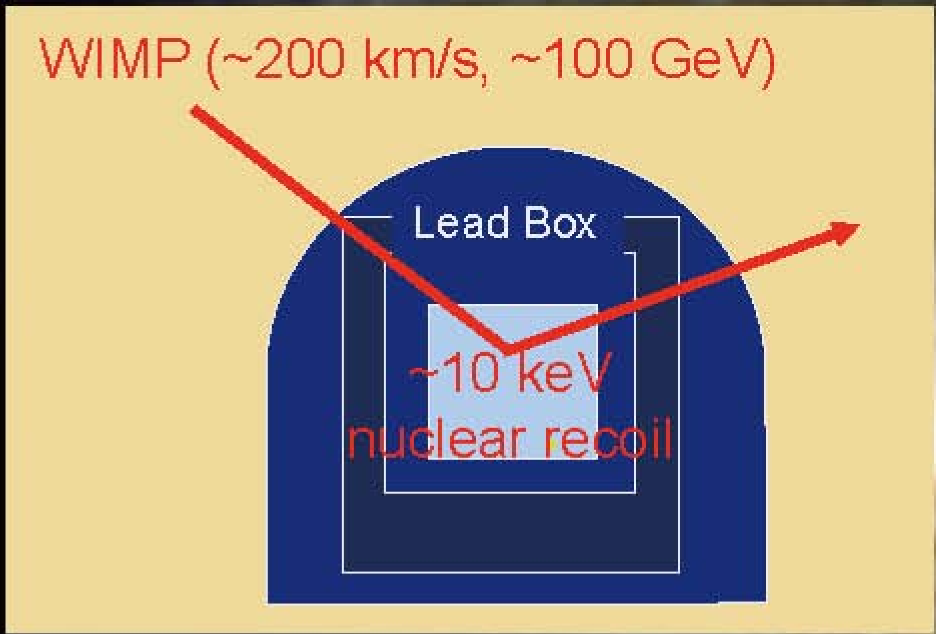
CERN-Fermilab Hadron Collider Physics Summer School

1st	Fermilab	August 9-18, 2006
2nd	CERN	June 6-15, 2007
3rd	Fermilab	August 12-22, 2008
4th	CERN	June 8-17, 2009


The Cosmic Frontier: Quarks to Cosmos.
We developed the connection.
Dark Matter
Dark Energy
Ultra High Energy Cosmic Rays
Other Initiatives

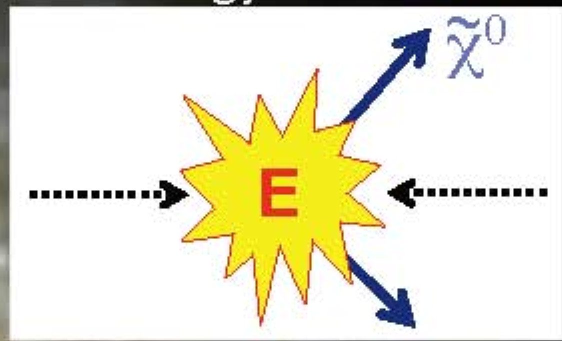
Dark Matter

Underground experiments may detect Dark Matter candidates.

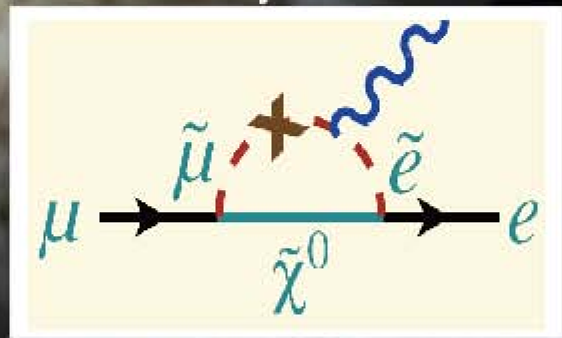


Cosmic Frontier

Energy Frontier



Intensity Frontier

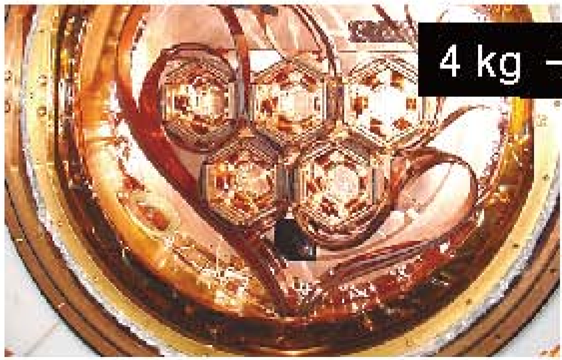


Accelerators can produce dark matter in the laboratory and understand exactly what it is.

The Cosmic Frontier: Dark Matter Searches

CDMS

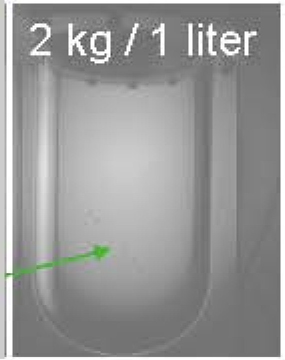
Low temp. Ge / Si crystals



World's Best Limits

UPP

Bubble Chamber

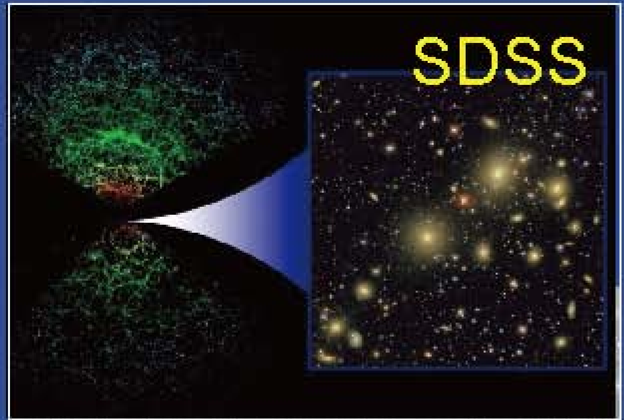


The Cosmic Frontier: Probing Dark Energy

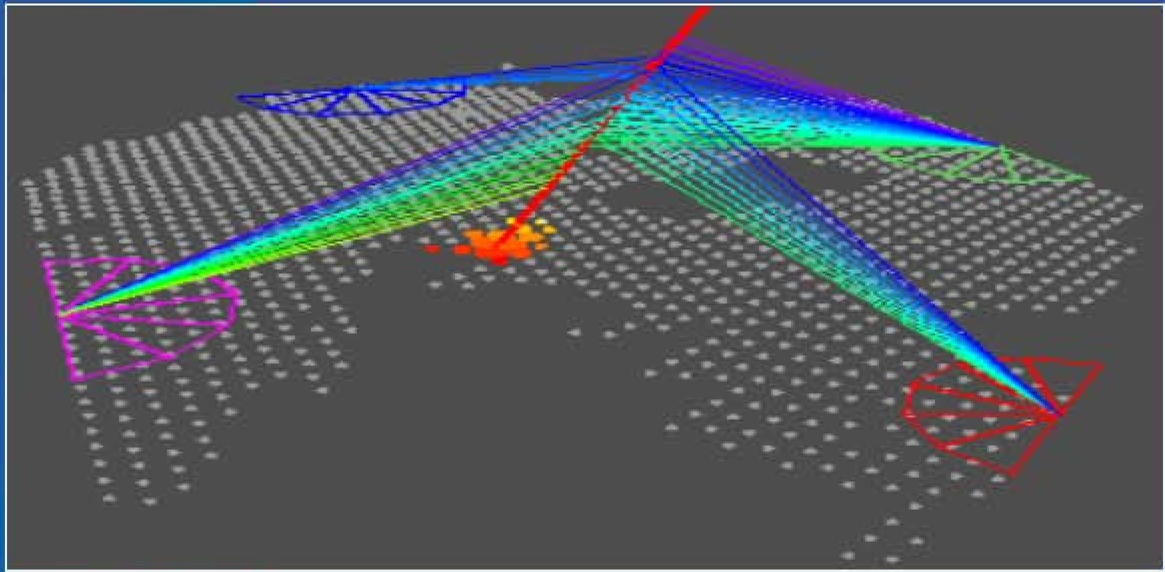
1. SDSS (Sloan Digital Sky Survey)
   - 2.5 meter telescope in New Mexico
   - Ranks as the facility with the highest impact in astronomy for the 3rd year in a row.
   - Power spectrum of galaxies constrain dark energy density parameter.

2. DES (Dark Energy Survey)
   - 4 meter telescope in Chile
   - DES Camera under construction
   - Operation: 2011 – 2016

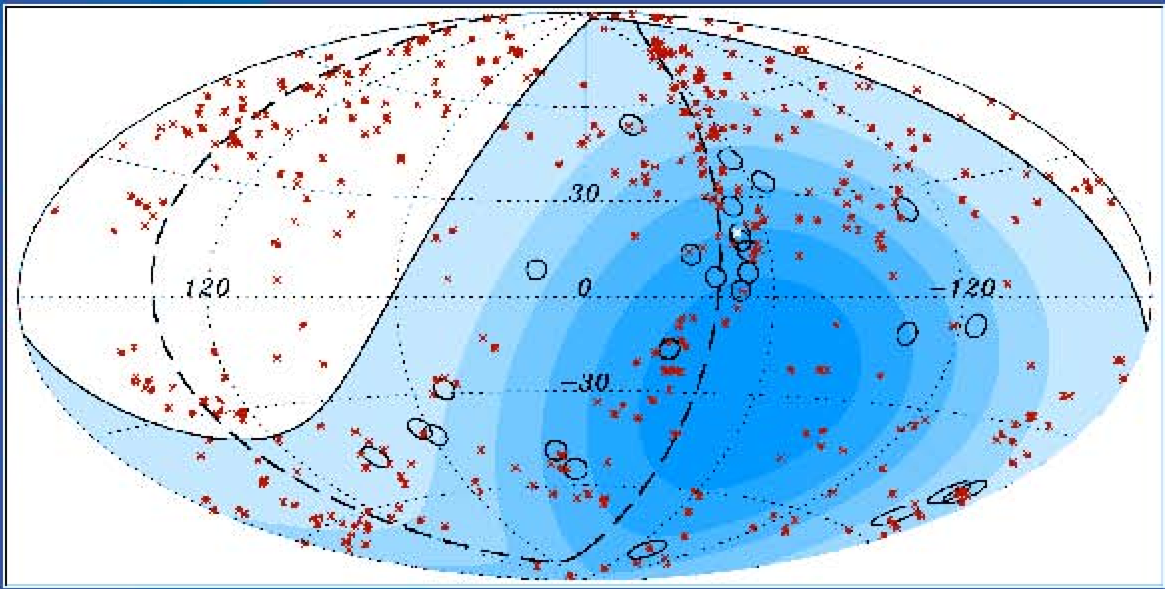
3. JDEM (Joint Dark Energy Mission)
   - Space telescope
   - Fermilab Goal: Science Operation Center



The Cosmic Frontier: High Energy Particles from Space



Auger Observatory studies ultra-high energy cosmic rays.



o – Cosmic rays with E > 57,000,000 TeV

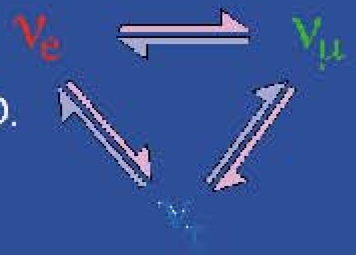
Correlation

x – Active Galactic Nuclei

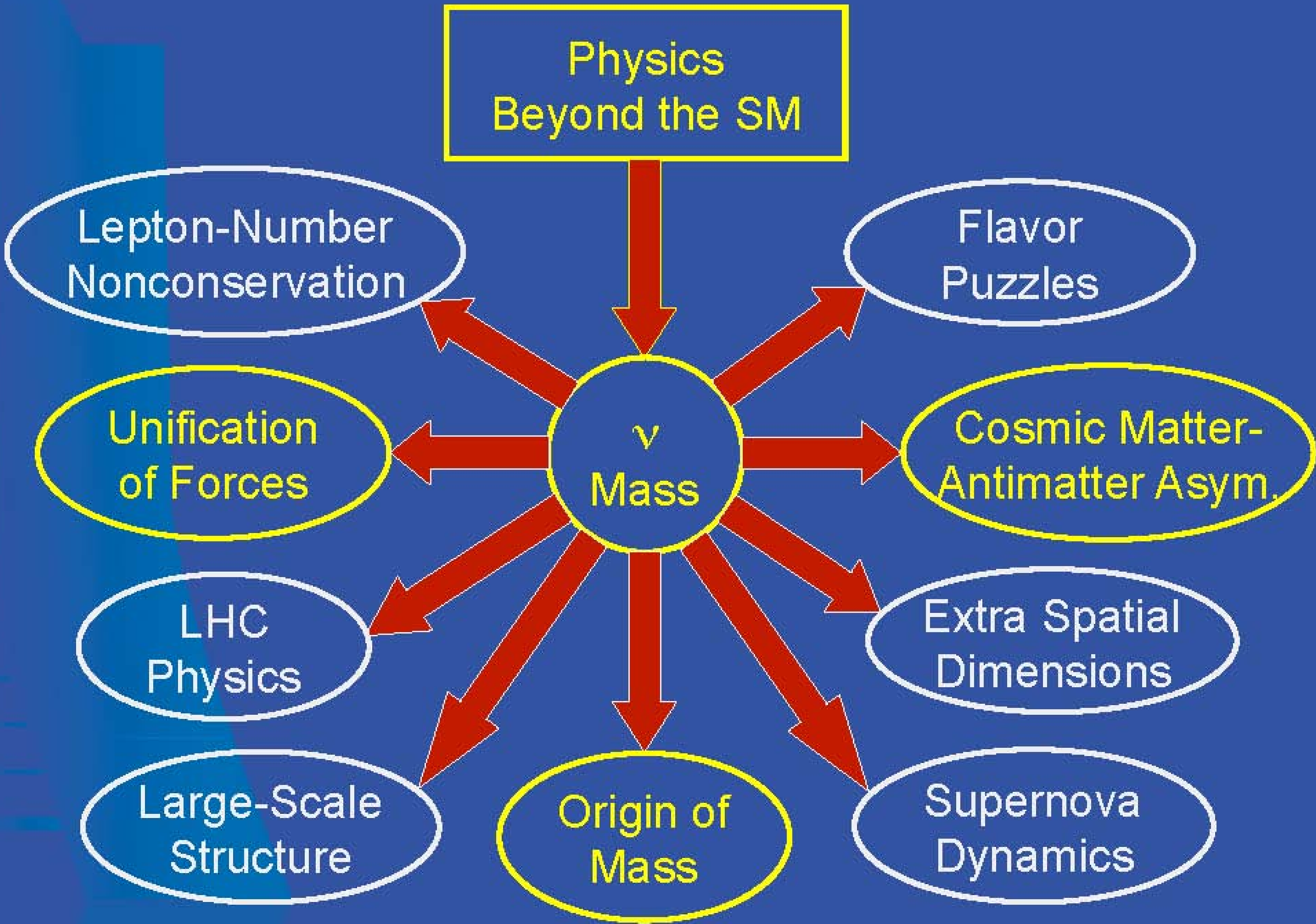
Fermilab

The Intensity Frontier: Neutrinos

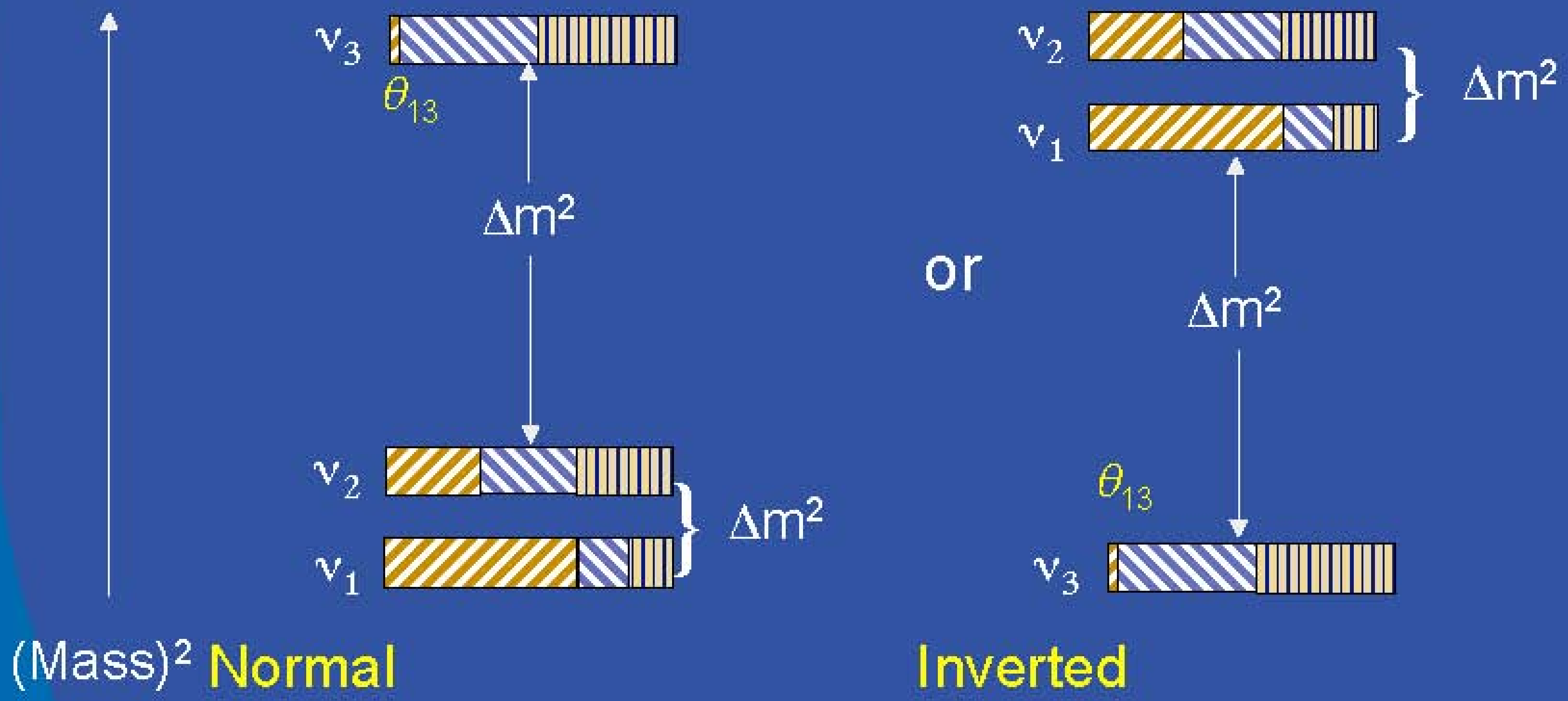
- Recent Discoveries
  - produced much excitement.
  - the only new physics seen so far in the lab.



- Behave so different from other particles
  - Mass, Oscillation pattern, $\nu = \bar{\nu}$ possibility
- A Matter-Dominate Universe
  - Require Matter-Antimatter Asymmetry (CP Violation)
  - Quarks can not explain. Maybe the leptons can.
- Unification
  - ν mass, mixing point toward new symmetries (unification)
- Cosmic Connection
  - $\sim 10^9$ neutrinos / nucleon or electron in the Universe.
  - Neutrino mass affects large scale structure.


Physics
Beyond the SM
ν
Mass
Lepton-Number
Nonconservation
Flavor
Puzzles
Unification
of Forces
Cosmic Matter-
Antimatter Asym.
LHC
Physics
Extra Spatial
Dimensions
Large-Scale
Structure
Origin of
Mass
Supernova
Dynamics

The neutrino spectrum: unknowns

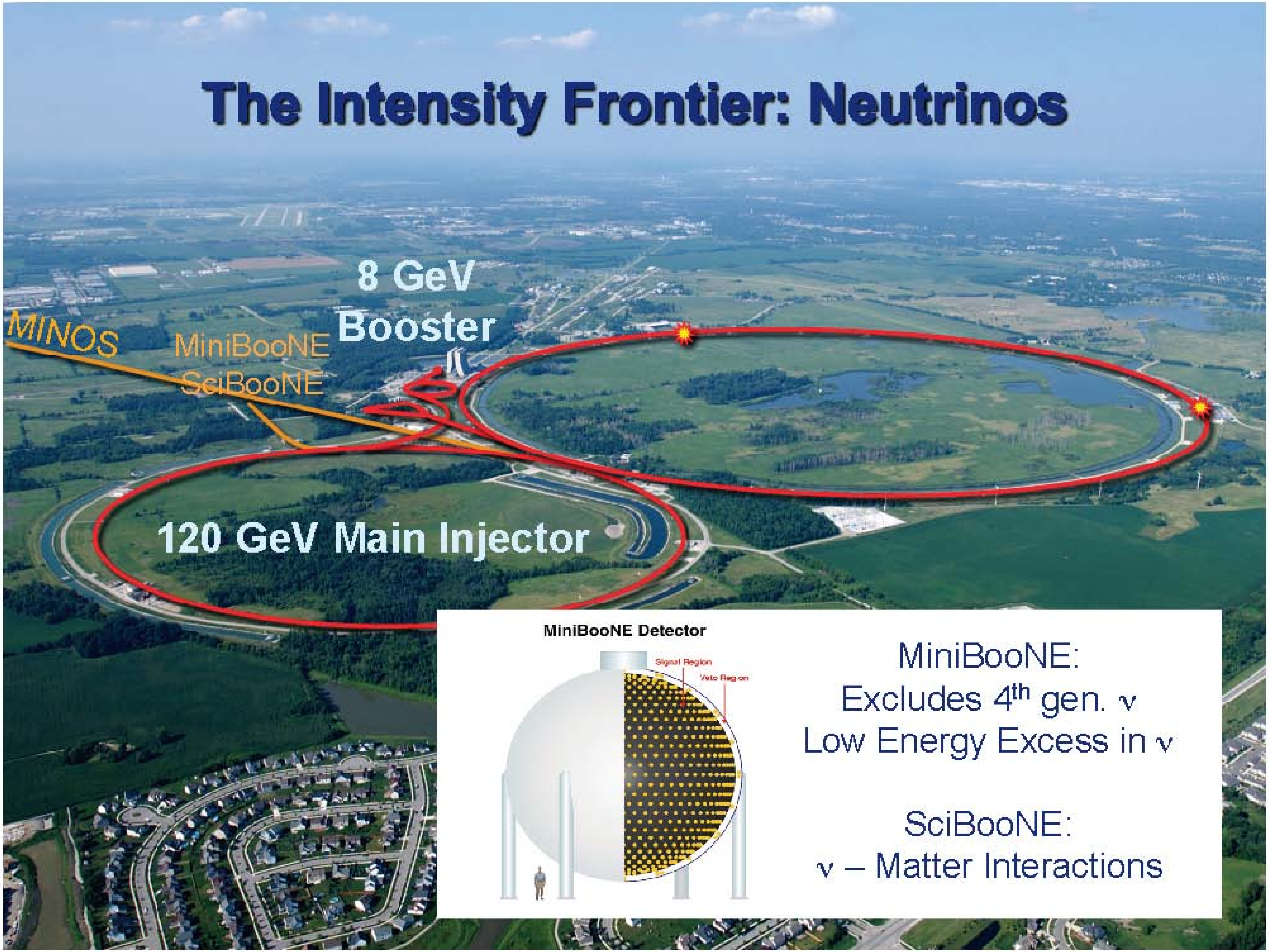


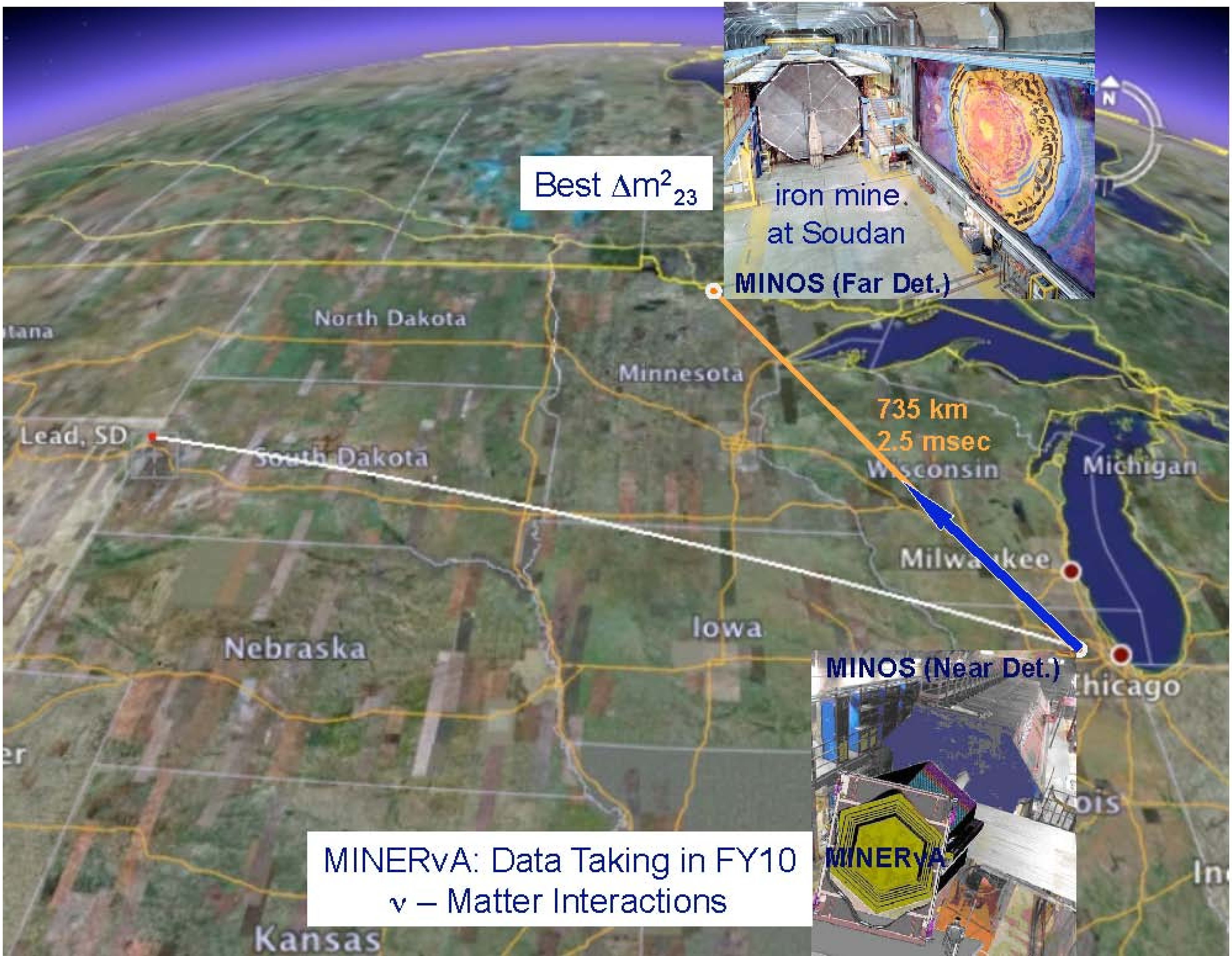
θ_{13}

Mass Hierarchy

Matter – Antimatter Asymmetry Phase δ

$\nu = \bar{\nu}$?


The Intensity Frontier: Neutrinos
8 GeV
Booster
MINOS
MiniBooNE
SciBooNE
120 GeV Main Injector
MiniBooNE Detector
Signal Region
Veto Region
MiniBooNE:
Excludes 4th gen. ν
Low Energy Excess in ν
SciBooNE:
ν – Matter Interactions



Best Δm^2_{23}
iron mine at Soudan
MINOS (Far Det.)
North Dakota
Minnesota
735 km
2.5 msec
Lead, SD
South Dakota
Wisconsin
Michigan
Milwaukee
Iowa
Nebraska
MINOS (Near Det.)
Chicago
MINERvA
MINERvA: Data Taking in FY10
ν – Matter Interactions
Kansas

What do we know now about θ_{13}?

Recent global fit to world data by Fogli et al. (arXiv:0905.3549)

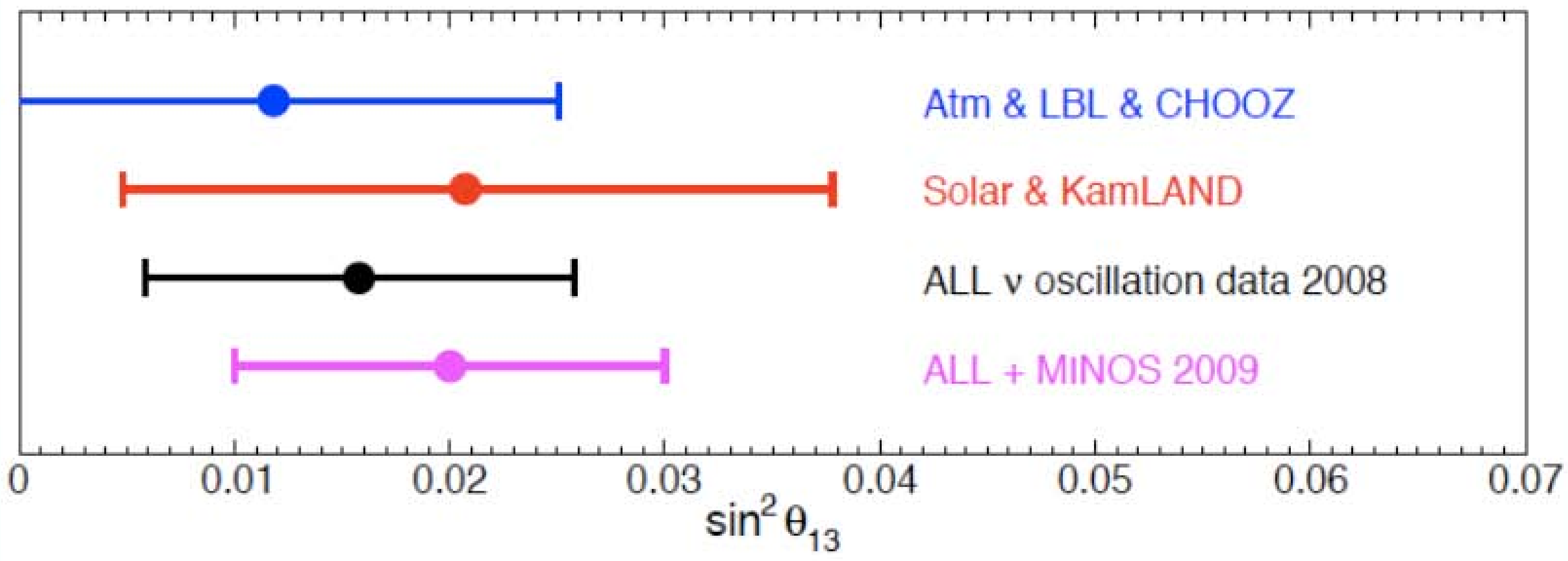
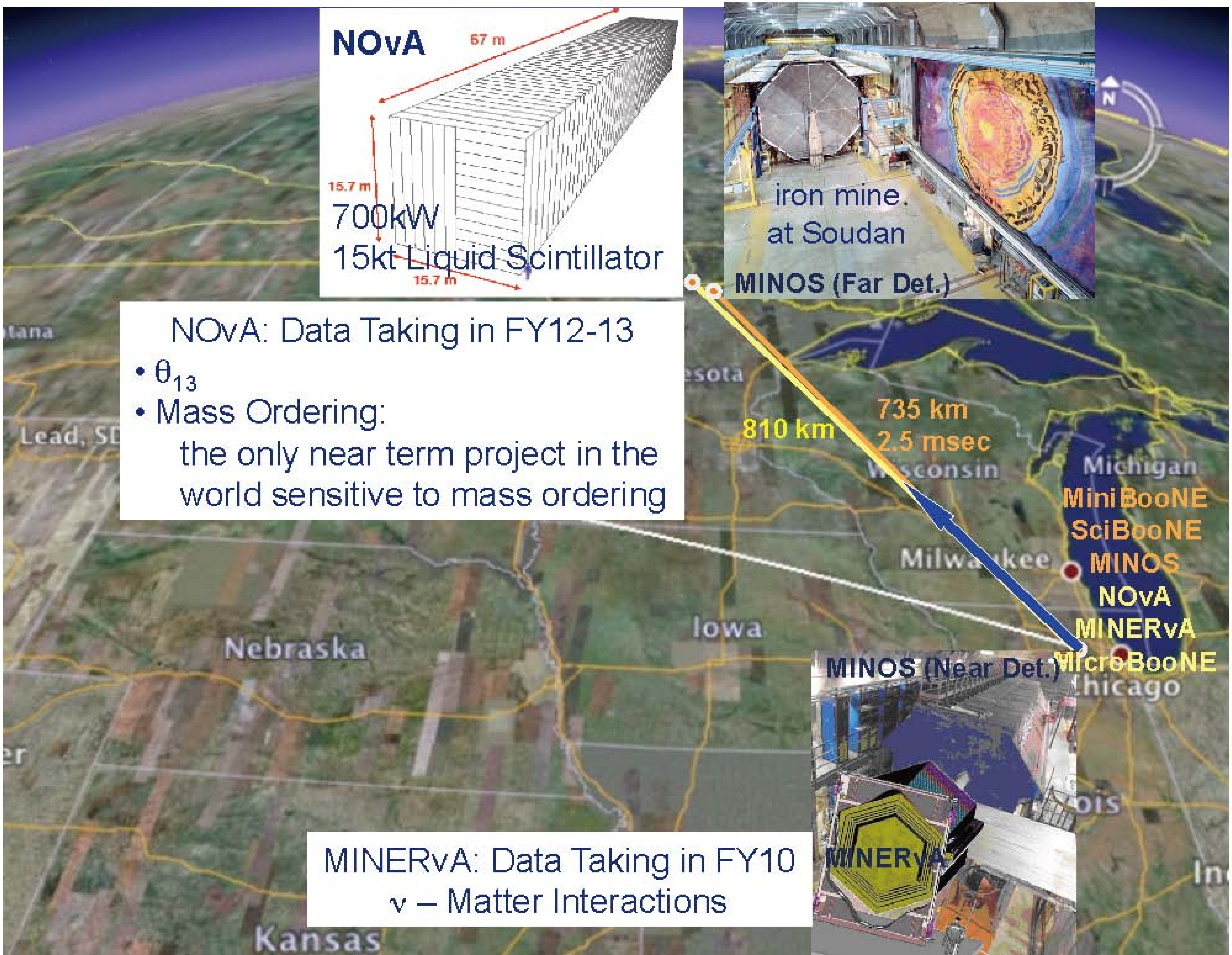


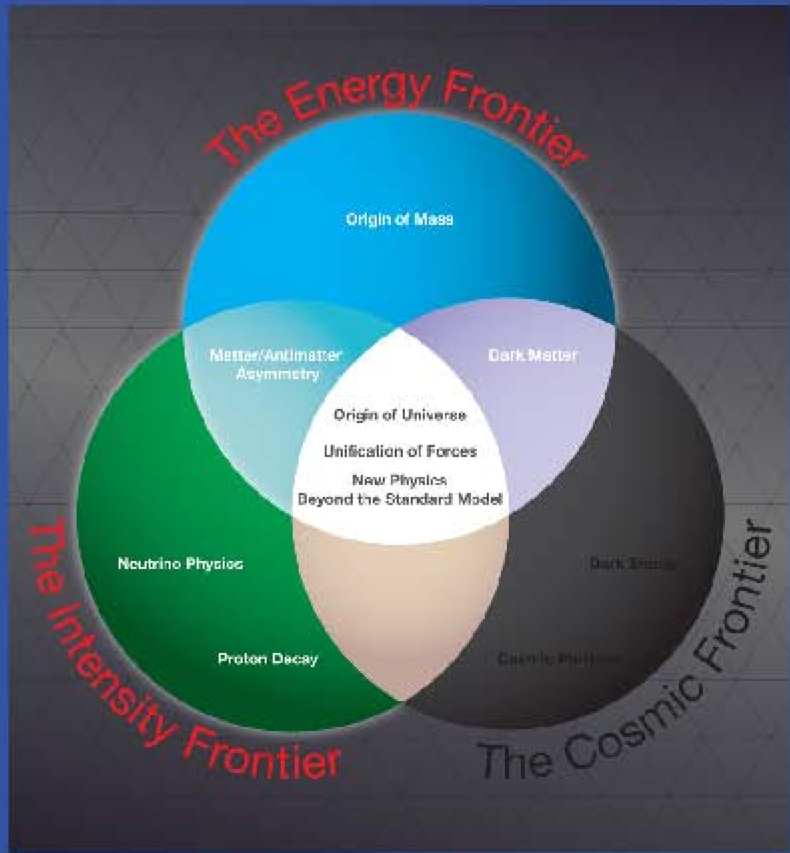
Figure 4: Hints of $\theta_{13} > 0$ from different data sets and combinations: 1σ ranges.

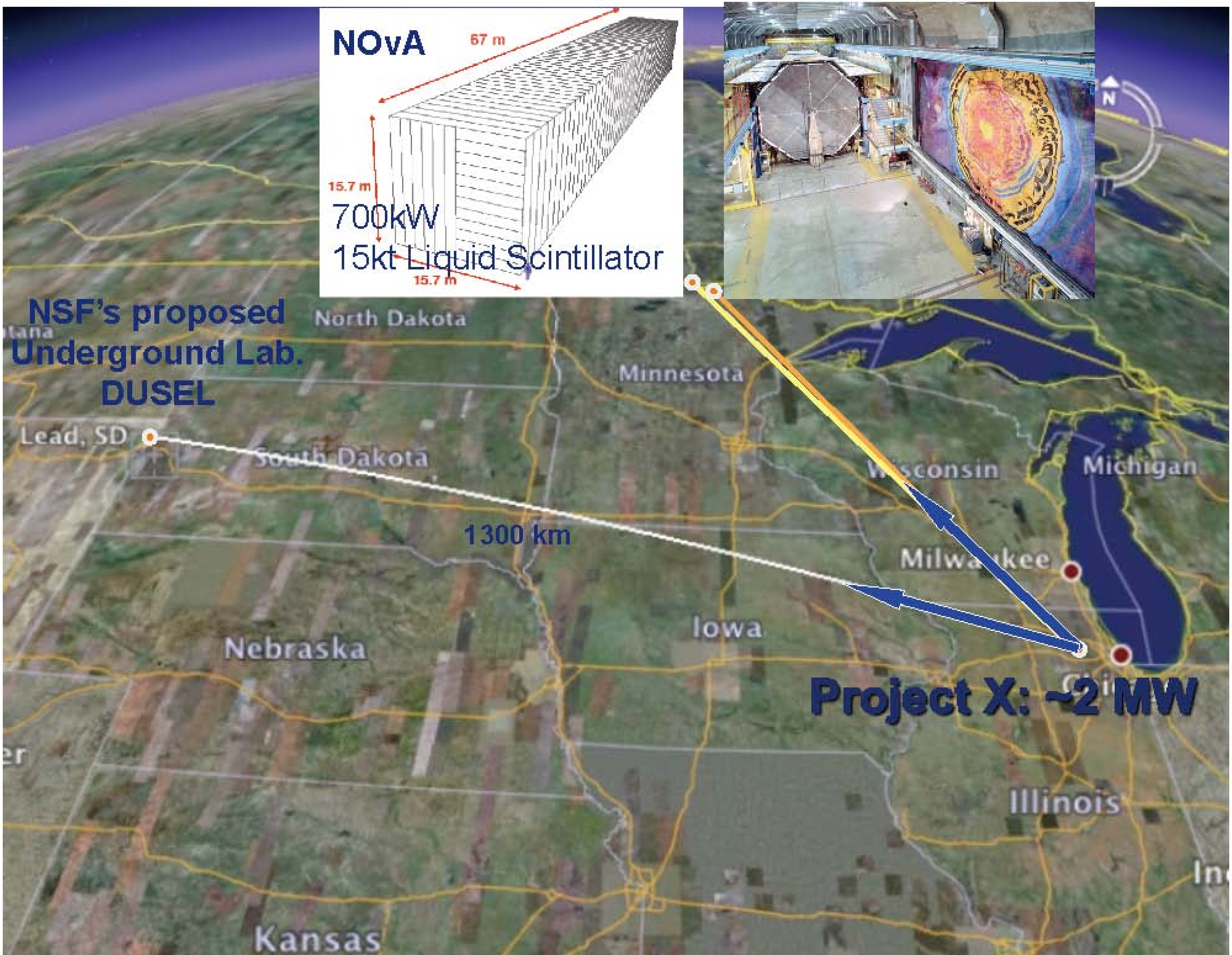
- $\theta_{13} = 0$ disfavored by ~2σ
- Central value $\sin^2\theta_{13} = 0.02$ or $\sin^2 2\theta_{13}=0.08$


NOvA
67 m
15.7 m
700kW
15kt Liquid Scintillator
15.7 m
iron mine
at Soudan
MINOS (Far Det.)
NOvA: Data Taking in FY12-13
• θ_{13}
• Mass Ordering:
the only near term project in the world sensitive to mass ordering
810 km
735 km
2.5 msec
Wisconsin
Michigan
Milwaukee
Iowa
Nebraska
Kansas
MiniBooNE
SciBooNE
MINOS
NOvA
MINERvA
MicroBooNE
Chicago
MINOS (Near Det.)
MINERvA
MINERvA: Data Taking in FY10
ν – Matter Interactions

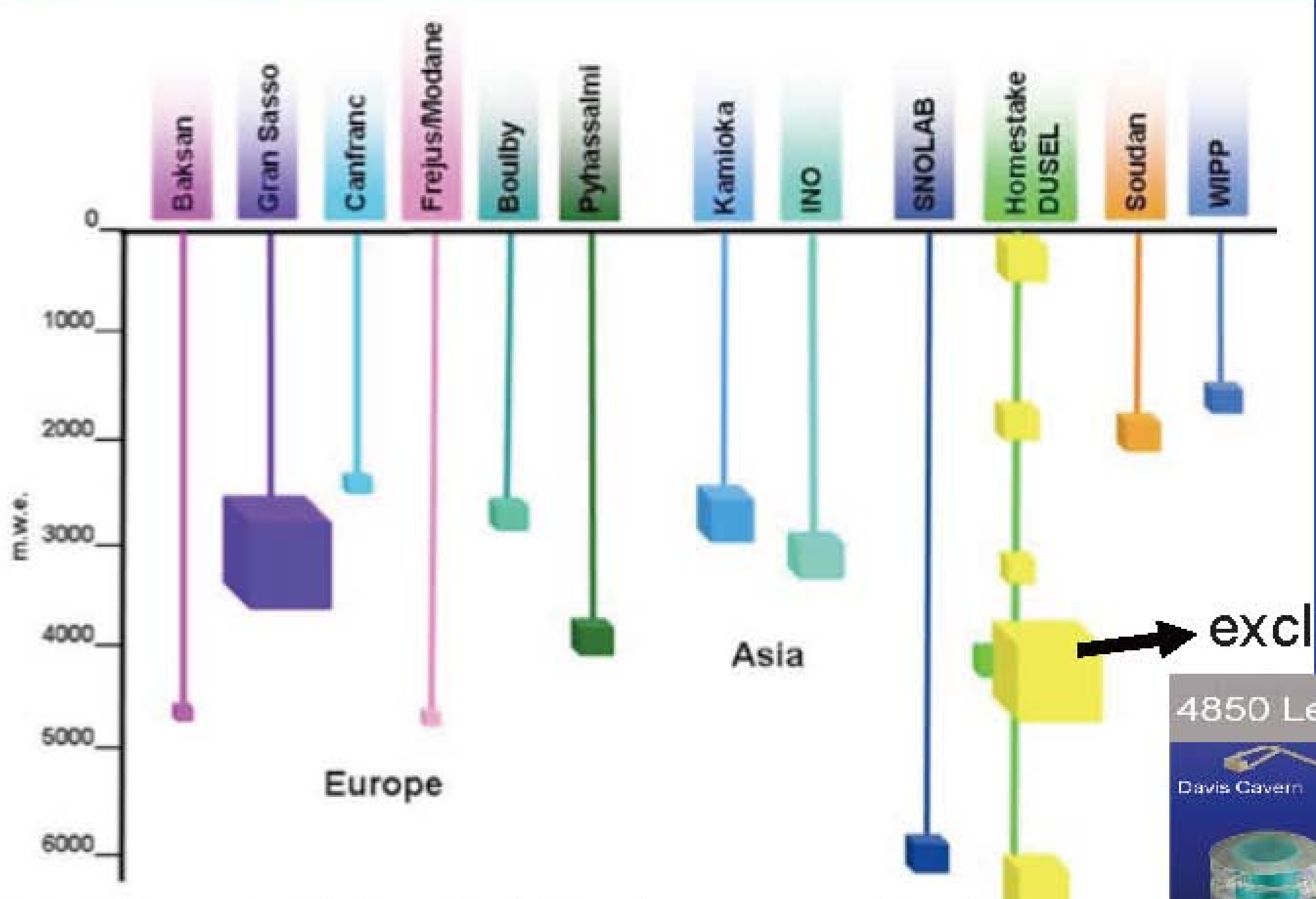
Project X: intense proton accelerator

- The intensity frontier answers fundamental questions
- Project X is the key
- Project X can lead us back to the energy frontier



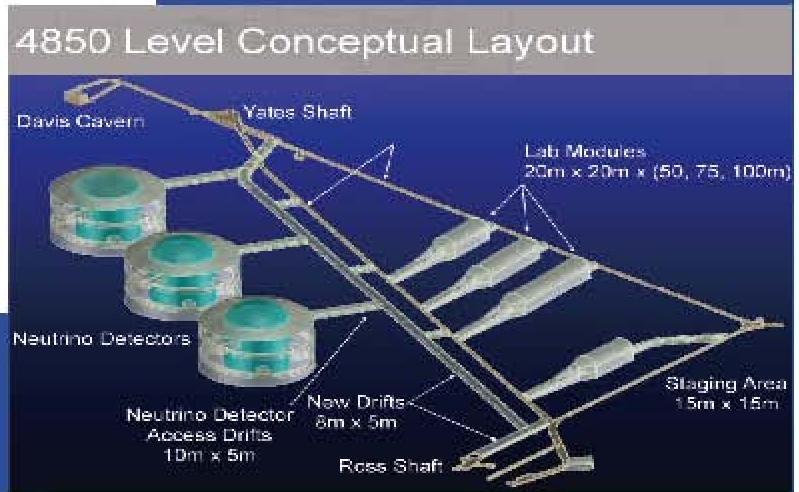

NOvA
67 m
15.7 m
700kW
15kt Liquid Scintillator
15.7 m
NSF's proposed
Underground Lab.
DUSEL
North Dakota
Minnesota
Lead, SD
South Dakota
Wisconsin
Michigan
1300 km
Milwaukee
Iowa
Nebraska
Project X: ~2 MW
Illinois
Kansas

The Intensity Frontier: Fermilab → DUSEL Option



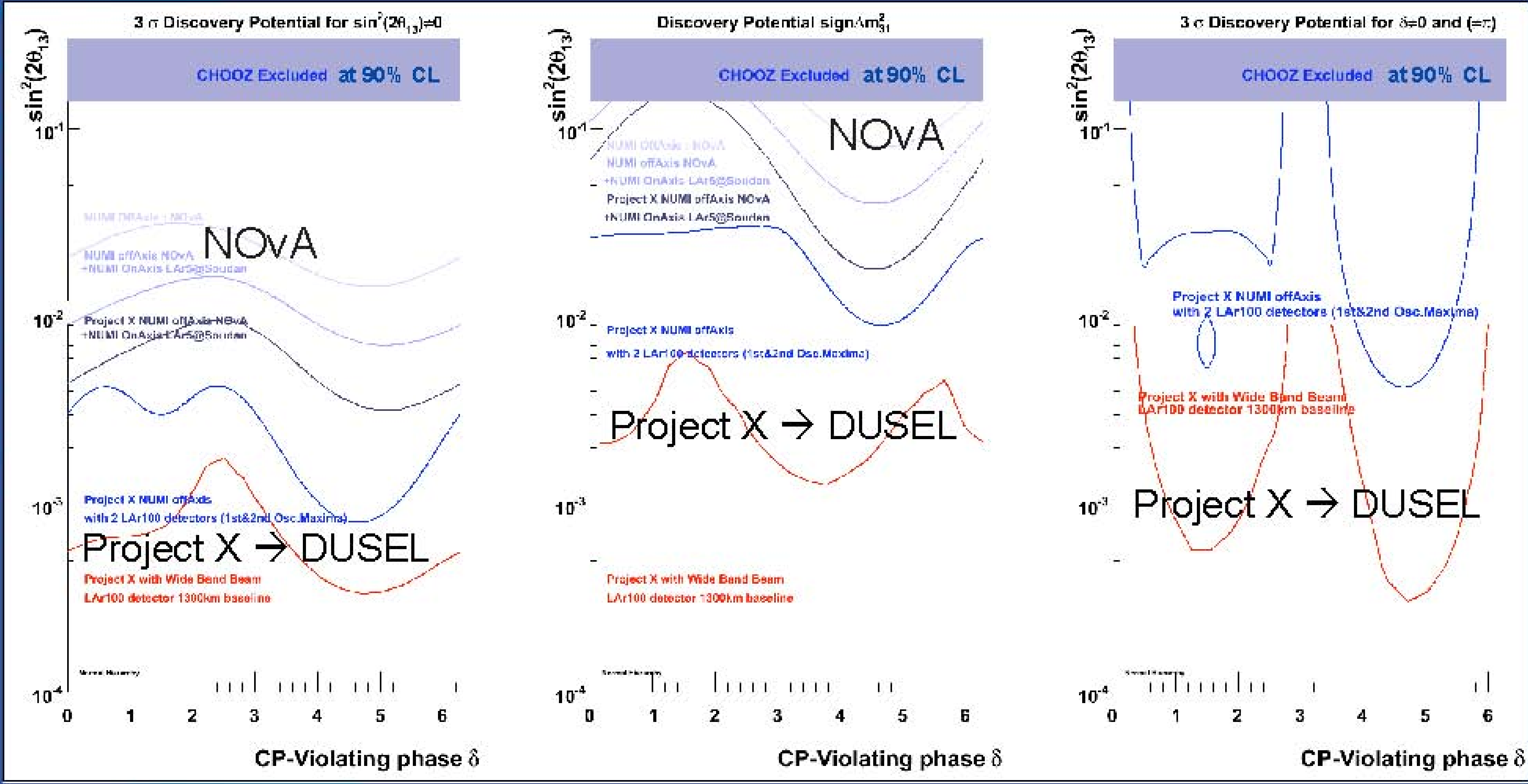
Existing + Potential Underground Lab.s

excluding the big cavern



The 3σ reach (2 MW, 100 kton LAr TPC)

$\sin^2 2\theta_{13}$ | Mass Hierarchy | CP Violation



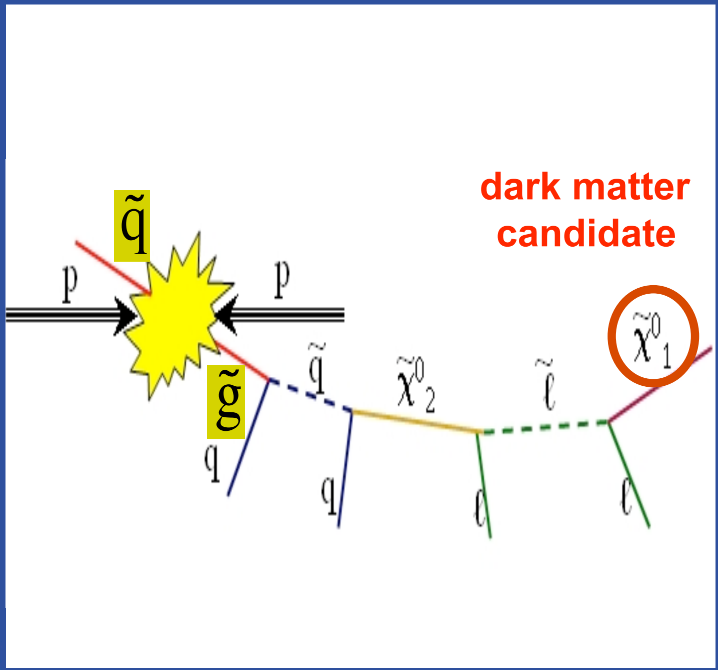
Fermilab

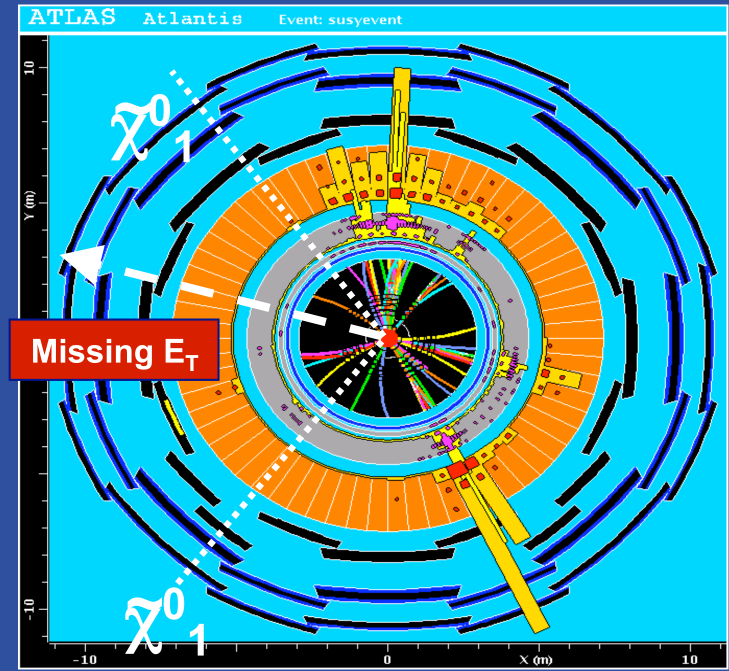
Interplay: LHC ⟷ Intensity Frontier

LHC		Intensity Frontier
nothing	→	Only handle on the next energy scale
LHC		Intensity Frontier
Lots	⟷	Determine/verify structure of new physics. Anything beyond?

Example: early discovery at LHC

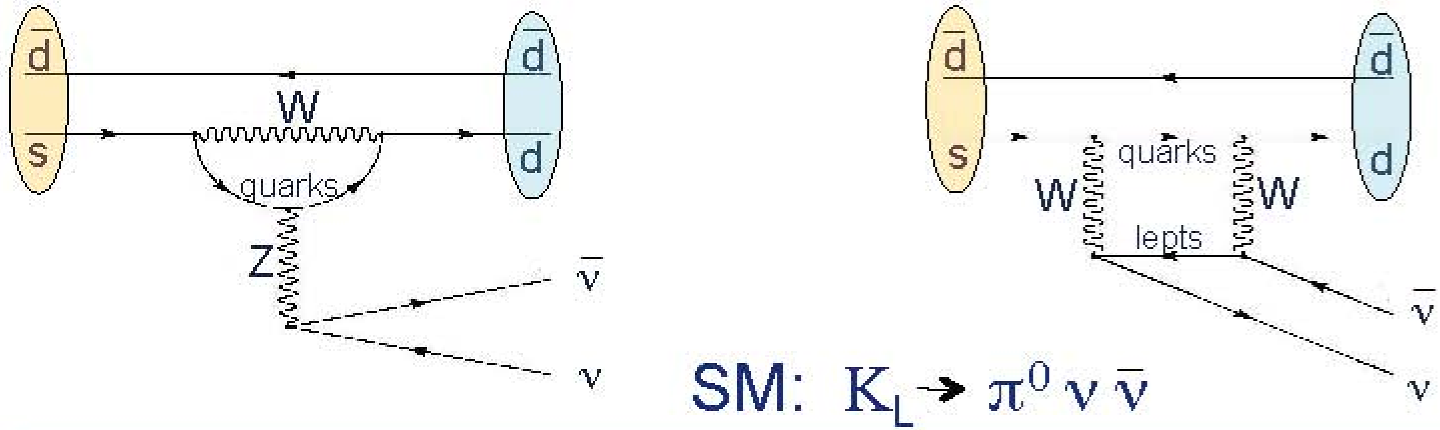
- LHC discovers strongly coupled SUSY



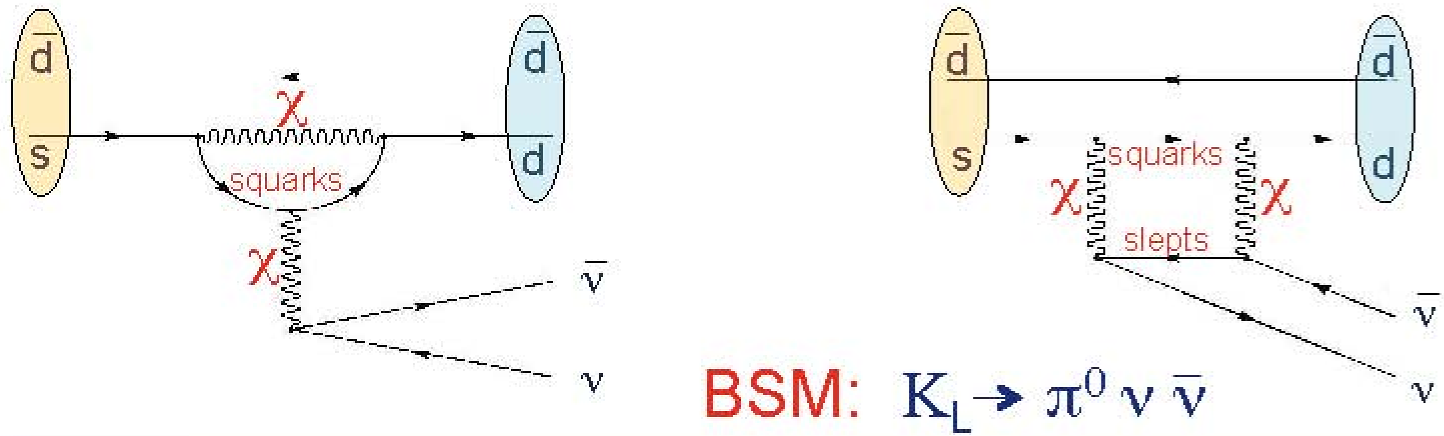


- A host of new particles: fit roughly some masses, make assumption on couplings

Large effects in kaon decay rates



SM: $K_L \rightarrow \pi^0 \nu \bar{\nu}$



BSM: $K_L \rightarrow \pi^0 \nu \bar{\nu}$

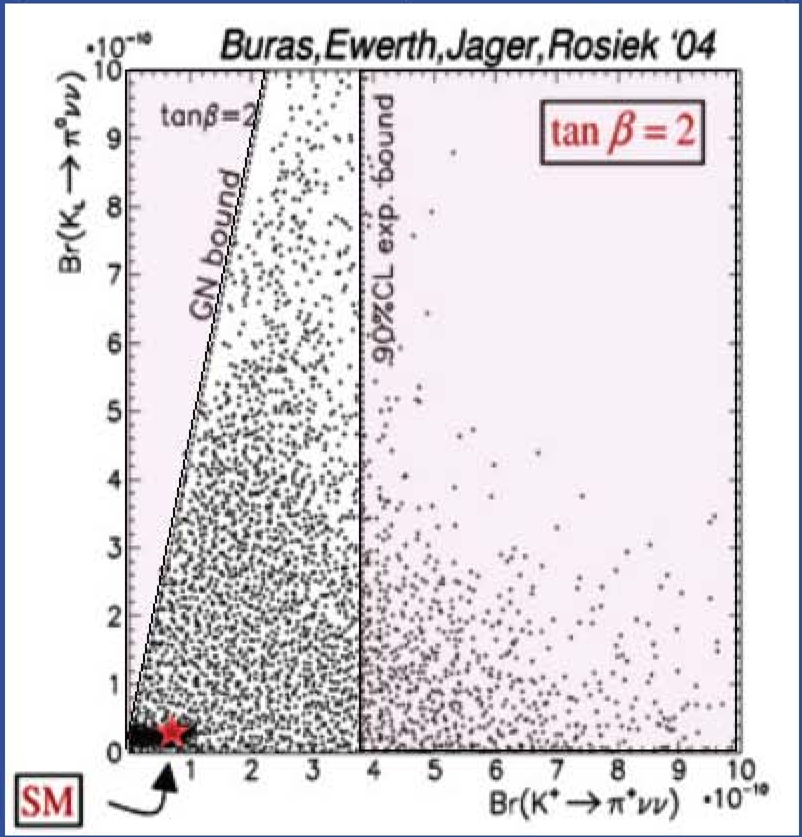
For particular classes of SUSY

Branching Ratio (10^{-10})

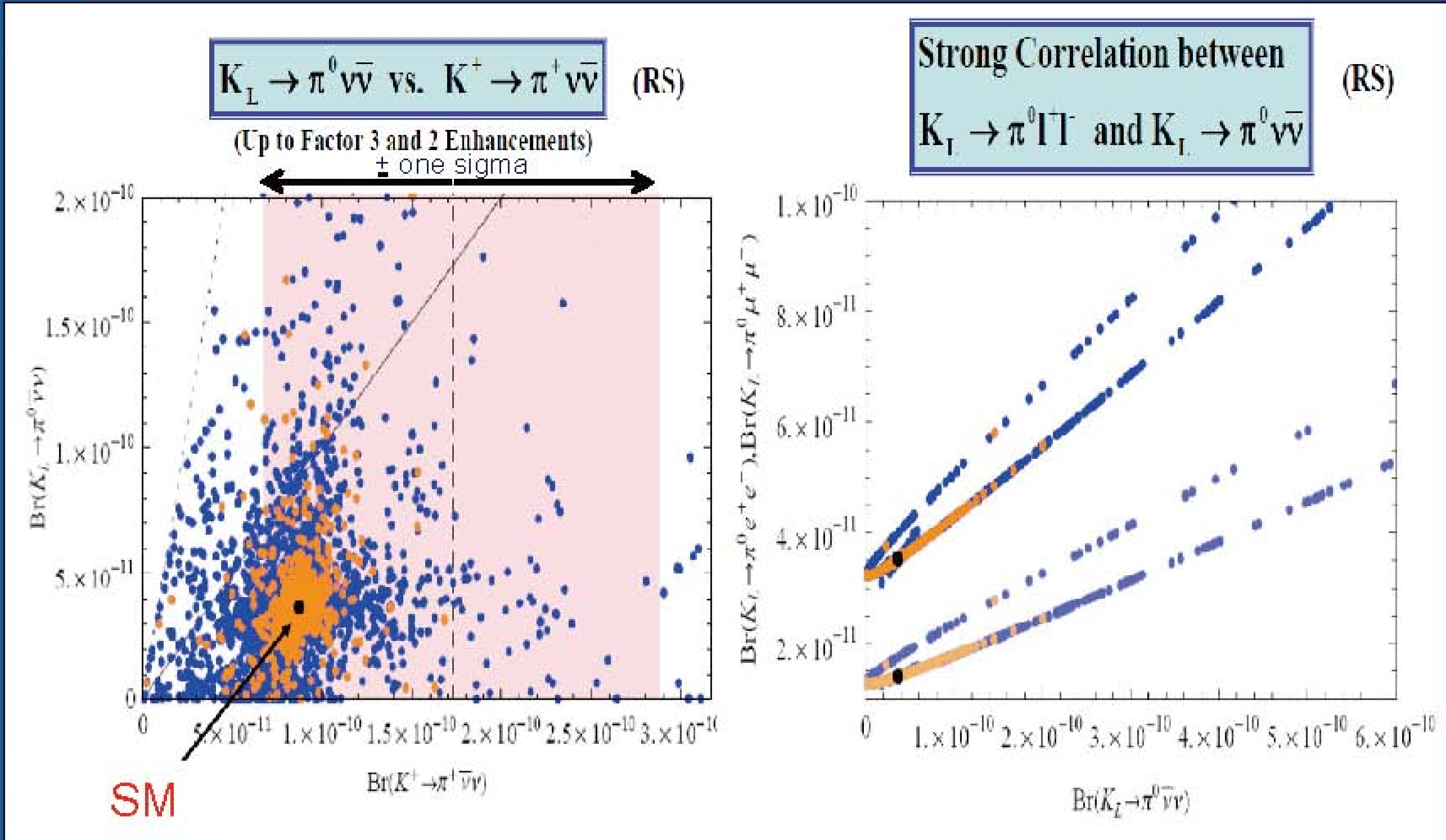
Decay	Theory (SM)	Experiment
$K^+ \rightarrow \pi^+ \nu\nu(\gamma)$	0.85 +/- 0.07	$1.73^{+1.15}_{-1.05}$
$K_L \rightarrow \pi^0 \nu\nu$	0.28 +/- 0.04	< 670 (90% CL)

- Large effect on rare K decay modes highly suppressed with SM particles

- Much higher SM backgrounds
- in B and C decays



Or models with extra dimensions



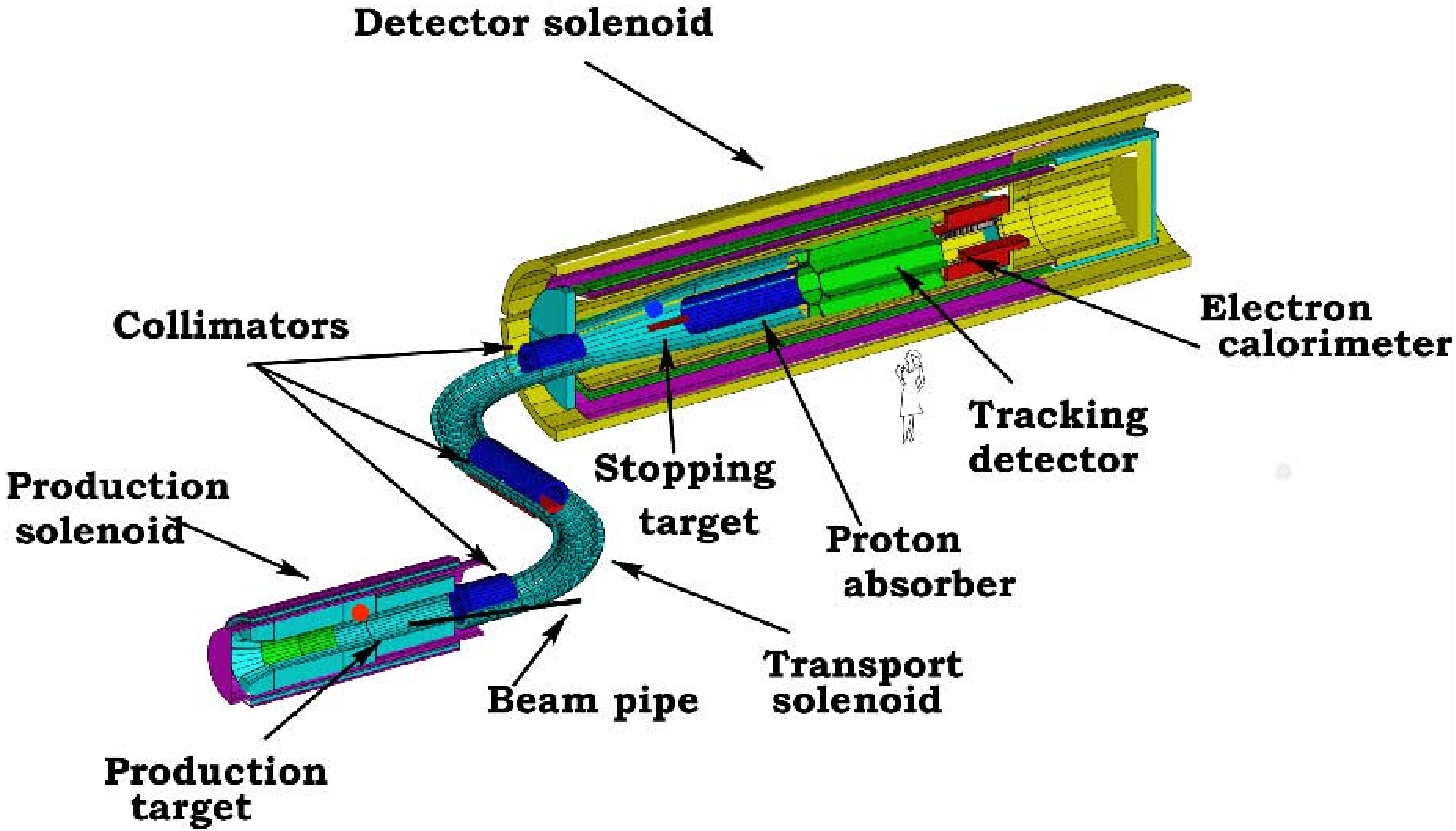
Current Sensitivities

- CERN NA62: 100×10^{-12} measurement sensitivity of $K^+ \rightarrow e^+ \nu$
- Fermilab KTeV: 20×10^{-12} measurement sensitivity of $K_L \rightarrow \mu\mu ee$
- Fermilab KTeV: 20×10^{-12} search sensitivity for $K_L \rightarrow \pi\mu e$, $\pi\pi\mu e$
- BNL E949: 20×10^{-12} measurement sensitivity of $K^+ \rightarrow \pi^+ \nu\nu$
- BNL E871: 2×10^{-12} measurement sensitivity of $K_L \rightarrow e^+ e^-$
- BNL E871: 1×10^{-12} search sensitivity for $K_L \rightarrow \mu e$

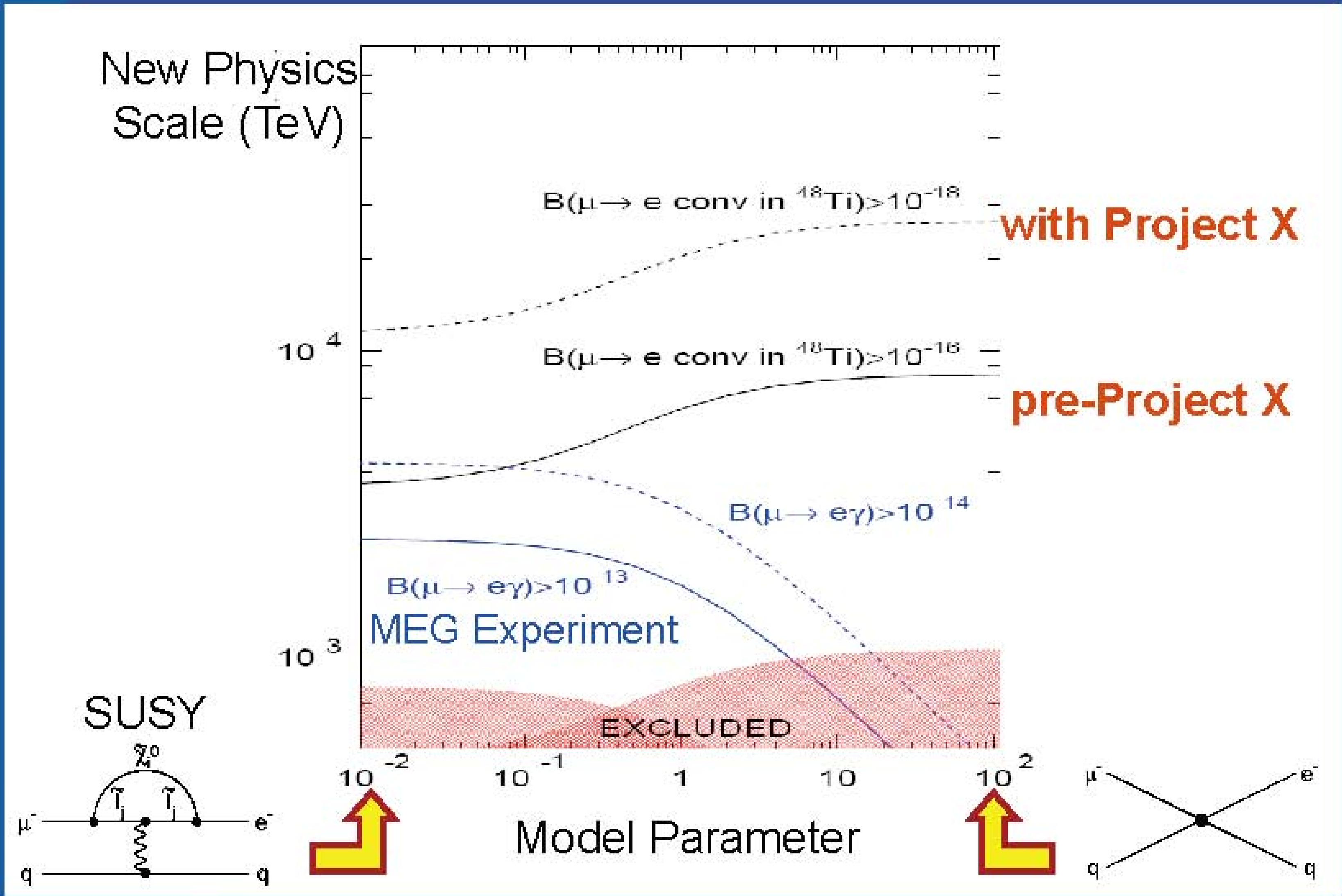
In the past probed new physics
above a 10 TeV scale with 20-50 kW

Next goal: 1000-event $\pi\nu\nu$ experiments...10^{-14} sensitivty.

The Intensity Frontier: μ to e Conversion (μN → eN)



Mu2e can probe $10^3 - 10^4$ TeV



Muon experiments

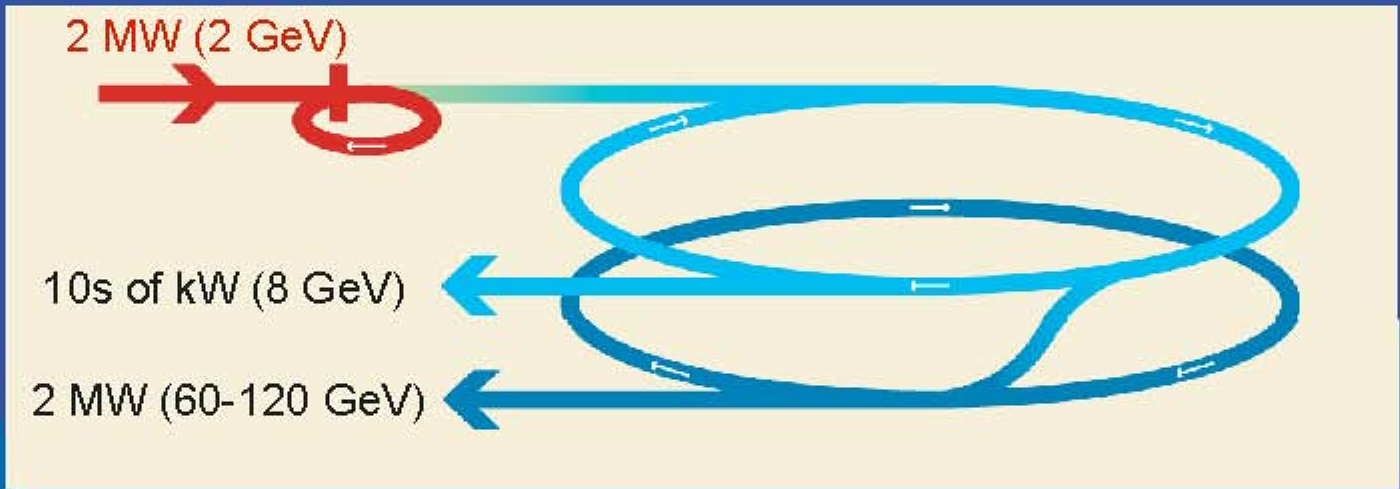
- Next generation $\mu \rightarrow e$ conversion experiment, new techniques for higher sensitivity and/or other nuclei.
- $\mu \rightarrow 3e$
- Next generation (g-2) if motivated by theory, next round, LHC
- Other:
  - μ edm.
  - $\mu^+ e^- \rightarrow \mu^- e^+$
  - $\mu^- A \rightarrow \mu^+ A'$
- Systematic study of radiative μ capture on nuclei.

To achieve this: we need Project X

- Provide a powerful beam of neutrinos to the Homestake site for the highest parameter reach in neutrino physics
- Provide intense proton beams for muon, kaon, low energy neutrino physics and other possible applications
  - without affecting the neutrino program
  - flexible time patterns and pulse intensities (different experiments)
- Develop Project X to serve as the front end of future facilities like a neutrino factory or muon collider

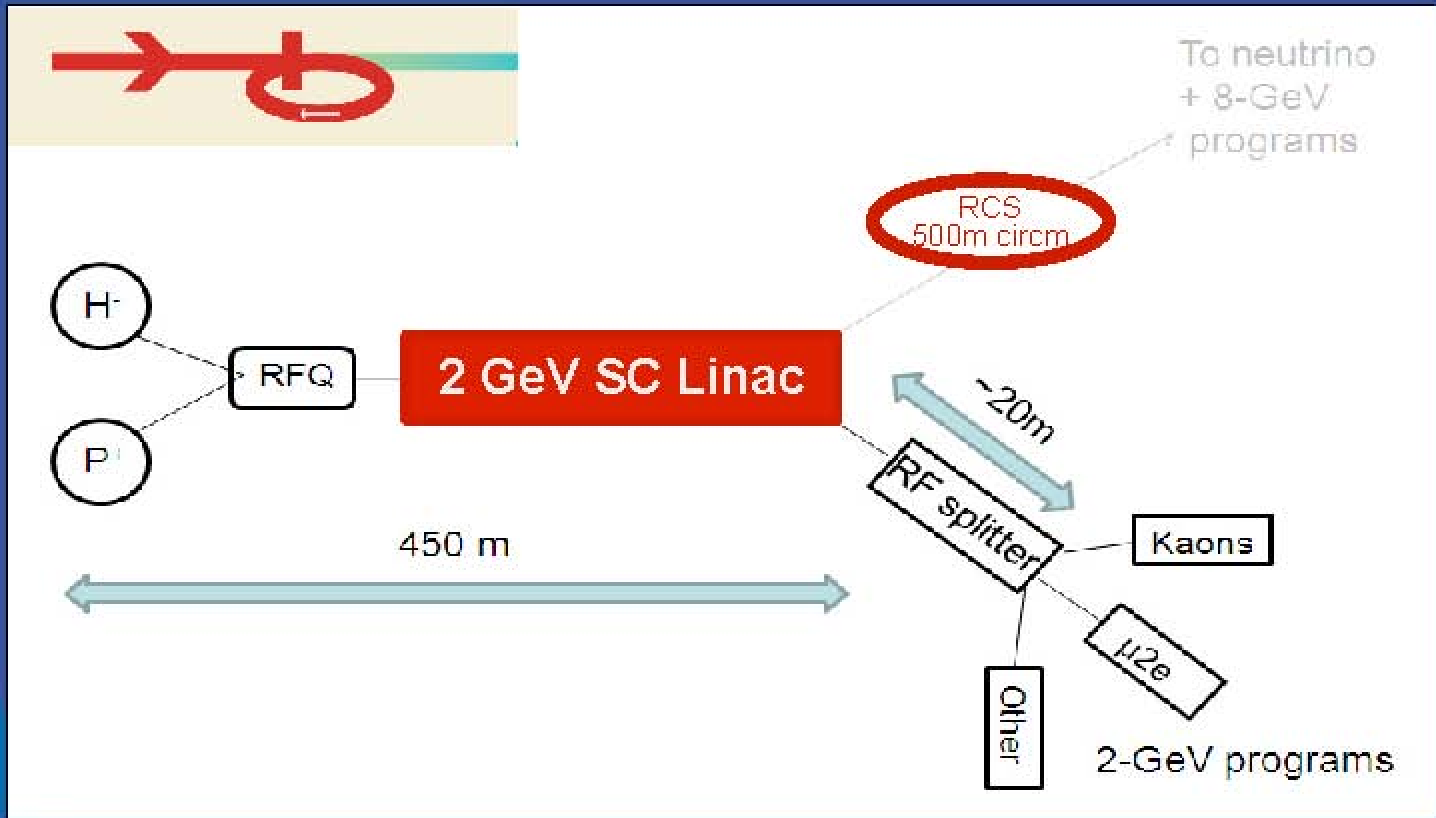
Project X with 3 Simultaneous Beams

- 2 MW (2 GeV) beams
  - rare processes and precision measurements
  - flexible time patterns and pulse intensities
- 10s of kW (8 GeV) beams
  - rare processes and precision measurements
- 2 MW (60-120 GeV) beams (to Homestake) for neutrinos



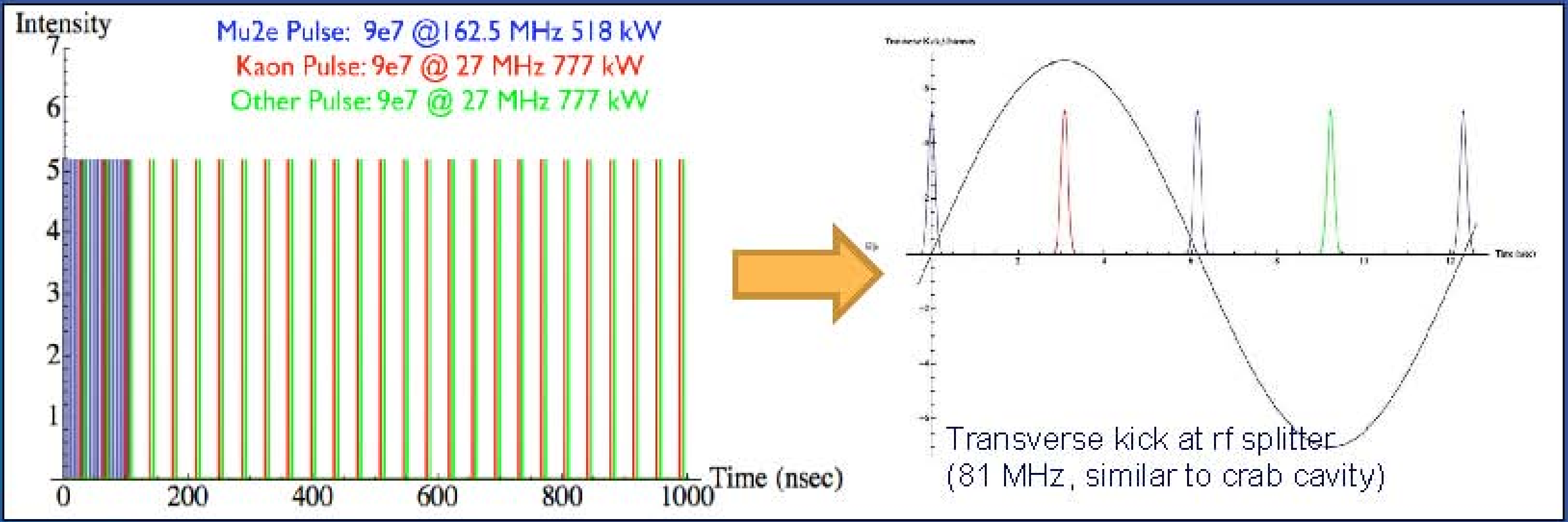
Project X and 2 GeV beams

- Great potential for rare processes comes from 2 MW continuous beam. Intensity experiments need continuous beam: pile up is the main limitation in pulsed beams



Flexible bunch format

- Variable H- ion source provides current 1 to 10 mA DC
- Variable bunch formats:
  1. Ion source at 1 mA, no beam chopping: $1.9x10^7$ protons per bunch at 325 MHz rate
  2. Ion source at 10 mA, 90% beam chopping: $1.9x10^8$ protons per bunch at 32.5 MHz rate (1 mA ave current)
  3. Bunch-by-bunch chopping example (ion source at 4.7 mA), chopping and rf splitting for 3 experiments



Other applications

- Nuclear Physics
  - Can drive an ISOL target for Nuclear Physics applications. Totally complementary program for nuclear EDMs and fundamental experiments on atomic traps just with ISOL target
- Muon Spin Rotation
  - Currently done in Rikken, PSI and TRIUMF
  - Would produce the most intense muon beams available, including, polarization and monochromatization

A path back to the energy frontier?

Lepton colliders beyond LHC

- LHC Results
  - ILC Enough → By far the easiest!
  - or
  - ILC not enough
    - CLIC
    - or
    - Muon collider

Muon Collider approach

- Collider based on a secondary beam: we have experience basing colliders on antiprotons. For muons we must do it in 20 msec.
- The biggest advantages are: narrow energy spread (no beamstrahlung) and small physical footprint (no synchrotron radiation)
- No new methods of acceleration, but new method of deceleration!: muon cooling

Muon Collider Conceptual Layout

Project X
Accelerate hydrogen ions to 8 GeV using SRF technology.

Compressor Ring
Reduce size of beam.

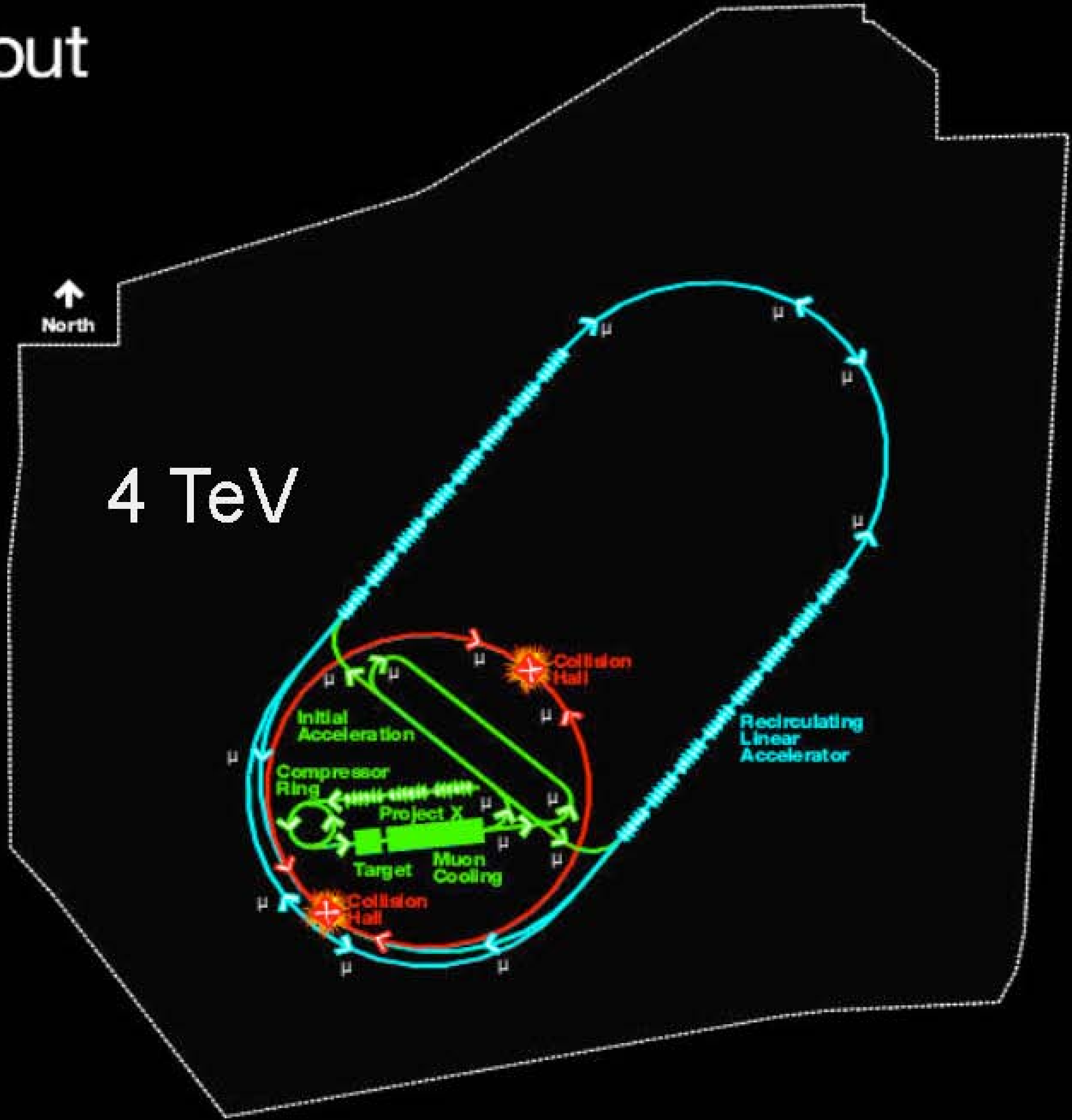
Target
Collisions lead to muons with energy of about 200 MeV.

Muon Cooling
Reduce the transverse motion of the muons and create a tight beam.

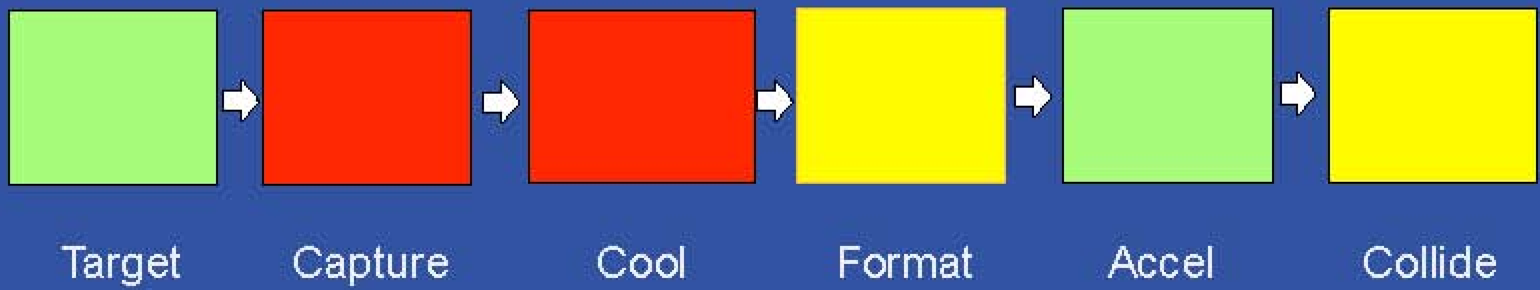
Initial Acceleration
In a dozen turns, accelerate muons to 20 GeV.

Recirculating Linear Accelerator
In a number of turns, accelerate muons up to 2 TeV using SRF technology.

Collider Ring
Located 100 meters underground. Muons live long enough to make about 1000 turns.



Muon collider functional layout

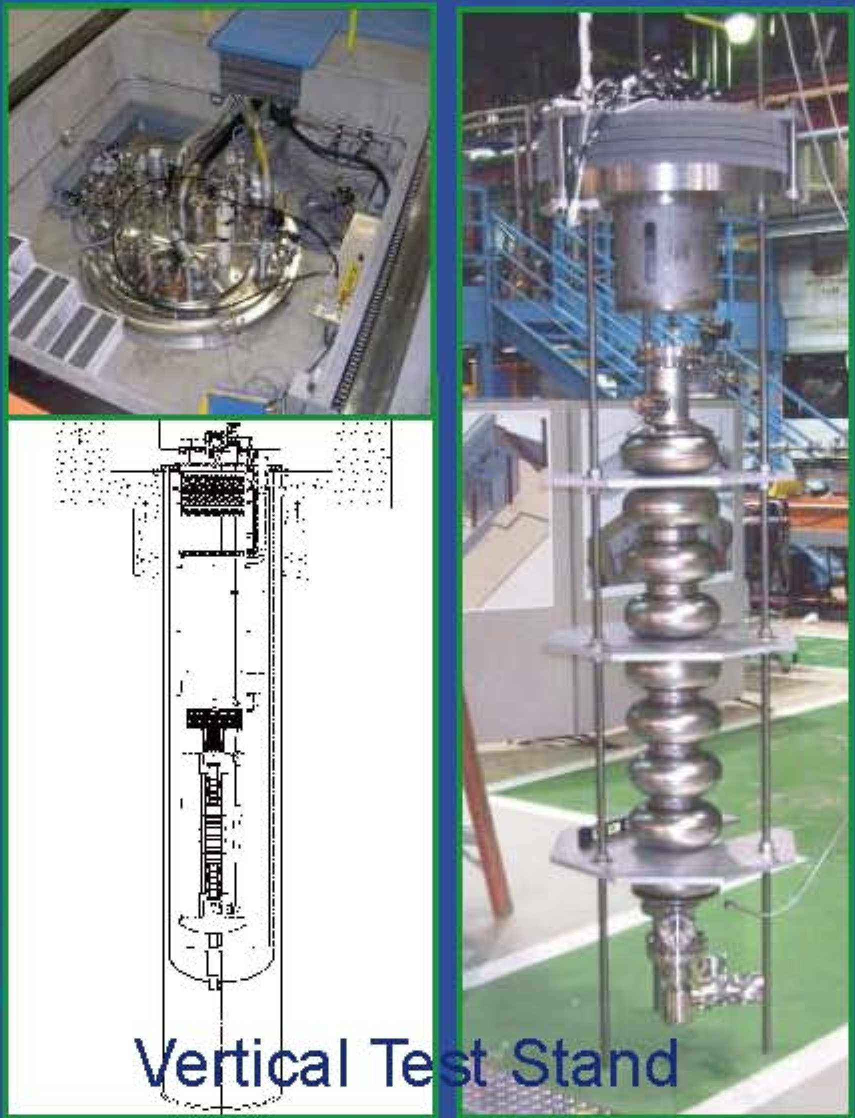


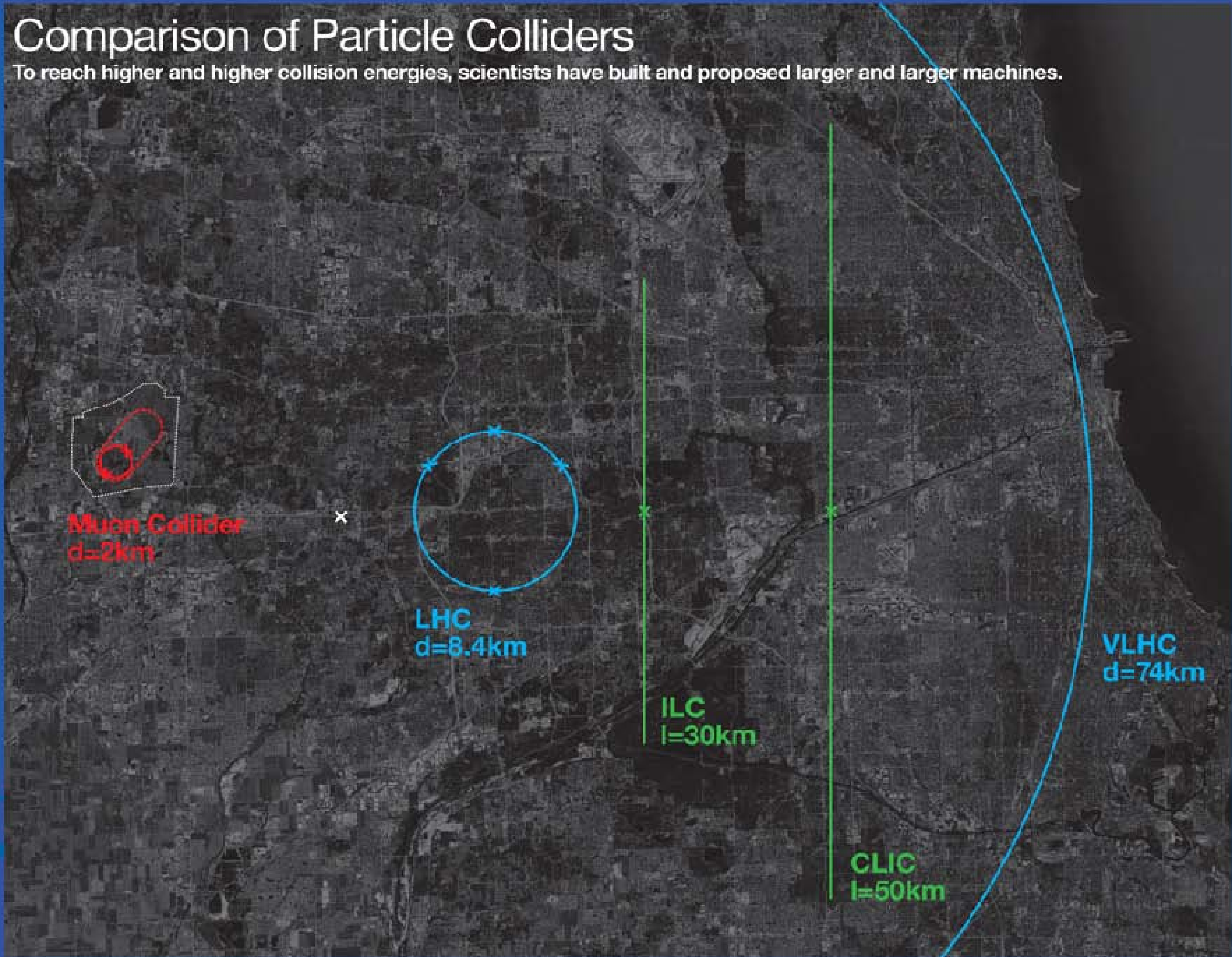
Color indicates degree of needed R&D (difficulty) and demonstration

Muon collider / ILC / Project X

- ILC and Project X developing very efficient accelerating structures that can be run economically
- Muon collider requires substantial acceleration (few km) that ideally would use ILC / Project X technology

ILC/Project X technology at Fermilab





Comparison of Particle Colliders
To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.
Muon Collider
d=2km
LHC
d=8.4km
ILC
l=30km
CLIC
l=50km
VLHC
d=74km

Project X

- Would be a fantastic machine at the intensity frontier for neutrino, kaon and muon beams

- Would develop and exercise the technologies to position the US to host a global facility at the energy frontier (or contribute to one elsewhere)
  - ILC and muon collider

Closing Remarks

- Compelling Questions in Particle Physics
  - Require three interrelated frontiers
    - The Energy Frontier
    - The Intensity Frontier
    - The Cosmic Frontier

- Fermilab: Current and Future
  - A balanced program at 3 interrelated frontiers
  - Project X (intense proton source)
    - Intensity Frontier Facility (broad physics program)
    - A path back to the Energy Frontier
      - ILC technology
      - Front end of a muon collider (and/or ν factory), Acceleration technology for a muon collider