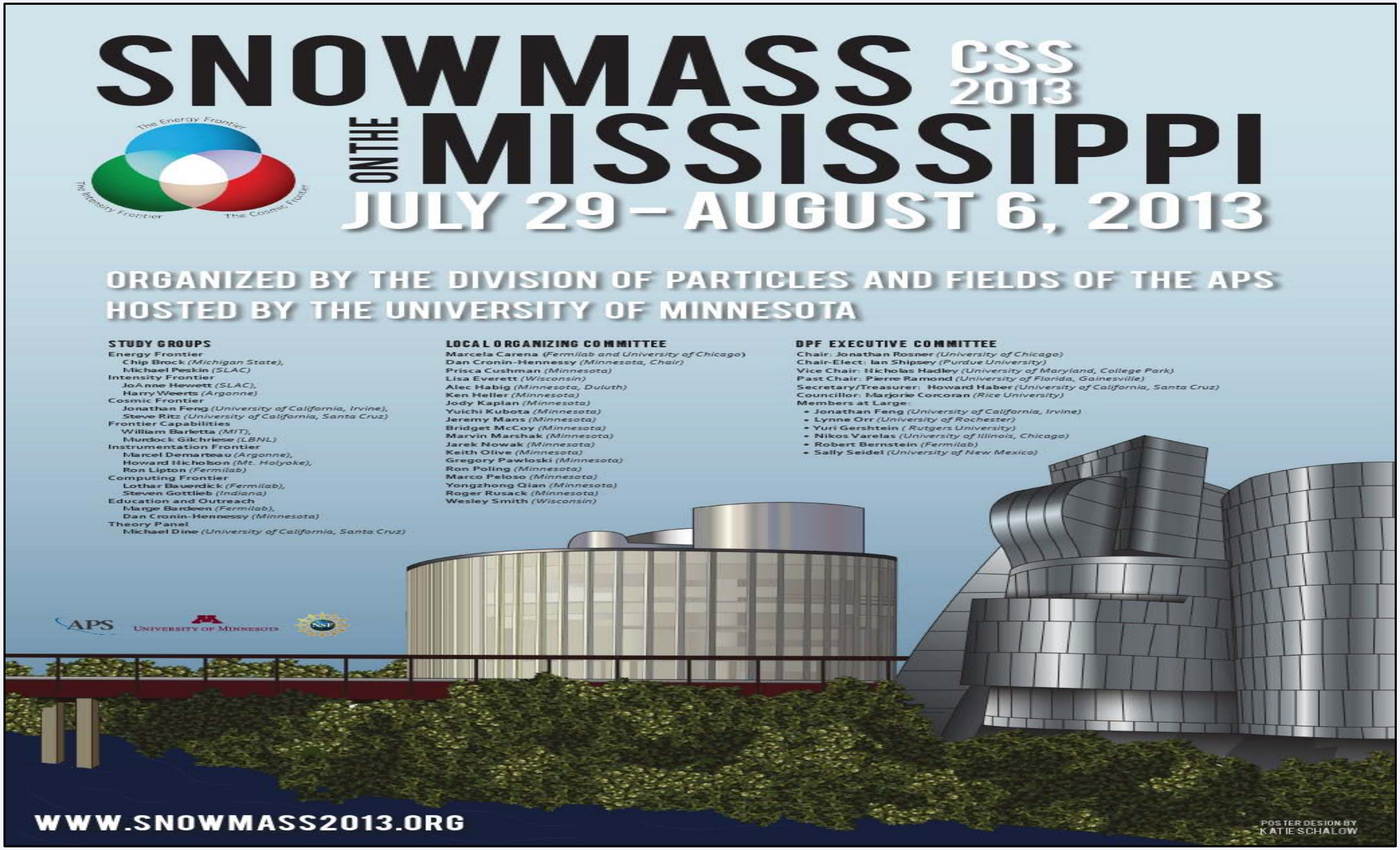
Future Projects in US Particle Physics



Dmitri Denisov (Fermilab)

Session of NP Division, November 6 2013, IHEP Protvino

Talk Outline

- **Process of selecting future particle physics projects in US**
  - **Of relatively large scale, about $50 million and above**
- **Outcome of the "Snowmass process"**
  - **Main questions for particle physics**
- **Main projects**
  - **Accelerators**
  - **Experiments: energy, intensity and cosmic frontiers**
- **"P5 process" – prioritization of the projects**
- **Conclusions**

The Talk Coverage

- Snowmass process created wealth of information
  - ~1000 of scientists involved and 100’s of papers
  - Can only cover very few topics in a brief review talk

- Important items I will not have time to discuss
  - Detectors developments
  - Computing for particle physics
  - Outreach activities

- What is “particle physics” have different definitions in different countries. For example in US heavy ion collisions (RHIC, ALICE), fixed target electron experiment (CEBAF) are not part of “particle physics”, because funding is coming from different sources
  - Clearly there is scientific overlap in many areas
  - Sometime challenging to cooperate as it requires agreements between different US government entities

Selection of Projects in US - 5 Steps Process

- Step 1
  - Groups of scientists develop proposals for future projects/experiments
- Step 2
  - “Snowmass” community wide process discusses proposals, evaluates physics reach and costs and summarizes outcome in a written form
  - Organized by Division of Particles and Fields (DPF) – professional organization, not Laboratories or NSF (National Science Foundation) or DOE (Department of Energy)
- Step 3
  - P5 committee (Particle Physics Projects Prioritization Panel) is formed consisting of ~25 scientists representing all areas of particle physics
  - The committee, within about 6 months, will recommend priorities for funding based on available funds and expected cost of the projects
- Step 4
  - HEPAP (High Energy Physics Advisory Panel) appointed by DOE reviews the P5 proposal and recommends it to be considered by DOE/NSF
- Step 5
  - DOE/NSF fund recommended projects (assuming funds are available)

Snowmass 2013

- The DPF Charge for "Snowmass 2013"

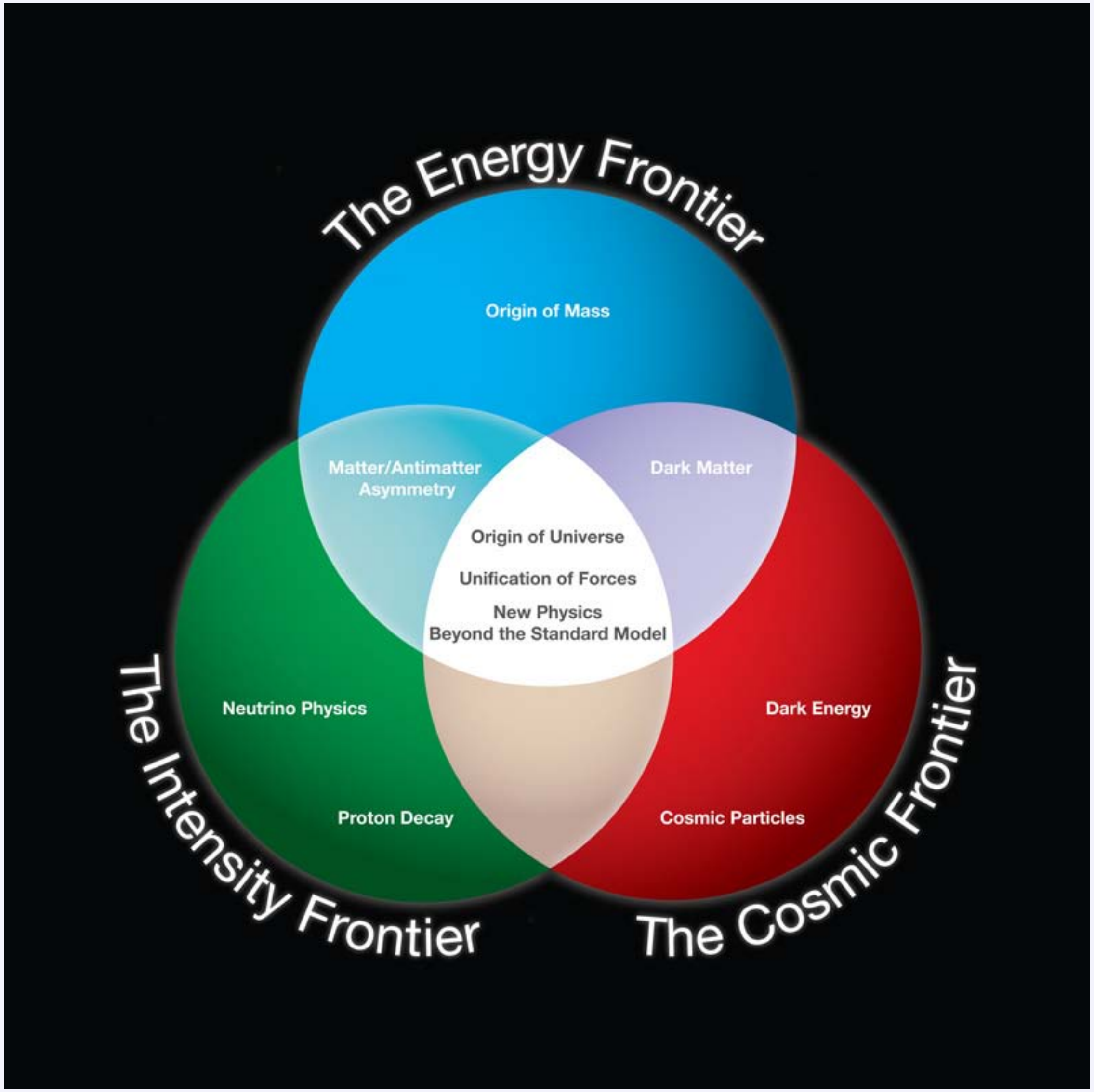
  "To develop the community's long term physics aspirations. Its narrative will communicate the opportunities for discovery in high energy physics to the broader scientific community and to the government"

- Organized around Frontiers
  - Energy, Intensity, Cosmic, Instrumentation, Facilities (mainly new accelerators), Education and Outreach, Theory

- Time scale for proposals is ~10 years, taking into account ~20 years time span

- Process continued for about a year (since late 2012) and culminated in ~10 days community meeting at the University of Minnesota late July 2013
  - "Snowmass" is the name of the village in Colorado where similar exercises have been done in the past (last time in 2001)

Energy, Intensity and Cosmic Frontiers



Efforts (and funding) in US are organized around "frontiers"

Snowmass 2013

By now Snowmass process is almost over with final reports available or expected shortly (arXiv)

“The” Snowmass

Outcome of Snowmass - Big Questions

1. How do we understand the Higgs boson? What principle determines its couplings to quarks and leptons? Why does it condense and acquire a vacuum value throughout the universe? Is there one Higgs particle or many? Is the Higgs particle elementary or composite?

2. What principle determines the masses and mixings of quarks and leptons? Why is the mixing pattern apparently different for quarks and leptons? Why is the CKM CP phase nonzero? Is there CP violation in the lepton sector?

3. Why are neutrinos so light compared to other matter particles? Are neutrinos their own antiparticles? Are their small masses connected to the presence of a very high mass scale? Are there new interactions invisible except through their role in neutrino physics?

4. What mechanism produced the excess of matter over anti-matter that we see in the universe? Why are the interactions of particles and antiparticles not exactly mirror opposites?

Big Questions - Continues

5. Dark matter is the dominant component of mass in the universe. What is the dark matter made of? Is it composed of one type of new particle or several? What principle determined the current density of dark matter in the universe? Are the dark matter particles connected to the particles of the Standard Model, or are they part of an entirely new dark sector of particles?

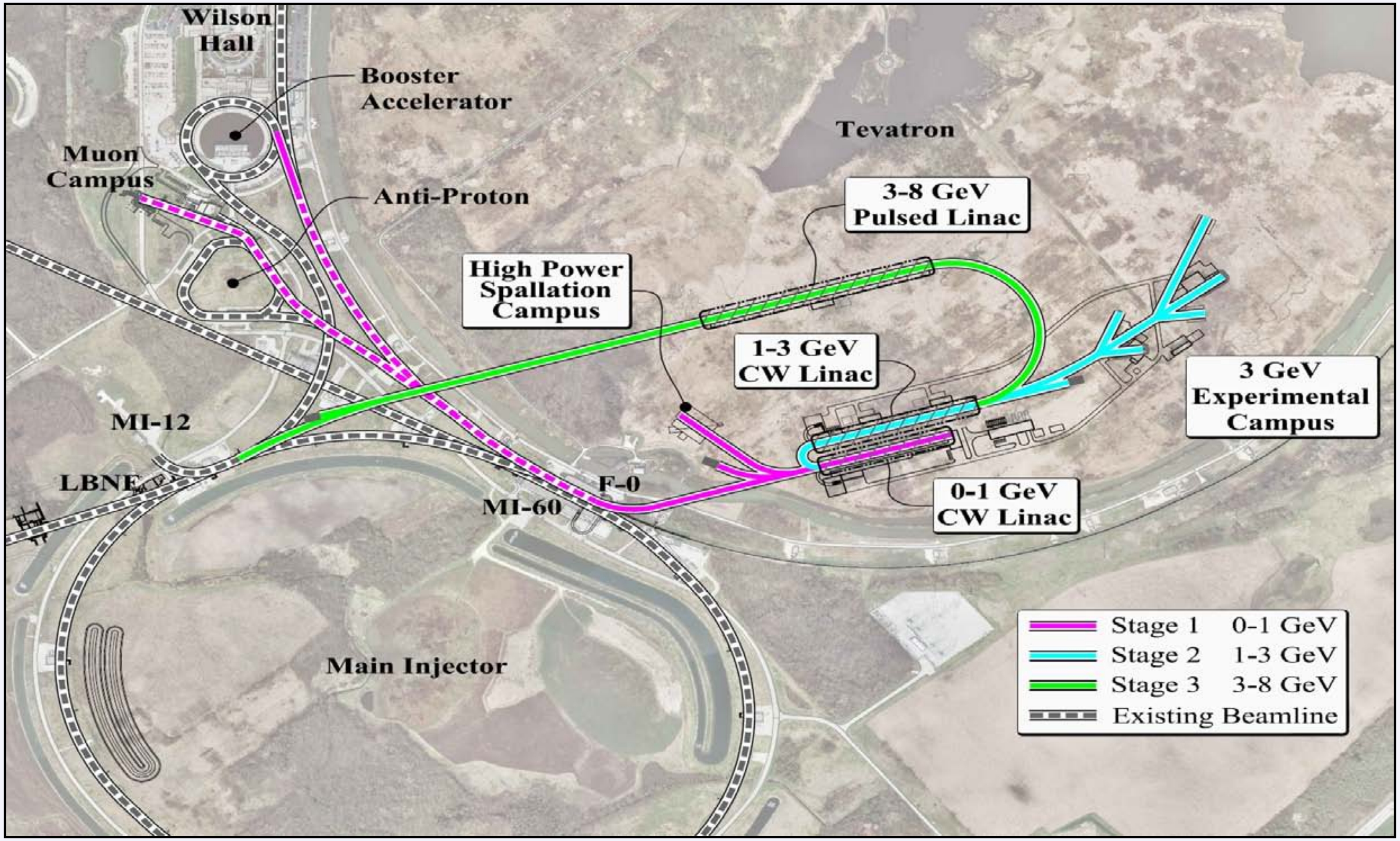
6. What is dark energy? Is it a static energy per unit volume of the vacuum, or is it dynamical and evolving with the universe? What principle determines its value?

7. What did the universe look like in its earliest moments, and how did it evolve to contain the structures we observe today? The inflationary universe model requires new fields active in the early universe. Where did these come from, and how can we probe them today?

Future Accelerators

- How would one build a 100 TeV scale hadron collider?
- How would one build a lepton collider at >1 TeV?
- How would one generate 10 MW of proton beam power?
- Can multi-MW targets survive? If so, for how long?
- Can plasma-based accelerators achieve energies & luminosities relevant to particle physics?
- Can accelerators be made 10x cheaper per GeV? Per MW?

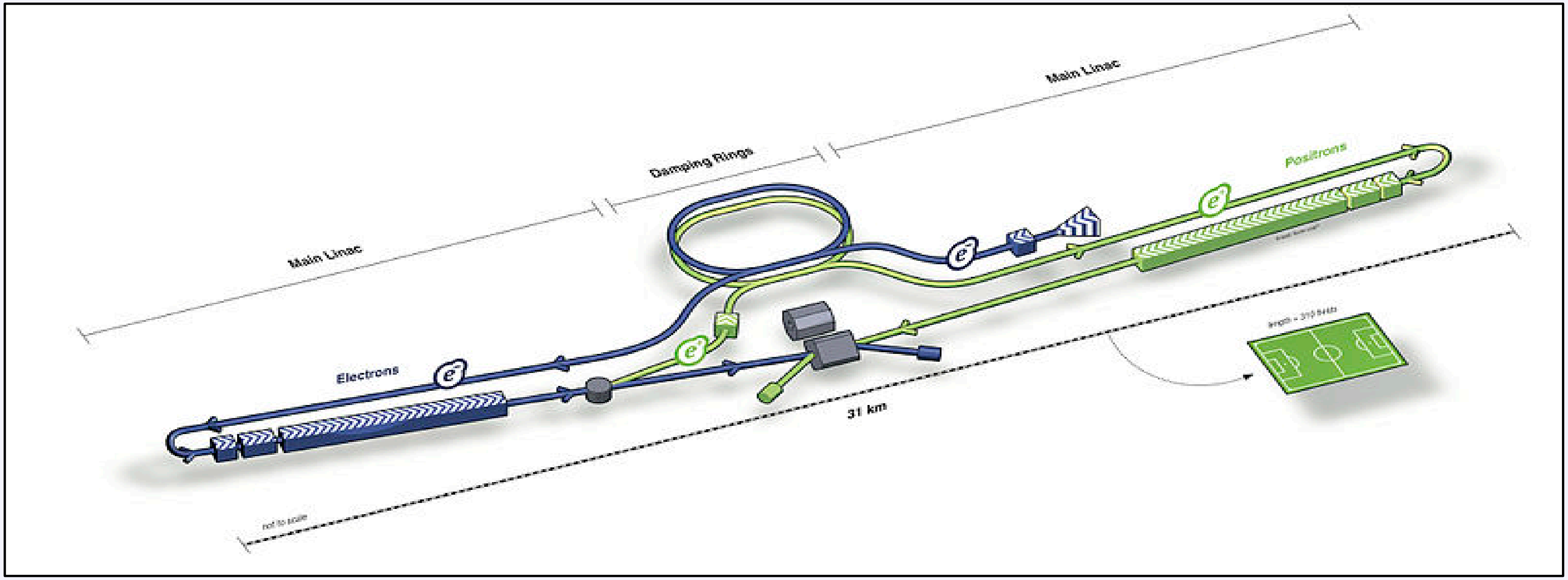
Project X at Fermilab



- **Multi-MW proton linear accelerator with flexible "on-demand" beam structure based on SCRF technology: ~1 MW at 1 GeV, more at 3-8 GeV**
- **Could serve multiple experiments over broad energy range**
- **Platform for future neutrino and muon facilities (including muon collider)**

Participation in ILC (in Japan)

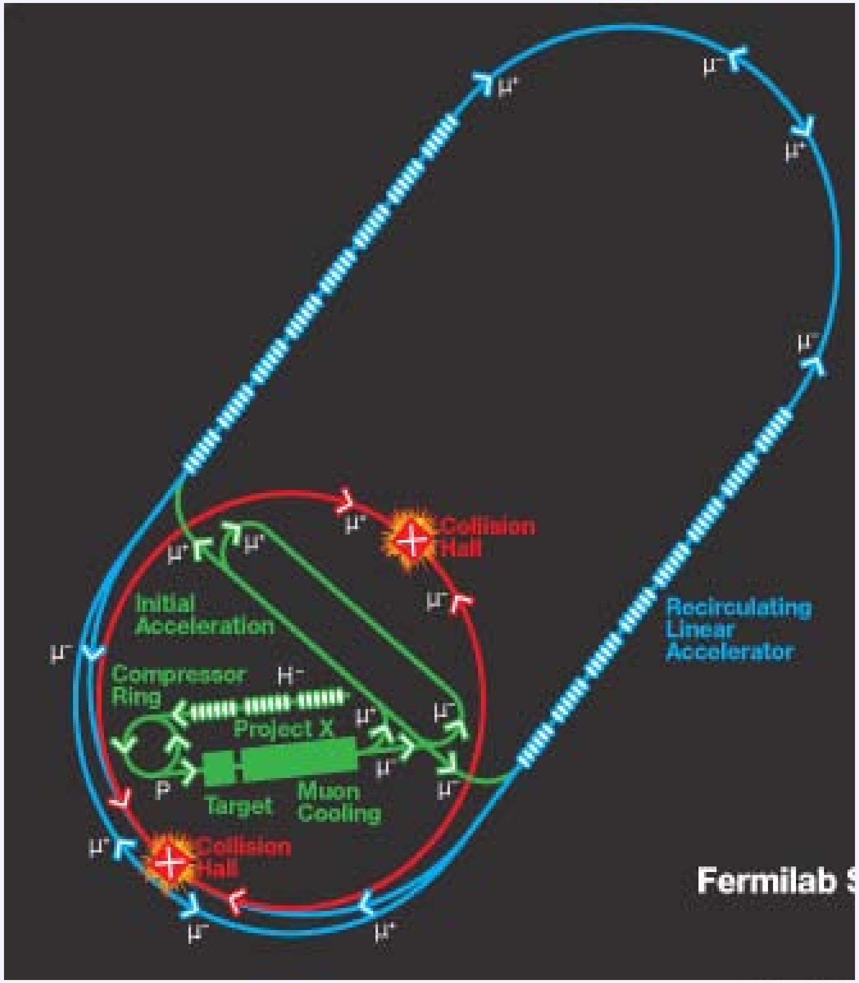
- U.S. accelerator community is capable to contribute
  - Supported by strong physics case
- ILC design is technically ready to go
  - TDR incorporates U.S. contributions to machine physics & technology
    - SRF, high power targetry (e^+ source), beam delivery, damping rings, beam dynamics
- Important that there is an upgrade path of ILC to higher energy & luminosity (> 500 GeV, > 10^{34} $cm^{-2}s^{-1}$)



Muon Collider

- Muons do not have high synchrotron radiation making circular accelerator viable for multi TeV energies
- Muons are unstable with life-time of 2 μs
- Main accelerator challenge
  - To make large number of muons quickly and then “cool” them to focus into small diameter beams to collide
- Another issue are decays and irradiation by electrons from muon decays
  - and neutrinos irradiation!
- Active program in US, while many technical challenges exist
  - Maximum energy is ~10 TeV

2x2 TeV



Fits on Fermilab’s Site

VLHC – 100 TeV Hadron Collider

- **While "post-SSC effects" still present in US, there are more and more discussions of 100 TeV and 100 km long circular pp hadron collider**
  - **Especially if full energy LHC will not bring new physics**
  - **33 TeV energy collider did not get support at Snowmass, while 100 TeV did**
- **Technically feasible option**
  - **100's of km of underground tunnels near Chicago**
  - **Accelerator technology is similar to Tevatron, SSC and LHC**
- **Snowmass conclusions recommend to increase efforts on VLHC accelerator/physics/detectors development**

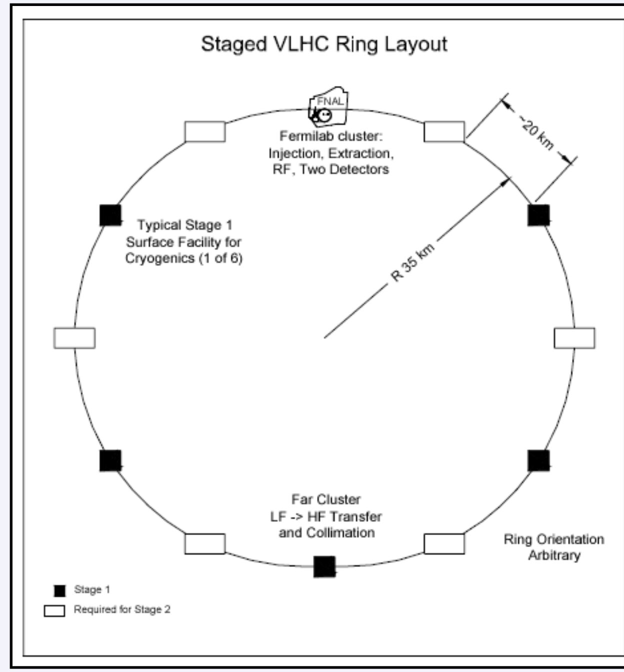
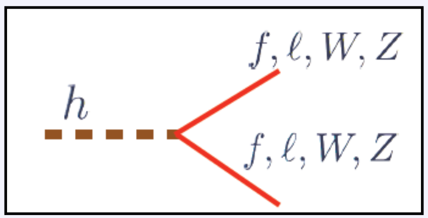


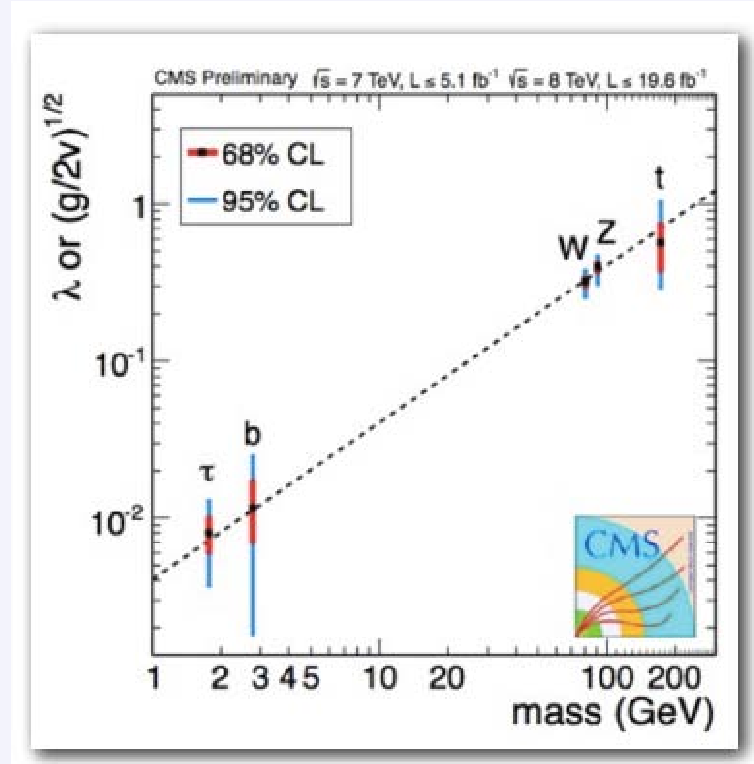
Table 1.1. The high-level parameters of both stages of the VLHC.

	Stage 1	Stage 2
Total Circumference (km)	233	233
Center-of-Mass Energy (TeV)	40	175
Number of interaction regions	2	2
Peak luminosity ($cm^{-2}s^{-1}$)	1×10^{34}	2.0×10^{34}
Luminosity lifetime (hrs)	24	8
Injection energy (TeV)	0.9	10.0
Dipole field at collision energy (T)	2	9.8
Average arc bend radius (km)	35.0	35.0
Initial number of protons per bunch	2.6×10^{10}	7.5×10^{9}
Bunch spacing (ns)	18.8	18.8
β^* at collision (m)	0.3	0.71
Free space in the interaction region (m)	± 20	± 30
Inelastic cross section (mb)	100	130
Interactions per bunch crossing at L_{peak}	21	54
Synchrotron radiation power per meter (W/m/beam)	0.03	4.7
Average power use (MW) for collider ring	25	100
Total installed power (MW) for collider ring	35	250

Higgs Couplings

- Critical to study of all properties of the Higgs
  - Mass, width, spin, couplings, etc.
- Sub- percent accuracy is important as predicted in beyond Standard Model theories
- LHC/ILC/CLIC/muon collider reach was estimated for Snowmass

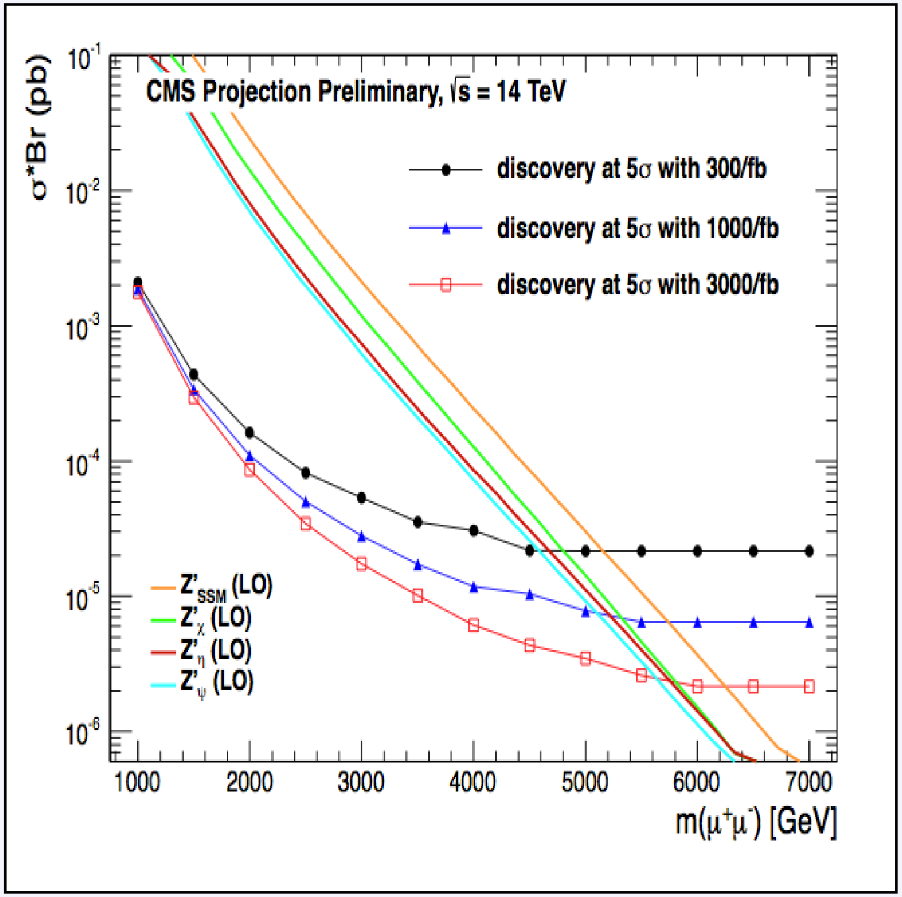




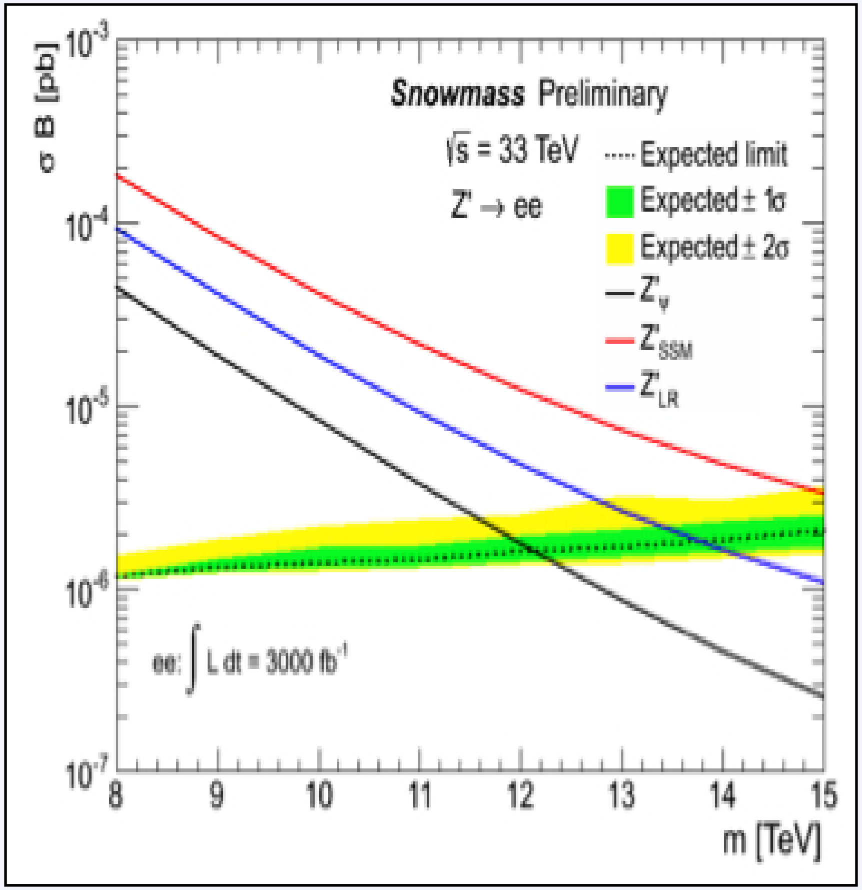
Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.13%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.44%	0.22%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
κ_d	10 – 13%	4 – 7%	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
κ_u	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.76%	3.1/1.0/0.7%	0.69%

Search for Heavy Particles

5 TeV discovery range at 14 TeV LHC



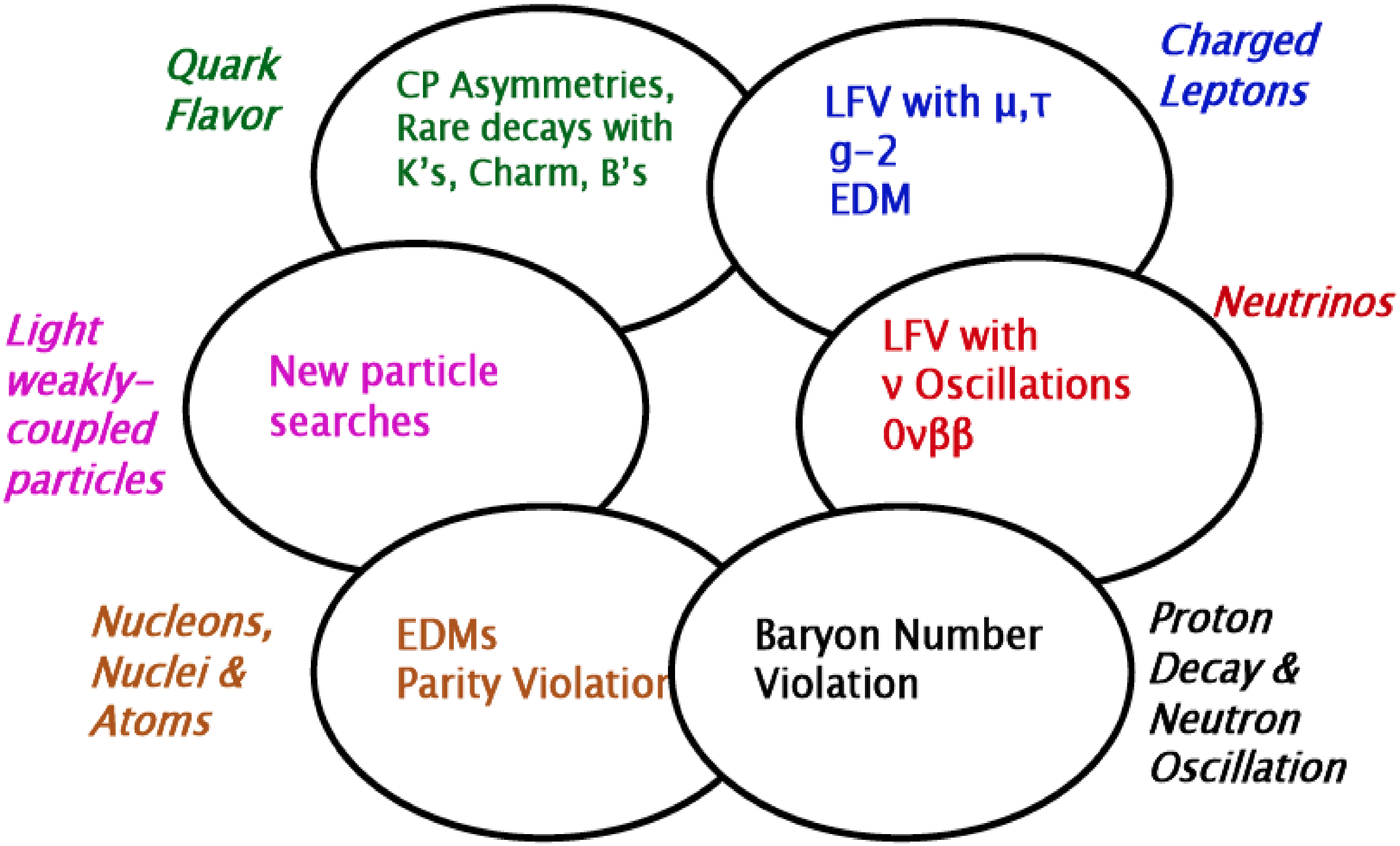
14 TeV discovery range at 33 TeV



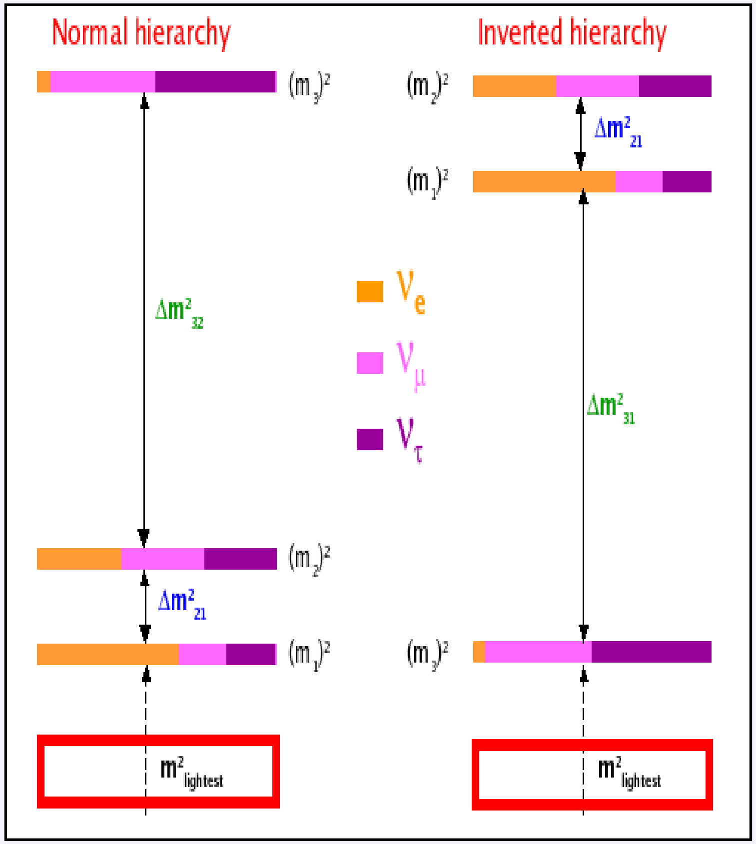
- No hints of heavy particles at the Tevatron (2 TeV) or LHC (8 TeV)
- Mass reach is proportional to energy (and weakly to luminosity)
- This is partly why next step beyond 14 TeV LHC should be ~100 TeV

Snowmass Intensity Frontier

The Intensity Frontier is a broad and diverse, yet connected, set of science opportunities

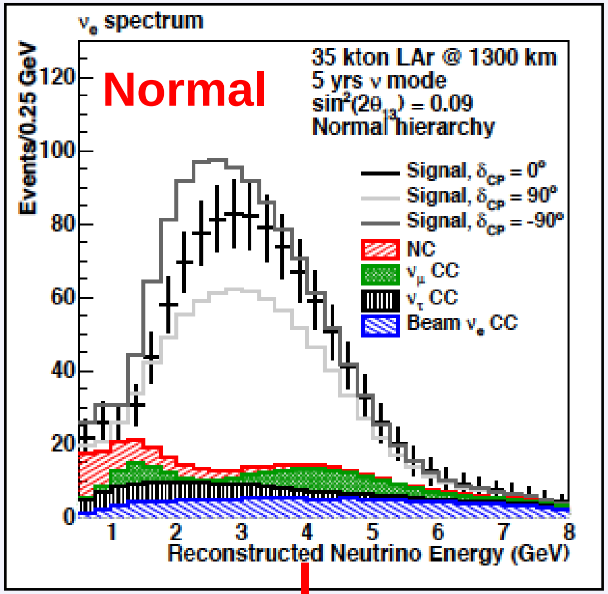


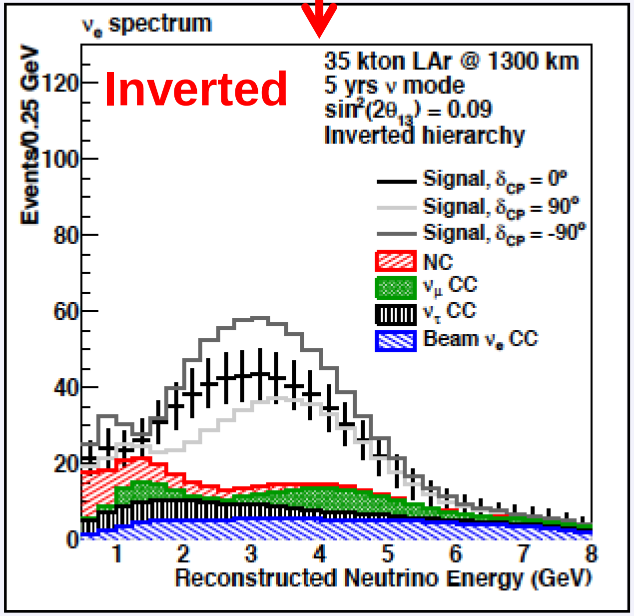
Long Baseline Neutrino Experiment - LBNE

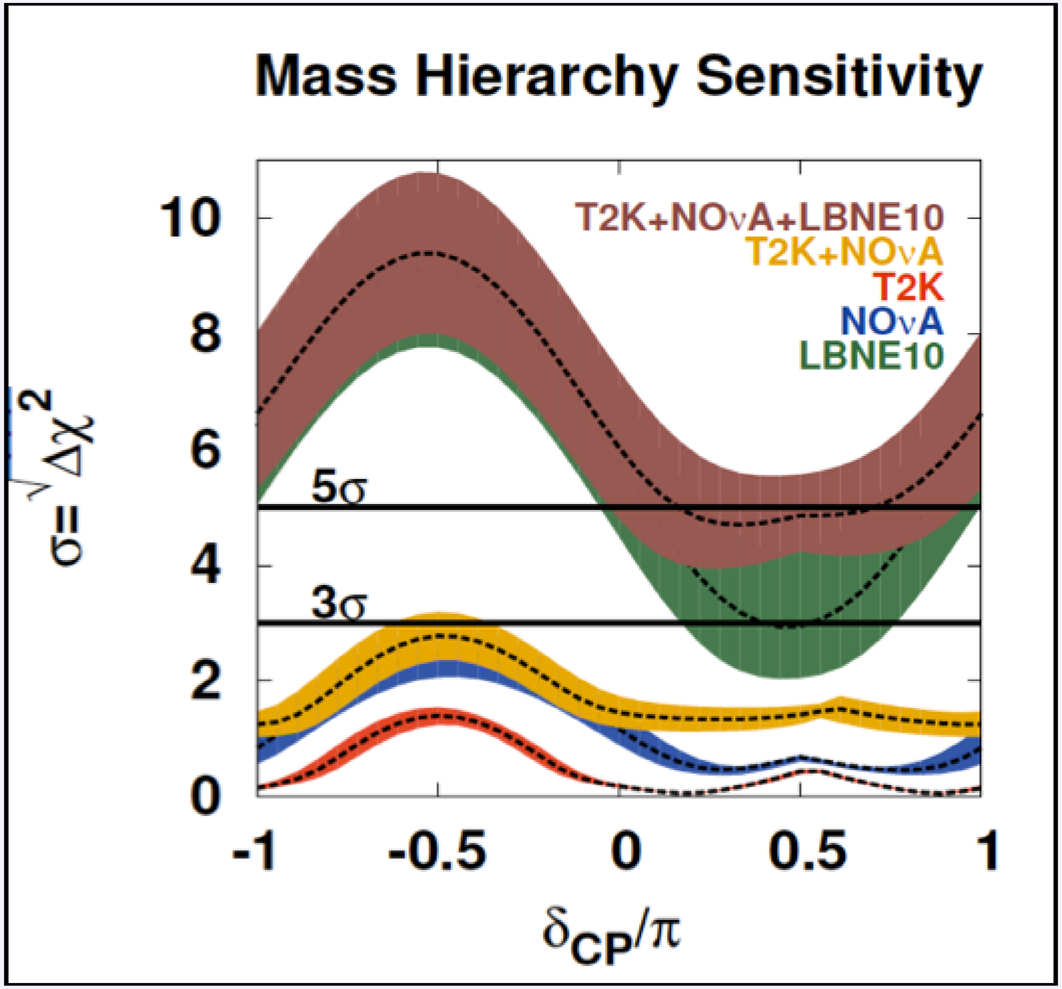


- LBNE is LAr ~30kton experiment deep underground using neutrino beam from Fermilab
- Goals: neutrino mass hierarchy and CP violation as well as supernova detection and proton decay (up to 10^{35} years)

Long Baseline Neutrino Experiment - LBNE



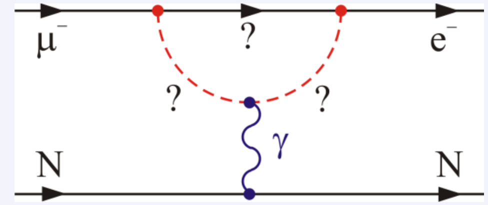


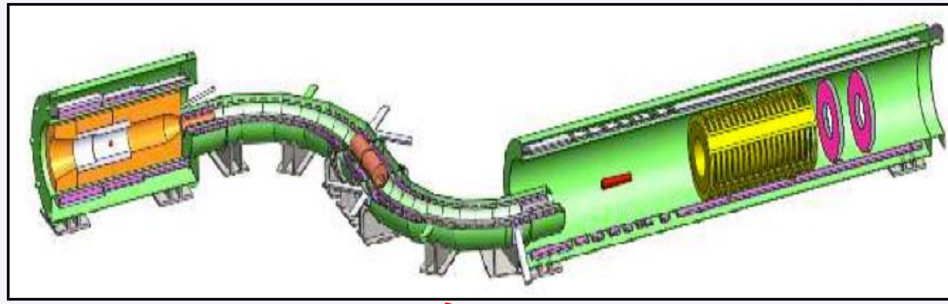


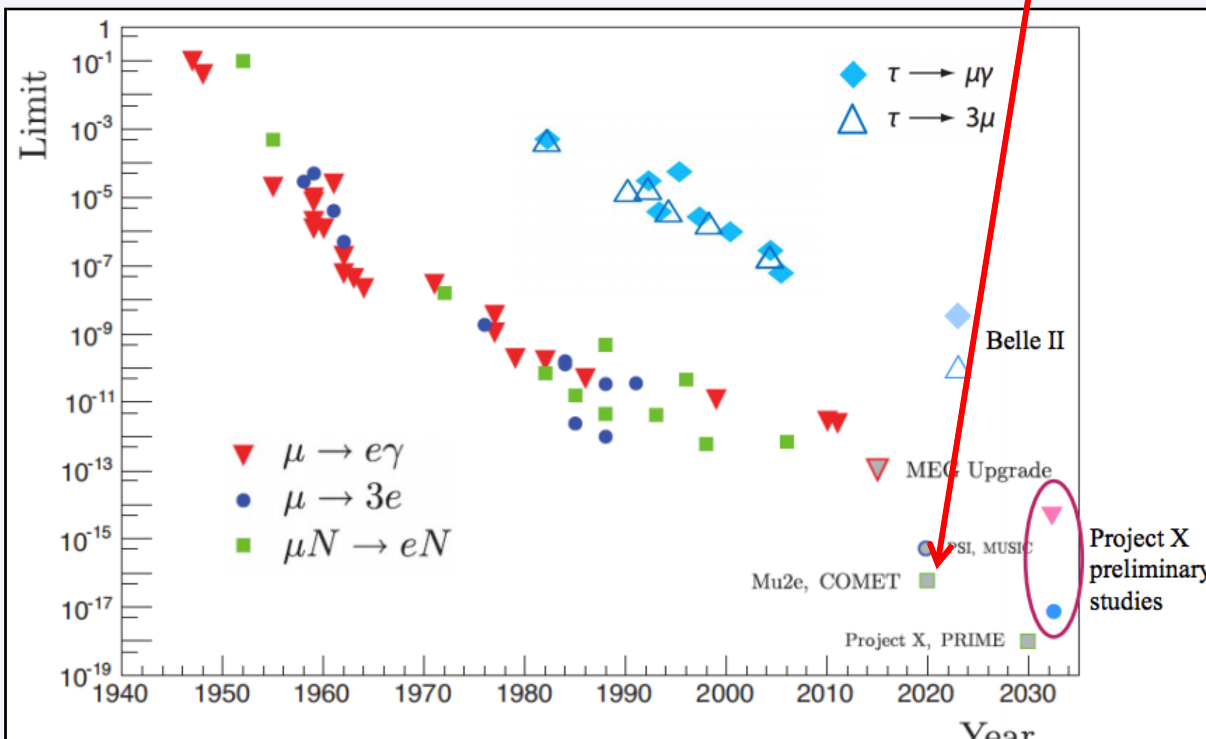
- Superior option to resolve mass hierarchy
- Find proton decay up to lifetime of 10^{35} years
- Detect supernova neutrinos

Lepton Flavor Violation: Mu2e

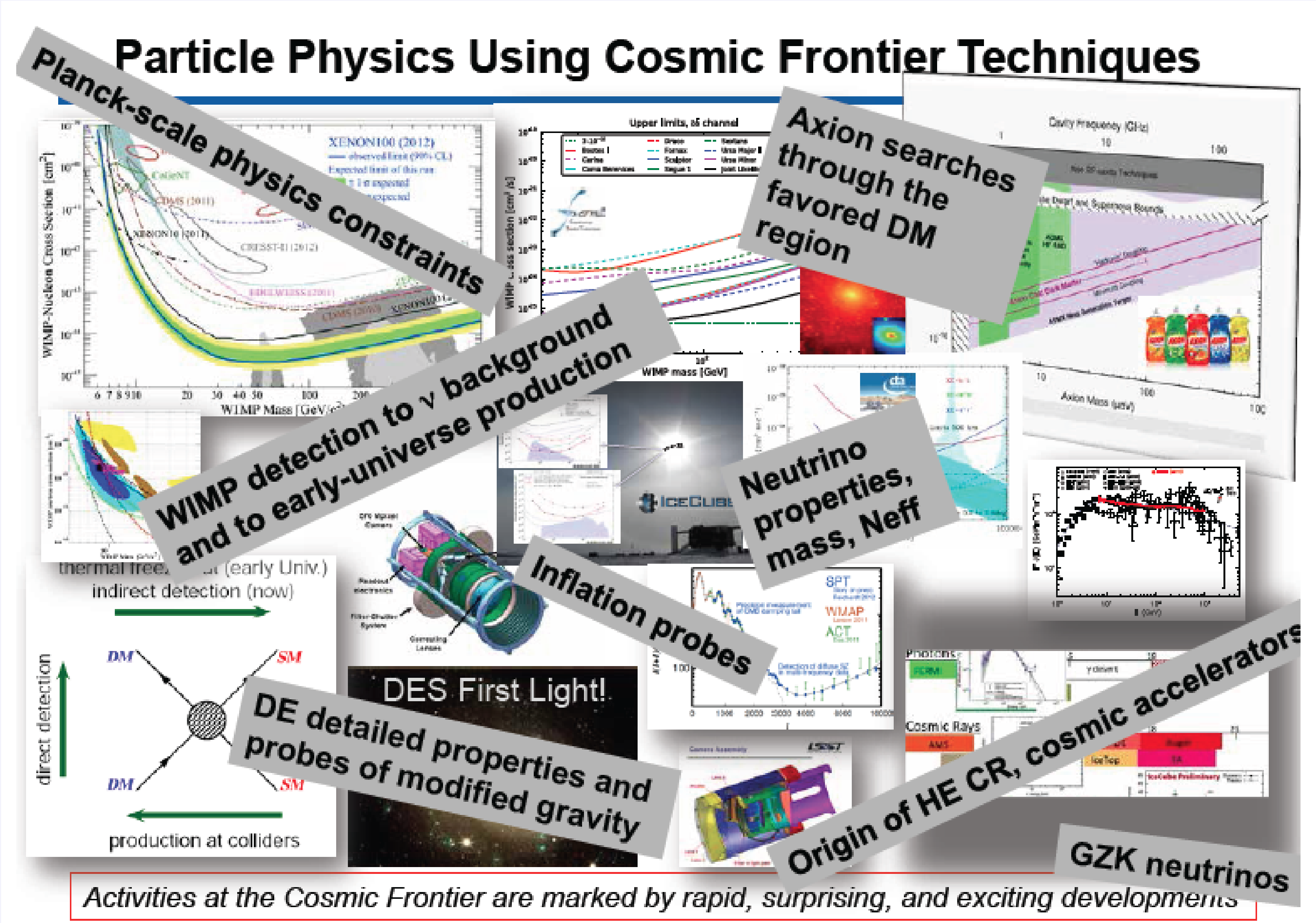
- New experiment Mu2e at Fermilab
  - High intensity muon flux stopped on a nuclear target
- Monochromatic electron emission from μ to e conversion
  - 4 orders of magnitude improvement



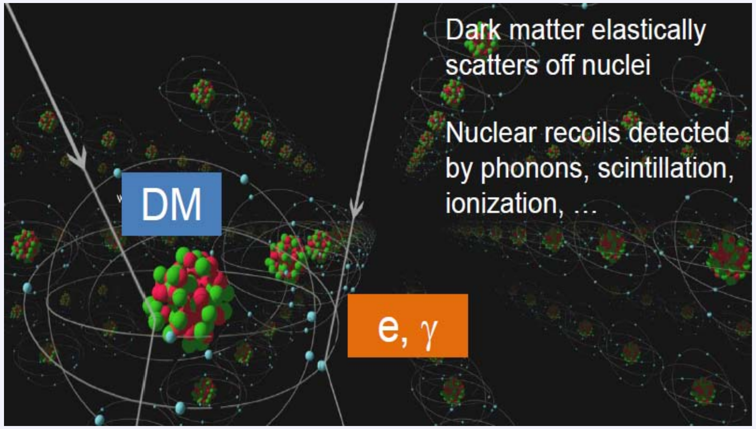




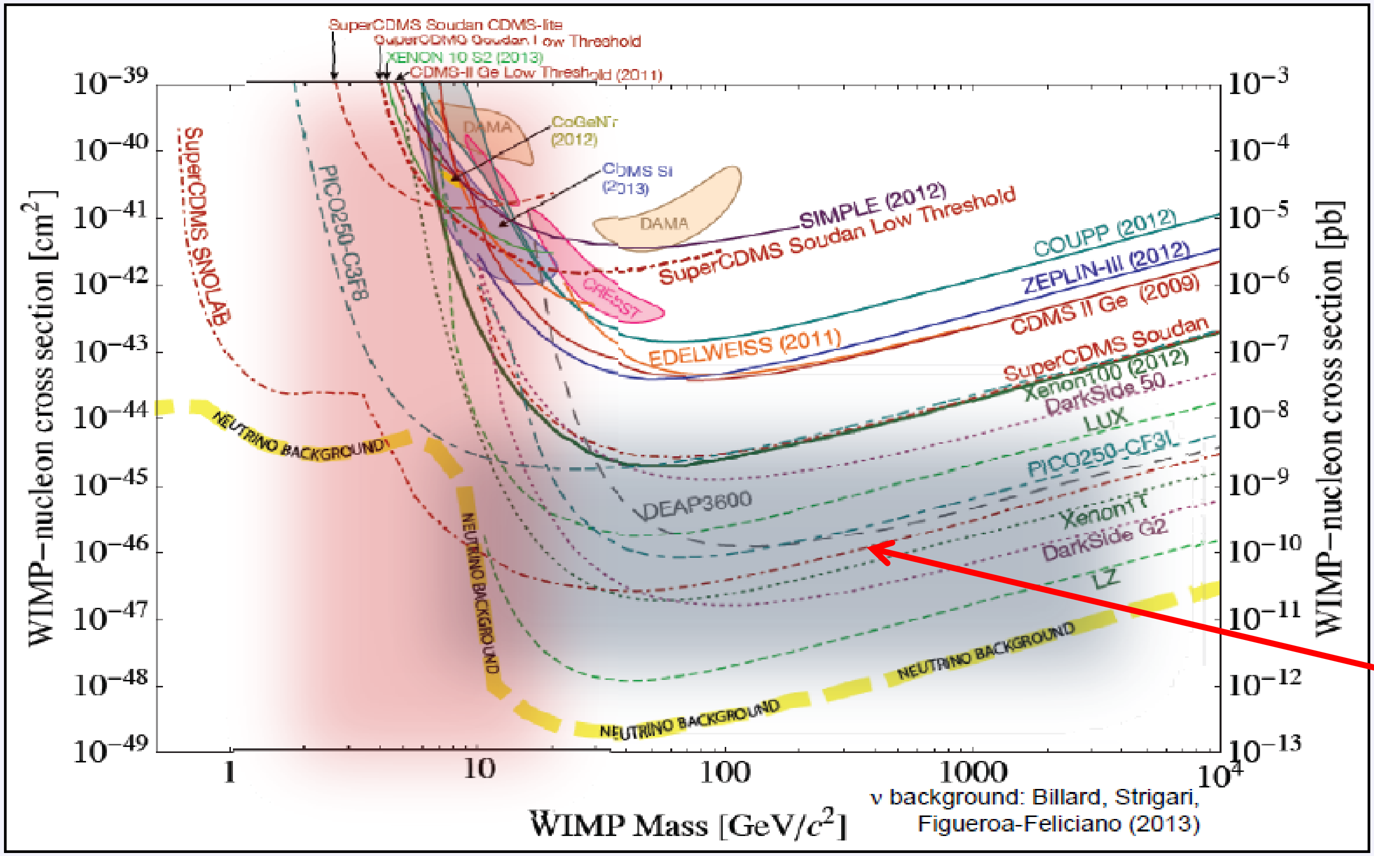
Snowmass Cosmic Frontier



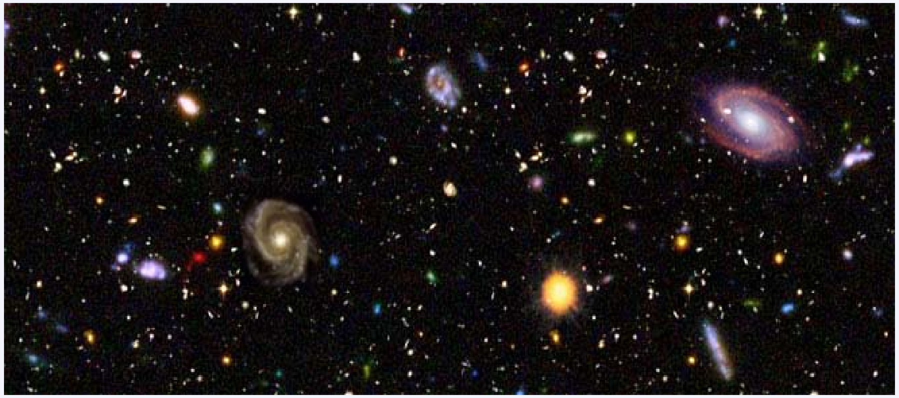
Dark Matter Direct Detection

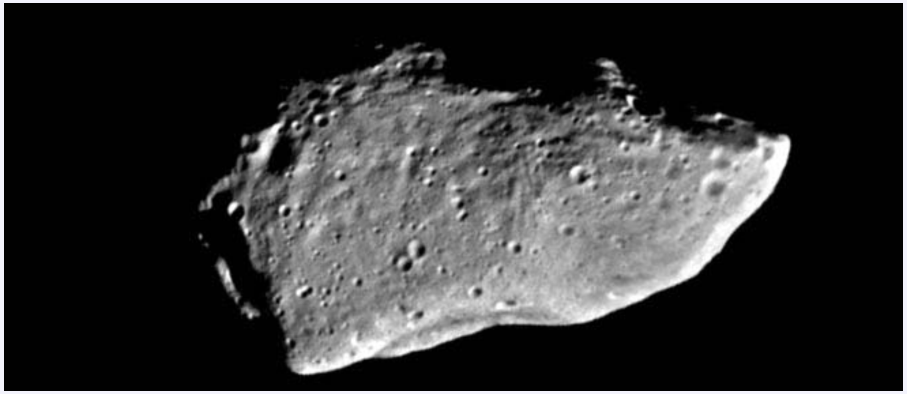


- Many models expect dark matter to consist of heavy WIMP particles
- Multiple methods used to detect elastic scattering of WIMPs: ionization, scintillation, phonons. Results mixed…
- Major road is "larger sensitive mass" from 10 kg scale to 1000 kg scale



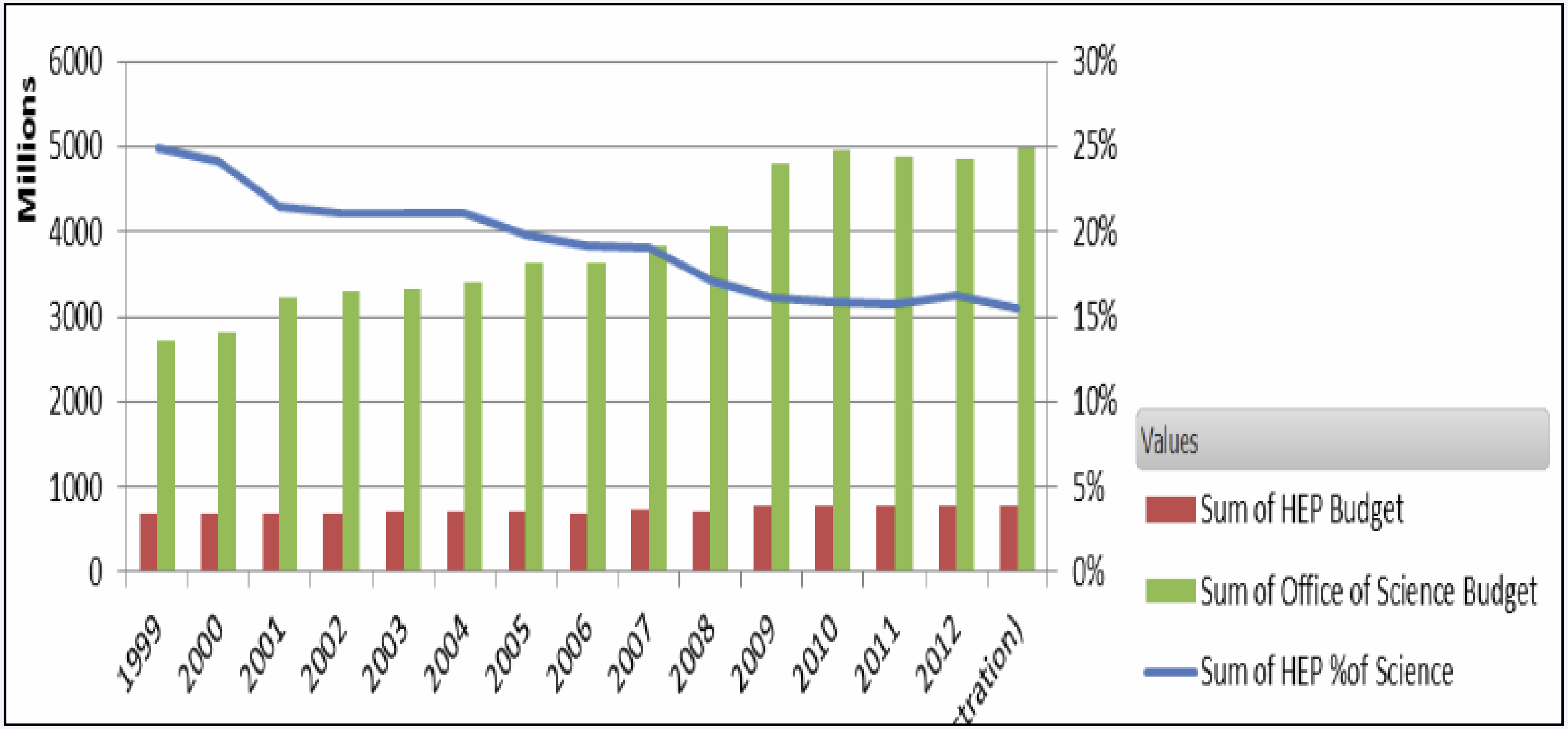
Large Synoptic Survey Telescope: LSST





- **LSST is based on 8.6m diameter telescope with 3200 Megapixels camera to scan sky image every ~3 days creating ~30 Terabytes of data nightly, located in Chile**
  - **Factor of ~10 better resolution and faster scanning**
- **Major scientific areas: studies of dark matter, dark energy, supernova, solar system survey and many other topics**

Where the Problem is…



- Funding is "flat" vs year at ~$760M per year over past ~13 years
- But… everything is more expensive today vs 1999
  - Effective reduction in HEP budget is ~25% over past decade or about $170 millions per year
  - And there are no expectations for a change of the slope for now…
- What funding is required for projects considered at Snowmass for "next 10 years"?

Funding Required

Project	M$
Near-term Projects (Mu2e, g-2, muon campus)	350
LBNE	900 (+700)
Project-X through stage 3 (w/o expts)	1,700
Project-X stage 1 experiments	485
Project-X stage 2 and 3 experiments	500
NuSTORM	400
ORKA	80
LSST	175
Other Cosmic (G2-DM, CMB, DESI)	170
Near-term LHC detector upgrades	60
G3 Dark Matter	200
LHC Accelerator Upgrades	250
CMS+ATLAS Upgrades	600
ILC-250 GeV (US contribution)	1,700
ILC Detector (US contribution)	300
R&D for future Intensity Frontier accelerator	100
R&D for future colliders	300
Total	**8,270**

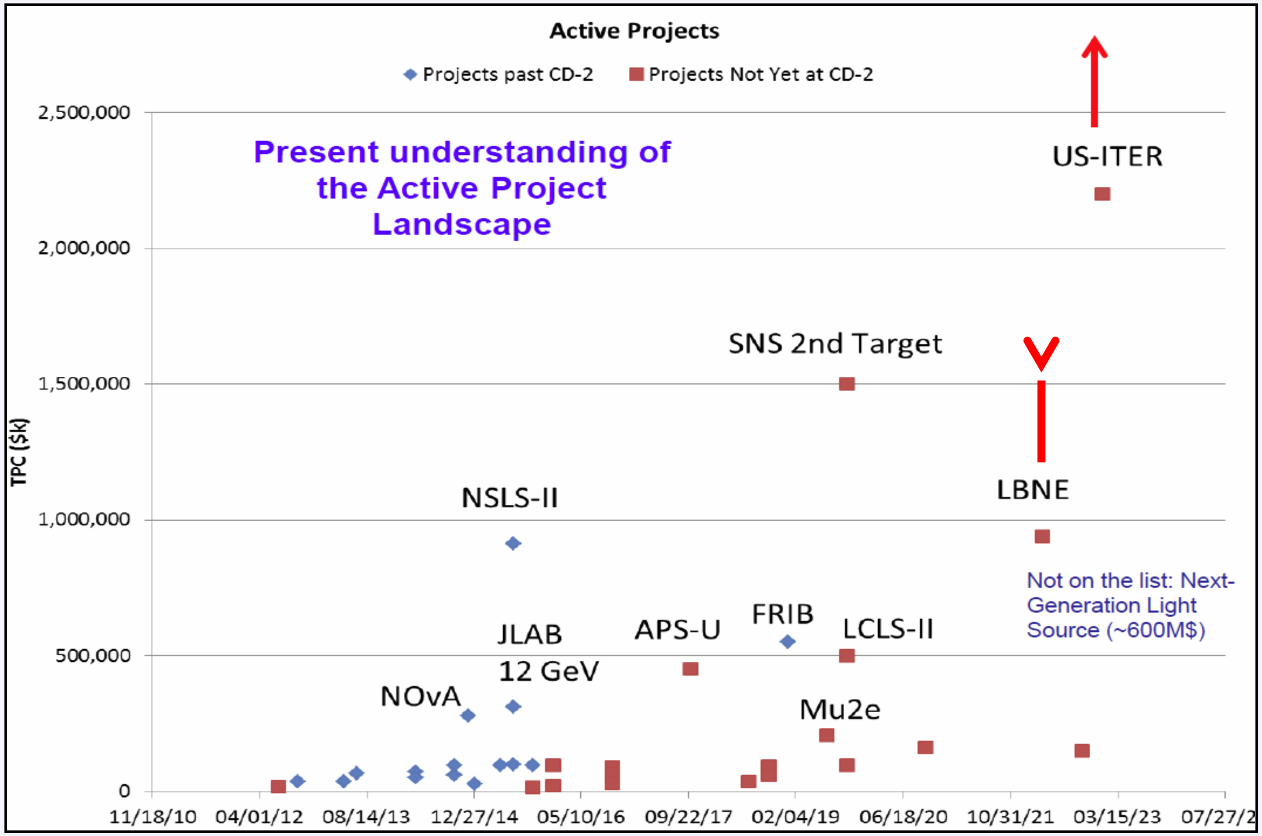
- **Above is one among many estimates of “Snowmass projects costs”**
- **R&D projects as well as ILC probably do not belong to this exercise**
- **Total around $7 billion is required over for the above projects**

Available vs Required Funding

- DOE estimates that total funding we can expect for new projects in the coming 10 years is $100 to $200 millions per year
  - Total over a decade, if optimistic, is $2 billion
  - And we need ~$7 billion…
- Our "appetite" is well above what we can afford (factor of ~3)
  - And this is where P5 prioritization will be critical
  - P5 work is progressing right now
  - Recommendations are expected in March 2014 - soon
- What we can expect from P5 recommendations
  - Some projects will be de-scoped (means less complex/ambitious)
  - Some projects will have to wait to be constructed (if relevant at that time) for beyond 10 years
  - Some projects might not materialize

And What About "Super" Projects

- Any new large accelerator has price tag of "many billions"
- Even large detectors, like ATLAS/CMS/LBNE , cost in excess of a billion dollars
- Such projects were affordable in the past
  - Cost of the first Fermilab accelerator in today's dollars was ~$4 billions and it was constructed over ~4 years…
- Recent history shows that "any project has to be below ~$1 billion"



Concluding Remarks

- Particle physics in US is undergoing changes after shutdowns of SLAC B factory and Fermilab Tevatron over last 5 years
- Snowmass process created well documented list of exciting proposals for accelerators and experiments
  - Energy, Intensity and Cosmic frontiers

- Most probable accelerator projects for this decade
  - Project X, ILC and LHC high luminosity upgrades
- List of large new upgrades/experiments is
  - g-2, Mu2e, LBNE, ATLAS/CMS upgrades, LSST, Generation-3 dark matter searches
- P5 process is progressing over next 6 months to set priorities for the coming ~10 years
  - Any scientist from anywhere in the world is welcome to comment
- Funding situation, while challenging, creates opportunities
  - US groups are very interested to attract participants from other countries
  - US groups are interested to join projects in other countries where excellent results could be obtained

Спасибо!

Project X Research Program

Program:	Onset of NOvA operations in 2013	Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW +0-50kW**	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	0-172 kW*	1000 kW
1-3 GeV Muon program, e.g. Mu2e-2	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1870 kW	1870 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
# Programs:	4	8	8	8	8
Total max power:	735 kW	2222 kW	4284 kW	6492 kW	11870kW

* Operating point in range depends on MI energy for neutrinos.
** Operating point in range depends on MI injector slow-spill duty factor (df) for kaon program.

Snowmass Aspirations

- Probe the highest possible energies and smallest distance scales with the existing and upgraded Large Hadron Collider and reach for even higher precision with a lepton collider; study the properties of the Higgs boson in full detail
- Develop technologies for the long-term future to build multi-TeV lepton colliders and 100 TeV hadron colliders
- Execute a program with the U.S. as host that provides precision tests of the neutrino sector with an underground detector; search for new physics in quark and lepton decays in conjunction with precision measurements of electric dipole and anomalous magnetic moments
- Identify the particles that make up dark matter through complementary experiments deep underground, on the Earth's surface, and in space, and determine the properties of the dark sector
- Map the evolution of the universe to reveal the origin of cosmic inflation, unravel the mystery of dark energy, and determine the ultimate fate of the cosmos

Snowmass Aspirations - II

- Invest in the development of new, enabling instrumentation and accelerator technology
- Invest in advanced computing technology and programming expertise essential to both experiment and theory
- Carry on theoretical work in support of these projects and to explore new unifying frameworks
- Invest in the training of physicists to develop the most creative minds to generate new ideas in theory and experiment that advance science and benefit the broader society
- Increase our efforts to convey the excitement of our field to others

Snowmass Energy Frontier

- HL-LHC – Higgs couplings, VV scattering, new particles (NP) searches
- 500 GeV ILC – Higgs couplings, top couplings, NP in LHC blind spots
- 1 TeV ILC – Higgs self coupling (13%), precision NP
- 350-3000 GeV CLIC - Higgs self coupling (10%), NP
- 0.125, 3-6 TeV Muon Collider – s-channel Higgs, NP, measurements of Higgs self coupling + anything e^+e^- can do
- TLEP (350 GeV circular e^+e^-) - 10x higher luminosity than linear e^+e^- colliders
- 100 TeV pp – NP search, electroweak WIMPs over the full allowed mass range, constraints on “naturalness”

Experiments in Antarctica

- **Unique, U.S. led facility**
  - Only Southern Hemisphere site so far
  - ~500 scientists involved
- **Dark matter, neutrino program, including operation and proposals for future experiments**
- **Synergy with astronomy/cosmology**
- **Future plans**
  - Continue operation of Ice Cube well into 2020’s
  - Dark matter experiments proposed
  - ν experiments proposed