# Journeys Through the Frontier: an introduction

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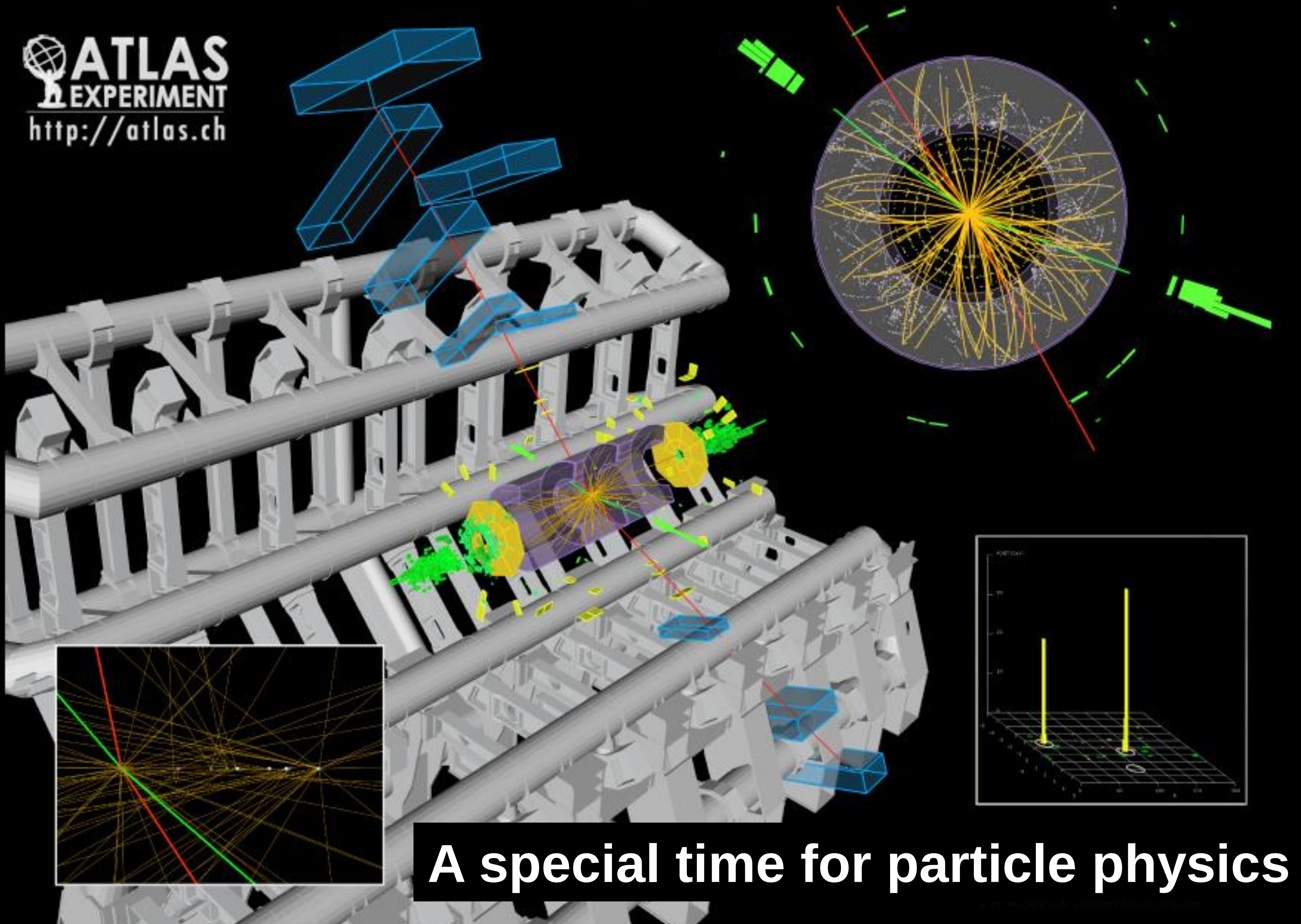
41st SLAC Summer Institute

July 8, 2013

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

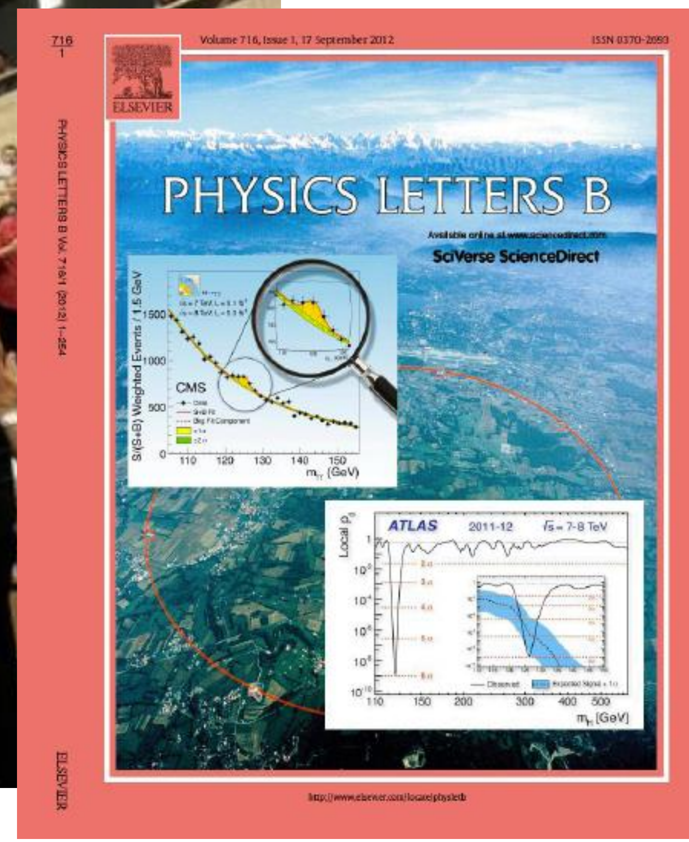
$H \to ZZ \to e^+e^- \mu^+ \mu^-$ candidate event




**A special time for particle physics**

# Fulfillment of a 50 year quest

- Discovery of a Higgs-like particle at the LHC announced on July 4, 2012



## The LHC, the experiments and the observation of a Higgs-like boson is a global phenomena


# PRESS COVERAGE

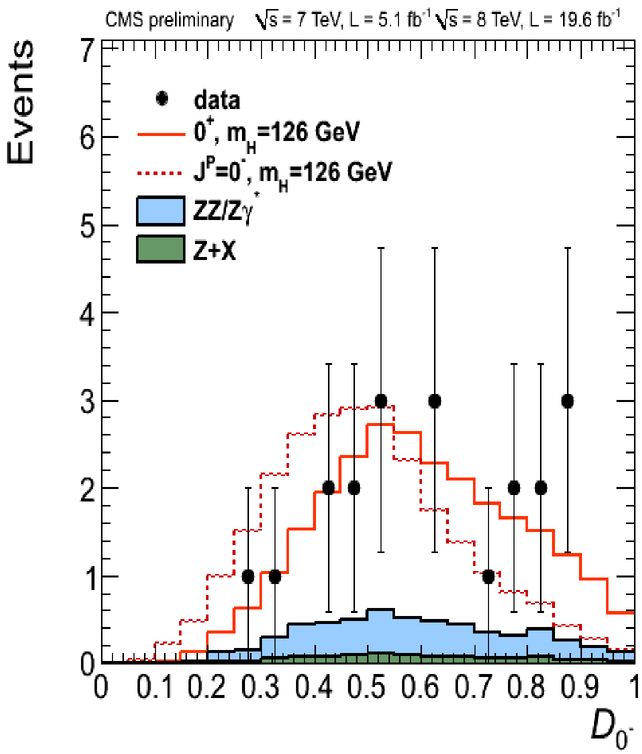
after July 4th seminars at CERN

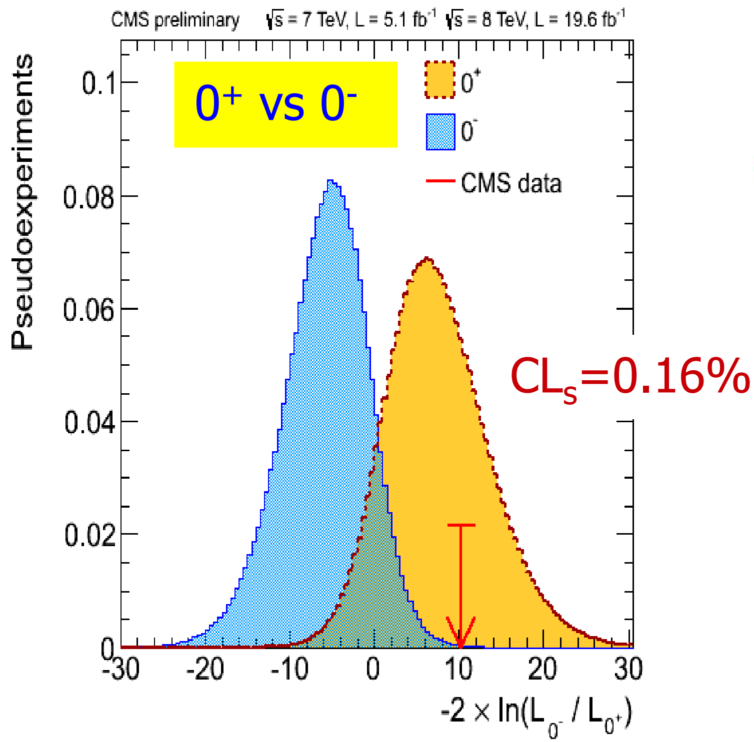
CERN black board, Jul 2012

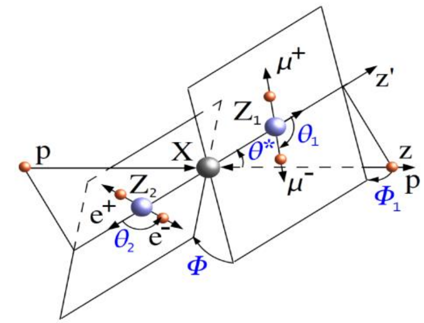
# Latest results from Lepton-Photon 2013

## Spin/parity hypothesis tests: $H \rightarrow ZZ \rightarrow 4l$ channel

Discriminant built to describe the kinematics of production and decay of different $J^P$ state of a "Higgs"

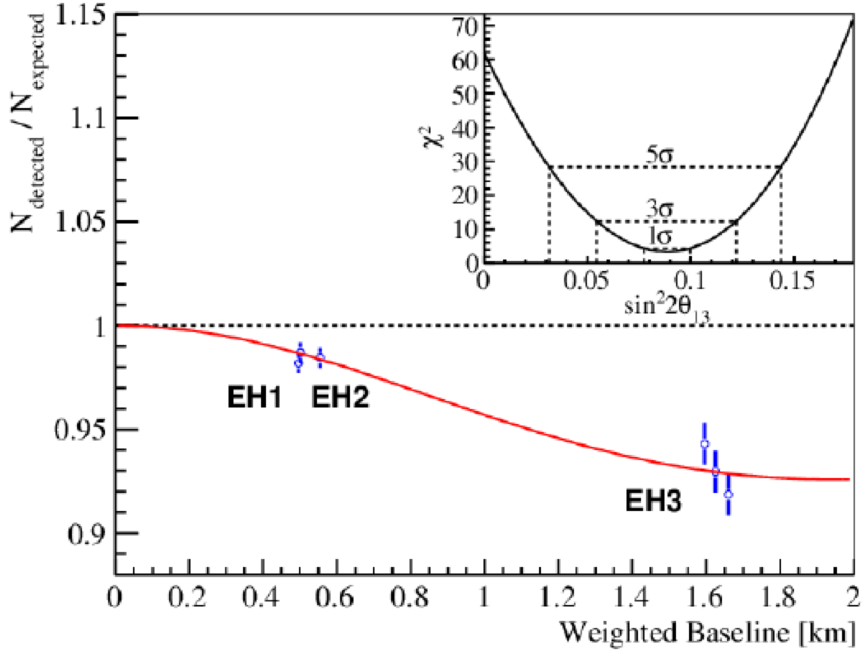


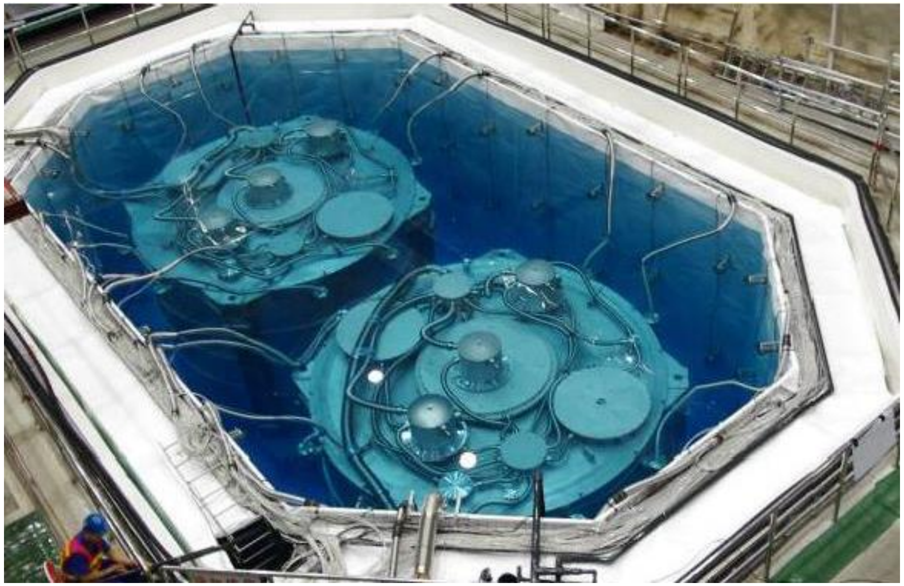



# Filling in the missing piece for neutrino mixing

- Daya Bay neutrino oscillation experiment reports large value for $\theta_{13}$ in March 2012

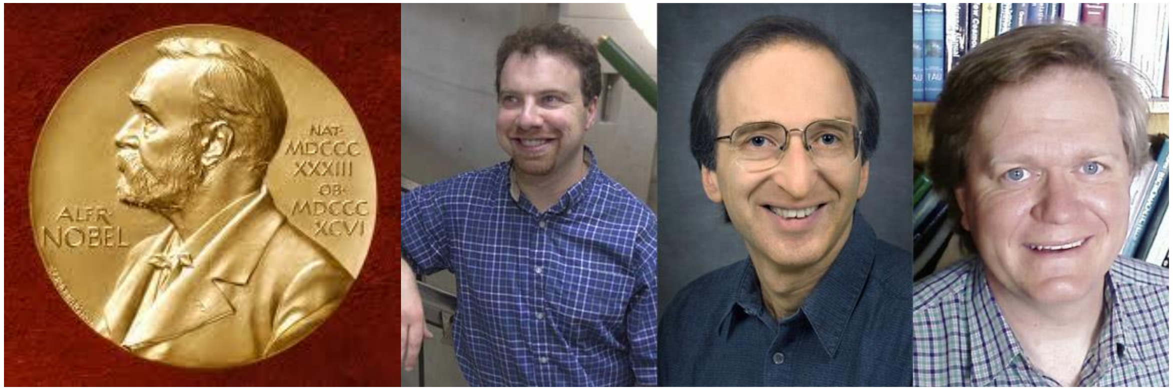


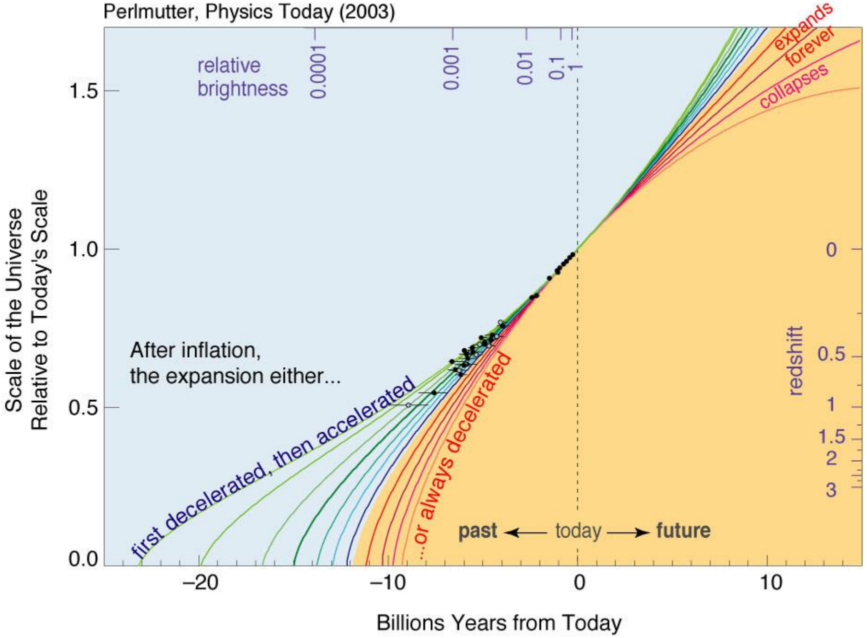
$$\mathrm{Sin}^2 2\theta_{13} = 0.089 \pm 0.010(\mathrm{stat}) \pm 0.005(\mathrm{syst})$$

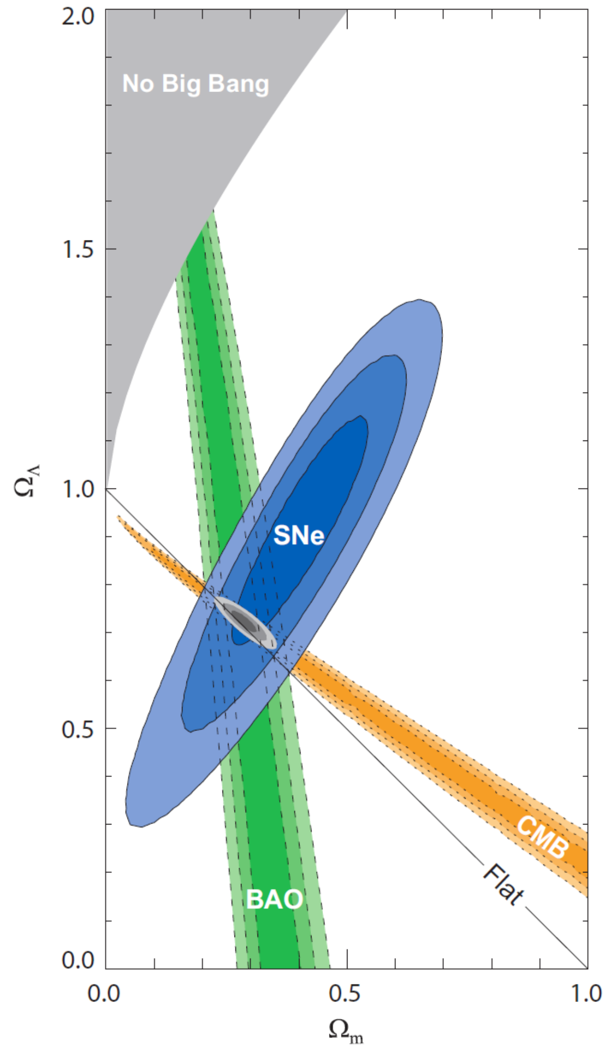
All the ingredients in place for designing experiments to resolve the neutrino mass hierarchy problem and search for CP violation

# Nobel Prize for discovery of dark energy in Oct 2011

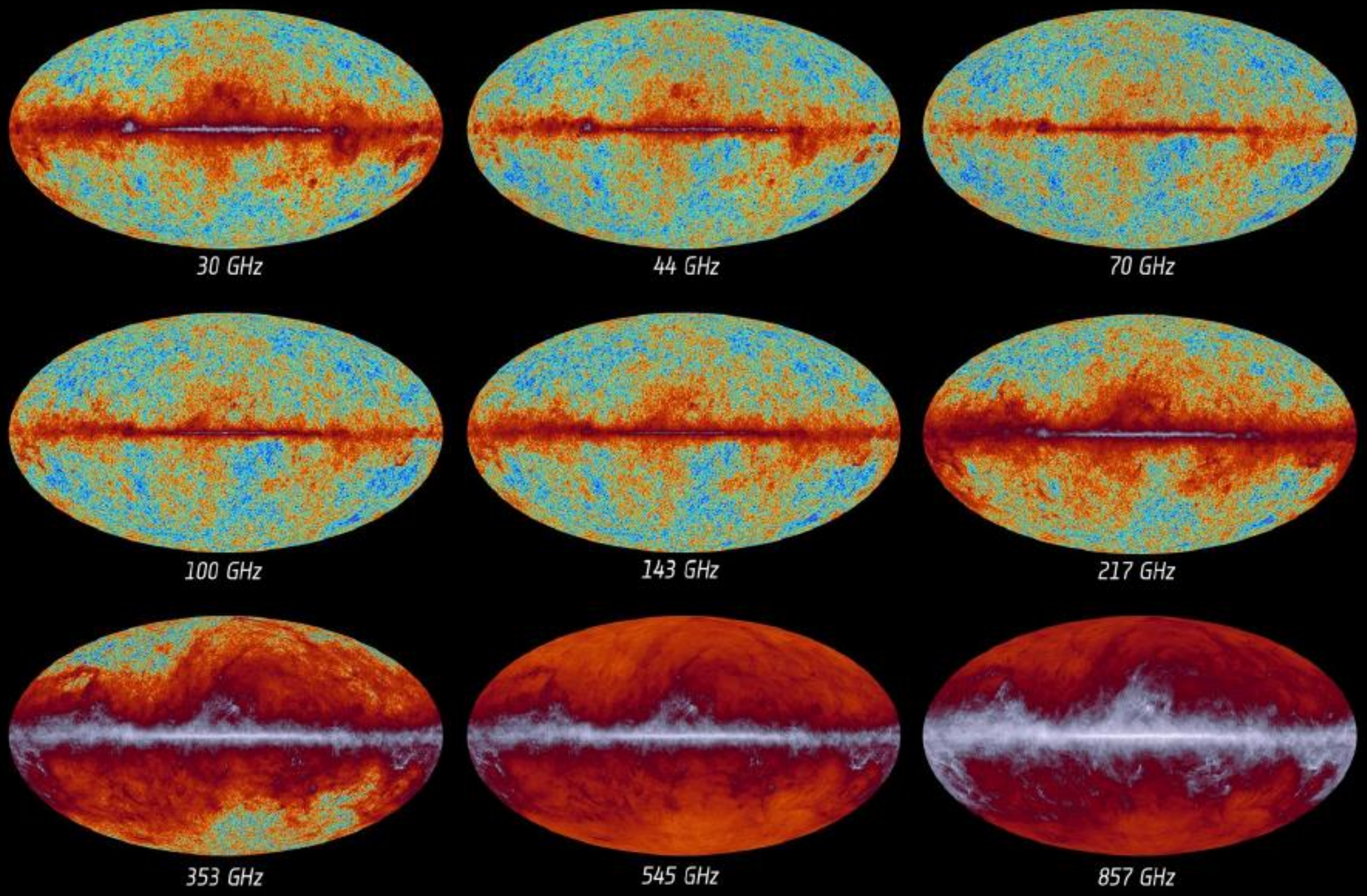



Perlmutter, Physics Today (2003)



# Latest results from Planck: March 21st



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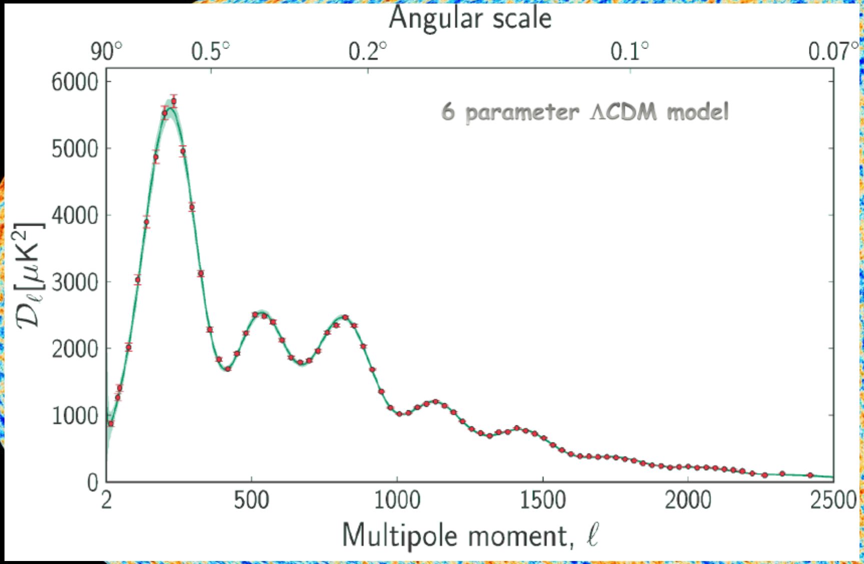
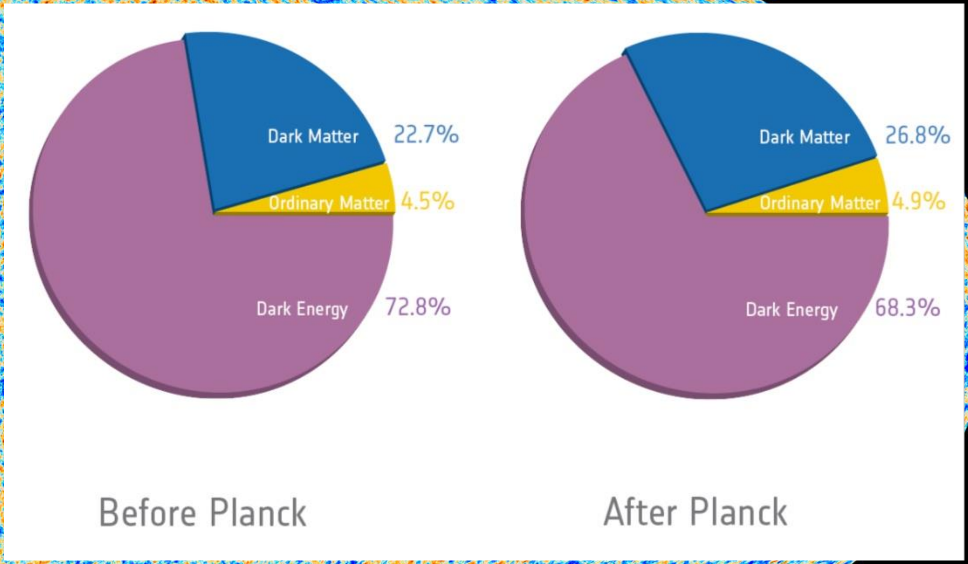



Planck + ACT/SPT + BAO: $n_s = 0.9608 \pm 0.0054$
Ruling out scale invariance at 7 sigma

Cosmic Microwave Background seen by Planck

# Is particle physics over?

- LHC discovery looks very much like the Standard Model Higgs boson, with no sign of SUSY
- Now have a UV complete theory of strong, weak, EM forces possibly valid even up to $M_{\text{Planck}}$
- Cosmology also looks minimal and consistent with a single-field inflationary model

- Where do we go next?

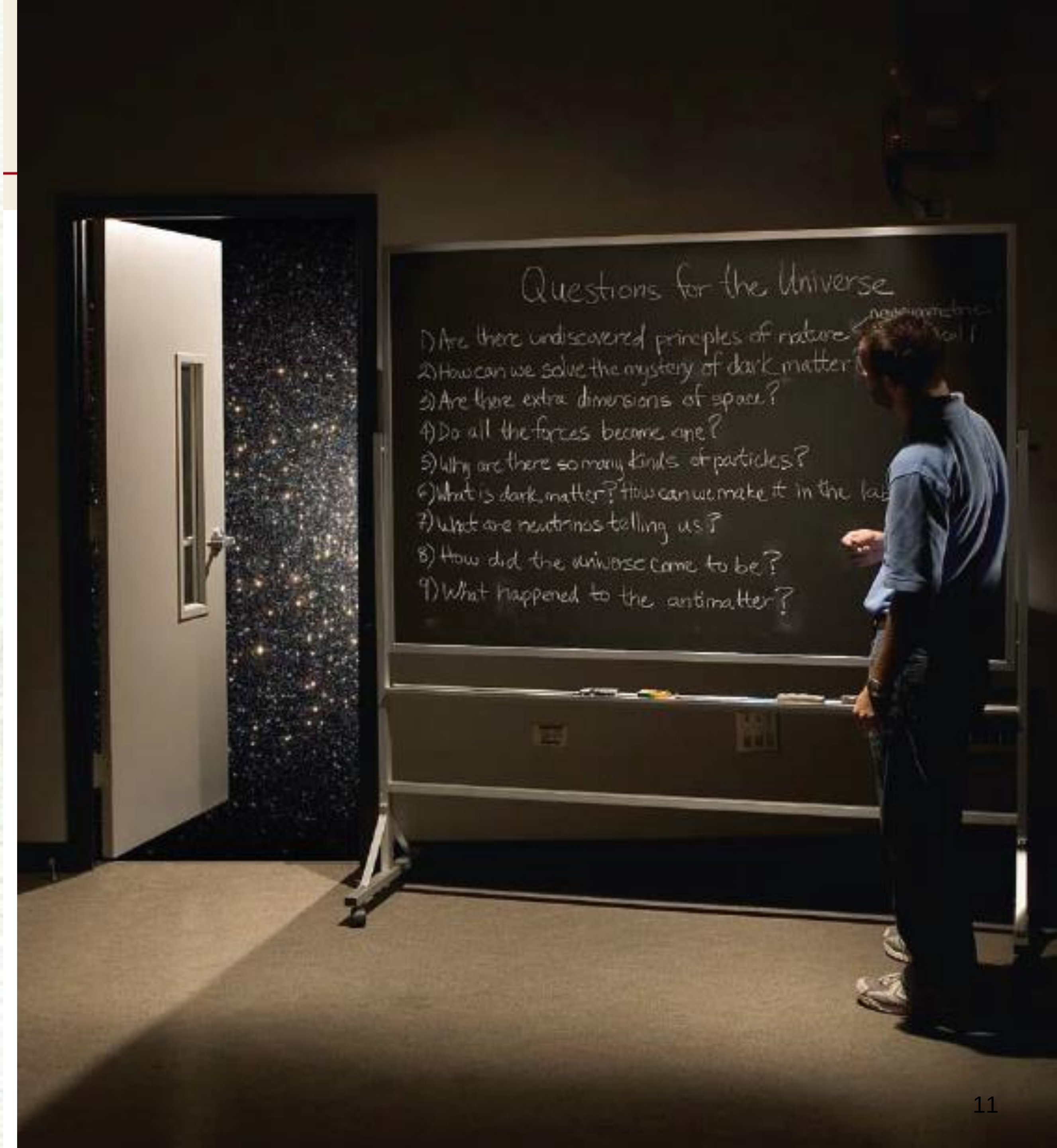
Hitoshi Murayama,
LP2013 outlook talk

## Universal questions

We are asking fundamental questions about the universe:

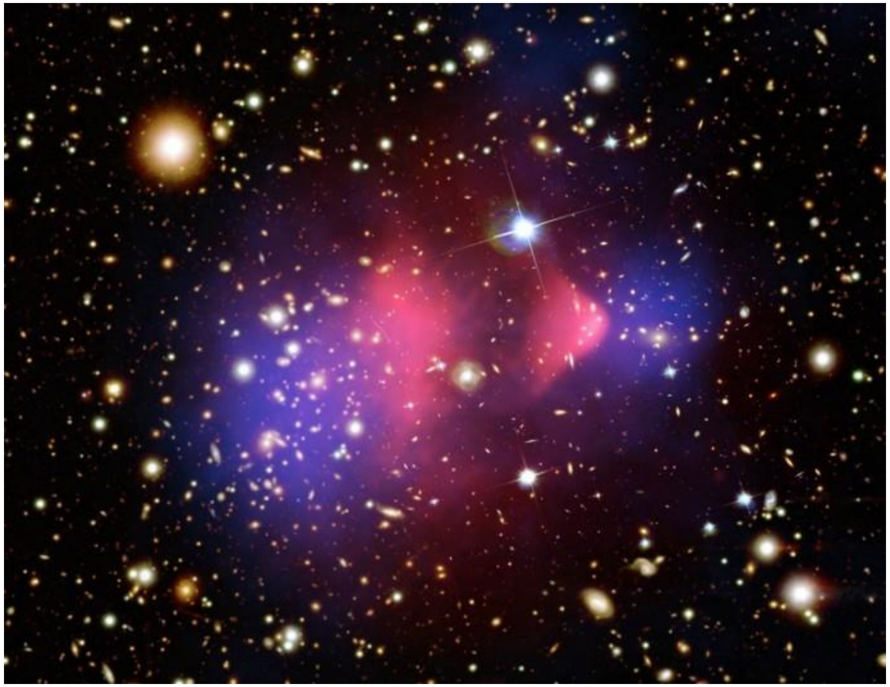
1. Are there undiscovered principles of nature?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter?
   How can we make it in the lab?
7. What are neutrinos telling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

The next-generation particle accelerators will help us to discover the answers.



# Plenty of evidence for physics beyond the SM

- Non-baryonic dark matter
  - » Cold, long-lived, interacts gravitationally
- Neutrino mass
  - » Origin, Majorana or Dirac?
- Dark energy
  - » Cosmological constant or GR?
- Apparently acausal density fluctuations and inflation
- Cosmological baryon asymmetry
  - » New sources of CP: quarks, leptons, proton decay



# Snowmass: create a vision for 2020s and beyond

- Output from Snowmass process
  - Vision of US HEP program through the 2020s and beyond
- What should the program look like if?
  - Supersymmetry is discovered at the LHC
  - The Higgs sector turns out to be complex
  - CP violation or Dark Matter is discovered
  - Dark Energy is not the cosmological constant
- How should we position the US program for the 2030s?
  - Develop technology for a terascale lepton collider to regain Energy Frontier on US soil?
  - Develop the Intensity Frontier to answer critical questions?
  - Provide an answer to the Dark Energy/Dark Matter quest?

# Overarching principles for Snowmass process

- Particle physics & particle astrophysics is global
  - » US program integrated into global plan will be much stronger
- US HEP also needs a strong domestic program
  - » Need a healthy Fermilab as the foundation
  - » Need a strong domestic science program as well, based on LBNE over the next decade, but what beyond?
- Snowmass is about defining great science opportunities
  - » Real world constraints will come later from HEPAP/P5/DOE
- Should emphasize the underlying science questions and their connections

# Broad effort organized around seven working groups

| Working Group | Targeted subgroups [Total] | Conveners |
|---|---|---|
| Energy Frontier | Higgs Boson [6] | Brock (MSU) & Peskin (SLAC) |
| Intensity Frontier | Neutrinos [6] | Hewett (SLAC) & Weerts (ANL) |
| Cosmic Frontier | Direct DM, Indirect DM, complementarity, DE & CMB [6] | Feng (UCI) & Ritz (UCSC) |
| Facility Capabilities | Frontier lepton & gamma colliders [8] | Barletta (MIT) & Gilchriese (LBNL) |
| Instrumentation Frontier | Sensors, detector systems, DAQ & electronics [6] | Demarteau (ANL), Nicholson (Mt. Holyoke), Lipton (Fermilab) |
| Computing Frontier | Astrophysics & Cosmology [12] | Bauerdick (Fermilab) & Gottlieb (Indiana) |
| Education & Outreach | | Bardeen (Fermilab) & Cronin-Hennessy (Minn) |

# Cosmic Frontier Working Group meeting

- Hosted by SLAC on March 6-8 [web site]
  - » Over 300 registered participants
  - » Overlap with Neutrino subgroup meeting on March 6-7 with another 100 participants
  - » Plenary and large number of parallel sessions
  - » Exciting program with many young scientists in attendance

| | | | | | |
|---|---|---|---|---|---|
| 11:00 | Direct Searches for Dark Matter in Perspective<br><br>More Precise Computations of WIMP Scattering<br><br>New Directions for Direct Detection of Dark Matter | Introduction to CF2<br>*Sycamore, SLAC*<br><br>Introduction to Complementarity<br><br>Overview: Gamma Rays<br>*Sycamore, SLAC* | Sikivie *SIKIVIE*<br>An Argument that the D...<br><br>*GIANNOTTI*<br>Giannotti, Astrophy...<br><br>Kyu Jung Bae, Cosmology of SU... | Welcome to CF5<br>*Kavli Auditorium, SLAC*<br><br>Dark Energy in the 2020's<br>*Kavli Auditorium, SLAC* | A personal view of present and future theory on the basic nature of space and time<br><br>Experimentally testable ideas about quantum geometry |
| 12:00 | Discussion | Overview: Neutrinos<br><br>Overview: Cosmic | *Aaron CHOU*<br>The Fermilab Holometer | CMB Science | |

# From John Carlstrom's CMB summary talk

***Inflation-era High Energy Physics and neutrino constraints via CMB measurements***

***Gearing up for a Stage IV CMB polarization experiment***

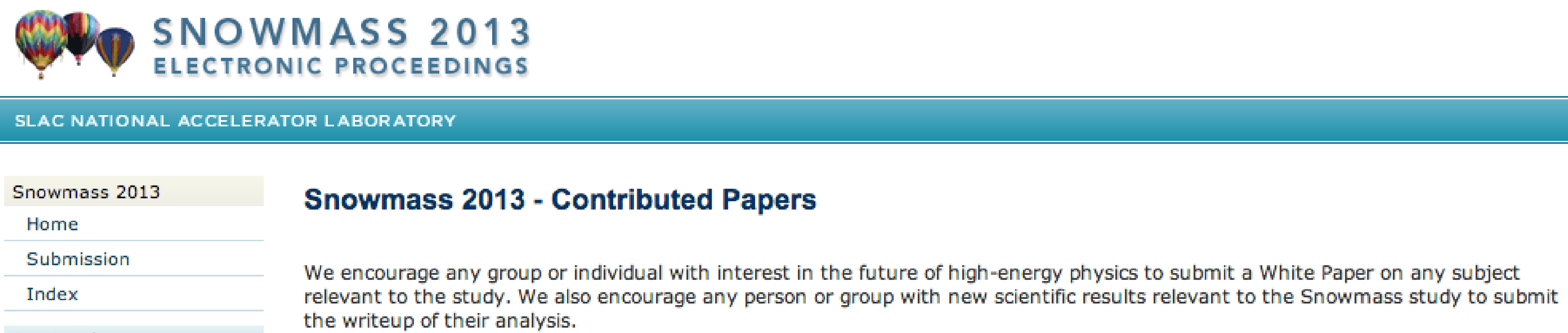
**WARNING**

**Read before opening**

1) This is a quickly assembled talk. Many of the future projections are gross estimates of work in progress, or from someone in the audience during one the sessions, or rumors from experiments.
2) The momentum and excitement of the field is very real and highly addictive.

# How to Submit an Individual Contribution

- https://www-public.slac.stanford.edu/snowmass2013/




- Submit to the arXiv
- Register @ Snowmass proceedings site and link arXiv number
- Revisions handled through the arXiv
- Deadline for contributions: 30 Sep, 2013
- SLAC involved in many white paper submissions across spectrum of working groups

# Planned output from Snowmass process

| Deliverables from Snowmass | Timeline |
|---|---|
| Each subgroup in each frontier produces 30-50 page subgroup write-up | Draft by July 1 |
| Each subgroup in each frontier produces 5-6 page subgroup summary | Draft by start of Snowmass |
| Each frontier combines subgroup summaries into ~30 page frontier write-up | Draft by start of Snowmass |
| Each frontier produces 5-6 page frontier summary | Draft by end of Snowmass |
| Snowmass book [240 pages]: 30 page overall summary and 7 frontier summaries (7x30 pages) | Draft by end of Snowmass + few days |
| Snowmass summary | Present at DPF2013 |

# Draft Block Program for Snowmass program

| Time | 29 July | 30 July | 31 July | 1 Aug | 2 Aug | 3 Aug | 4 Aug | 5 Aug | 6 Aug |
|---|---|---|---|---|---|---|---|---|---|
| morning | Grand Plenaries | **Subgroup Parallel Sessions and Joint Parallel Sessions** | | | | | | Grand Plenaries | |
| early afternoon | | **Subgroup Parallel Sessions and Joint Parallel Sessions** | | | | | | | |
| late afternoon | | Grand Plenary Sessions and Discussions | | | | | | | |
| evening | | **Parallel DISCUSSIONS** | | | | | | | |

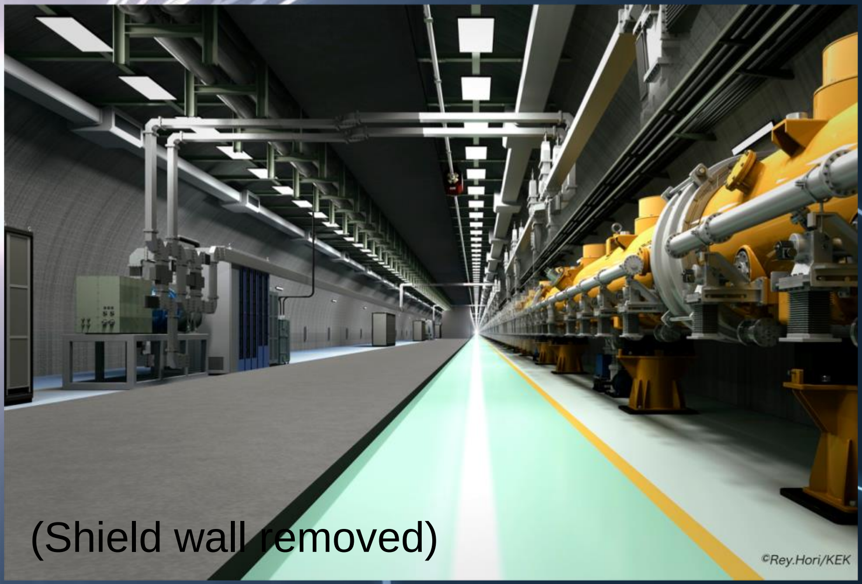
# Multi-step planning process for US HEP program

- HEP Facilities Subpanel: Winter 2013
  - » Advise DOE/SC on the scientific impact and technical maturity of planned and proposed SC Facilities (>$100M)
- DPF/CSS2013 “Snowmass”: Fall 2012 to summer 2013
  - » Identify compelling HEP science opportunities
  - » Not a prioritization but can make scientific judgments
  - » Extended set of working group/subgroup meetings culminating in “Snowmass” meeting in Minneapolis
- HEPAP/P5: Fall 2013 to spring 2014
  - » Develop new strategic plan and priorities for US HEP under various funding scenarios
- Parallel to European & Japanese planning efforts

# Directly producing new physics at the Energy Frontier

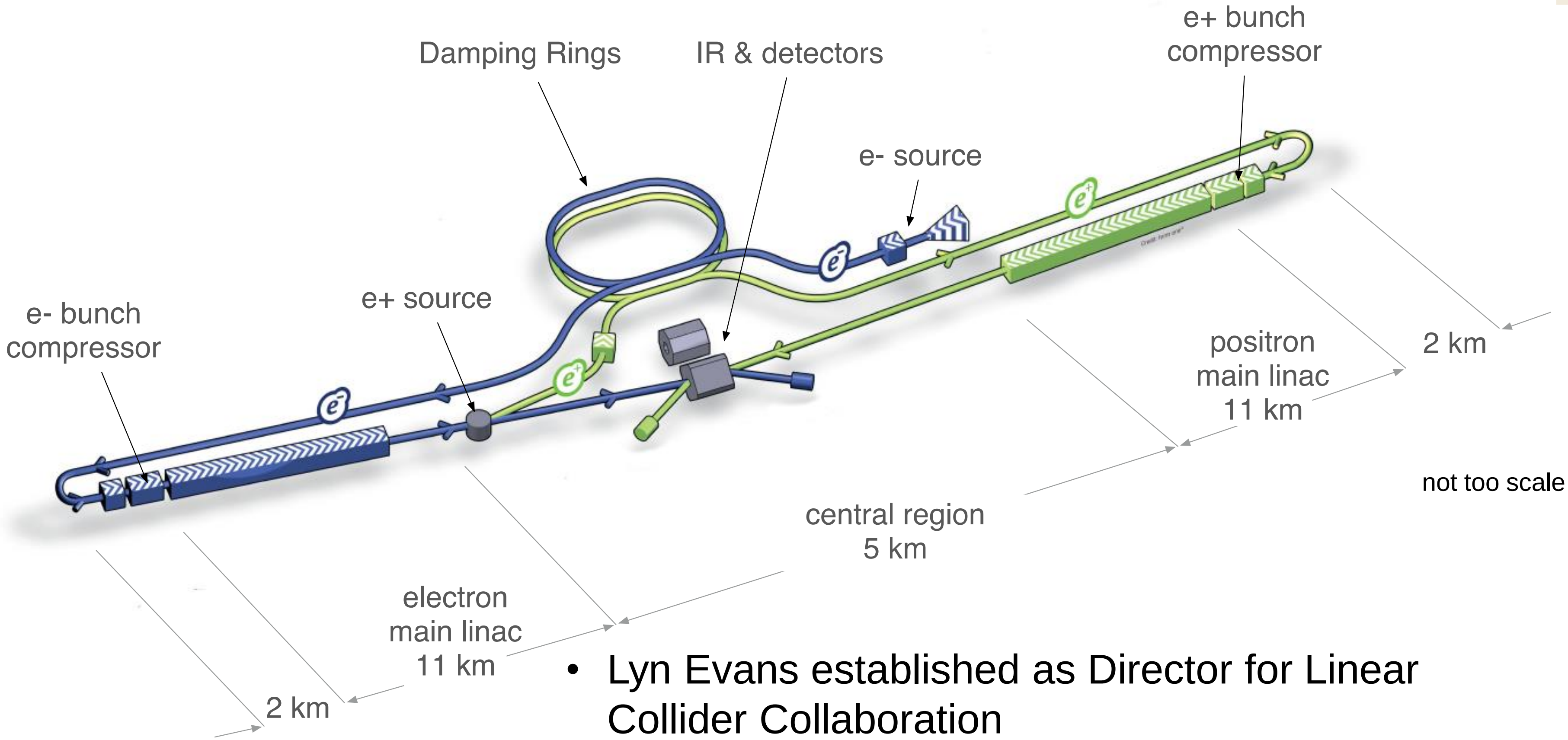
Large Hadron Collider @ CERN

International Linear Collider in Japan



# Detailed Baseline Design for the ILC now completed

SLAC




not too scale

- Lyn Evans established as Director for Linear Collider Collaboration
- Process underway in Japan to select a site
- Japanese decision expected this year on intention to host the ILC

# Higgs big questions

- How many Higgs bosons are there
- Does the Higgs couple to matter particles proportional to their masses
- Is the electroweak scale stabilized by new symmetries, new forces, new particles

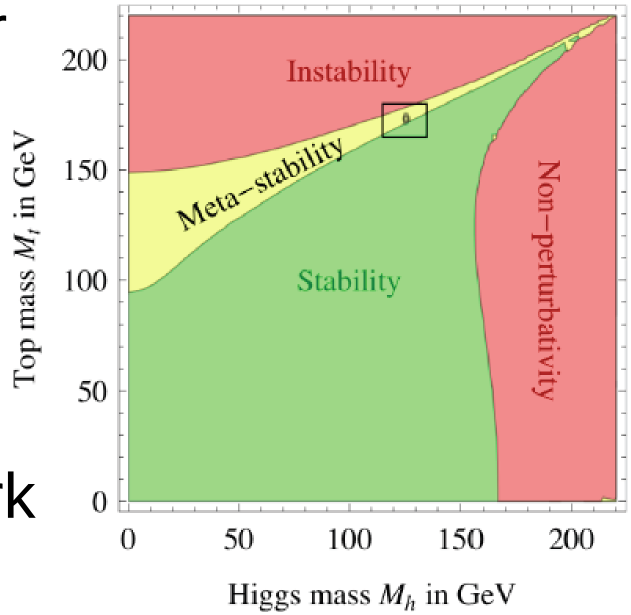
Already this makes it pretty obvious what you need:

- Direct searches for new particles: LHC
- Indirect searches for new particles: g-2 etc.
- Precision measurements of Higgs and other particle properties: ILC

Joe Lykken, ILC Worldwide Event

# Higgs Connections

- Is there a Higgs portal to Dark Matter
- Does the Higgs make the Universe unstable
- Did the Higgs trigger the genesis of matter
- How does the Higgs talk to neutrinos
- Is the Higgs related to inflation or dark energy

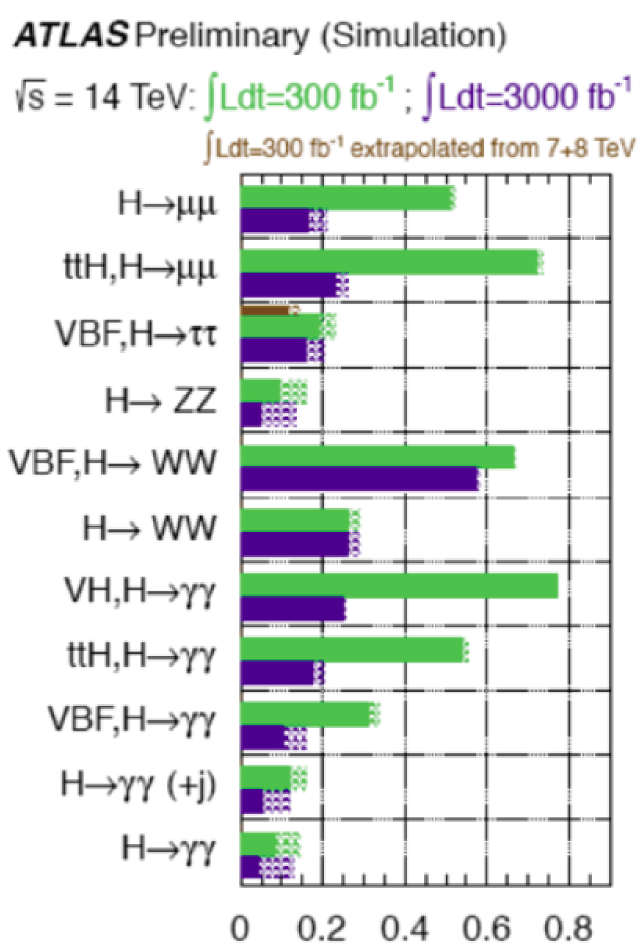



- These ambitious questions motivate a multi-decade worldwide experimental program across all of the frontiers of particle physics
- ILC, integrating and extending the discoveries of this global program, will be a key unlocking the deepest secrets of Nature

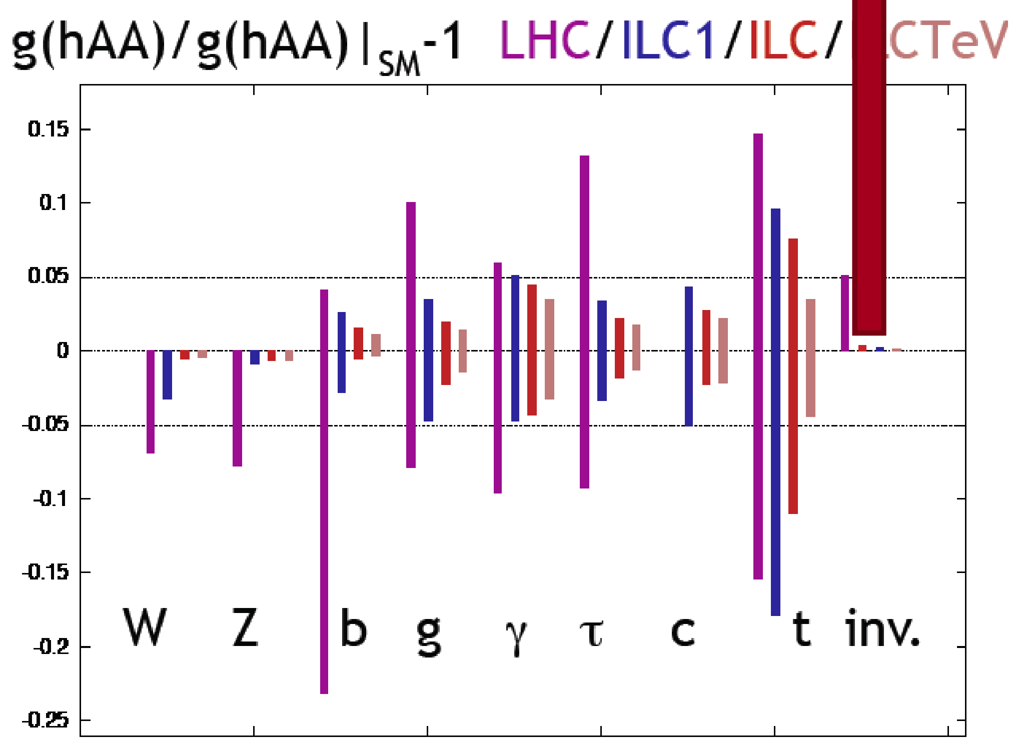
Joe Lykken, ILC Worldwide Event

# Precision measurements of Higgs couplings

SLAC

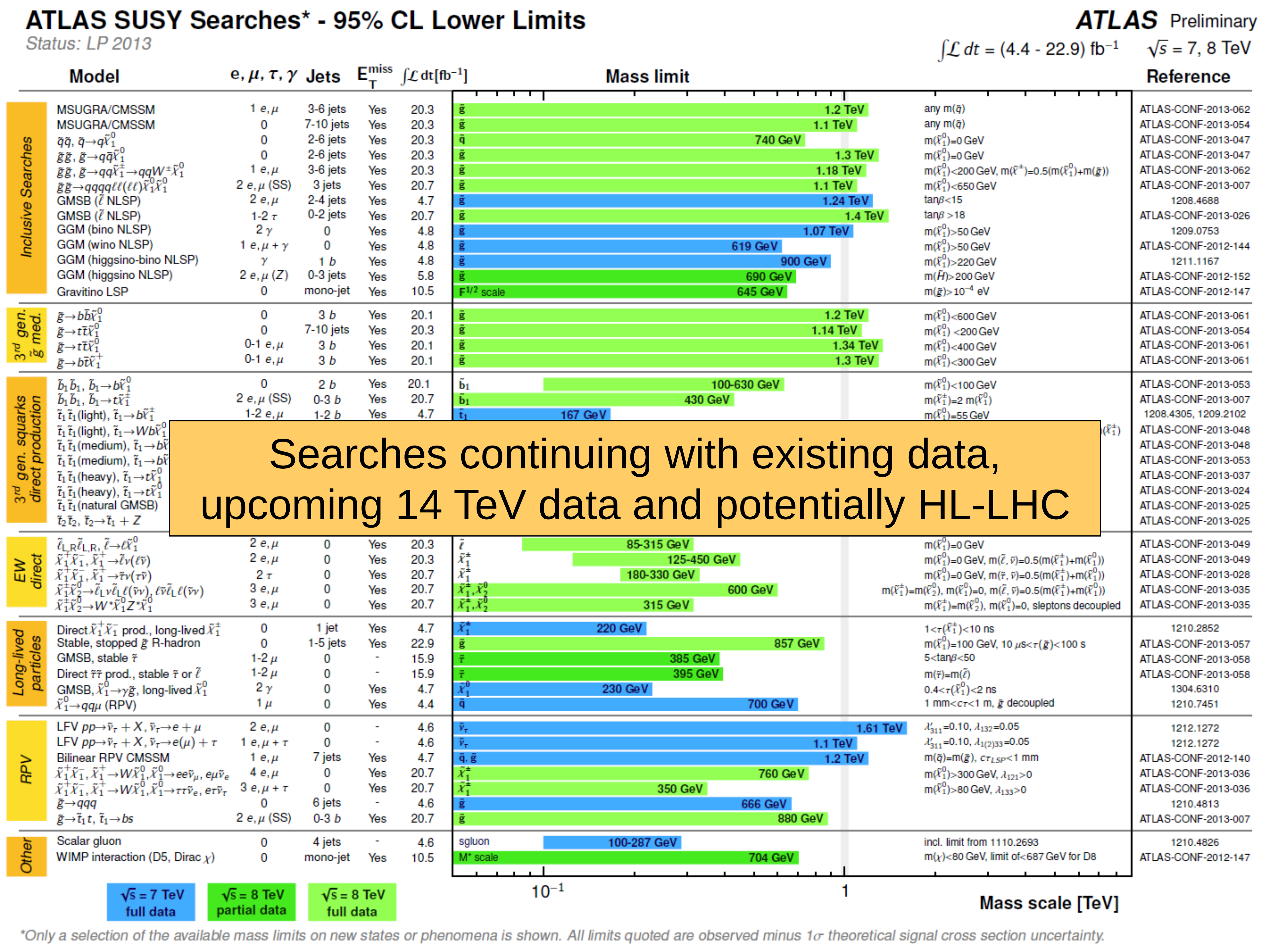



Dark Matter?




Energy reach $\propto$ (precision)$^{-1/2}$

For Snowmass: elucidate the discovery reach of the HL-LHC and the impact of precision physics with the ILC

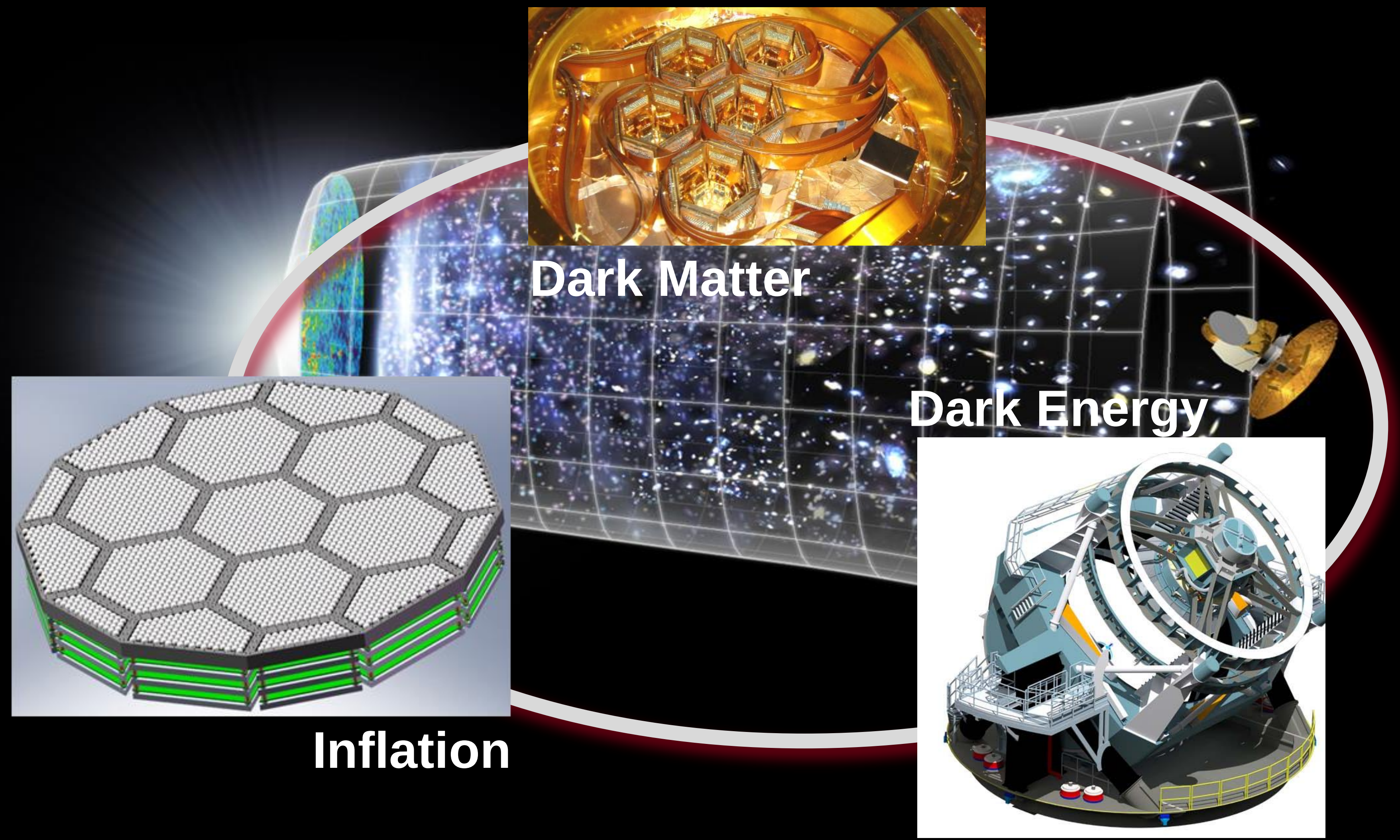



Searches continuing with existing data, upcoming 14 TeV data and potentially HL-LHC

# Project Questions: Energy Frontier

- EF1: Under which circumstances is a fourth generation still allowed? If a b'-quark is discovered at 850 GeV, what experiment would you perform to study its properties?
- EF2: Compare and contrast the Higgs coupling measurements at the ILC, LHC upgrades, and a potential muon collider. Describe the sensitivity to potential BSM effects in each Higgs coupling.
- EF3: Compute the search reach at future colliders for a new heavy neutral gauge boson that has the same fermionic couplings as the Standard Model Z, taking into account experimental uncertainties. Which collider has the best reach and why?
- EF4: If a signal is observed at the LHC that is consistent with a 750 GeV stop-squark decaying into a top-quark plus missing energy, what other experiments would you perform to determine its characteristics and the model from which it arises?

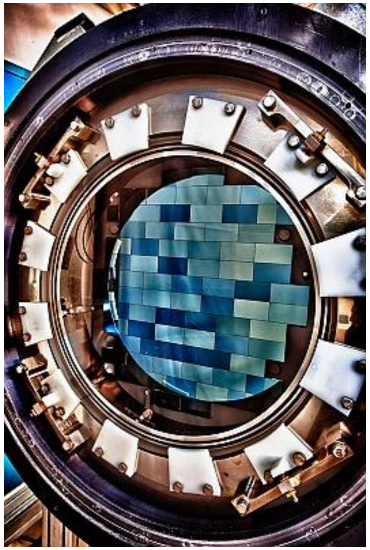
# Fundamental physics and cosmology questions addressed on Cosmic Frontier



# Strategy for dark energy investigations

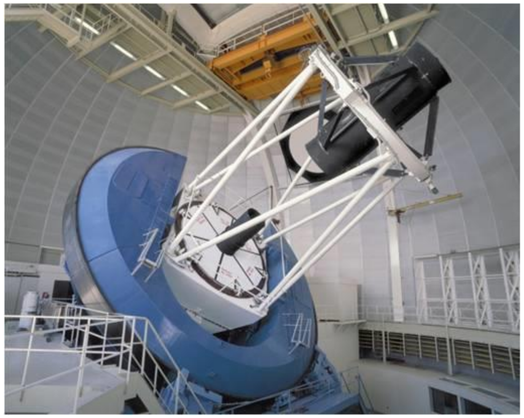
Stage III: Dark Energy Survey

– Survey 2013-2018



Stage IV BAO: MS-DESI

– Massively parallel spectroscopic survey 2017-2022

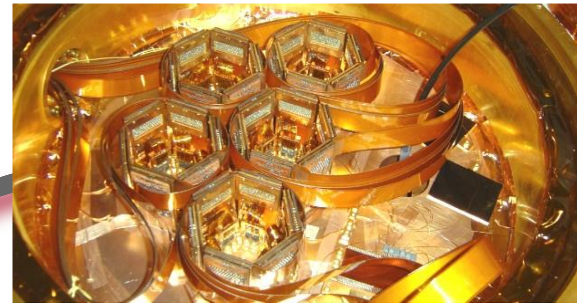


Stage IV: Large Synoptic Survey Telescope

– Construction 2014-2019
– Commission: 2020-2021
– Survey: 2022-2031

For Snowmass: need to understand synergies for enhanced dark energy program, e.g. Euclid, and strategy beyond LSST

# Strategies in searching for Dark Matter

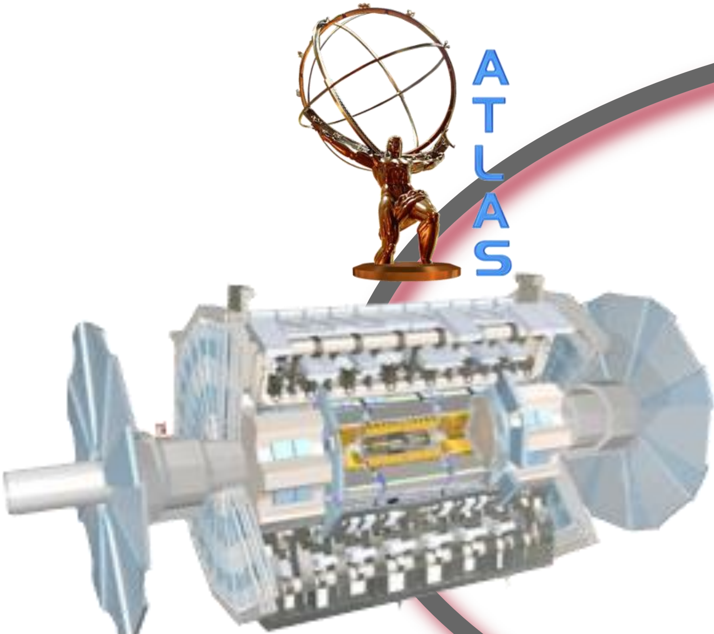


Direct Detection:
nuclear recoils

SuperCDM @ Queen's

LUX

darkside
two-phase argon TPC for Dark Matter Direct Detection



Production of
new particles

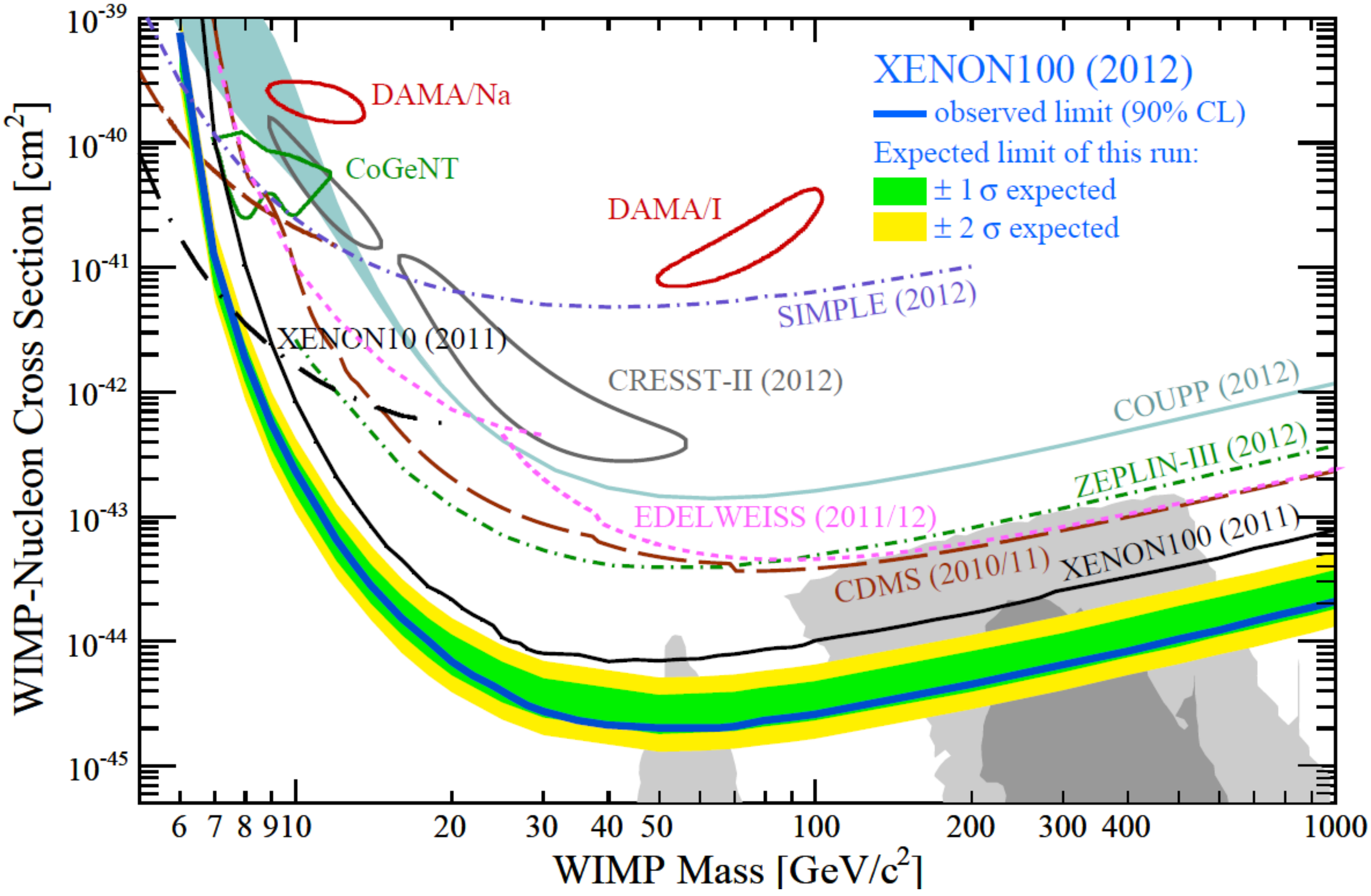
Fermi
Gamma-ray
Space Telescope

cta
cherenkov telescope array

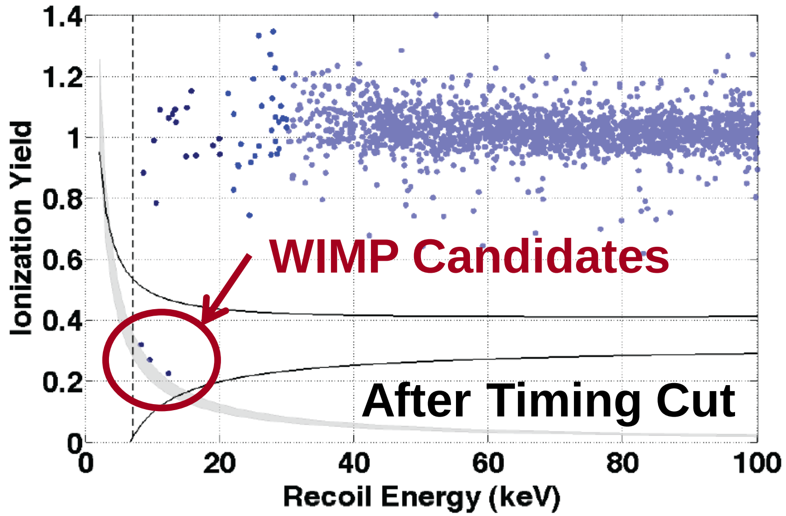
For Snowmass: need overall strategy for portfolio of direct & indirect dark matter searches

Indirect Detection:
annihilation products

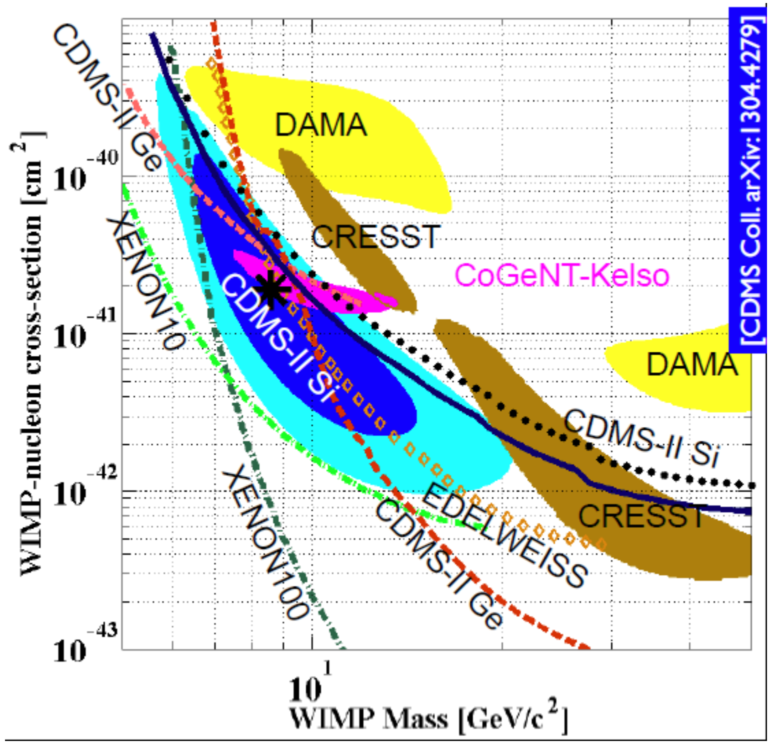
# Existing direct detection searches for dark matter



# Possible hints for low-mass WIMP from CDMS




CDMS II silicon data

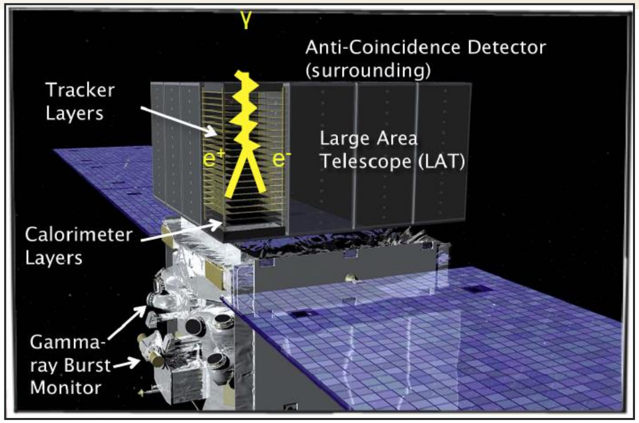


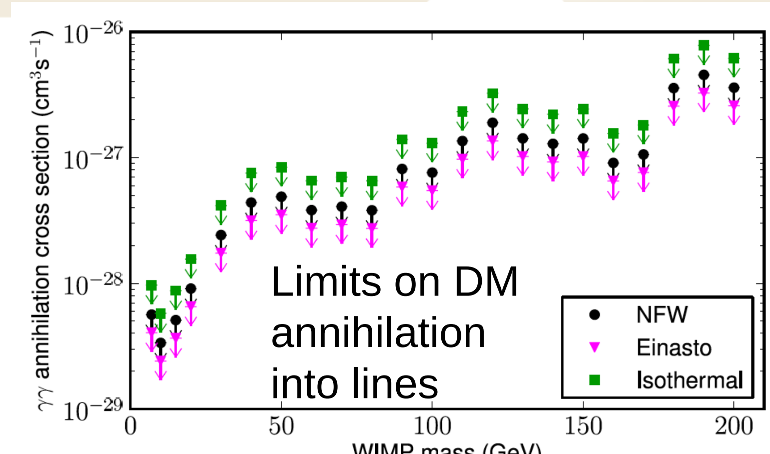

- Most likely 8.6 GeV WIMP mass & $1.9\times10^{-41}$ $cm^2$ cross section
- Consistent with earlier CDMS Si & Ge data
- Consistent with WIMP interpretation of Cogent
- In tension with limits from Xenon-10, Xenon-100

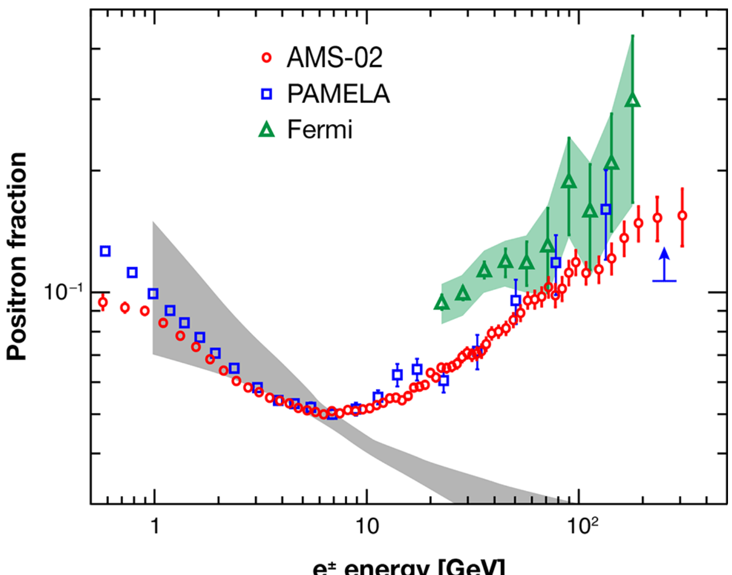
# Strategy for future direct detection DM experiments

- DOE & NSF intend to make G2 technology selection(s)
  - Planned for fall 2013, with construction FY2014-FY2016
  - FY2013 funded R&D includes SuperCDMS based on cryogenic Ge sensors, LUX/LZ & ZENON-1K based on liquid Xenon, DarkSide based on liquid Argon, COUP bubble chamber, and ADMX (Axion search)
- Discovery would lead to new round of G3 experiments aimed at understanding properties of Dark Matter
  - Desirable to search for signals through production and/or indirect methods
  - Need to understand scalability of current technologies, develop new approaches for directional detection

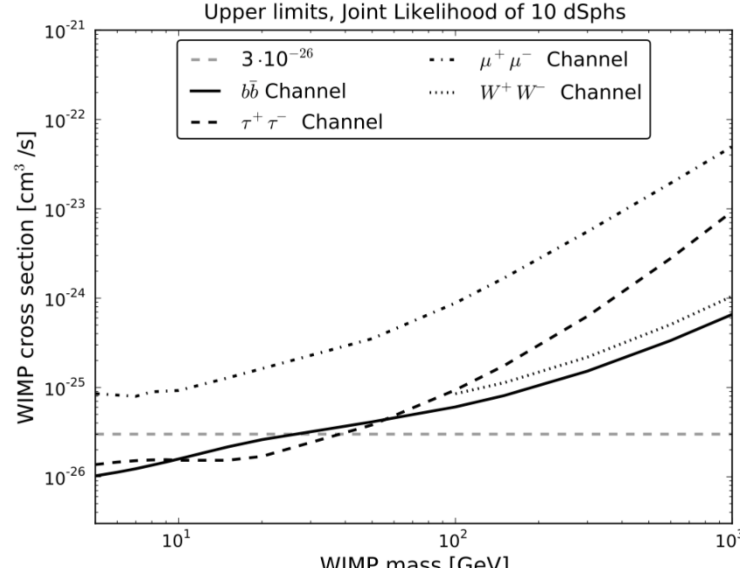
# Existing indirect detection searches for dark matter



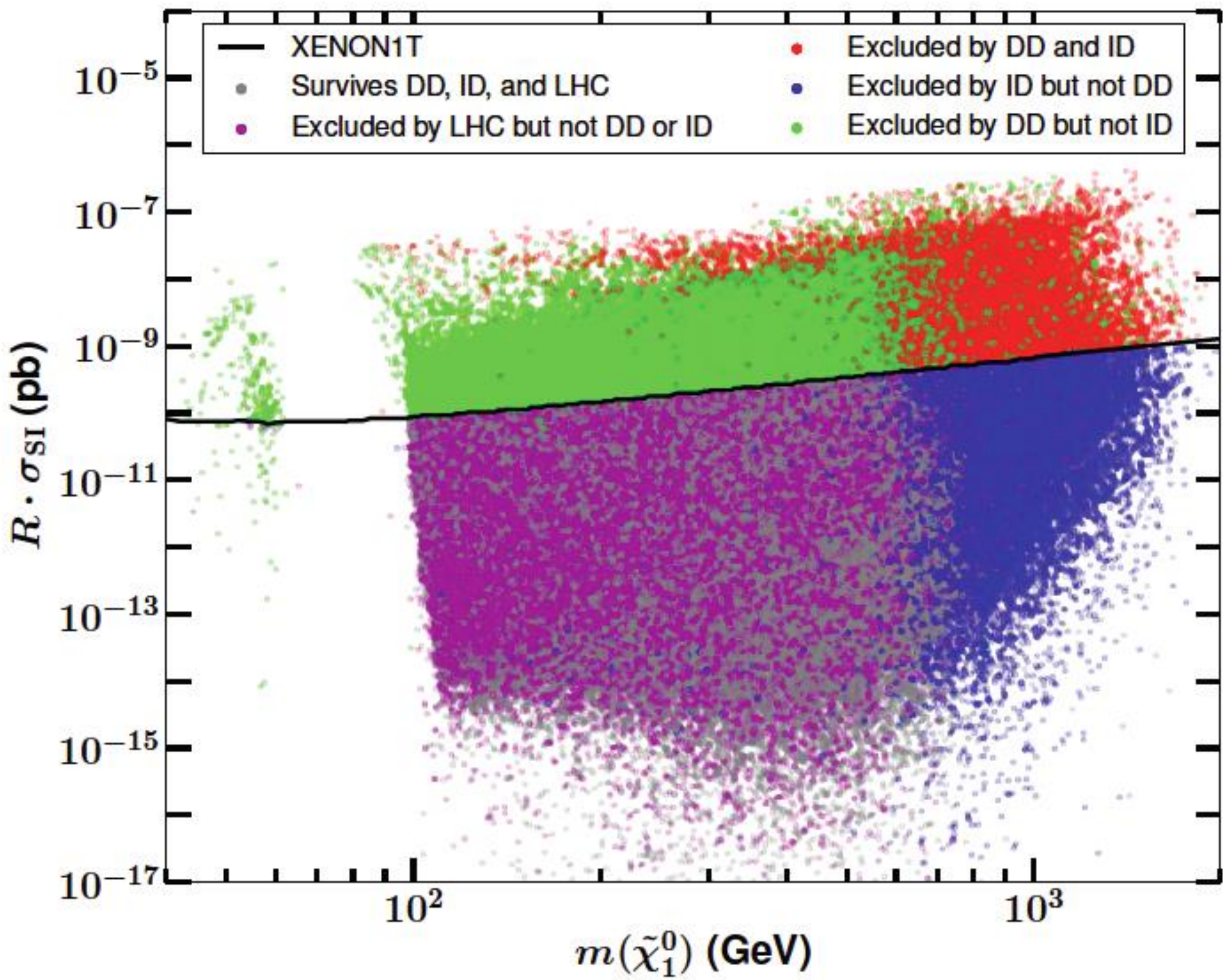




Positron fraction > 100 GeV




Fermi LAT limits on annihilation from Dwarf Galaxies

# All three techniques are needed

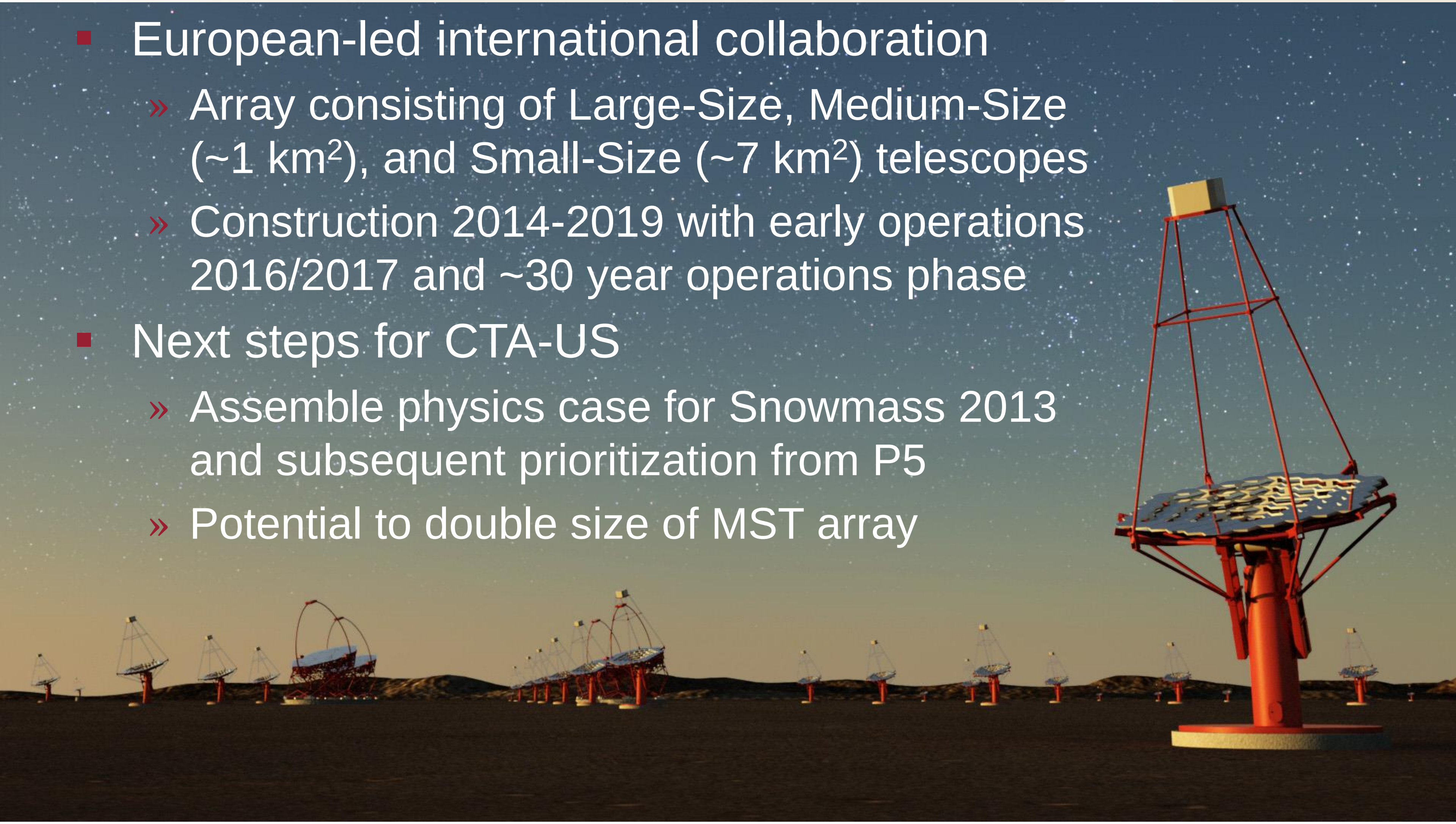



Allowed SUSY models

Mass [GeV]

# Future of indirect detection DM: Ground-based CTA

- European-led international collaboration
  - » Array consisting of Large-Size, Medium-Size ($\sim$1 km$^2$), and Small-Size ($\sim$7 km$^2$) telescopes
  - » Construction 2014-2019 with early operations 2016/2017 and ~30 year operations phase
- Next steps for CTA-US
  - » Assemble physics case for Snowmass 2013 and subsequent prioritization from P5
  - » Potential to double size of MST array



# Strategy for evolution of CMB polarization experiments

SLAC

## *B-modes timeline*

From J. Carlstrom, CF Working Group Meeting

- 2009: $r < 0.7$ (BICEP) Chiang et al, 0906.1181
- 2012: no detections of inflationary or lensing B-modes

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- 2013: $r \lesssim 0.1$ from Inflationary B-modes (BICEP II) ?
- 2013: Stage II experiments detect lensing B-modes
- 2013+ Stage II experiments $\sigma(r) \lesssim 0.03$
  and $\sigma(\Sigma m_\nu) \sim 0.1$ eV from lensing B-modes
- 2016+: Stage III achieve $\sigma(r) \lesssim 0.01$ & $\sigma(\Sigma m_\nu) \sim 0.05$ eV; measure lensing B-modes to $L \sim 800$ with $s/n > 1$; allow "delensing" of inflation B-modes

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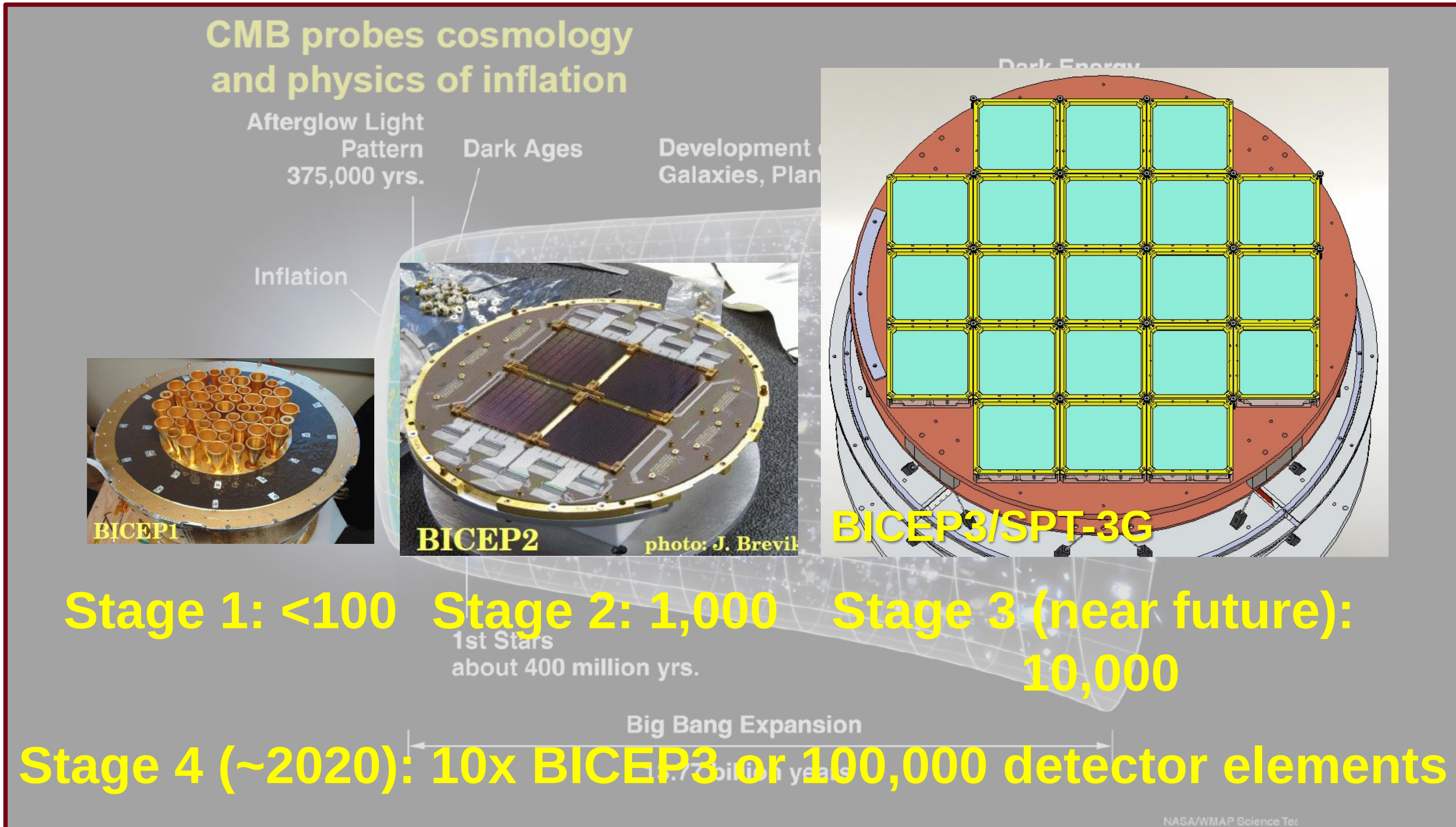
- 2020+: **Stage IV goal to reach $r \sim 0.001$ (or better?)**

For Snowmass: develop science case and strategy for new opportunities such as probing inflation through CMB B-modes

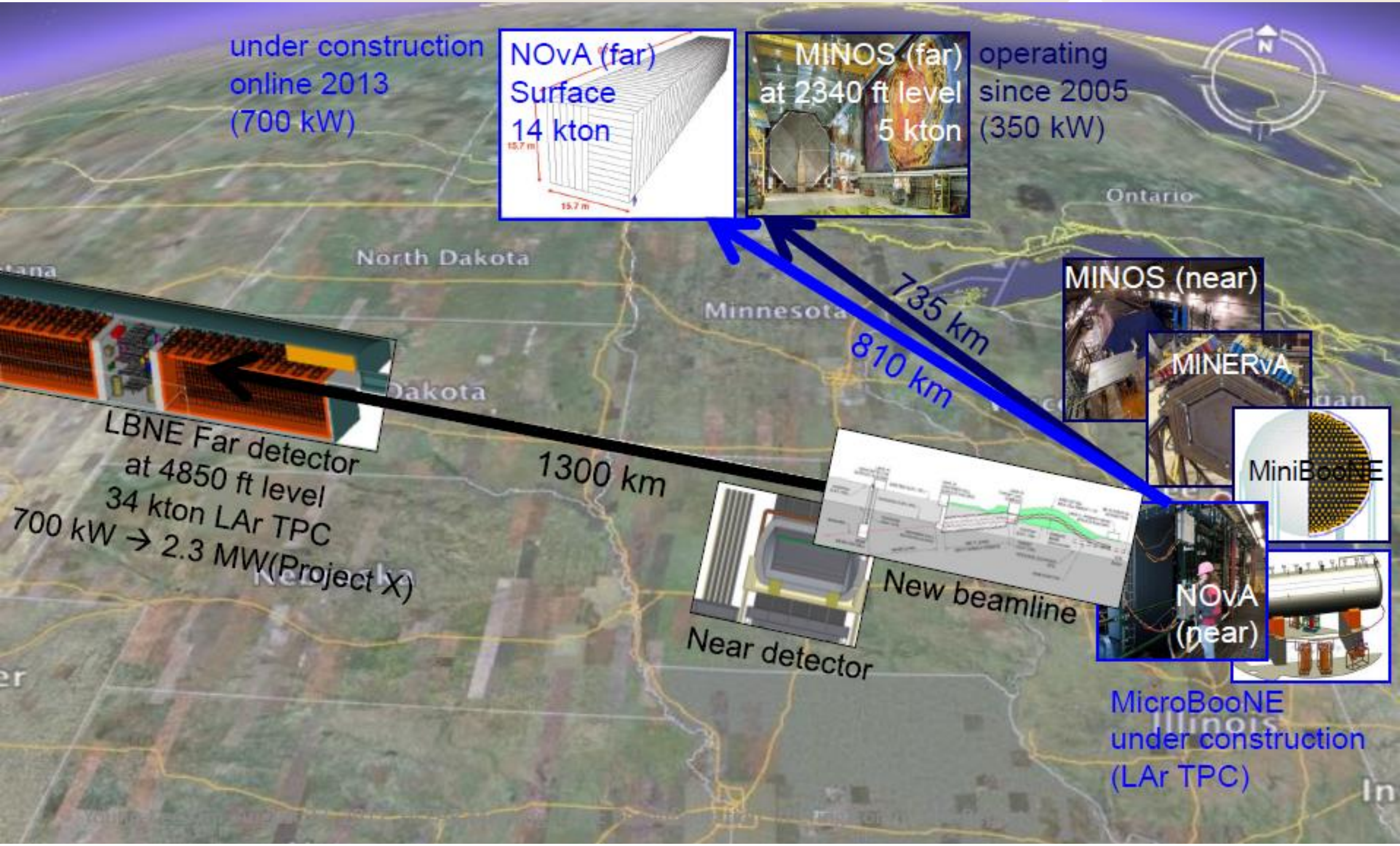
# Probing inflation with CMB: Key science problem at DOE laboratory scale



# Project Questions: Cosmic Frrontier

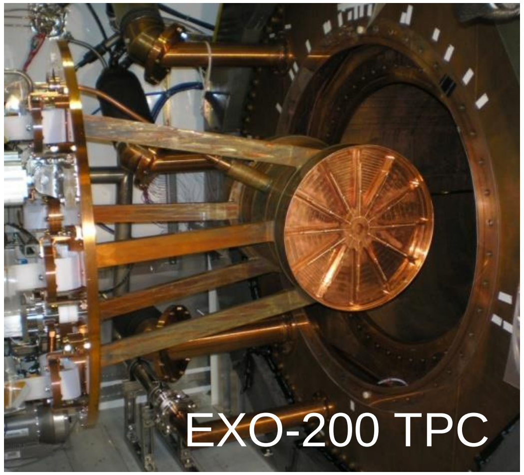
- CF1: If there is an ~8 GeV dark matter WIMP candidate, what follow up experiments would you perform to verify its existence and study it's properties?
- CF2: What experiment would you perform to clarify the situation of the 130 GeV gamma ray line? What is the prospect for studying this phenomena in the lab?
- CF3: What experiments can be built to prove whether dark energy arises from the cosmological constant and how would you probe such models?

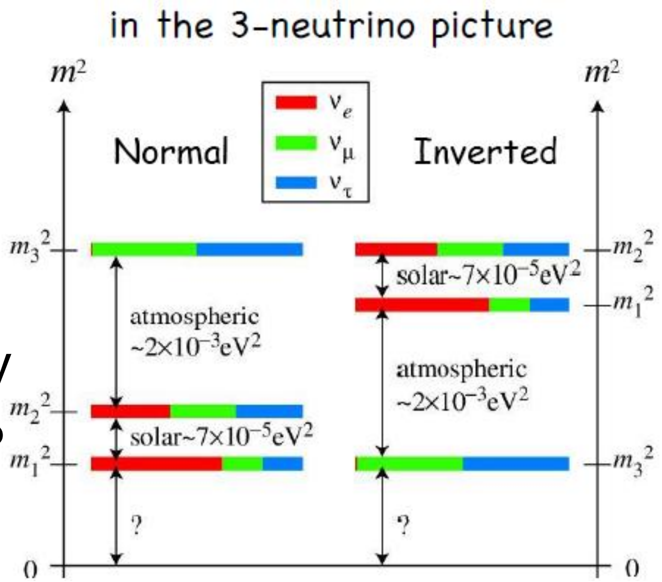
# Probing for new physics on the intensity frontier



# Neutrinos offer many windows into new physics

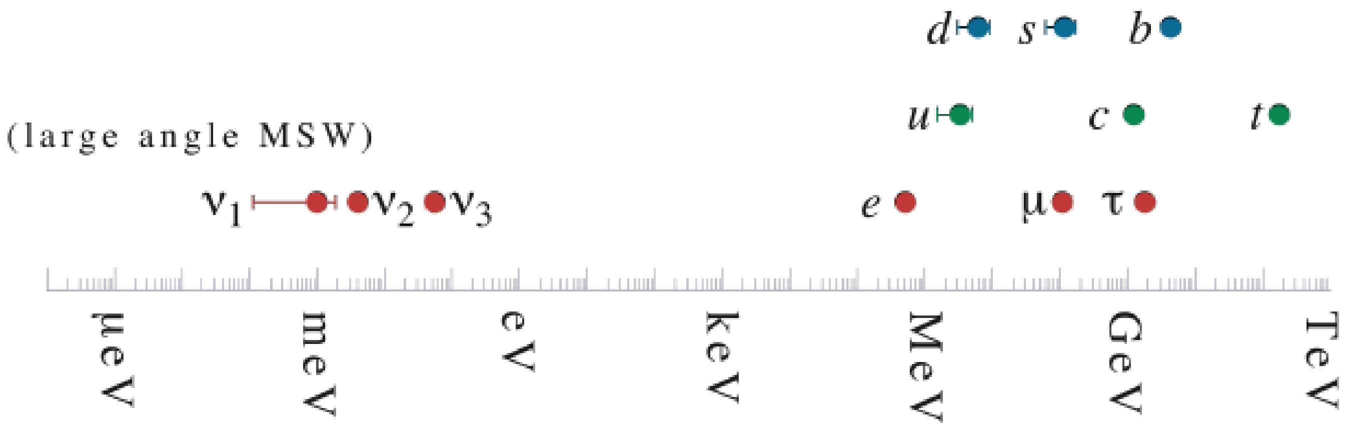
- What is the nature of the neutrino? Majorana or Dirac
  - If Majorana, neutrinoless double-beta decay should be observed
- What are the values of the masses and flavor mixings?
  - Mass hierarchy, origin of mass through Higgs terms (Dirac) or Majorana terms
  - See-Saw mechanism gives access to very high mass scales
- Is there CP violation?
  - Possible explanation for baryon asymmetry
- Is the standard 3-neutrino picture correct?



# Neutrinos are very different!

## Mass scales are very different: what is this telling us?




## Flavor mixings are very different: what is this telling us?

Quarks

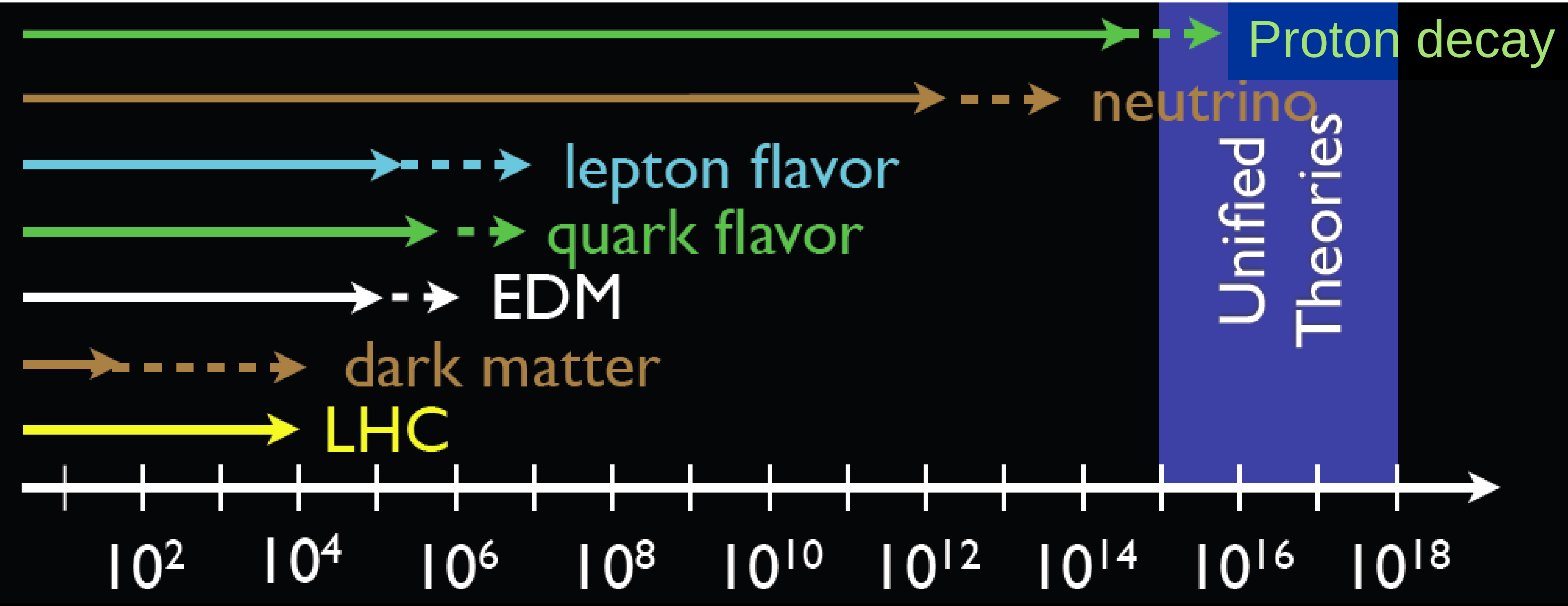
$$\begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

Neutrinos

$$\begin{pmatrix} 0.8 & 0.5 & 0.16 \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & 0.7 \end{pmatrix}$$

**For Snowmass: establish a long-term comprehensive strategy for neutrino physics**

# Windows to higher mass scales




**Experimental reach [GeV]**
**(with significant simplifying assumptions)**

For Snowmass: establish importance of precision physics tests & connections to other frontiers

# Project Questions: Intensity Frontier

- IF1: Compare the advantages and disadvantages between on-axis and off-axis experiments for measuring the mass hierarchy and delta, the CP violating parameter, in the neutrino sector?
- IF2: How would you design an experiment to measure CP Violation in charm decays at the level of $O(10^{-3})$?
- IF3: If the presently observed deviation in the measurement of the anomalous magnetic moment of the muon persists, how can one quantify this with better precision? If this discrepancy were due to new physics, what BSM explanations can be observed by direct searches for new particles at a 1 TeV ILC or 14 TeV LHC?

# Snowmass 2013: HEP in the 2020's

- Contest: your challenge over the next two weeks:
  - » What physics do you want to be pursuing 2023 and why?
  - » Or, in more concrete terms, what exciting physics do you want to be lecturing about at the 2023 SSI?
- One page maximum input to be judged by organizers
  - » Entries including your name (!) to be collected in a designated paper box anytime during the SSI

# From 1988 DPF Summer Study on HEP in the 1990's

- Report Of The B Factory Group. 1. Physics And Techniques

**Table 2. Comparison of B–Factory Techniques**

| Factor/Case | Asymmetric $\Upsilon(4S)$ | Symmetric $\Upsilon(4S)+$ | $\sqrt{s} = 16$ GeV | Z $\mathcal{P} = 0$ | Z $\mathcal{P} = 0.9$ ($\mathcal{P} = 0.45$) |
|---|---|---|---|---|---|
| $b\bar{b}$ cross section, $\sigma$ (nb) | 1.2 | 0.3 | 0.11 | 6.3 | 6.3 |
| Fraction of $B^0$, $f_0$ | 0.43 | 0.34 | 0.35 | 0.35 | 0.35 |
| $\psi K_s$ reconstruction efficiency, $\epsilon_r$ | 0.61 | 0.61 | 0.61 | 0.46 | 0.46 |
| Tag efficiency, $\epsilon_t$ (and method) | 0.48 ($\ell$, K) | 0.48 ($\ell$, K) | 0.30 ($\ell$, D) | 0.18 ($\ell$, D) | 0.61 ($A_{FB}$) |
| Wrong tag fraction, $w$ | 0.08 | 0.08 | 0.08 | 0.08 | 0.125 (0.27) |
| Asymmetry dilution, $d$ | 0.61 | 0.63 | 0.45 | 0.45 | 0.61 |
| $\int \mathcal{L}dt$ needed for $3\sigma$ effect ($10^{40}$ cm$^{-2}$) * | 0.45–16 | 2.1–77 | 18–640 | 0.68–25 | 0.14–5.0 (0.37–13) |
| Relative $\int \mathcal{L}dt$ needed | 1.0 | 4.7 | 40 | 1.5 | 0.3 (0.8) |

*peak luminosity needed in units of $10^{33}$ cm$^{-2}$ sec$^{-1}$ for $10^7$ seconds of fully efficient running at peak luminosity.

- First step on the path to the asymmetric energy $e^+e^-$ *B* Factories at SLAC and KEK

# A special time for particle physics: 1987

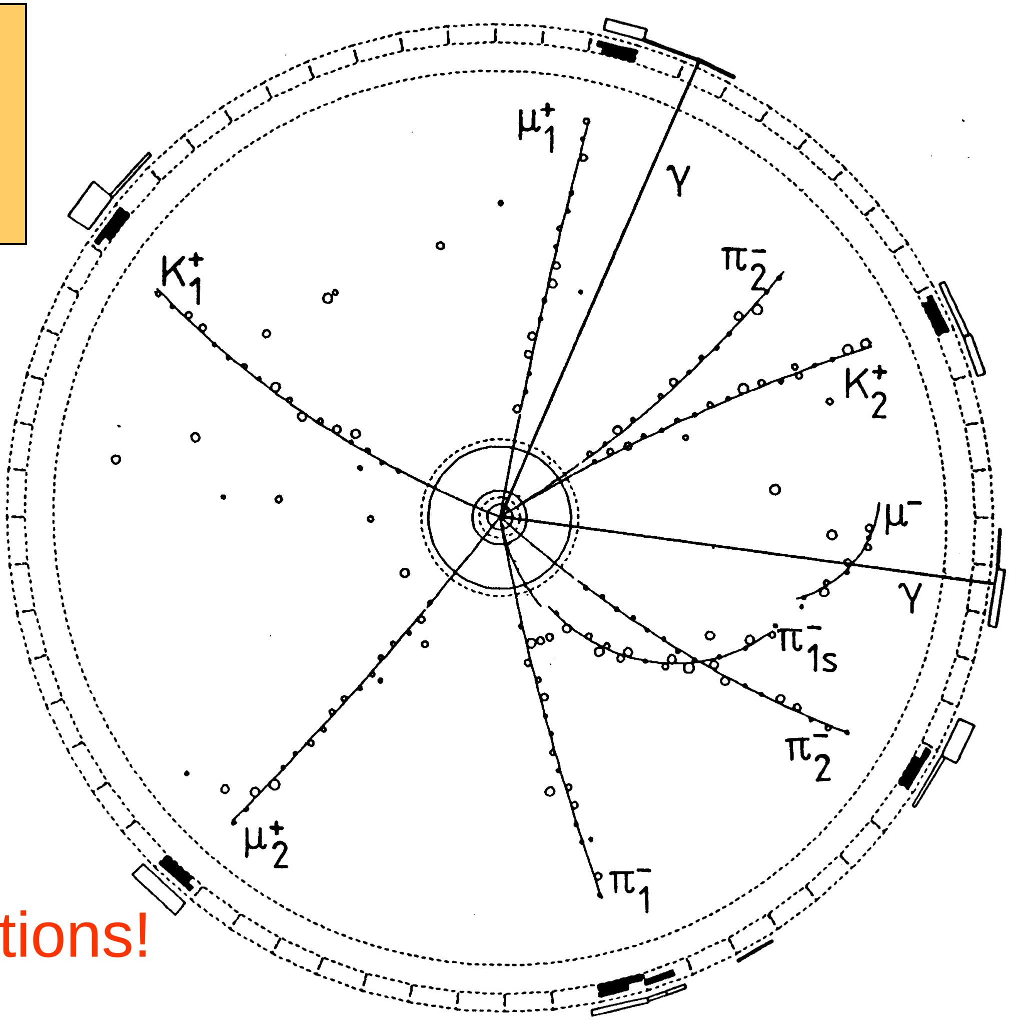
Produce matter-antimatter pairs in ARGUS at DESY

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0$

By the time of decay

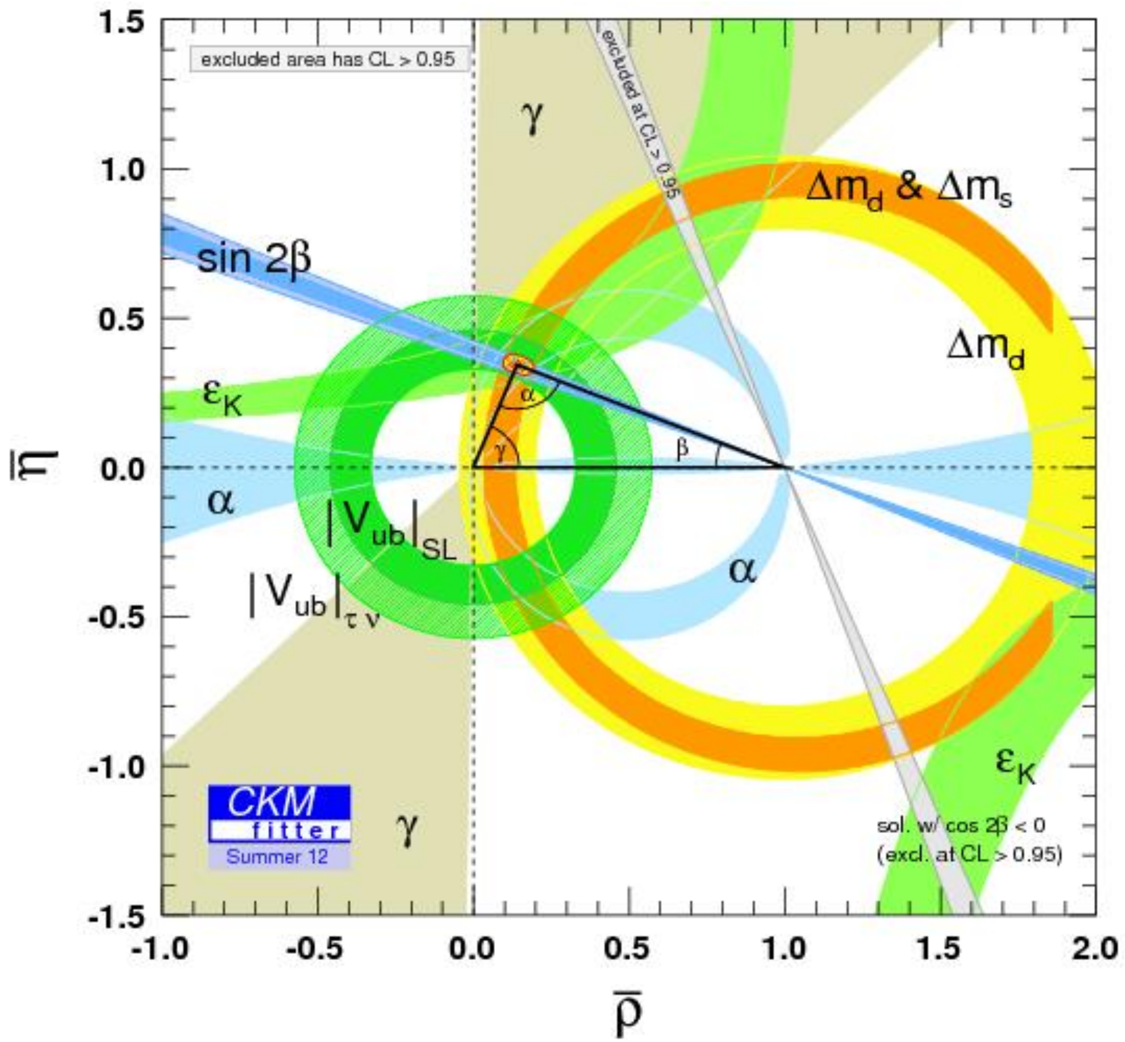
$B^0\bar{B}^0 \rightarrow B_1^0 B_2^0$

Matter-Antimatter oscillations!



# From that small seed…

- In 2012, after two B Factories, involving ~$1B investment and a thousand physicists
- And ~900 published papers that define the SM in the quark sector



# References

- I benefited from many excellent presentations at:
  - » The 2013 Lepton-Photon Symposium
  - » The ILC Worldwide Event
  - » And the Snowmass working group meetings and presentations [web site]