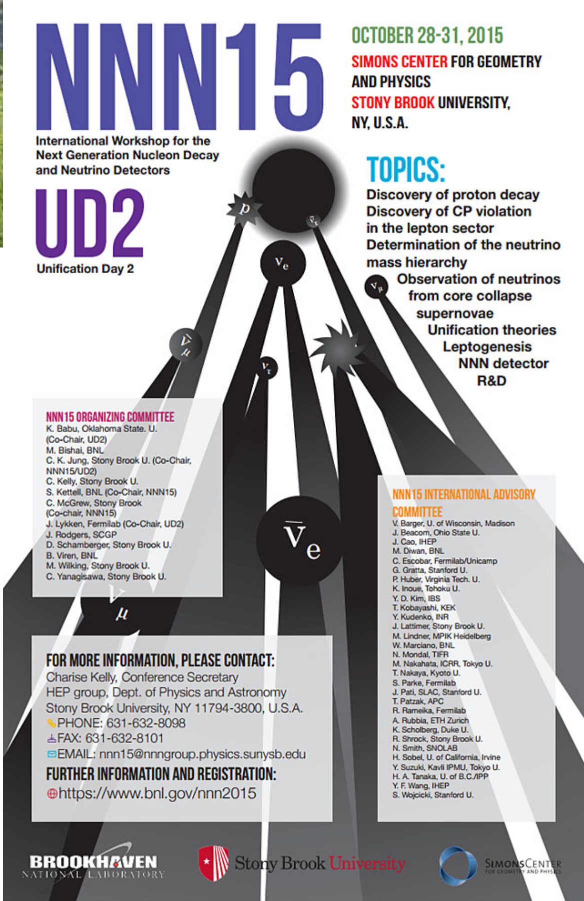


Concluding remarks

Joe Lykken

Outline

- Unification and neutrinos
- How little we know
- Neutrino science maturing
- Resolving anomalies
- Big new initiatives moving fast

Caveats and disclaimers

- These remarks are mostly addressed to the younger people in the audience
- They reflect my theory, experimental, regional, and institutional biases
- Although I have written a couple of papers about neutrinos, I am a lapsed string theorist who became a CMS collaborator ☺ and then ended up in lab management ☹

Unification Day 2, October 28-29 2015: Subworkshop of the International Workshop for the Next Generation Nucleon Decay and Neutrino Detector (NNN15) October 28-31, 2015

- The idea of unification is at the heart of particle physics

- Pulls together our seemingly very different communities studying neutrinos, Higgs, dark matter, string theory, etc

Unification of Forces and Matter

Electromagnetic, weak and strong forces share identical structure: all belong to gauge theories with unitary symmetry

The high energy behavior of these theories support unification idea

Ordinary matter – quarks and leptons – fit neatly within multiplets of the unified symmetry

Unified theories are more predictive, many predictions agree with observations

Nucleon decay is the missing link; its discovery would be monumental

3

- Lots of reasons to believe that there is an underlying unified framework
- And no shortage of specific proposals

More Hints in favor of Unification

- Electric charge quantization
  - $Q_p = -Q_e$ to better than 1 part in 10^{21}
- Miraculous cancellation of anomalies
- Quantum numbers of quarks and leptons
- Existence of ν_R and thus neutrino mass
- Unification of gauge couplings with low energy SUSY
- $b - \tau$ unification
- Baryon asymmetry of the universe

6

K. Babu, UD2

The challenge of top-down unification

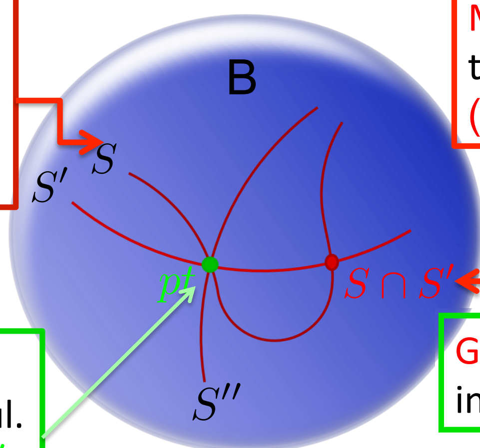
F-theory: basic ingredients

- Total space of torus-fibration: singular elliptic Calabi-Yau manifold X

  D=4, N=1 vacua: fourfold X_4
- Singularities encode complicated set-up of intersecting D-branes:

Non-Abelian gauge symmetry in codimension-one singul. in B (divisors wrapped by branes)

Matter in codimension-two singul. in B (intersecting branes)



G_4-flux at intersection induces chiral 4D matter

Yukawa couplings in codimension-three singul. in B $pt = S \cap S' \cap S''$

M. Cvetic,UD2

- Don't know what is the right framework to start with
- Even if you have the right starting point, may not have the tools to connect it to enough concrete observables

Unification should be predictive

3 family SO_{10} SUSY Model

- D_3 x U(1) Family Symmetry
- Superpotential
- Yukawa couplings
- Global χ^2 analysis
- Charged fermion masses & mixing
- Neutrino masses & mixing

S. Raby, UD2

Some Benchmark points

m_{16}	25	25	25	25
α	0	1.5	0	1.5
χ^2/d.o.f	2.158	2.275	2.220	2.505
$m_{\tilde{t}_1}$	4.903	5.011	4.909	5.249
$m_{\tilde{t}_2}$	6.021	6.120	6.033	6.301
$m_{\tilde{b}_1}$	5.989	6.088	6.455	6.606
$m_{\tilde{b}_2}$	6.454	6.541	6.445	6.267
$m_{\tilde{\tau}_1}$	9.880	9.931	9.912	10.040
$m_{\tilde{\tau}_2}$	15.369	15.365	15.393	15.516
$M_{\tilde{g}}$	1.202	1.187	1.613	1.690
$m_{\tilde{\chi}_1^0}$	0.203	0.551	0.279	0.900
$m_{\tilde{\chi}_2^0}$	0.404	0.665	0.538	1.018
$m_{\tilde{\chi}_1^+}$	0.404	0.665	0.538	1.018
$m_{\tilde{\chi}_2^+}$	1.128	1.243	1.232	1.537
M_A	2.194	2.082	2.477	3.352
$\sin\delta$	-0.289	-0.482	-0.520	-0.576
$BR(\mu \to e\gamma) \times 10^{13}$	1.108	1.430	1.239	1.340
$\mathrm{edm}_e \times 10^{30}$(e cm)	-1.403	-3.305	-1.763	-5.886

[TeV]

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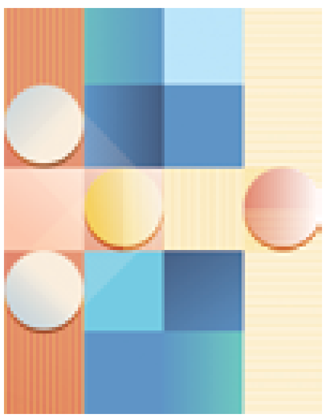
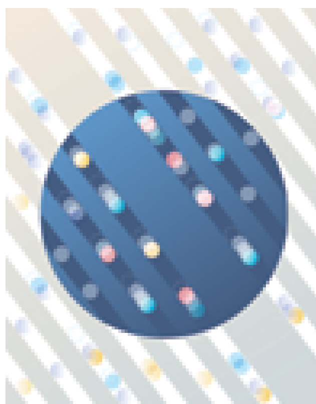
P5: Science drivers are intertwined

Five intertwined scientific Drivers were distilled from the results of a yearlong community-wide study:

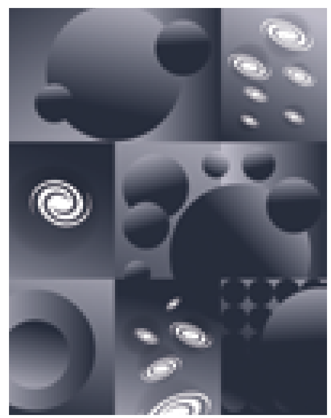
- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles



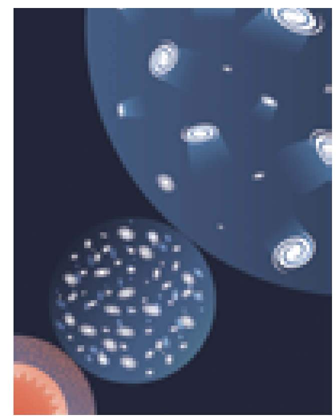
Higgs boson



Neutrino mass



Dark matter



Cosmic acceleration

Explore the unknown

Science drivers are intertwined: e.g. Higgs connections

- Is the Higgs boson connected to supersymmetry or other naturalness-preserving new physics
- Does the Higgs field destabilize the vacuum
- How does the Higgs talk to neutrinos
- Are there more Higgs-like bosons and a “Higgs sector”
- Is there a Higgs portal to dark matter
- Is the Higgs sector related to baryogenesis
- Extra credit: Is the Higgs related to inflation or dark energy

Another example: neutrino connections

- How do neutrinos talk to the Higgs boson
- How are tiny neutrino masses related to the origin of particle masses in general
- Are neutrinos responsible for leptogenesis/baryogenesis
- Are neutrinos related to superhigh energy scales and unification
- How are neutrinos related to dark matter
- Extra credit: are neutrinos related to inflation or dark energy

Photo: AIP, Emilio Segrè Visual Archives

Neutrinos and inflation?

Affleck-Dine Sneutrino Inflation
└ Sneutrino Chaotic Inflation

Neutrinos and the seesaw Mechanism

- Neutrinos oscillations well established
- Right-handed neutrinos possible explanation

$$W = W_{MSSM} + Y_\nu H_u L N + \frac{1}{2} N^T M_N N$$

- Seesaw explains small neutrino masses

$$M_N \sim 10^{13} GeV \quad \rightarrow \quad Y_\nu \sim 1$$

- Snuetrino is natural candidate for inflation
  - Seesaw scale $\sim$ inflation scale
- Simple models are complicated by SUGRA

$$V \simeq e^{|N_1|^2} \left(M_N |N_1|^2 - 3 \frac{|M_N|^2}{M_P^2} |N_1|^4 \right)$$

J. Evans, UD2

Affleck-Dine Sneutrino Inflation
└ Leptogenesis

Leptogenesis

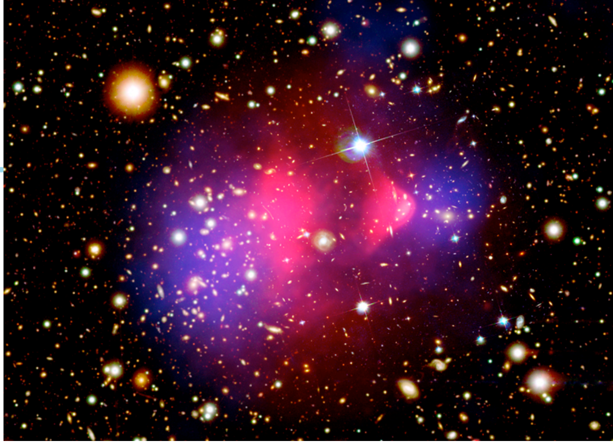
- Generating the BAU
  - Baryon number violation
  - CP violation
  - Non-equilibrium
- Neutrino decays violate L (+ Sphaleron) and CP
  - N decay to particles and anti-particles
  - non-trivial phase in neutrino sector
- Non-equilibrium from inflaton decays
  - Don't produce thermal densities
- Decay of lightest right handed neutrino generate BAU

$$M_{N_1} \gtrsim 10^9 \mathrm{GeV} \qquad T_{RH} \gtrsim M_{N_1}$$

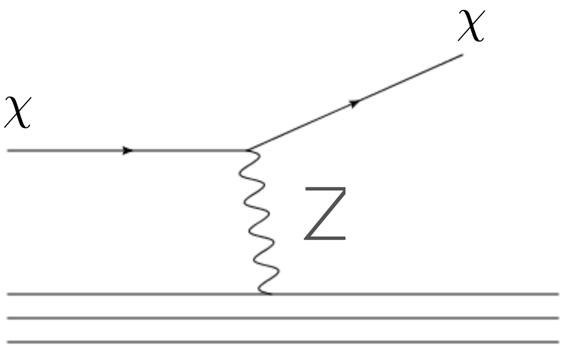
- Works for both sneutrino inflations

Neutrinos, in addition to being interesting and important themselves, hold great promise to hint at connections we might not otherwise suspect

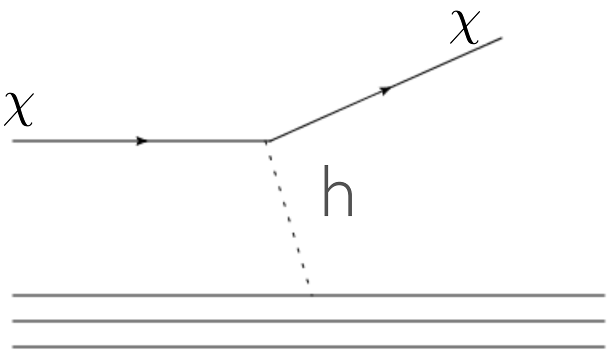
How does dark matter interact with ordinary matter?



via gravity we know



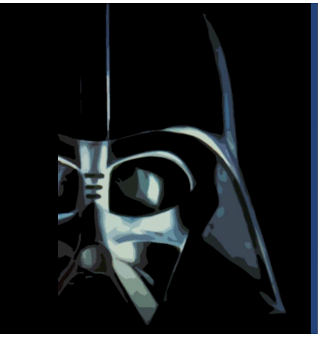
via the known weak interactions, like neutrinos?



via the Higgs boson?

$$\mathcal{L} \sim LH\nu_R + \nu_D\eta\nu_R + M\nu_R\nu_R$$

via a neutrino portal?



Or: via some exotic unknown “dark forces”?

How little we know

Maybe it happens this way
Maybe we really belong together
But after all, how little we know

Maybe it's just for a day
Love is as changeable as the weather
And after all, how little we know

Who knows why an April breeze never remains
Why stars in the trees hide when it rains
Love comes along, casting a spell
Will it sing you a song
Will it say a farewell
Who can tell

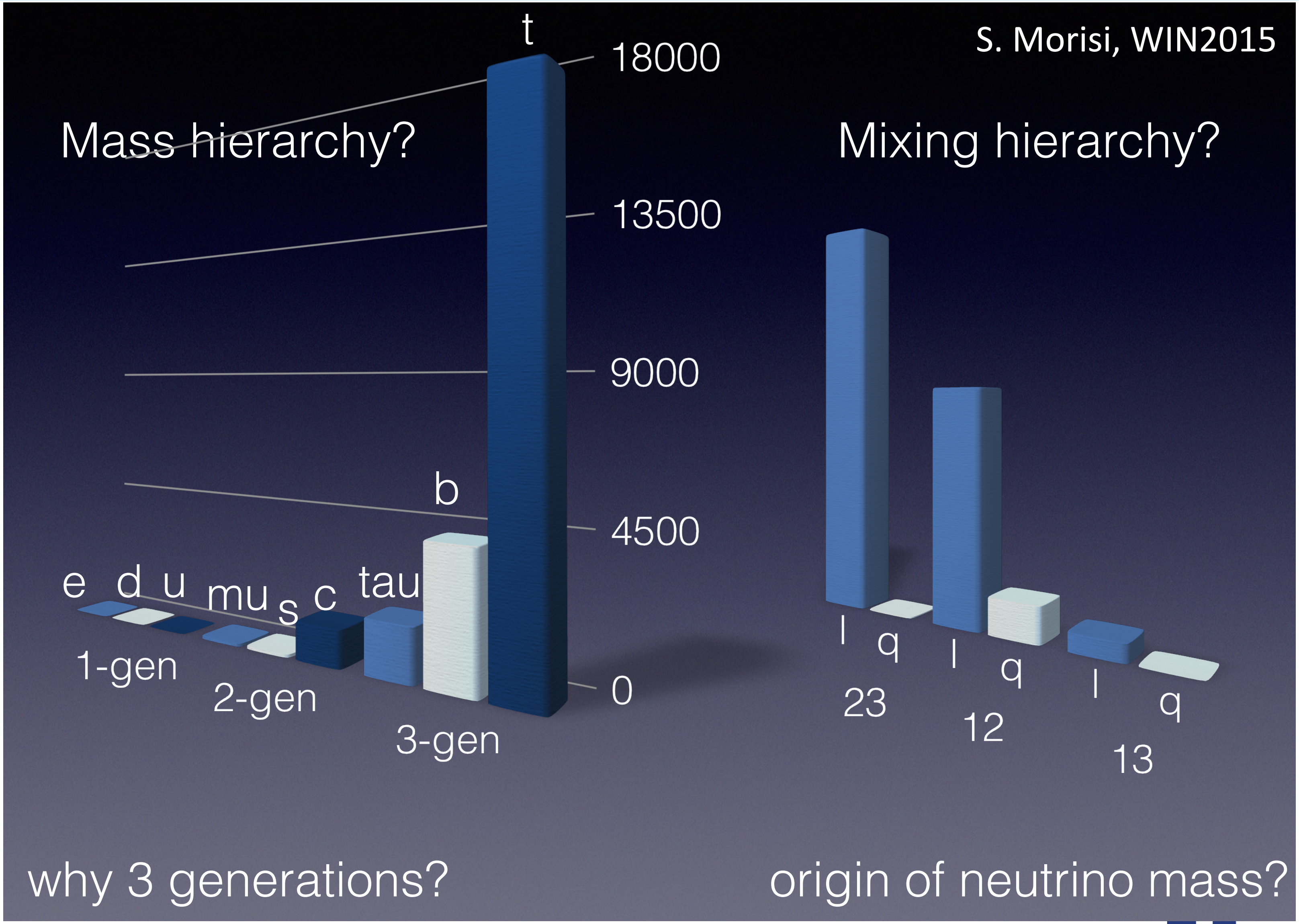
Maybe you're meant to be mine
Maybe I'm only supposed to stay in your arms a while
As others have done

Is this what I've waited for, am I the one
Oh, I hope in my heart that it's so
In spite of how little we know

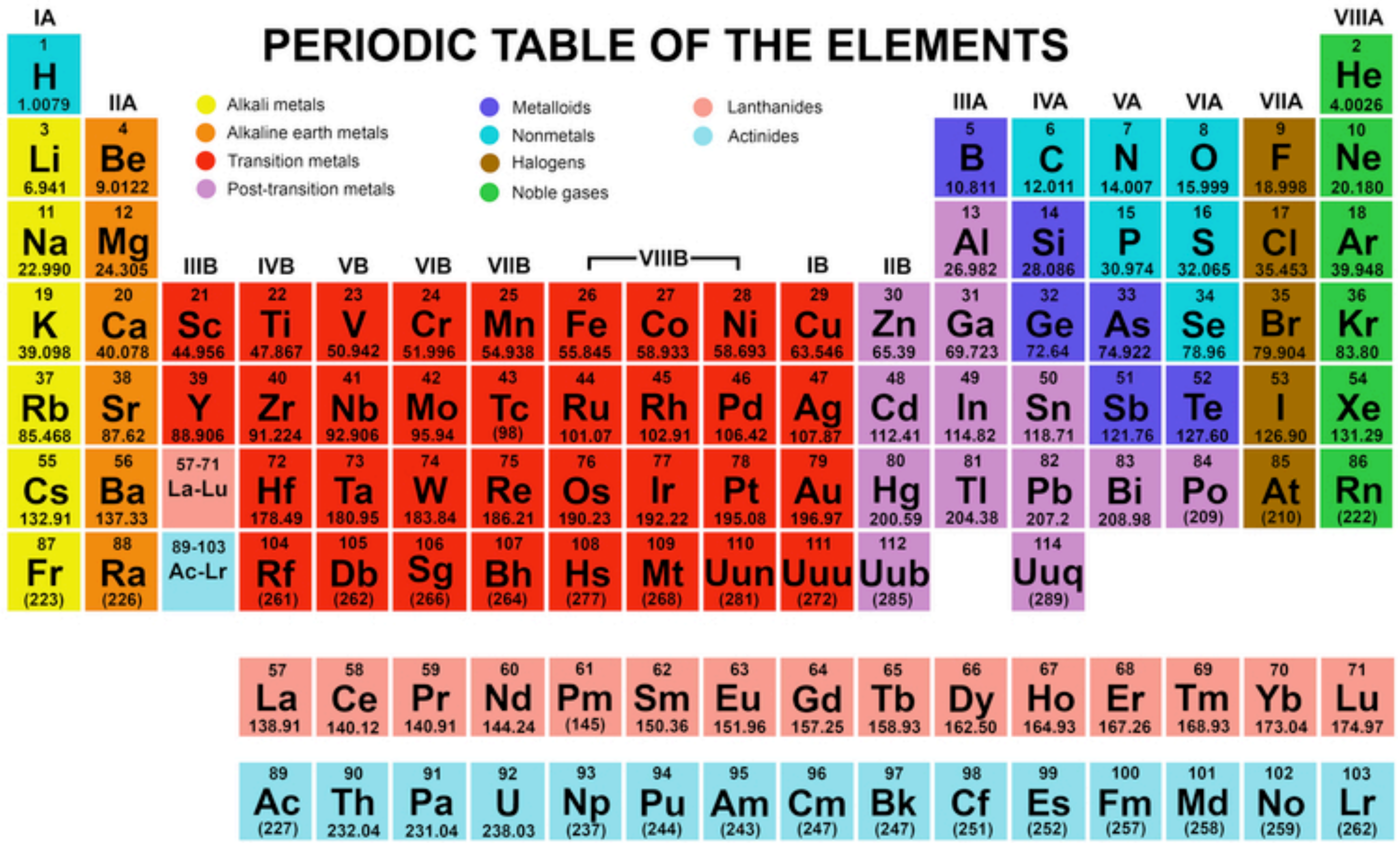
Is this what I've waited for, am I the one
Oh, I hope in my heart that it's so
In spite of how little we know

Hoagy Carmichael

What is all this telling us?



What is the underlying dynamics of flavor?



Saying that the Standard Model with the Higgs mechanism is a successful theory of fermion masses is like saying that the Periodic Table is a successful theory of atoms

Flavor (broadly defined) is a big over-arching challenge of particle physics for the first half of this century

- What are the dynamical origins of fermion masses, mixings, and CP violation?
- What are the scales associated with this dynamics?
- What are the symmetries and symmetry breakings?
- What is the complete Higgs sector and how does it work?
- How are quark and lepton flavor related?
- What other flavor sectors are accessible, e.g.
  - superpartners
  - dark sector

Pressing Questions for Neutrinos

Talk by K. Babu

- Are neutrinos their own antiparticles?
- Is there CP violation in neutrino oscillations?
- Is the mass hierarchy normal or inverted?
- Are there light sterile neutrinos?
- What is the scale of neutrino mass generation?
- What explains the pattern of neutrino mixings?
- Can neutrinos be unified with quarks?
- Is neutrino CP violation related to baryon asymmetry?

Can be addressed strongly with current and planned experiments

Very interesting and very important, but also very hard to address experimentally

How little we know: which see-saw? what scale?

M. Hirsch, WIN2015

Smallness of neutrino mass can be "explained" by:

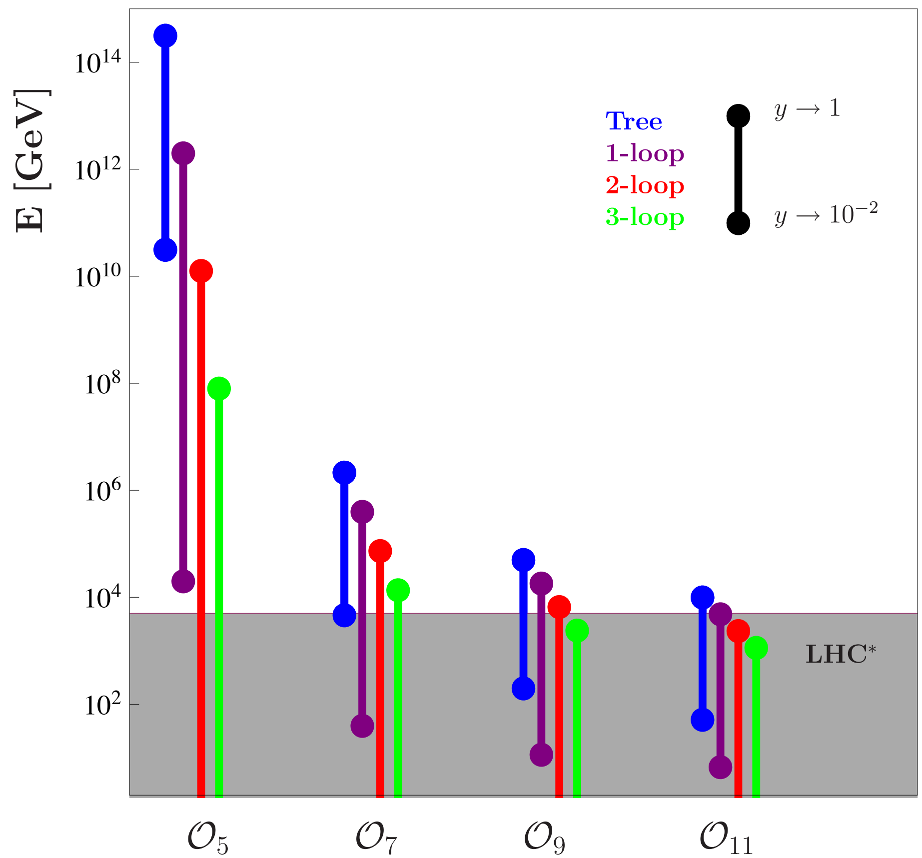
$\Rightarrow$ High scale: Large Λ
"classical" seesaw

$\Rightarrow$ Loop factor: $n \geq 1$
+ "smallish" $Y \sim \mathcal{O}(10^{-3} - 10^{-1})$

$\Rightarrow$ Higher order: $d = 7, 9, 11$

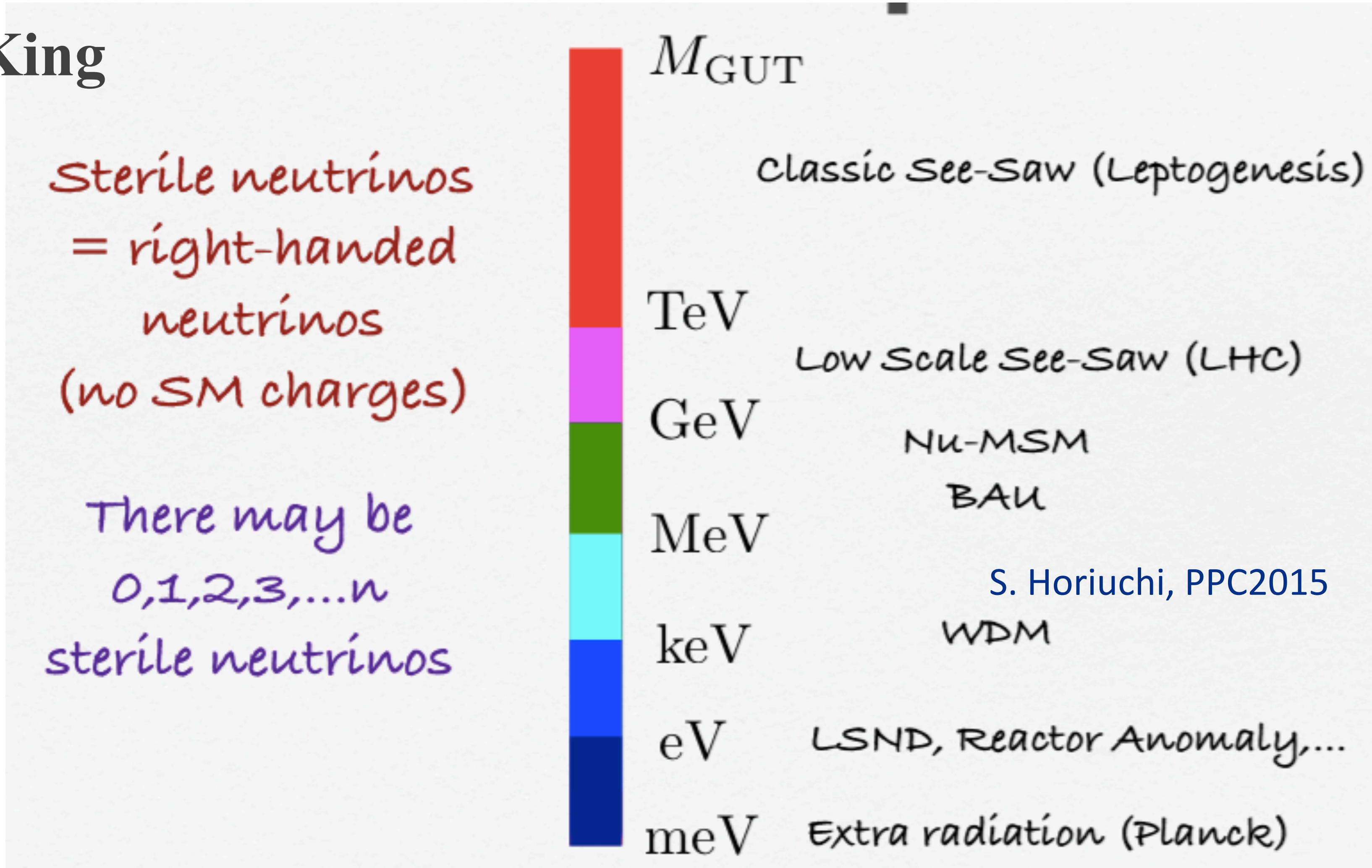
$\Rightarrow$ Nearly conserved L,
i.e. small ϵ ("inverse seesaw")

$\cdots$ or combination thereof



How little we know: sterile neutrinos

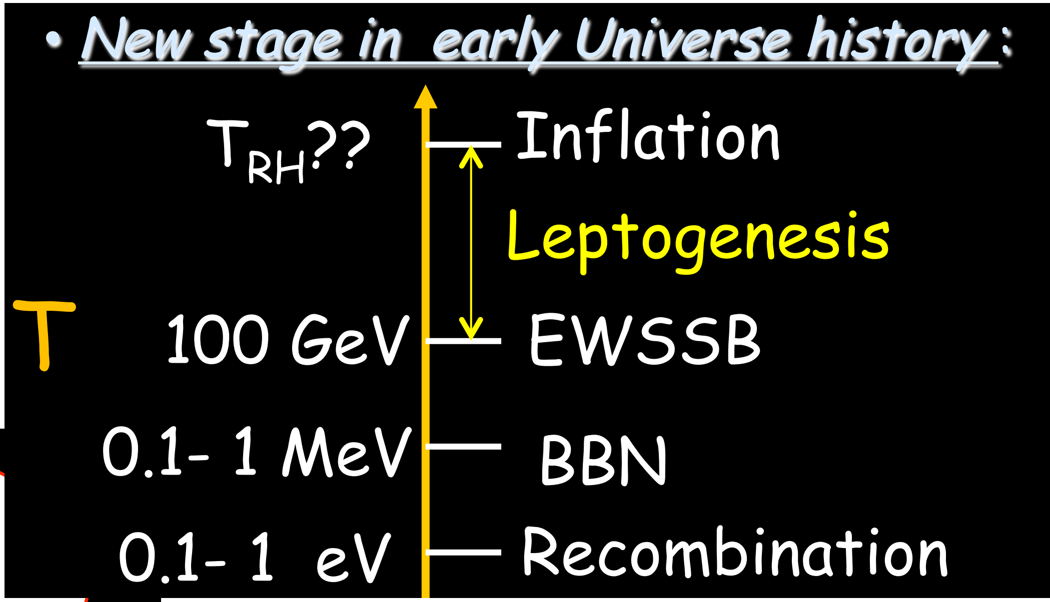
S. King

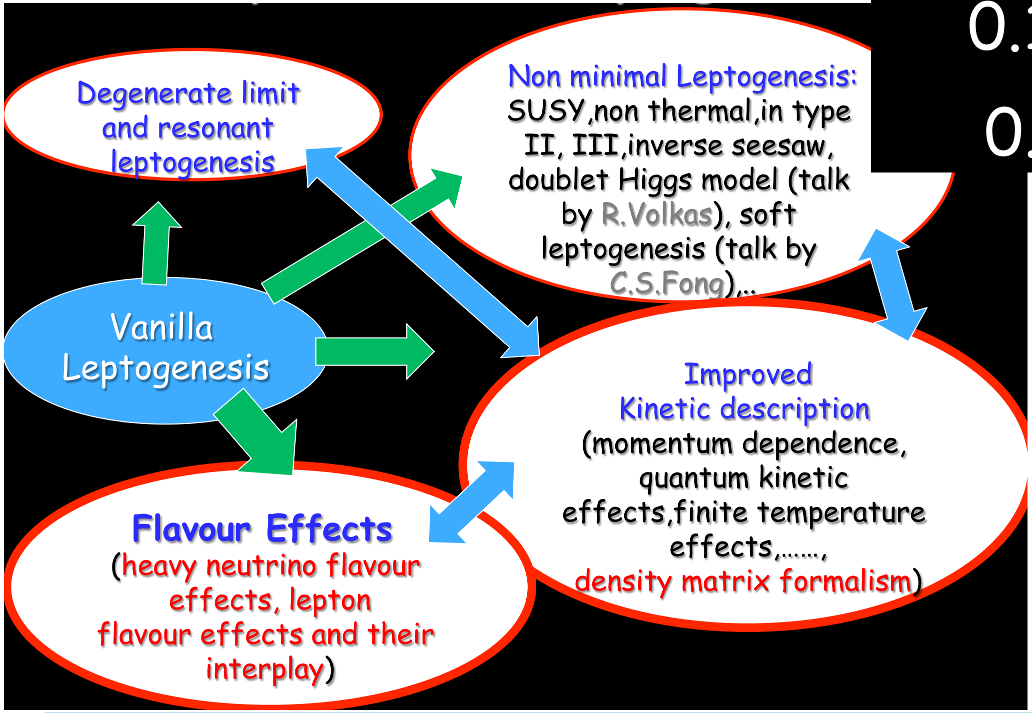


S. Horiuchi, PPC2015

Good news / bad news: leptogenesis

Good news: not the only possibility to explain the baryon asymmetry, but looking very attractive!





Bad news: many possibilities, how will you ever sort it out?

P. di Bari PPC2015

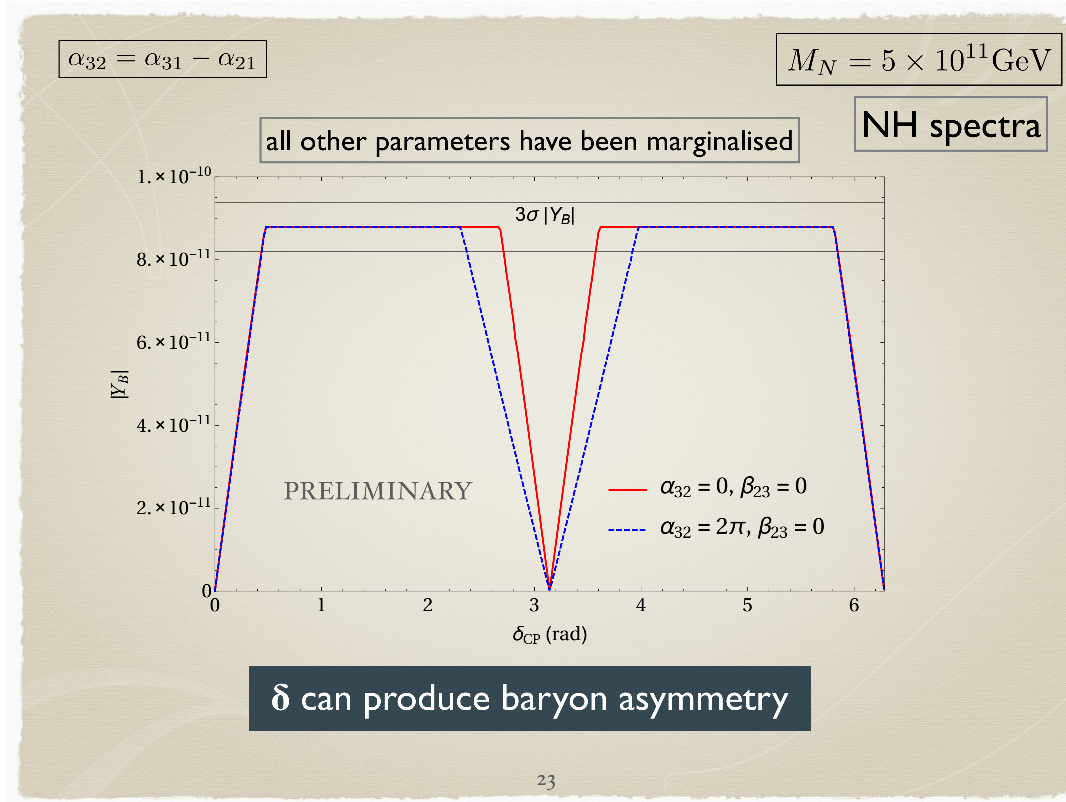
CPV in the lepton sector

- Is CPV in δ sufficient to produce the baryon asymmetry?
- T2K and reactor data have shown a slight preference for maximal CPV.

- Observation of CP violation in long-baseline neutrino oscillations would be a huge discovery
- Doesn't *necessarily* mean that the observed CPV is the CPV of leptogenesis, or even that leptogenesis occurs

- But we are not trying to match onto a *generic* high scale theory; the high scale theory is *special*

- Occam's razor is a good thing

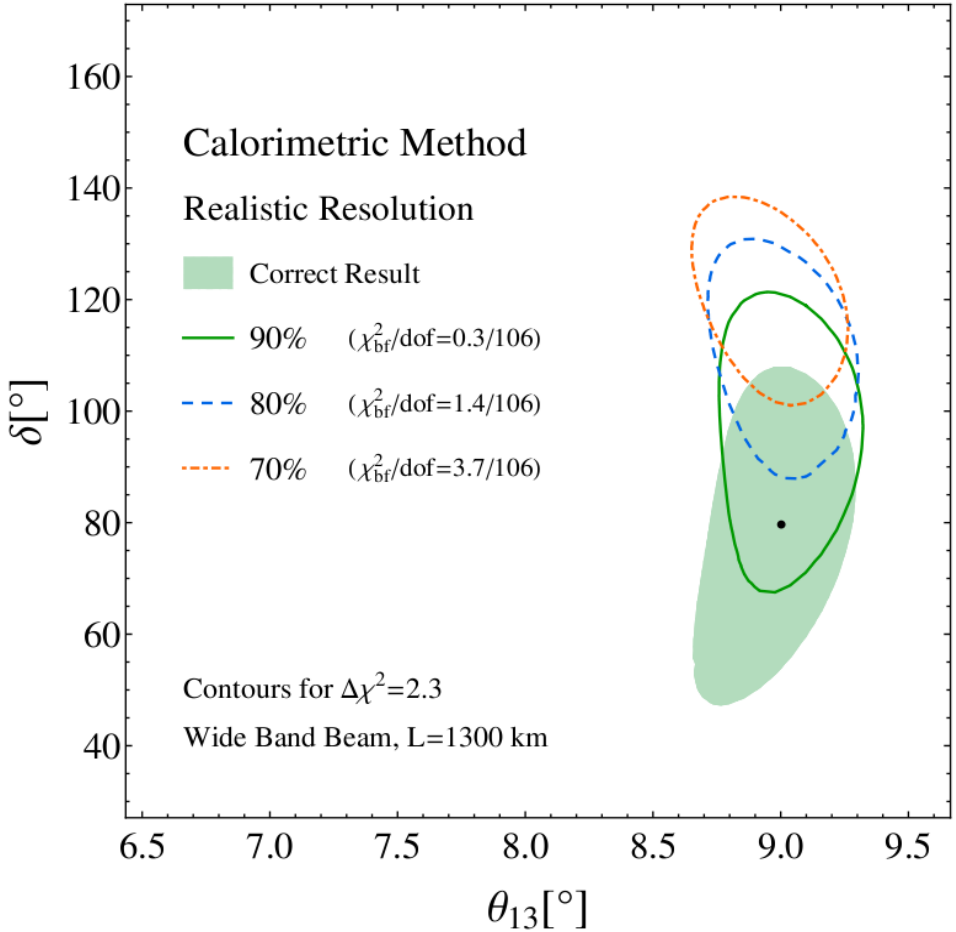


J. Turner, NNN15

Some trends apparent at this meeting

- Neutrino statistics progressing from “social science” (90% CL) to “collider physics” (5 sigma)
- Neutrino physicists getting serious about systematics
- Golden Age of liquid argon TPCs is upon us
- The push to conclusively resolve neutrino anomalies
- BIG new detectors underground/underwater/under-ice: JUNO, DUNE, Hyper-K, INO, ORCA, PINGU

Neutrino systematics: understand the physics of your detector



- Hey we also had to do this for CMS and ATLAS
- Lot's of opportunities for younger people here

P. Coloma, NNN15

Ankowski et al, 1507.08561 [hep-ph]

Neutrino interaction physics: high priority, big opportunity

Improving Interaction Models

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Worldwide effort that will benefit DUNE!
- Alternative models being implemented in GENIE include:
  - Long- and short-range correlations among nucleons
  - Effect of random phase approximations
  - Meson exchange currents
  - 2p-2h effects in CCQE
  - Effective spectral functions
  - Coherent pion production
  - Alternative model of DIS interactions
  - Variation of tunable parameters within existing models
- Comparisons among generators
  - GENIE, NuWro, GiBUU, FLUKA
- Neutrino interaction data available or coming soon from:
  - ArgoNeuT, MINERvA, CAPTAIN-MINERvA, NOvA-ND, T2K-ND280, μBooNE, SBND, ICARUS, …
- Electron-argon scattering data coming soon from JLab

DUNE collaborators active in all of these efforts!

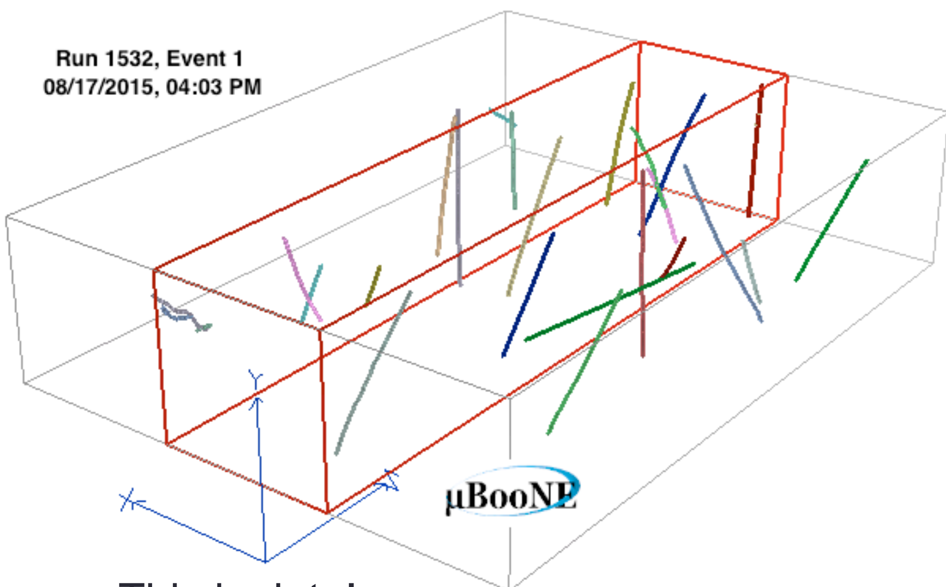
E. Worcester, NNN15

NNN2015: DUNE Systematics 11

Automated reconstruction in LAr TPCs

We use fully automated event reconstruction

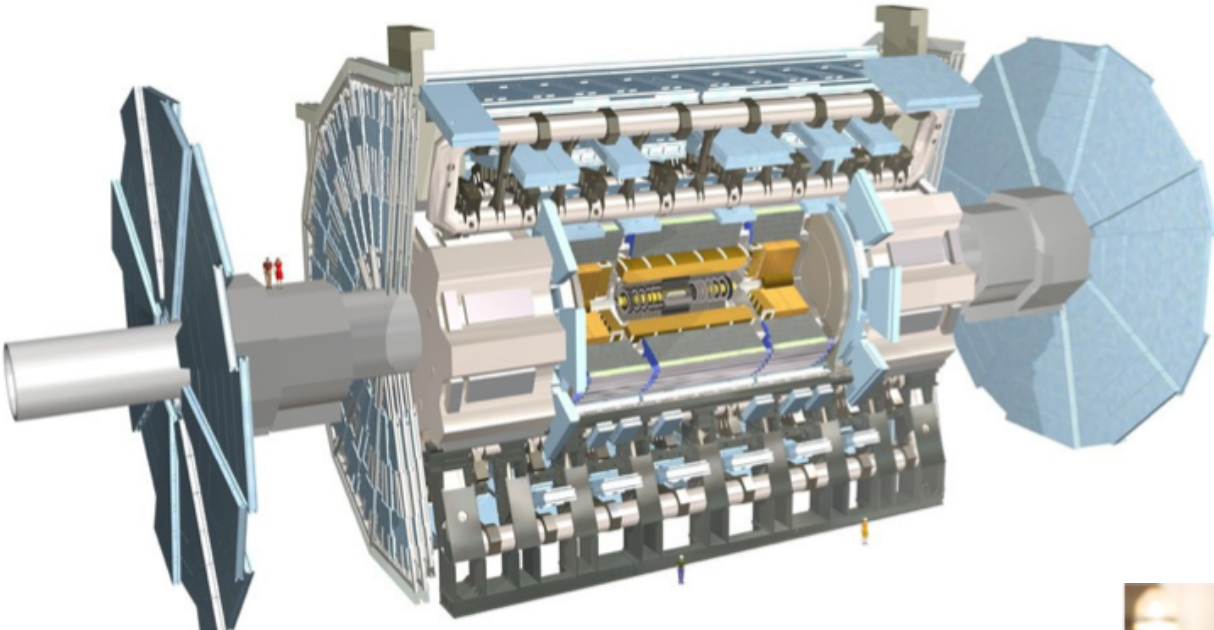
- This event display comes from LArSoft, showing 3D tracks
- Display shows the full drift window of 4.8 ms
  - —We take a window before and after beam
  - —Red wireframe represents the physical detector
- Different colors are different tracks



This is data!

B. Carls, NNN15

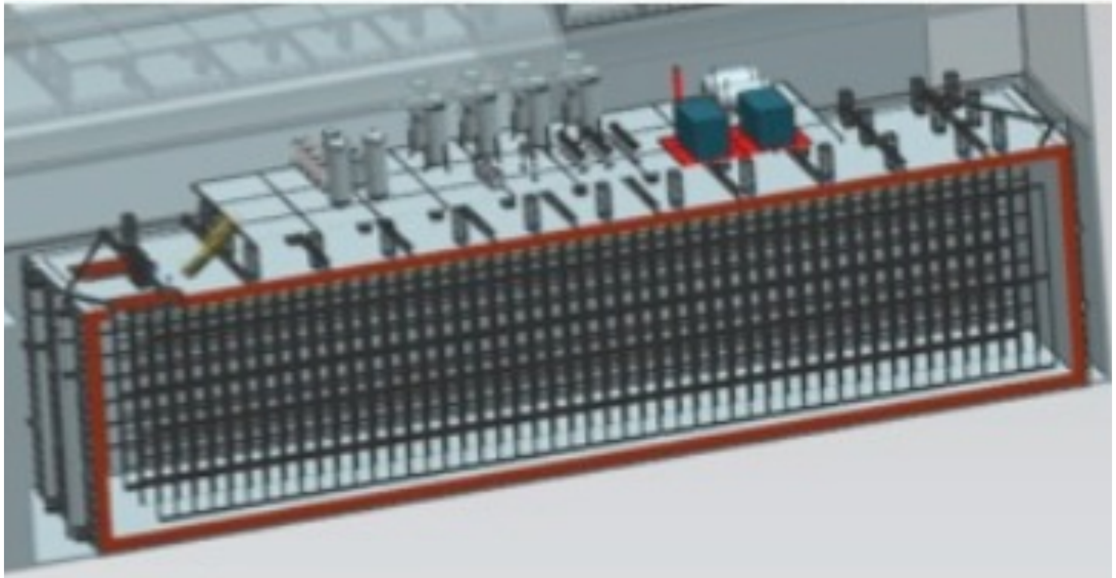
From LHC to LBNF



ATLAS detector
7,000 tons

Marzio Nessi, Technical Coordinator for ATLAS construction

From LHC to LBNF

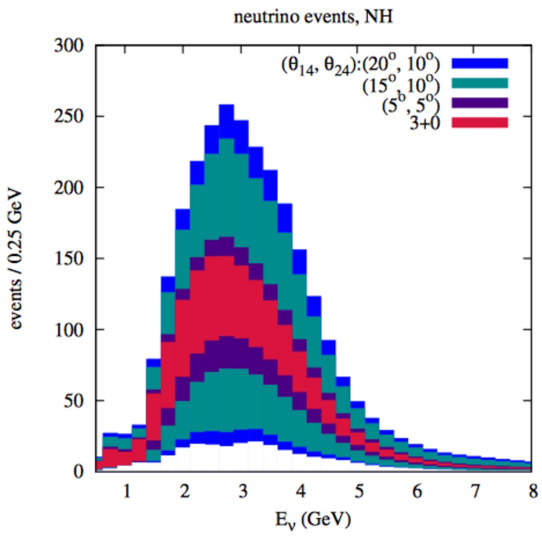


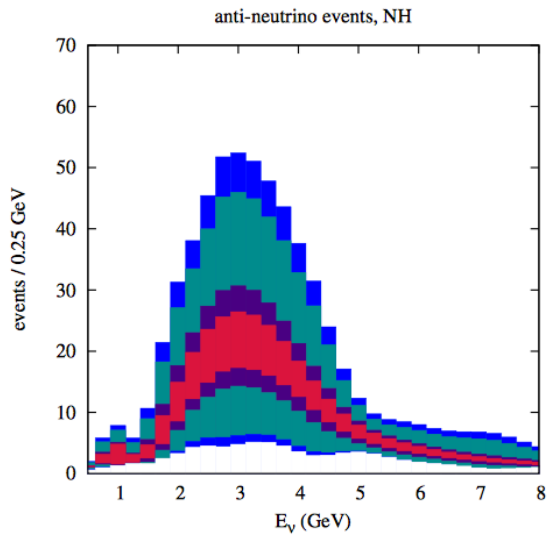
4 LBNF cryostats for DUNE: each one holds 17,000 tons of liquid argon

Marzio Nessi, CERN LBNF project manager

Why a Short-baseline neutrino program?

Impact on flagship measurement of long-baseline experiments: CP Violation





R. Gandhi, B. Kayser, M. Masud, S. Pakrash, arXiv:1508.06275

5

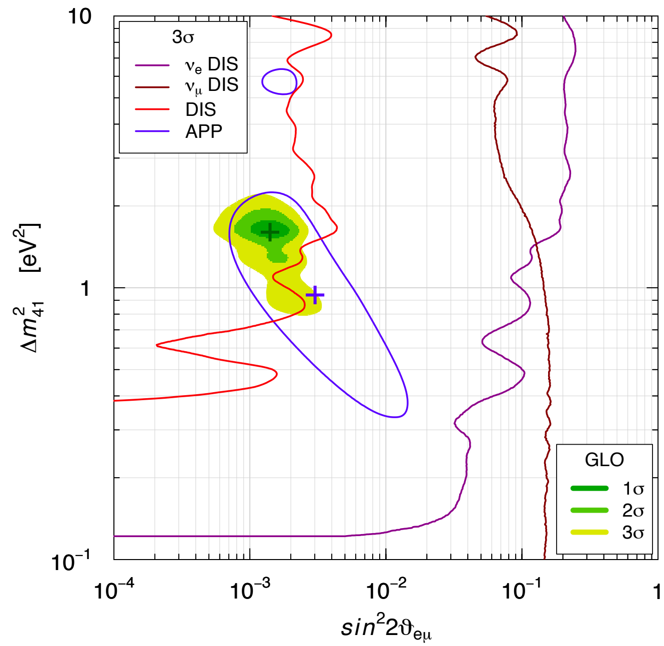
R. Guenette, NNN15

Being pragmatic about global fits

- Don't include the MiniBooNE low energy excess in global fits (awaiting insight from MicroBooNE)
- Be conservative about assigning uncertainties to some older results
- 3+1 is good enough!

Pragmatic Global 3+1 Fit

[PRD 88 (2013) 073008; arXiv:1507.08204]



- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND ($\nu_s$), MiniBooNE (?), OPERA ($\cancel{\nu_s}$), ICARUS ($\cancel{\nu_s}$), KARMEN ($\cancel{\nu_s}$), NOMAD ($\cancel{\nu_s}$), BNL-E776 ($\cancel{\nu_s}$)
- DIS ν_e & $\bar{\nu}_e$: Reactors (ν_s), Gallium (ν_s), ν_eC ($\cancel{\nu_s}$), Solar ($\cancel{\nu_s}$)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW ($\cancel{\nu_s}$), MINOS ($\cancel{\nu_s}$), Atmospheric ($\cancel{\nu_s}$), MiniBooNE/SciBooNE ($\cancel{\nu_s}$)

MiniBooNE $E > 475$ MeV

GoF = 26% PGoF = 7%

No Osc. nominally disfavored at $\approx 6.3\sigma$

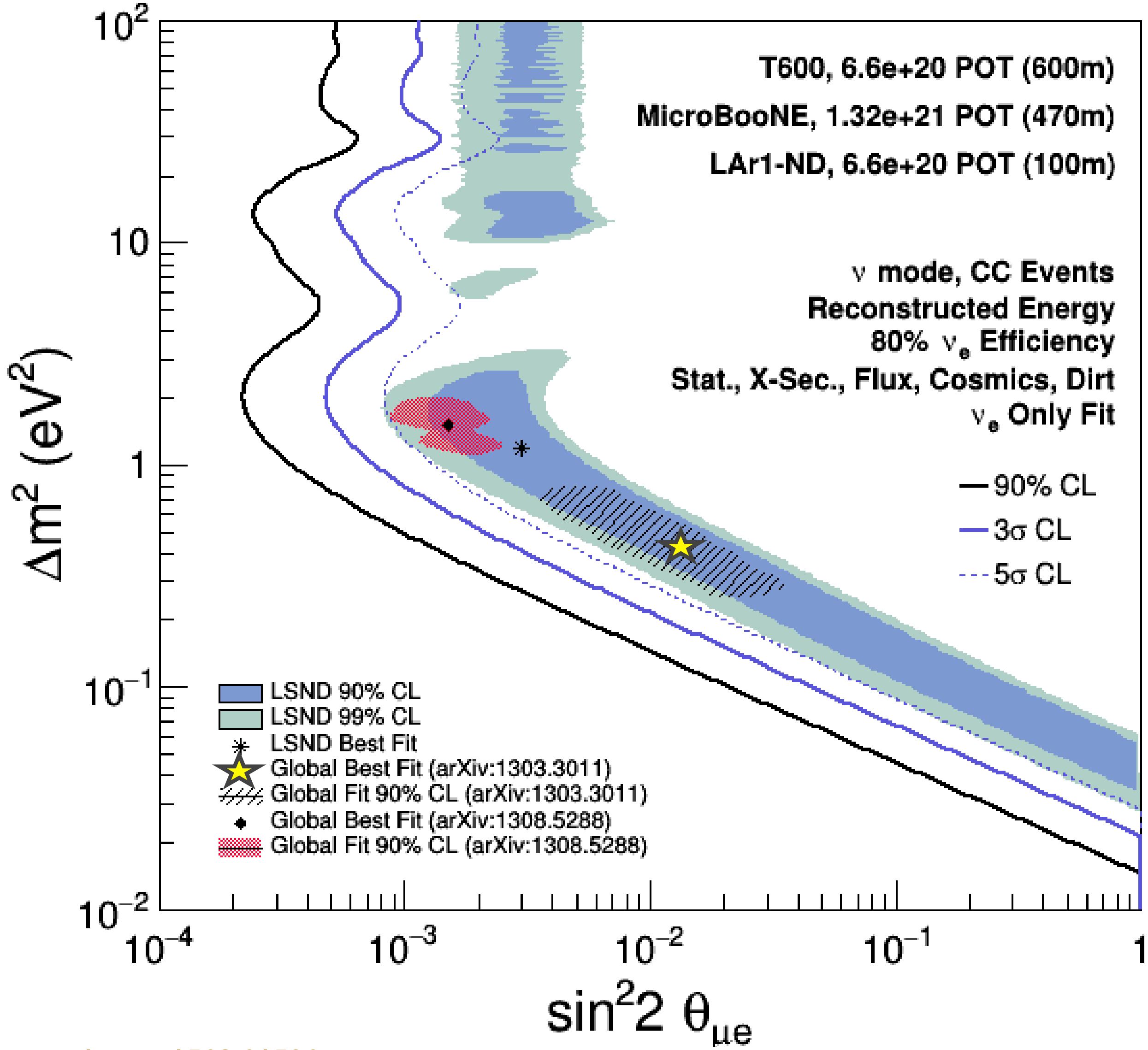
$\Delta\chi^2/\mathrm{NDF} = 47.7/3$

C. Giunti — Review of Sterile Neutrino Searches — NNN15 — 30 October 2015 — 15/22

C. Giunti, NNN15

SBN prospects

- I do expect the SBN program to produce conclusive results about the LSND anomaly
- Do we have to run with antineutrinos too…



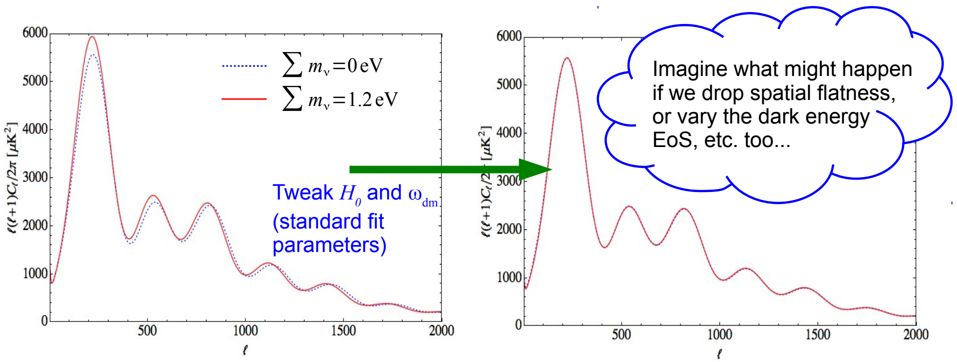
R. Guenette, NNN15

SBN proposal arxiv:1503.01520

Cosmic constraints on steriles

Model dependence: parameter degeneracies...

- We **do not** measure the neutrino mass *per se*, but rather its indirect effect on the clustering statistics of the CMB/large-scale structure.
  - It is **not impossible** that other cosmological parameters could give rise to similar effects (within measurement errors/cosmic variance).



Y. Wong, NNN15

Can we get around these constraints?

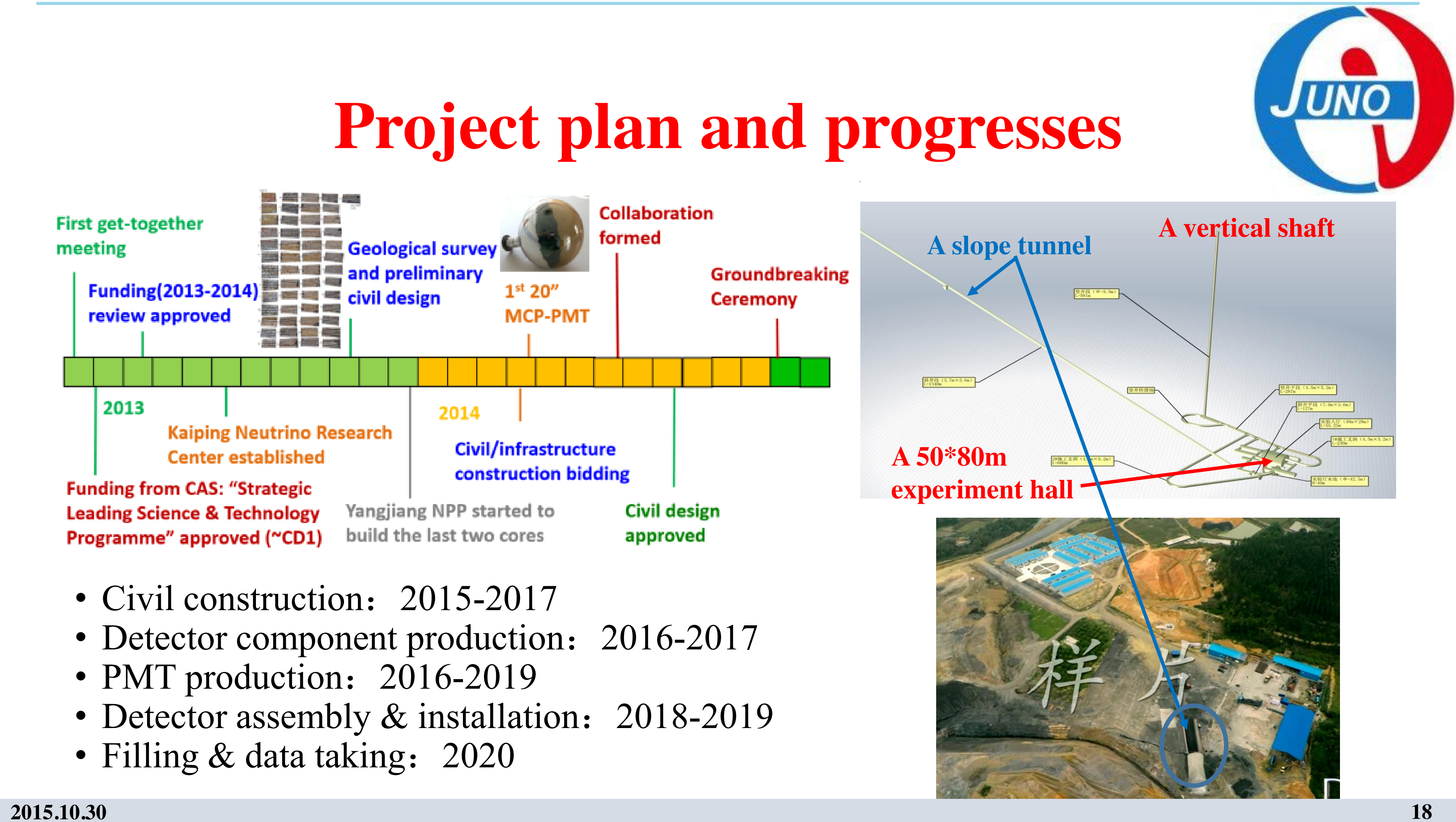
The SBL sterile neutrino is problematic for cosmology only because it is produced in abundance in the early universe.

→ If production can be **suppressed**, then there should be no conflict.

- **Some possible mechanisms**:
  - Suppress the effective mixing angle with new matter effects in the early universe:

New physics required
    - A large lepton asymmetry ($L \gg B \sim 10^{-10}$); $L \sim 10^{-2}$ will do. Foot & Volkas 1995
    - Hidden sterile neutrino self-interaction Dasgupta & Kopp 2014, Hannestad, Hansen & Tram 2014 Saviano et al. 2014, Archidiacono et al. 2015
  - A low reheating temperature (T_R < 10 MeV) → incomplete thermalisation of even the SM neutrinos. May run into problems with baryogenesis and dark matter production.

Moving fast on new big detectors: JUNO



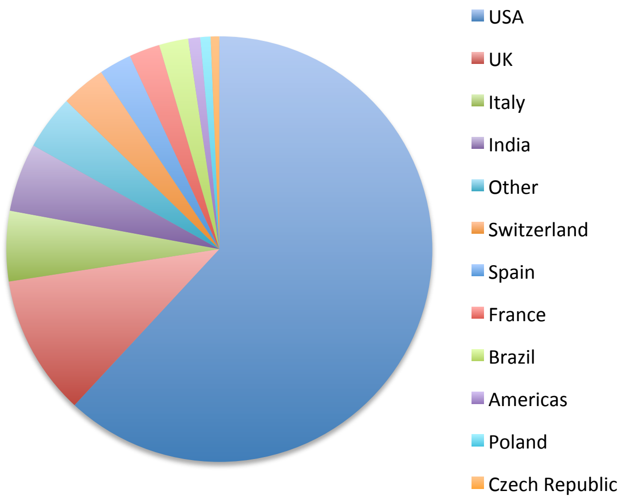
Z. Yu, NNN15

Moving fast on new big detectors: DUNE

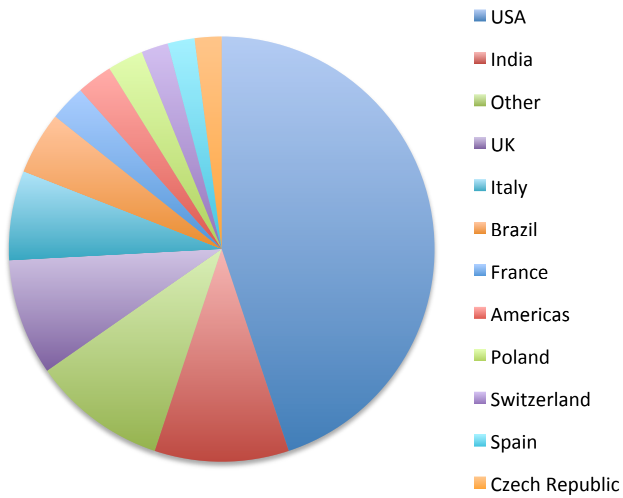
The DUNE Collaboration

As of today: from

792 Collaborators

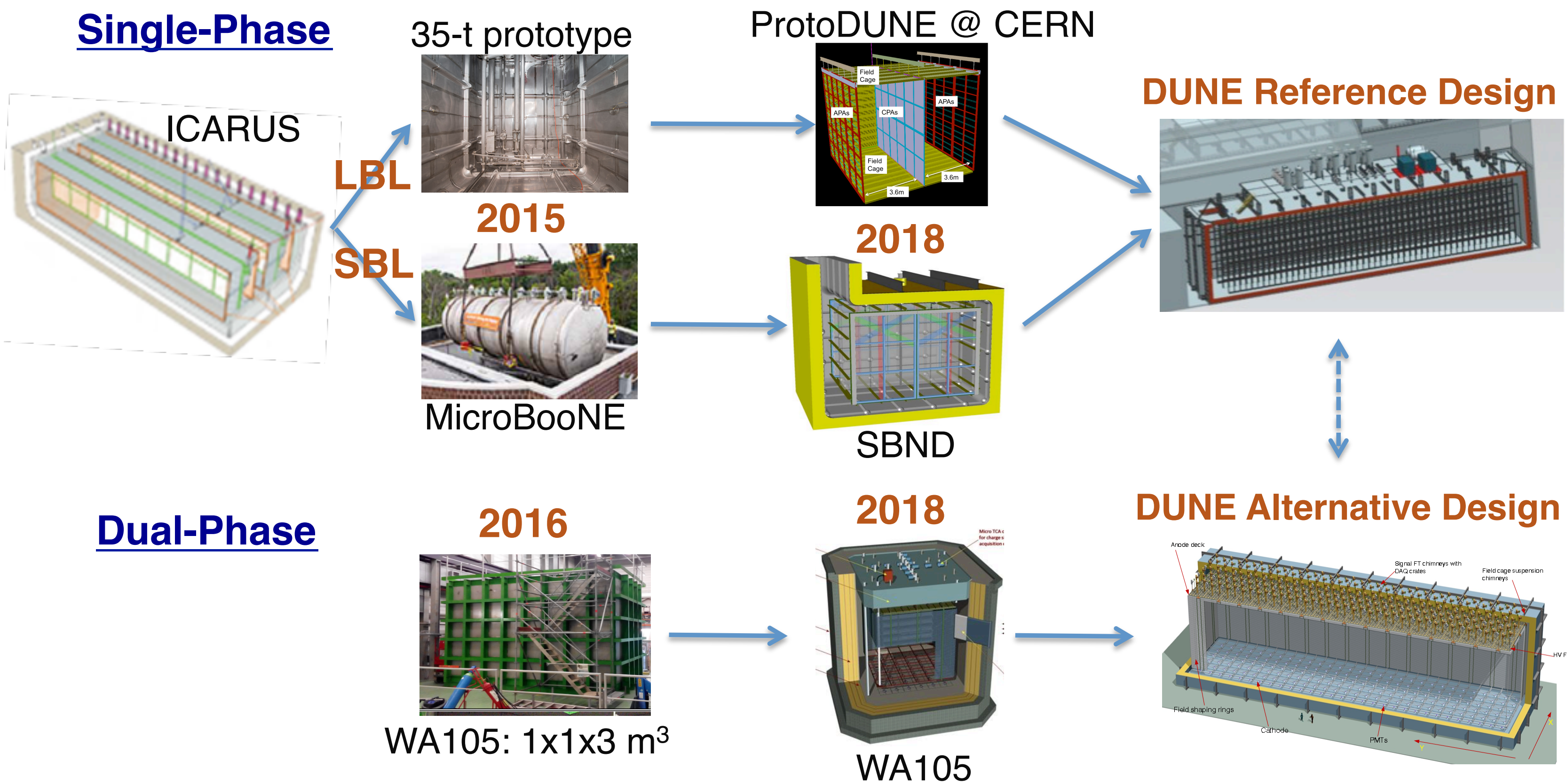


145 Institutes

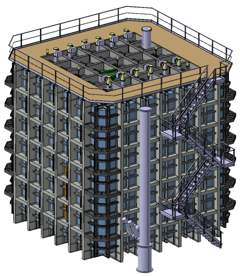


LArTPC Development Path

Fermilab SBN and CERN neutrino platform provide a strong LArTPC development and prototyping program



protoDUNE Parameters



- Total LAr mass of 700t with active mass of 400t
- 6 full size APAs with identical design to DUNE FD 10 kt module
- 15360 total readout wires in TPC
- 60 photon detector panels (dimensions $2.1\times1.1\text{m}^2$) with total of 240 PDS readout channels
- 6 cathode plane assemblies (CPAs)

Dimensions: (transverse × parallel × height)

- Internal: 8.5m × 8.5m × 8.6m
- External: 10.6m × 11.7m × 10.9m
- Tank capacity: ~600m^3 (liquid volume ~0.96%)

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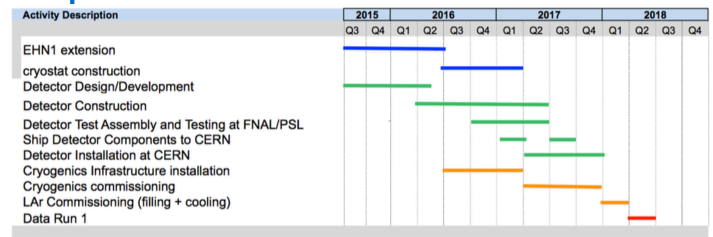
protoDUNE Timeline and Goals



protoDUNE has been approved by CERN!

Milestones:

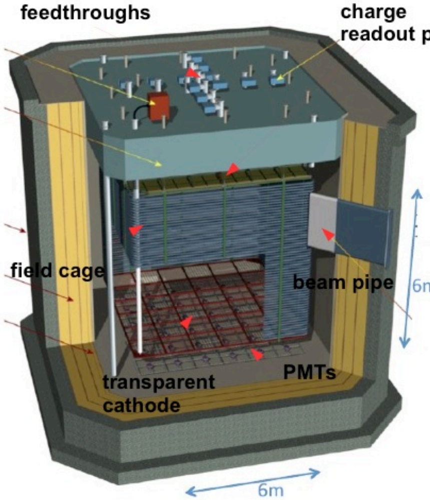
J. Insler, NNN15

- 2016: TPC Production readiness review
- 2016/17: Engineering trial assembly
- 2017: Detector installation complete
- 2018: Commission detector and collect cosmics data

Goal: Collect initial beam data in 2018

WA105

LBNO-DEMO TDR arXiv:1409.44



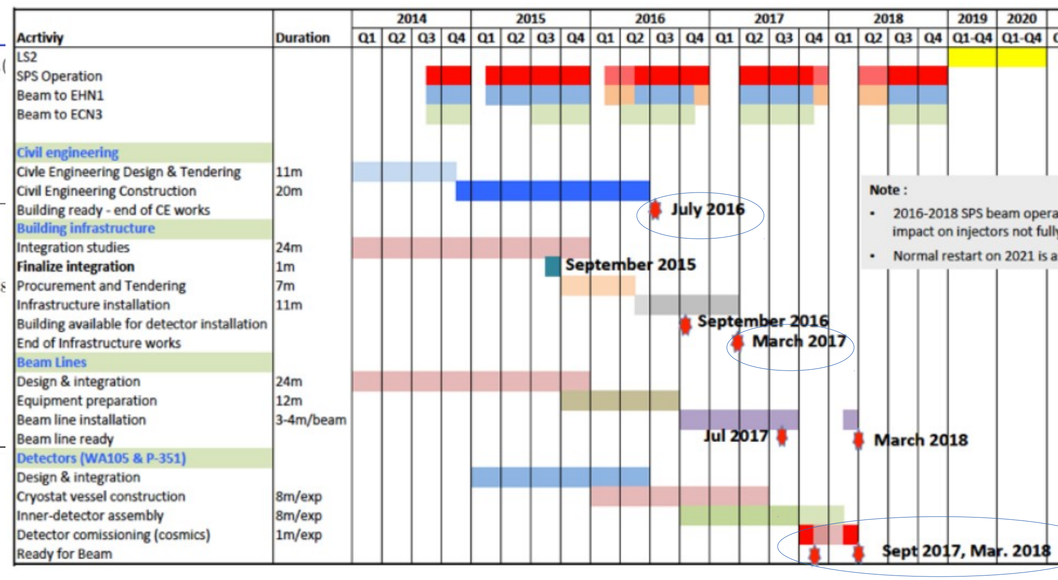
Fiducial volume $6\text{x}6\text{x}6\text{m}^3$
(4 DUNE CRP modules $3\text{x}3\text{m}^2$)

Liquid argon density	T/m^3	1.38
Liquid argon volume height	m	7.6
Active liquid argon height	m	5.99
Hydrostatic pressure at the bottom	bar	1.03
Inner vessel size (WxLxH)	m^3	8.3 × 8.3 × 8
Inner vessel base surface	m^2	67.6
Total liquid argon volume	m^3	509.6
Total liquid argon mass	t	705
Active LAr area	m^2	36
Charge readout module ($0.5 \text{x} 0.5 \text{ m}^2$)		36
N of signal feedthrough		12
N of readout channels		7680
N of PMT		36

S. Bolognesi, NNN15

On CERN dedicated test-beam line in extension of North Experimental Hall

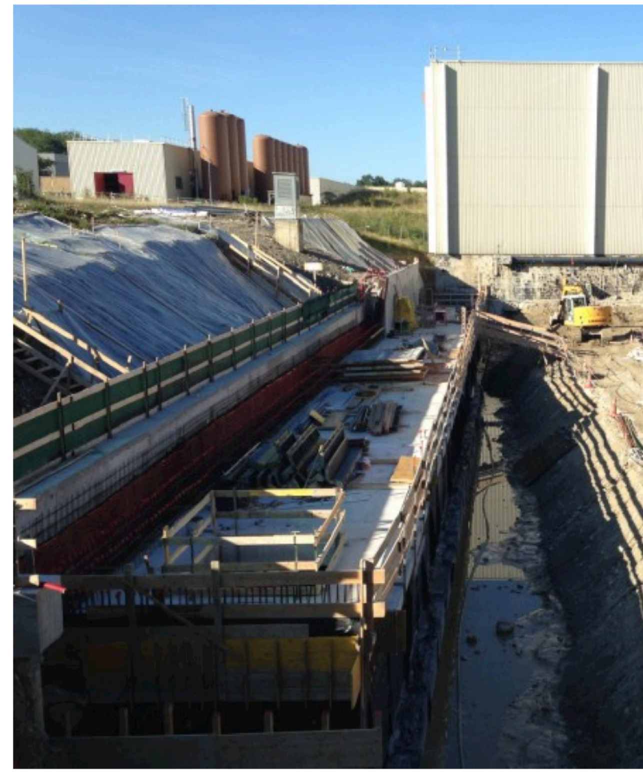
S.Bolognesi – NNN2015 5



See you in few years with beam events !

Moving fast on new big detectors: CERN neutrino platform

New building under construction,
to be delivered in July 2016

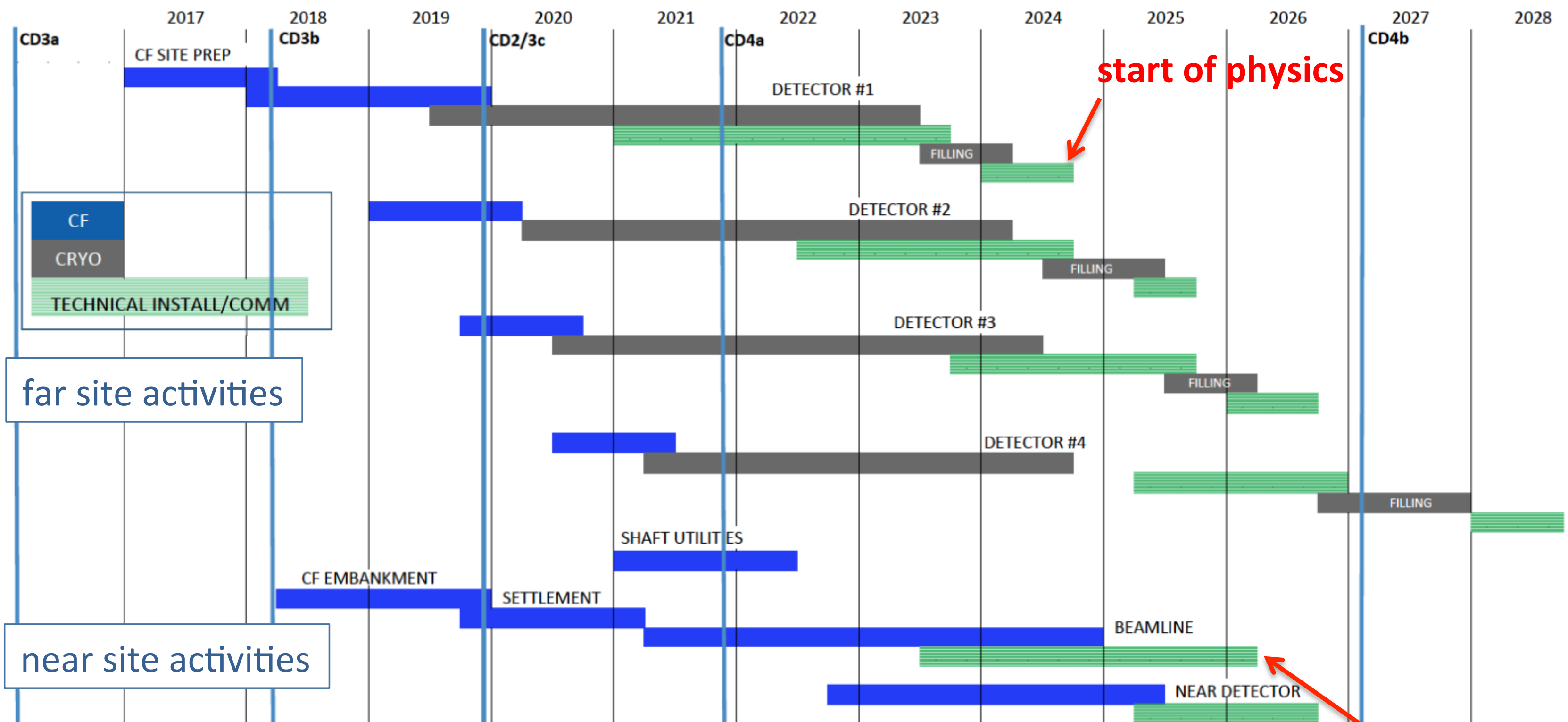


S.Bolognesi – NNN2015 7

S. Bolognesi, NNN15

LBNF/DUNE Timeline

T. Kutter, NNN15



Milestones:

7/2015: successfully passed DOE CD-1-R

10/2015: protoDUNE approved at CERN

12/2015: DOE CD-3a review → approval means start of construction (far site excavation starting in 2017))

start of ν-beam physics

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“Director’s Review” of LBNF CD-3a, this past week at Sanford Underground Research Facility

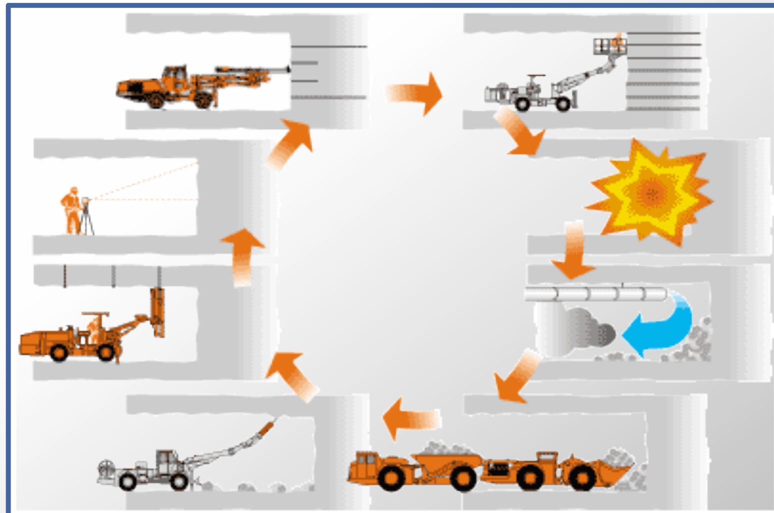
Cost & Schedule Drivers: Blasting Logistics

ILF CONSULTING ENGINEERS

Survey Next Round

Drill Blast-holes

Charge Blast-holes



Blast Warning & Evacuation

Ventilate Blast Dust/Gases

Install Rock Support

Scale Loose Rock

Remove Muck (Store/Skip)

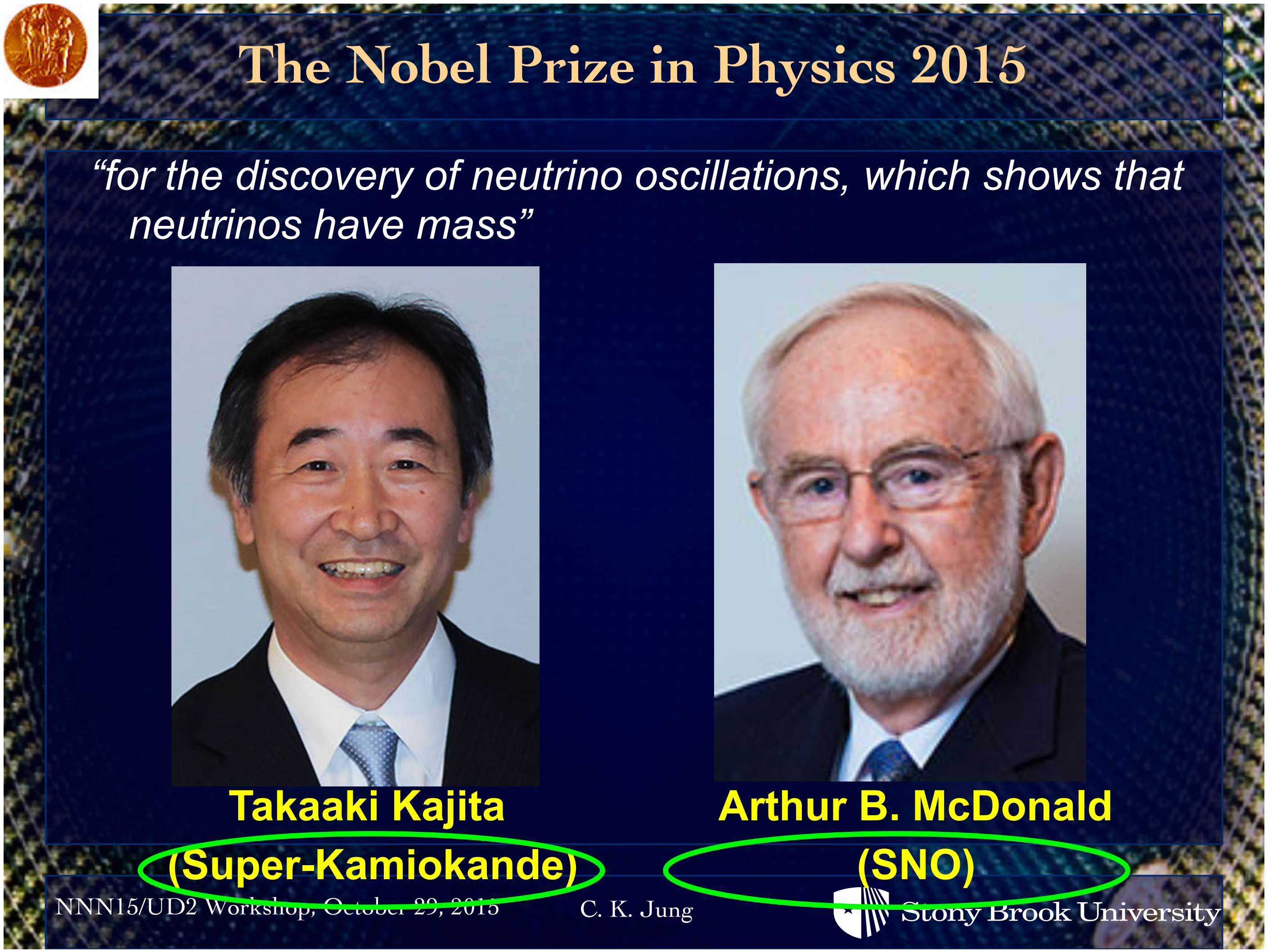
Potential Blast-Related Constraints; Explosives Transport and Magazine Storage on Surface and Underground, Vibration Limitations/Monitoring, Post-Blast Ventilation Capacity, etc.. Dedicated "Contractor Space" will be at a premium on 4850L.

Laughton, ILF Consultants NNN15/UD2.

23

C. Laughton, NNN15

Neutrinos are hot



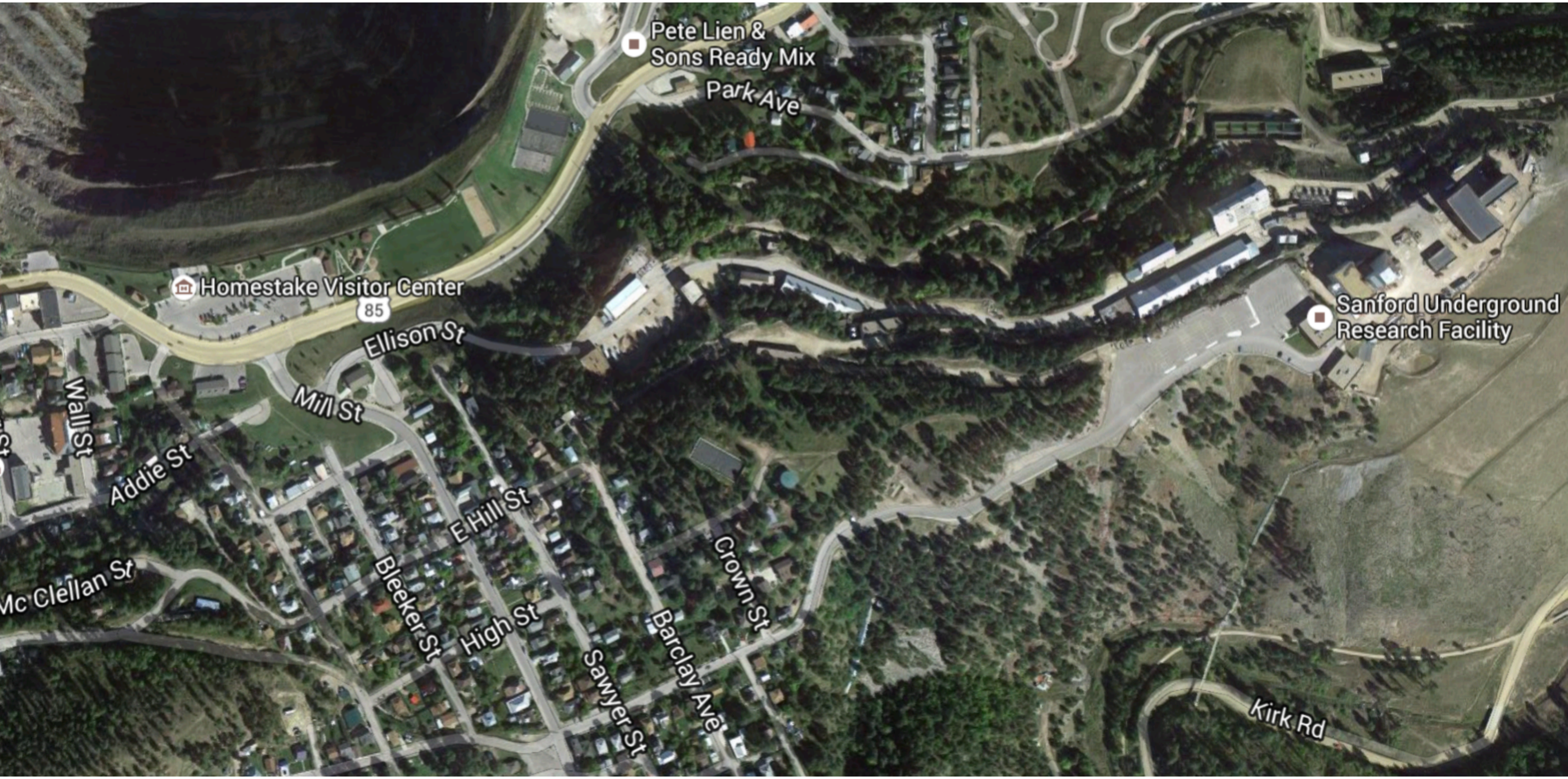
Opening of Sanford Homestake Visitor Center 6/30/15

Governor Dennis Daugaard 10 minute lecture on neutrinos

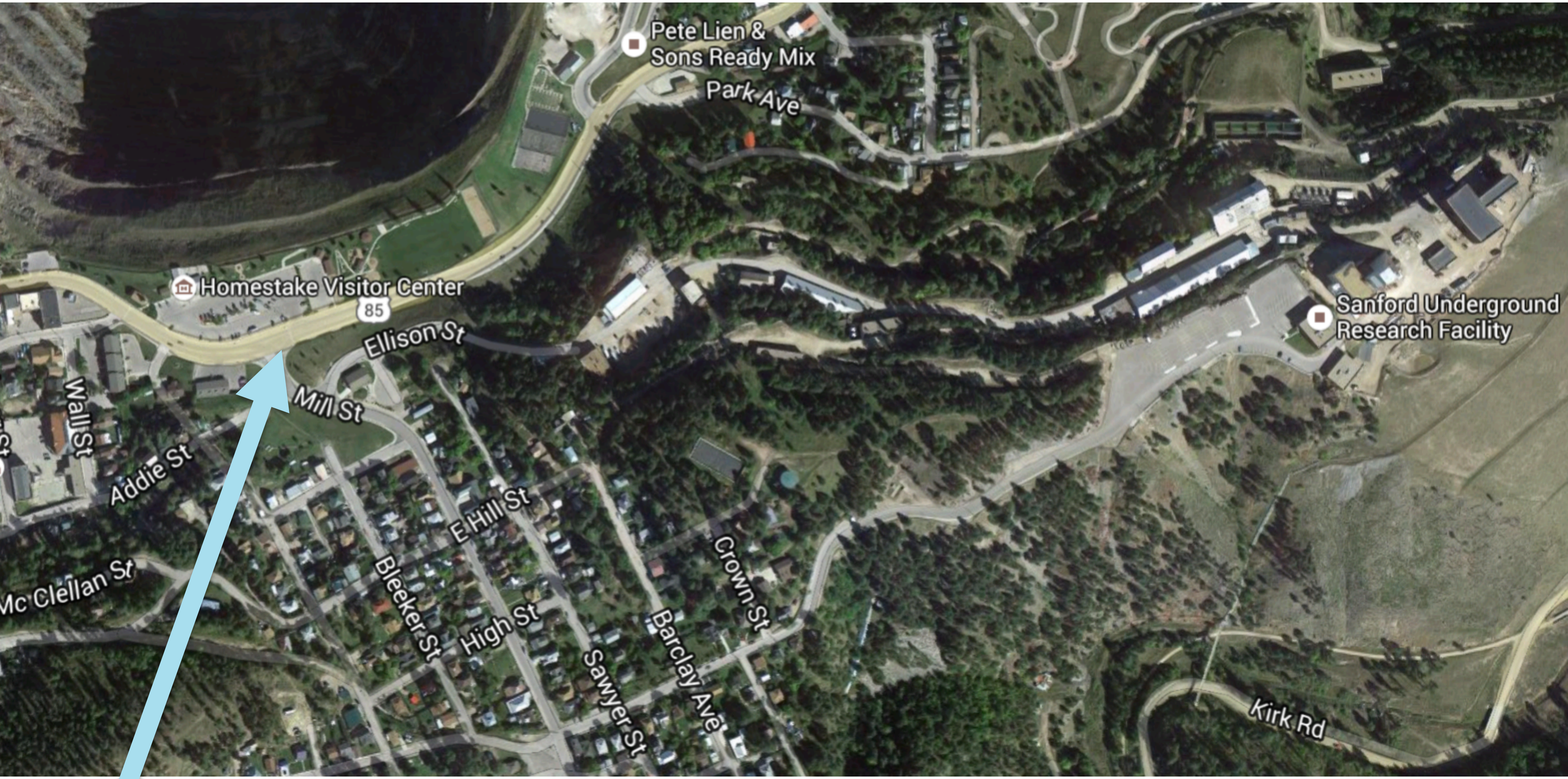
Real-life applications of neutrino physics

Jamie Gilcrease,
Café owner

Real-life applications of neutrino physics



Real-life applications of neutrino physics



New location of Lotus Up espresso, summer 2016

Thanks to Chang Kee and all the organizers

(don't look down)