Outlook

Joe Lykken

Fermilab

Outline

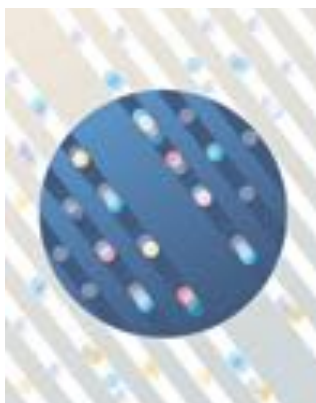
- Science drivers and connections
- Excitement and confusion
- Speculation about prospects for
  - Neutrinos
  - Dark matter

Science Drivers of Particle Physics (from P5)

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

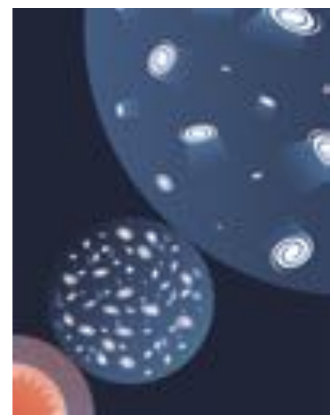
- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles

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 the unification of matter and forces
- How are neutrinos related to dark matter
- Extra credit: are neutrinos related to dark energy

Photo: AIP, Emilio Segrè Visual Archives

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Particle physics connections to other fields

- Cosmology: probes dark matter, dark energy, the number of types of neutrinos and their masses, primordial inflation and the superhigh energy scale associated with it
- Nuclear physics: Majorana nature of neutrino mass, neutrino-nuclear physics underlying neutrino oscillation experiments, nuclear recoil physics for dark matter experiments, nuclear astrophysics connects to solar and supernova neutrino fluxes, heavy ion collisions as probes of quark-gluon plasma and gluon structure of the nucleon
- Astrophysics: dark matter indirect detection, neutrinos as probes of supernovae and cosmic accelerators
- Condensed matter: theory connections (Higgs mechanism! string theory, entanglement,…)

We live in exciting times for particle physicists

- The Higgs boson / Higgs field is a completely new kind of beast
  - We have just scratched the surface of the Higgs sector
- LHC 13 TeV run begins now!
  - Anything new will be a revolution in particle physics
- Neutrino science is both maturing and ramping up fast
  - Answers to many of our basic questions appear within reach
  - Could confirm anomalies or discover new surprises
- Dark matter direct detection could be just around the corner
  - The most (?) interesting region for WIMPS is being probed soon
  - Could also detect signs of a dark mediator

We live in exciting times for particle physicists

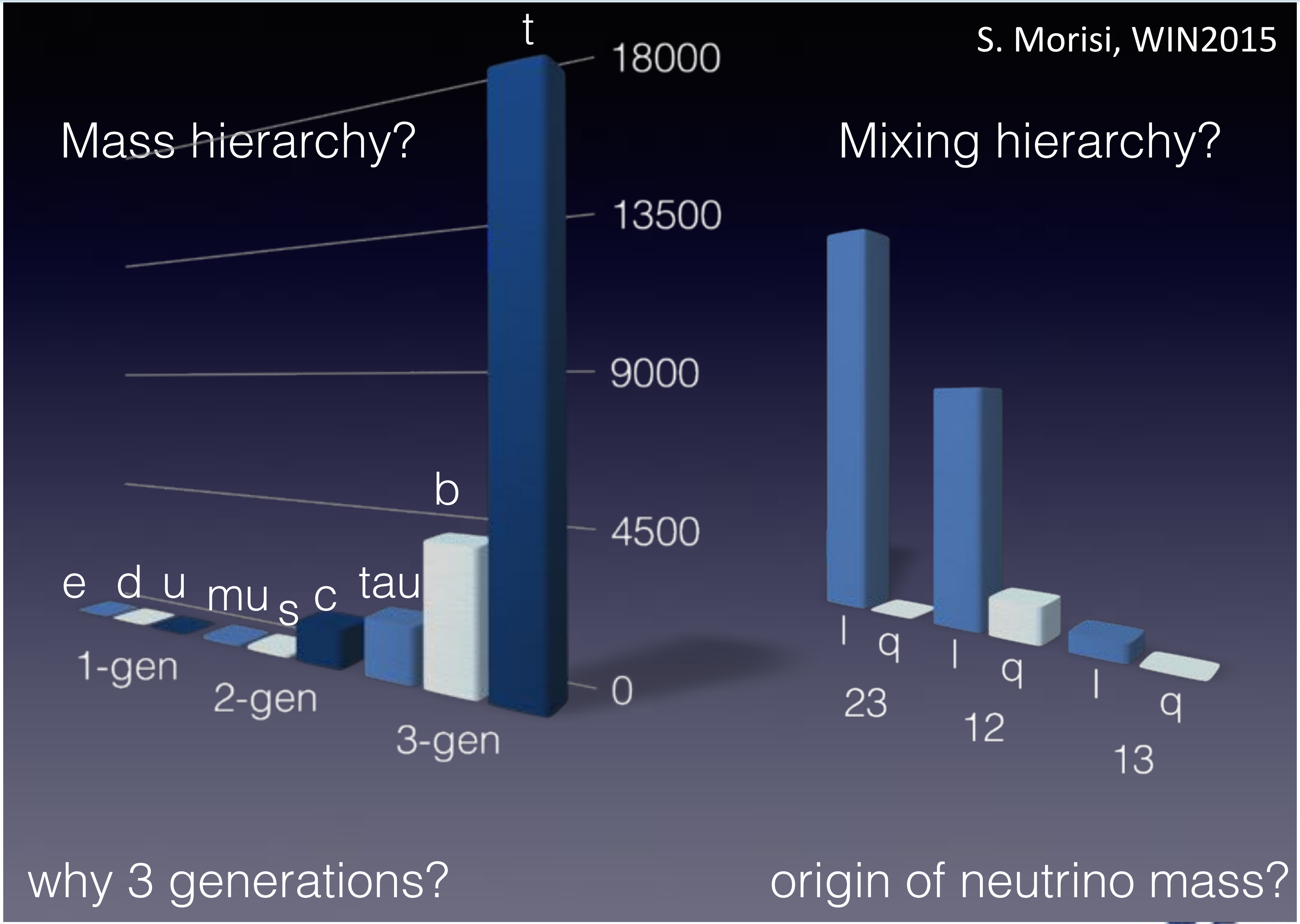
Surprises may arise from a variety of experiments that explore the unknown:

- Flavor surprises:
  - in B decays at BELLE II or LHCb
  - muon to electron conversion and other CLFV processes
  - flavor-violating Higgs decays (a hint already?)
  - Lepton non-universality (CMS eejj excess, LHCb $B \to K\ell^+\ell^-$)
- Other potential surprises:
  - muon g-2
  - electric dipole moments or other EM anomalies
  - production and decay of heavy neutral leptons
  - proton decay
- And there could be signals from the “unknown unknowns”

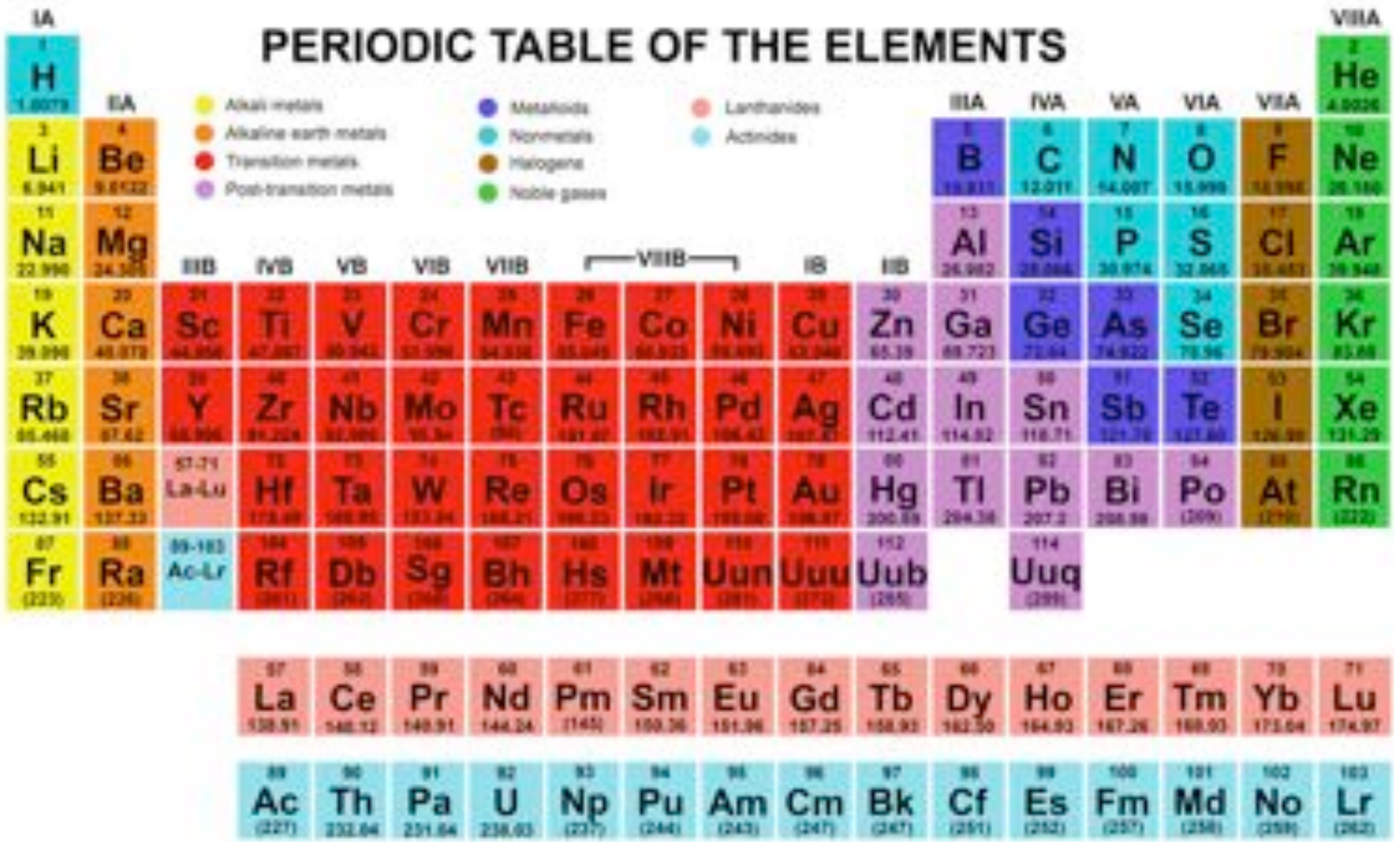
We live in confusing times for particle physicists

- For the past 30 years, particle theorists have used the idea of naturalness to argue that a relatively light Higgs boson implies superpartner particles with mass below a TeV
- Light Higgs boson discovered, but no sign of superpartners
- No sign of any other new particles at LHC either!
- Precision measurements (almost) all agree with Standard Model predictions, with frightening regularity
- Meanwhile the pattern of masses and mixings of Standard Model particles are a total mystery…

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

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My view (also a prediction):

Flavor (broadly defined) is the 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

Today we are confused but nature is surely following some logic

A. Strumia, Moriond 2015

Natural solution: Napoli = Salerno. But not supported by geo data
Anthropic solution: mafia sells signposts. Plausible but untestable
Or think different

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Thinking different is a healthy exercise

- Maybe superpartners are there, but heavier than we thought
- Maybe lots of new physics with O(1) flavor violation at 10-100 TeV, out of reach of the LHC
- Dark matter sector may be much richer, more complicated
- Maybe the neutrino sector is richer and neutrino mass generation is a more complicated story
- Maybe a lot of the seemingly arbitrary features of the Standard Model are explained by the multiverse and the anthropic principle (not my favorite…)

The naturalness argument: how far are you willing to go?

$m_H << M_P$?

A. Pomarol, WIN2015

Towards naturalness

"fermionizing" the Higgs

No new TeV-physics

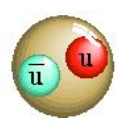
Supersymmetry

"marrying" a fermion:

Higgs ⟷ Higgsino

Compositeness

The "transvestite" Higgs:

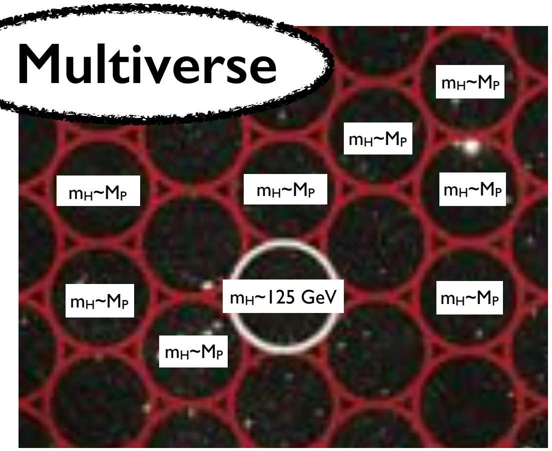
H = 

new TeV-physics

relaxation mechanism?

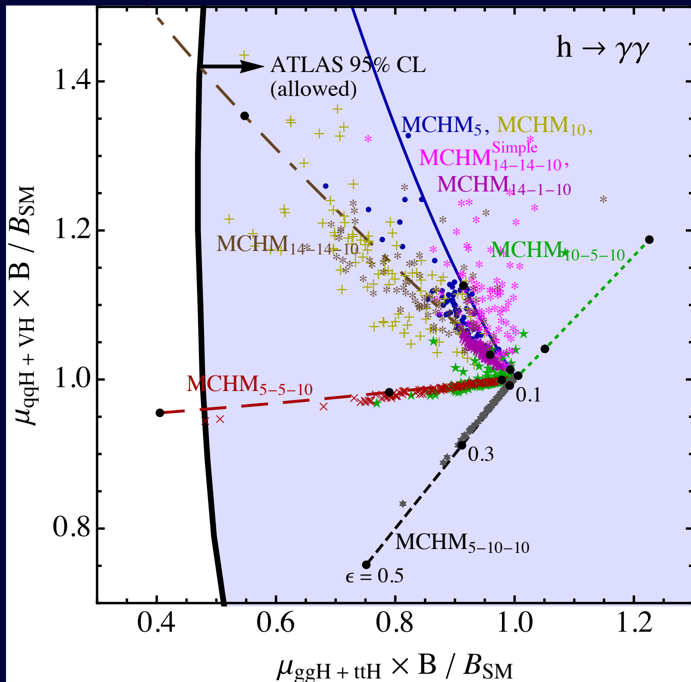
arXiv:1504.07551

Multiverse

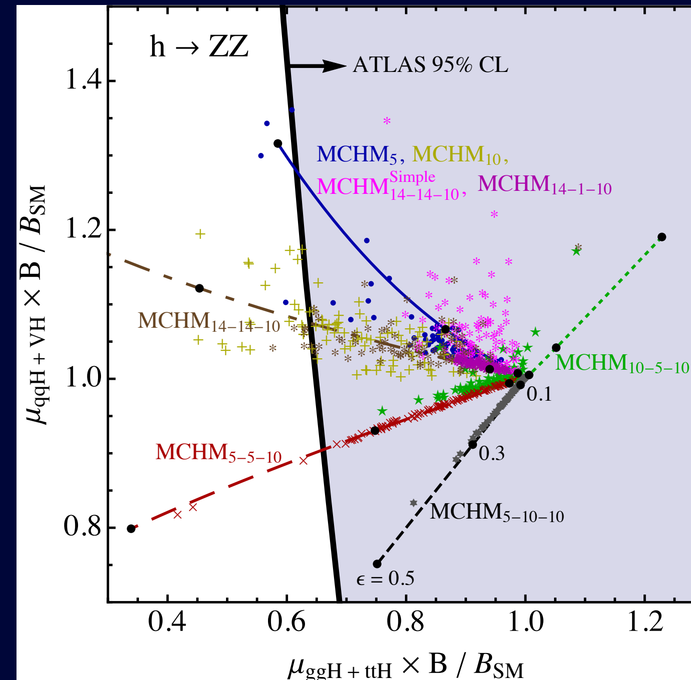


Minimal Composite Higgs models confronting data

h to di-photons



h to ZZ



M.C., Da Rold, Ponton'14

Talk by M. Carena

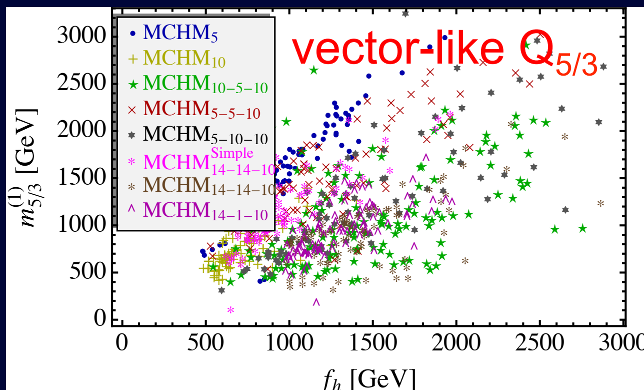
After EWSB: $\varepsilon = v_{SM}/f$ and precision data demands f > 500 GeV

More data on Higgs observables will distinguish between different realizations in the fermionic sector, providing information on the nature of the UV dynamics

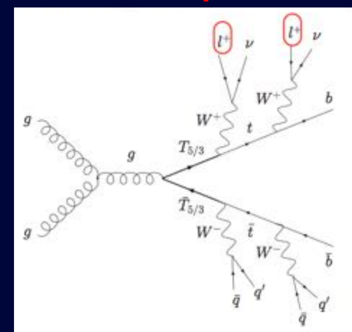
Other global symmetry patterns allow for additional Higgs Bosons in the spectrum

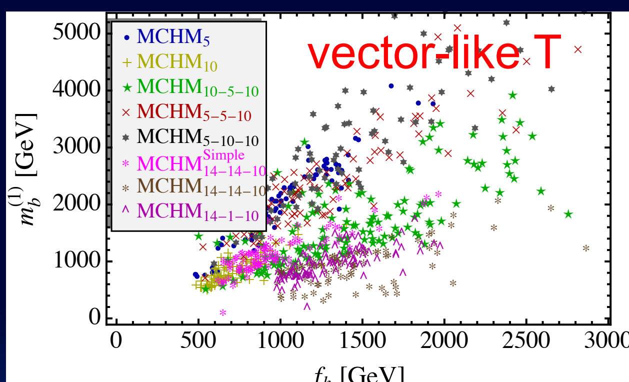
Composite pNGB Higgs Models predict light Fermions

Pair production, single production, or exotic Higgs production of vector-like fermions
[masses in the TeV range and possibly with exotic charges: Q = 2/3,−1/3, 5/3,8/3,−4/3]



SS di-leptons





Large variety of signatures, many with energetic leptons

M.C., Da Rold, Ponton’14

Talk by M. Carena

LHC exclusion for M_f < 800 GeV]

Is the Standard Model (almost) all there is?

Maybe the naturalness argument applied to the Higgs is just wrong (well, it was apparently wrong for the vacuum energy too)

- The Standard Model plus some TeV scale renormalizable additions (like dark matter) might be all there is
- The Standard Model itself, or with such modest additions, is completely natural
- Usual counterargument involves the putative Planck scale threshold, but this is speculative
- An unsatisfying scenario, leaving many questions unanswered, but has a certain minimalist appeal…

The canonical Beyond the Standard Model paradigm

- Superpartners at the LHC
- Dark matter from supersymmetry
- "Grand" or similar unification of matter and gauge forces somewhere around 10^{16} or 10^{17} GeV
- Tiny neutrino masses from a "see-saw" related to the new physics at superhigh energies
- Superstrings at the Planck scale with lots of extra structure to explain flavor structure, primordial inflation, etc.

There are lots of good arguments for this picture

The canonical Beyond the Standard Model paradigm

The experimental program that goes with this paradigm is pretty clear:

- Find superpartners, map properties
- Nail down the physics of the Higgs
- Close the circle of dark matter between direct detection, indirect detection, LHC production, and large scale structure
- Nail down the neutrino sector including CP violation and Majorana mass
- Find proton decay and possibly charged lepton flavor violation
- Cosmic Microwave Background probes primordial inflation
- Use all these clues to extract a more concrete picture of the unified theory at superhigh energies

Neutrino Outlook

The appeal of the neutrino see-saw

See-saw mechanism type I

- Introduce a right handed neutrino **N**
- Couple it to the Higgs

$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \Rightarrow m_\nu = \frac{Y_\nu^2 v_H}{M_N} \sim \frac{1\ \mathrm{GeV}^2}{10^{10}\mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

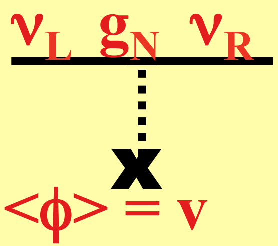
Minkowski;Yanagida; Glashow; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic

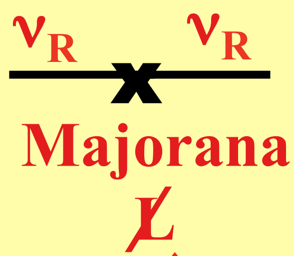
Talk by S. Pascoli

See-saw type I models can be embedded in GUT theories and explain the baryon asymmetry via leptogenesis.

Neutrino mass: a complicated story

Simplest possibility: assume 3 right handed singlets (1_L)





$$\rightarrow \begin{pmatrix}\bar{\nu}_L & \bar{\nu}_R^{c}\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & M_R\end{pmatrix}\begin{pmatrix}\nu_L^{c} \\ \nu_R\end{pmatrix}$$

like quarks and charged leptons ➔ Dirac mass terms (including NMS mixing)

+9+ new ingredients: ➔ SM+
1) Majorana mass = scales
2) lepton number violation

6x6 block mass matrix
block diagonalization
M_R heavy ➔ 3 light ν's

M. Lindner, ApPEC@ Fermilab

Neutrino mass: a complicated story

3x3 matrix

3   0 … N   3xN   NxN

$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^{c} \end{pmatrix} \begin{pmatrix} M_L & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^{c} \\ \nu_R \end{pmatrix}$$

M_L, m_D, M_R may have almost any form / values:

- zeros (symmetries)
- 0 + tiny corrections
- scales: M_W, M_{GUT}, …

➔ **diagonalization: 3+N EV**

➔ **3x3 active almost unitary**

M. Lindner, ApPEC@ Fermilab

For further complications see talk by S. Parke WIN2015

How little we know: the neutrino see-saw

M. Hirsch, WIN2015

Smallness of neutrino mass can be "explained" by:

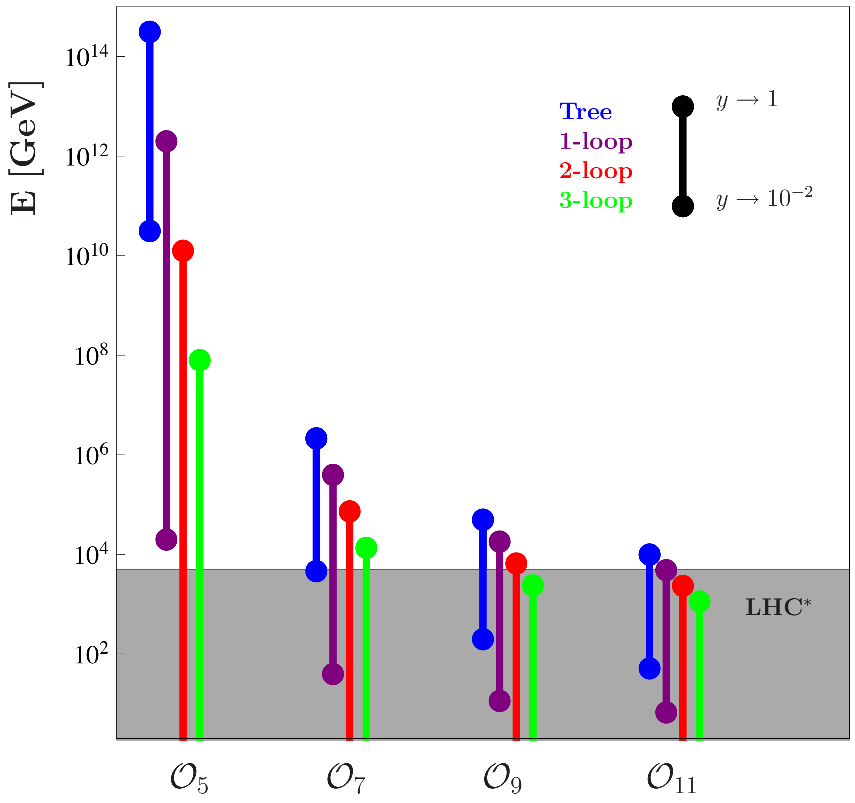
$\Rightarrow$ High scale: Large Λ
"classical" seesaw

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

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

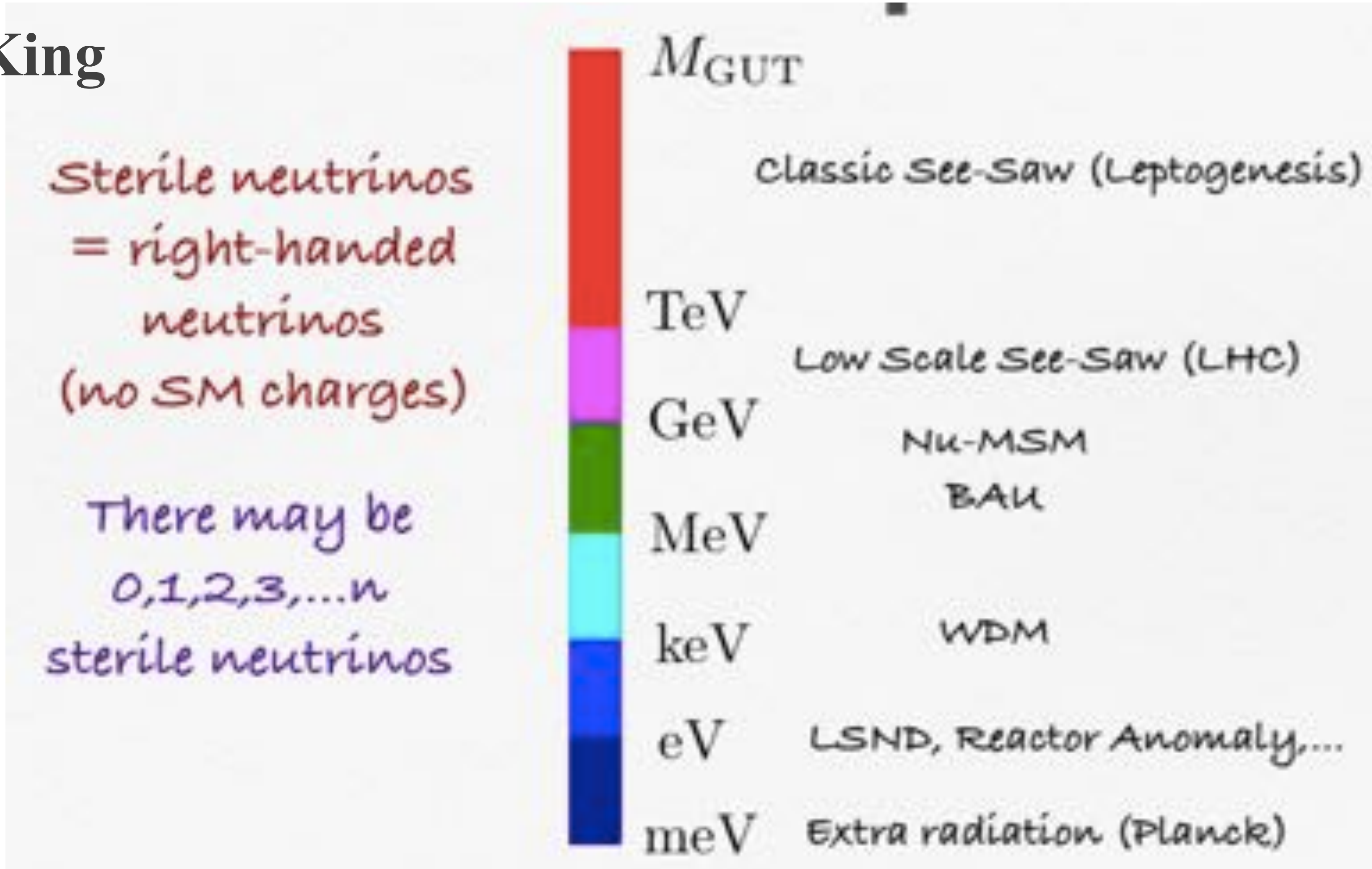
$\Rightarrow$ Nearly conserved L,
i.e. small ϵ ("inverse seesaw")

$\cdots$ or combination thereof



How little we know: sterile neutrinos

S. King



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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?

Can be addressed strongly with current and planned experiments

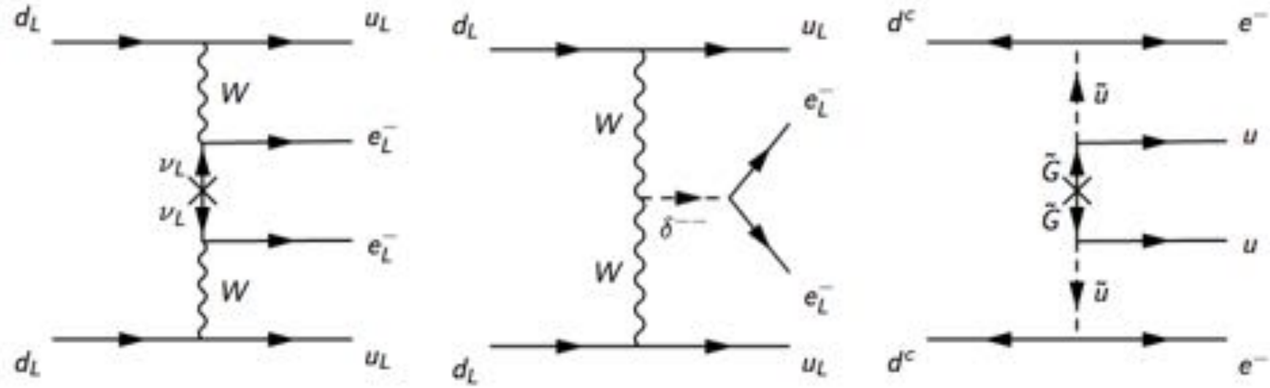
- What is the scale of neutrino mass generation?
- What explains the pattern of neutrino mixings?
- Can neutrinos be unified with quarks?
- Is neutrino CP violation related to baryon asymmetry?

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

Good news / bad news: $0\nu\beta\beta$

Majorana ν-masses or other ΔL=2 physics: ➔ 2 electrons

0νββ



…

M. Lindner, ApPEC@ Fermilab

Majorana neutrino masses ←→ Dirac?

SM + Higgs triplet

SUSY

important connections to LHC and LFV …
sub eV Majorana mass ←→ TeV scale physics

- Good news: observation of neutrinoless double beta decay would be a huge discovery, violation of an important symmetry
- Bad news: doesn't *necessarily* mean that the decay is driven by Majorana masses of neutrinos
- Good news: the "loopholes" are themselves interesting for LHC etc

Good news / bad news: CP violation in oscillations

- Good news: observation of CP violation in long-baseline neutrino oscillations would be a huge discovery, violation of an important symmetry
- Bad news: doesn't *necessarily* mean that the observed CPV is the CPV of leptogenesis, or even that leptogenesis occurs
- Good news: a point in favor of the canonical BSM paradigm, will focus the attention of the community

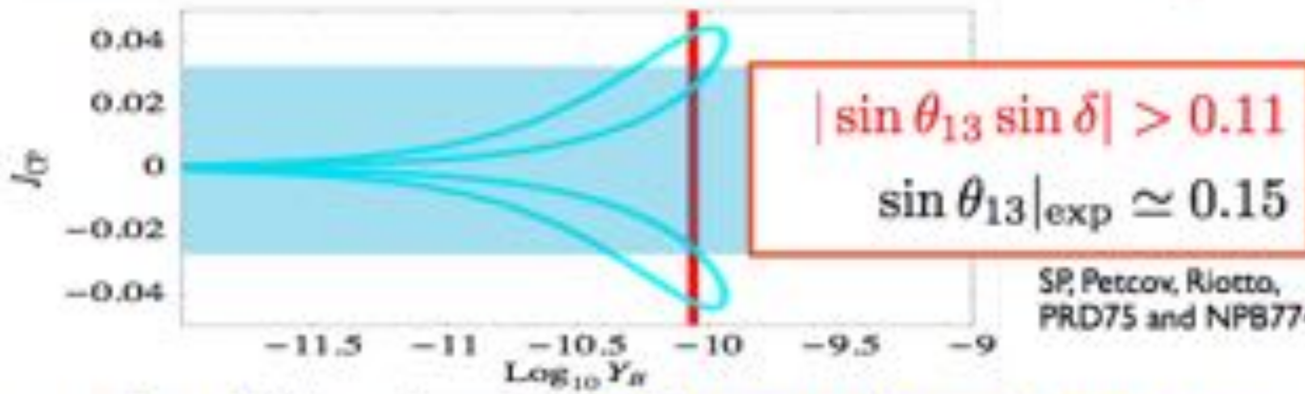
Possible bridge between leptogenesis and δ_{CP}

Does observing low energy CPV imply a baryon asymmetry?

It has been shown that, thanks to flavour effects, the low energy phases enter directly the baryon asymmetry.

Example in see-saw type I, with NH (m1<< m2 <<m3), M1<M2<M3, M1~5 10^11 GeV:

$$\epsilon_\tau \propto M_1 f(R_{ij}) \left[c_{23} s_{23} c_{12} \sin\frac{\alpha_{32}}{2} - c_{23}^2 s_{12} s_{13} \sin(\delta - \frac{\alpha_{32}}{2}) \right]$$



SP, Petcov, Riotto, PRD75 and NPB774

- G Large theta13 implies that delta can give an important (even dominant) contribution to the baryon asymmetry. Large CPV is needed and a NH spectrum.

Talk by S. Pascoli

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Good news / bad news: PMNS matrix

- Good news: next generation experiments will do a lot to nail down the parameters of the PMNS matrix and start to over constrain the minimal picture
- Bad news: could be the CKM all over again…
- Good news: neutrinos are different from quarks: neutral fermions (thus can mix with steriles) large mixings and tiny masses that hint at beyond-SM mass generation (how beyond is beyond?)

	3σ range	3σ knowledge
$\sin^2\theta_{12}$	$0.270 \to 0.344$	
$\theta_{12}/^\circ$	$31.29 \to 35.91$	~14%
$\sin^2\theta_{23}$	$0.385 \to 0.644$	
$\theta_{23}/^\circ$	$38.3 \to 53.3$	~33%
$\sin^2\theta_{13}$	$0.0188 \to 0.0251$	
$\theta_{13}/^\circ$	$7.87 \to 9.11$	~15%
$\delta_{CP}/^\circ$	$0 \to 360$	~no info
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.02 \to 8.09$	~14%
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$	~12%

M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T. Schwetz, 10.1007/JHEP11(2014)052

Neutrino model building

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}$$

$$U_{TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

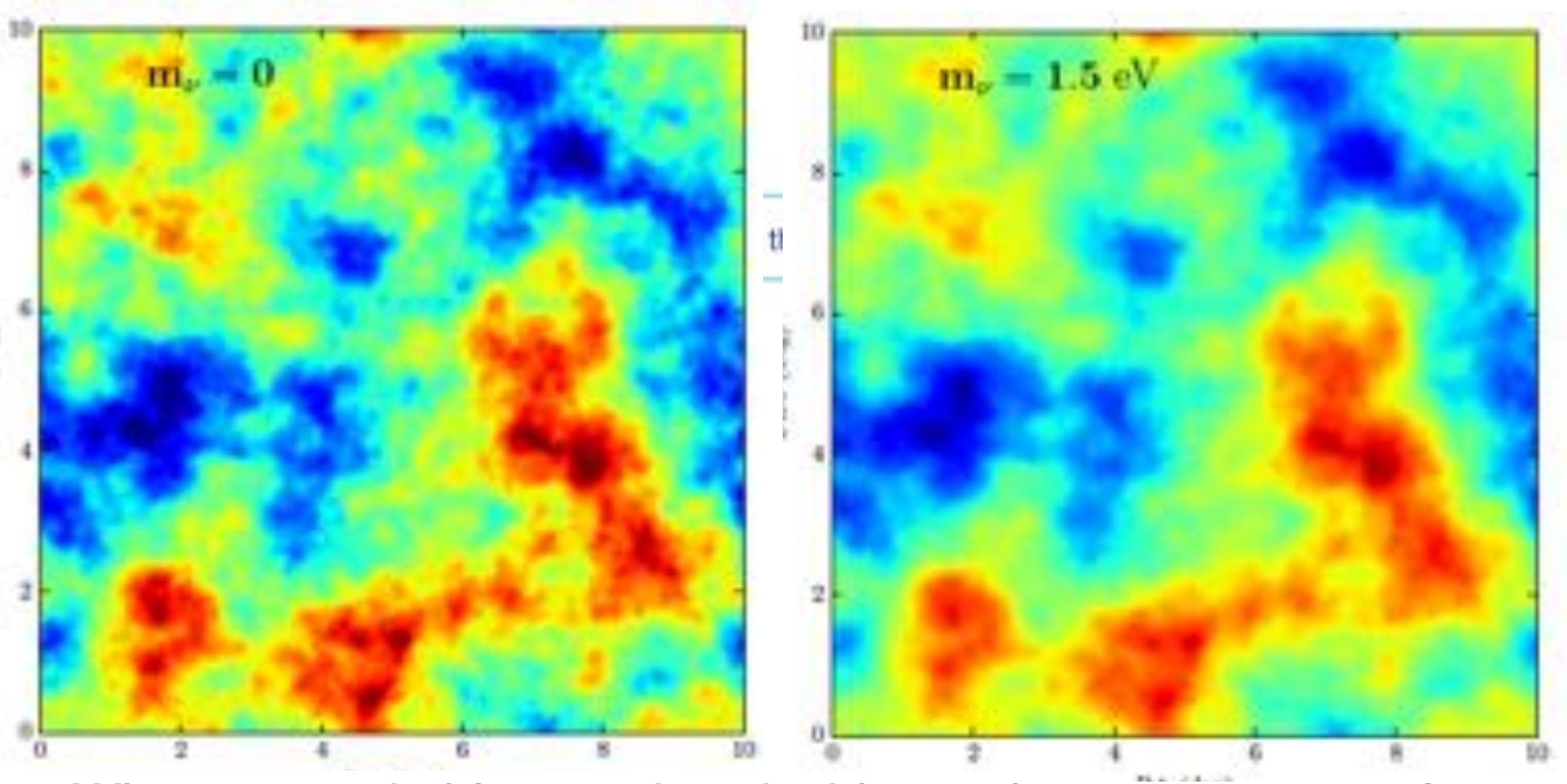
$$U_{BM} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$U_{LC} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{c^{\nu}_{23}}{\sqrt{2}} & \frac{c^{\nu}_{23}}{\sqrt{2}} & s^{\nu}_{23} \\ \frac{s^{\nu}_{23}}{\sqrt{2}} & -\frac{s^{\nu}_{23}}{\sqrt{2}} & c^{\nu}_{23} \end{pmatrix}$$

$$L_e - L_\mu - L_\tau$$

- Theorists making models of quark masses and mixings focus on explaining the hierarchies of masses and mixings, and ignore O(1) factors
- Theorists making models of neutrino masses tend to do the opposite
- Usually assume that the PMNS picture is correct, and try to reproduce the numbers
- Make extra assumptions in order to make testable predictions
- An ambitious but exciting strategy

Good news: neutrino mass affects the observed universe



What a remarkable cosmic coincidence that we can strongly constrain and perhaps measure Σm_{ν_i} from the effect of neutrinos on large-scale structure!

some neutrino news from Fermilab

SBN Program – Three detectors with one mission

	ICARUS	MicroBooNE	SBND	Produce
ν_μ Disappearance	Fewer ν_μ ?	Fewer ν_μ ?	ν_μ	ν_μ
ν_e Appearance	More ν_e?	More ν_e?	~1% ν_e	~1% ν_e

110m

See talk by J. Asaadi

470m

600m

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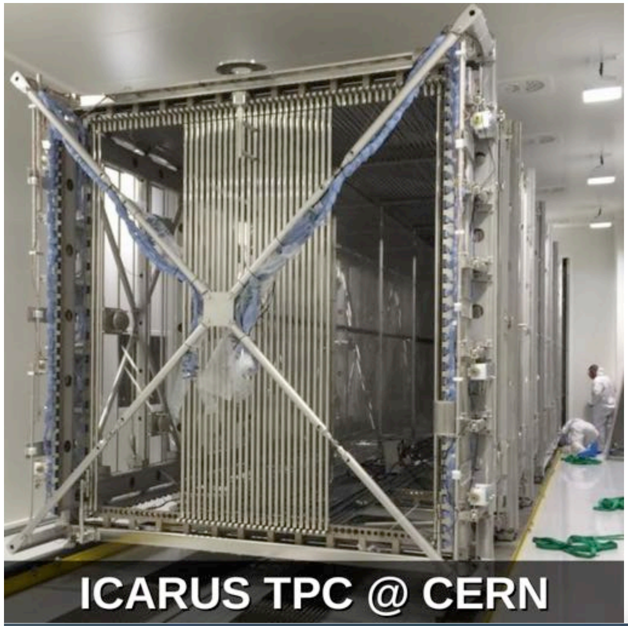
SBN program…growing and roaring ahead



Sunday, April 26, 2015 9:42 AM

Dear Colleagues

this is to let know that all the ICARUS participating groups have been formally consulted and have unanimously agreed to extend the ICARUS collaboration to you and your teams. Argonne National Laboratory, Colorado State University, Los Alamos National Laboratory, FermiLab, University of Pittsburgh and SLAC are presently new participants in the Collaboration.

Welcome in ICARUS !

Sincerely

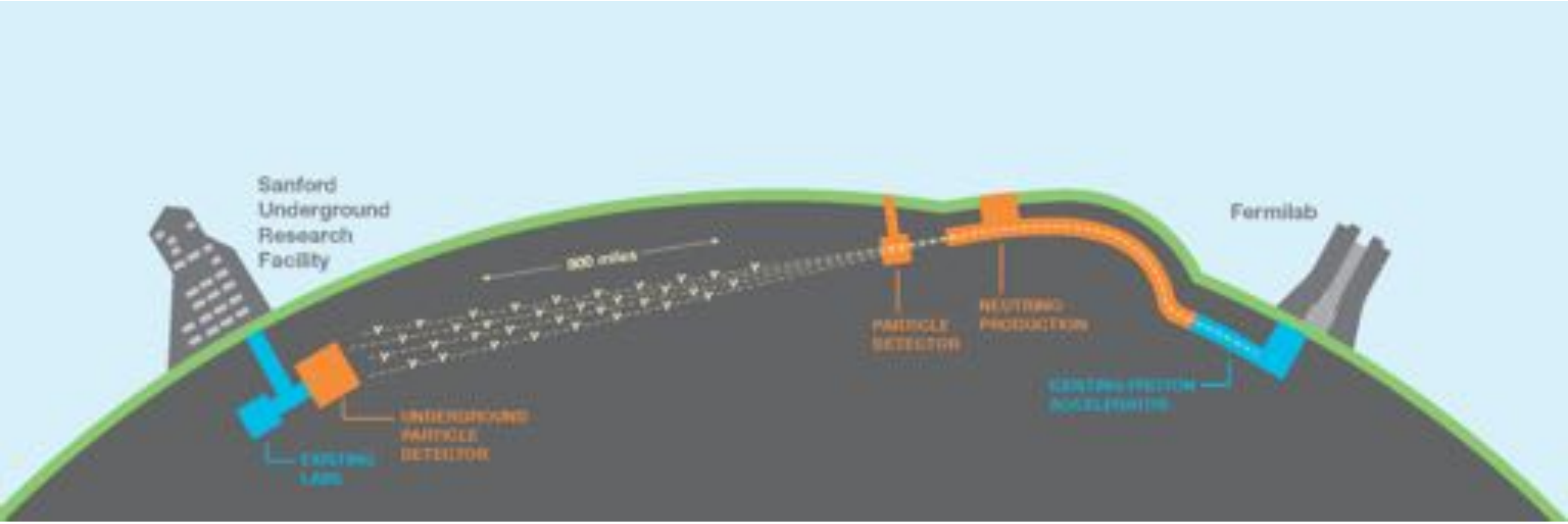
Carlo Rubbia

Far Detector Building
Construction Start – Summer 2015

Near Detector Building
Construction Start – Fall 2015

See talk by J. Asaadi

A new era begins: LBNF and DUNE



LBNF/DUNE will be the first truly international facility at Fermilab, and the first-ever international “mega science” project hosted by the U.S. DOE. Bigger than anything at Fermilab in last 40 years, expected to eventually serve more than 2,000 physicists from around the world.

Deep Underground Neutrino Experiment

See talk by D. Cherdack

A growing global science collaboration:

- **776 members**
- **144 institutions**
- **26 countries**

Spokesperson:
André Rubbia
ETH

Spokesperson:
Mark Thomson
Cambridge

Technical Coordinator:
Eric James
FNAL

Resource Coordinator:
Chang Kee Jung
Stony Brook

DUNE/LBNF…rapid progress

- This is a special year: support from U.S. government is strong
- Next milestone is July 14-16 "CD-1 refresh" review
  - Full scope cost and schedule to be presented
  - Successful Director's review just completed June 2-4
- Nov 2015: "CD-3a review" for far site…this is baseline and construction start for the caverns in South Dakota
- Single and dual phase LAr TPC prototypes will test at CERN
- First 10 kt fiducial module to begin installation by end of 2021
- Cascading schedule to complete full scope:
  - 40 kt fiducial of LAr TPCs deep underground
  - Megawatt beam from Fermilab sensitive to both 1st & 2nd oscillation maximum
  - Fine-grained near detector

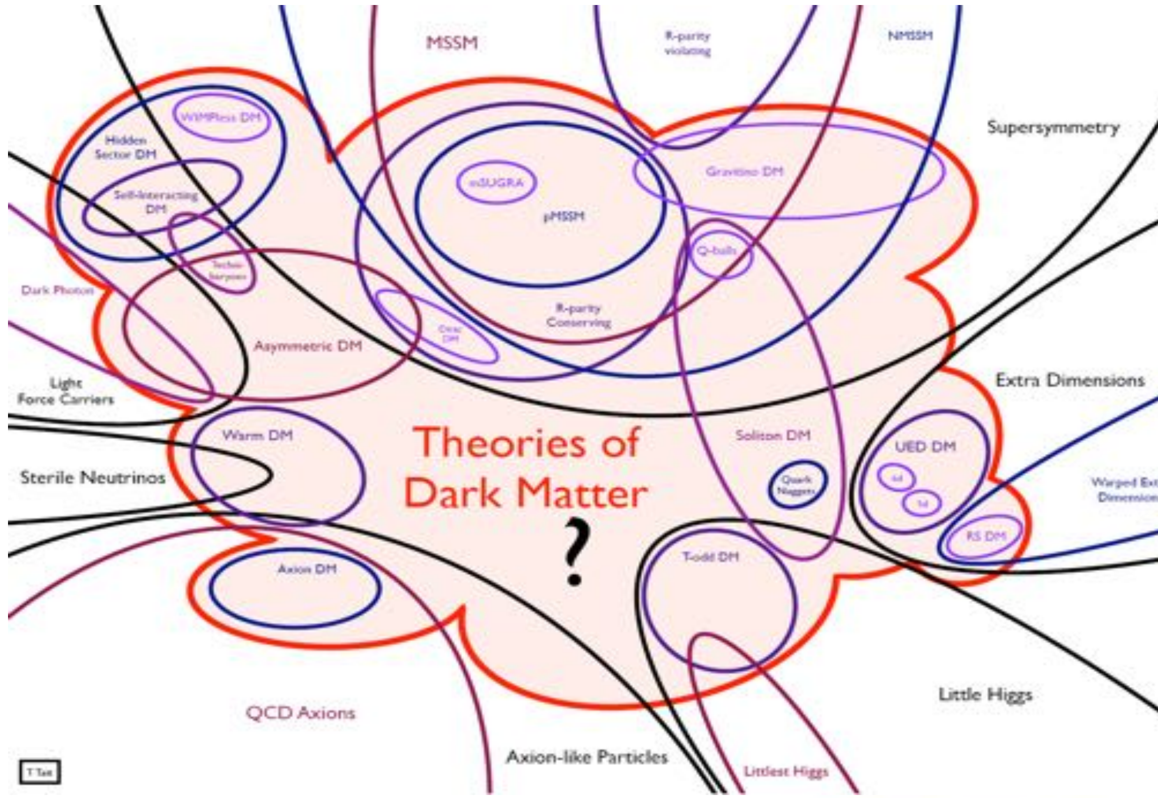
"*The sky is full of ghosts*" – William Herschel (1813)

- 650 light-centuries to the far side of the Milky Way
- Neutrinos from ~2000 supernovae are already on their way here

Dark Matter Outlook

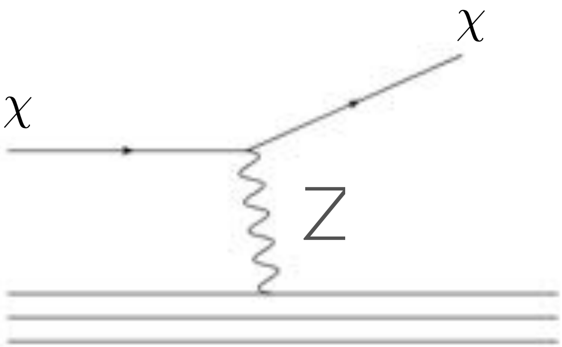
Dark matter bestiary

- Superpartner particles: Wino, Bino, Higgsino, sneutrino, …
- Axions
- Kaluza-Klein particles from extra dimensions
- Sterile neutrinos
- Asymmetric dark matter
- WIMPzillas (don't ask…)

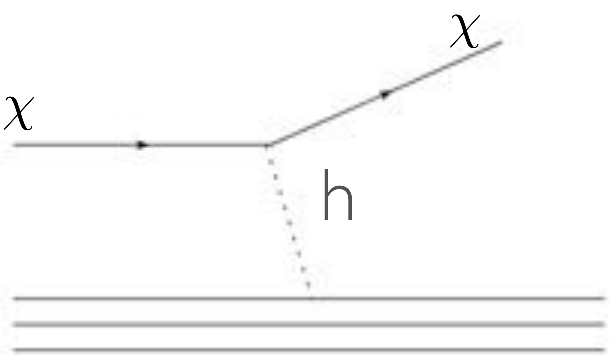


How does dark matter interact with ordinary matter?

via gravity we know

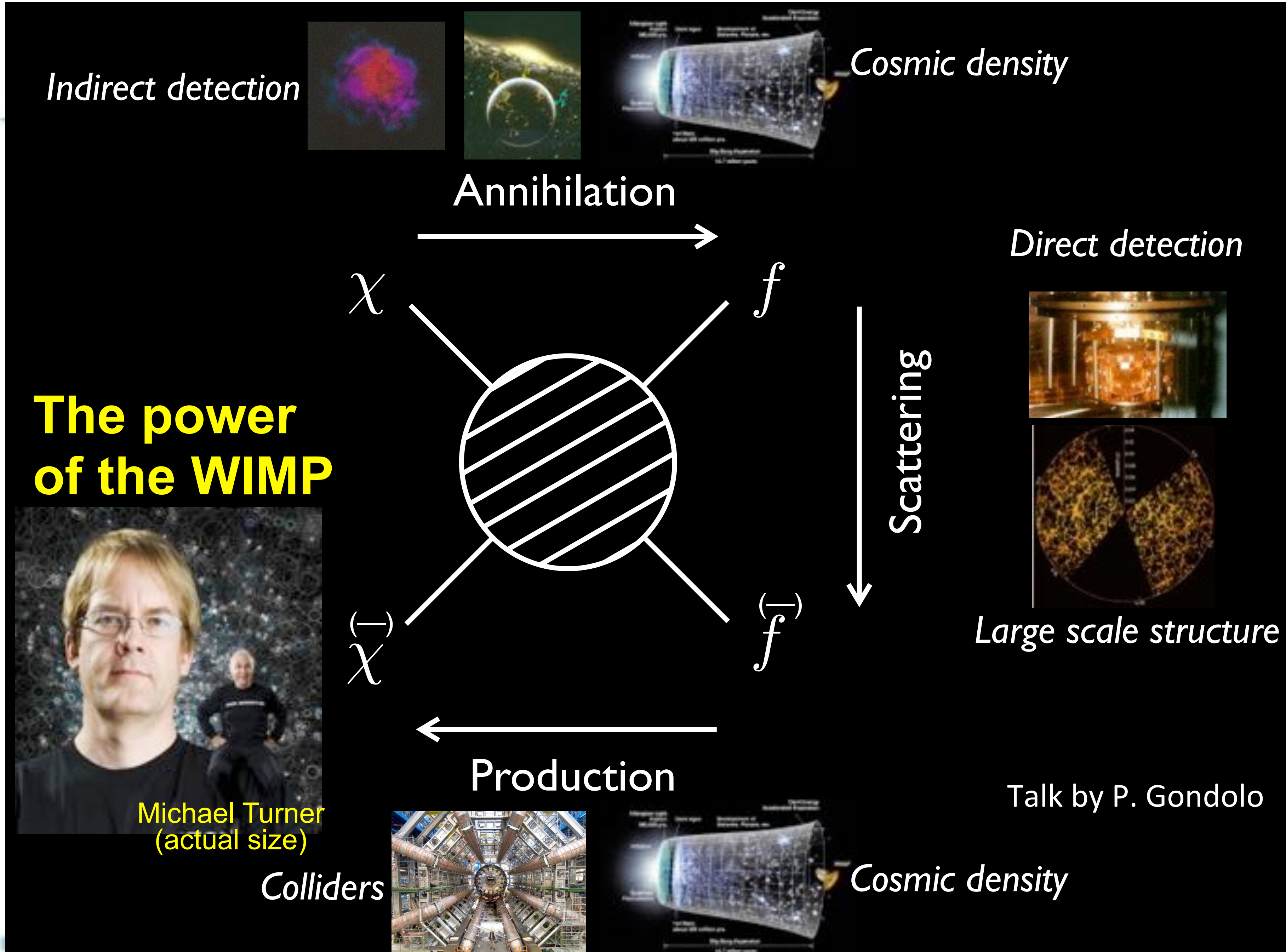


via the known weak interactions, like neutrinos?



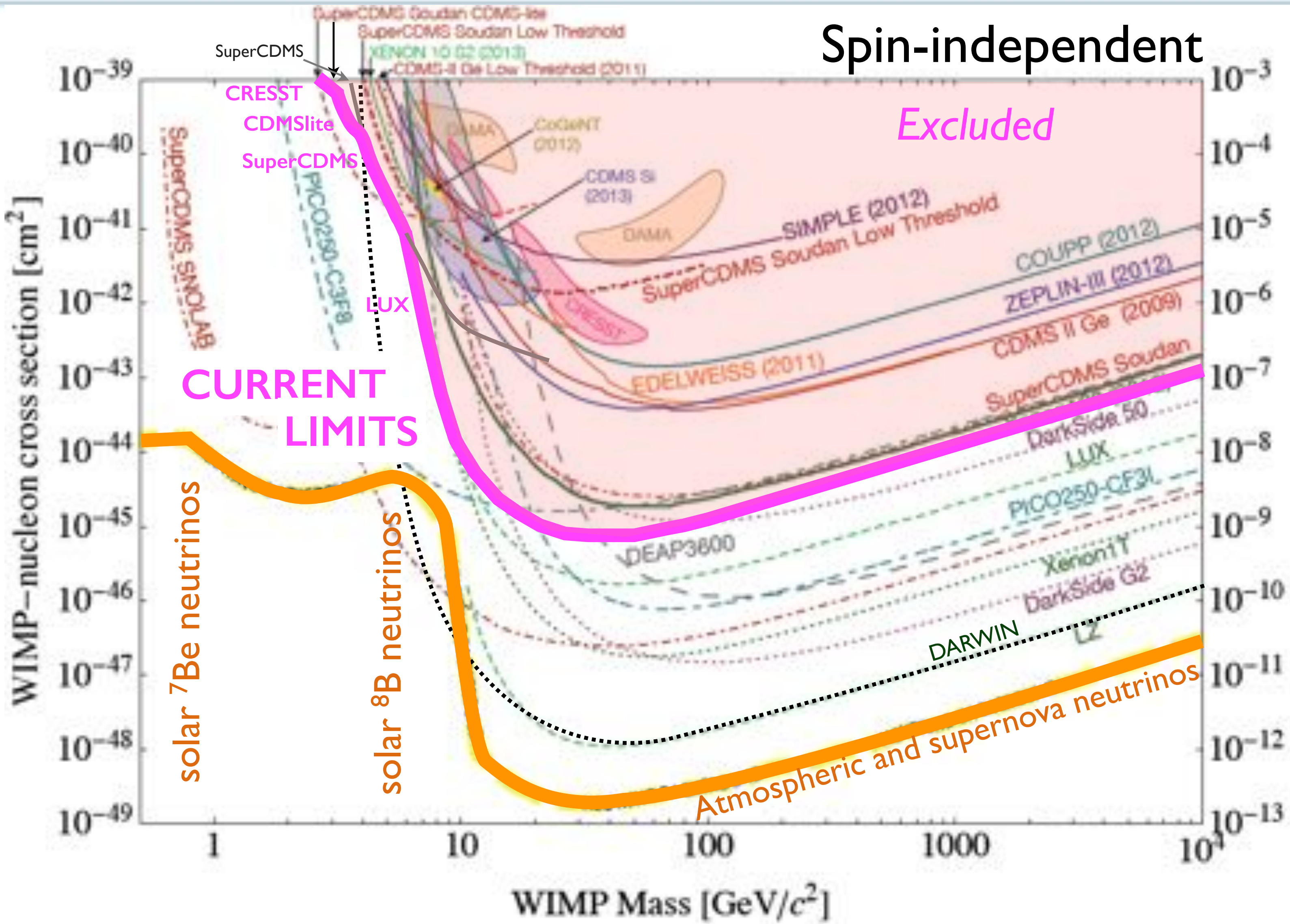
via the newly-discovered Higgs boson?

Or: via some exotic unknown “dark forces”?



Indirect detection
Cosmic density
Annihilation
Direct detection
χ
f
Scattering
The power of the WIMP
$\overset{(-)}{\chi}$
$\overset{(-)}{f}$
Large scale structure
Production
Talk by P. Gondolo
Michael Turner (actual size)
Colliders
Cosmic density

Direct WIMP searches approaching the neutrino floor



Supersymmetry and the WIMP miracle

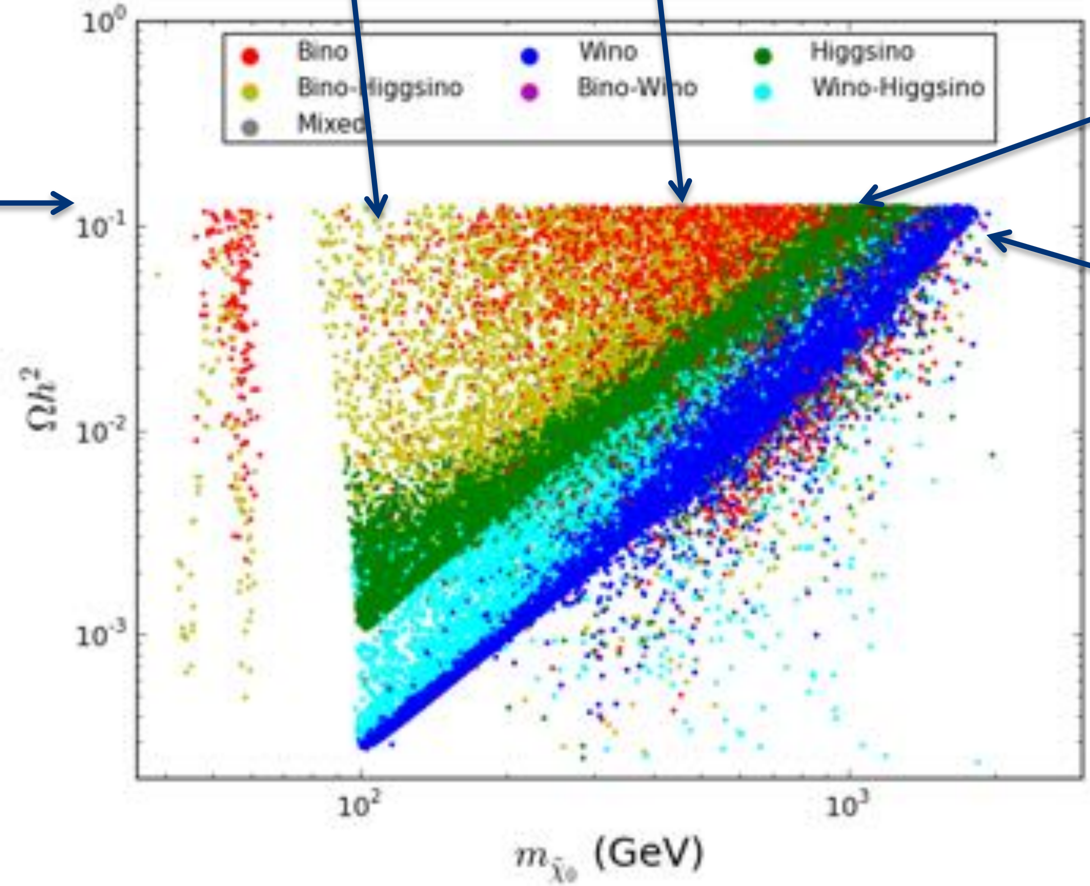
Bino-Higgsino mixture, closest case to the WIMP Miracle

Pure Bino needs co-annihilation with other quasi-degenerate superpartners

"correct" thermal relic density

Higgsino, ~ 1.5 TeV

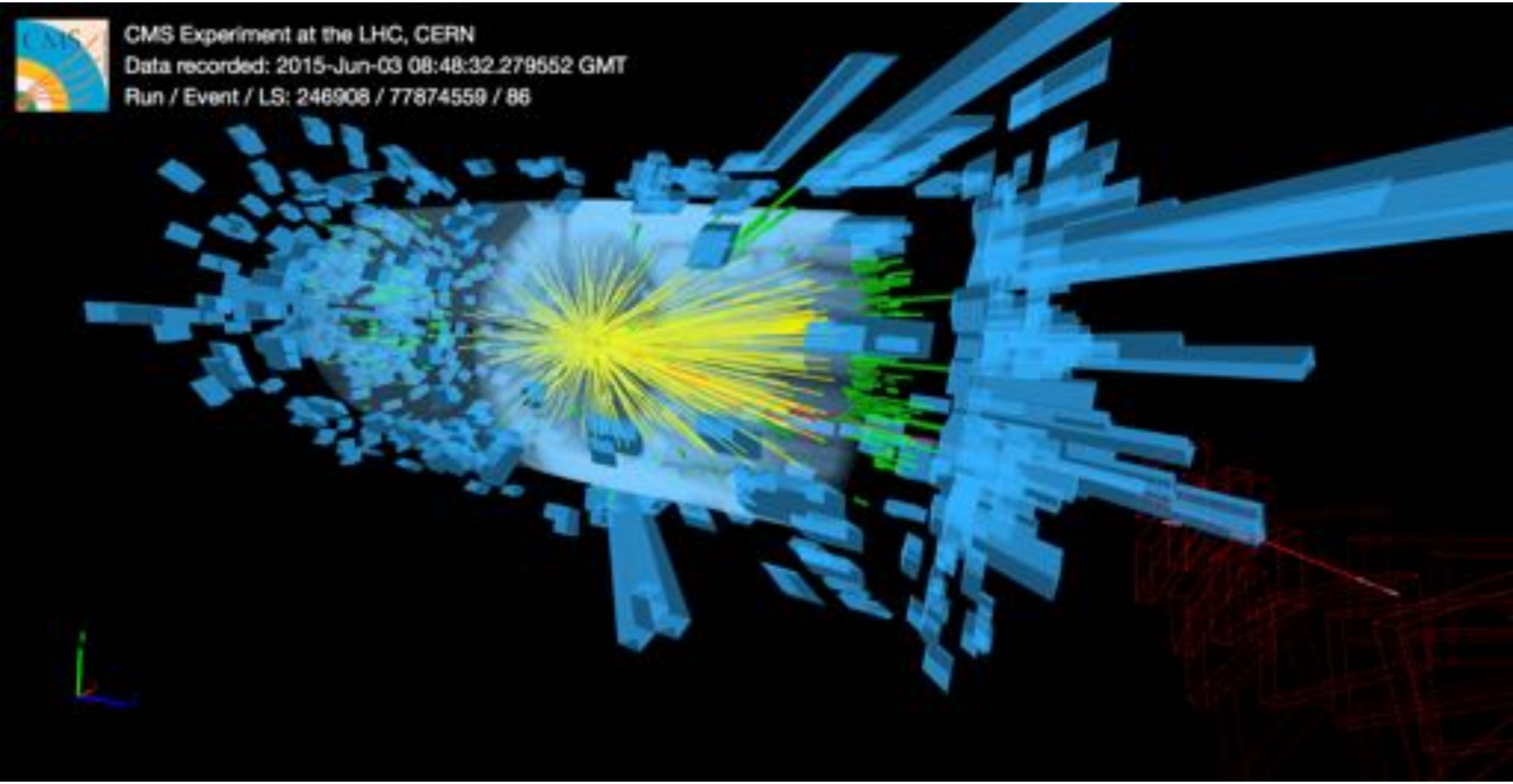
Wino, ~ 3 TeV



M. Cahill-Rowley et al, 1405.6716

Fermilab

Dark matter at the 13 TeV LHC



What do we hope to learn from dark matter?

- Z boson decays in 0.3 yocktoseconds
- top quark decays in 1 yocktosecond
- dark matter particles live for at least 13 billion years

What is the conserved charge that creates this new form of stable matter?

Is dark matter like visible matter?

- why should the dark sector be any simpler than the visible sector?
- the visible sector has 5 different massive stable particles
(6 if you count the neutron)
- the abundance of visible matter is *not* a thermal relic abundance,
it is set by the unknown process of baryogenesis or leptogenesis

Is dark matter like visible matter?

- perhaps dark matter has several different stable components (a little of this and a little of that)
- perhaps have mass and abundance linked directly to the mass and abundance of visible matter: “asymmetric dark matter”
- perhaps some component of DM has significant self-interactions affecting the evolution of galactic structure…

…and killing the dinosaurs?


Thank you