Future perspectives on Neutrino Physics

... some aspects from a theorist's perspective

Stefan Antusch

University of Basel,
Department of Physics

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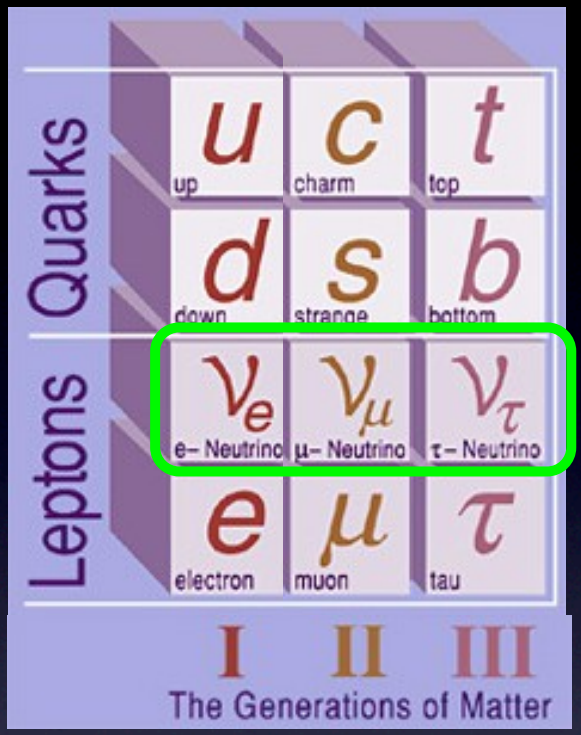
Neutrinos in the Standard Model (SM)



Gauge Symmetry of the SM:

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

With the particle content and the gauge symmetry of the SM (as a renormalisable theory):
Neutrinos can only be massless!
(→ also: no leptonic mixing)

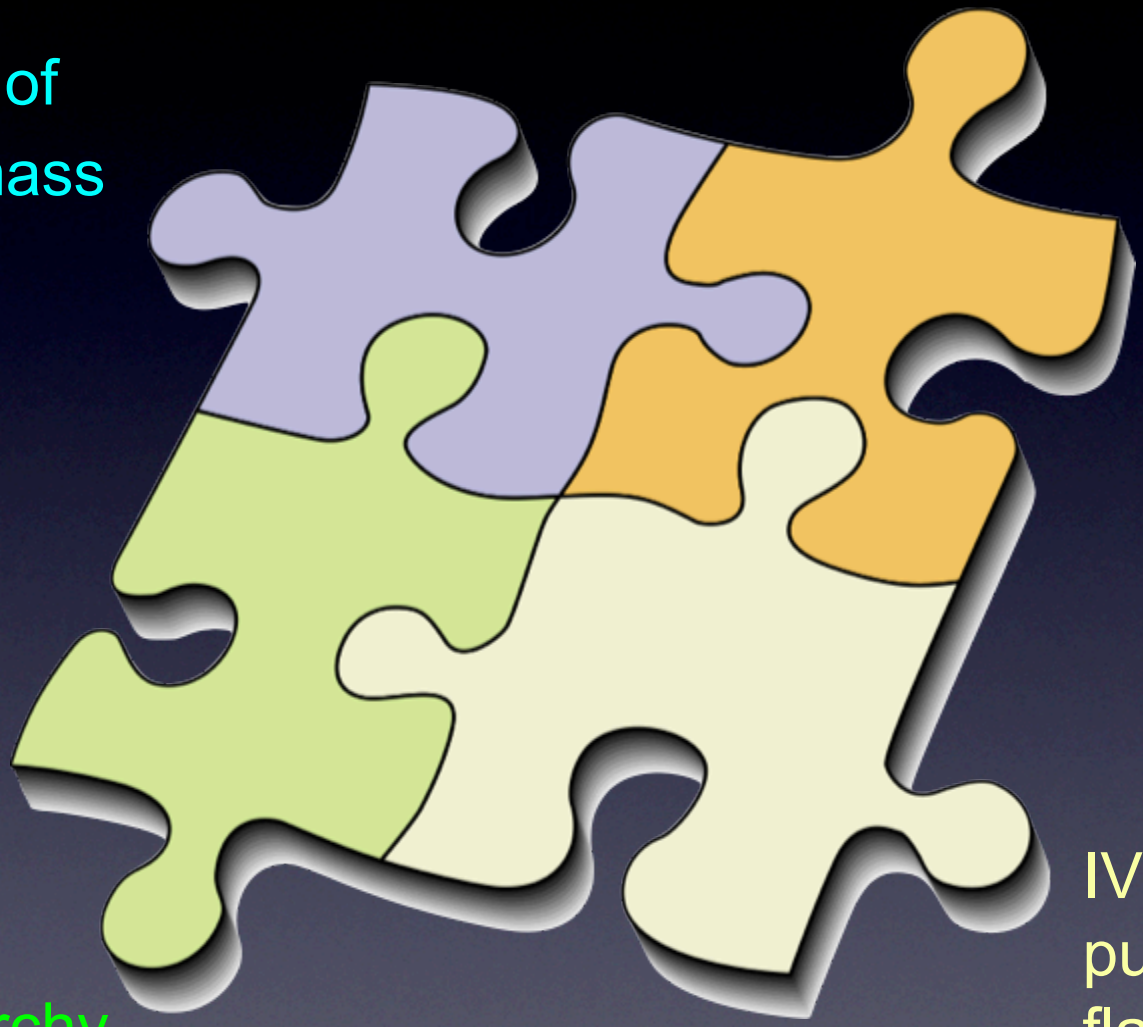
Neutrino oscillation experiments tell us that neutrinos have mass

→ Physics Beyond the Standard Model (BSM)

Neutrino masses: Part of the BSM Puzzle

Some pieces of the puzzle …

I) The origin of neutrino mass

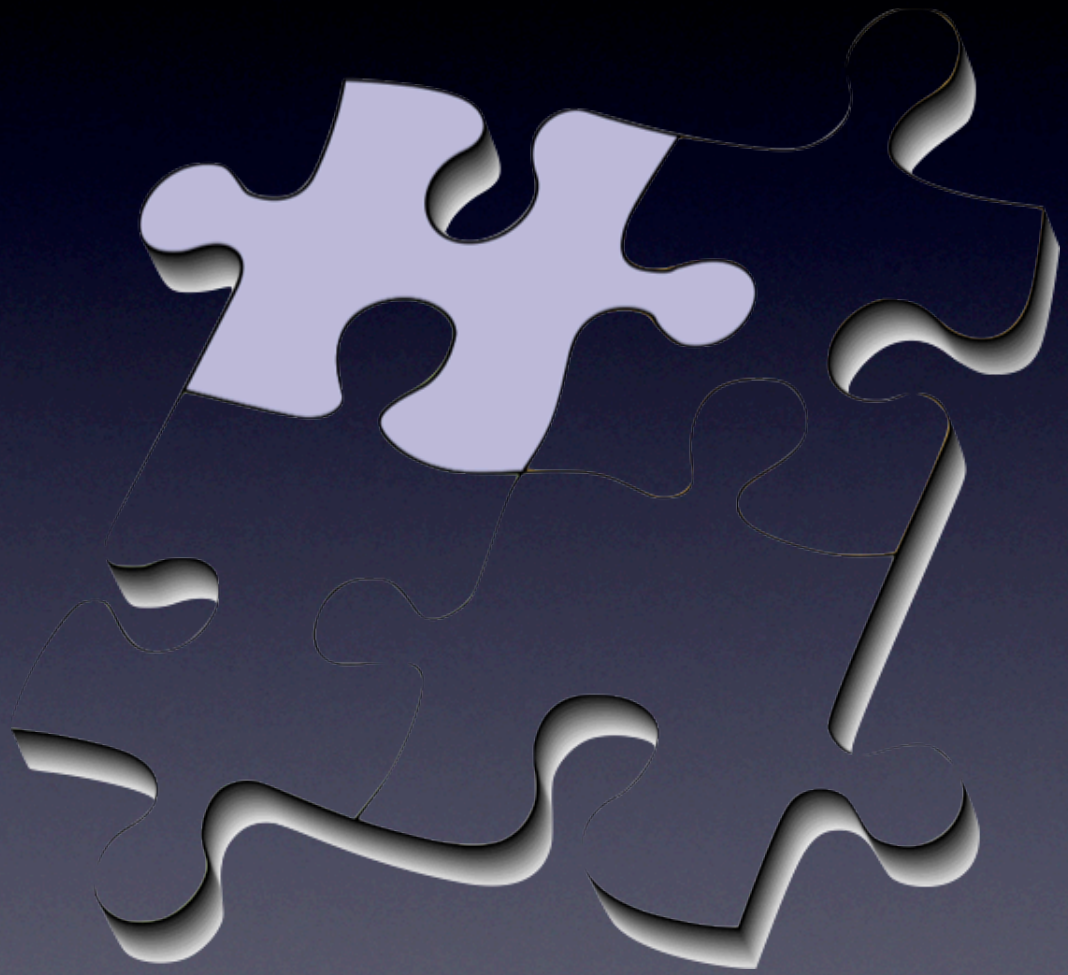


II) The flavour puzzle

III) The hierarchy problem

IV) The cosmology puzzle (DM, DE, BAU flatness and horizon problems, …)

Three main aspects of the "neutrino puzzle"



Neutrino masses:
Why so small?
How to extend the SM?

Neutrinos and the universe:
What is the role of neutrinos in cosmology (e.g. regarding DM, baryogenesis, inflation, ...)?

Lepton mixing:
Why so large (compared to the quark mixings)?

Regarding the flavour puzzle, the measurement of θ_{13}^{PMNS} had a large impact:

$$\theta_{13}^{PMNS} \approx 9° \pm 0.5°$$

T2K, Minos, Double CHOOZ, Daya Bay, RENO

Finally, out of the many models …

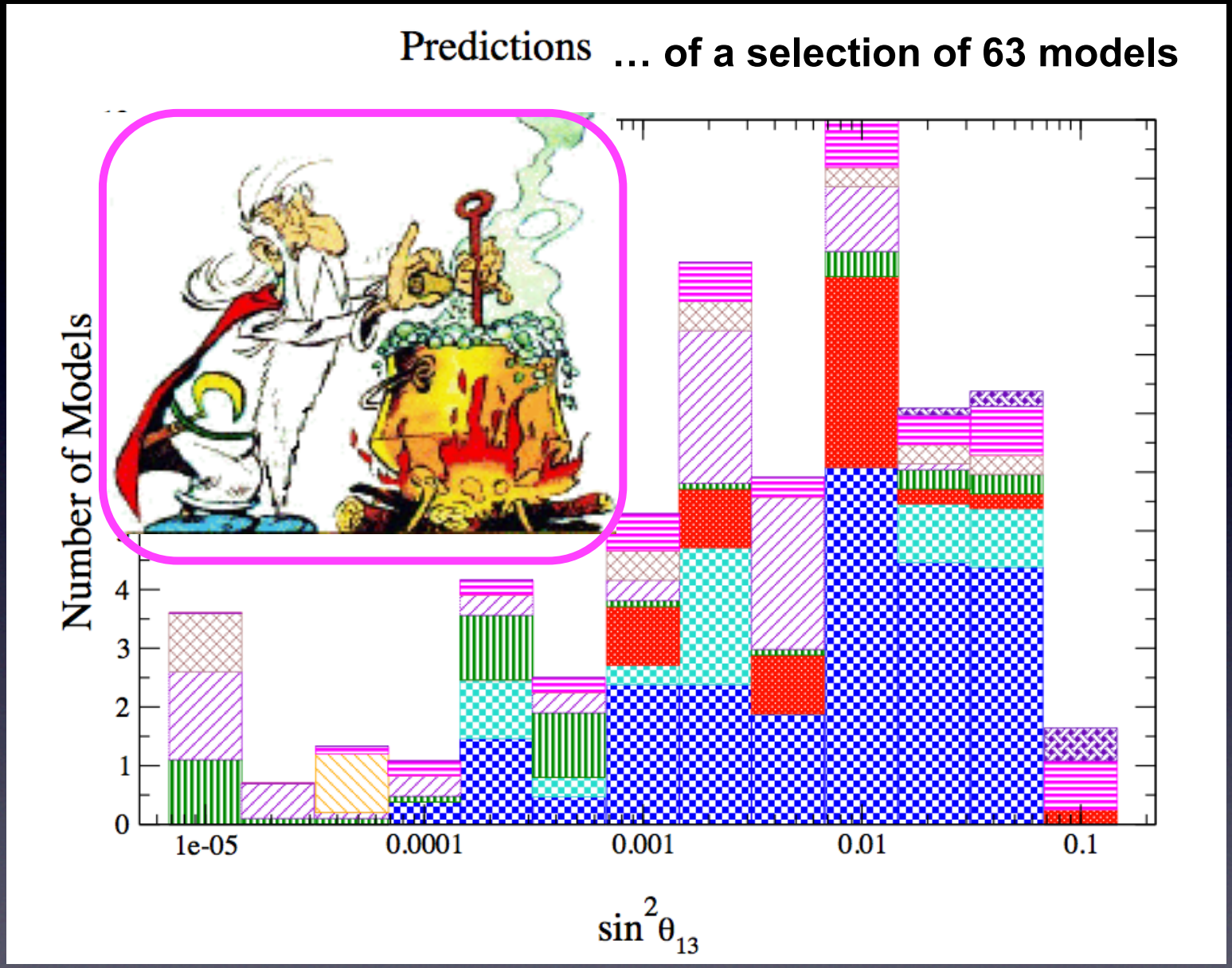
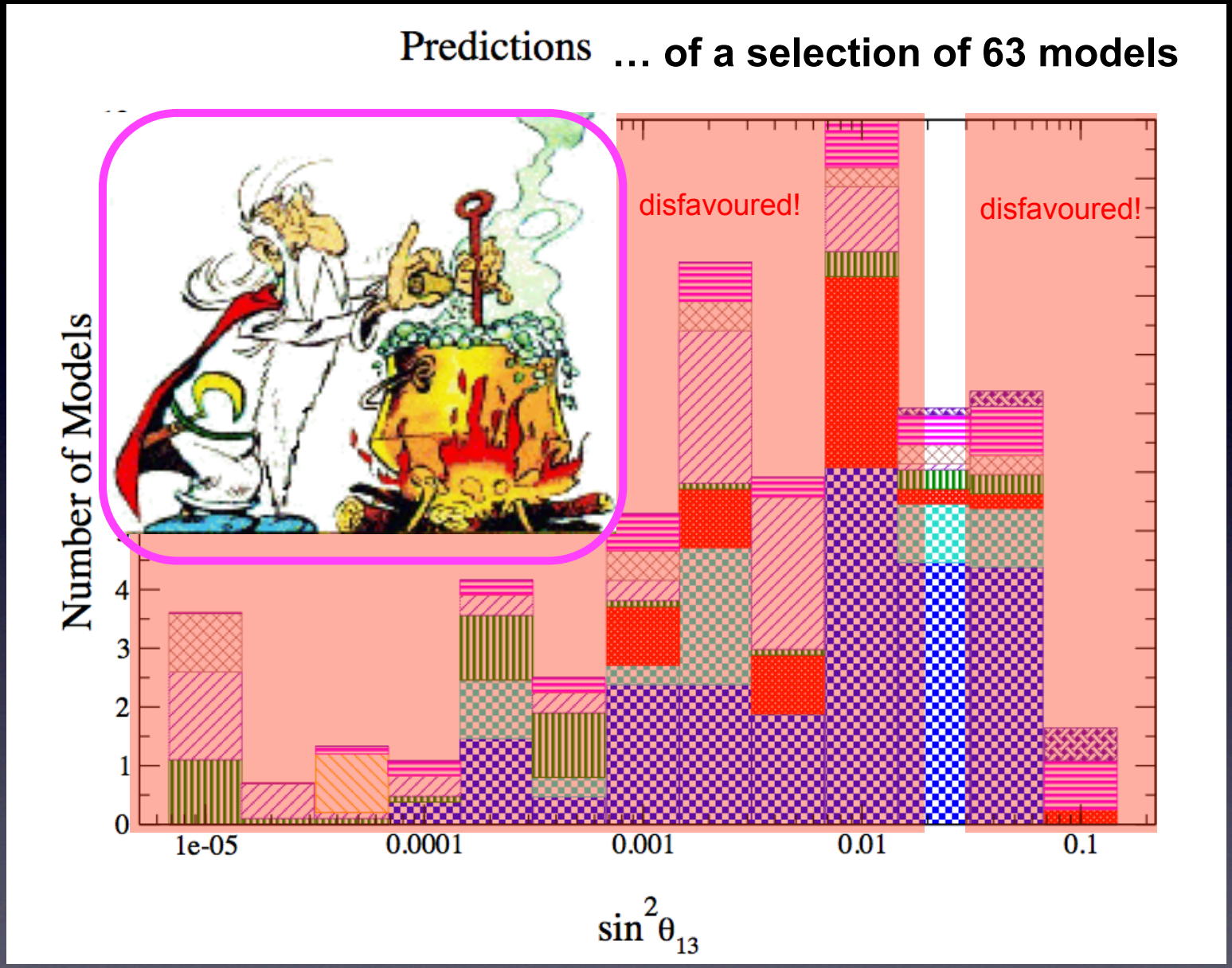


Figure shows only a small subset of the existing models … !

based on figure from Albright, Mu-Chun Chen ('06)

… a large fraction has been excluded!



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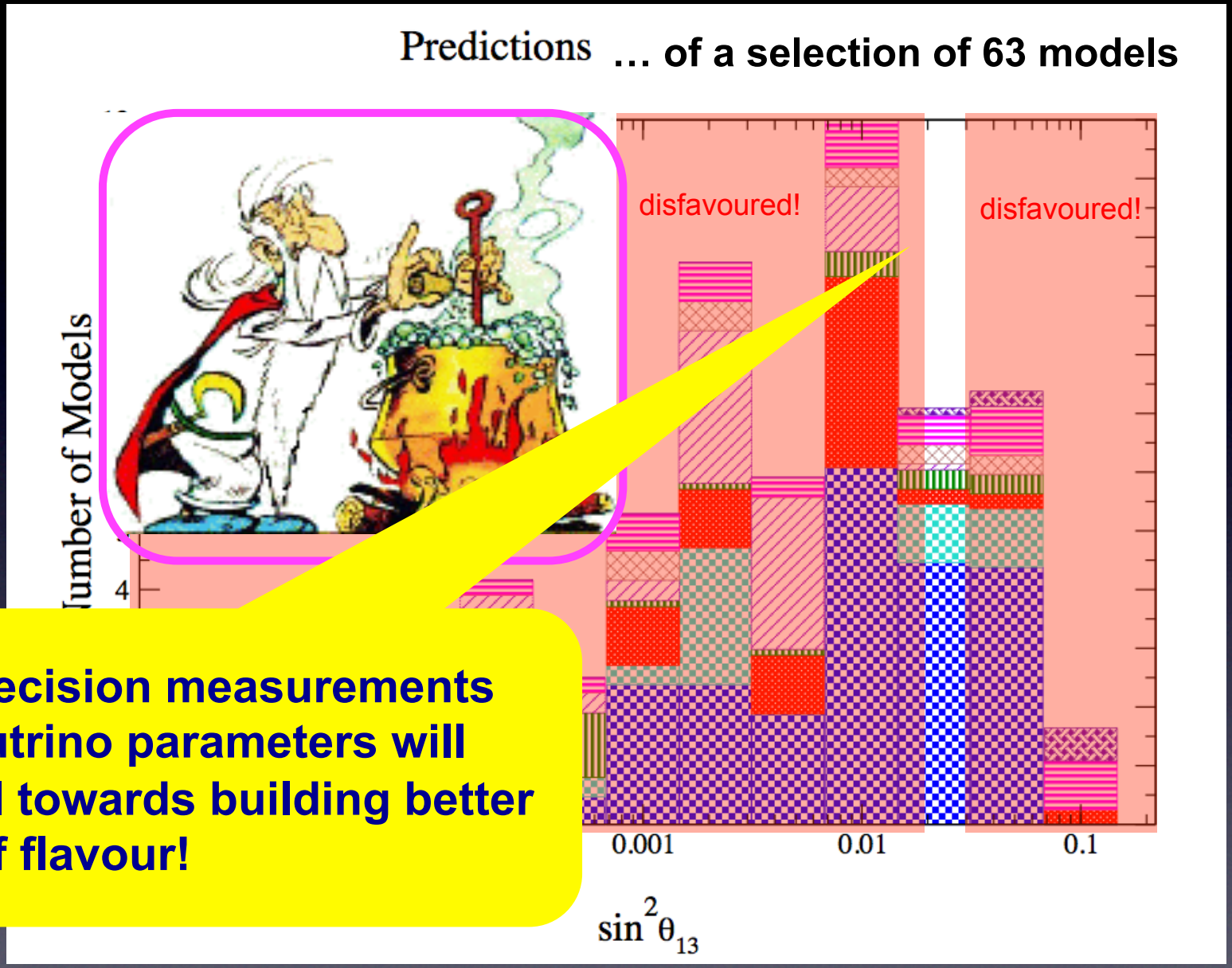


Future precision measurements of the neutrino parameters will be crucial towards building better models of flavour!

Figure shows only a small subset of the existing models … !

based on figure from Albright, Mu-Chun Chen ('06)

Present status: Fermion masses and mixing parameters

Present status: Fermion masses

Up-type quarks

$m_u \approx 0.0013$ GeV ± 30%
$m_c \approx 0.63$ GeV ± 3%
$m_t \approx 172.2$ GeV ± 1%

M_u

→ hierarchical masses
(even more hierarchical than M_d, M_e)

Down-type quarks

M_d

Running masses at $\mu = M_Z$ from
S. A., V. Maurer (arXiv:1306.6879)

$m_d \approx 0.0026$ GeV ± 10%
$m_s \approx 0.054$ GeV ± 5%
$m_b \approx 2.86$ GeV ± 1%

→ hierarchical masses

Neutrinos

m_ν

from NuFIT Collaboration:

$|m_3^2 - m_1^2| \approx 2.4 \cdot 10^{-3}$ eV^2
$m_2^2 - m_1^2 \approx 7.5 \cdot 10^{-5}$ eV^2
all three m_i below ~ 0.5 eV

→ tiny masses, scheme unknown

Charged leptons

M_e

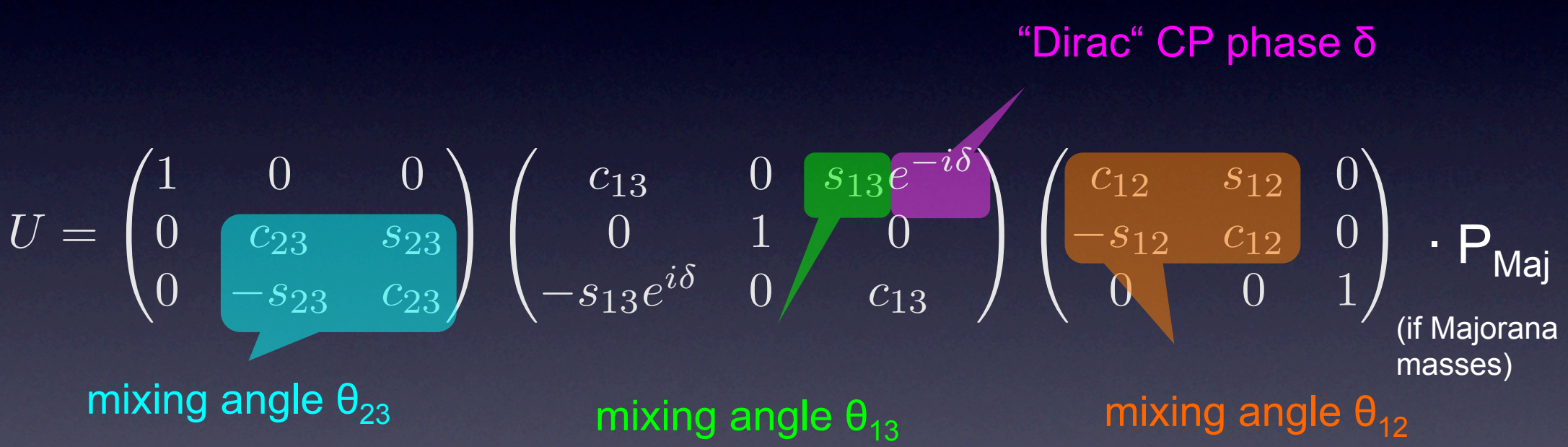
Since recently: Higher accuracy in the quark sector!

$m_e \approx 0.000485$ GeV
$m_\mu \approx 0.103$ GeV
$m_\tau \approx 1.75$ GeV

→ hierarchical masses

Mixing parameters

- Conventional (PDG) parameterization for the mixing matrices U_{CKM} and U_{PMNS}:



Present status: Mixing parameters

from NuFIT Collaboration:

U_{PMNS}:

$\theta_{12}^{PMNS} \approx 34° \pm 1°$
$\theta_{23}^{PMNS} \approx 42° \pm 3°$
$\theta_{13}^{PMNS} \approx 9° \pm 0.5°$

δ^{PMNS} = unknown
($\varphi_{1,2}^{Maj}$ = unknown)

→ two large mixings
→ $\theta_{13}^{PMNS} = O(\theta_C)$
→ unknown phases

Up-type quarks — Down-type quarks

$M_u \longleftrightarrow M_d$

$U_{CKM} = U^{u\dagger} U^{d}$

Neutrinos — Charged leptons

$m_\nu \longleftrightarrow M_e$

$U_{PMNS} = U^{e\dagger} U^{\nu}$

from UTfit Collaboration:

U_{CKM}:

$\theta_{12}^{CKM} \equiv \theta_C \approx 13.0°$
$\theta_{23}^{CKM} \approx 2.4°$
$\theta_{13}^{CKM} \approx 0.2°$

$\delta^{CKM} \approx 69° \pm 3°$

→ very small 2-3 and 1-3 mixings
→ only not-so-small mixing is the Cabibbo angle θ_C
→ "large" CP phase δ^{CKM}

Many unknowns remain …

- What are the values of the Dirac CP phase δ^{PMNS}
- Is the mass scheme “normal” or “inverse”, i.e., what is sgn(Δm_{31}^2)?
- What is the deviation of θ_{23}^{PMNS} from maximal (i.e. from 45°)
- What is the absolute neutrino mass scale?
- Are neutrino masses of Dirac- or Majorana-type?
- If they are Majorana-type, what are the values of the Majorana phases?

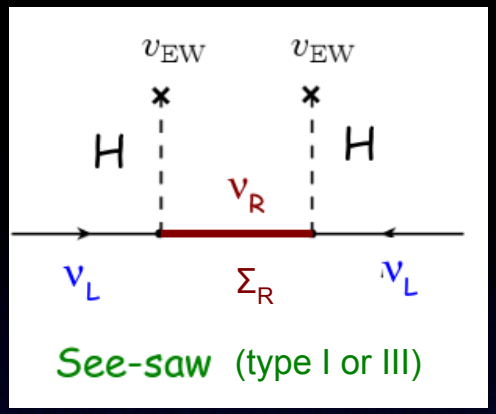
Great also for theorists! It means we can still make predictions to be tested in future experiments!

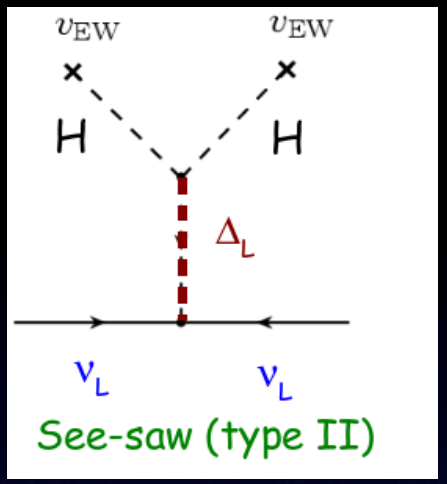
Challenge for BSM physics:

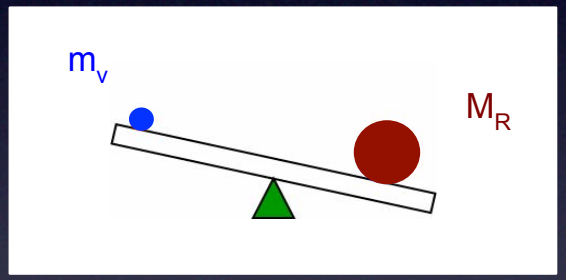
Which is the right extension of the SM to include neutrino masses?

Neutrino masses:
How to extend the SM?

... in model building, most approaches are based on:







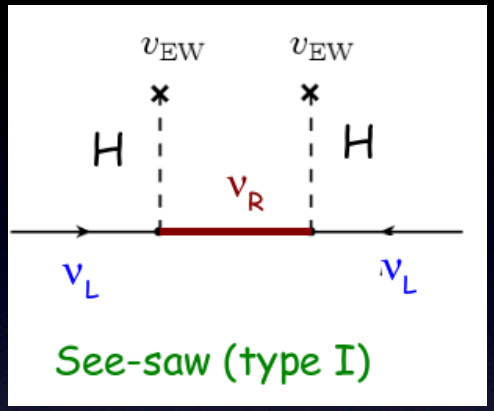
Is it a tree-level "Seesaw"?

P. Minkowski ('77), Mohapatra, Senjanovic, Yanagida, Gell-Mann, Ramond, Slansky, Schechter, Valle, Magg, Wetterich, Ma, Foot, Lew, He, Joshi, ...

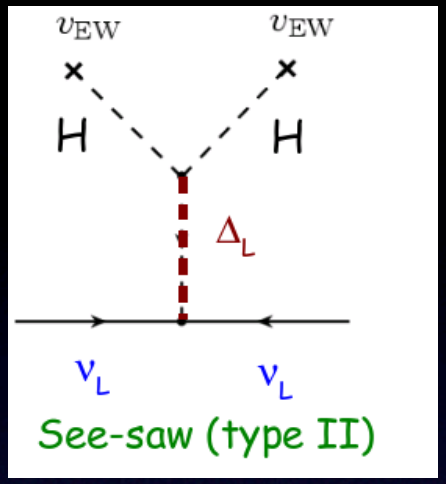
At which scale?

(A) At high scale (~ M_{GUT})
(B) At TeV scale (→ colliders, LHC)
(C) At eV energies (light sterile v's)

Neutrino masses:
How to extend the SM?



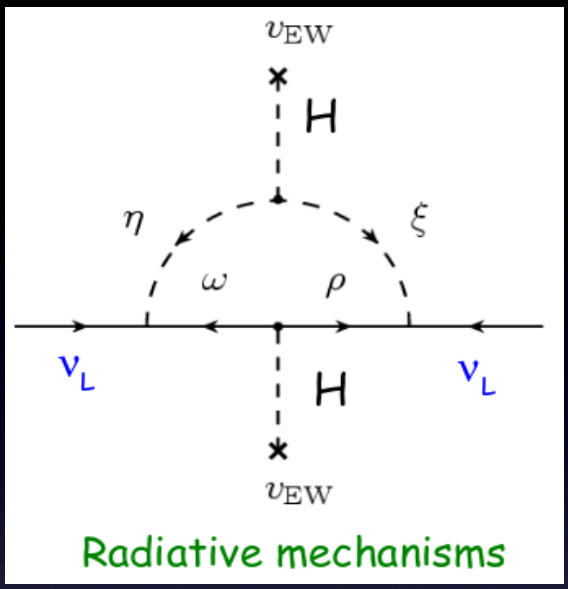
See-saw (type I)



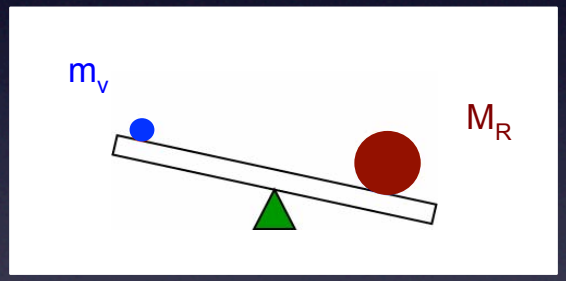
See-saw (type II)

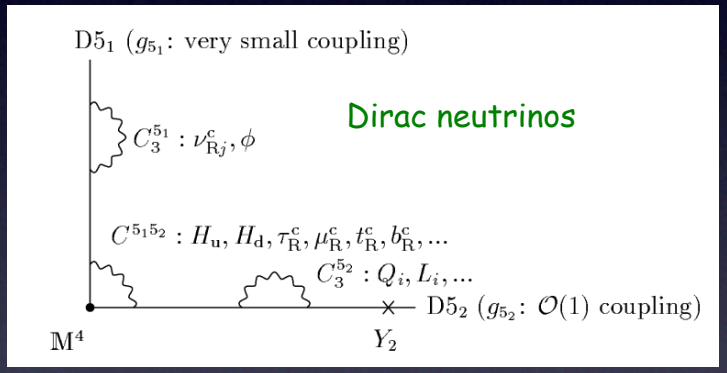
?

... or something completely different

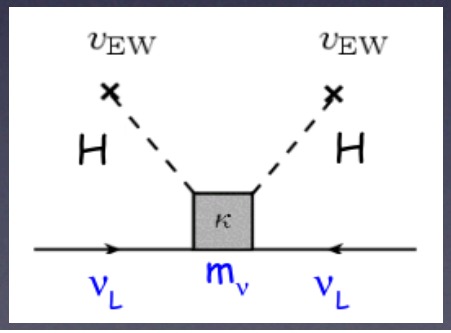


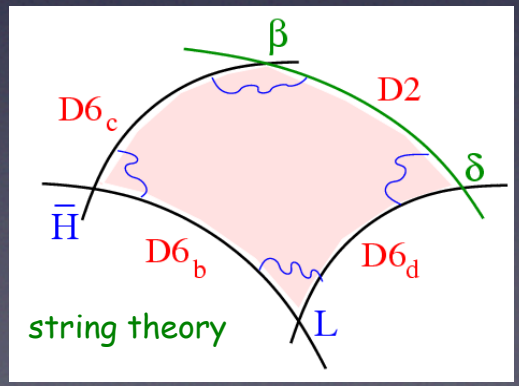
Radiative mechanisms

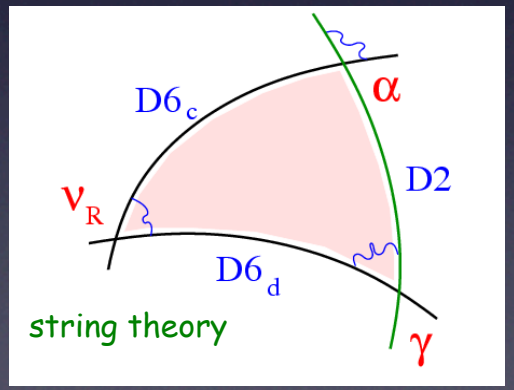




Effective theory:

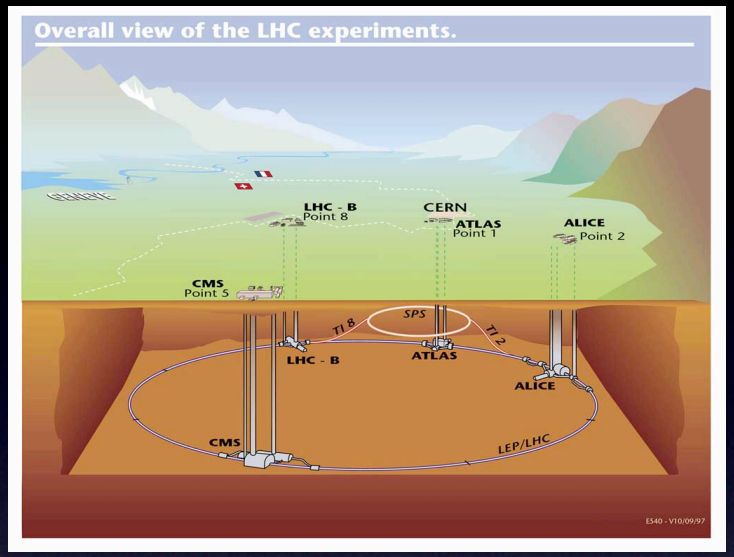




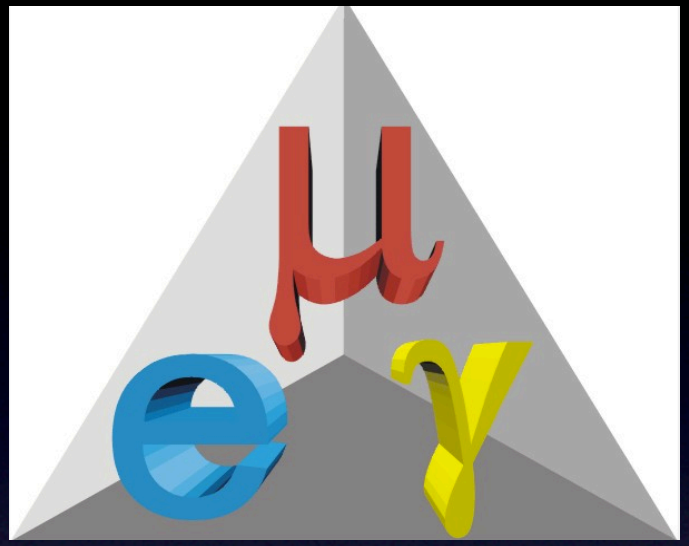


$$\delta\mathcal{L}^{d=5} = \frac{1}{2}\, c_{\alpha\beta}^{d=5} \left(\overline{L^c}_\alpha \tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L_\beta\right) + h.c.$$

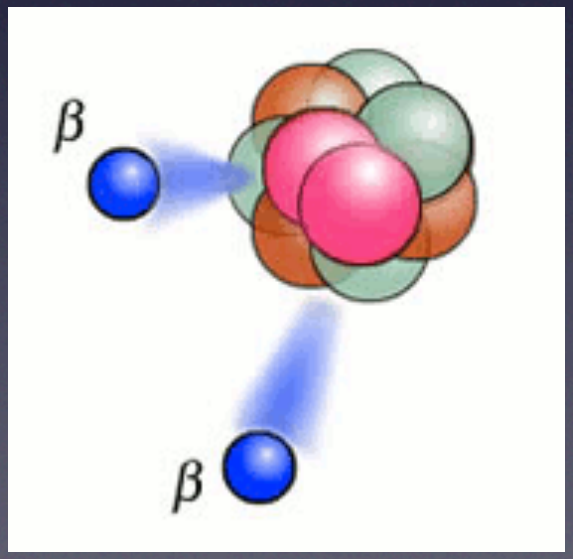
Future: To find answers we need to combine data from various sources ...



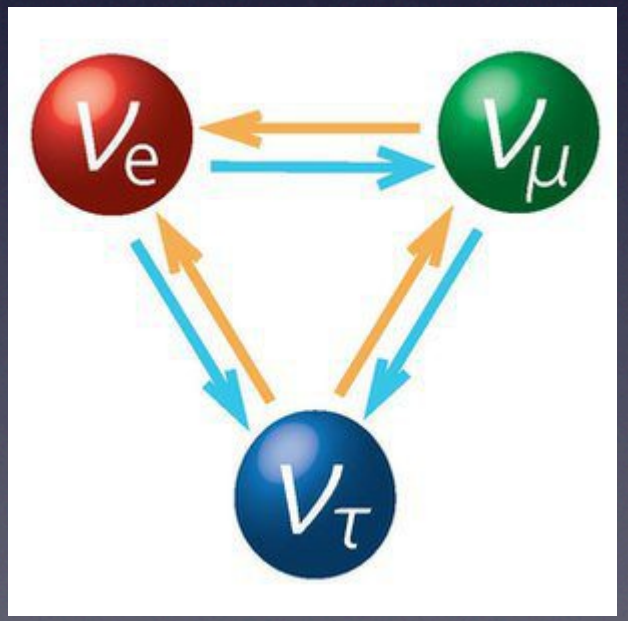
Colliders



indirect tests (e.g. LFV, non-unitarity)



0νββ decay, Tritium β decay, cosmology



Neutrino oscillations

Theory: Top-down vs. bottom-up …

Various top-down approaches:

- Grand Unified Theories (GUTs)
- Family symmetries?
- Anarchy in the neutrino sector?
- Extra dimensions ...
- String theory …
- …

Bottom-up observations/suggestions:

- Tri-bimaximal (TB) mixing?
- Bimaximal mixing?
- Quark lepton complementarity (QLC): $\theta_{12}^{PMNS} + \theta_C = 45°$?
- $\theta_{13}^{PMNS} = \theta_C / \sqrt{2} \approx 9.2°$?

  Can emerge from GUTs ...
- ...

→ **Recent progress: Highly predictive GUT models with $\theta_{13}^{PMNS} = \theta_C / \sqrt{2} \approx 9.2°$** from 'GUT mixing relations'

NH: S. A., C. Gross, V. Maurer, C. Sluka (arXiv:1305.6612)
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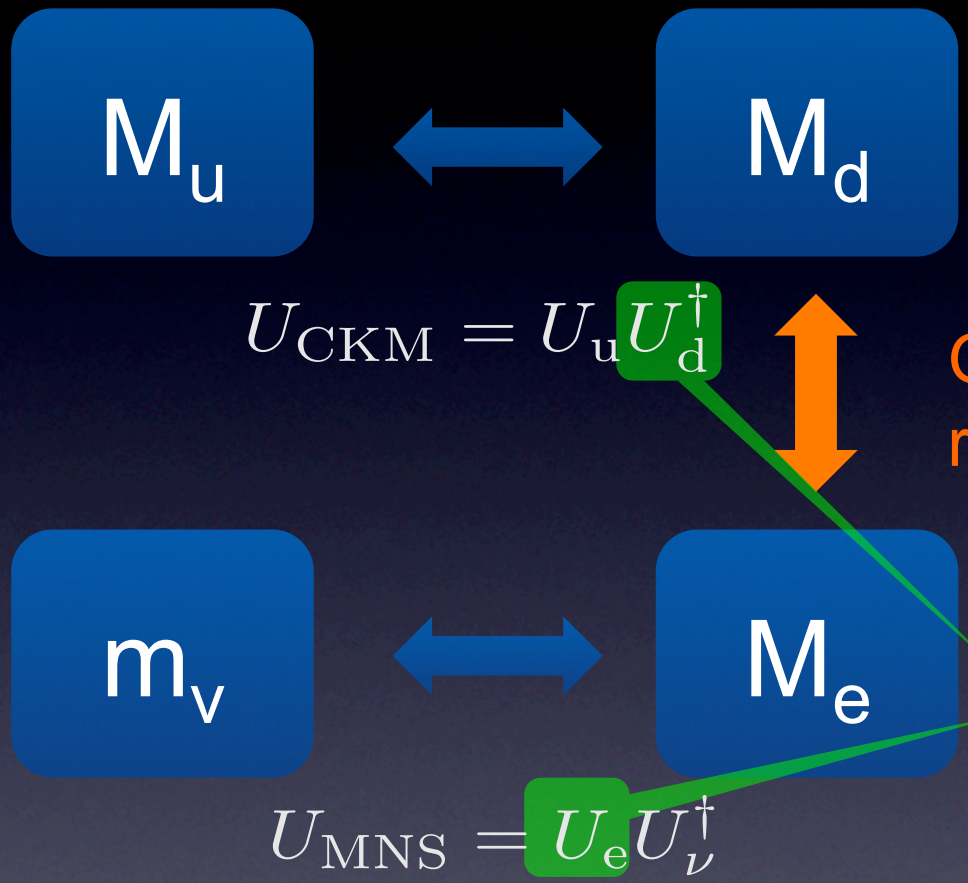

NH: χ^2/d.o.f. = 2.0
IH: χ^2/d.o.f. = 1.1

✓ Excellent fit to the present exp. data: 6 predictions, e.g. $\theta_{13}^{MNS} \approx \theta_C / \sqrt{2}$, $\delta^{MNS} \sim 270°$ (NH) or $180°$ (IH), ... , (plus: constraints on SUSY spectrum)

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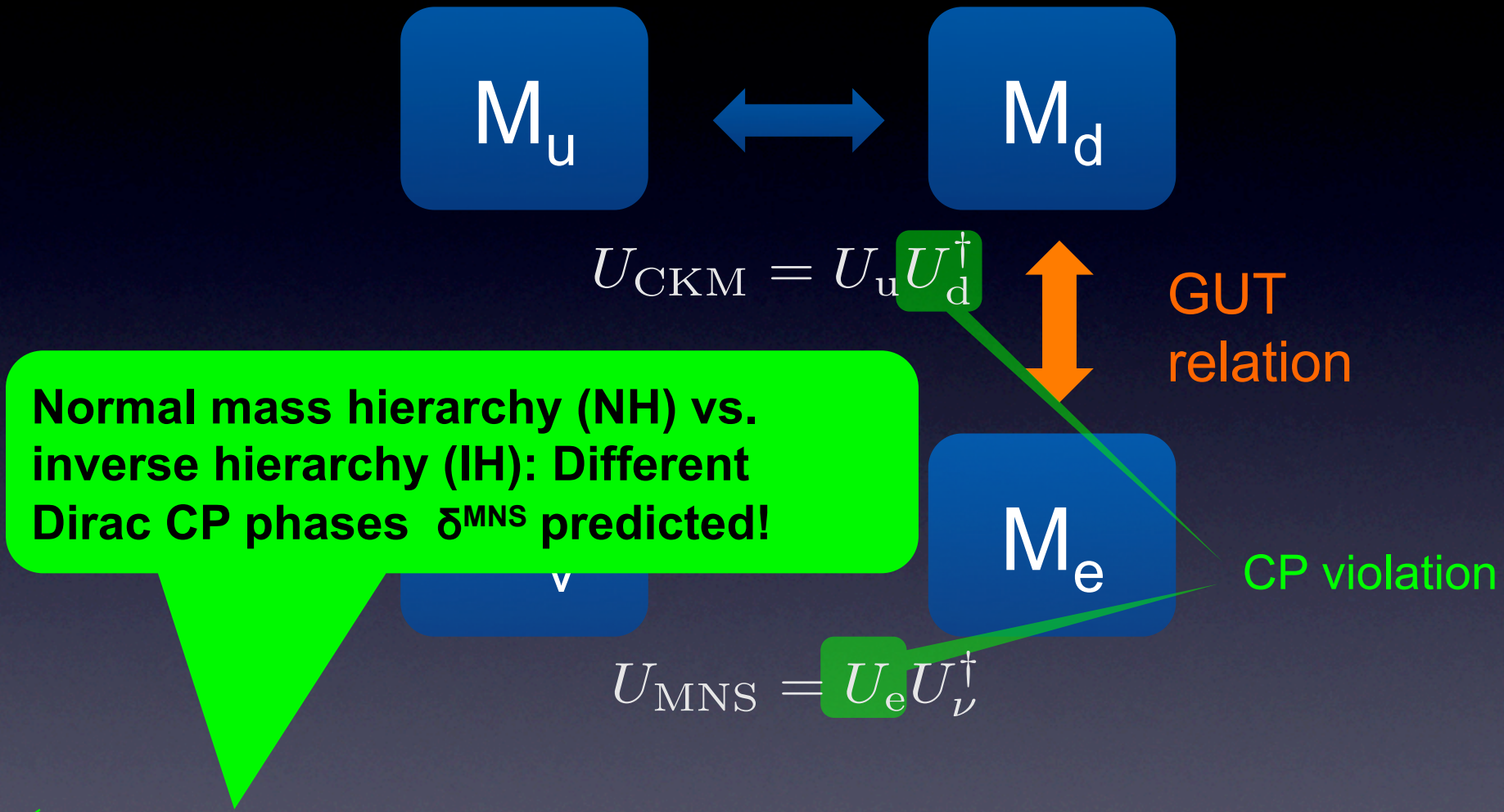

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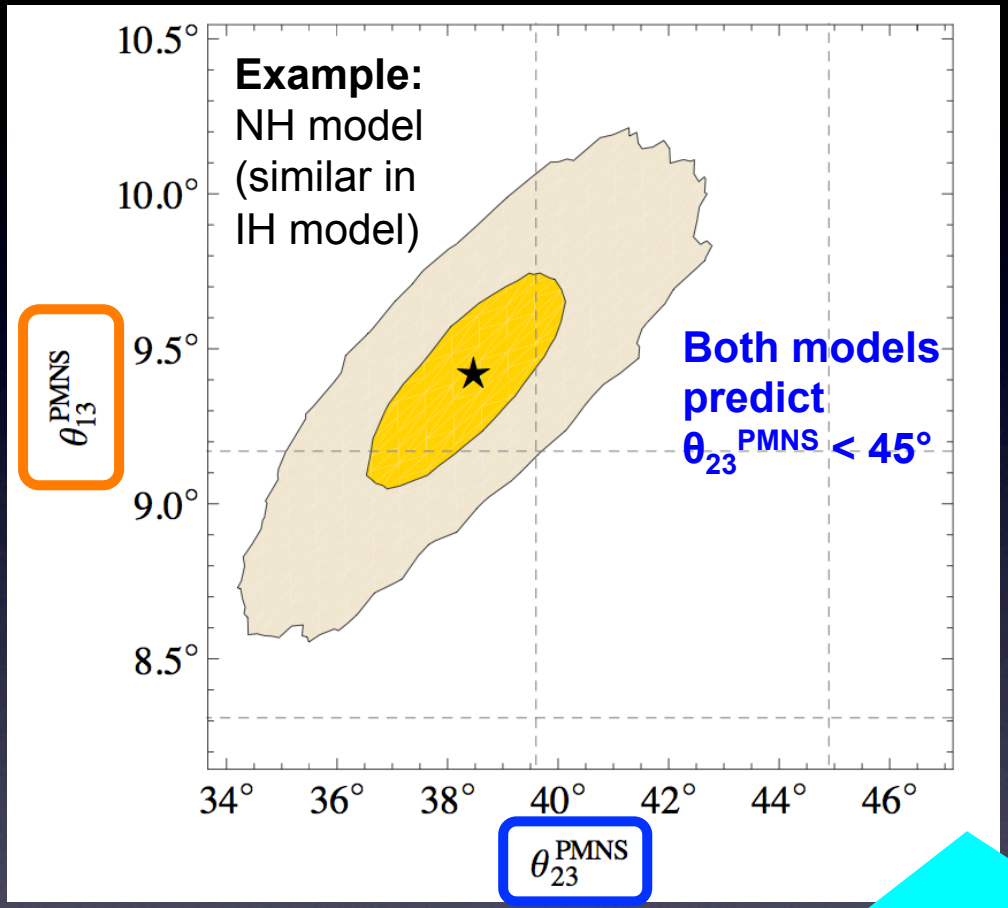
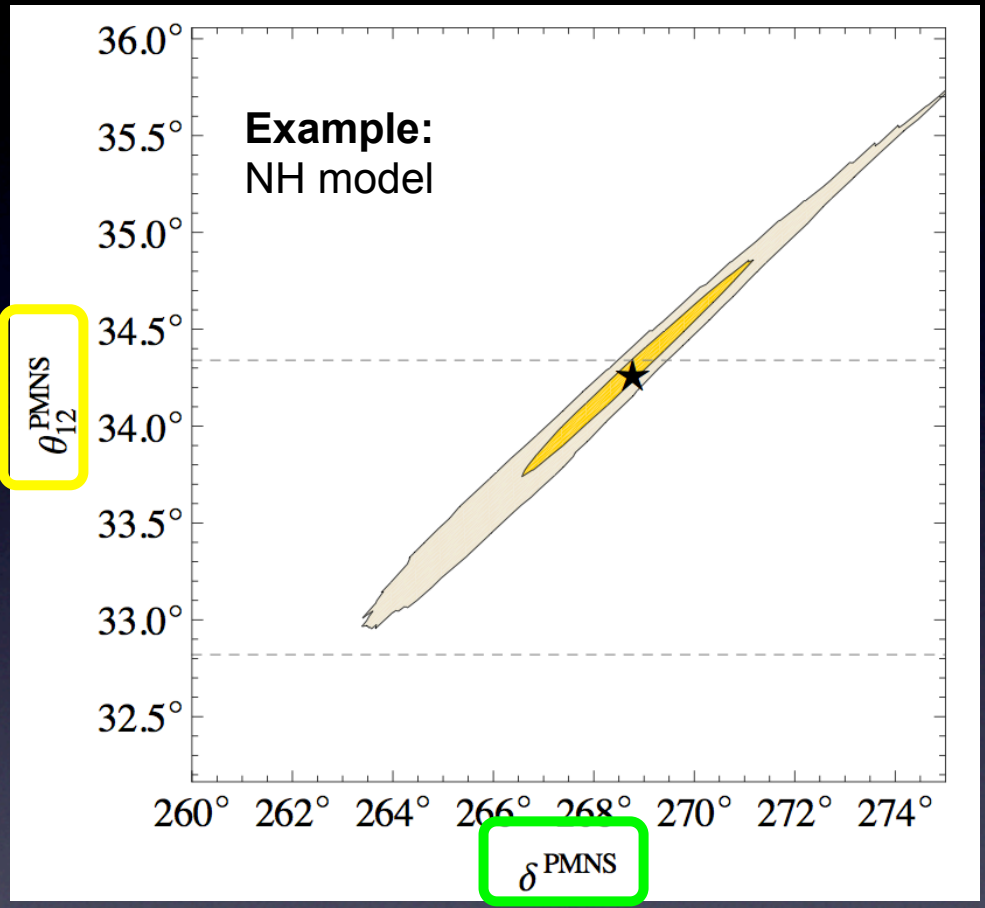




✓ Excellent fit to the
$\delta^{MNS} \sim 270°$ (NH)

MC Monte Carlo fit to the data: → Theory predictions with confidence regions! Can be compared with present and future experimentally found regions ...

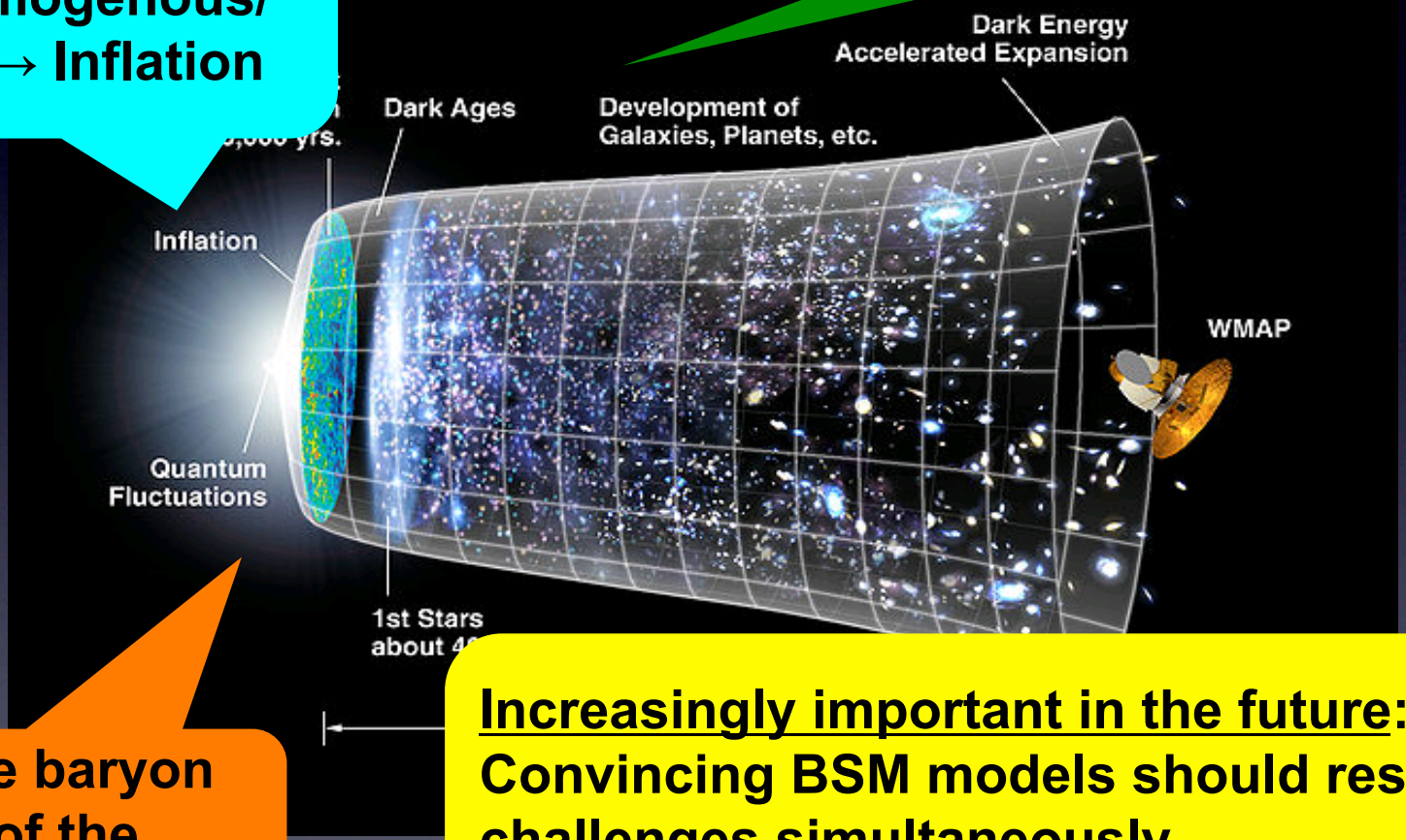
What is the role of neutrinos in cosmology?

Neutrinos in cosmology

Why is the universe so flat and homogenous/ isotropic? → Inflation

e.g.: sneutrino (hybrid) inflation, flavon inflation, ...

Who is the dark matter particle?

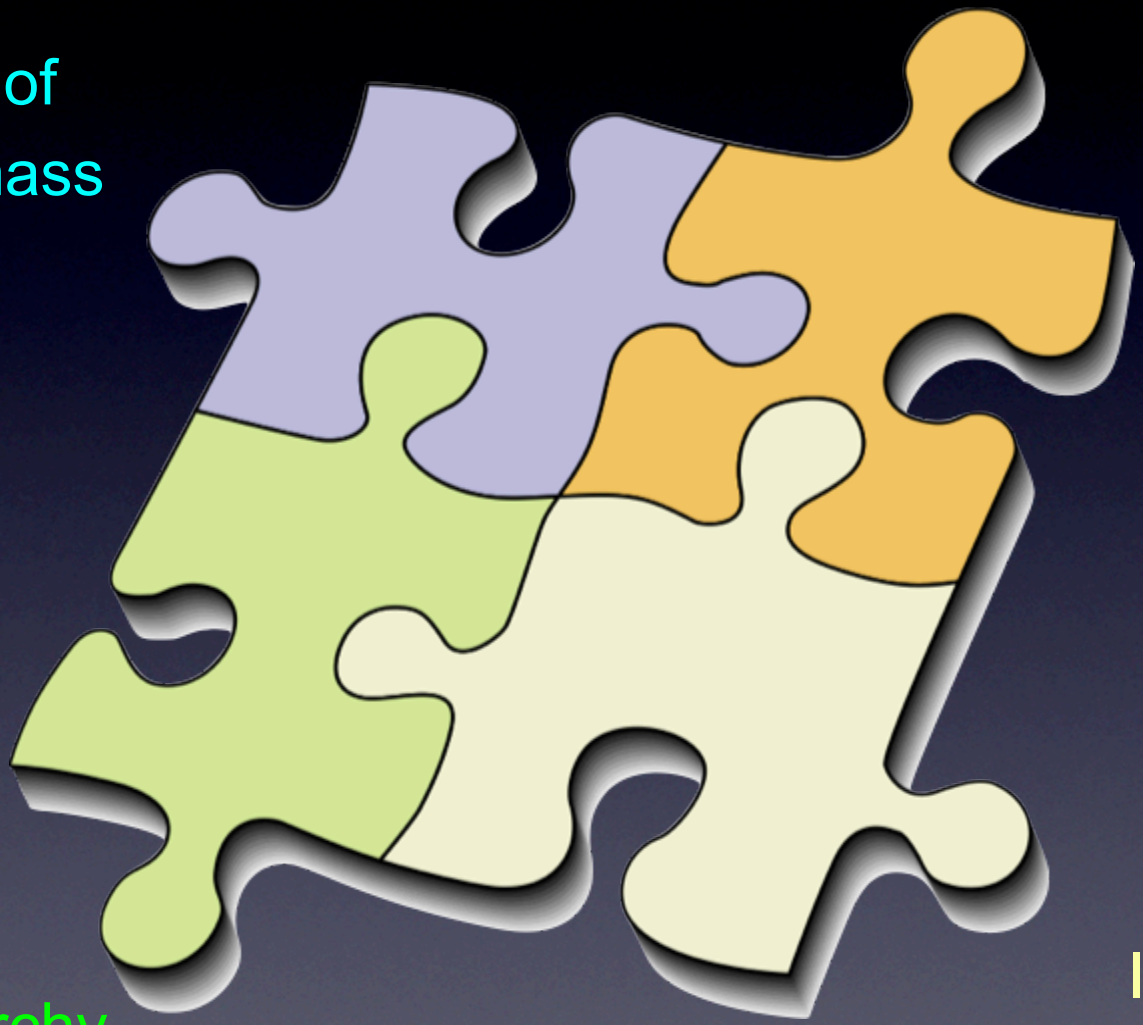


How was the baryon asymmetry of the universe generated?

<u>Increasingly important in the future</u>:
Convincing BSM models should resolve challenges simultaneously ...
→ interesting connections to neutrino physics!

Exciting future for neutrino physics ... and BSM physics in general!

I) The origin of neutrino mass



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