New Physics after the Higgs discovery

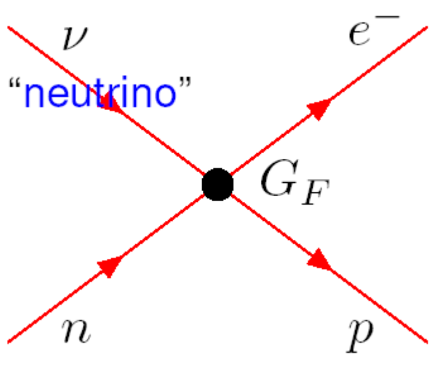
KIAS KOREA INSTITUTE FOR ADVANCED STUDY
Eung Jin Chun

What we learned from the Higgs discovery

From Fermi to EBH

- SM is the UV theory of Weak Interactions

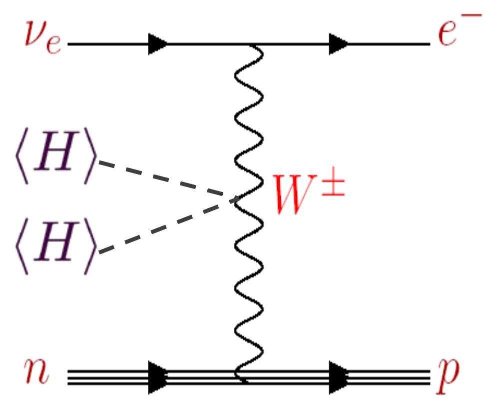
1933



Missing energy
in radioactivity

$$G_F = \frac{1}{\sqrt{2}v^2}$$

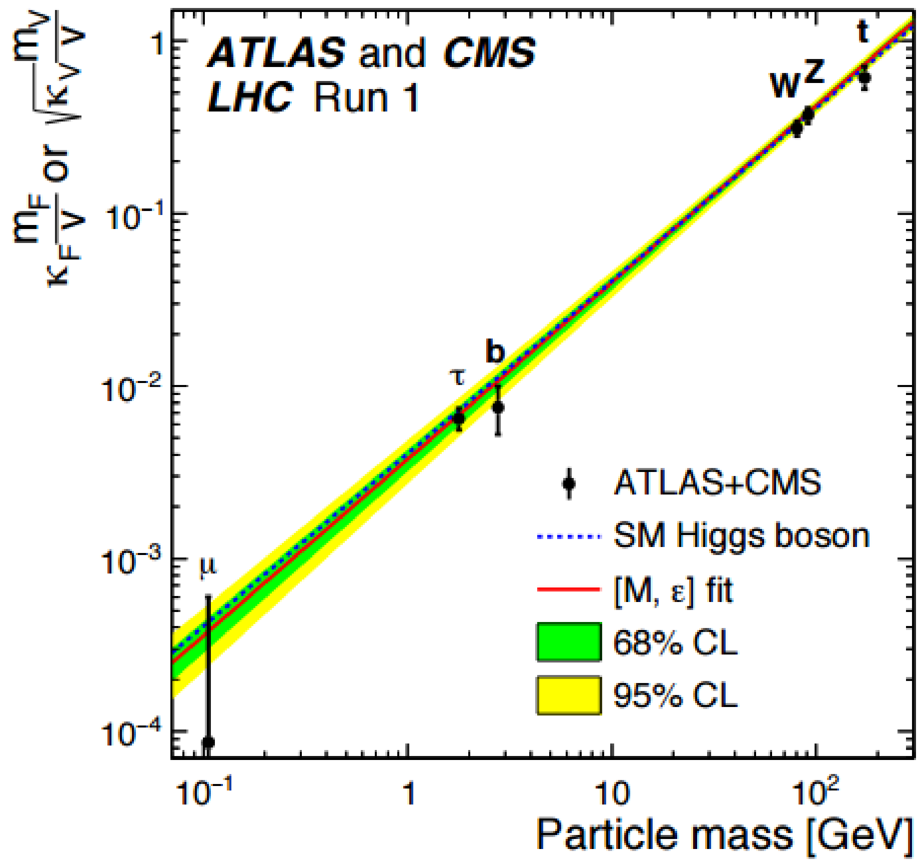
2012



$$m_h = 125\ GeV$$

Higgs boson as the origin of masses

arXiv:1606.02266



Standard Model is a well-designed framework based on

- Renormalizability
- Symmetry principle
- Gauge theory
- EBH mechanism
- Broken/unbroken local/global symmetries
- Mysterious flavor structure

Is this the final story?

SM is an "effective" model

- SM Higgs sector:

$$V = \lambda|H|^4 - \mu^2|H|^2 = \frac{m_h^2}{2}\,h^2 + \frac{m_h^2}{2v}h^3 + 2\,\frac{m_h^2}{v^2}h^4$$

$$\lambda = \frac{m_h^2}{2v^2} = 0.13\,, \qquad \mu = \frac{v}{\sqrt{\lambda}} = 89\;GeV$$

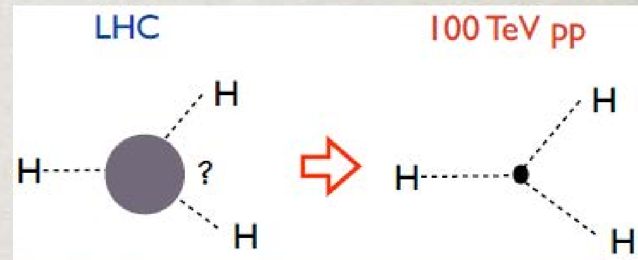
- Need further confirmation: measure Higgs self-couplings.

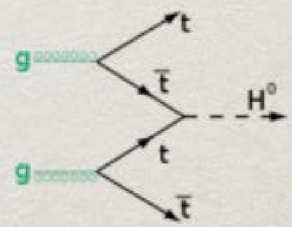
$$g_{hhh}^{SM} = 3\,\frac{m_h^2}{v} = 0.77v$$

Tao Han

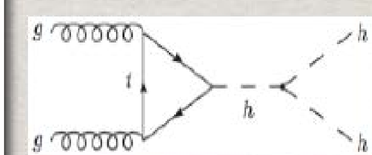
The Next Energy Frontier: 100 TeV Hadron Collider

Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10³





λ_t : 1%



λ: 8%

EW phase transition strong 1^{st} order:

→ O(1) deviation on λ_{hhh}

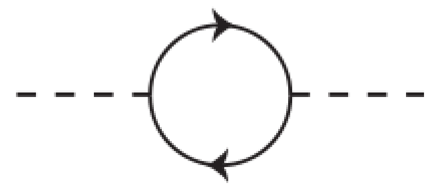
Snowmass QCD Working Group: 1310.5189

Arkani-Hamed, TH, Mangano, LT Wang, 1511.06495, to appear in Phys Report

Is the SM valid up to a high scale Λ?

- $|H|^2$ is not protected:

$$\delta m_h^2 = (-1)^F \frac{\lambda}{8\pi^2} \int^\Lambda \frac{d^4p}{p^2 - m^2}$$
$$= \frac{3}{8\pi^2 v^2}(4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2)\Lambda^2$$
$$= m_h^2 \left(\frac{\Lambda}{500\text{GeV}}\right)^2$$



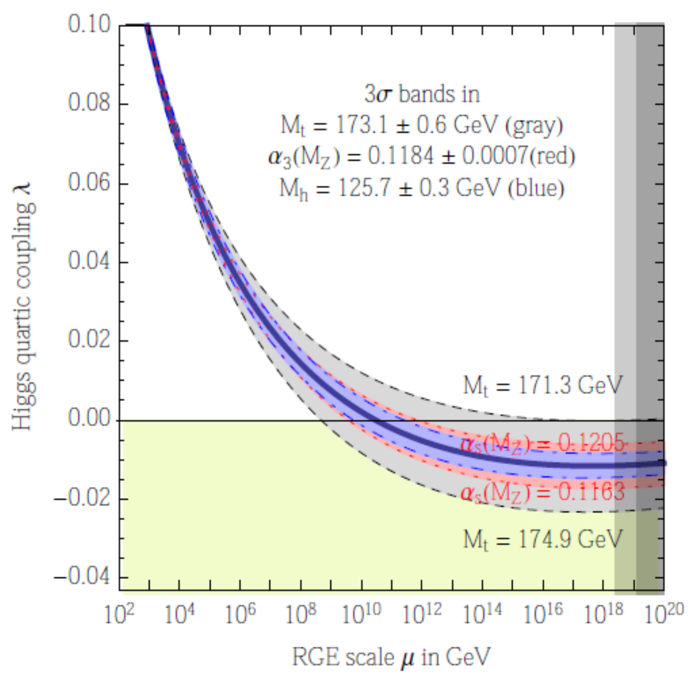
- NP better be close to TeV.

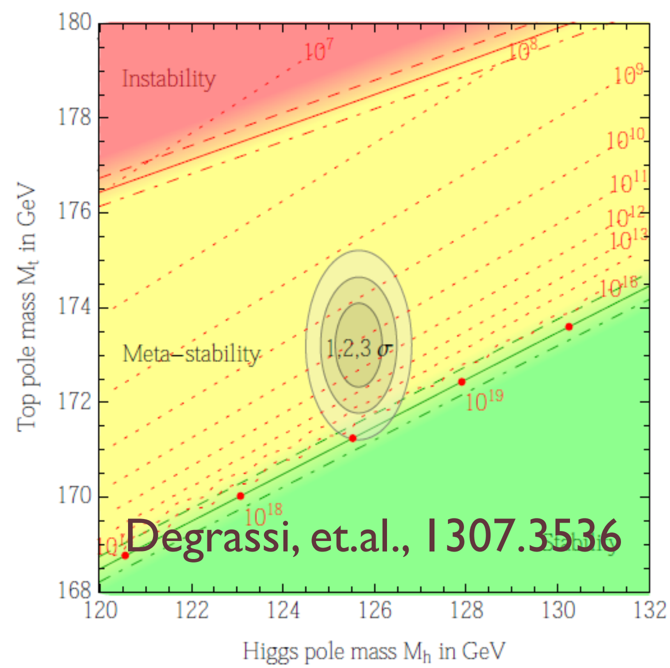
(You define "being close")

Is the SM valid up to a high scale Λ?

- Do we live in a metastable vacuum?

$$32\pi^2 \frac{d\lambda}{dt} = 24\lambda^2 - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2g^2 + \frac{9}{8}g^4 - 24y_t^4 + \cdots$$



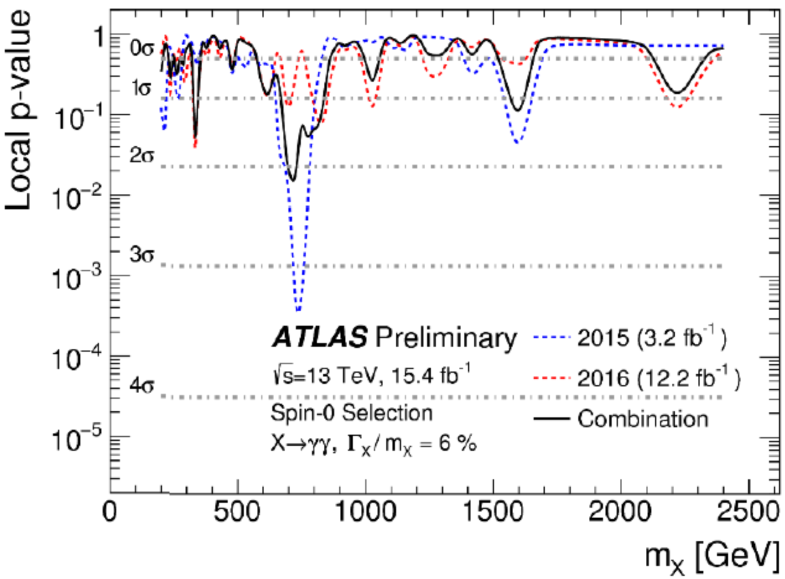


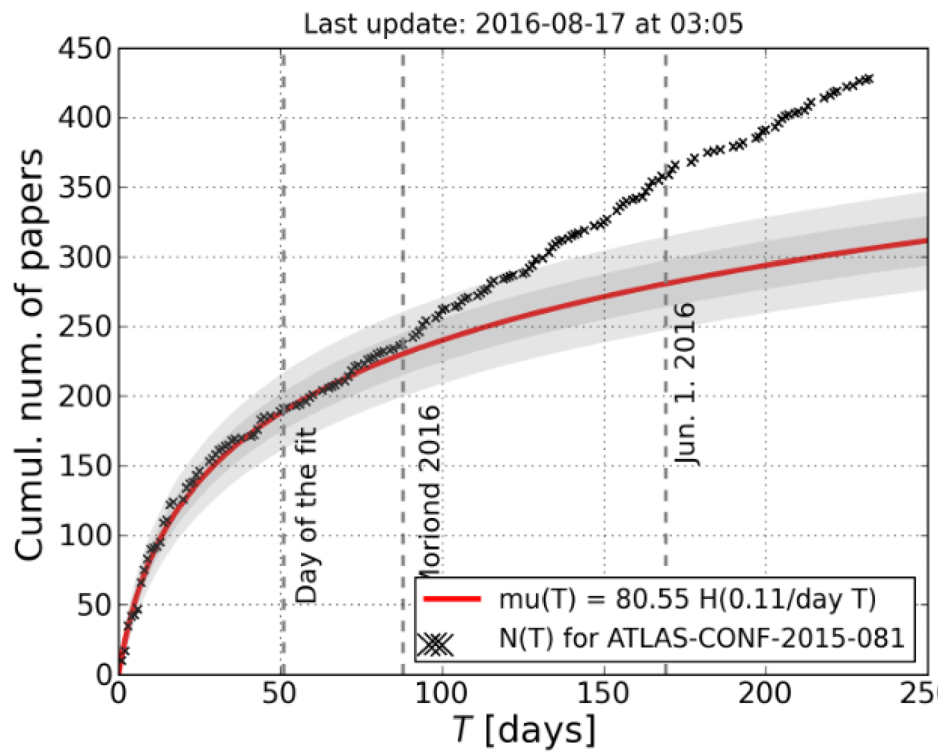
Degrassi, et.al., 1307.3536

- Maybe an indication of NP below ~ $10^{10}\,GeV$.

Where is New Physics?

Era of Desperation





A theory of ambulance chasing

1603.01204

Additional bosons at TeV

Why An Extended Higgs Sector? Tao Liu

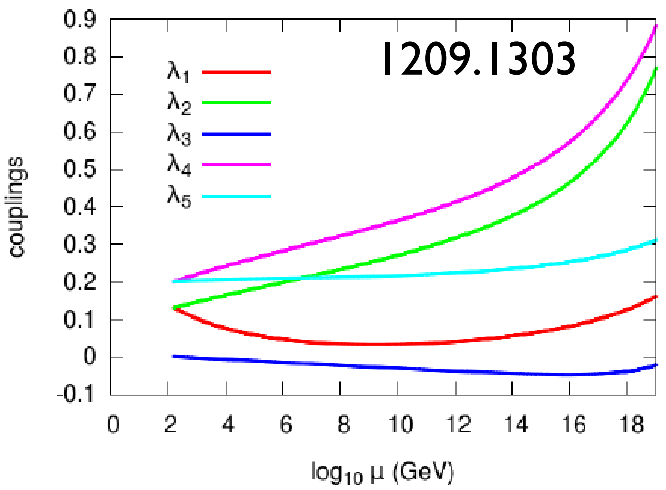
- Dark matter: e.g., interaction mediator
- Baryon asymmetry in the Universe, e.g., new Jarlskog invariants
  - Yukawa sector: Yukawa couplings misaligned with fermion mass $\sim \mathrm{Im}[\mathrm{Tr}[MY^\dagger]]$
  - Higgs potential: relative phases of Higgs interactions
- SM + singlet
- SM + doublets with Y = +1 or -1
- Georgi-Machacek model: SM + Higgs triplets
- ... ...

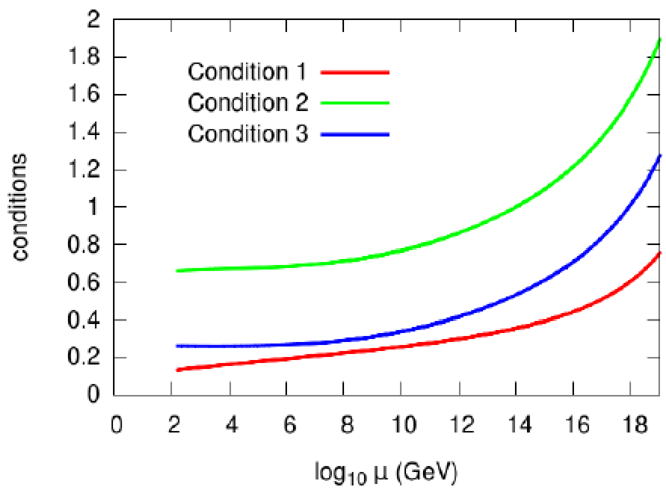
- Guaranteeing the vacuum stability.

Ex) Triplet Higgs for neutrino mass

$\mathcal{L} = f_{ij} L_i L_j \Delta$ where $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$ with $v_\Delta \ll v_H$

$$
\begin{aligned}
V(H,\Delta) = & \; m^2 H^\dagger H + M^2 \mathrm{Tr}(\Delta^\dagger \Delta) \\
& + \lambda_1 (H^\dagger H)^2 + \lambda_2 [\mathrm{Tr}(\Delta^\dagger \Delta)]^2 + 2\lambda_3 \mathrm{Det}(\Delta^\dagger \Delta) \\
& + \lambda_4 (H^\dagger H)\mathrm{Tr}(\Delta^\dagger \Delta) + \lambda_5 (H^\dagger \tau_i H)\mathrm{Tr}(\Delta^\dagger \tau_i \Delta) \\
& + \frac{1}{\sqrt{2}} \mu H^T i\tau_2 \Delta H + h.c.
\end{aligned}
$$



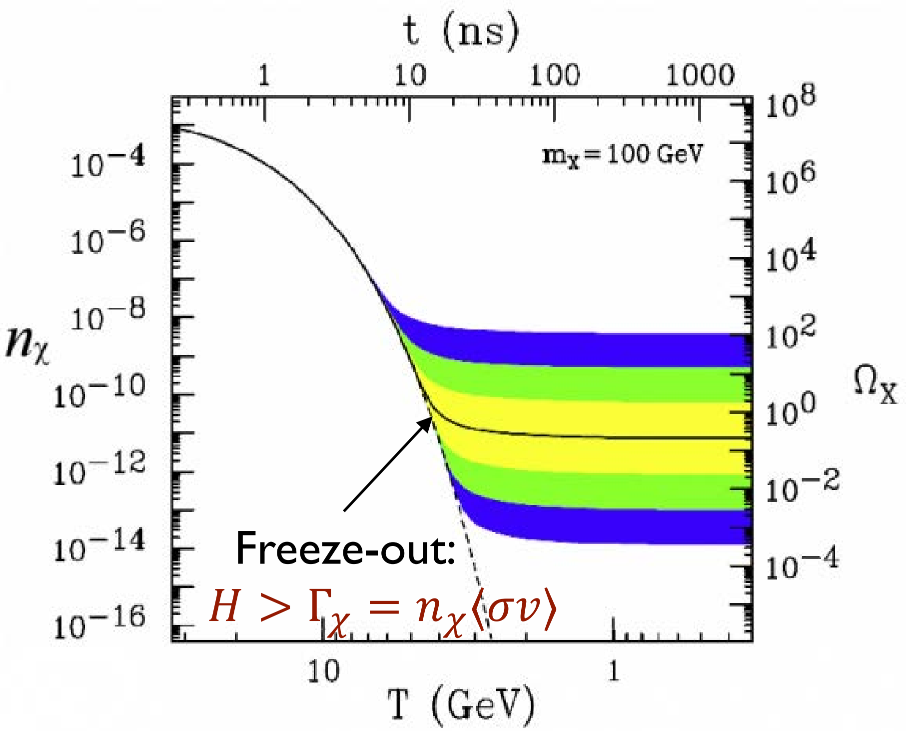


	10^{19} GeV
λ_2	$(0, 0.25)$
λ_3	$(-0.55, 0.62)$
λ_4	$(0, 0.5)$
λ_5	$(-0.4, 0.4)$

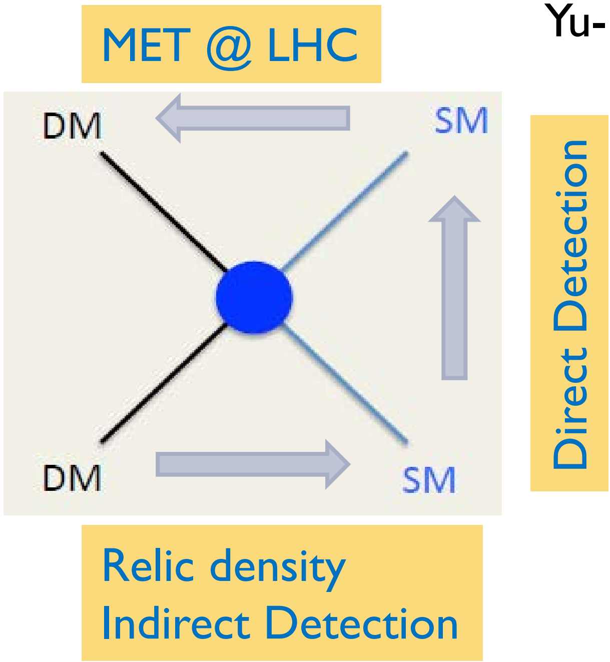
WIMP DM at TeV

- Any TeV-scale DM coupled weakly to SM can "naturally" have a right thermal relic density (miracle of easiness).

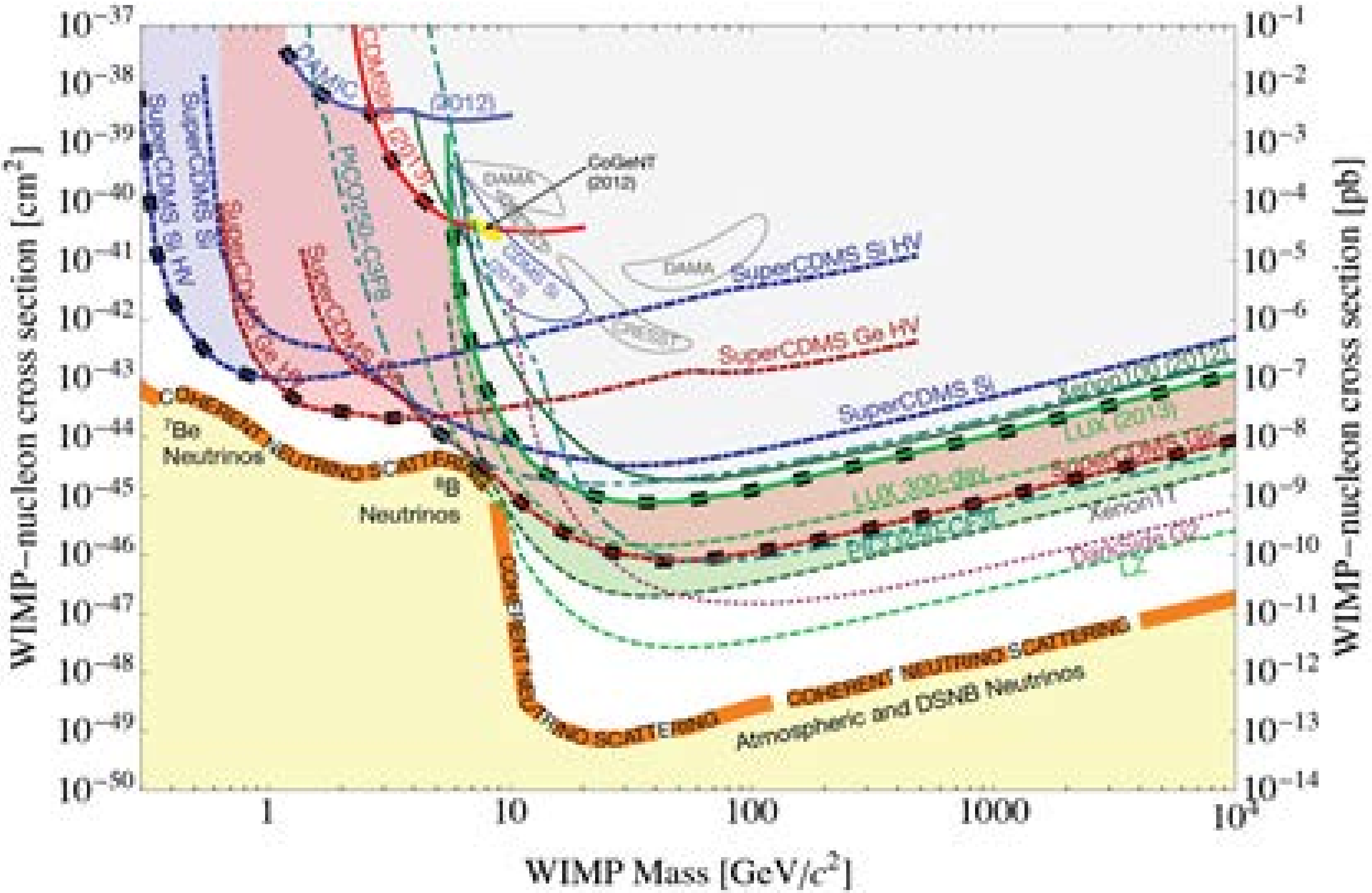
$$\Omega_\chi h^2 \sim 0.1 \frac{1pb}{\langle \sigma v \rangle}$$

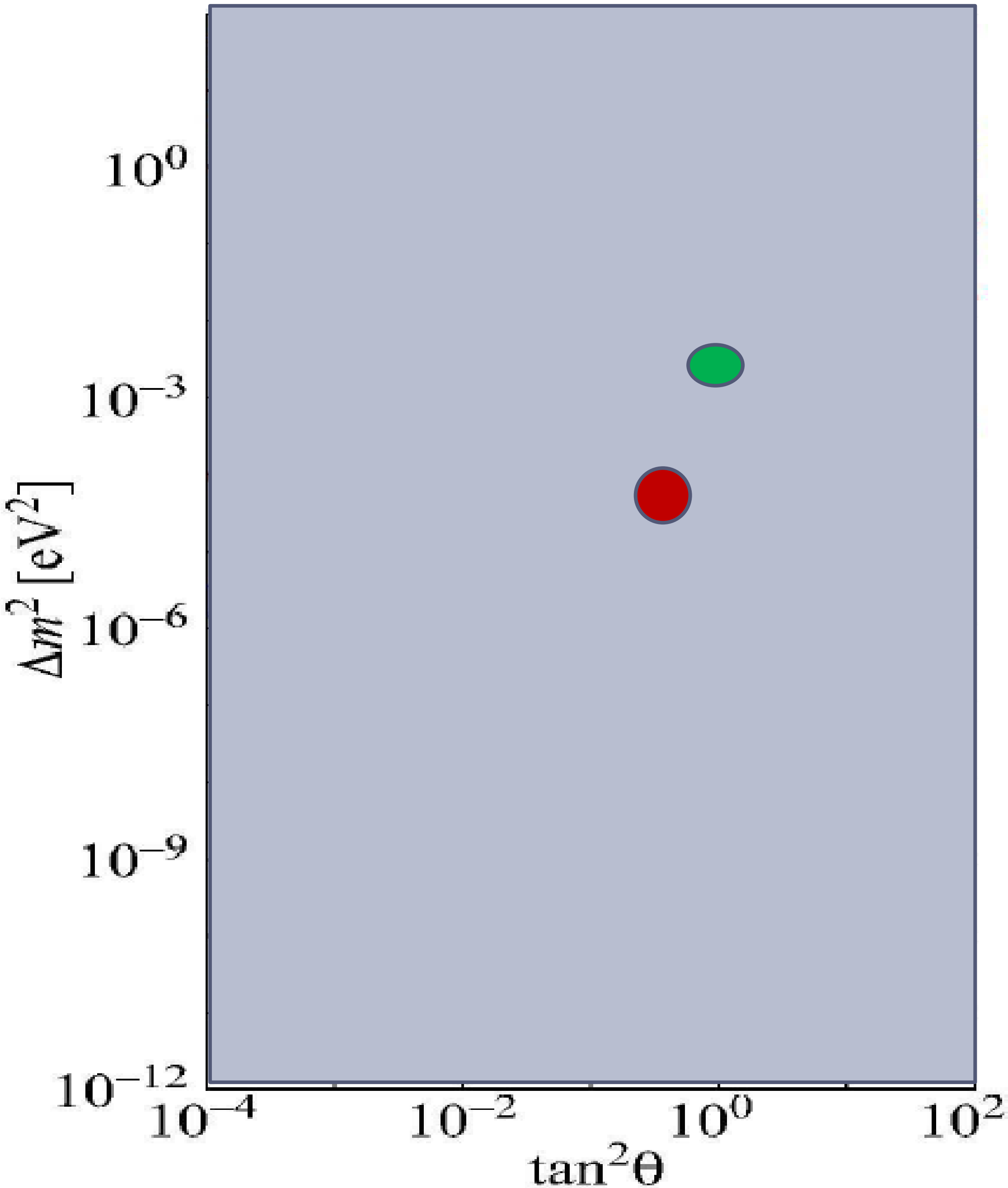


Yu-Feng Zhou

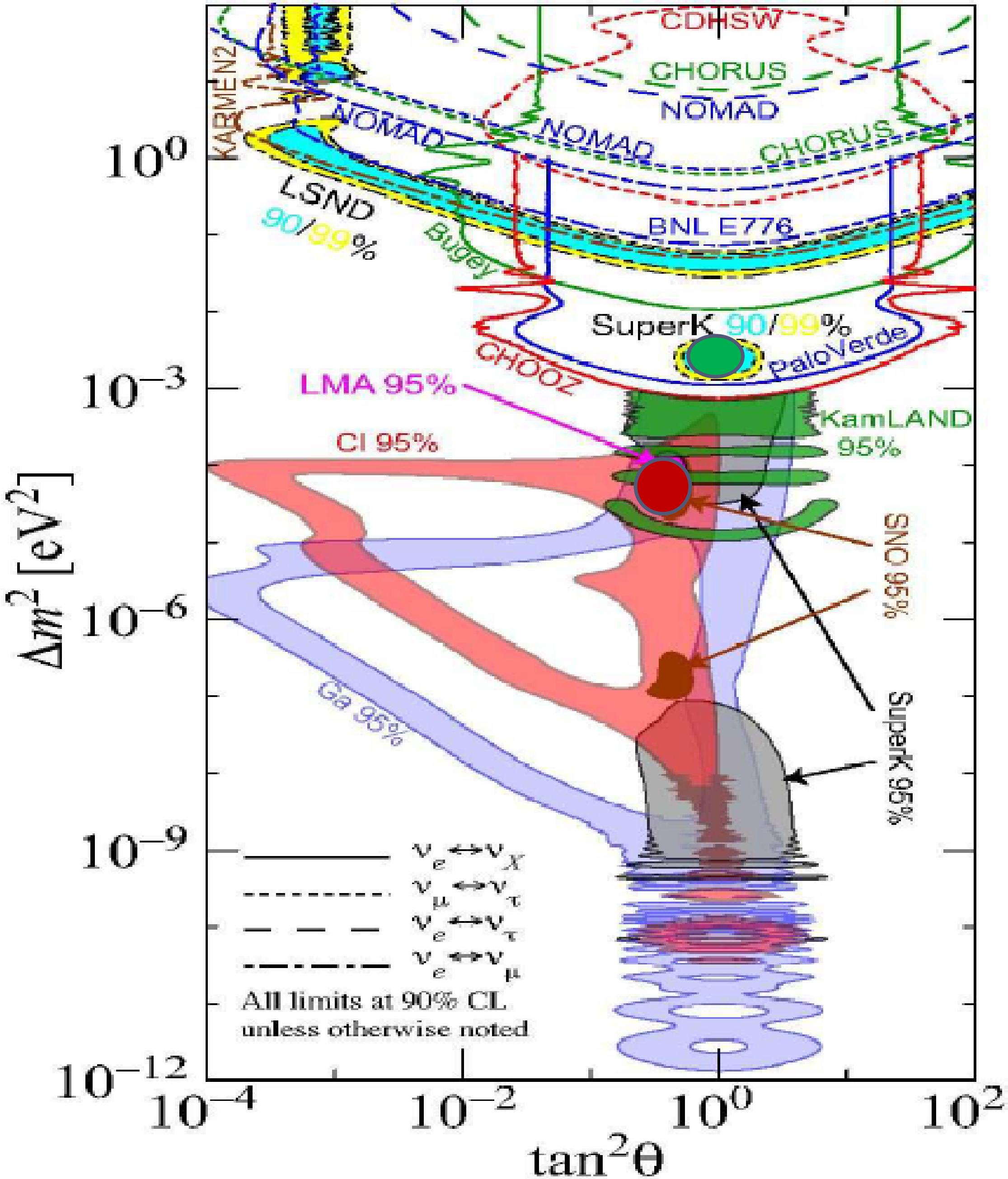


Direct detections



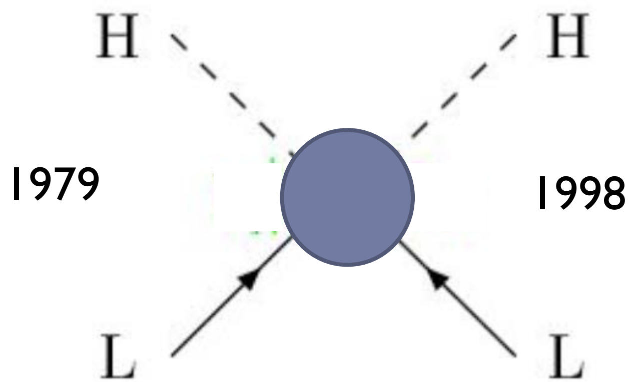


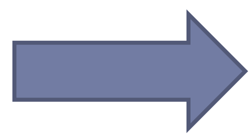
10^0
10^{-3}
10^{-6}
10^{-9}
10^{-12}
$\Delta m^2\ [\mathrm{eV}^2]$
10^{-4}
10^{-2}
10^0
10^2
$\tan^2\theta$


CDHSW
CHORUS
NOMAD
NOMAD
NOMAD
CHORUS
KARMEN2
LSND
90/99%
Bugey
BNL E776
SuperK 90/99%
CHOOZ
PaloVerde
LMA 95%
KamLAND
95%
Cl 95%
SNO 95%
Ga 95%
SuperK 95%
$\nu_e \leftrightarrow \nu_X$
$\nu_\mu \leftrightarrow \nu_\tau$
$\nu_e \leftrightarrow \nu_\tau$
$\nu_e \leftrightarrow \nu_\mu$
All limits at 90% CL
unless otherwise noted
Δm^2 [eV^2]
10^0
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-4}
10^{-2}
10^0
10^2
$\tan^2\theta$

Neutrino masses from $TeV \sim 10^{14} GeV$

- From Weinberg to …





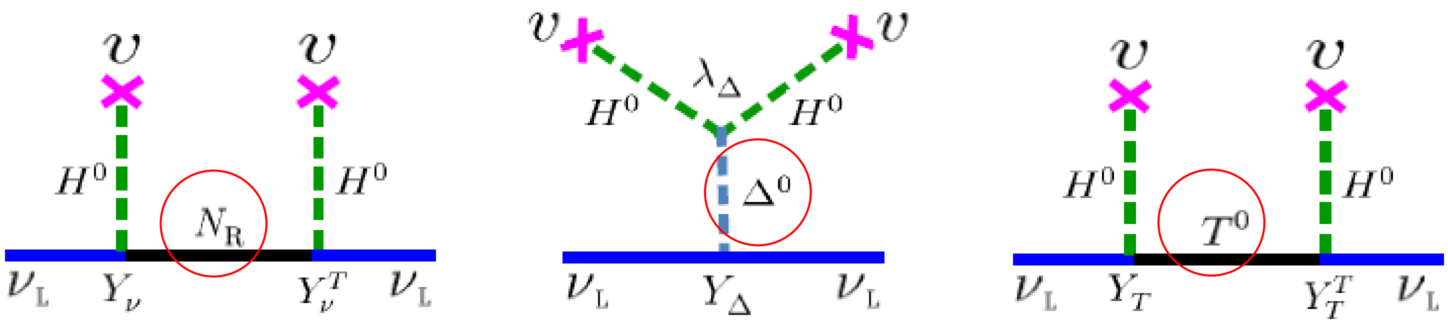
Origin of Neutrino Masses

Shun Zhou

Difficulties with Dirac neutrinos

- Tiny Dirac masses worsen fermion mass hierarchy problem (i.e., $m_i/m_t < 10^{-12}$)
- Mandatory lepton number conservation, which is actually accidental in the SM

Majorana neutrinos: a natural way to understand tiny neutrino masses (seesaw)



$$M_\nu \approx -v^2 Y_\nu \frac{1}{M_R} Y_\nu^T$$

$$M_\nu \approx \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}$$

$$M_\nu \approx -v^2 Y_T \frac{1}{M_T} Y_T^T$$

Type-I: SM + 3 right-handed Majorana ν's (Minkowski 77; Yanagida 79; Glashow 79; Gell-Mann, Ramond, Slanski 79; Mohapatra, Senjanovic 79)

Type-II: SM + 1 Higgs triplet (Magg, Wetterich 80; Schechter, Valle 80; Lazarides et al 80; Mohapatra, Senjanovic 80; Gelmini, Roncadelli 80)

Type-III: SM + 3 triplet fermions (Foot, Lew, He, Joshi 89)

- Can naturally be embedded into the SO(10) GUT (e.g., type-I + type-II seesaw)
- Responsible for both tiny neutrino masses and matter-antimatter asymmetry

Low-scale seesaw around *TeV*

- Seesaw particle contribution to Higgs mass:

$$\delta m_h^2 \lesssim m_h^2 \times \Delta$$

Farina, Pappadopulo, Strumia, 1303.7244

- Type I: $\delta m^2 = \frac{4\lambda_N^2}{(4\pi)^2} M^2 (\ln \frac{M^2}{\bar{\mu}^2} - 1)$ $\bar{\mu} \sim M_{\rm Pl}$

$$M \lesssim m_h \left(\Delta \frac{16\pi^2 m_h}{m_\nu} \right)^{1/3} \approx 0.7\ 10^7\ \mathrm{GeV} \times \sqrt[3]{\Delta}$$

- Type II: $\delta m^2 = -M^2 \frac{6g_2^4 + 3g_Y^4}{(4\pi)^4} (\frac{3}{2} \ln^2 \frac{M^2}{\bar{\mu}^2} + 2 \ln \frac{M^2}{\bar{\mu}^2} + \frac{7}{2})$

$$\delta m^2 = -\frac{6\lambda_H^2 M^2}{(4\pi)^2} (\ln \frac{M^2}{\bar{\mu}^2} - 1)$$

$$M \lesssim 200\,\mathrm{GeV} \times \sqrt{\Delta}$$

- Type III: $\delta m^2 = \frac{g_2^4}{(4\pi)^4} M^2 (36 \ln \frac{M^2}{\bar{\mu}^2} - 6)$

$$M \lesssim 0.94\,\mathrm{TeV} \times \sqrt{\Delta}$$

High scale seesaw above $10^9 GeV$

- Motivated by GUT.
- Maybe linked to other NP at an intermediate scale.
- Good for Leptogenesis – Davidson-Ibarra bound:

$$Y_B \approx 10^{-10} \sim \frac{\epsilon}{10\, g_*}\, \eta_{wo} < 10^{-3}\, \frac{3M}{8\pi v^2} \sqrt{\Delta m^2_{atm}}\, \eta_{wo}$$

$$\Rightarrow M > 10^9 GeV$$

Axion at around $10^{11}\ GeV$

- Strong CP problem – gauge invariance allows a CP-odd term in QCD dangerously contributing to EDM:

$$\mathcal{L}_\theta = \theta \frac{g_3^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

$$d_n \sim e\theta m_q / m_N^2 < 10^{-26} ecm \Rightarrow \theta < 10^{-11}$$ "Unnaturally small"

- Dynamically resolved by axion – a pseudo-Goldstone boson of an anomalous U(1) symmetry

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + (\theta + c_G \frac{a}{F_a}) \frac{g_3^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \Rightarrow \bar{\theta} \equiv \theta + c_G \frac{a}{F_a}$$

- QCD phase transition generates the axion potential:

$$V \sim \Lambda^4_{QCD} (1 - \cos \bar{\theta}) \Rightarrow \langle \bar{\theta} \rangle = 0$$

Axion DM

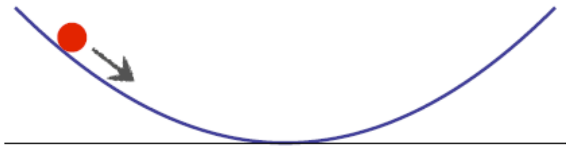
- Superlight axion

$$m_a \sim \frac{\Lambda^2_{QCD}}{F_a} \sim 10^{-3}\left(\frac{10^{10}\mathrm{GeV}}{F_a}\right)\mathrm{eV}$$

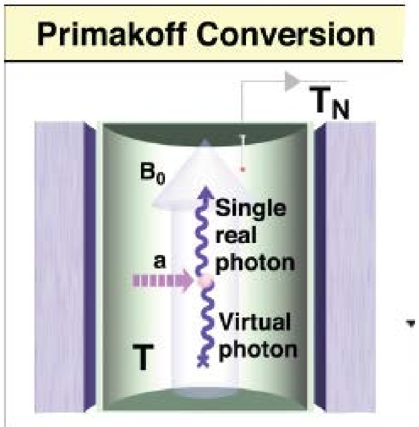
- Constraints from star cooling and dark matter density

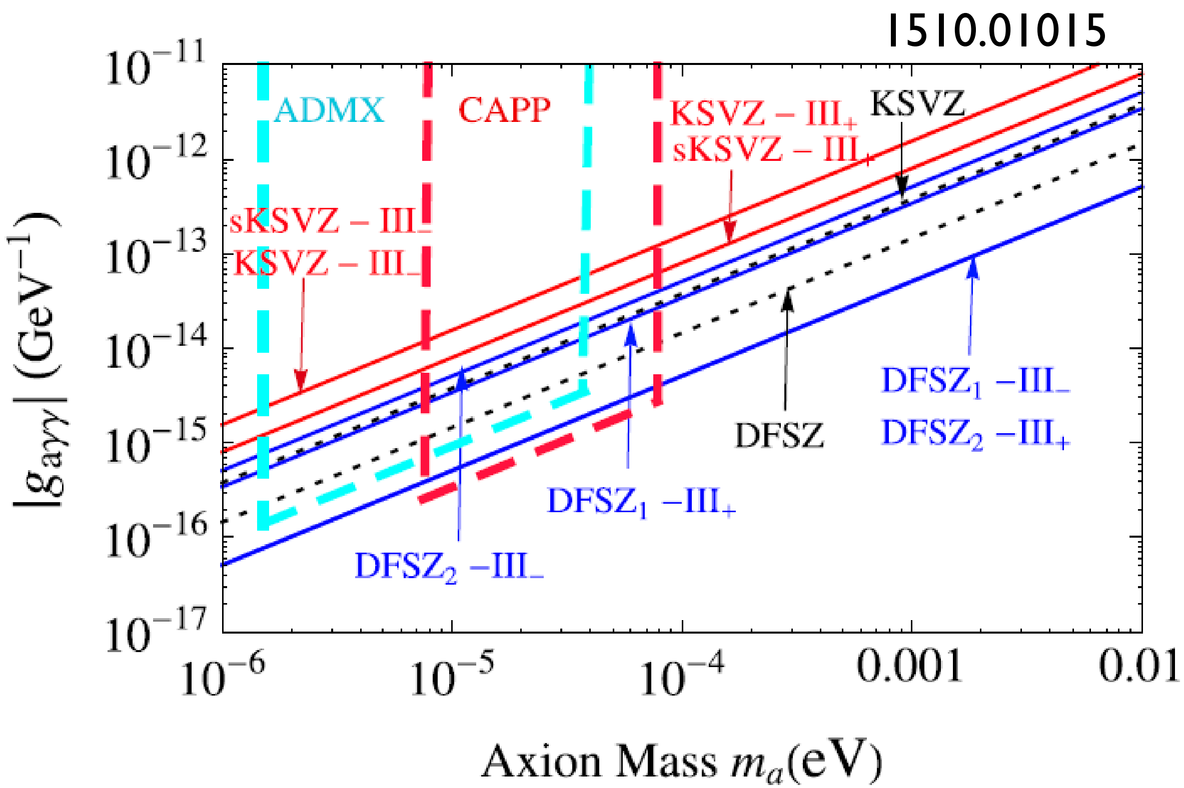
$$F_a \approx 10^{10} \sim 10^{12}\ GeV$$

- Axion coherent oscillation – another good CDM candidate for $F_a \sim 10^{11} GeV$.

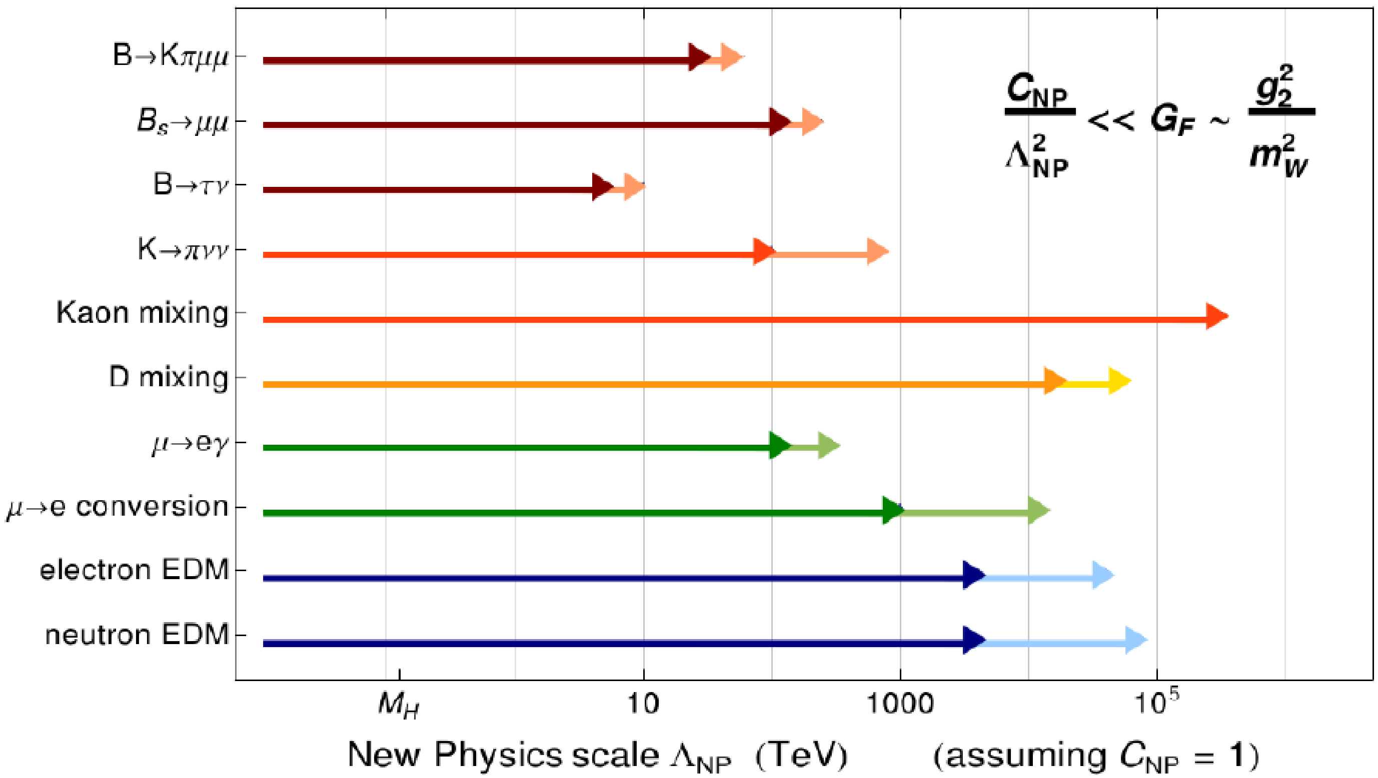


DM axion detection





Flavor Physics above $10^4 \sim 10^8\ GeV$



Ying Li

✓ Difficult to consider flavor beyond CKM around TeV

Supersymmetry

- Ensures "natural" EWSB and a light Higgs.
- Protects any new physics scale.
- SUSY breaking may occur a bit far from TeV.

> Although there is no evidence,
> SUSY is still the **most appealing**
> **candidate** for new physics

Jinmin Yang

Epilogue

Nature may not be kind enough any more, but

Do our best and wait with more patience.

盡人事 待天命

The 6th KIAS Workshop on Particle Physics and Cosmology and the 2nd Durham-KIPMU-KIAS Joint Workshop

Oct. 24 (Mon) - 28 (Fri), 2016
5th floor Seminar room #1503

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imagine the impossible
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