PHYSICS PROSPECTS

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2019.04.16 @ Hawaii

Disclaimer

I am planning to talk about my dreams

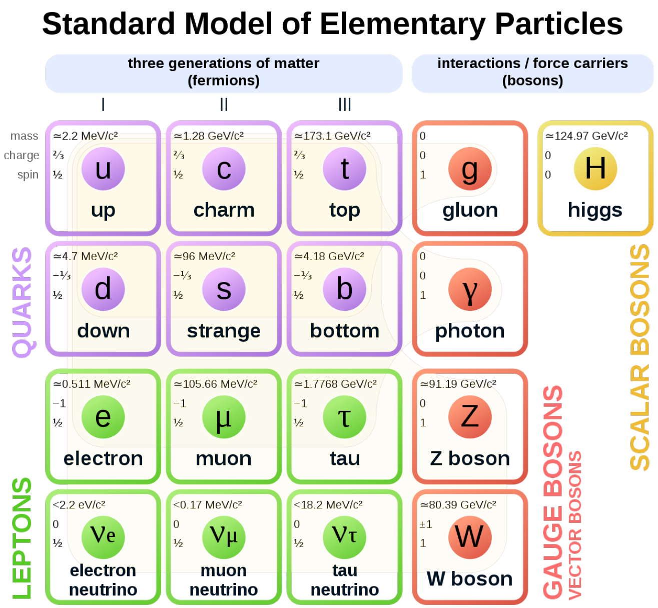
➡ I hope that they can become true in next few decades (~ 40 years, or maybe more?)

➡ I may not be responsible for my words because I'm not sure if I can live another ~ 40 years

Introduction

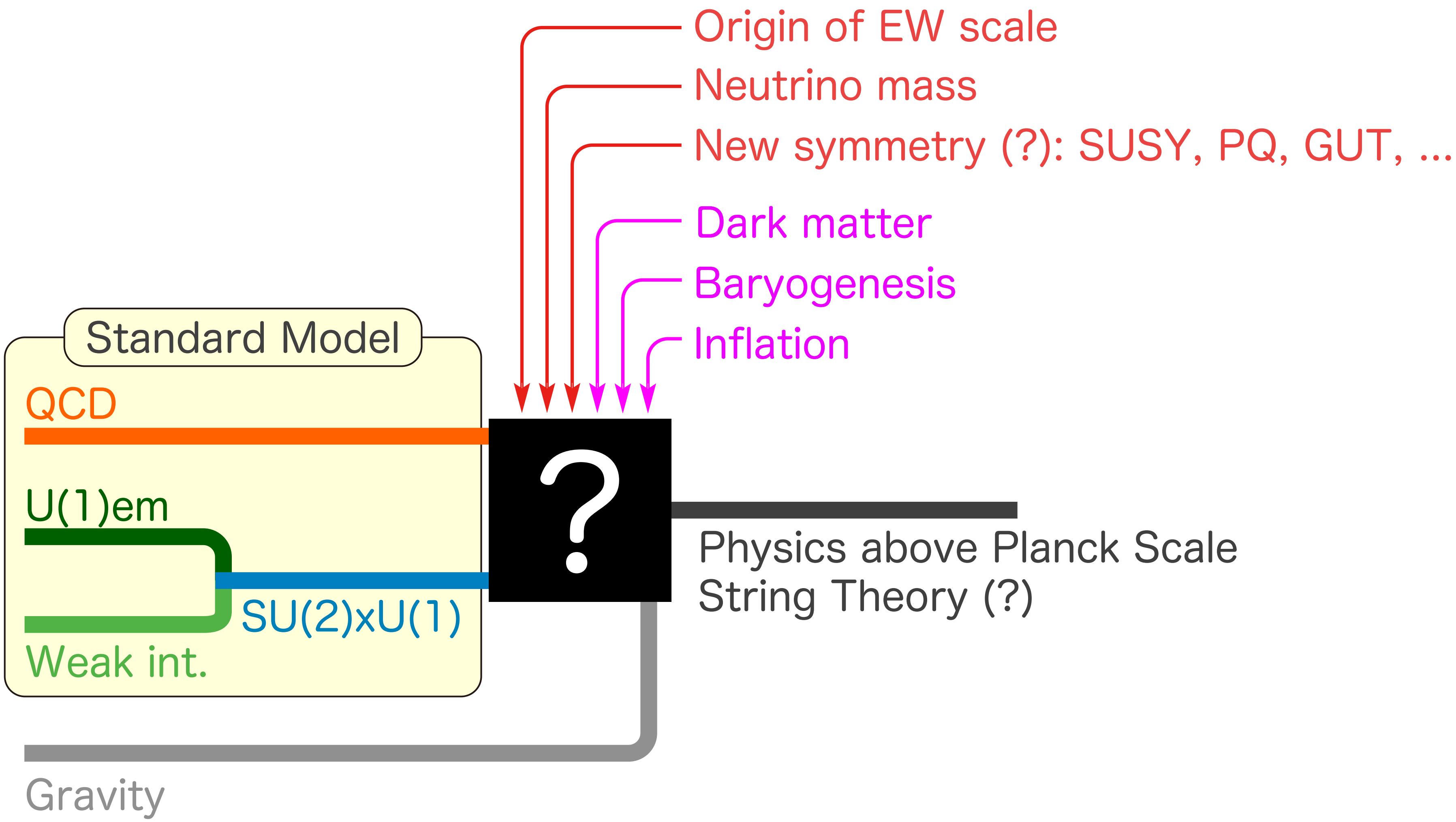
Current situation

- All the SM particles have been discovered



- Properties of particles are mostly consistent with SM predictions

SM is not enough



What kind of new physics?

I don’t know …

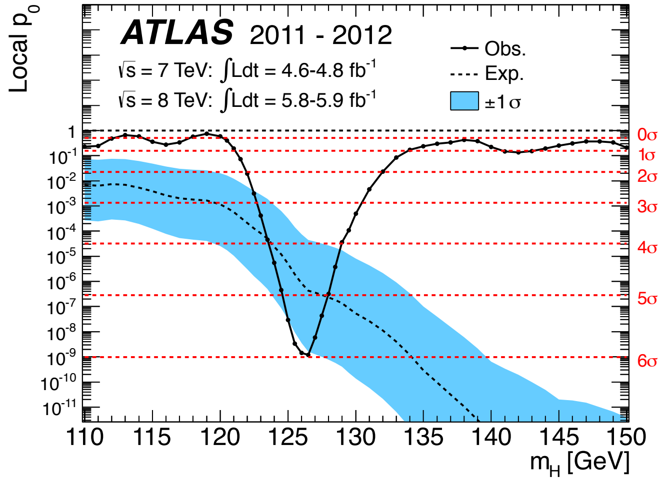
➡ We should consider various possibilities

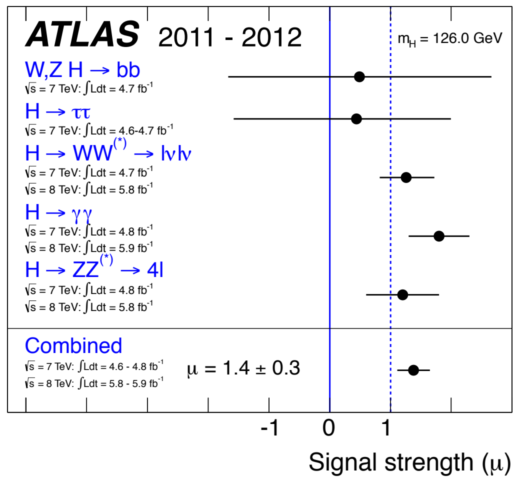
Today, I will talk about …

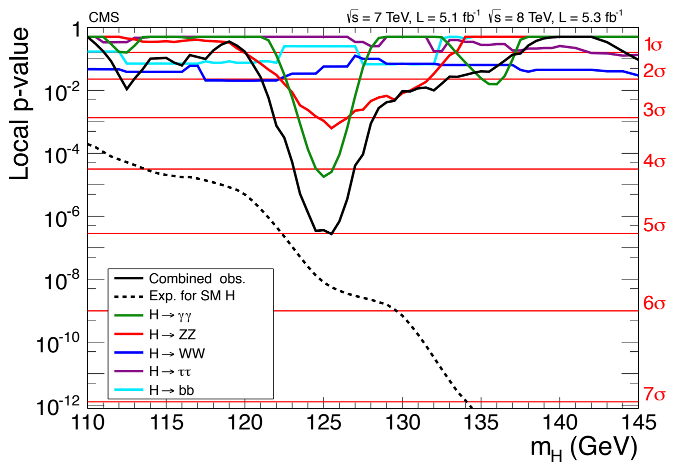
- Higgs studies
- Beyond-the-SM (BSM) at future colliders
- CMB, gravitational waves, and inflation

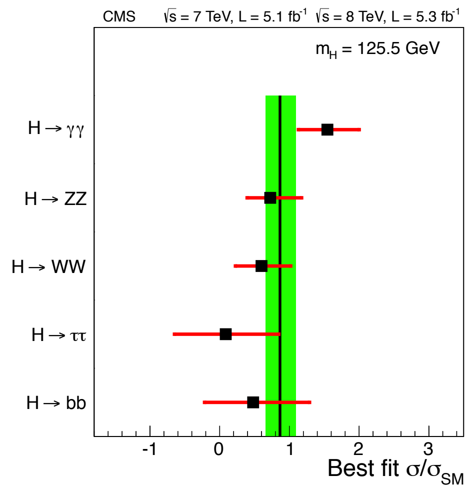
Higgs studies

Higgs discovery (2012)

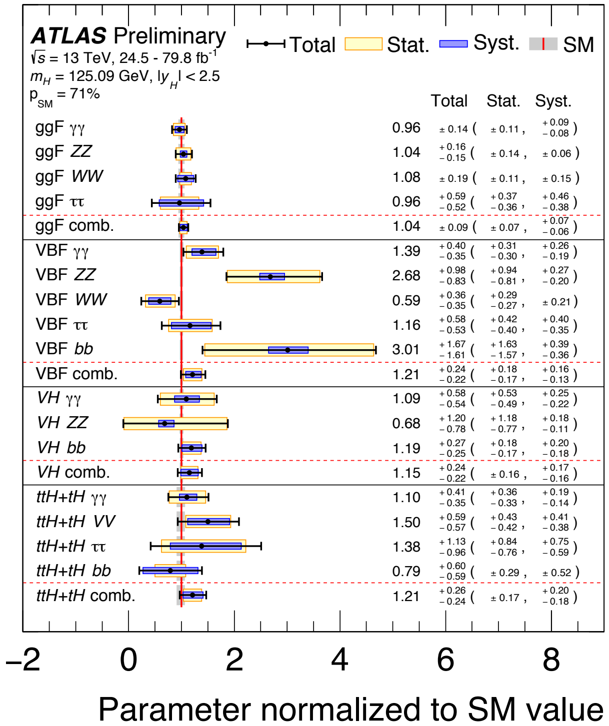




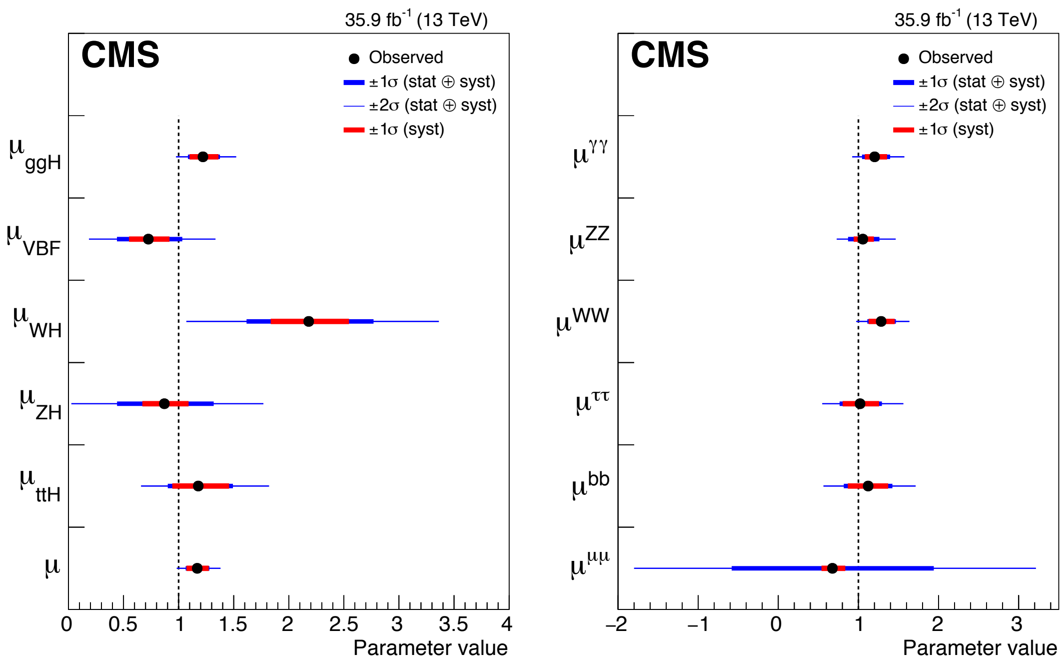




Higgs physics: from the discovery to precision studies



[ATLAS-CONF-2019-005]



[CMS Collaboration 1809.10733]

➡ Currently, Higgs looks like the SM Higgs

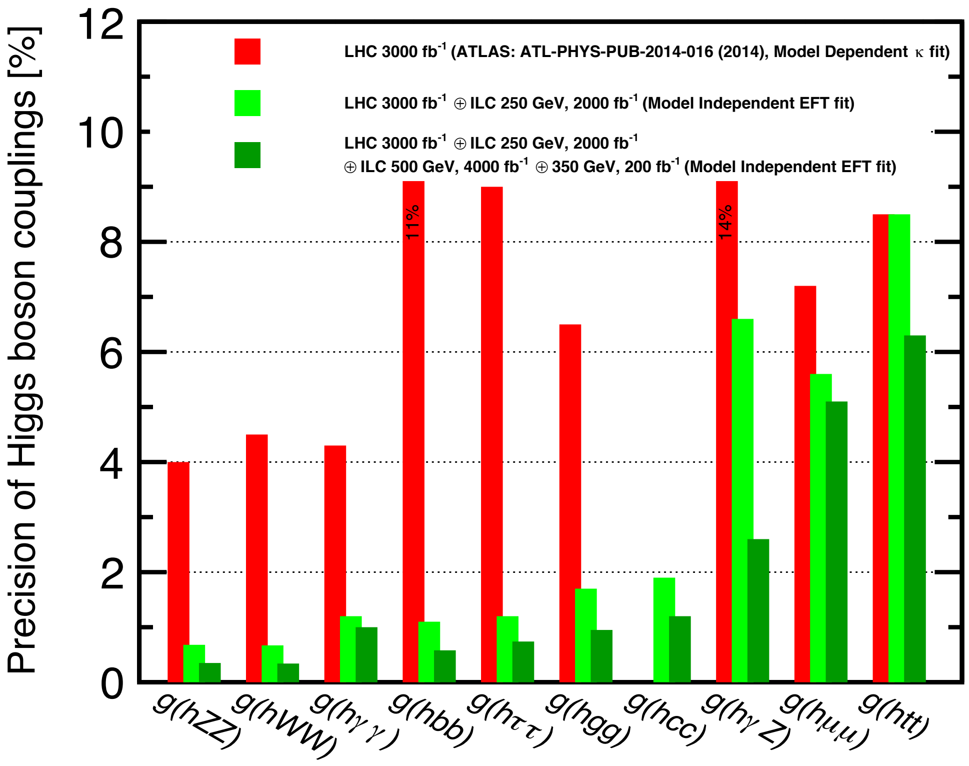
Is the Higgs really the SM Higgs?

Detailed study of Higgs properties is important

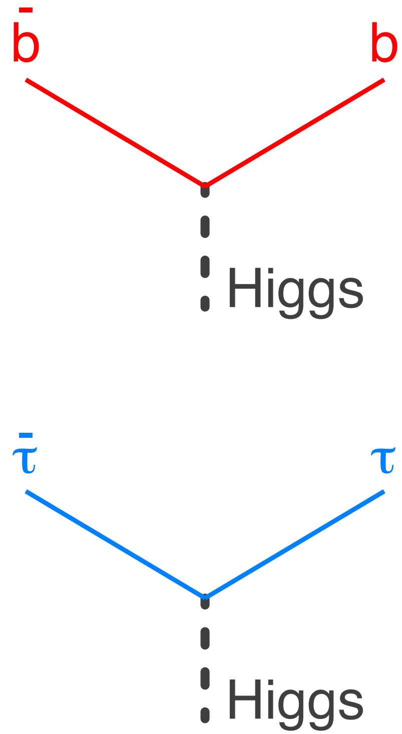
➡ Future colliders may precisely measure Higgs couplings to other particles

➡ Effects of the BSM physics may be imprinted in Higgs properties

Higgs coupling measurements with e+e- colliders



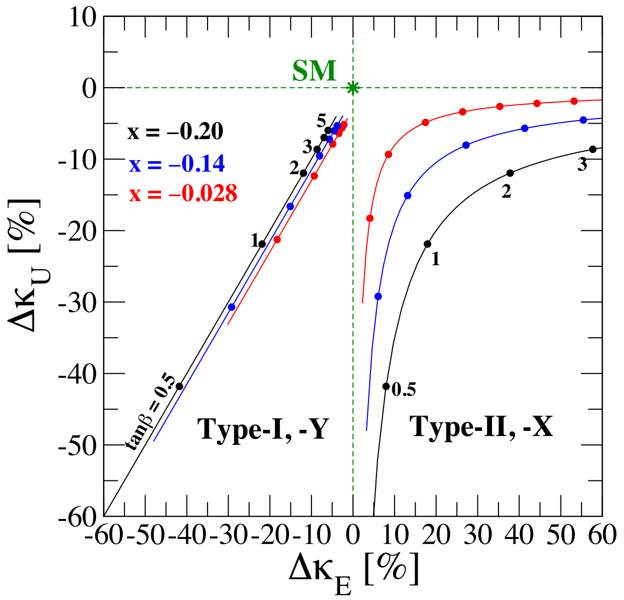
[Fujii et al., 1710.07621]

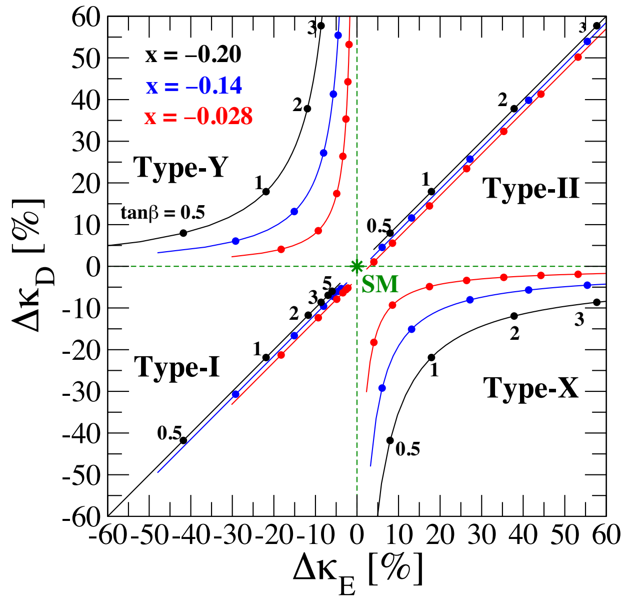


➡ Significant improvements in b b and $\tau\ \tau$

General two Higgs doublet model

Deviation from the predictions of the SM (tree level)



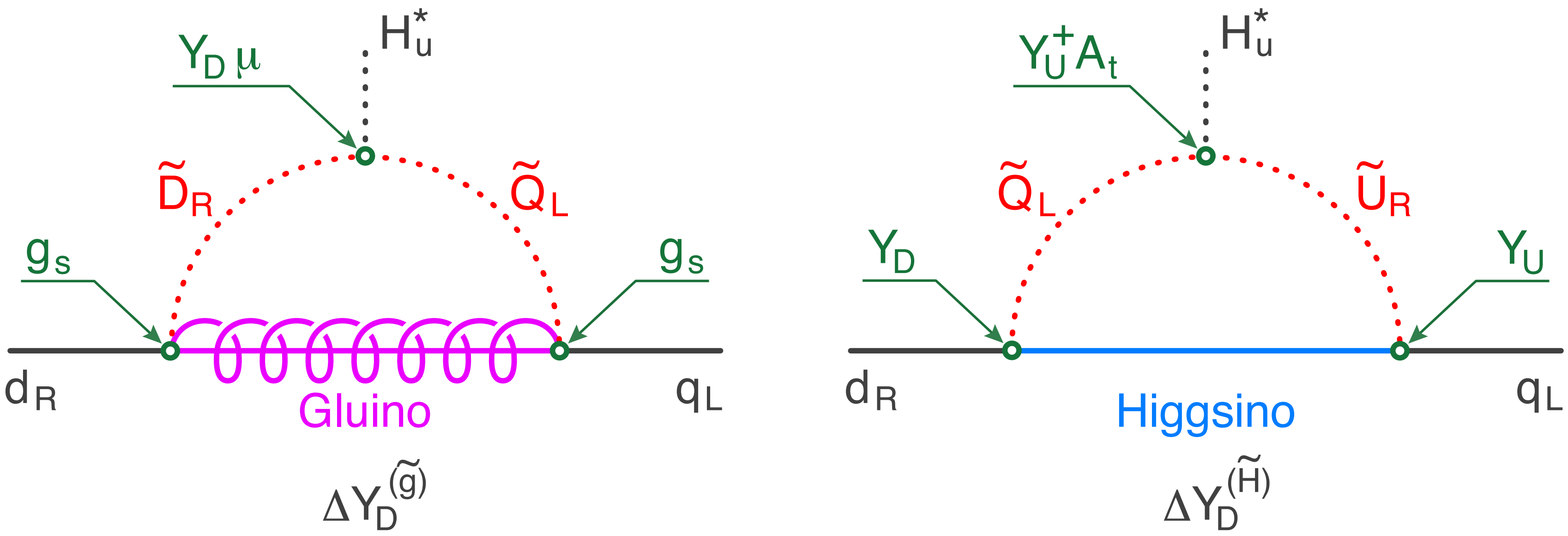


[Kanemura, Kikuchi, Yagyu]

	H_1	H_2
Type-I	u, d, e	
Type-II	u	d, e
Type-X	u, d	e
Type-Y	u, e	d

Loop effects of SUSY particles

SUSY loop correction to the couplings

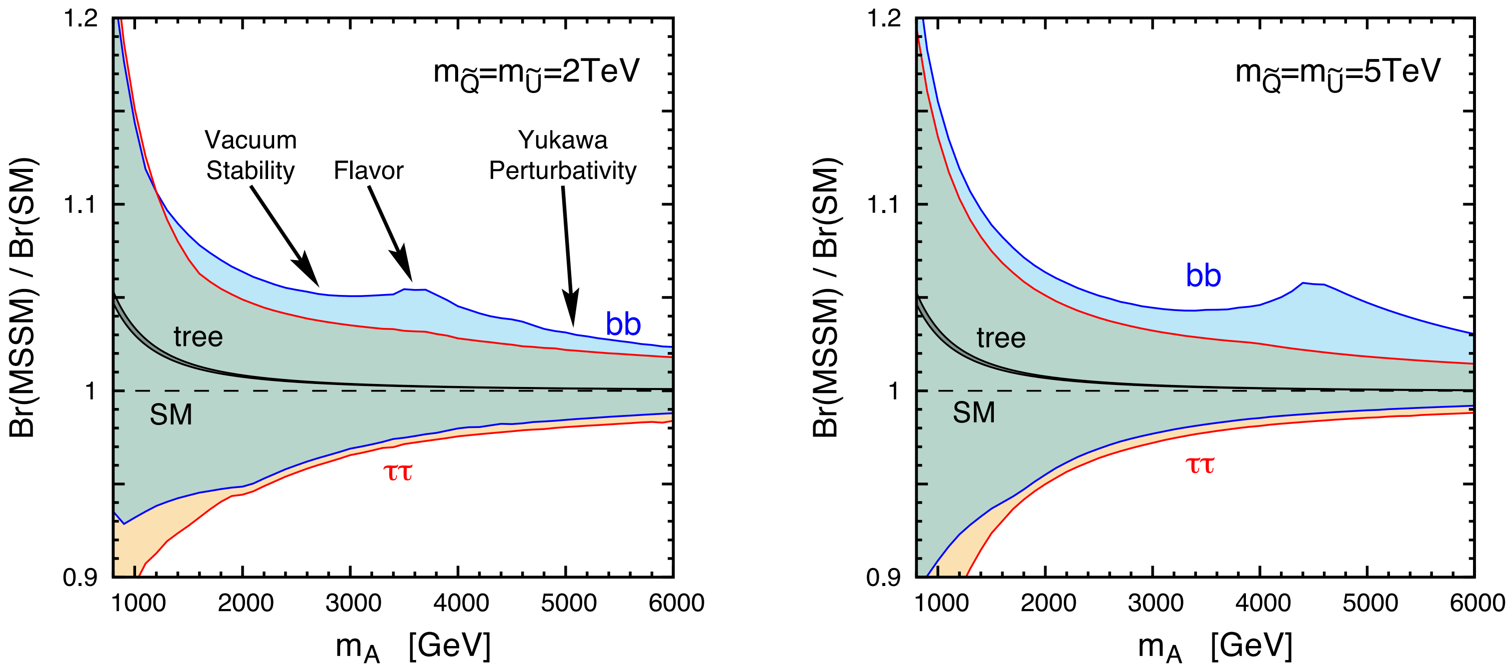


➡ Deviation from the Type-II structure

➡ Non-decoupling effect

Decay rate of h in the MSSM

Maximal possible deviations of Higgs decay rates



[Endo, TM, Nojiri]

➡ A few % change in Br($h \to b\,b$) and Br($h \to \tau\,\tau$)

Higgs physics is important

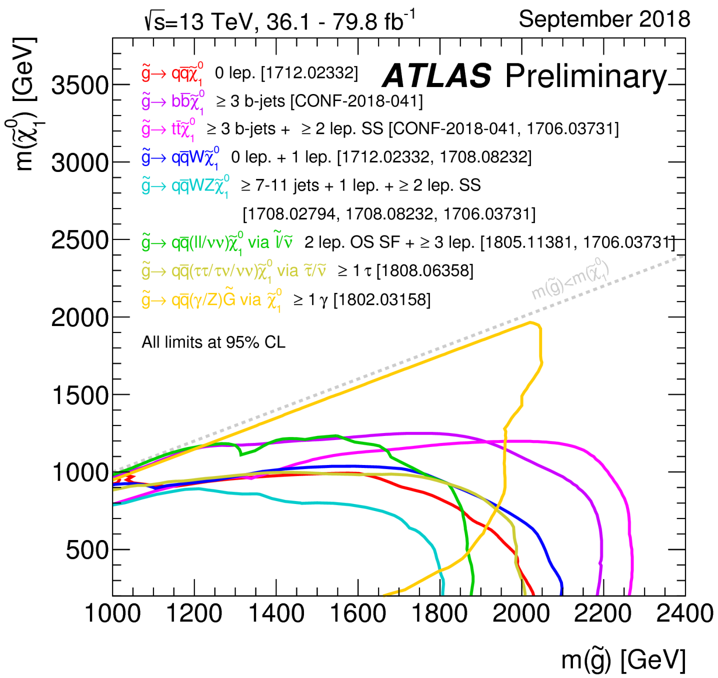
We should study the Higgs boson in detail

➡ A signal of BSM may be imprinted in Higgs properties

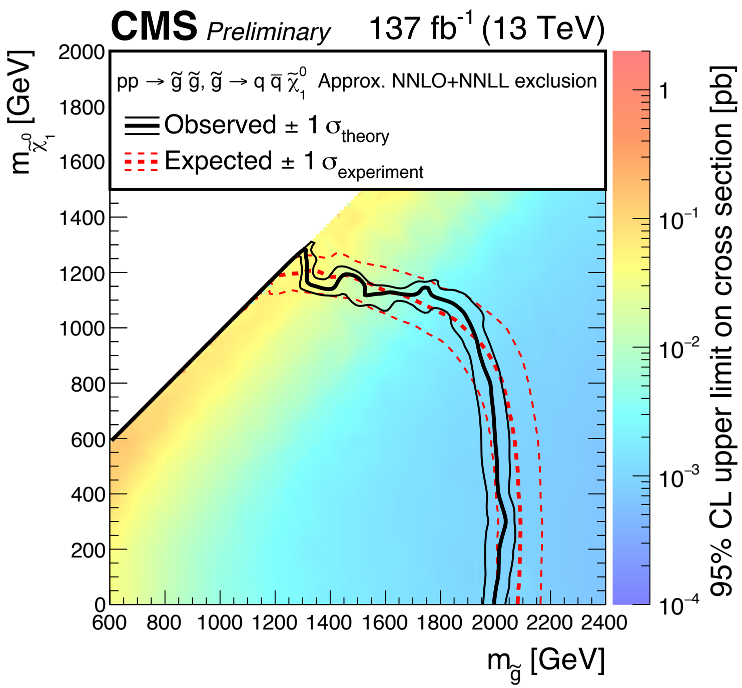
➡ e^+e^- colliders (like ILC, FCC-ee, CEPC) can play important role in Higgs studies (so let’s go for it)

BSM (SUSY) at future colliders

Example: SUSY



[ATLAS Collaboration ('18)]



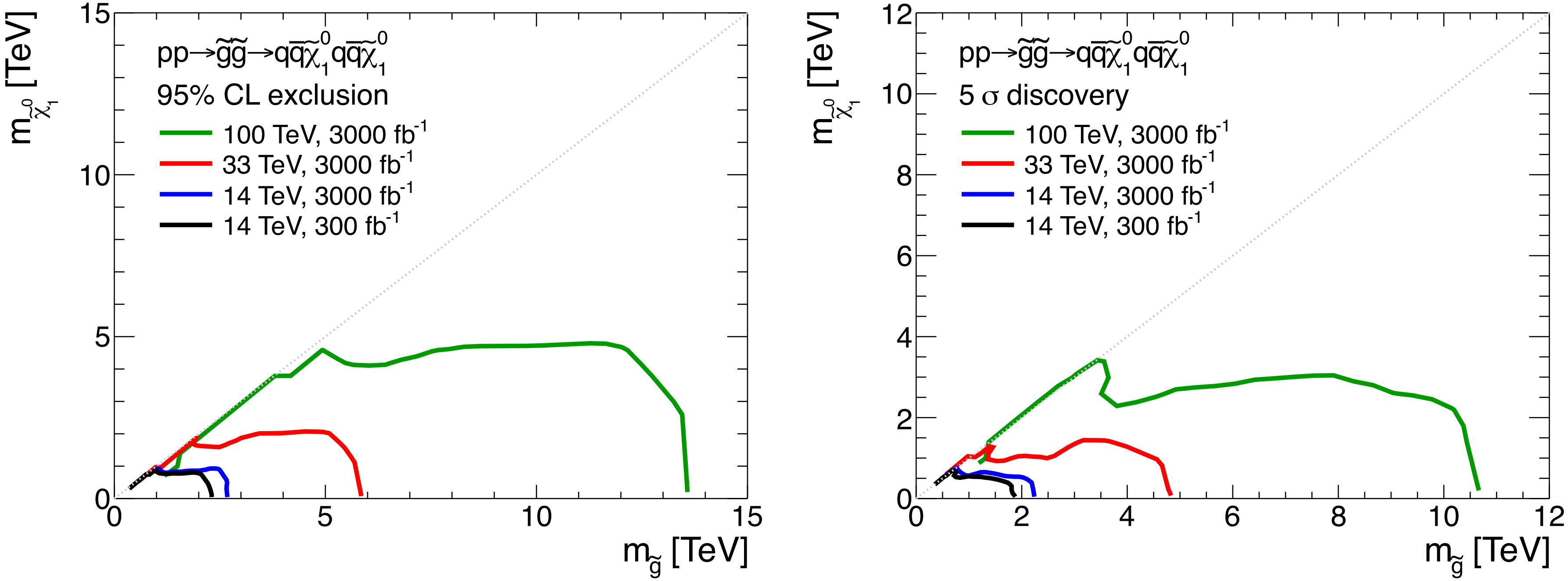
[CMS Collaboration ('19)]

No (apparent) sign of BSM physics at the LHC yet

➡ The energy of may not be high enough to find BSM

Let’s consider 100TeV pp collider (FCC-hh)

Reaches for gluino (and LSP): LHC vs. FCC-hh

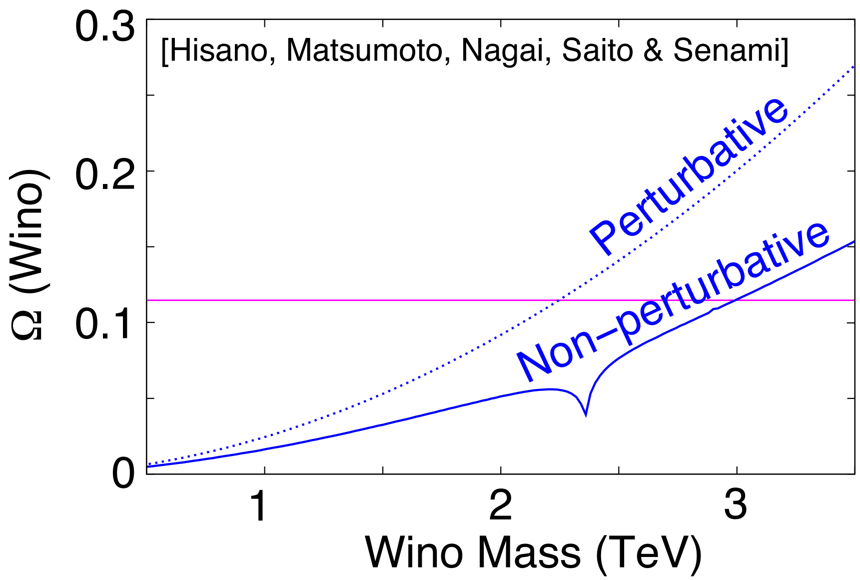


[Golling et al. 1606.00947]

3TeV Wino LSP is attractive

Wino ($\tilde{W}^{\pm}$ and $\tilde{W}^{0}$): superpartners for $SU(2)_L$

➡ $\tilde{W}^0$ is slightly lighter ($\Delta m_{\tilde{W}} \simeq 160$ MeV)



➡ $\tilde{W}^0$ can be DM

➡ mass ~ 3TeV

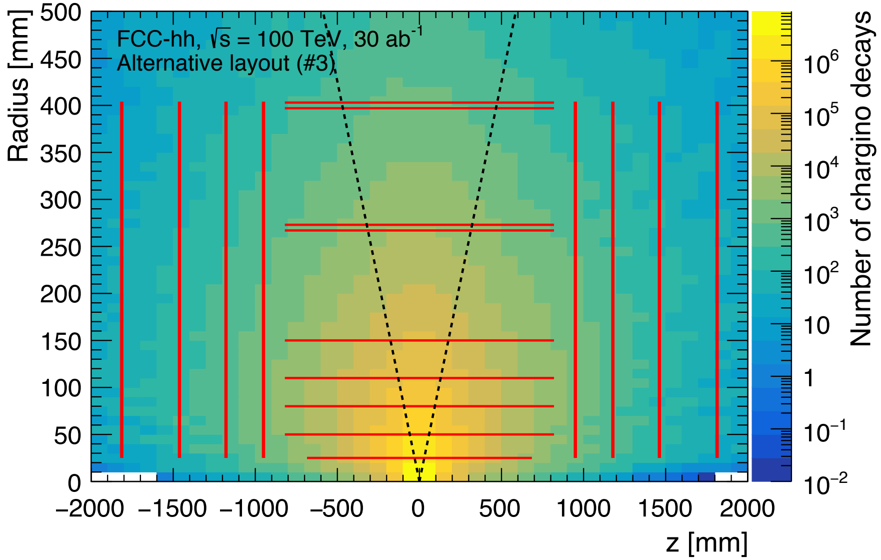
➡ Let me discuss what we can do in such a scenario

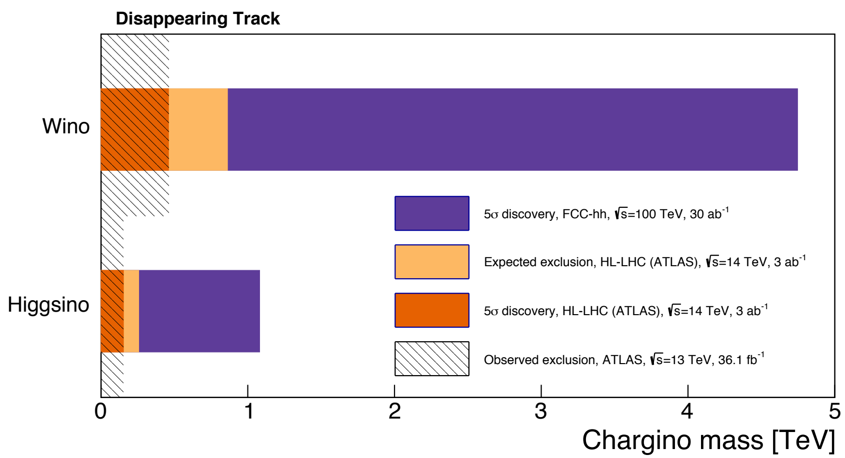
Wino @ FCC-hh (with Drell-Yan)

Lifetime of $\tilde{W}^{\pm}$: ~ 0.2 nsec

➡ $\tilde{W}^{\pm}$ may fly ~ 5 - 10cm

➡ $\tilde{W}^{\pm}$ can be identified as disappearing high-P_T track

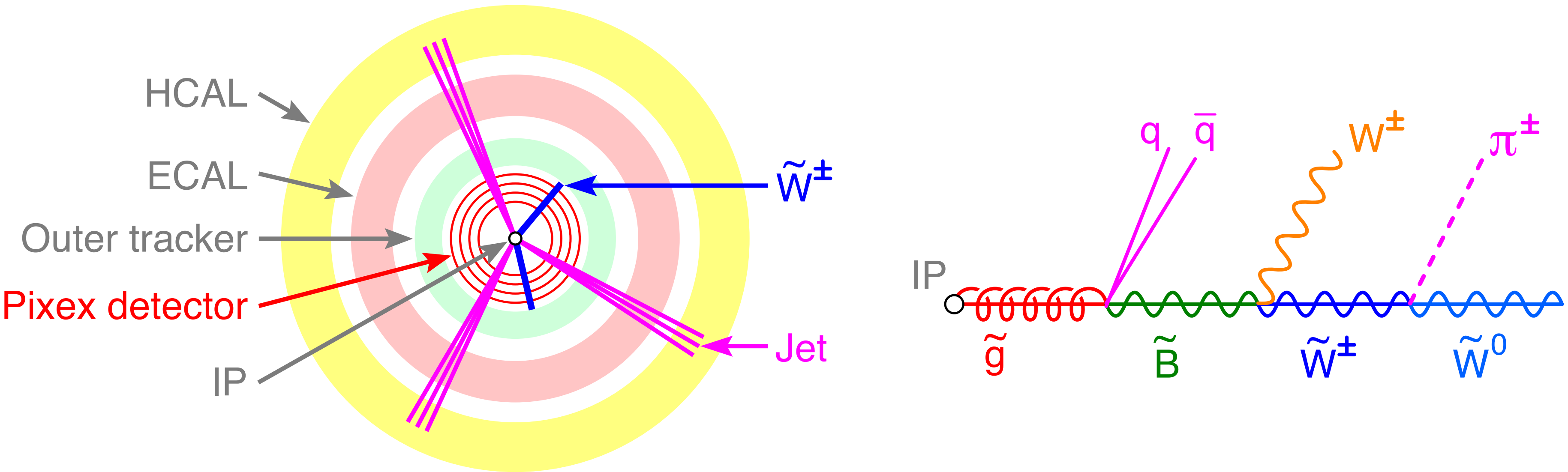




[Saito et al. 1901.02987]

If gluino is within kinematical reach …

Gaugino mass measurements using gluino production



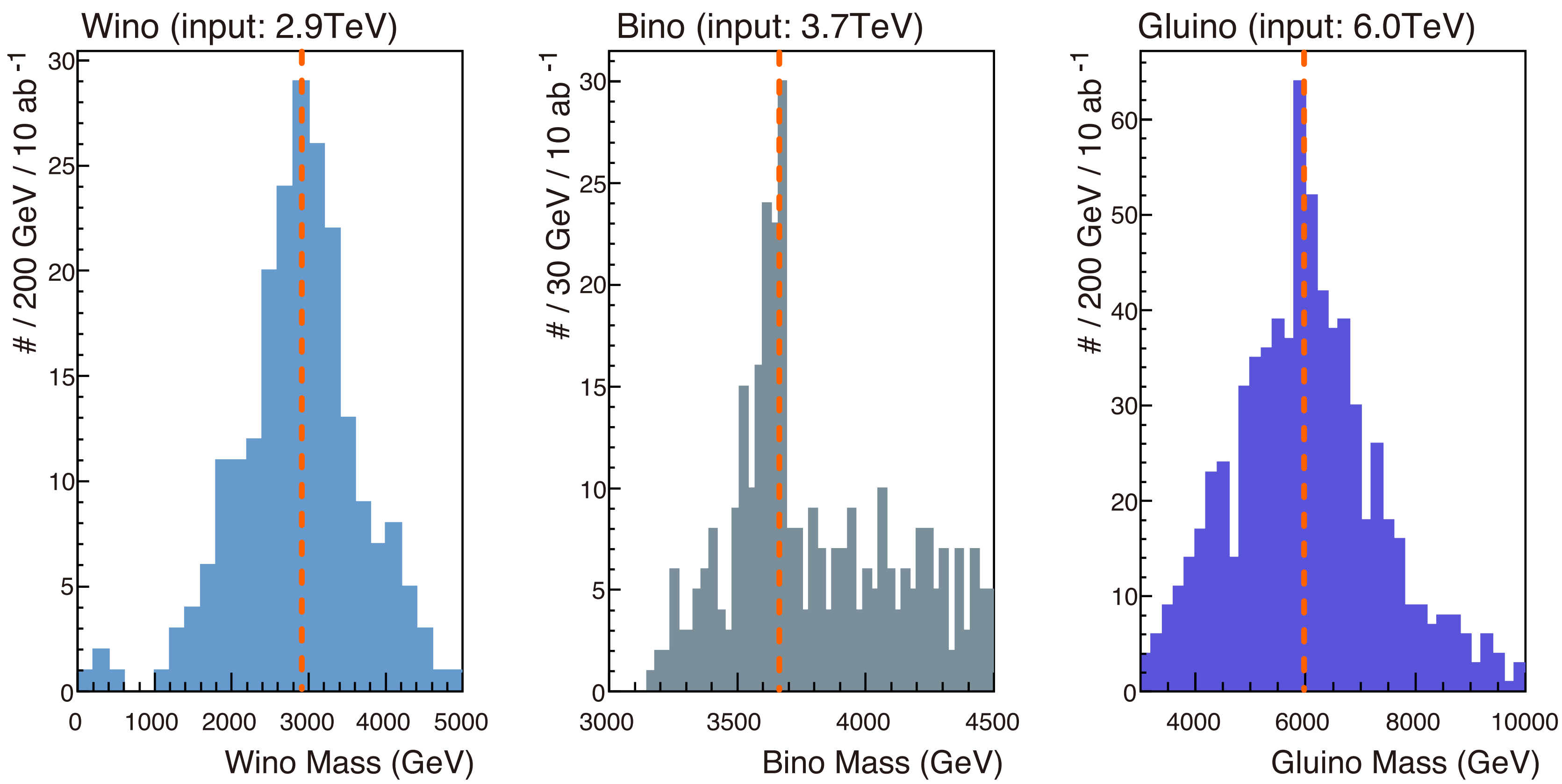
➡ We can use $\tilde{W}^{\pm}$-track for the event reconstruction

Gaugino mass determinatons

Gaugino masses from gluino pair production process

- Wino: momentum + velocity
- Bino: invariant mass of $\tilde{W}^{\pm} + W^{\pm}$
- Gluino: invariant mass of $\tilde{W}^{\pm}$ + jets (of one side)

Gaugino mass measurements @ FCC-hh: an example



➡ All the gaugino masses may be measured

[Asai et al. 1901.10389]

Wino LSP is naturally realised in anomaly-mediation

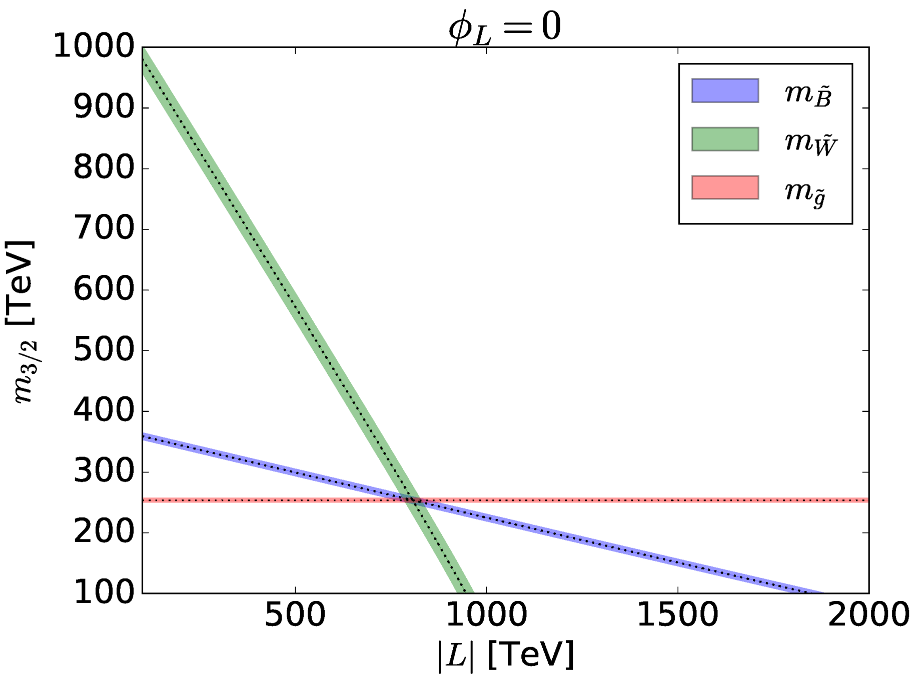
[Randall, Sundrum; Giudice, Luty, Murayama, Rattazzi]

$$m_{\tilde{B}} \simeq \frac{g_1^2}{16\pi^2}\left(11 m_{3/2} + L\right)$$

$$m_{\tilde{W}} \simeq \frac{g_2^2}{16\pi^2}\left(m_{3/2} + L\right)$$

$$m_{\tilde{g}} \simeq \frac{g_3^2}{16\pi^2}\left(-3 m_{3/2}\right)$$

$m_{3/2}$: Gravitino mass



➡ Gravitino mass may be determined

FCC-hh is an interesting possibility

FCC-hh gives new possibilities for BSM study

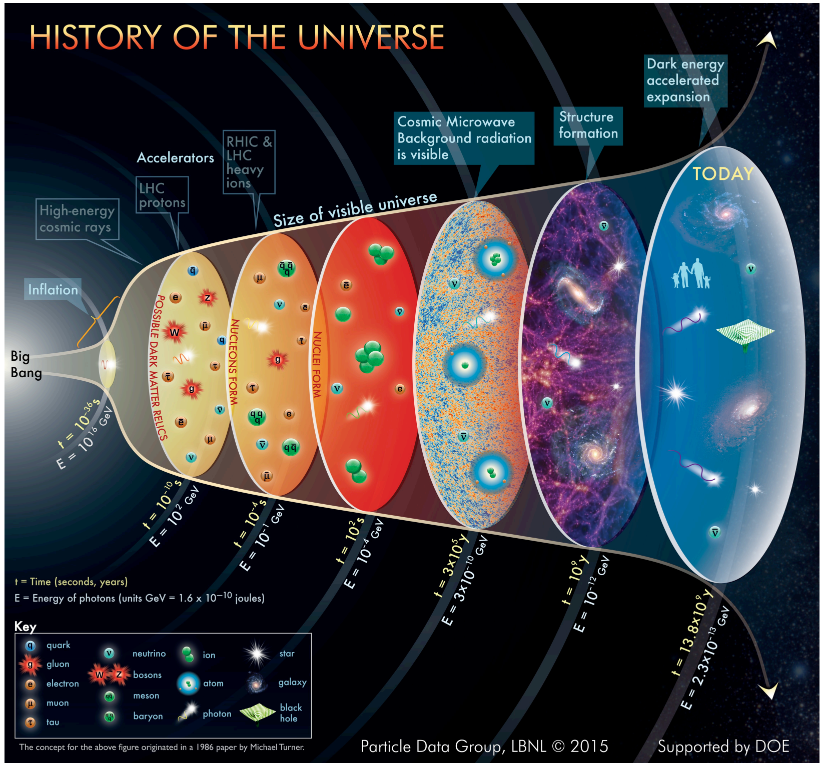
➡ Discovery reach is extended

➡ Detailed studies of BSM particles are also possible (if they are discovered)

CMB, GW, and inflation

Inflation

Inflation: accelerating expansion of the universe



- Solution to horizon and flatness problems
- Origin of the density fluctuation of the universe

Gravitational wave (GW) from inflation

During inflation, gravitational field fluctuates

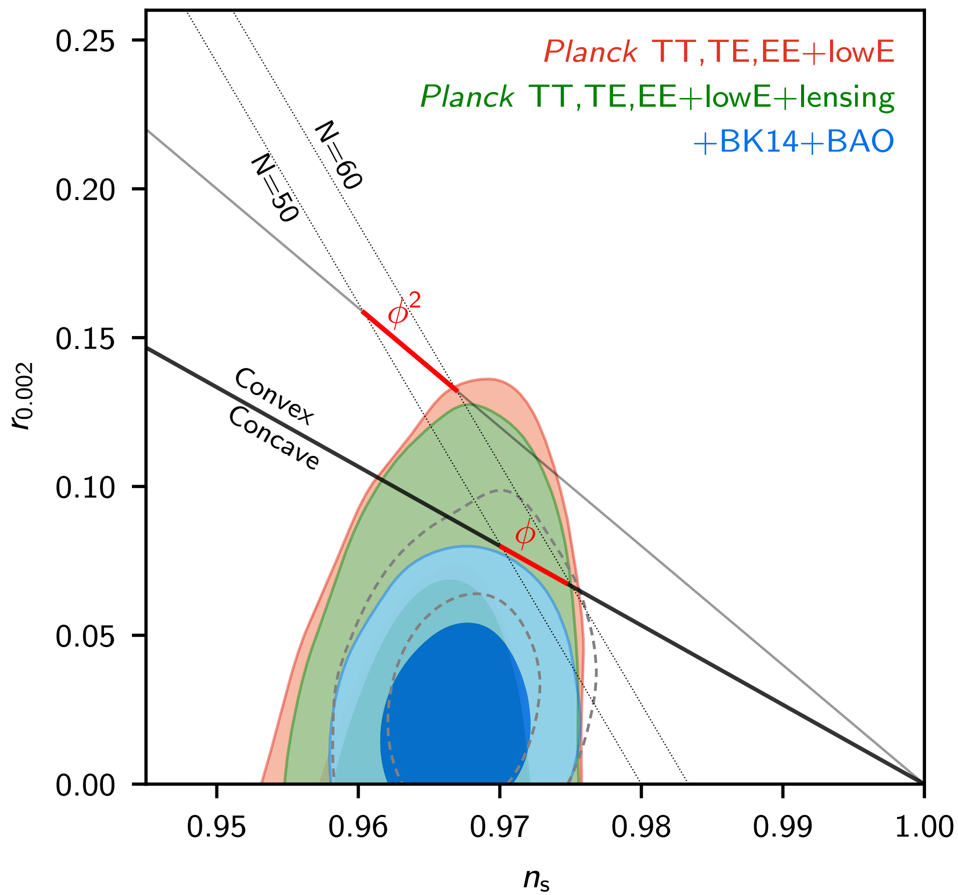
$$g_{ij} = -a^2(\delta_{ij} + h_{ij})$$

Fluctuation of GW (i.e., transverse-traceless mode)

$$\langle \tilde{h}^2_{\mathrm{TT}}(\vec{k}) \rangle = \frac{2}{M^2_{\mathrm{Pl}}} \left(\frac{H_{\mathrm{inf}}}{2\pi} \right)^2 \quad \text{where} \quad \begin{cases} k_i \tilde{h}^2_{\mathrm{TT},ij} = 0 \\ \tilde{h}^2_{\mathrm{TT},ii} = 0 \end{cases}$$

$$H^2_{\mathrm{inf}} = \frac{(\text{Energy density})}{3M^2_{\mathrm{Pl}}}$$: Expansion rate during inflation

No sign of inflationary GW yet



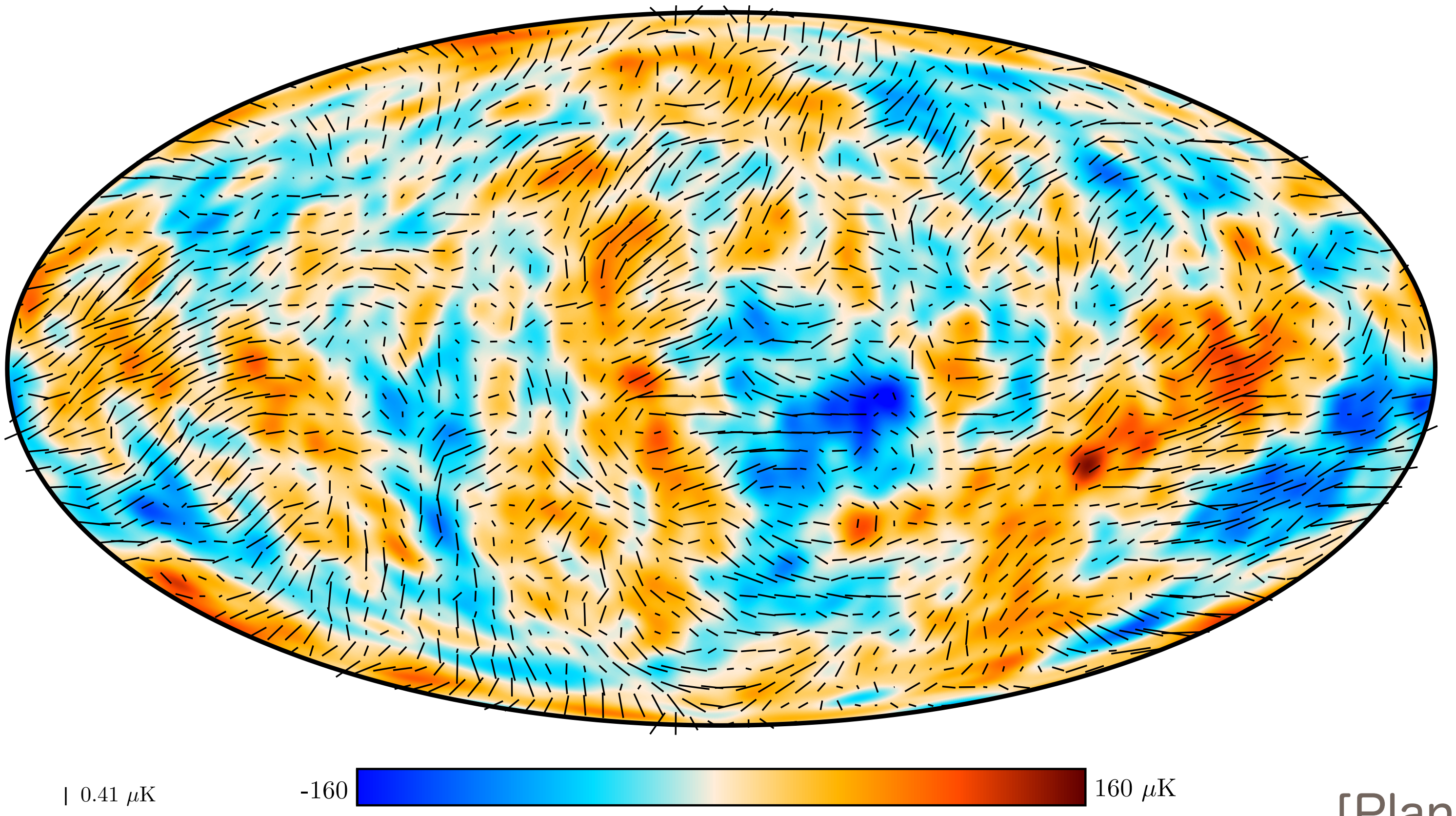
$$r \equiv \frac{4\langle \tilde{h}^2_{\mathsf{TT}} \rangle}{\langle \tilde{\mathcal{R}}^2 \rangle} \propto H^2_{\mathsf{inf}}$$

$$\langle \tilde{\mathcal{R}}^2 \rangle \simeq 2.1 \times 10^{-9}$$

[Planck 2018]

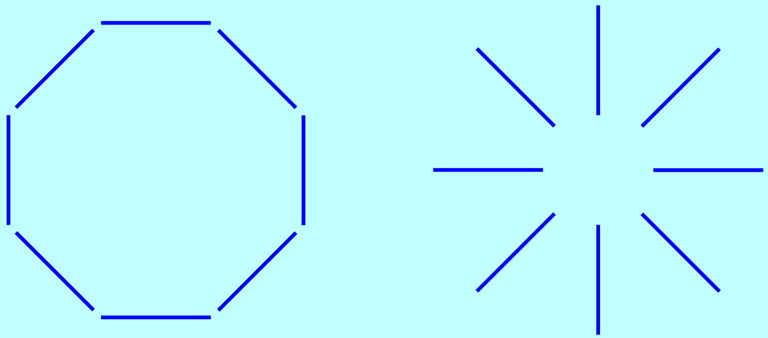
GW from inflation makes CMB polarized

Detailed study of the CMB polarization is important

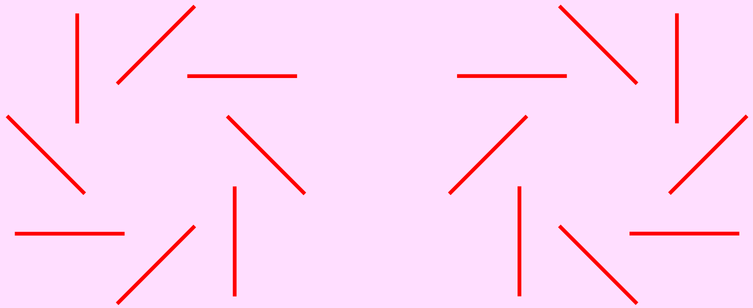


[Planck 2018]

E-mode and B-mode polarization



E-mode (Parity even)



B-mode (Parity odd)

➡ B-mode is more important to study inflationary GWs

After the discovery of B-mode …

We can study the spectrum of inflationary GW

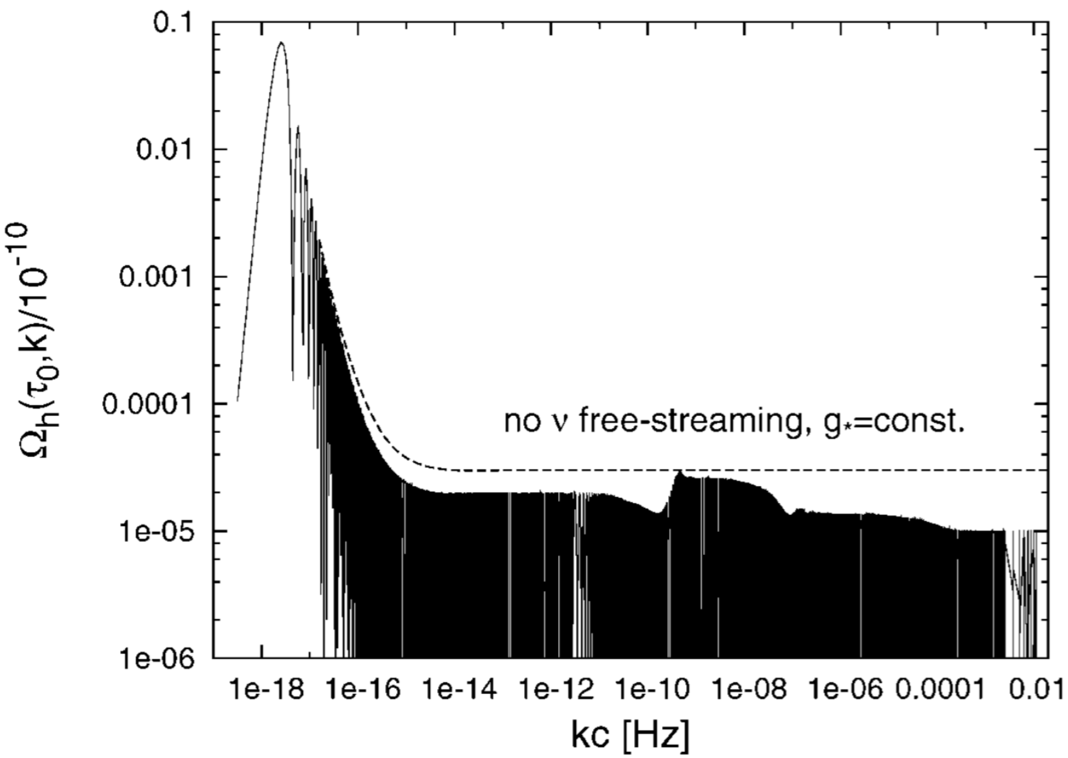
$$\ddot{\tilde{h}}_\alpha(\vec{k}) + 3H\dot{\tilde{h}}_\alpha(\vec{k}) + \left(\frac{k}{a}\right)^2 \tilde{h}_\alpha(\vec{k}) \simeq 0$$

GW spectrum (for modes entering the horizon in RD)

$$\frac{d\rho_{\mathrm{GW}}}{d\ln k} \sim \rho_{\mathrm{rad}} \times \frac{1}{3M_{\mathrm{Pl}}^2}\left(\frac{H_{\mathrm{inf}}}{2\pi}\right)^2$$

Spectrum of inflationary GW

Almost flat spectrum at high frequency (assuming RD)

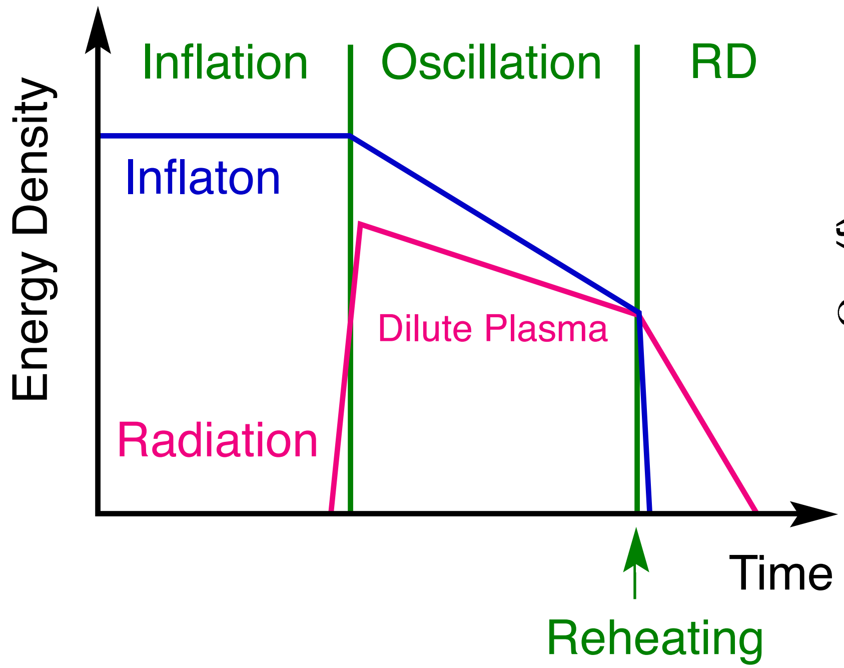


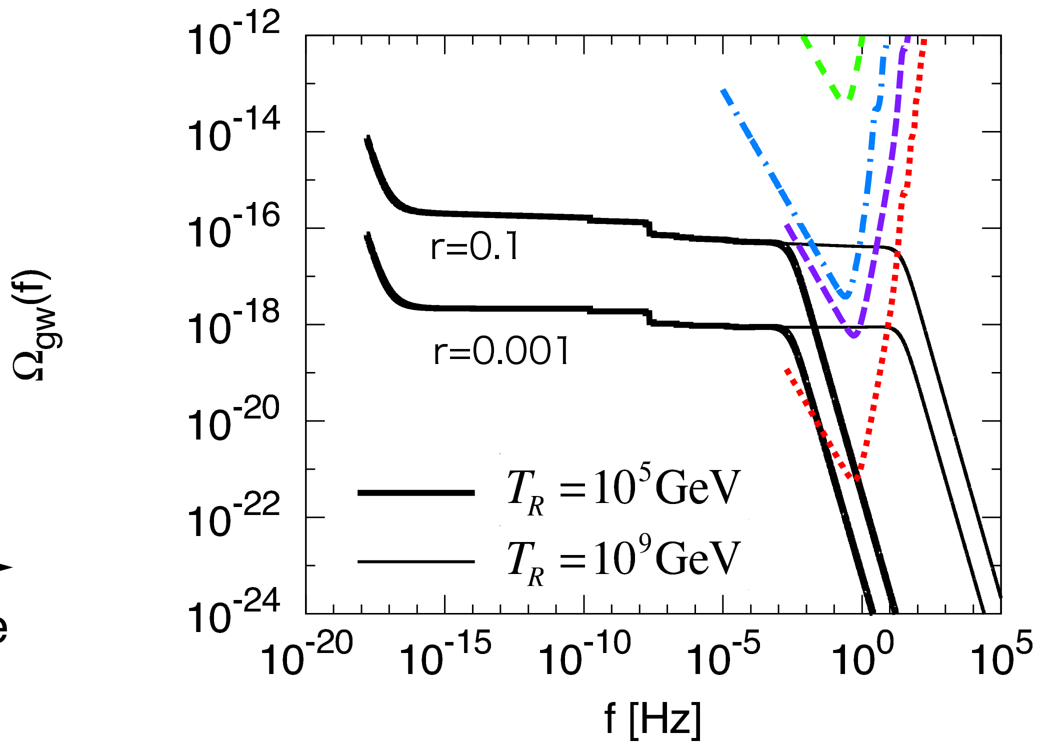
$$\Omega_{\rm GW} = \frac{1}{\rho_{\rm crit}} \frac{d\rho_{\rm GW}}{d\ln k}$$

[Watanabe & Komatsu ('06)]

Spectrum of inflationary GW depends on thermal history

Sharp drop-off due to the reheating after inflation

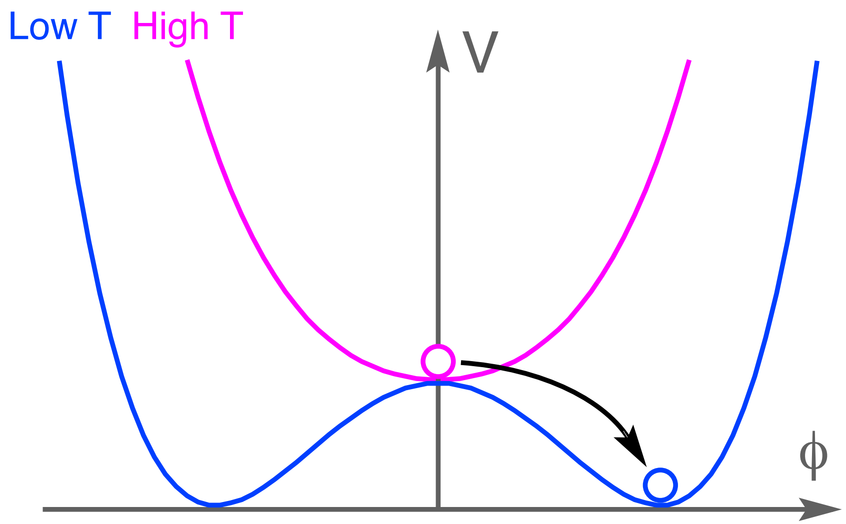


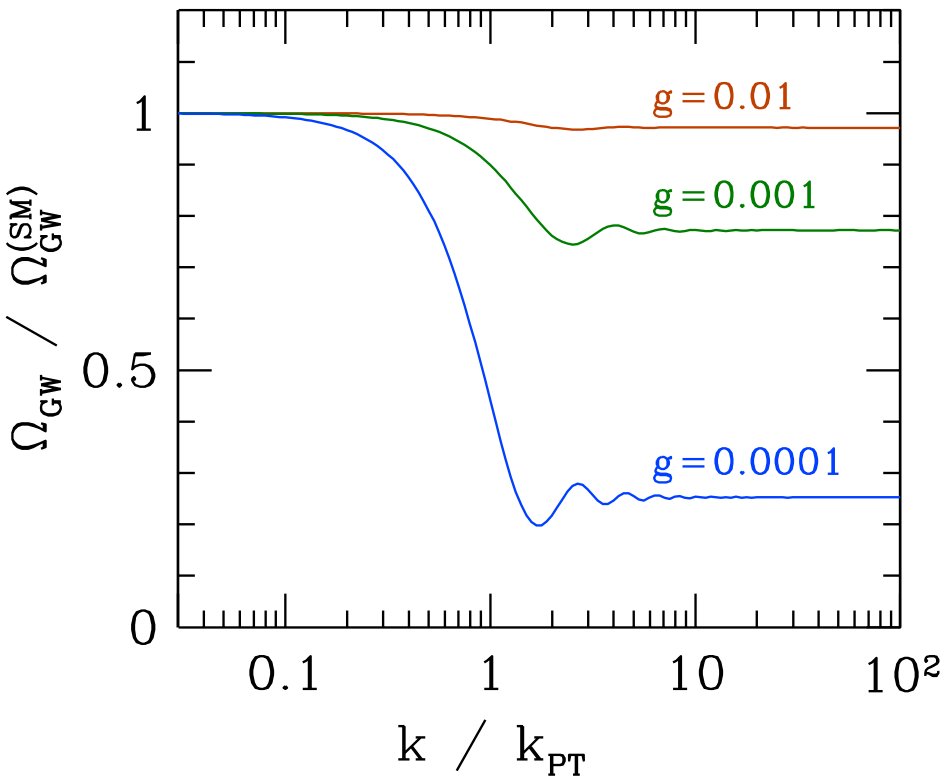


[Nakayama, Saito, Suwa, Yokoyama ('08)]

Even more: case with phase transition

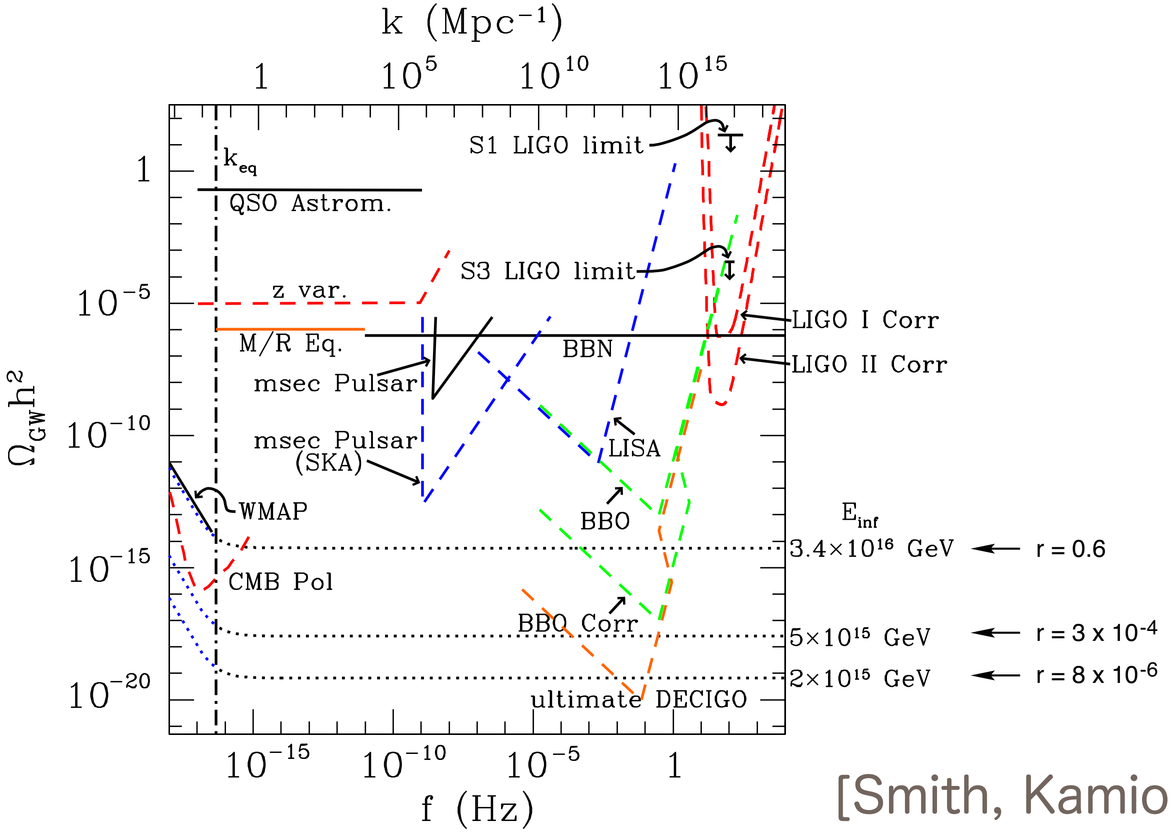
Phase transition gives distortion of the GW spectrum





[Jinno, TM, Nakayama ('12)]

Satellite-based GW detector



[Smith, Kamionkowski, Cooray ('06)]

➡ Discovery of the B-mode is the first step, because it fixes the normalization of the GW flux

Discovery of inflationary B-mode has great impact

With the discovery of the B-mode, we obtain

- Energy scale of inflation
- Flux of inflationary GW

Summary

Summary

There are many questions which should be answered

➡ We don’t know what kind of BSM physics exists

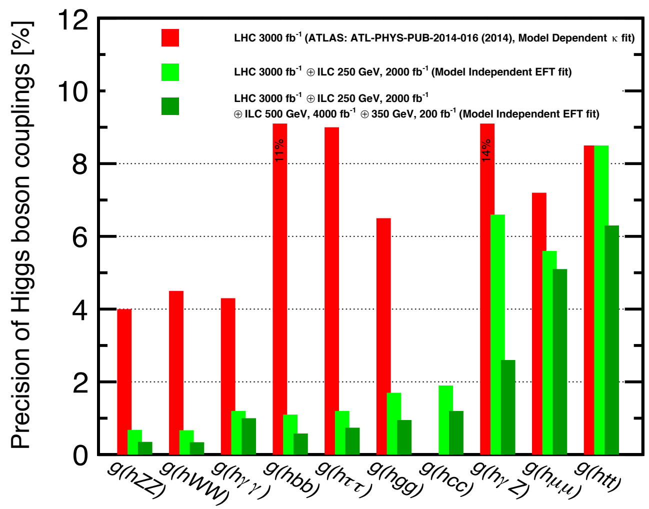
➡ Need new ideas and experimental inputs

Experiments are becoming more and more expensive

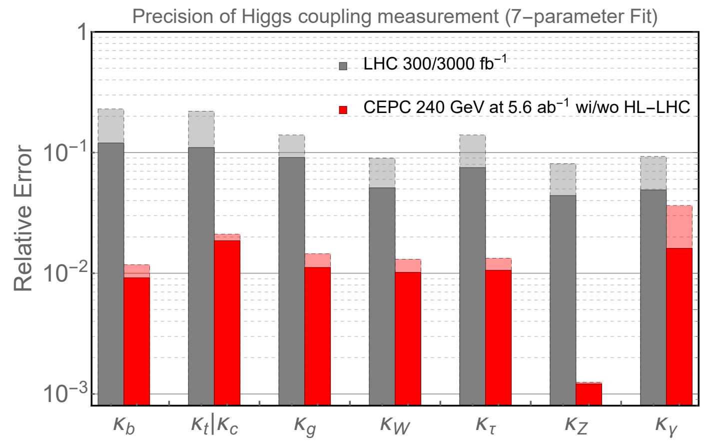
➡ International collaboration is important

Backups

Higgs coupling measurements with e^+e^- colliders



[Fujii et al., 1710.07621]



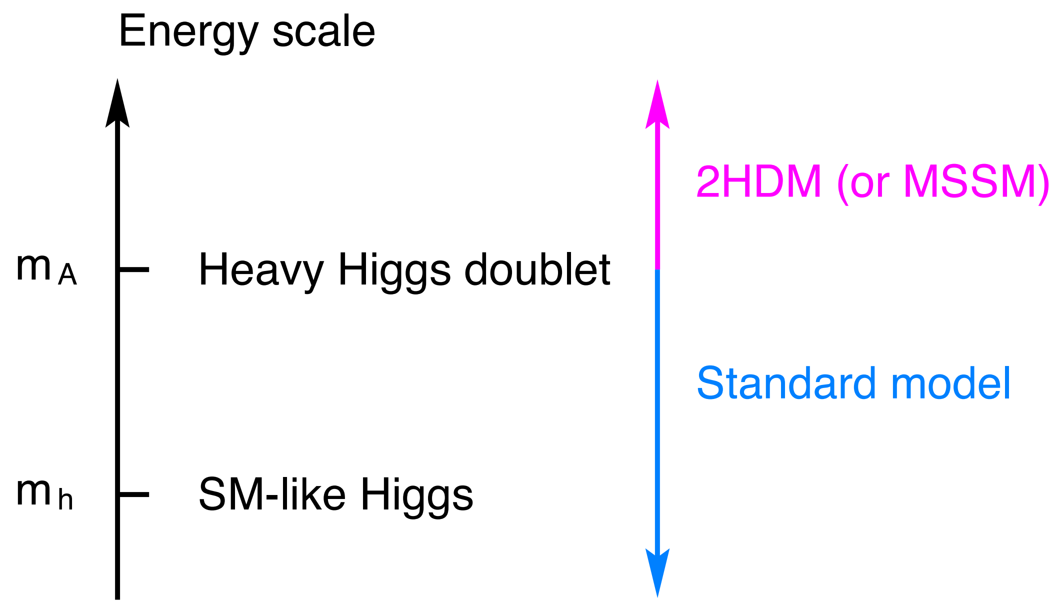
[Ann et al., 1810.09037]

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$LEP3_{240}$	$CEPC_{250}$	$FCC\text{-}ee_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	**0.61**	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	**1.01**	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	**0.74**	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	**9.0**	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	**3.9**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–	3.1
BR_{EXO} (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 1.2	< 1.0	< 1.0

[CERN-ACC-2018-0057]

Two Higgs doublet model (2HDM)

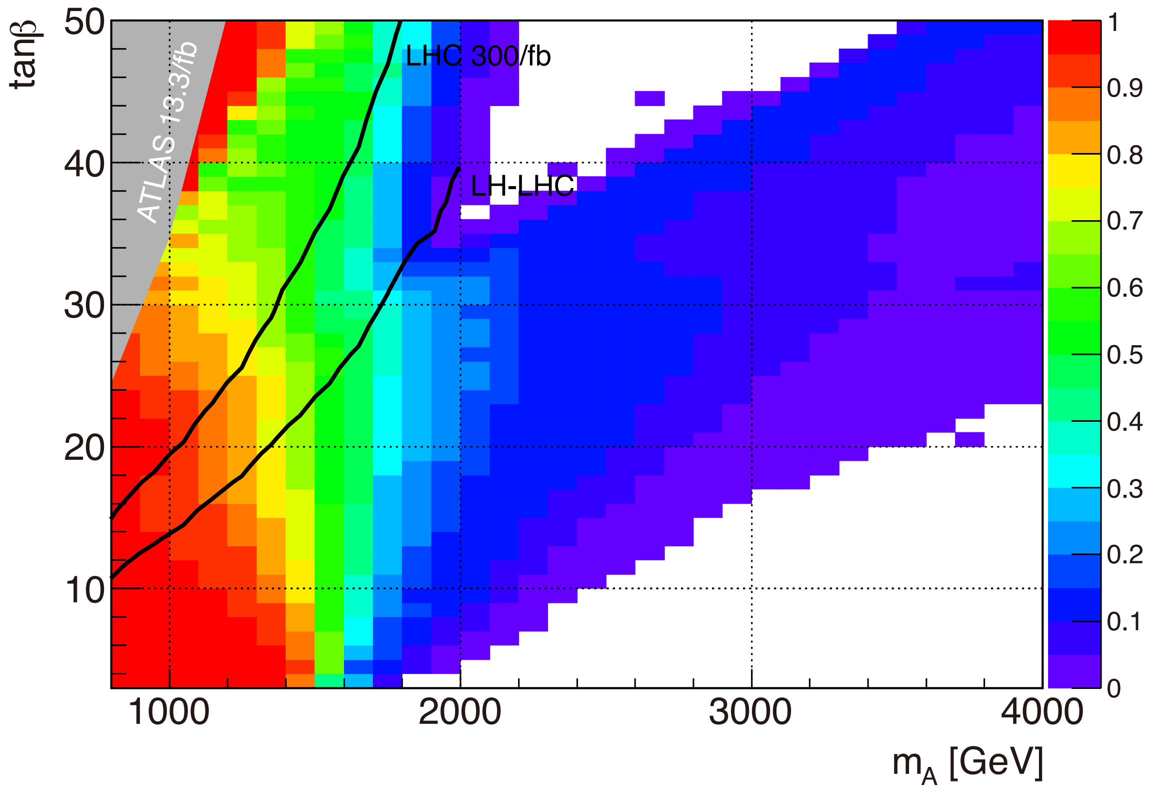
Physical degrees of freedom: h, $\Phi = (H^0, A, H^\pm)$



- Direct searches of heavy Higgses may be challenging
- Detailed study of the Higgs may give us hints

e^+e^- colliders may find a deviation from SM prediction

Fraction of points on which ILC observes a deviation



Assumption for ILC:

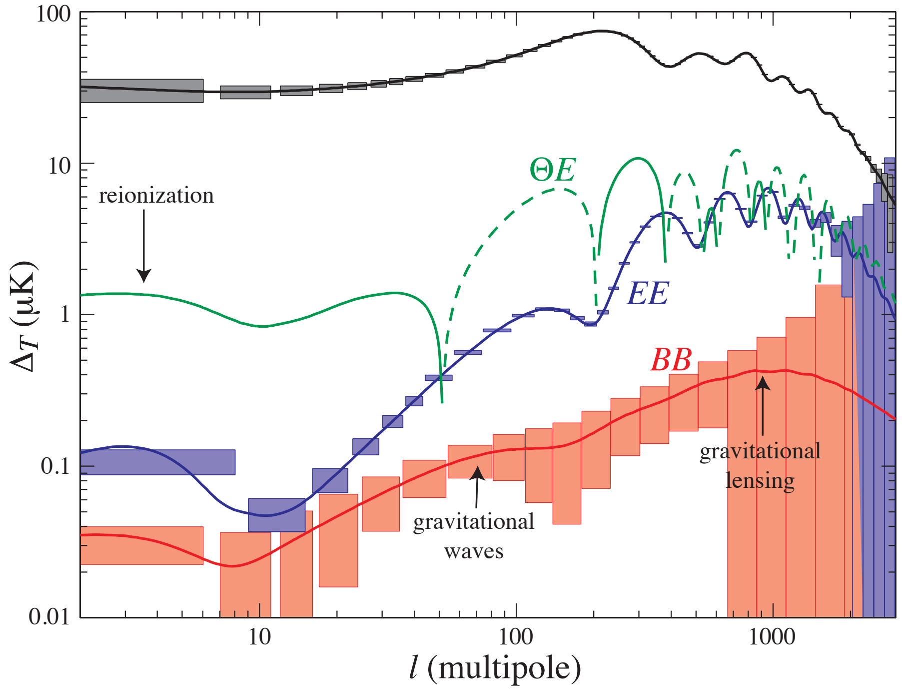
δBR(b b / WW) = 1.3%

δBR(τ τ / WW) = 1.9%

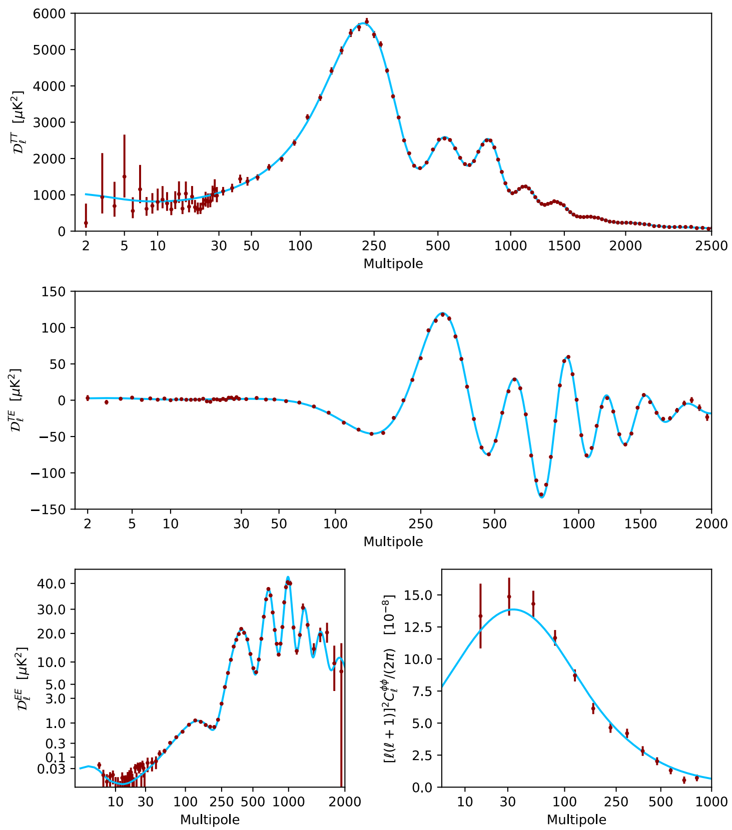
[Courtesy of M. Endo, based on 1502.03959]

➡ Region with m_A < 1.5 ~ 2 TeV can be well covered

E-mode signal



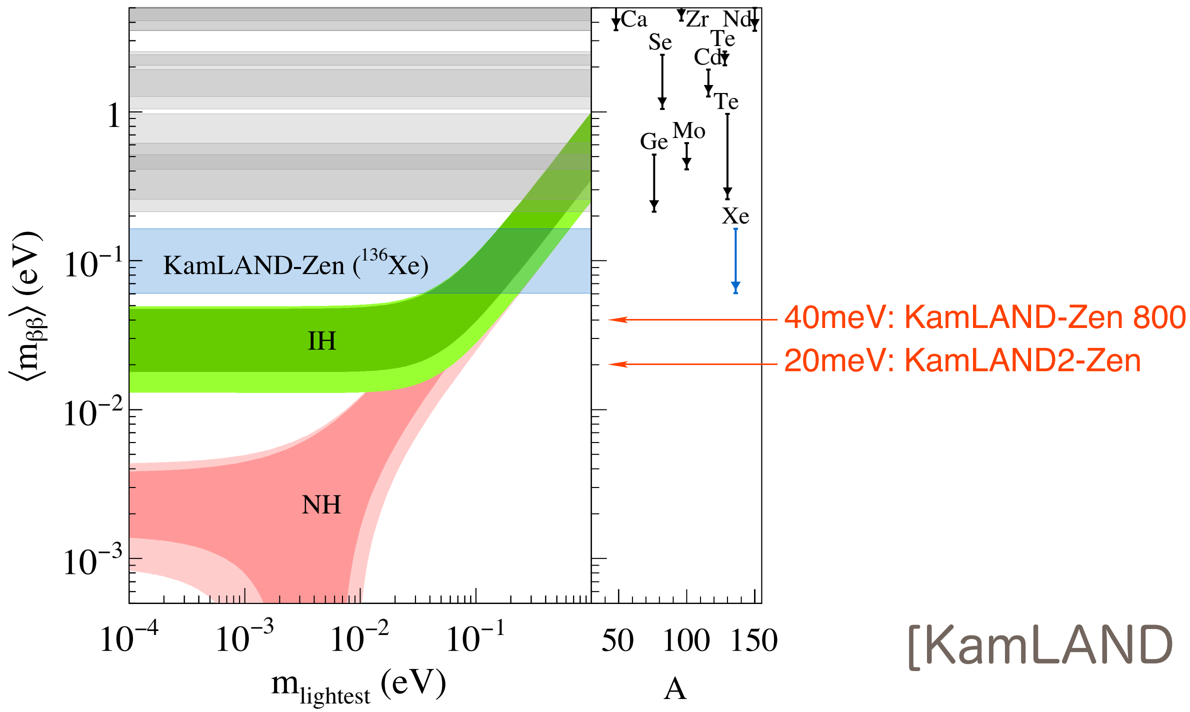
[Hu, Dodelson ('02)]



[Planck 2018]

Other interesting issues

Neutrino mass: Majorana or Dirac?

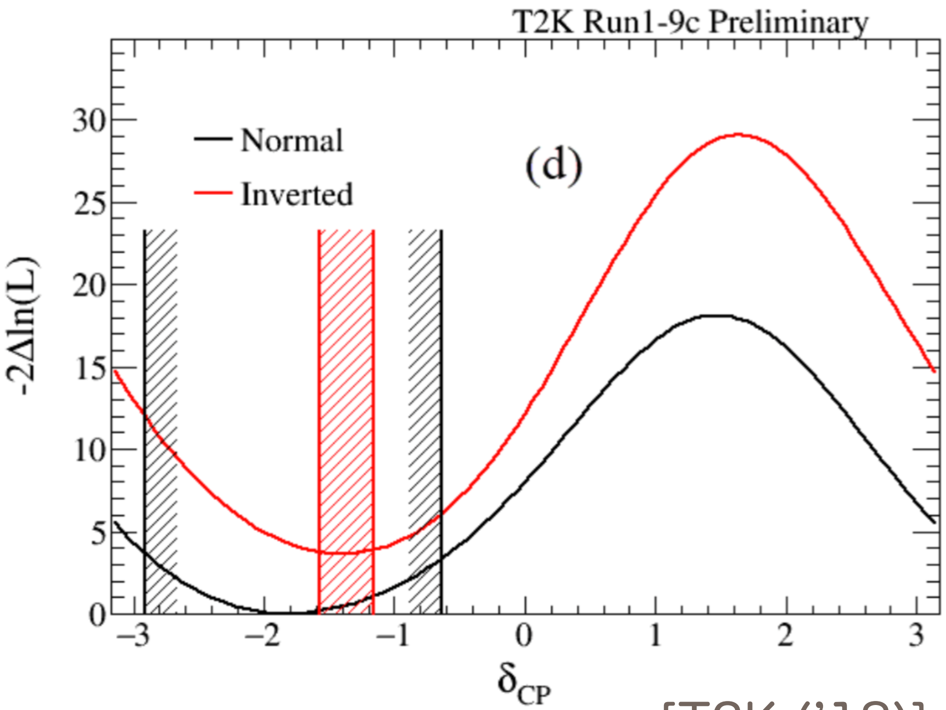


[KamLAND ('16)]

➡ Understandings of the origin of neutrino mass

➡ Important check point of leptogenesis

Neutrino: CP Violation

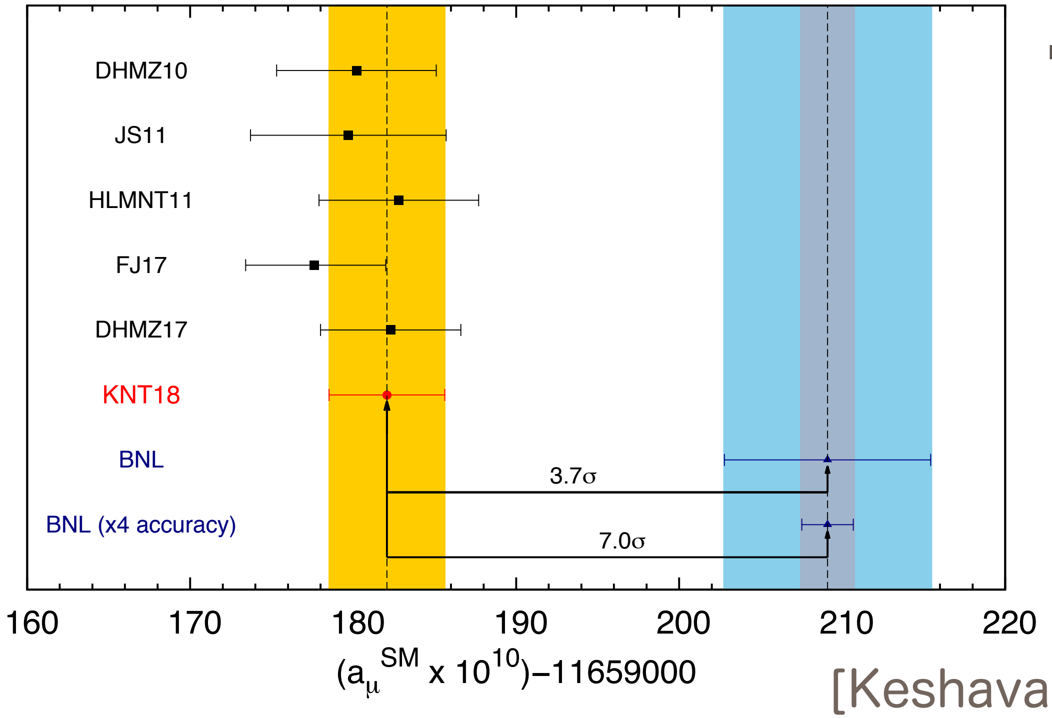


[T2K ('18)]

- $\sin\delta_{CP} = 0$ is disfavored
- Normal order is preferred (posterior odds of 7.9)

➡ Hyper-Kamiokande and DUNE will come

Muon g-2

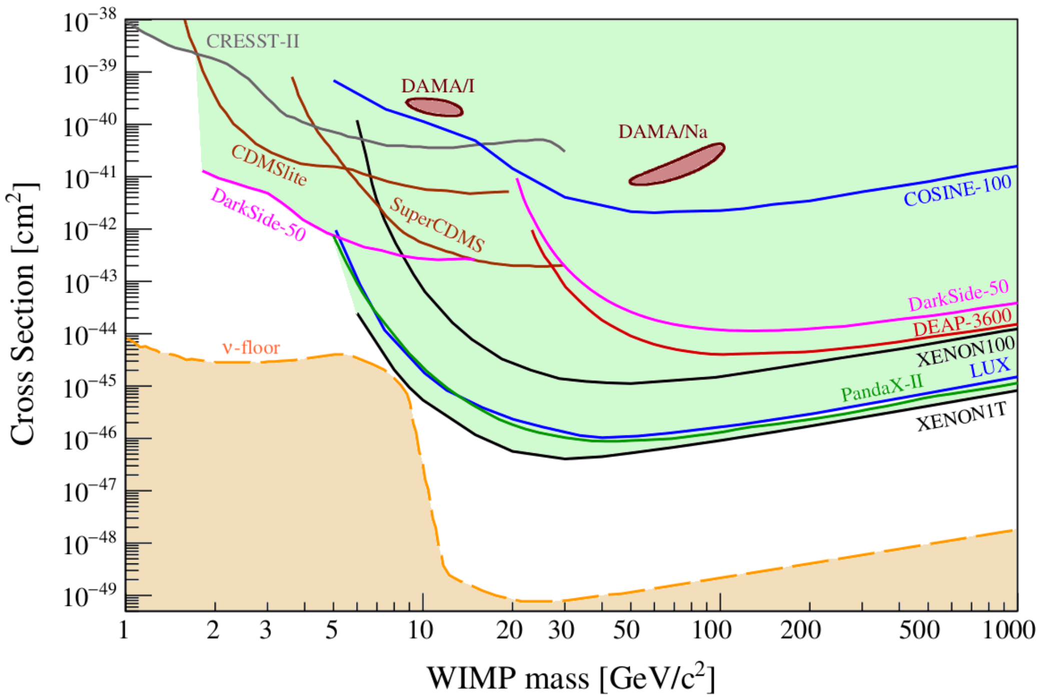


➡ 3.7σ deviation

[Keshavarzi, Nomura, Teubner ('18)]

➡ Results of FermiLab and J-PARC-KEK experiments will (hopefully) come out soon

DM direct detection

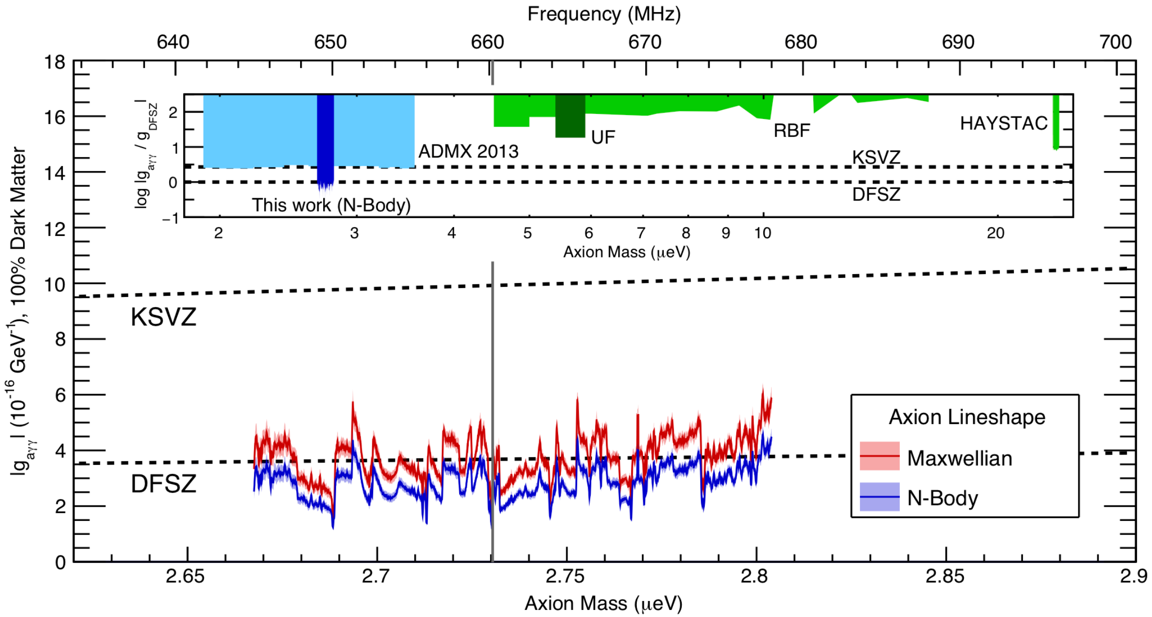


[Schumann 1903.03026]

➡ Stringent constraints on WIMP DM models

➡ Need new ideas to go beyond the neutrino floor

Axion



$$m_a \simeq 6\,\mu\text{eV} \times \left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$

[ADMX Collaboration ('18)]

➡ Touching the parameter region of QCD axion