# Gravitational wave searches of the type-II seesaw model

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In collaboration with
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Based on 2203.01561, to appear in JHEP

Disclaimer: Given the very specific topic chosen here, I apologize if your work is not mentioned.

# Introduction

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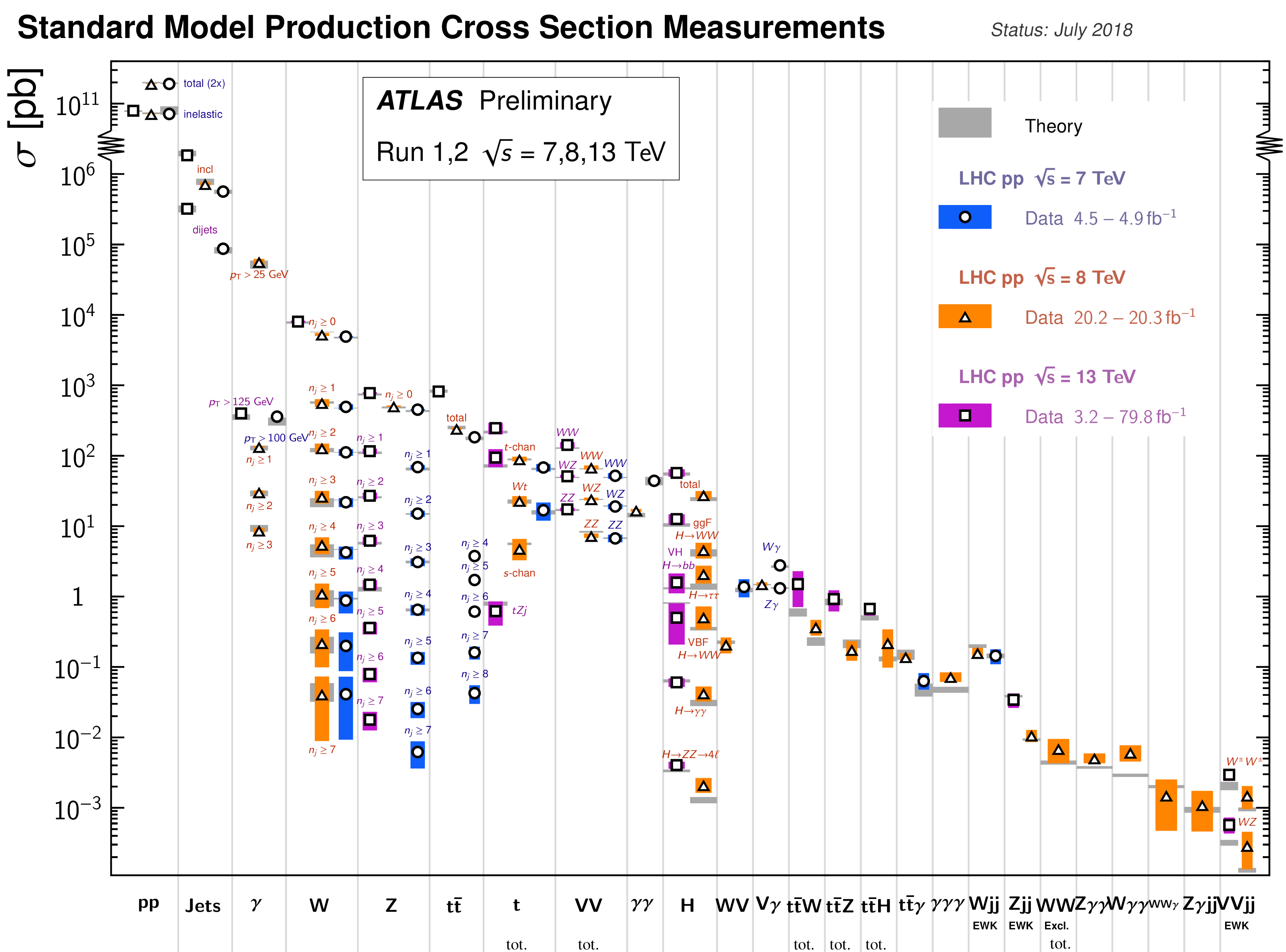

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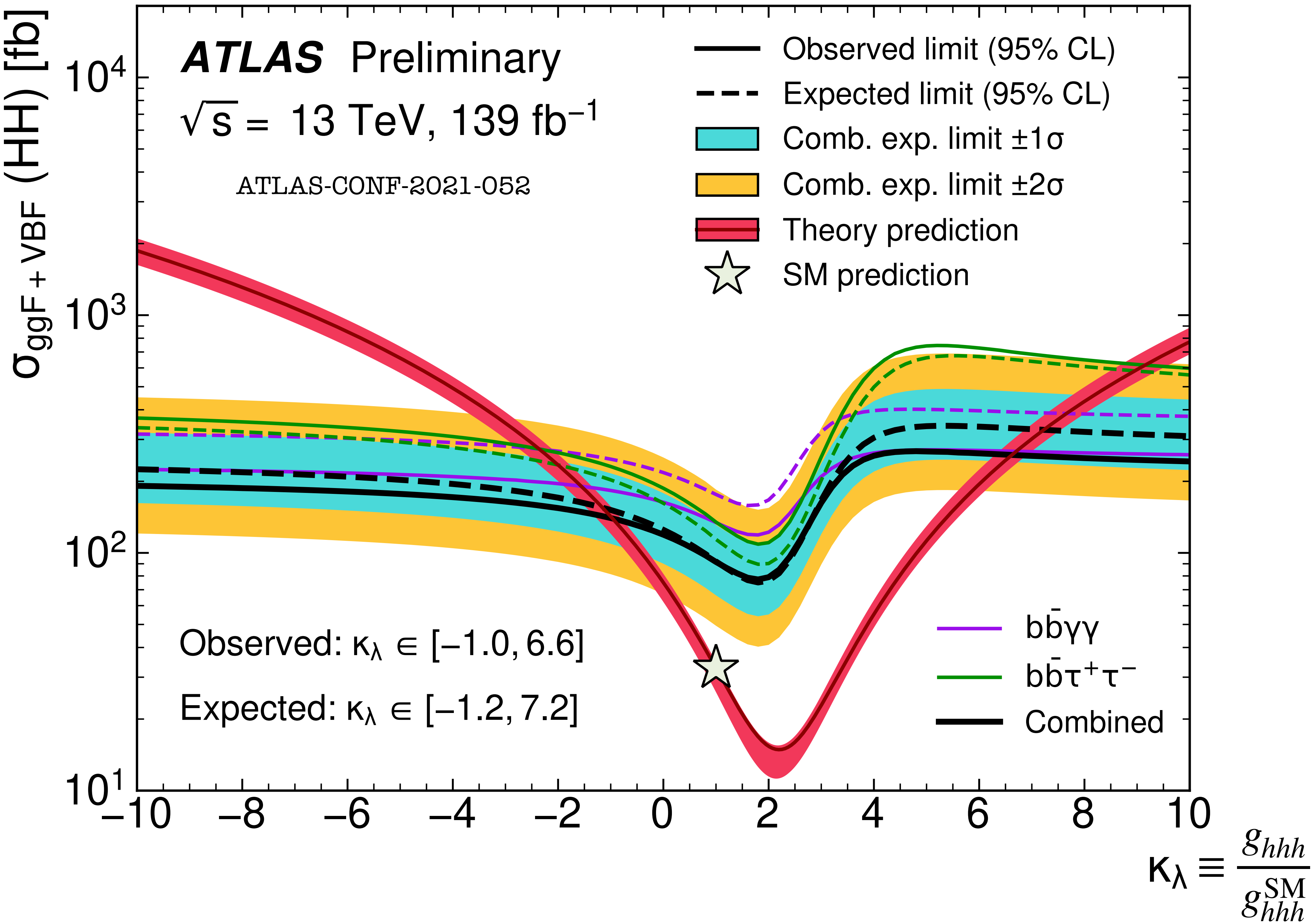
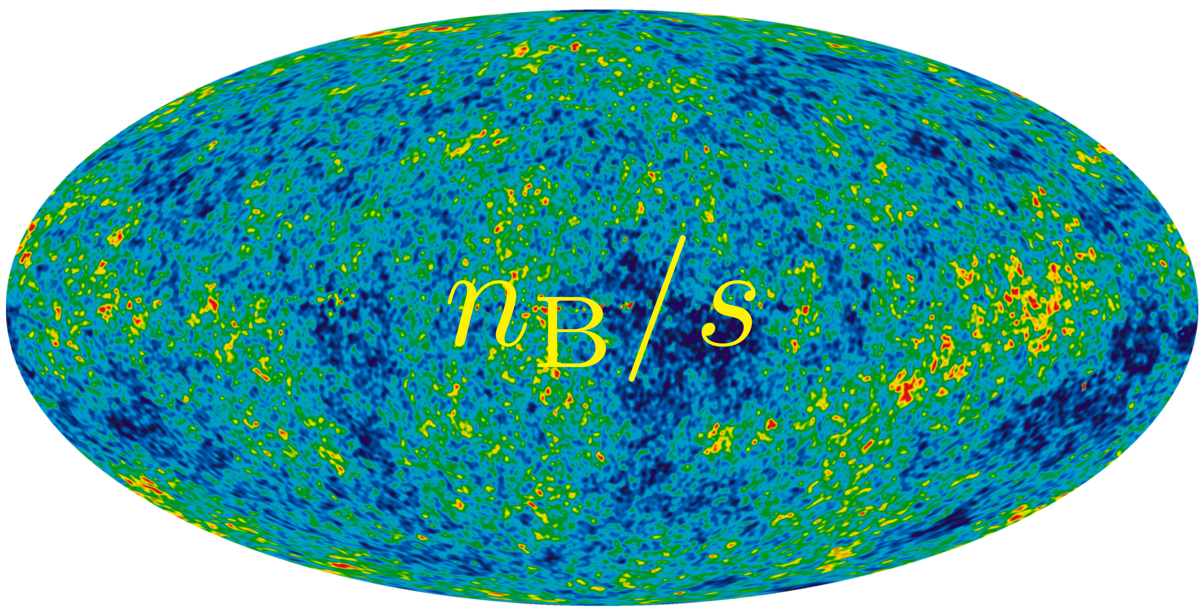
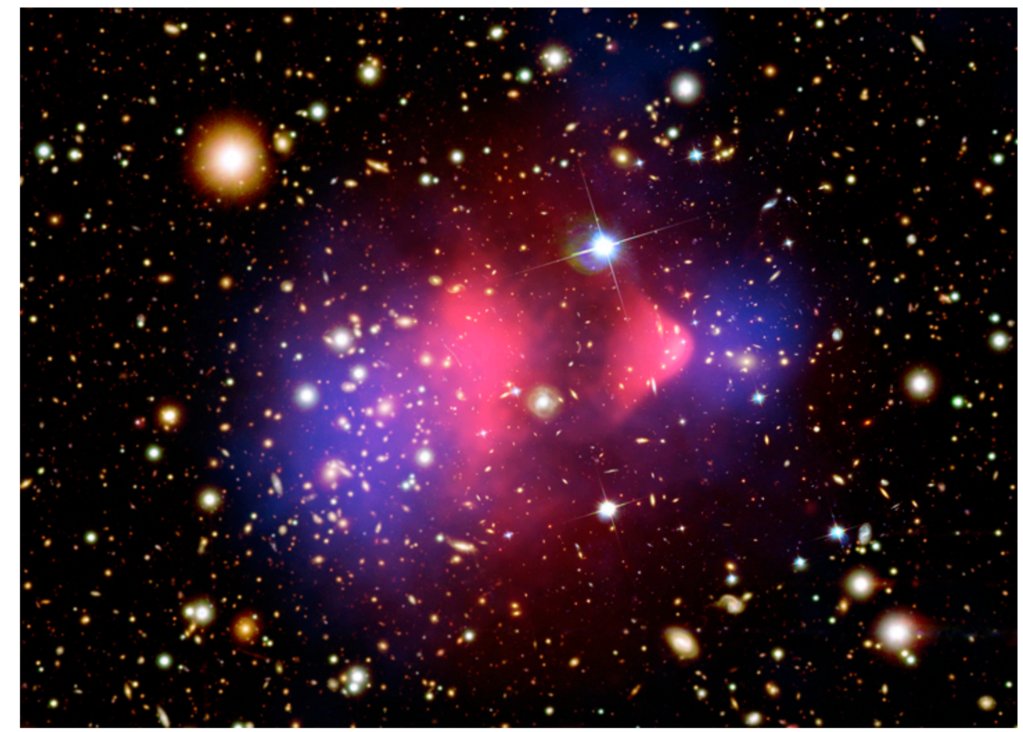
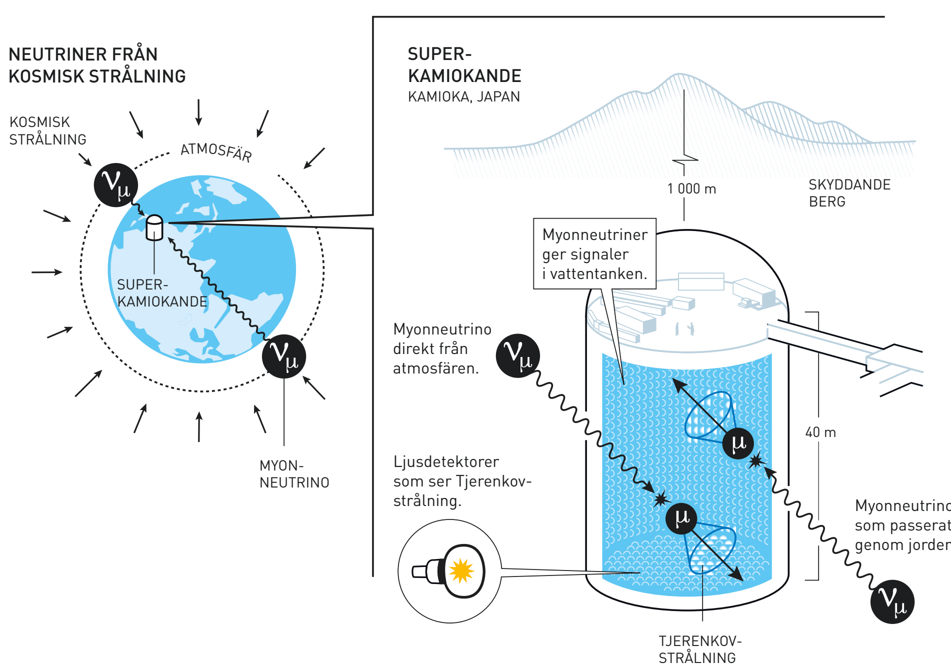


# Introduction

Even more problems: dark matter, matter-antimatter asymmetry, neutrino masses…



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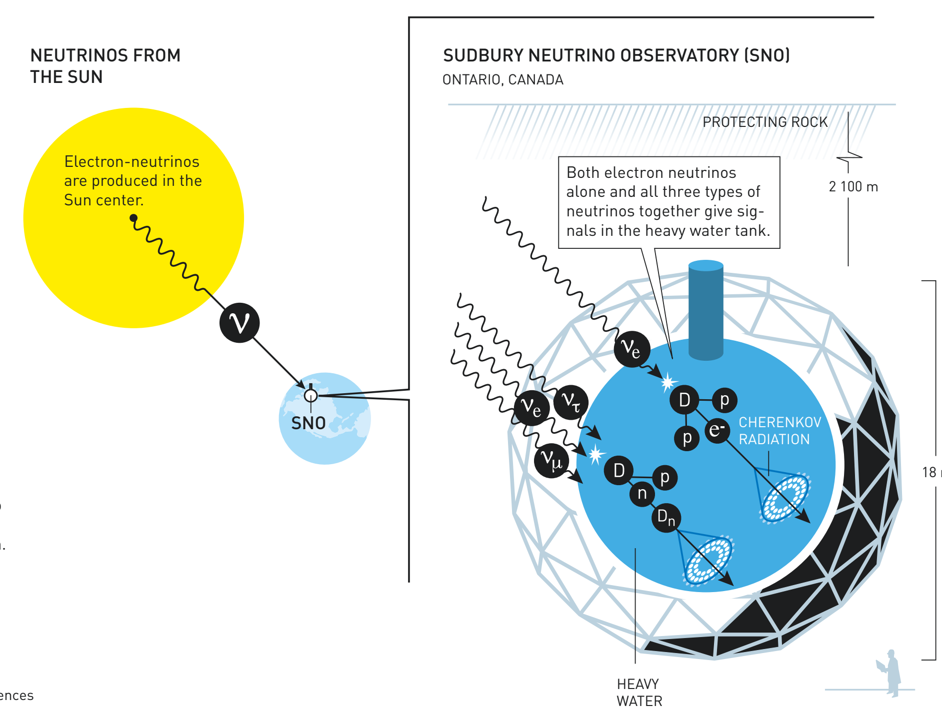


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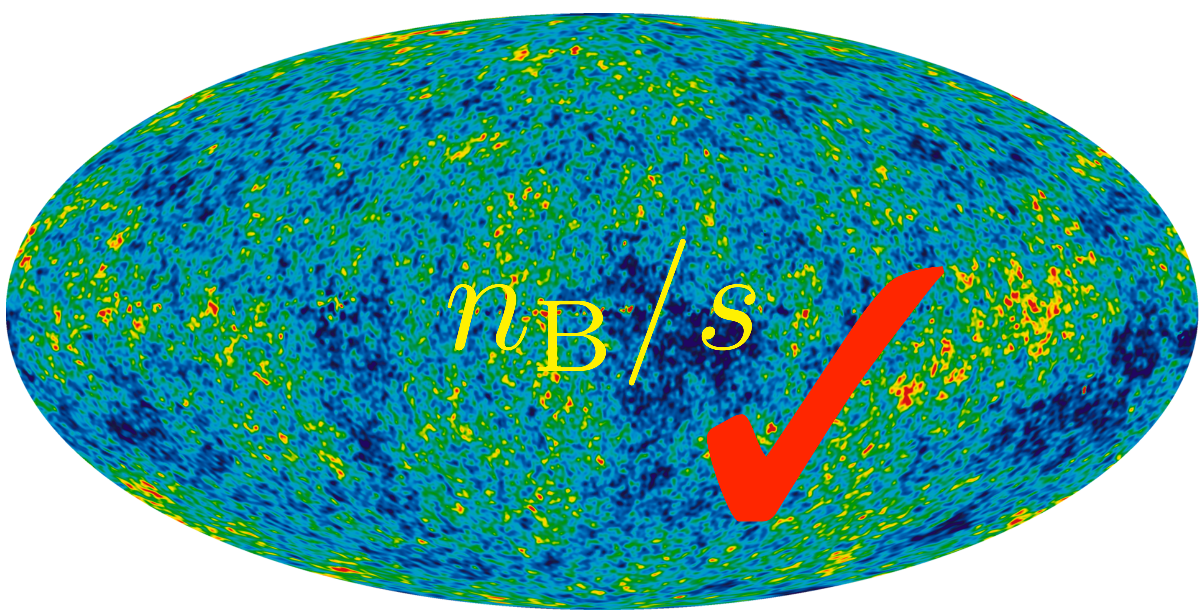


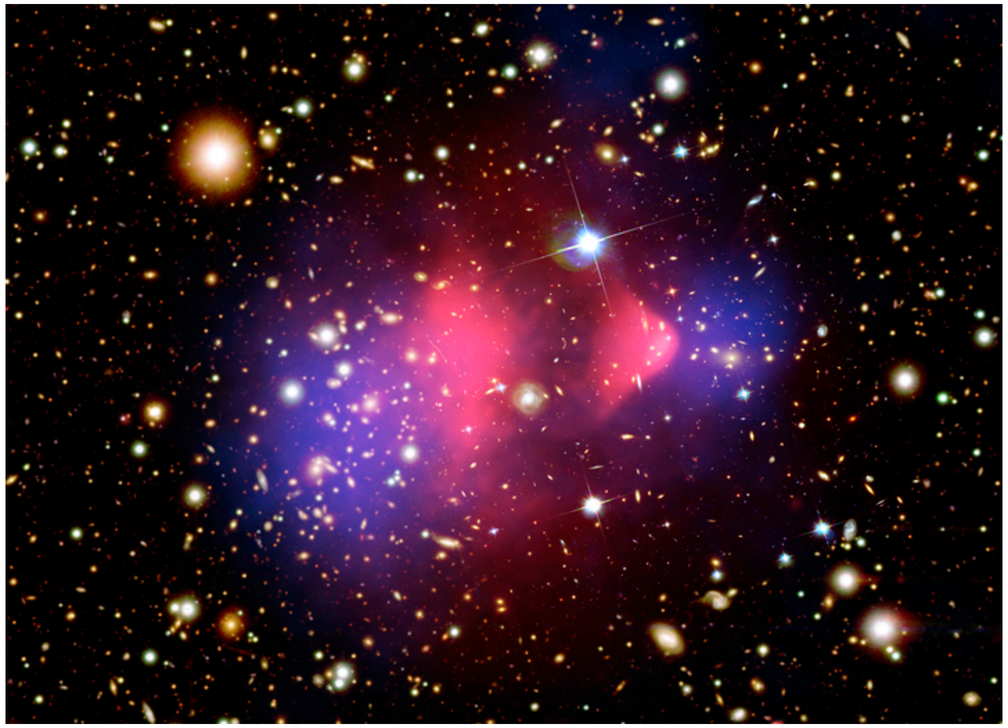

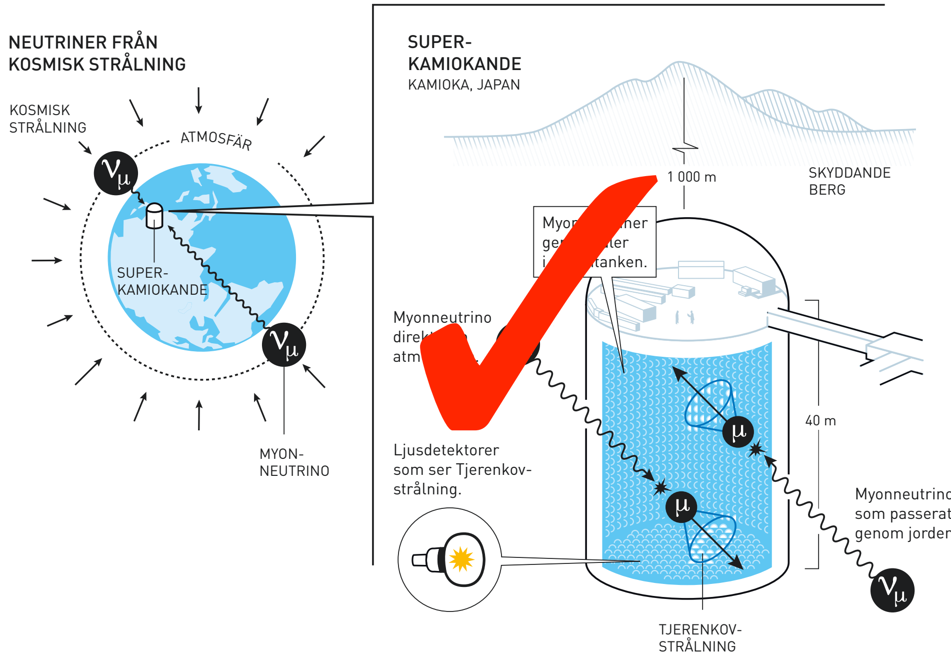


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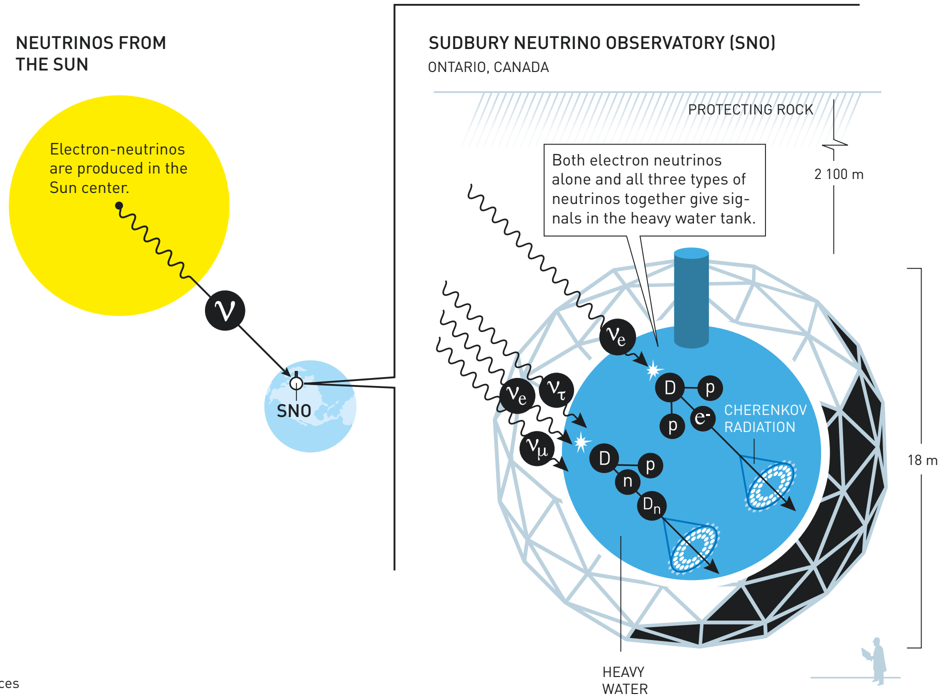


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# Outline

- Model setup
- Phase transition in the type-II seesaw model
- Gravitational wave searches
- Complementarity from collider searches
- Summary

# Model setup

# Model setup

The type-II seesaw model can be obtained by extending the SM Higgs sector with an SU(2) triplet

$$V(\Phi,\Delta) = -m^2\Phi^\dagger\Phi + M^2\,\mathrm{Tr}\left(\Delta^\dagger\Delta\right) + \left[\mu\Phi^T i\tau_2\Delta^\dagger\Phi + \textbf{ h.c. }\right] + \lambda_1\left(\Phi^\dagger\Phi\right)^2$$
$$+\lambda_2\left[\mathrm{Tr}\left(\Delta^\dagger\Delta\right)\right]^2 + \lambda_3\,\mathrm{Tr}\left[\Delta^\dagger\Delta\Delta^\dagger\Delta\right] + \lambda_4\left(\Phi^\dagger\Phi\right)\mathrm{Tr}\left(\Delta^\dagger\Delta\right) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$

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$$\Phi = \begin{pmatrix} \varphi^+ \\ \frac{1}{\sqrt{2}}(\varphi + v_\Phi + i\chi) \end{pmatrix} \qquad \Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & H^{++} \\ \frac{1}{\sqrt{2}}(\delta + v_\Delta + i\eta) & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$$

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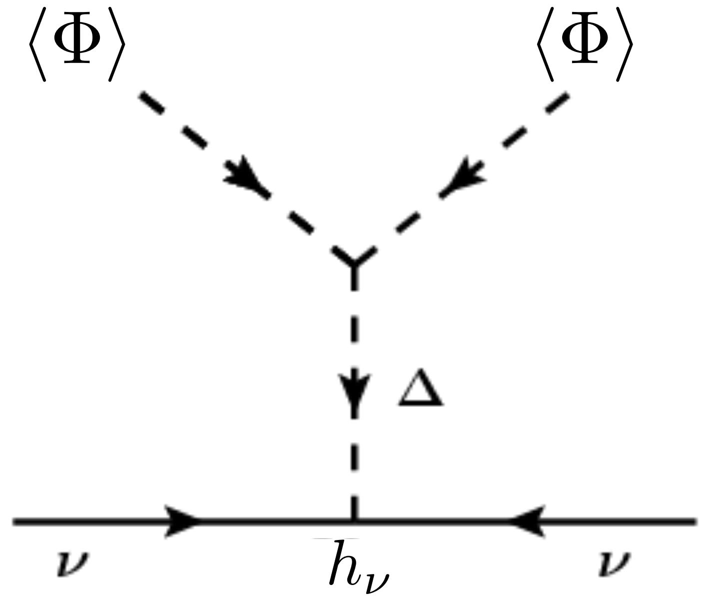
$$\mathcal{L}_Y = (h_\nu)_{ij}\overline{L^{ic}}i\tau_2\Delta L^j + \mathrm{h.c.}$$

$$\xrightarrow{\textbf{EWSB}} (m_\nu)_{ij} = \sqrt{2}(h_\nu)_{ij}v_\Delta$$



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$v_\Delta$ cannot be arbitrarily large though: Very strong constraints from the $\rho$ parameter as a result of gauge mixing

$$\rho \equiv \frac{m_W^2}{m_Z^2\cos^2\theta_W} = \frac{1+\frac{2v_\Delta^2}{v_\Phi^2}}{1+\frac{4v_\Delta^2}{v_\Phi^2}}$$

$$0 \leq v_\Delta \lesssim 3.0\ \ \mathrm{GeV}$$

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$$v = \sqrt{v_\Delta^2 + v_\Phi^2} = 246\,\mathrm{GeV}$$

$$v_\Delta \ll v_\Phi \simeq v$$

$$0 \leq v_\Delta \lesssim 3.0\ \ \mathrm{GeV}$$

(Global minimum of the triplet potential)

# Model setup

$$m_h^2 \simeq 2v_\Phi^2\lambda_1 \simeq 2v^2\lambda_1, \quad m_H \simeq m_\Delta \simeq m_A, \quad m_{H^\pm}^2 \simeq m_\Delta^2 - \frac{\lambda_5}{4}v_\Phi^2, \quad m_{H^{\pm\pm}}^2 \simeq m_\Delta^2 - \frac{\lambda_5}{2}v_\Phi^2$$

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**Fixed by SM Higgs mass**

$$\lambda_1 \simeq 0.129$$

# Model setup

$$\Delta m = |m_{H^{\pm\pm}} - m_{H^\pm}| \approx |m_{H^\pm} - m_{H,A}| \approx \frac{|\lambda_5| v_\Phi^2}{8 m_\Delta} \approx \frac{|\lambda_5| v^2}{8 m_\Delta}$$

**Determined by mass splitting**

$$m_h^2 \simeq 2 v_\Phi^2 \lambda_1 \simeq 2 v^2 \lambda_1, \quad m_H \simeq m_\Delta \simeq m_A, \quad m_{H^\pm}^2 \simeq m_\Delta^2 - \frac{\lambda_5}{4} v_\Phi^2, \quad m_{H^{\pm\pm}}^2 \simeq m_\Delta^2 - \frac{\lambda_5}{2} v_\Phi^2$$

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**Fixed by SM Higgs mass**

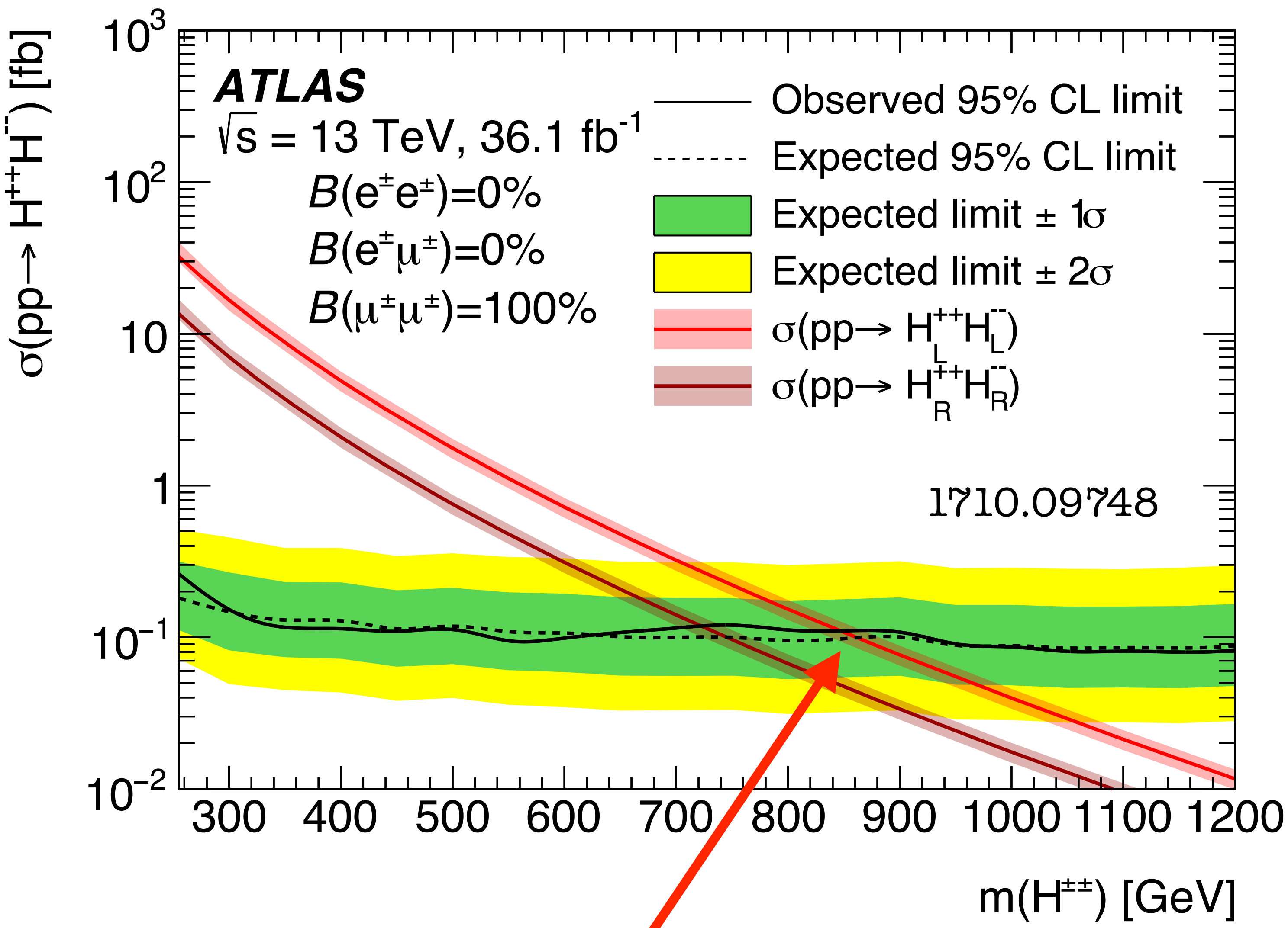
$$\lambda_1 \simeq 0.129$$

**Basically the mass scale of the triplet**

$$m_\Delta^2 \equiv \frac{v_\Phi^2 \mu}{\sqrt{2} v_\Delta}$$

# Model setup

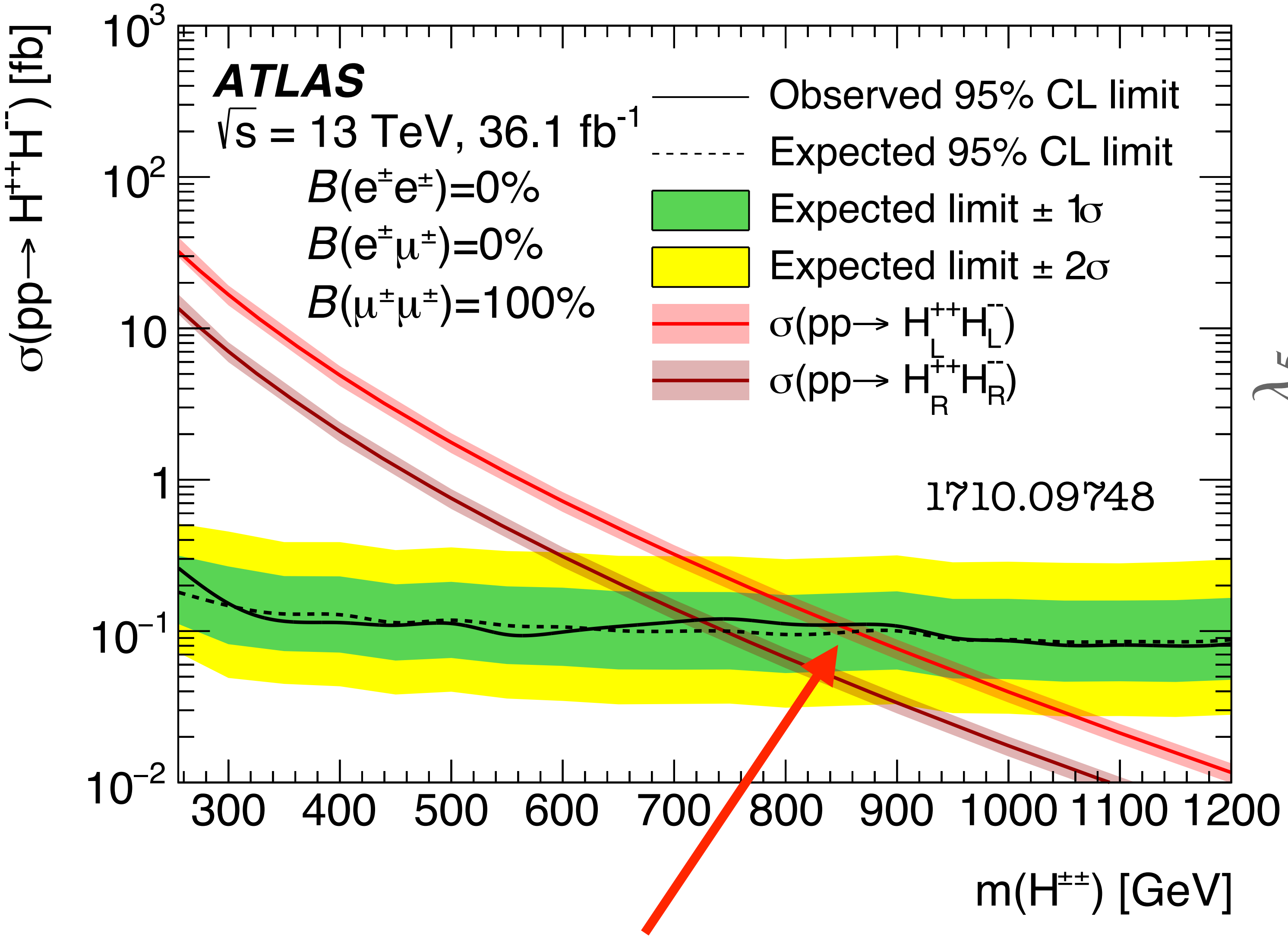
Current constraints on the triplet model




$m_\Delta \gtrsim 900\,\mathrm{GeV}$

# Model setup

Current constraints on the triplet model

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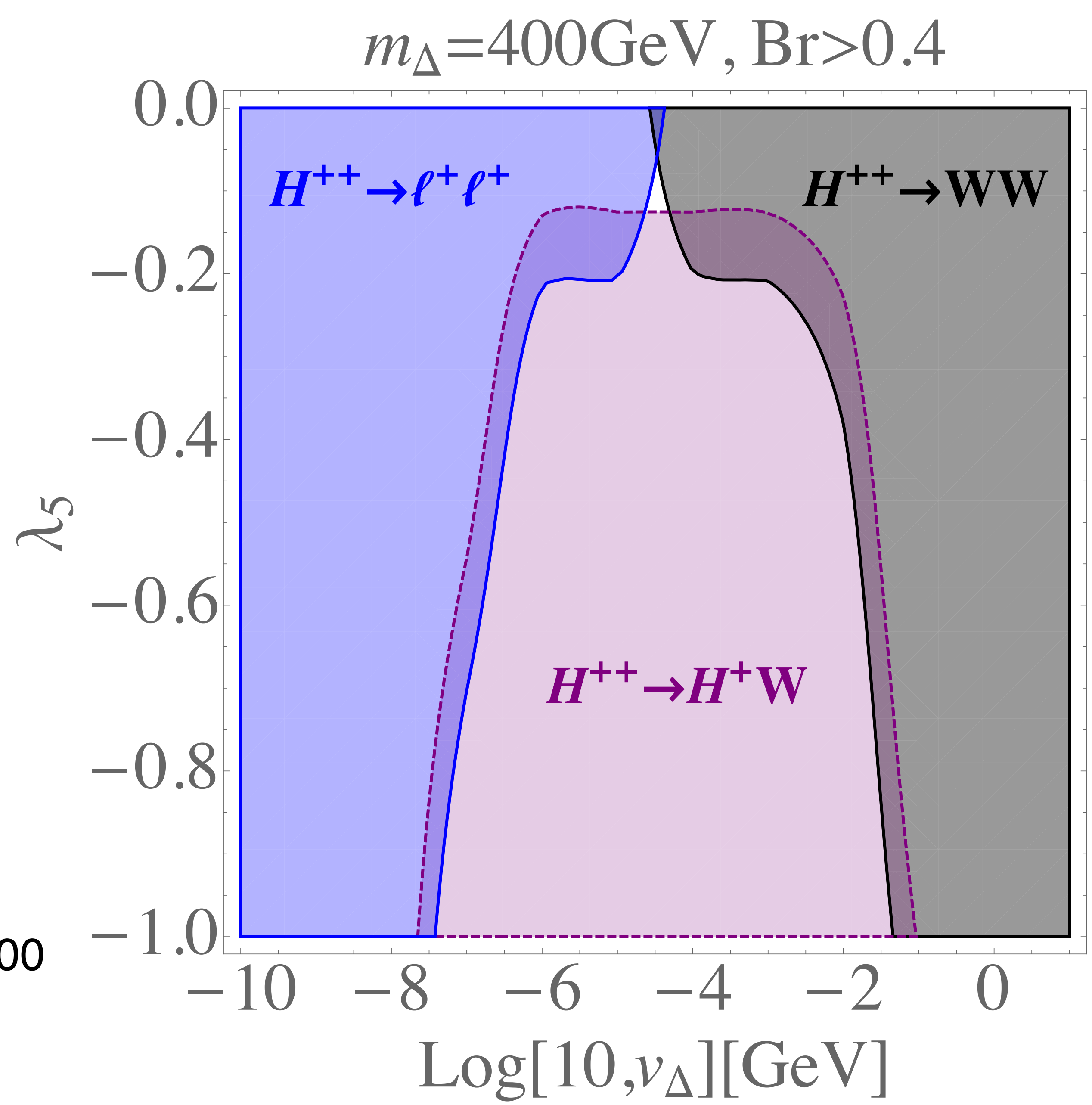
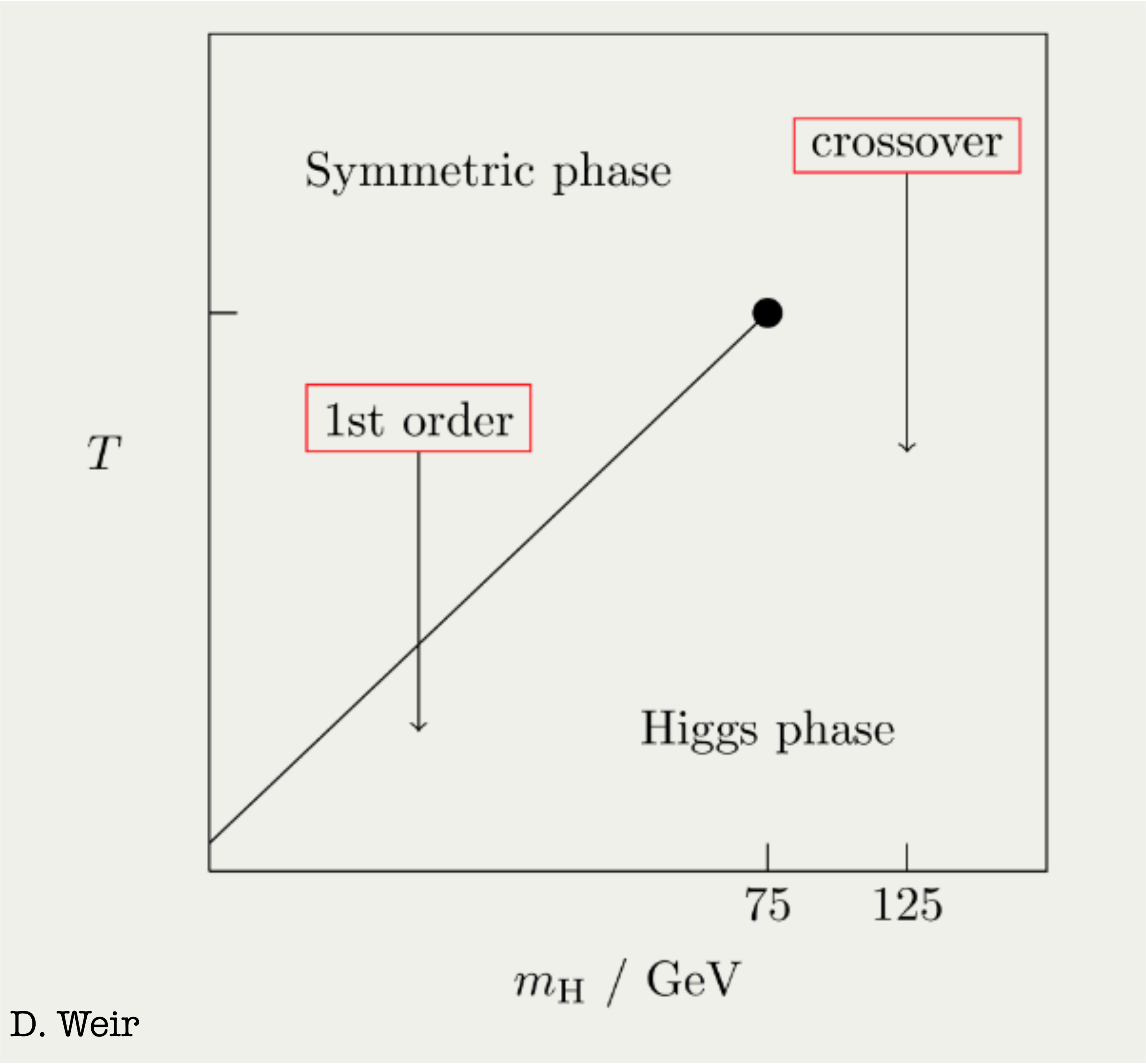
**YD** et al, JHEP 1901 (2019) 101



# Phase transition in the type-II seesaw model

# Phase transition: ***The effective potential***



# Phase transition: ***The effective potential***

$$V(\Phi, \Delta) \supset \lambda_4 \left(\Phi^\dagger \Phi\right) \mathrm{Tr}\left(\Delta^\dagger \Delta\right) + \lambda_5 \Phi^\dagger \Delta \Delta^\dagger \Phi$$

# Phase transition: *The effective potential*

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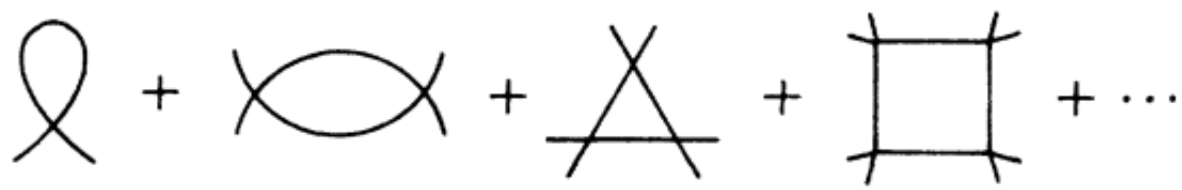
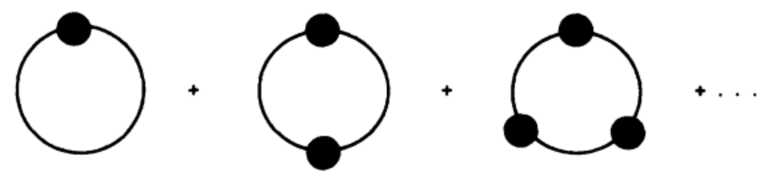


(CW potential)



(Thermal corrections)

Coleman, Weinberg, PRD 7 (1973) 1888
Dolan, Jackiw, PRD 9 (1974) 12, 3320
Carrington, PRD 8 (1992) 8, 2933

# Phase transition: ***The effective potential***

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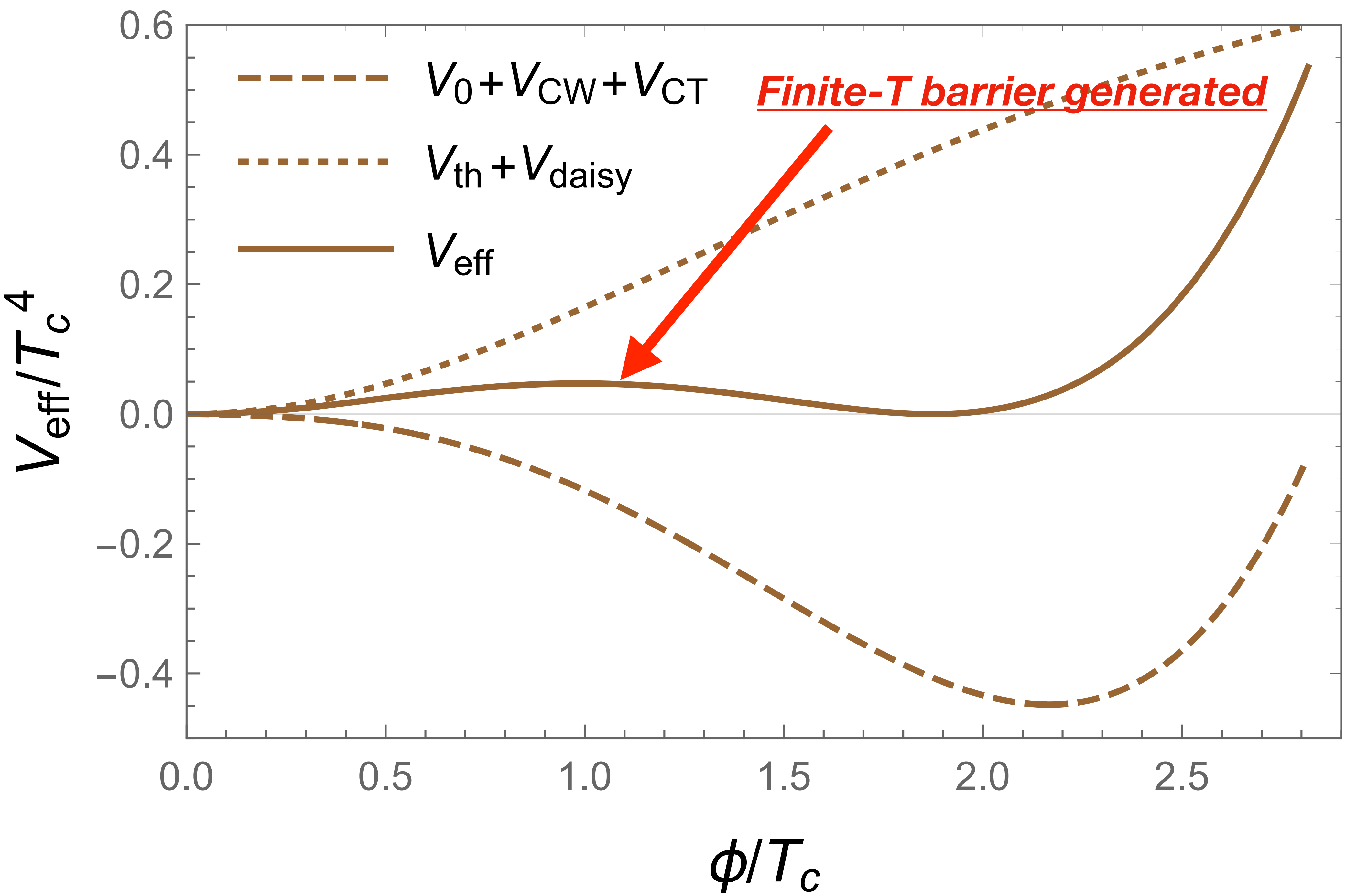



$\lambda_4 = 1.97$

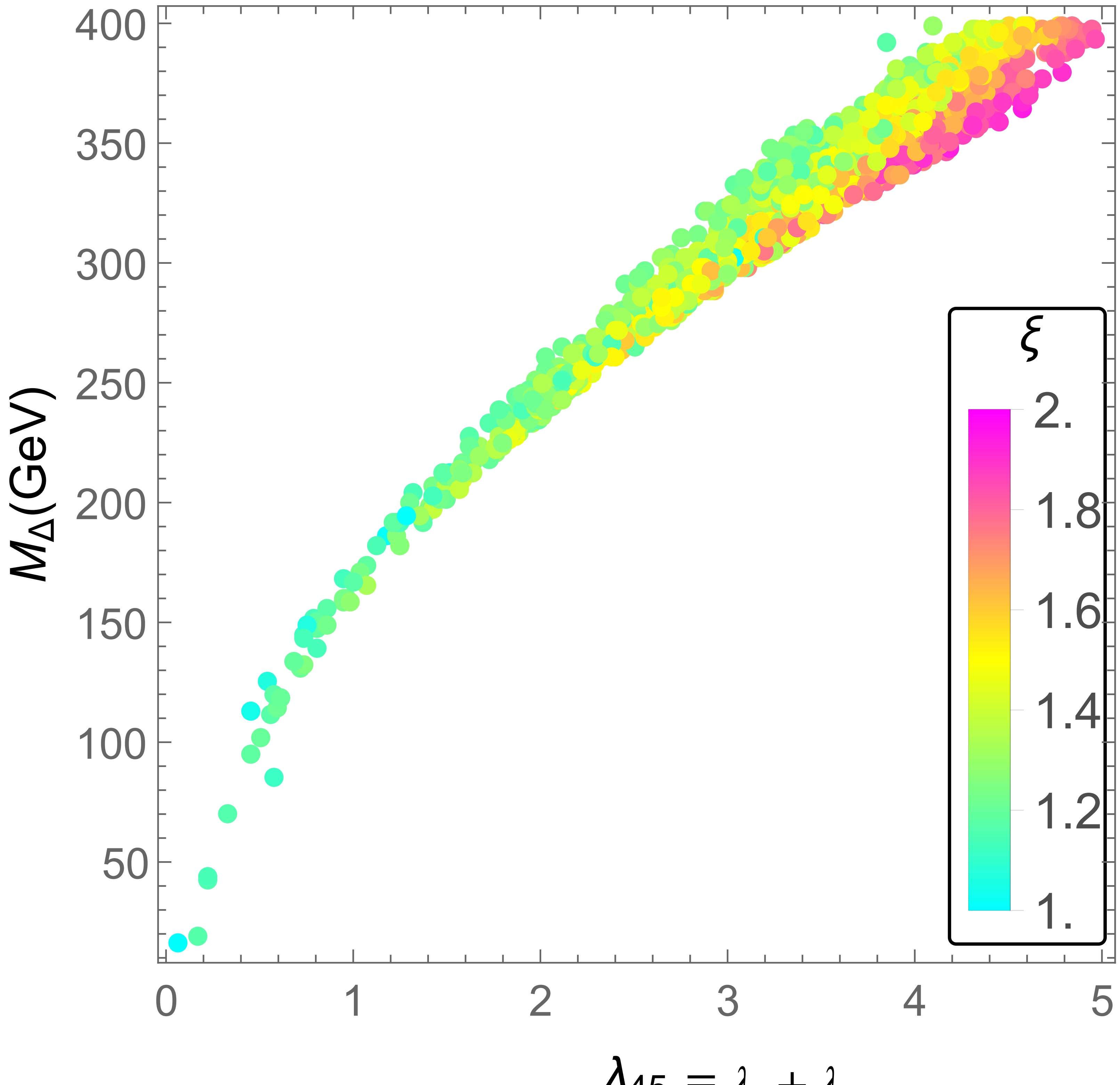
$\lambda_5 = 2.29$

$m_\Delta \simeq 354\,\mathrm{GeV}$

$v_\Delta \simeq 10^{-6}\,\mathrm{GeV}$

# Phase transition: ***The transition plots***

Viable param space for a strong first-order phase transition:




Case 1: $H^{\pm\pm} \to \ell^\pm \ell^\pm$

# Phase transition: ***The transition plots***

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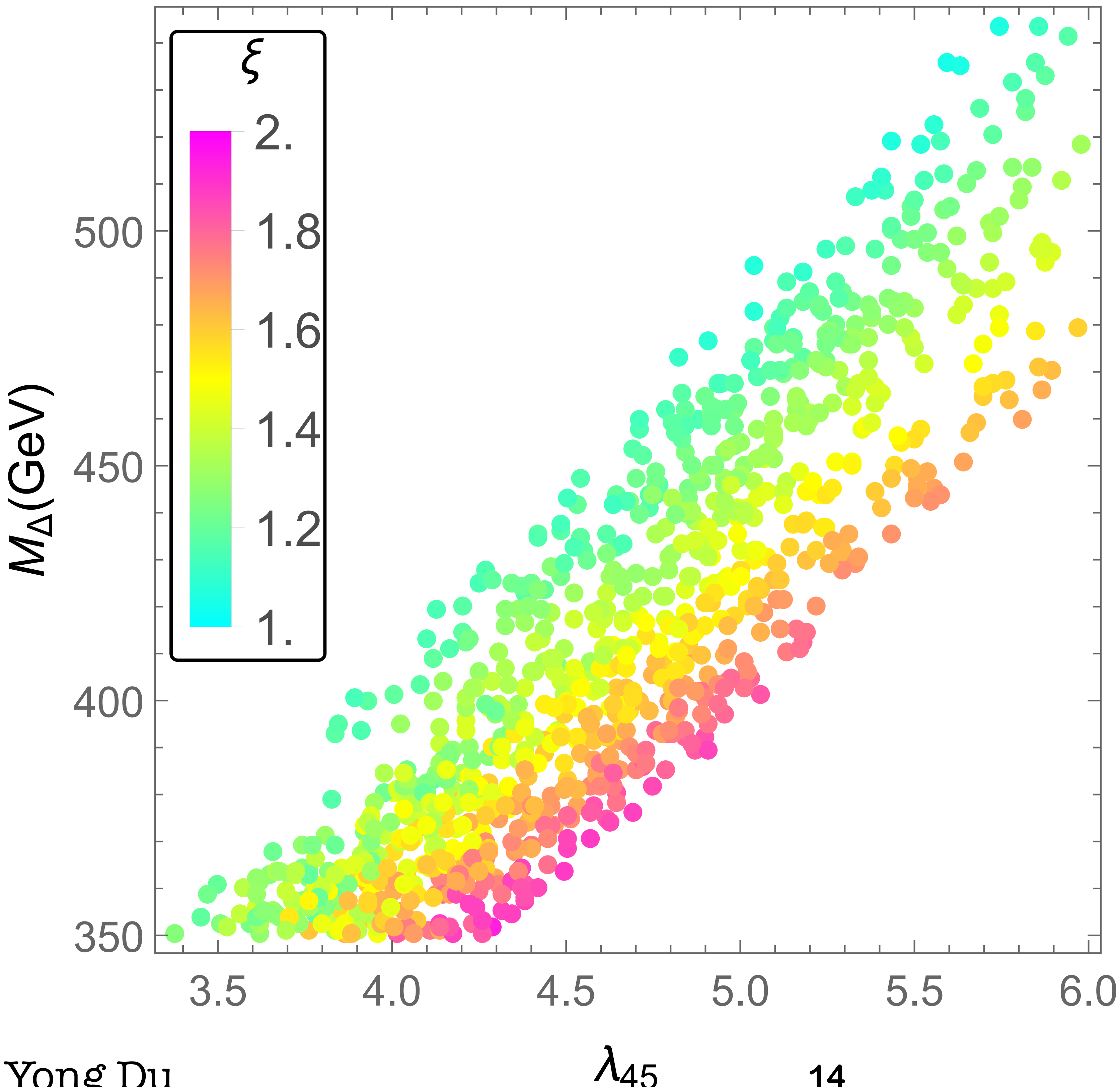
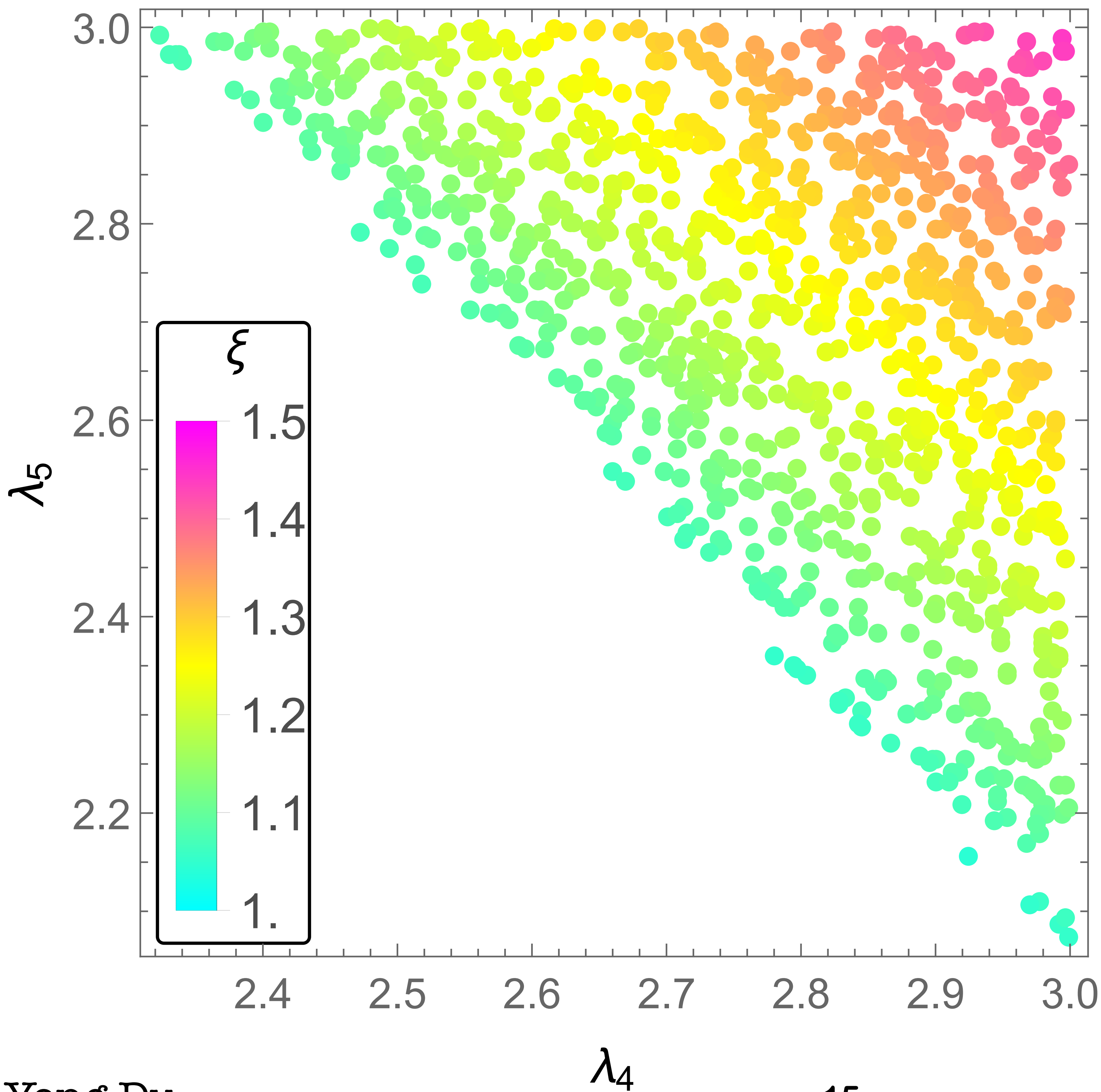



Case 2: $H^{\pm\pm} \to W^{\pm}W^{\pm}$

# Phase transition: ***The transition plots***

Viable param space for a strong first-order phase transition:




Case 3: After model discovery

$m_\Delta = 500\,\text{GeV}$

# Phase transition: ***The transition plots***

Now the question is:

Can we detect the generated gravitational waves during this phase transition now and in the future?

# Gravitational wave searches

# Gravitational wave searches: ***Tools***

Currently: LIGO and Virgo (terrestrial based)

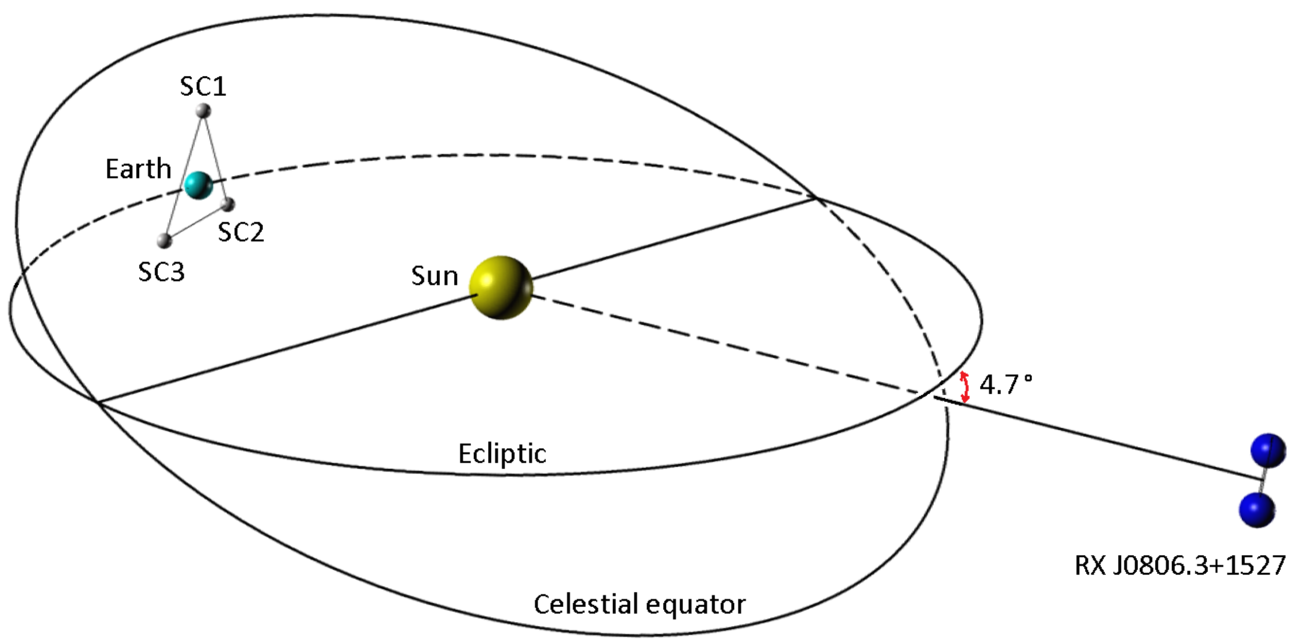

Plots credit: https://phys.org/news/2017-09-ligo-virgo-observatories-black-hole.html

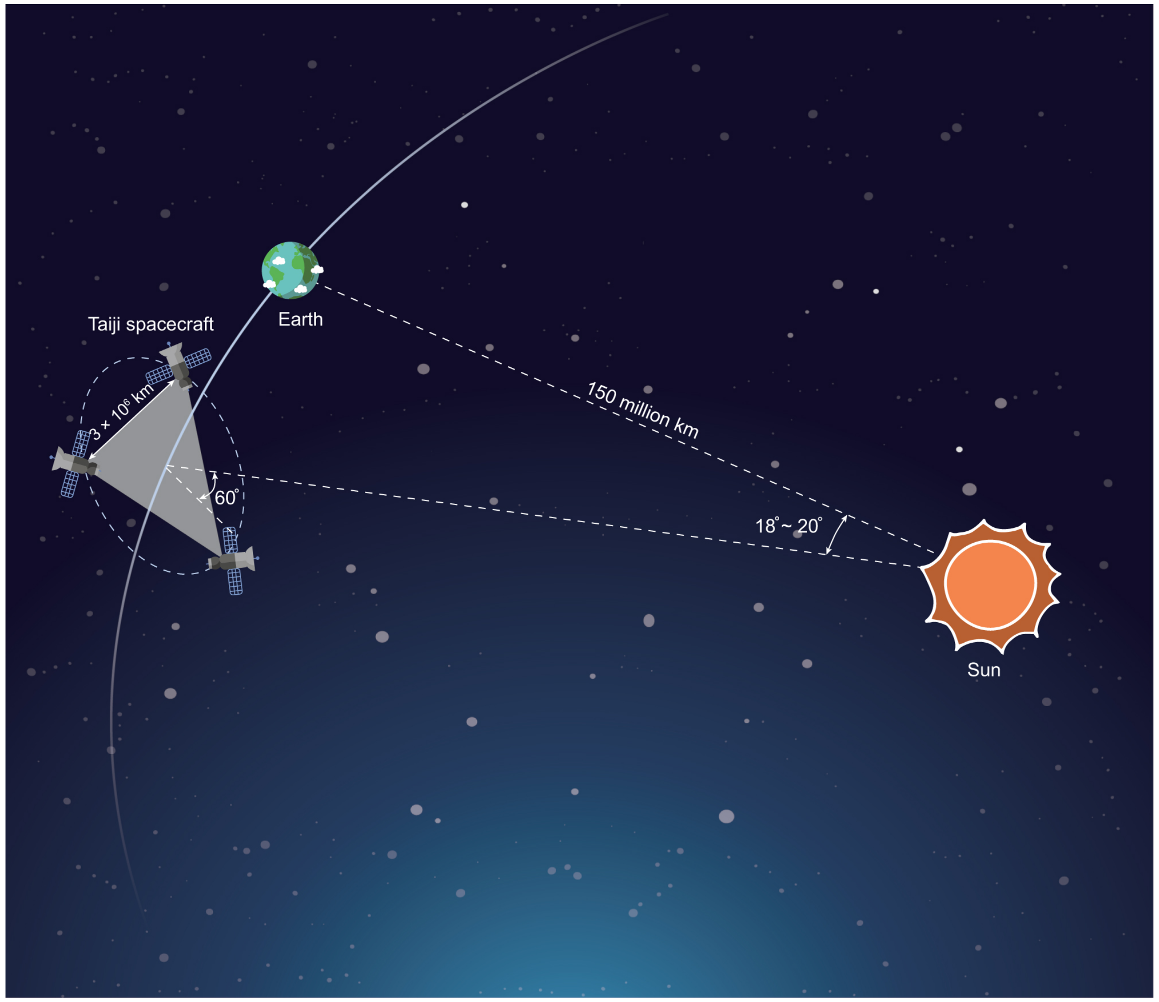
* Parkes Pulsar Timing Array (PPTA), see Xiao, Bian,  et al, PRL 127 (2021) 25

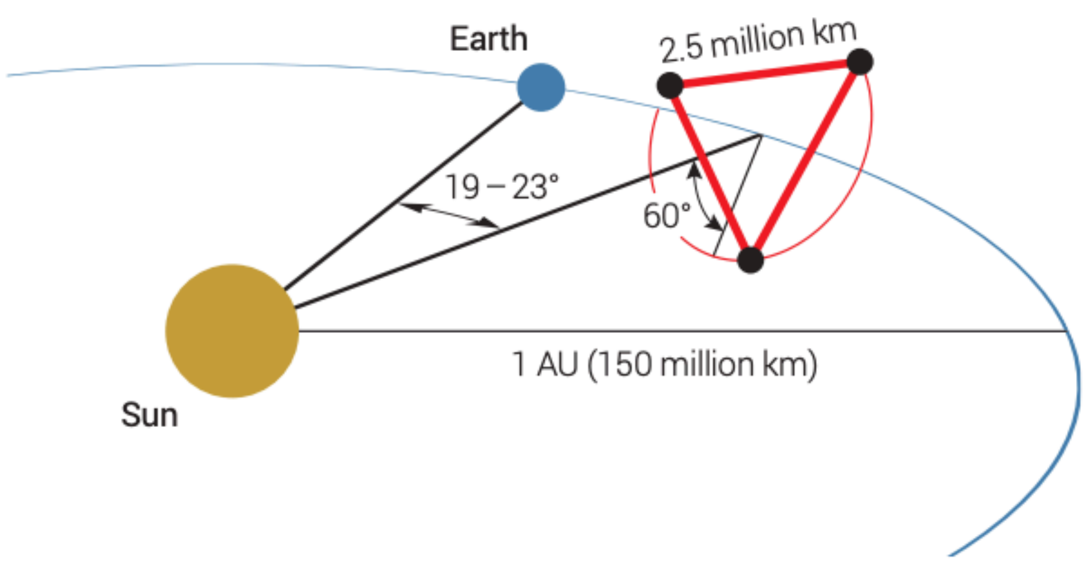
# Gravitational wave searches: *Tools*

In future: Taiji, Tianqin, LISA, DECIGO, BBO (space based)

Tianqin collaboration, 1512.02076
LISA collaboration, 1702.00786
Hu, Wu, *Natl.Sci.Rev.* 4 (2017) 5, 685



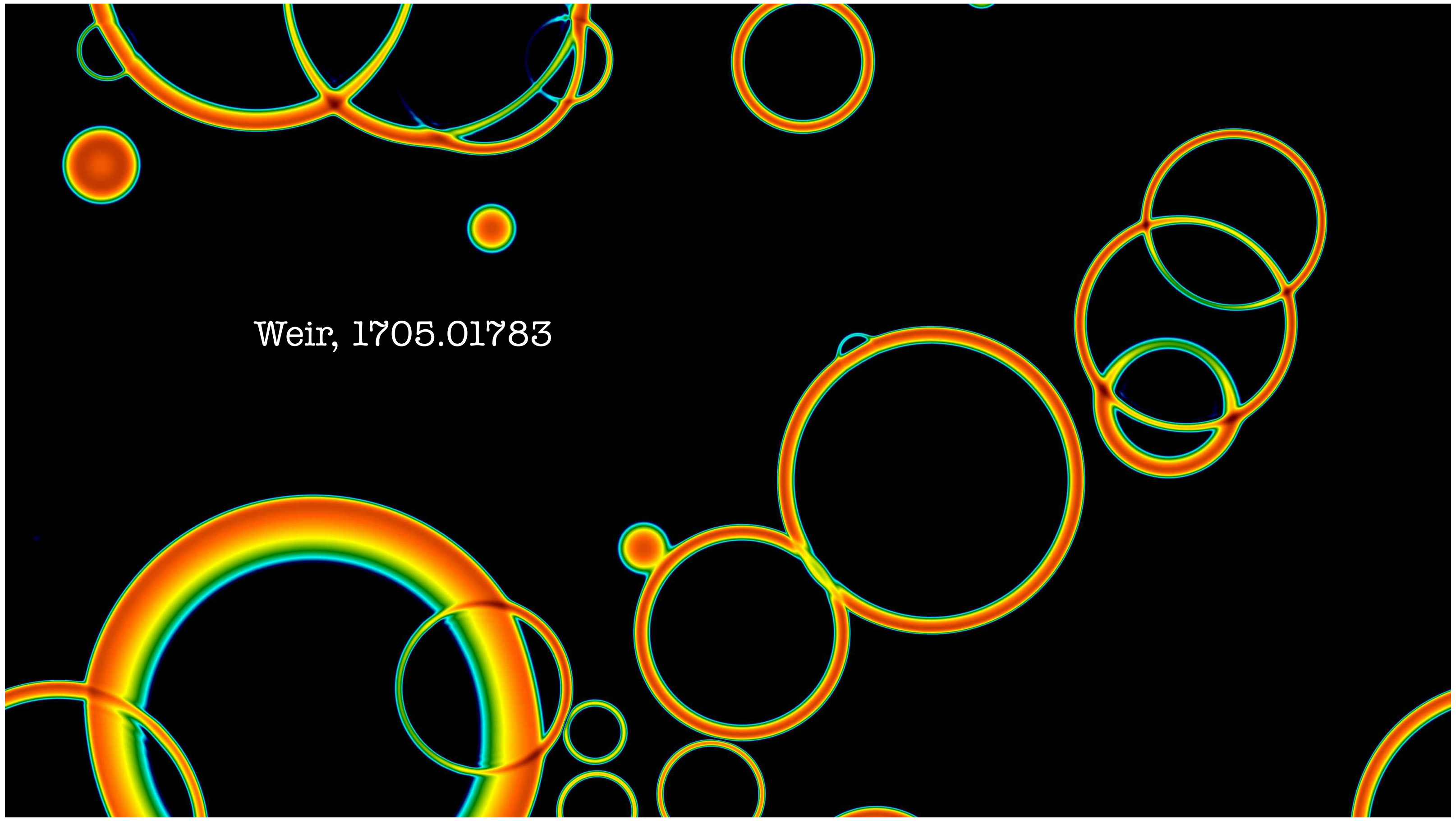



# Gravitational wave searches: *Sources*

Gravitational wave sources:

$$\Omega_{\rm GW}h^2 = \Omega h^2_{\rm coll}(f) + \Omega h^2_{\rm sw}(f) + \Omega_{\rm turb}h^2$$

Bubble collision



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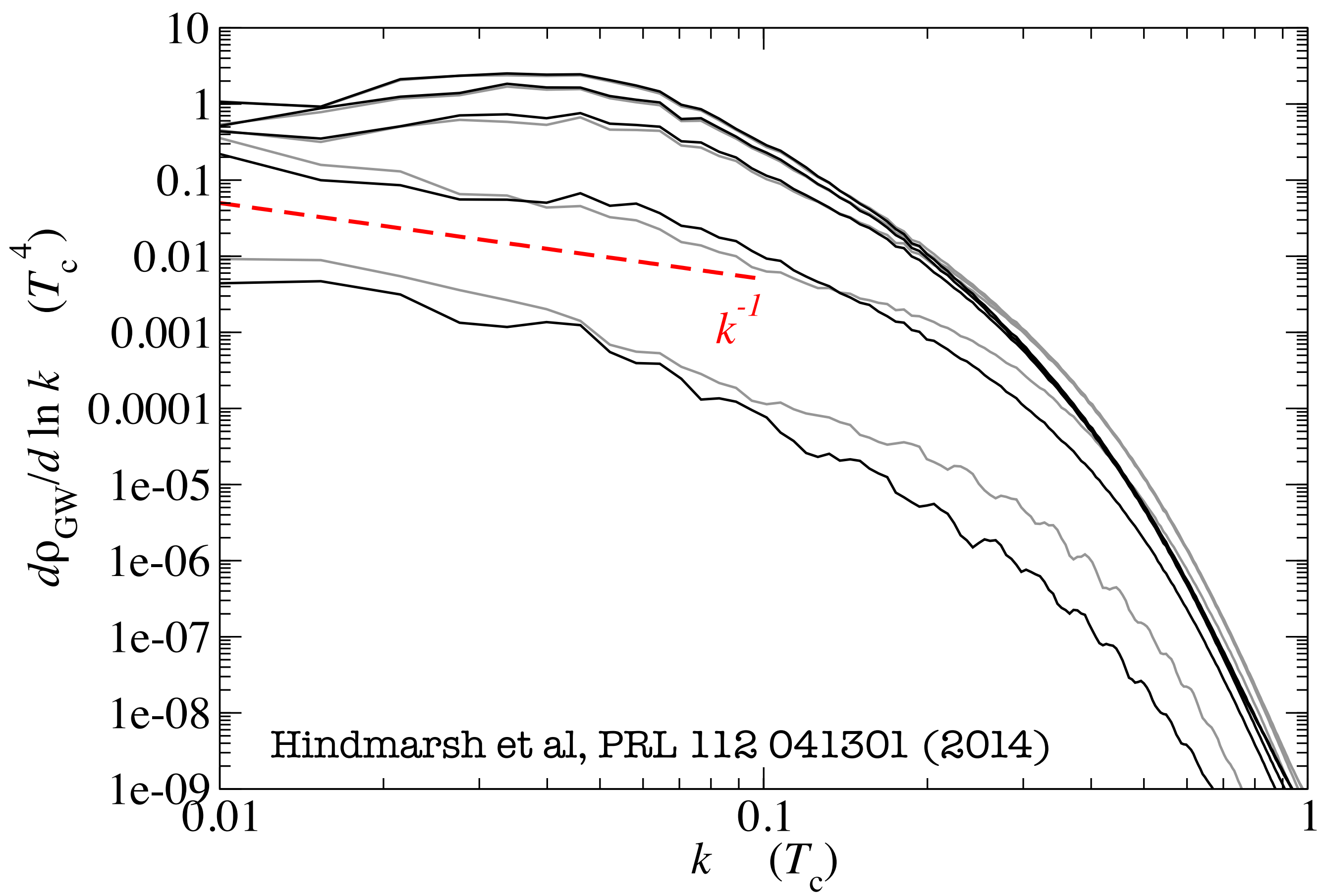
Bubble collision

Sound wave



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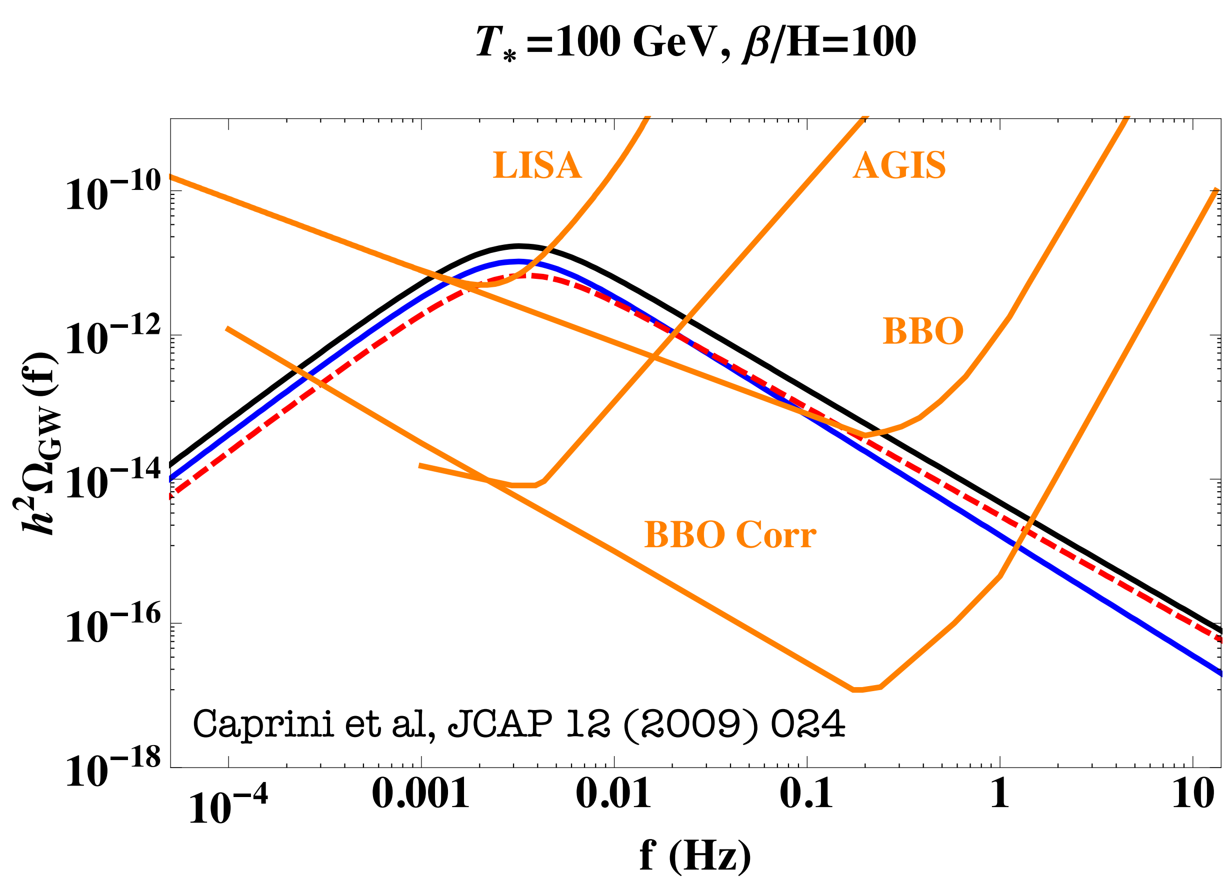
Gravitational wave sources:

$$\Omega_{\rm GW}h^2 = \Omega h^2_{\rm coll}(f) + \Omega h^2_{\rm sw}(f) + \Omega_{\rm turb}h^2$$

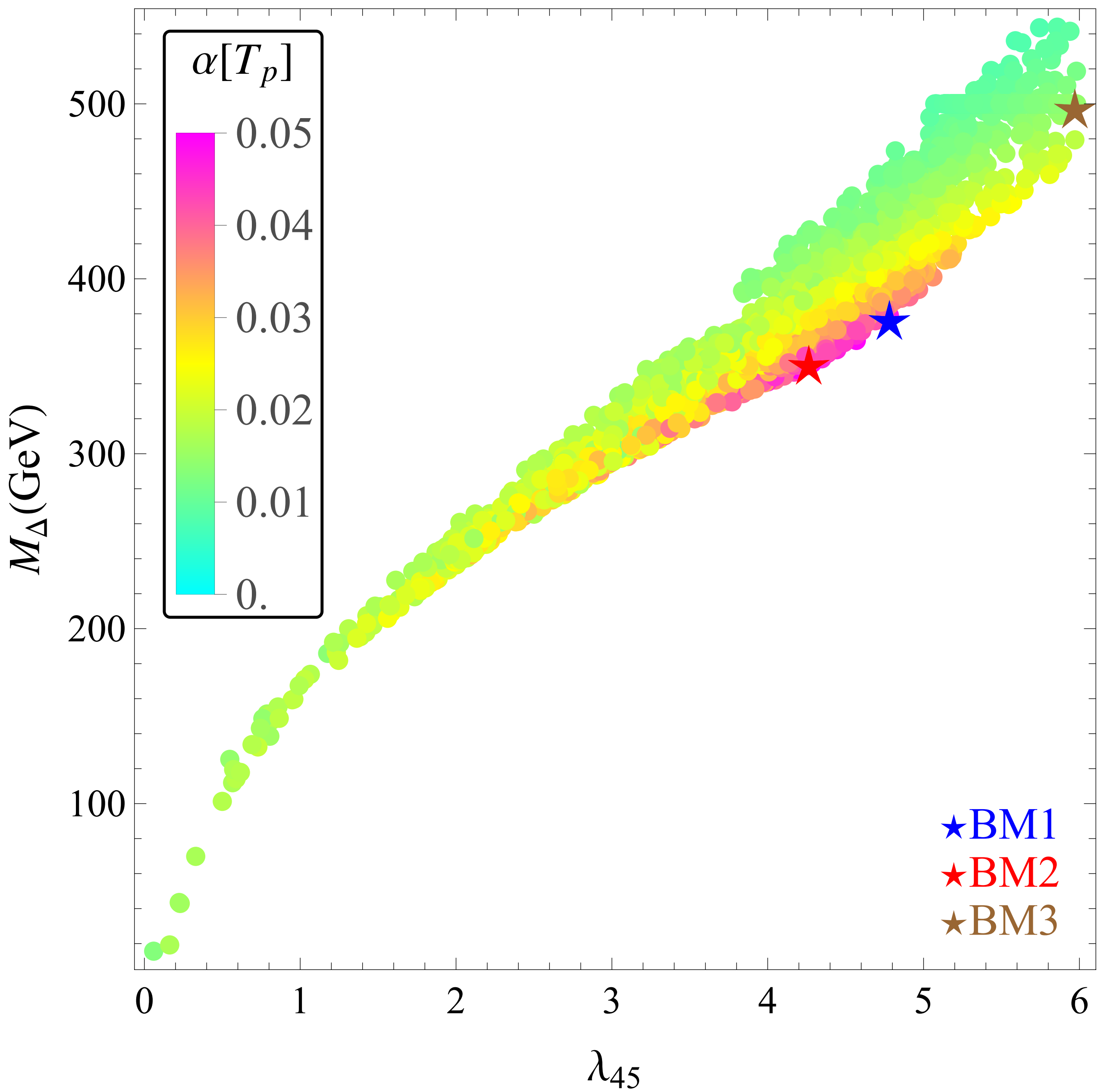
Bubble collision

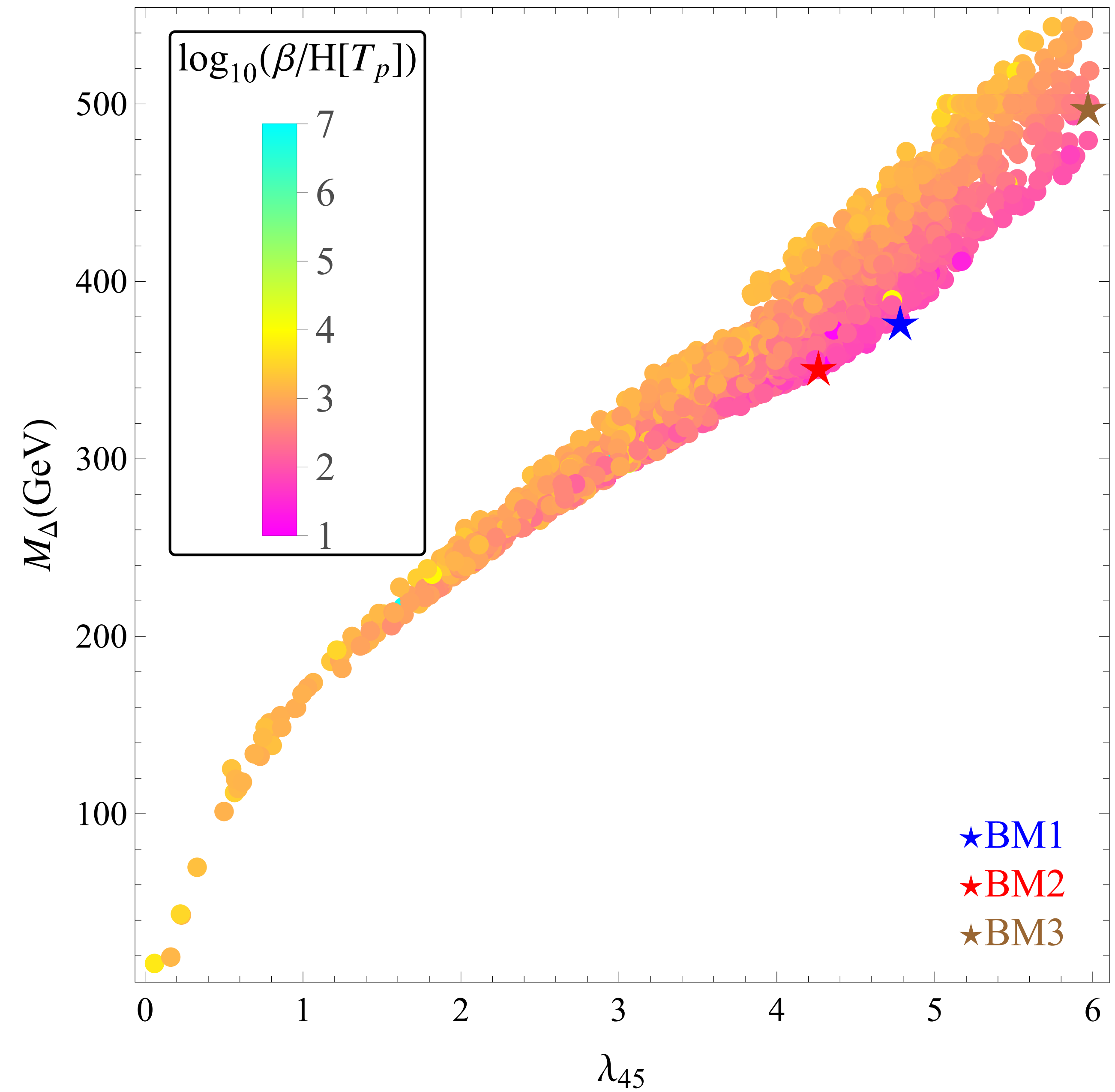
Sound wave

Magneto-hydrodynamic turbulence



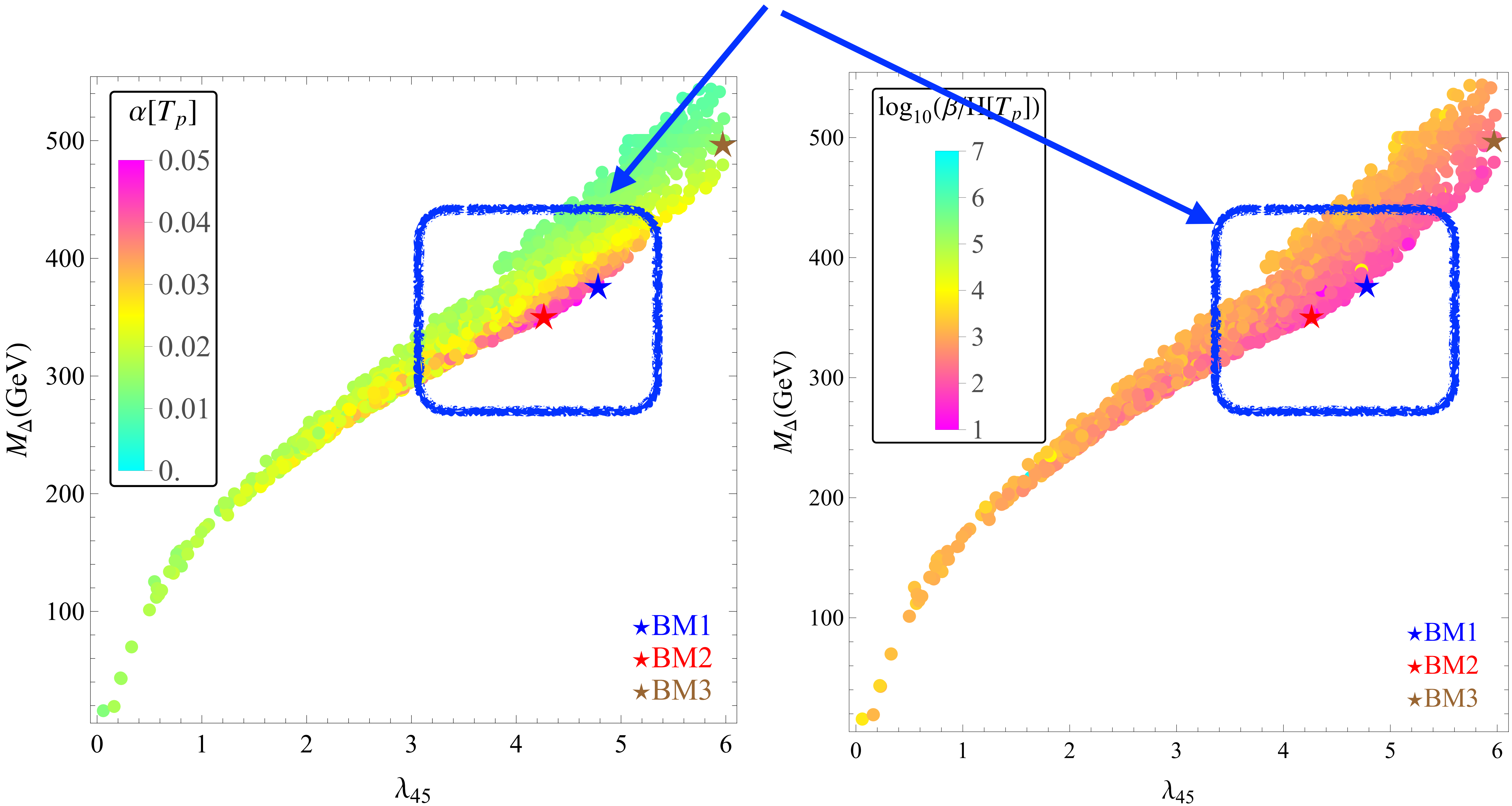
# Gravitational wave searches: ***Results***



# Gravitational wave searches: ***Results***

**Light triplet and large $\lambda_{45}$ generically preferred**



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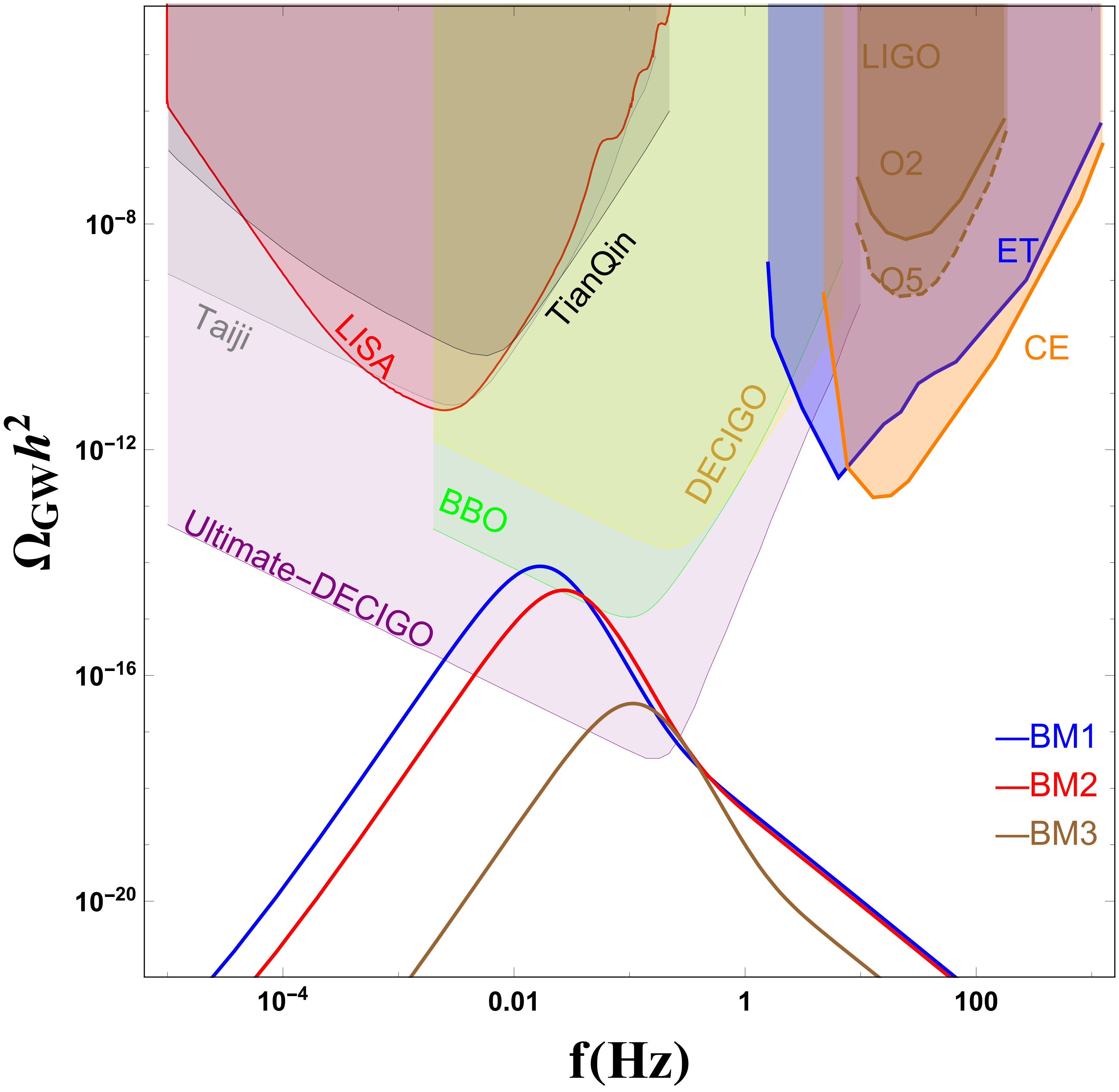
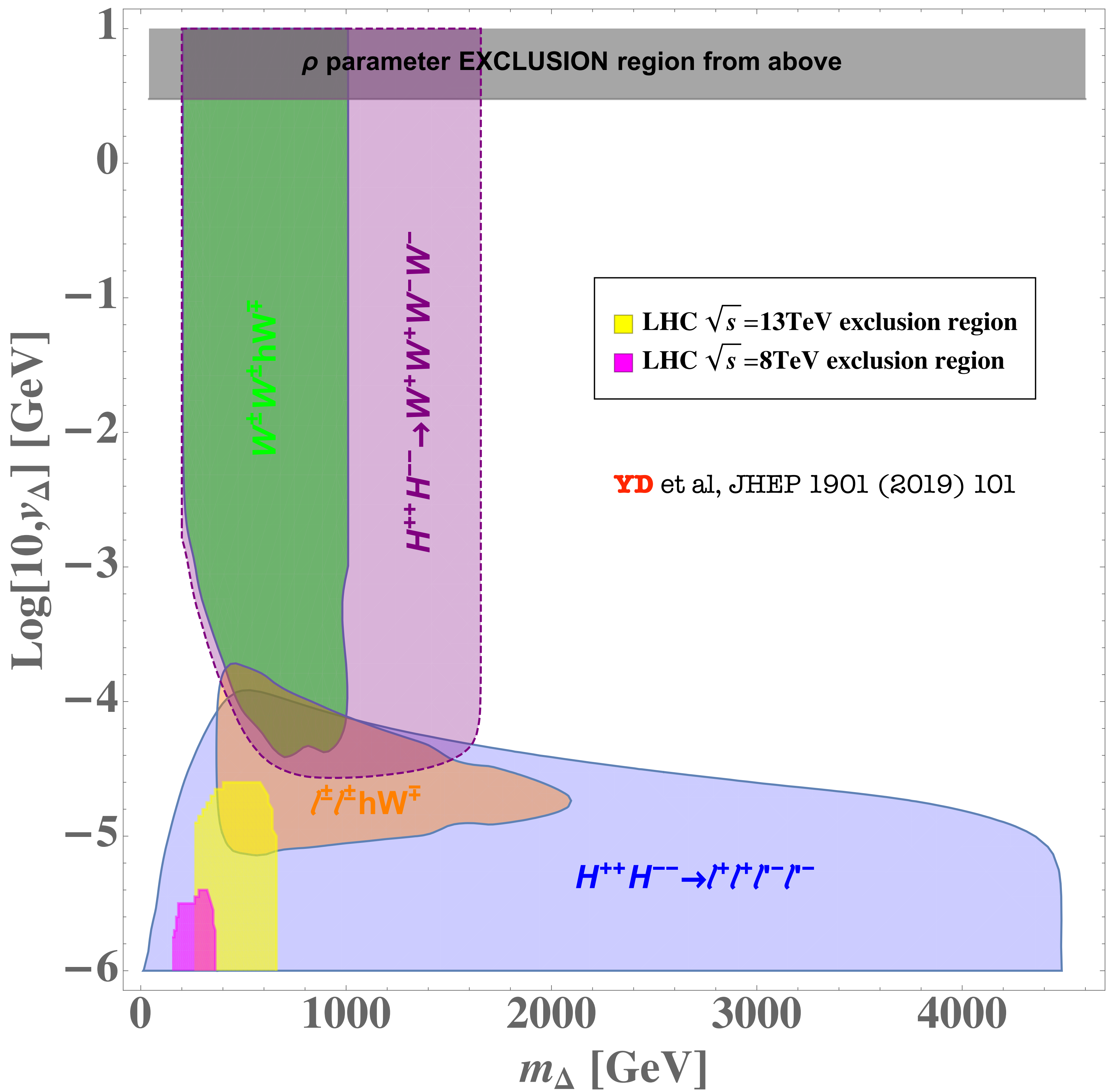


# Complementarity from collider searches

# Complementarity: *Collider searches*



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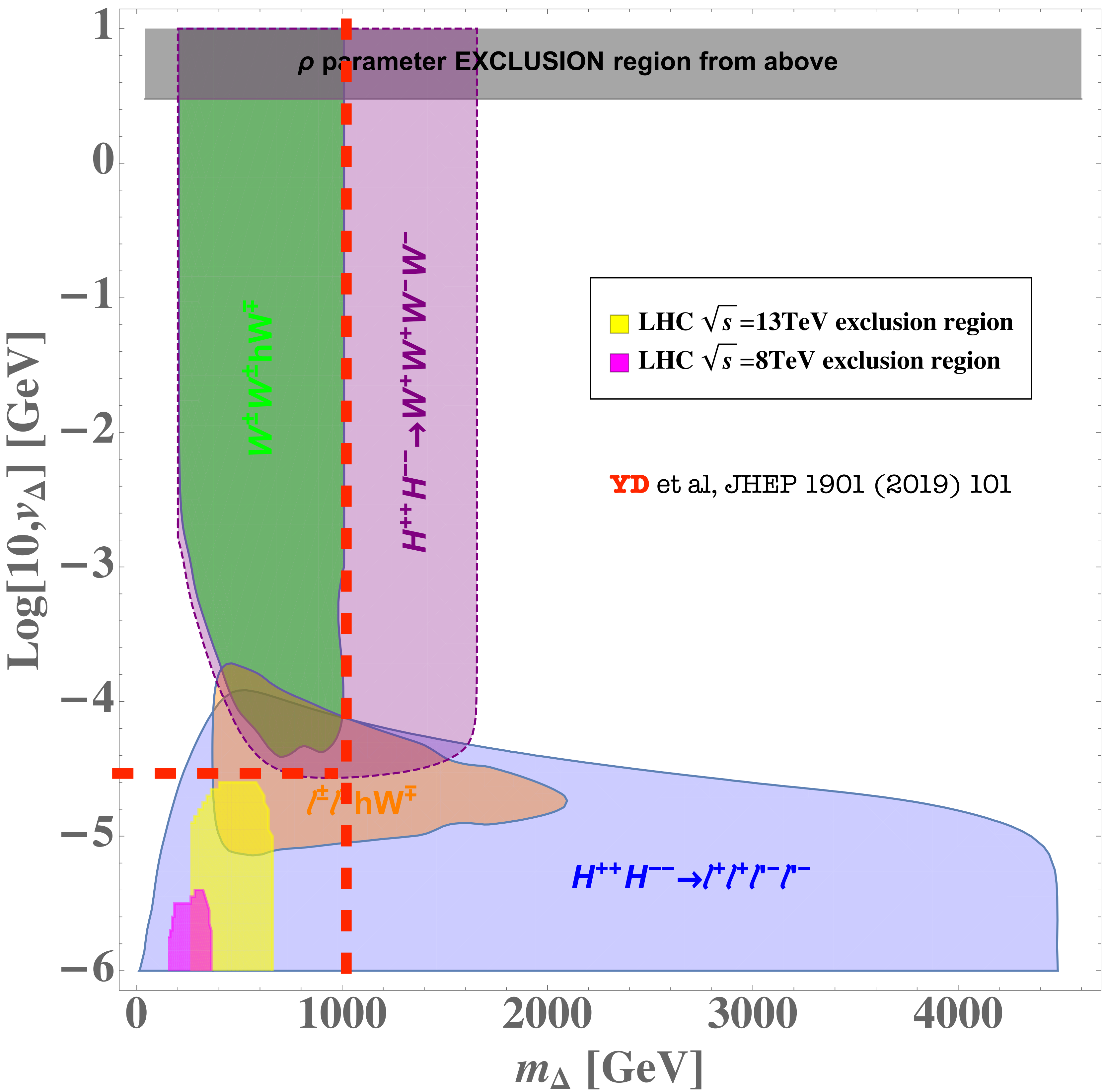

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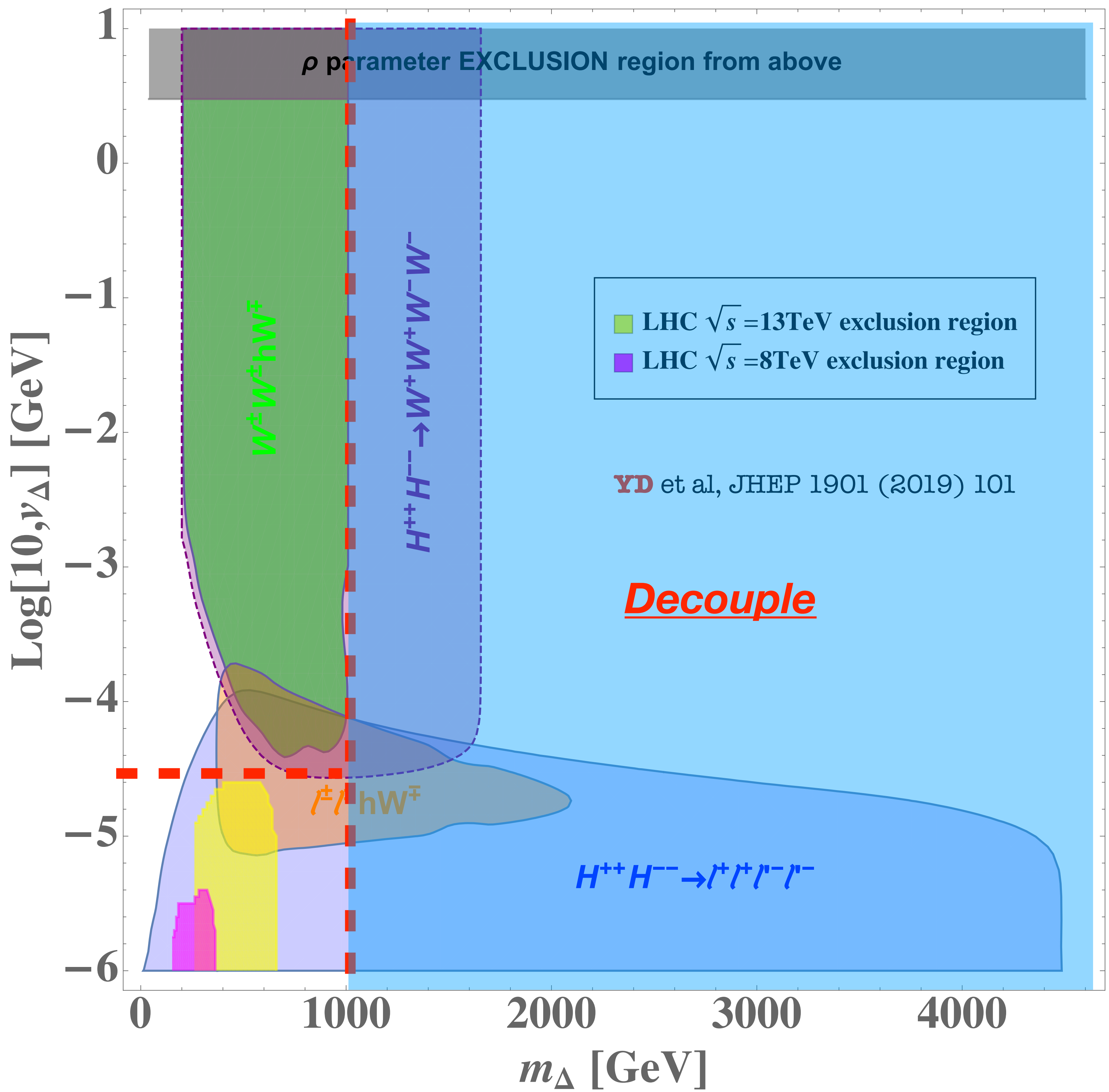
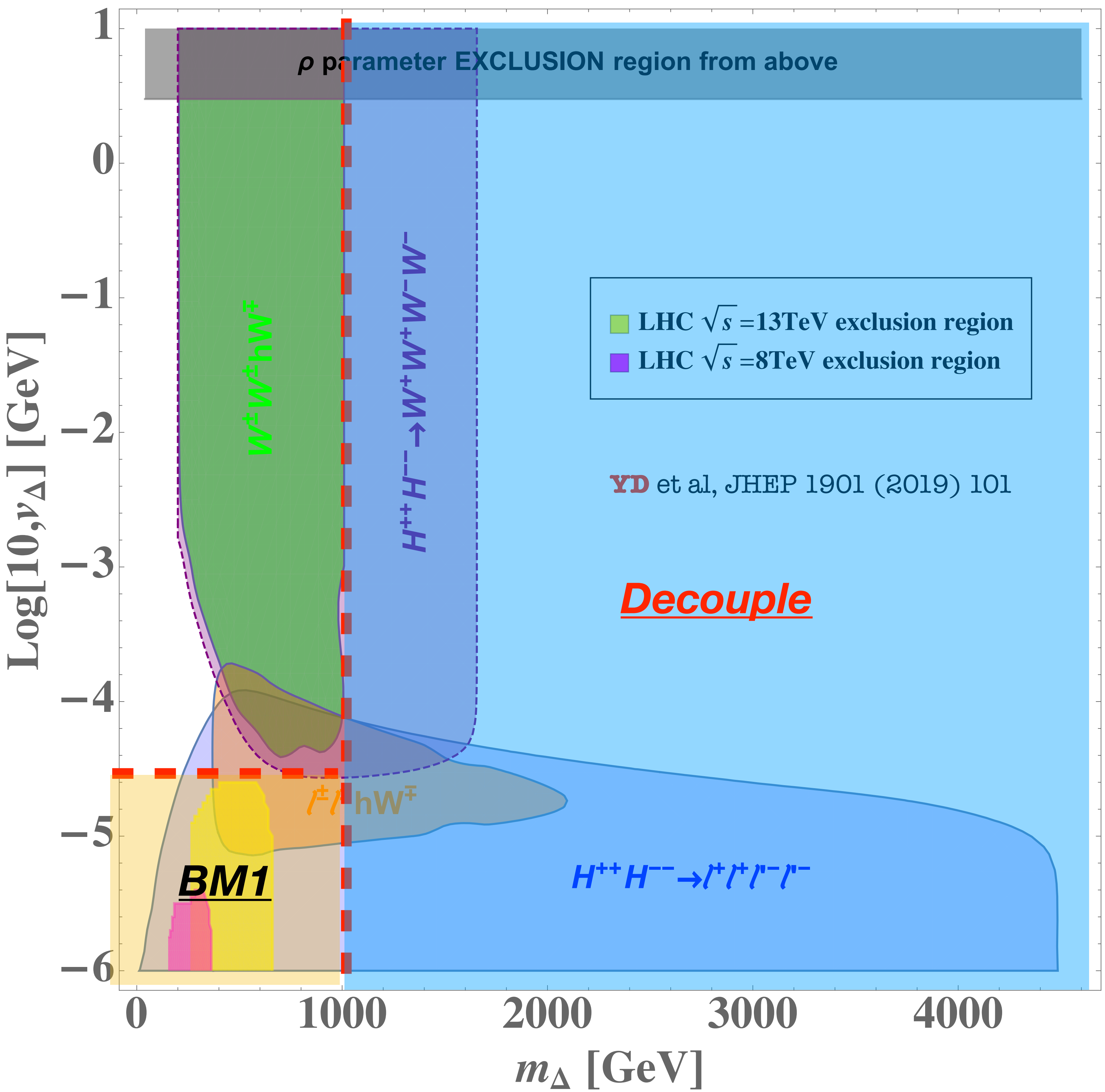


# Complementarity: <u>*Collider searches*</u>



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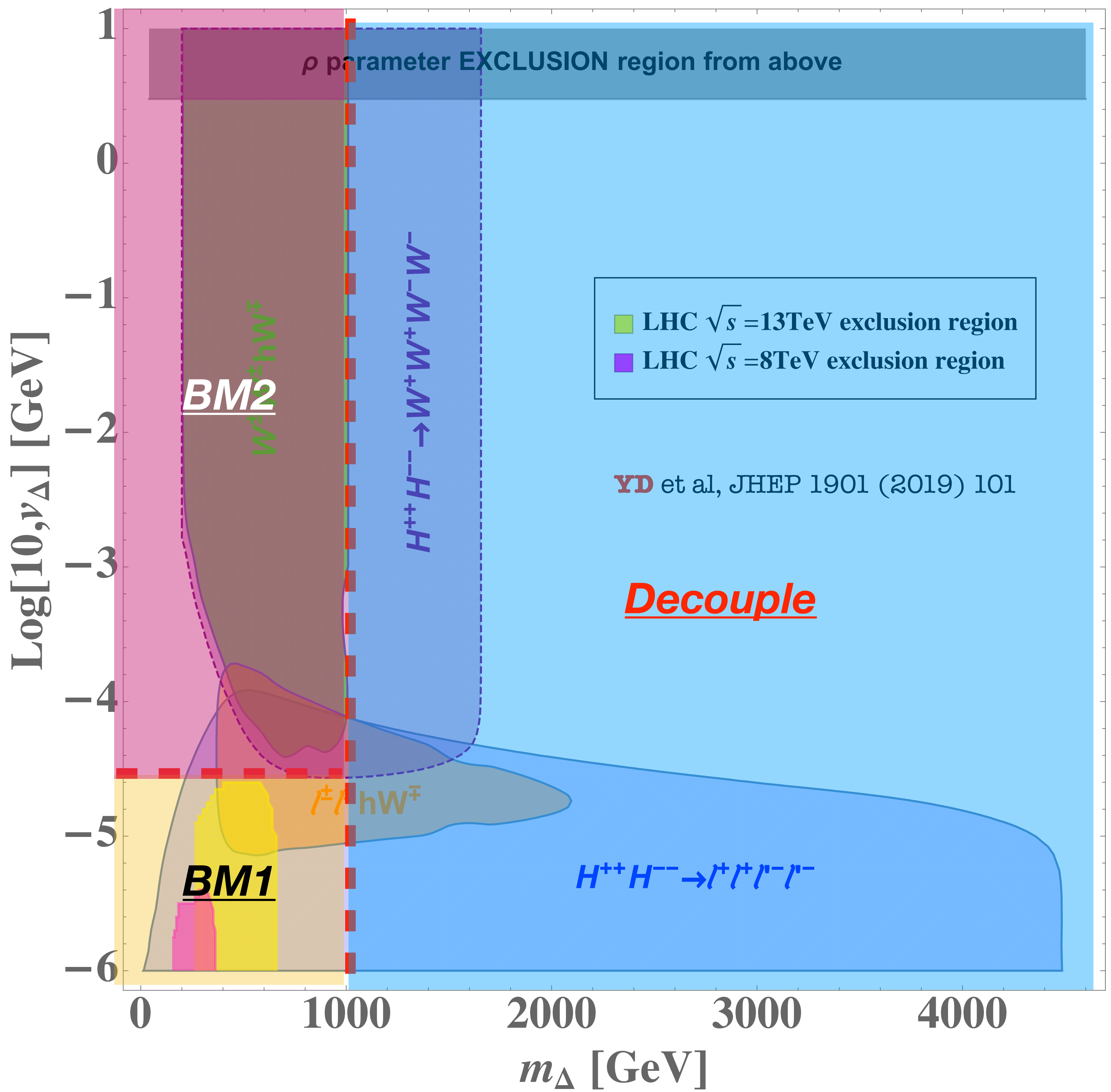
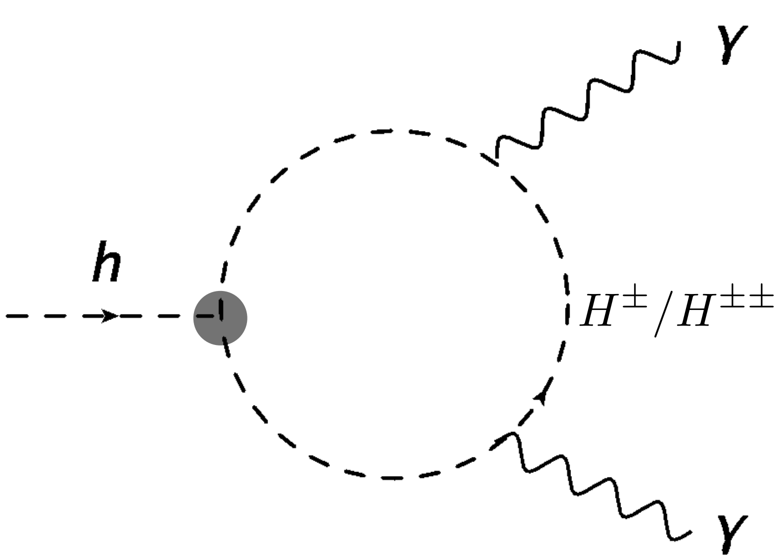
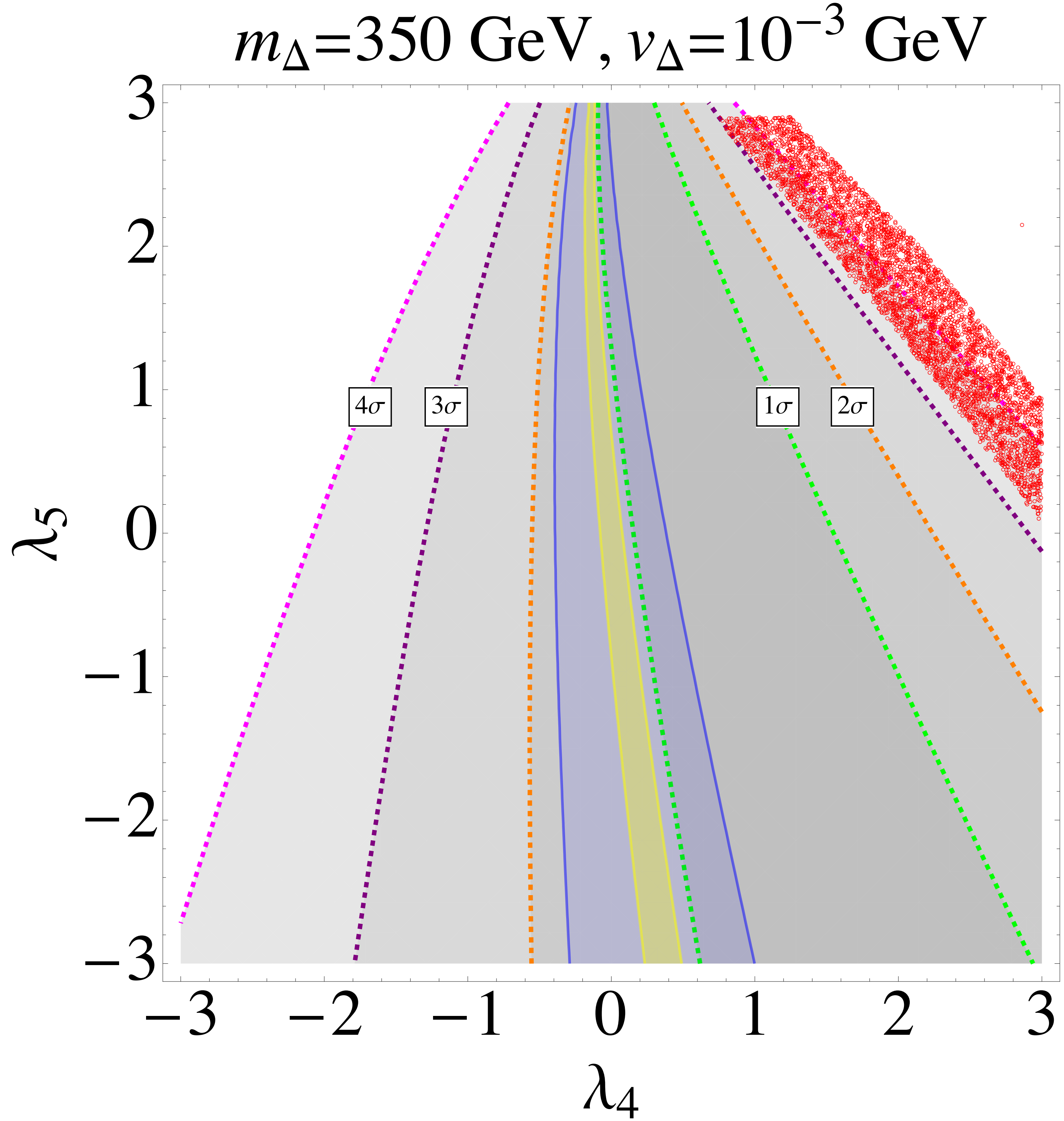


# Complementarity: *Precision tests*



# Summary

- Electroweak phase transition and gravitational wave production in the type-II seesaw model are investigated for the first time.

- Both phase transition and gravitational wave production prefer a light triplet near 500GeV.

- Being so light, direct searches at future colliders could be complementary (The same-sign same flavor di-lepton channel or the same-sign di-W boson channel could be the ideal channel, precision measurements of the $h \to \gamma\gamma$ decay rate could also provides extra information).