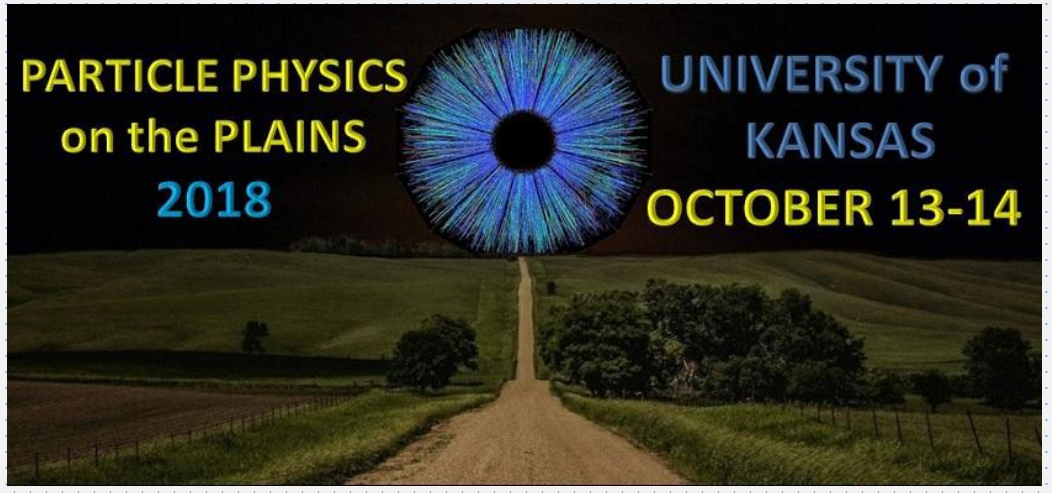
Resonant Di-Higgs Production at Gravitational Wave Benchmarks
A Collider Study using Machine Learning

Huaike Guo

University of Oklahoma

A. Alves, T.G., H. Guo, K. Sinha, arXiv:1808.08974
A. Alves, T.G., H. Guo, K. Sinha, D. Vagie [In progress]



First Direct Detection of Gravitational Waves

The Nobel Prize in Physics 2017

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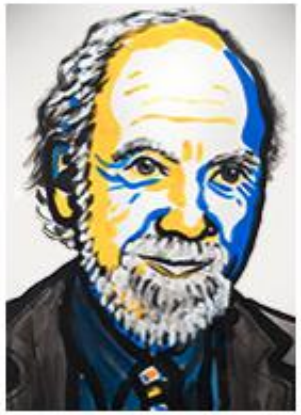
Rainer Weiss

Prize share: 1/2



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Barry C. Barish

Prize share: 1/4

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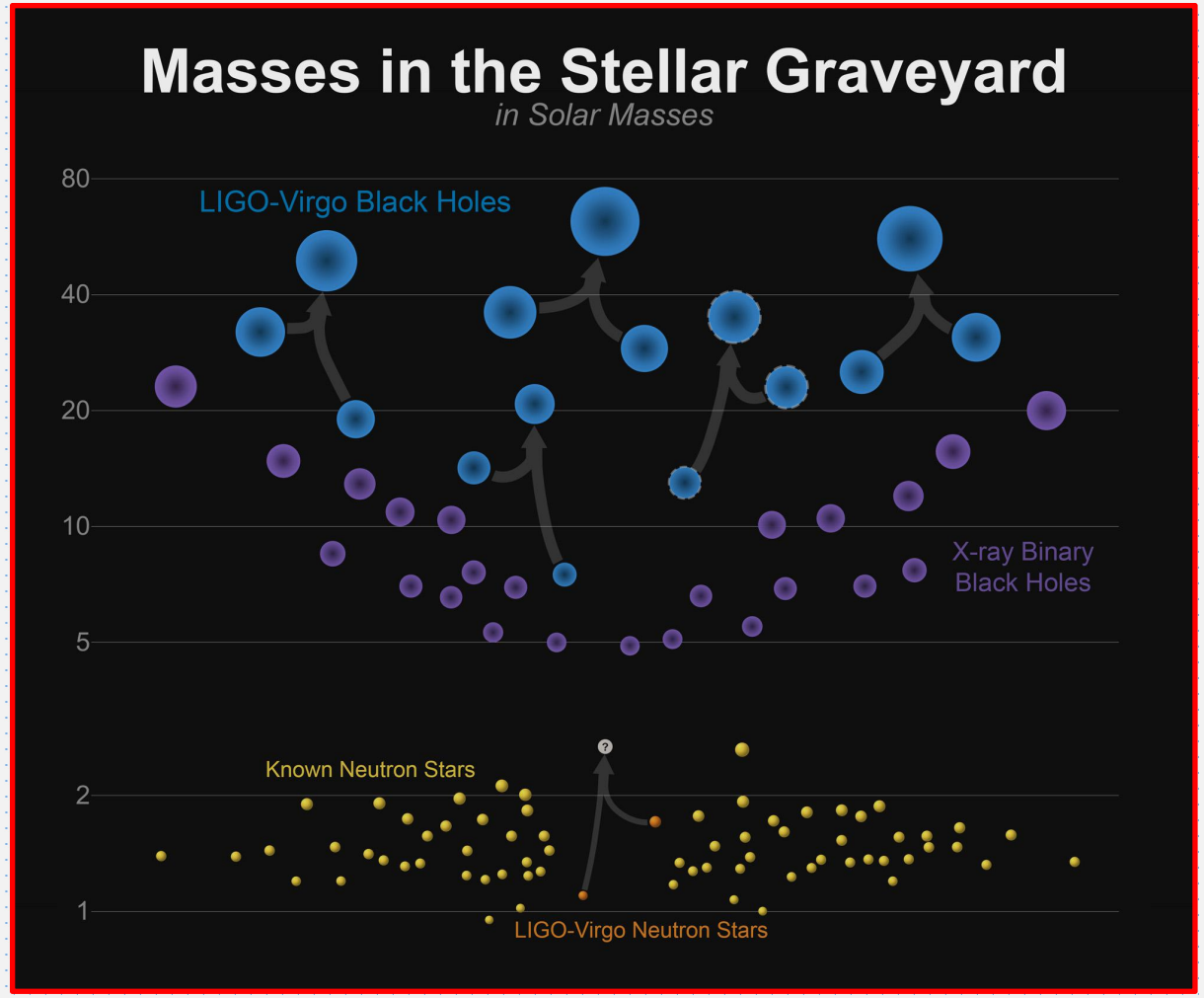
Kip S. Thorne

Prize share: 1/4

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.



What can gravitational waves be used for ?

- Test of General Relativity in the Strong Field Regime
- Gravitational-wave Astronomy
- Alternative Measurement of Cosmological Parameters
- Constrain Modified Gravities
- Probe of Particle Physics

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→ tensor fluctuations from inflaton
CMB B-mode polarization

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→ tensor fluctuations from inflaton
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→ weak scale ?

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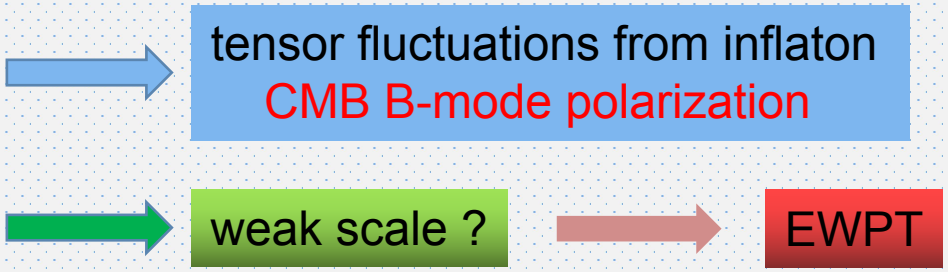
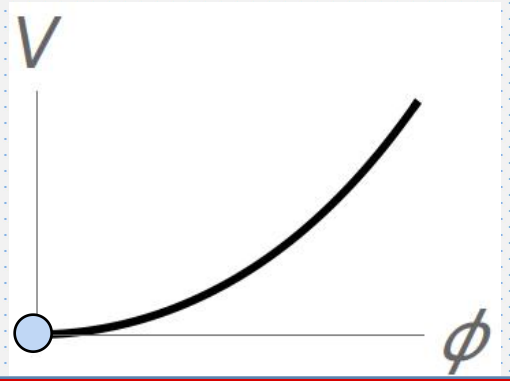
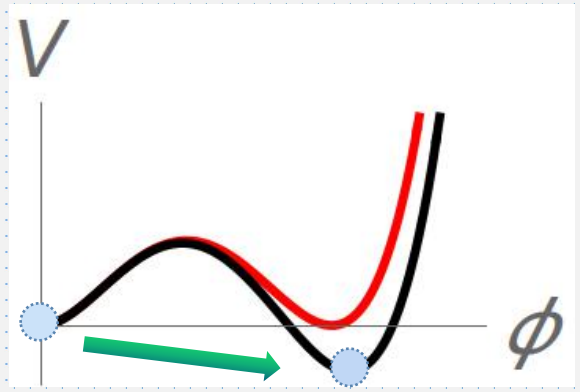
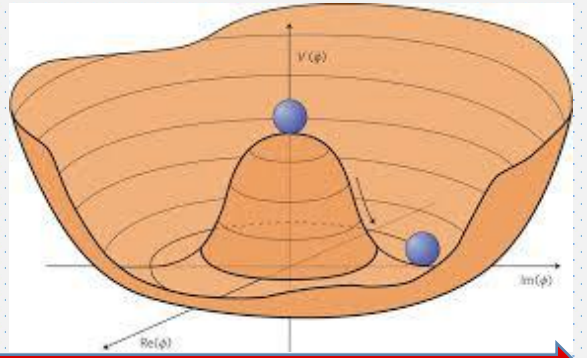


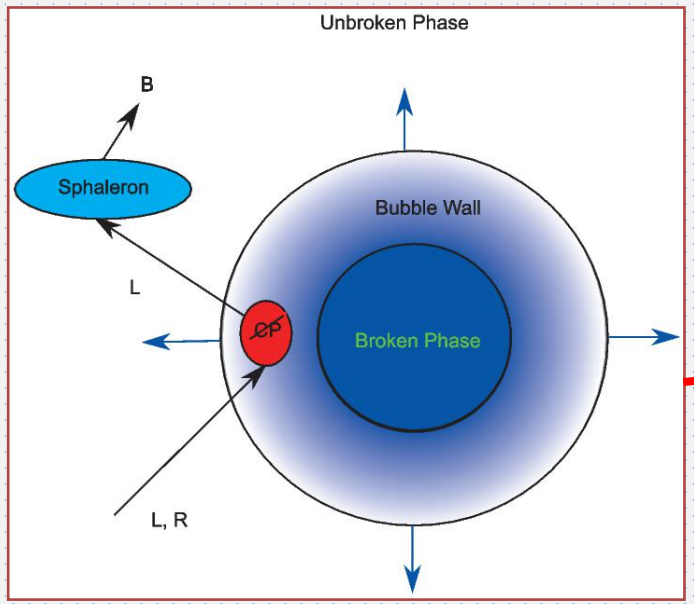


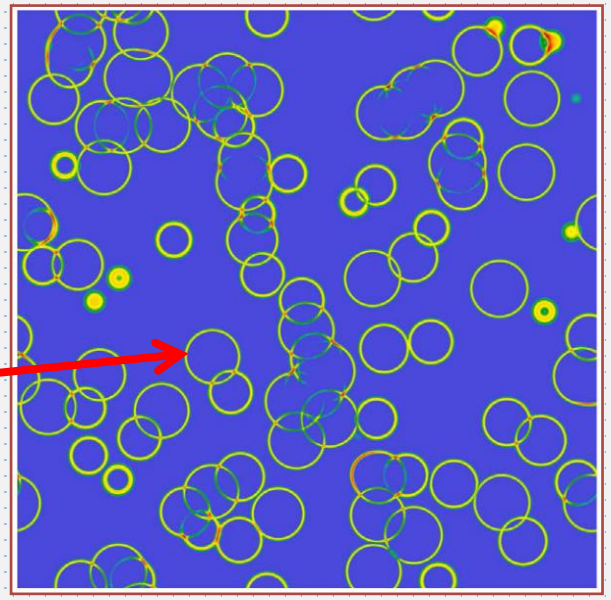




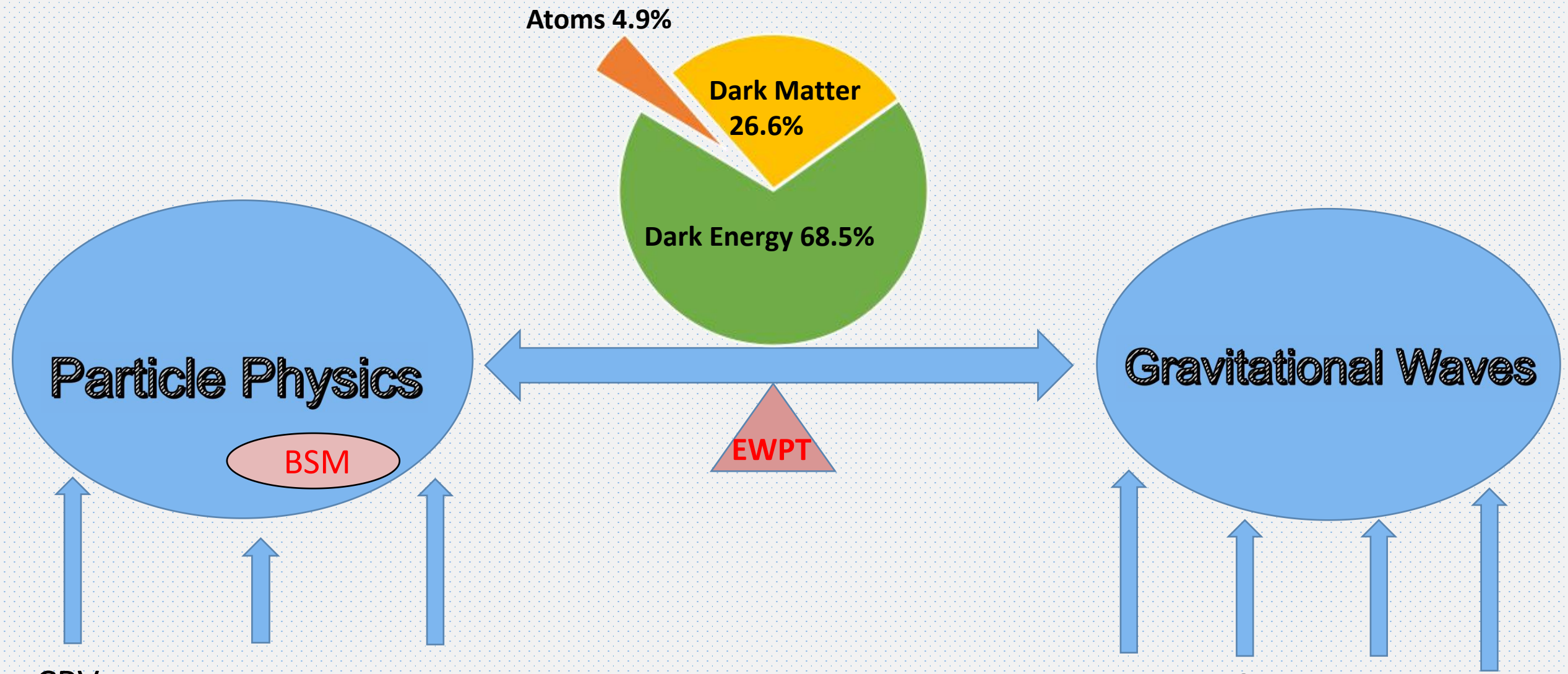
100

0 T(GeV)



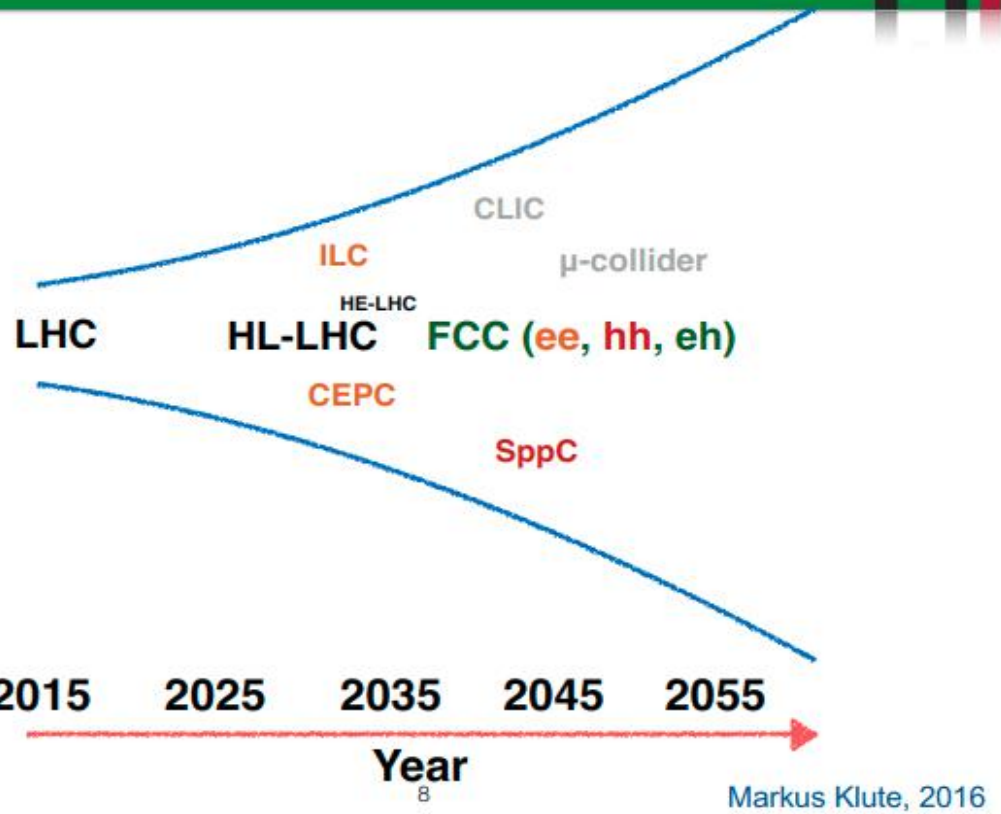


Hindmarsh, et al, 2015


Atoms 4.9%
Dark Matter
26.6%
Dark Energy 68.5%
Particle Physics
BSM
EWPT
Gravitational Waves
CPV
Higgs
LHC
LIGO
Virgo
...
LISA
Taiji
Tianqin
...
PTA
CMB

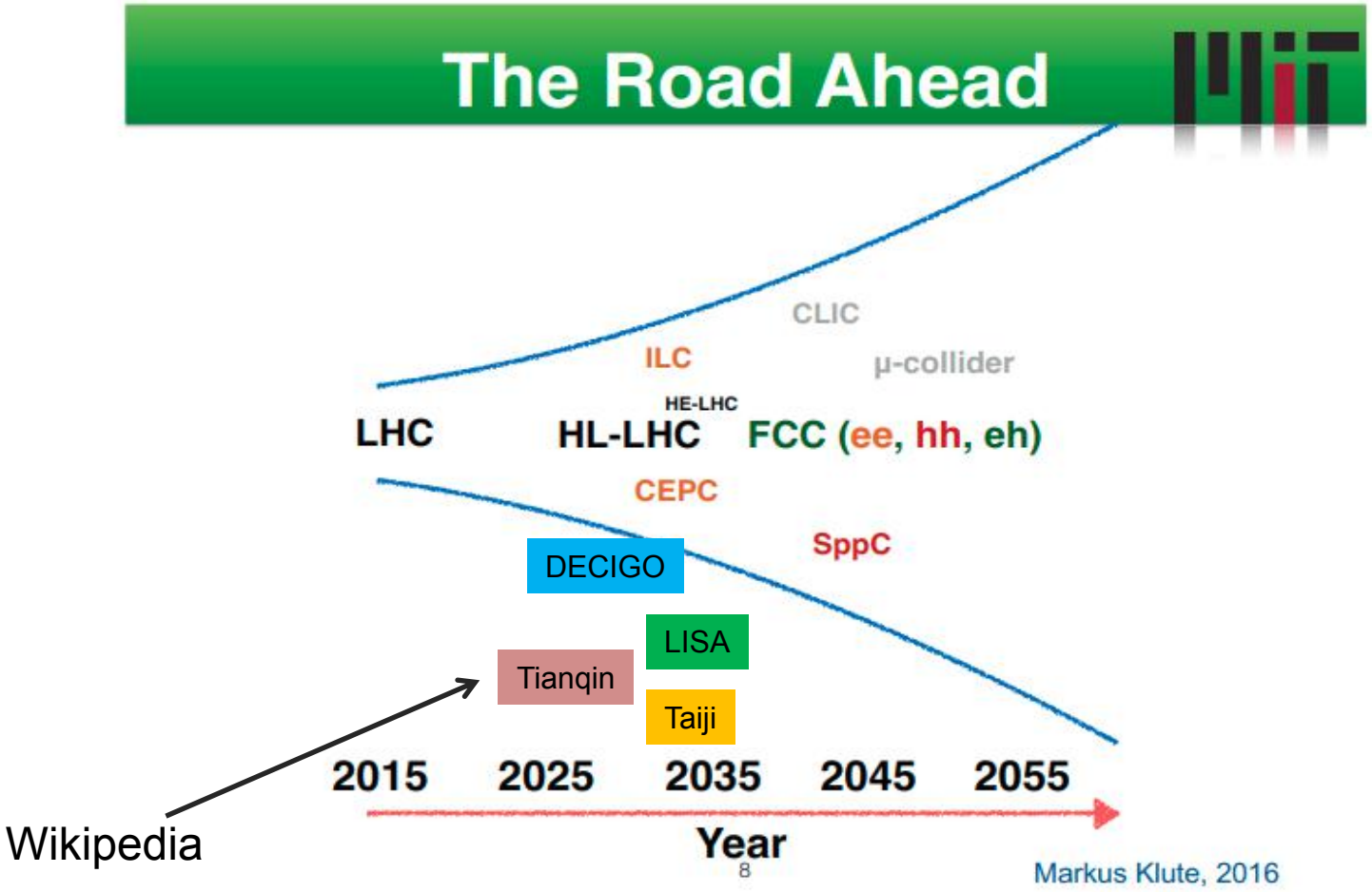
Many Colliders in the Horizon

The Road Ahead



Markus Klute, 2016

Many Colliders in the Horizon



Wikipedia

The Model

$$V(\phi, S) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{a_1}{2} H^\dagger H S + \frac{a_2}{2} H^\dagger H S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

$$v_s, \qquad m_{h_2}, \qquad \theta, \qquad b_3, \qquad b_4$$

The Model

Z_2

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The Model

v_s=0

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v_s, m_{h_2}, θ, b_3, b_4

a_2

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$v_s, \quad m_{h_2}, \quad \theta, \quad b_3, \quad b_4$

a_2

- Unitarity
- Stability
- Electroweak Precision Observables
- Collider Constraints

$$V(\phi, S) = -\mu^2 I$$

$$+ b_1 S + \frac{a_2}{2}$$

$$v_s, \qquad m_{h_2}$$

a_2

- Unitarity
- Stability
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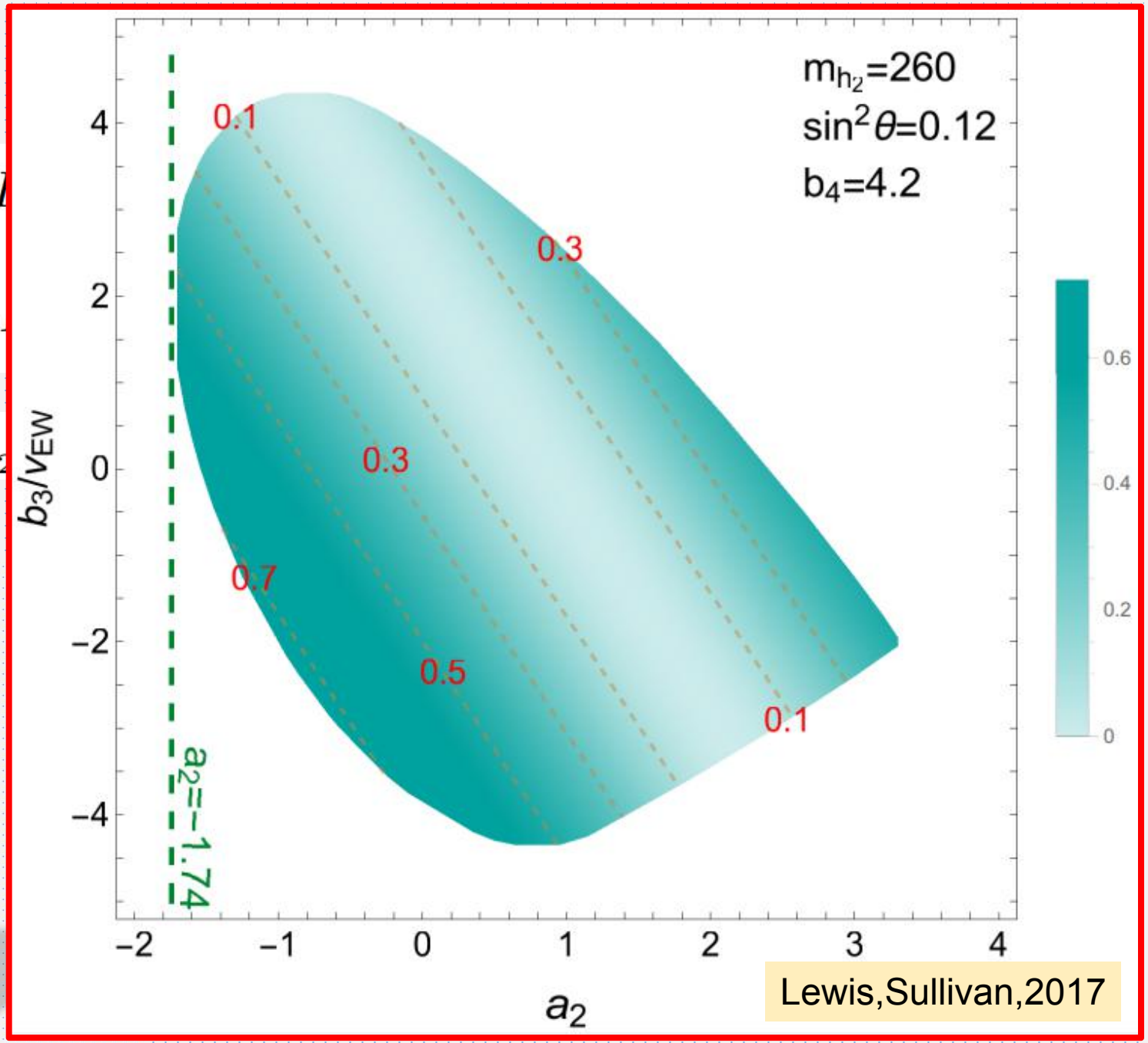

Lewis,Sullivan,2017

Electroweak Phase Transition and Gravitational Waves

$$\Pi_h(T) = \left(\frac{2m_W^2 + m_Z^2 + 2m_t^2}{4v^2} + \frac{\lambda}{2} + \frac{a_2}{24} \right) T^2$$

$$\Pi_s(T) = \left(\frac{a_2}{6} + \frac{b_4}{4} \right) T^2,$$

$$T_c, \quad T_n, \quad \alpha, \quad \beta, \quad v_w$$

- Bubble Collisions
- Sound Waves
- Magneto-Hydrodynamic Turbulence

Energy density Spectrum

$$\Omega_{\rm gw}(f) = \frac{4\pi^2}{3H_0^2} f^3 S_h(f)$$

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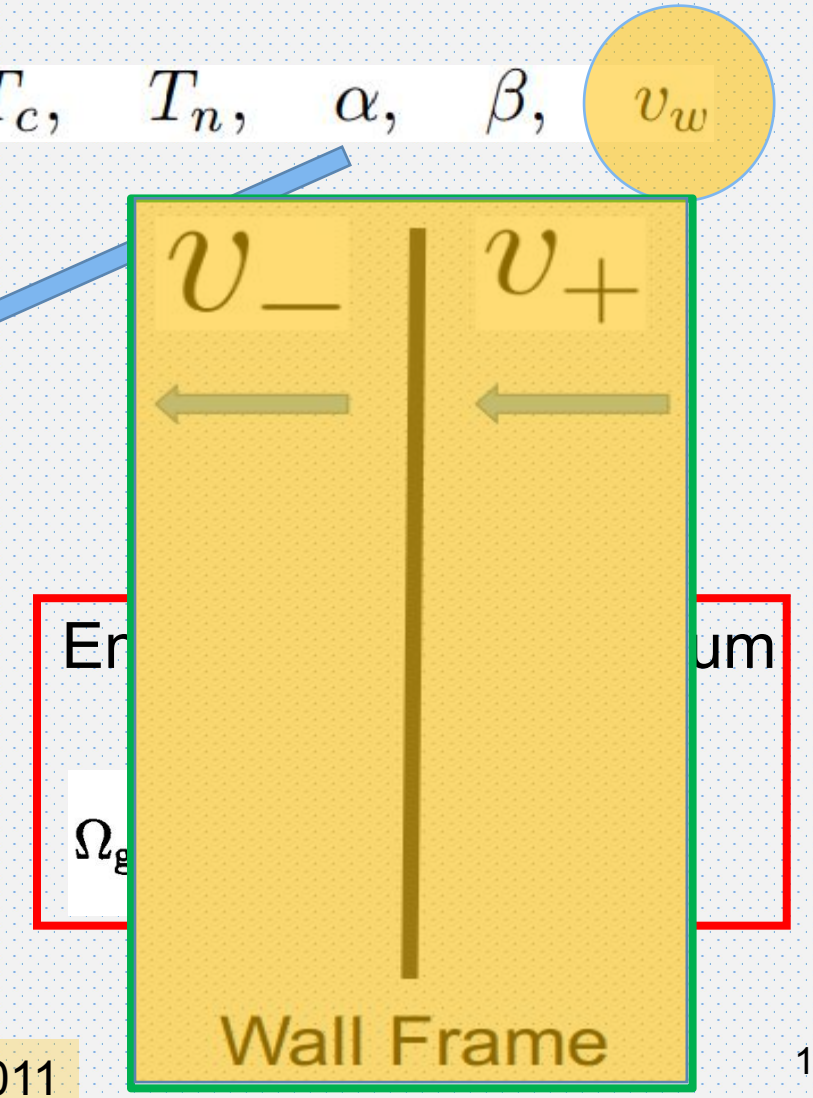

- Bubble Collisions
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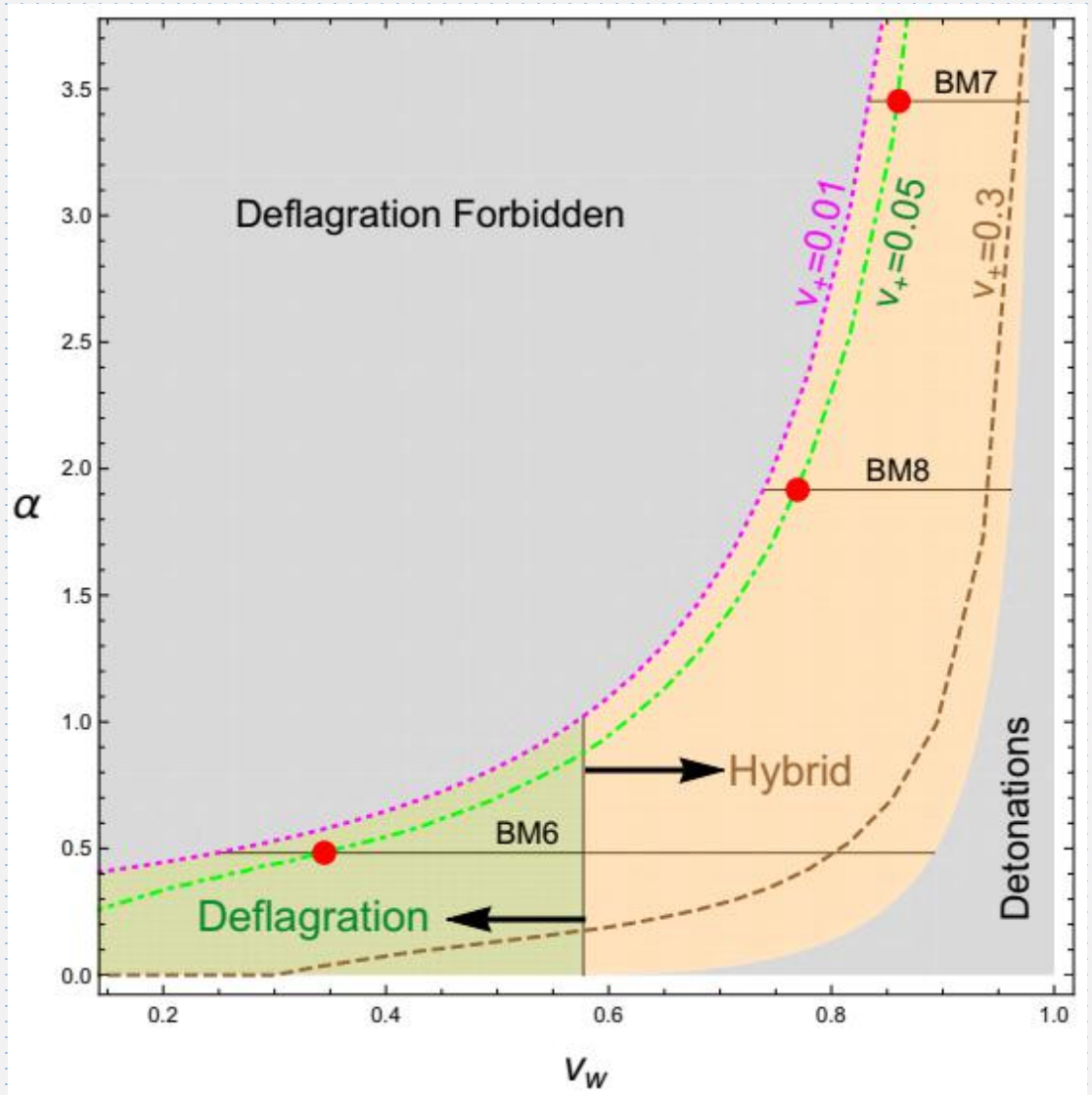
J. No, 2011



Espinosa, Konstandin, No, Servant, 2010

J. No, 2011

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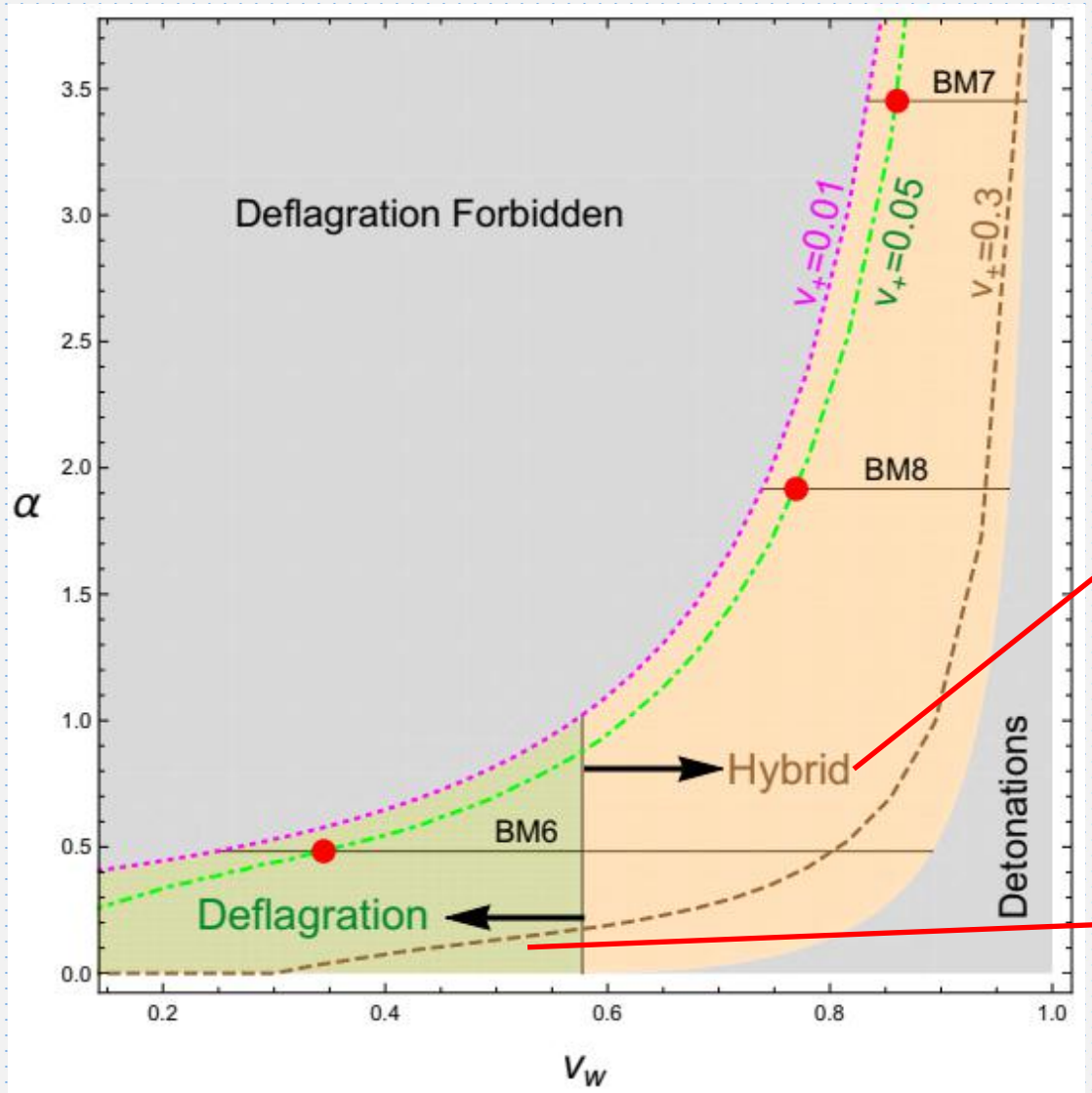
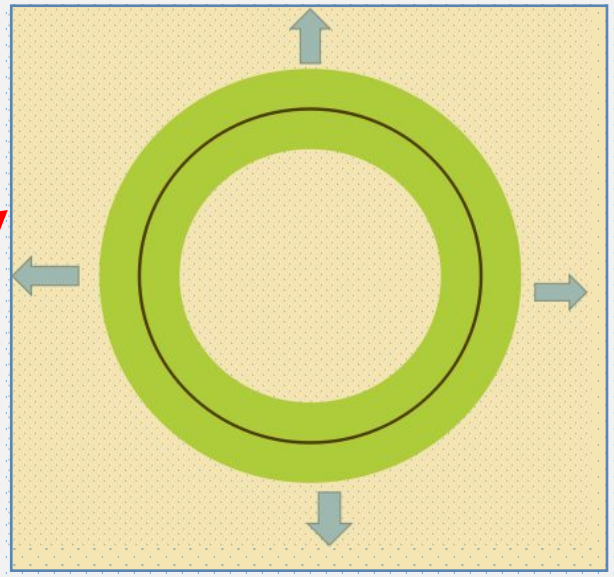
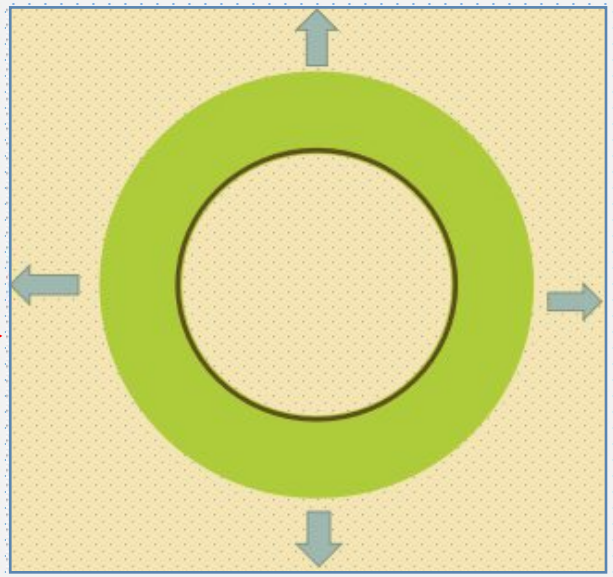
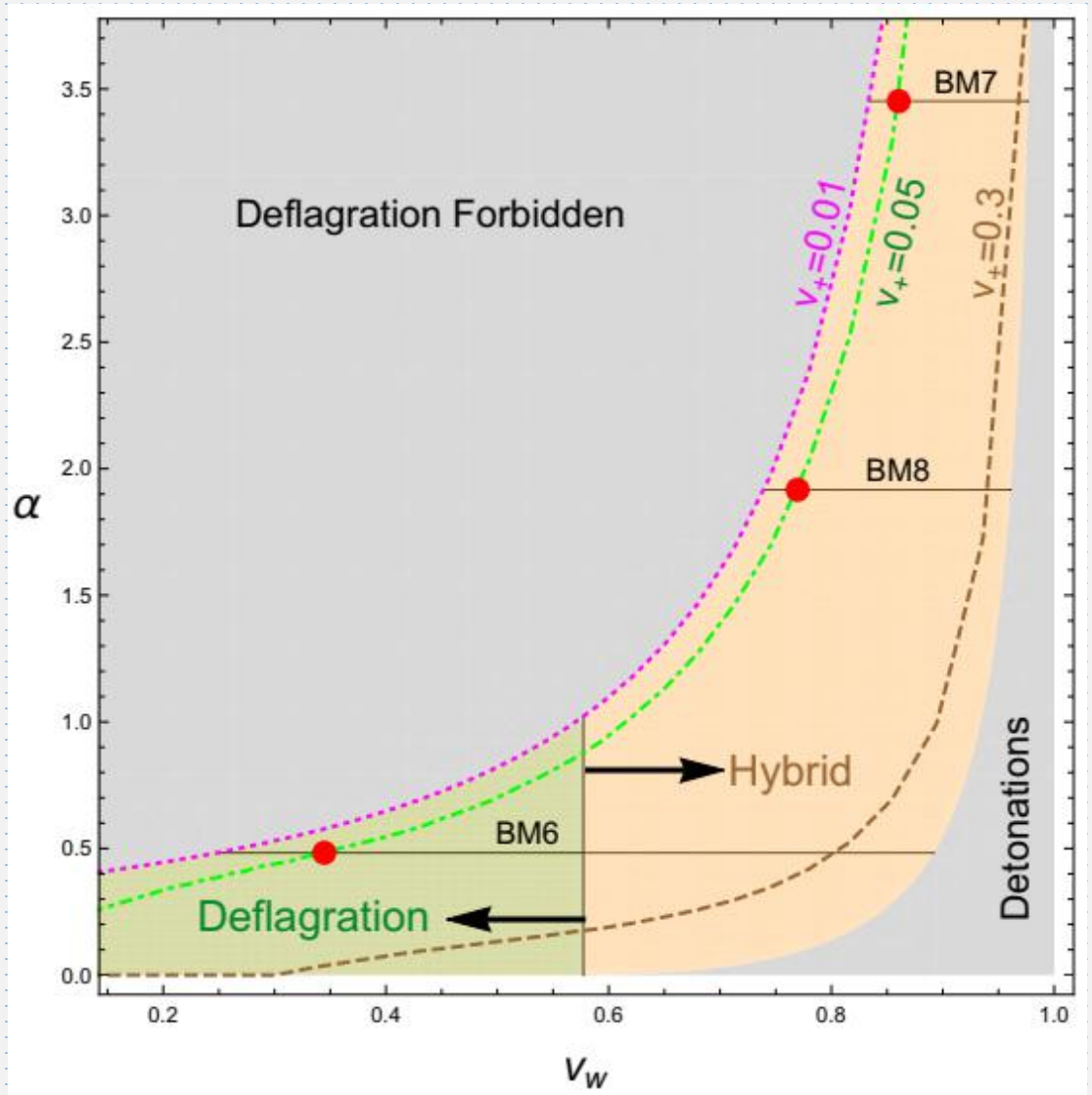




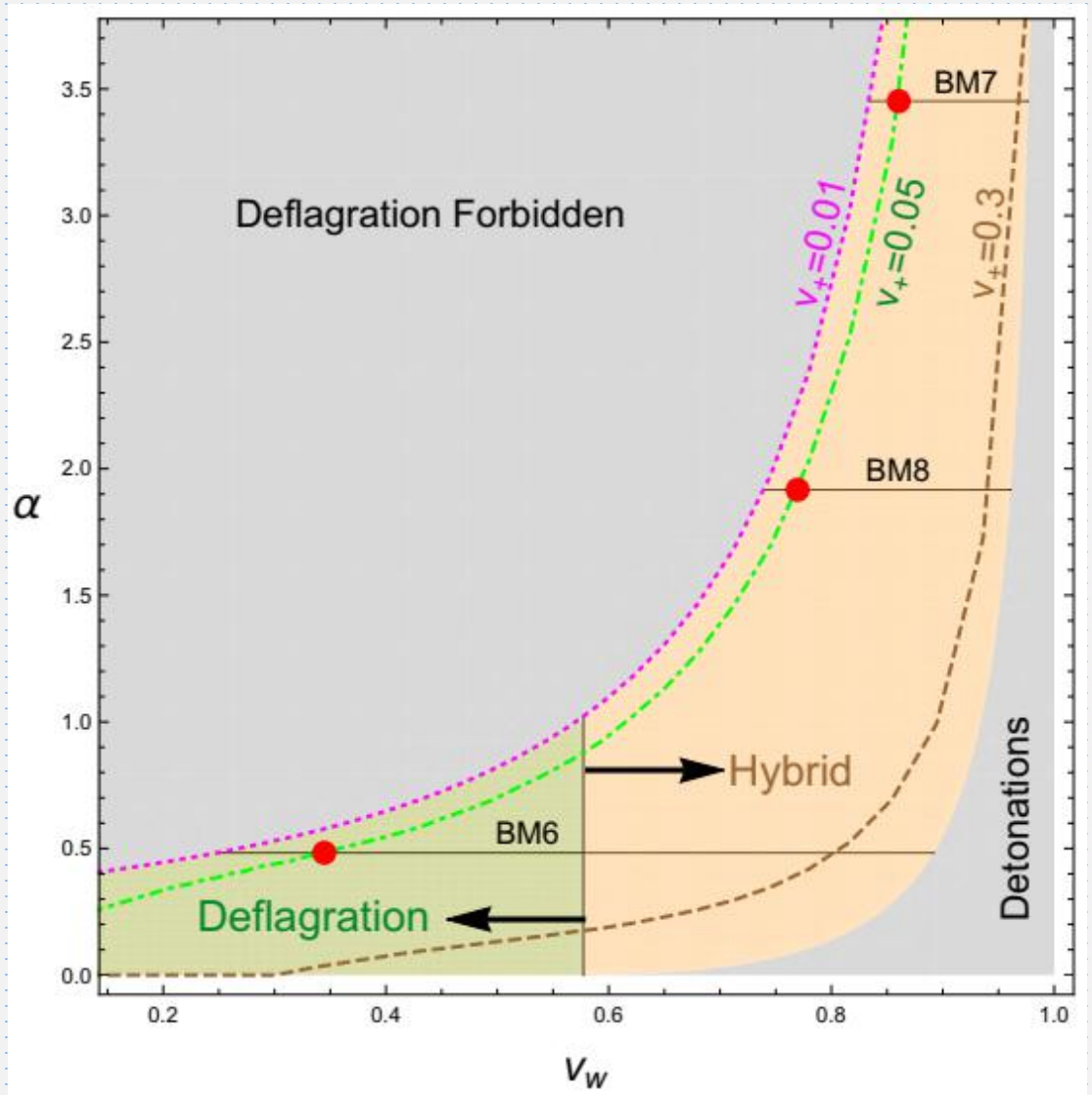


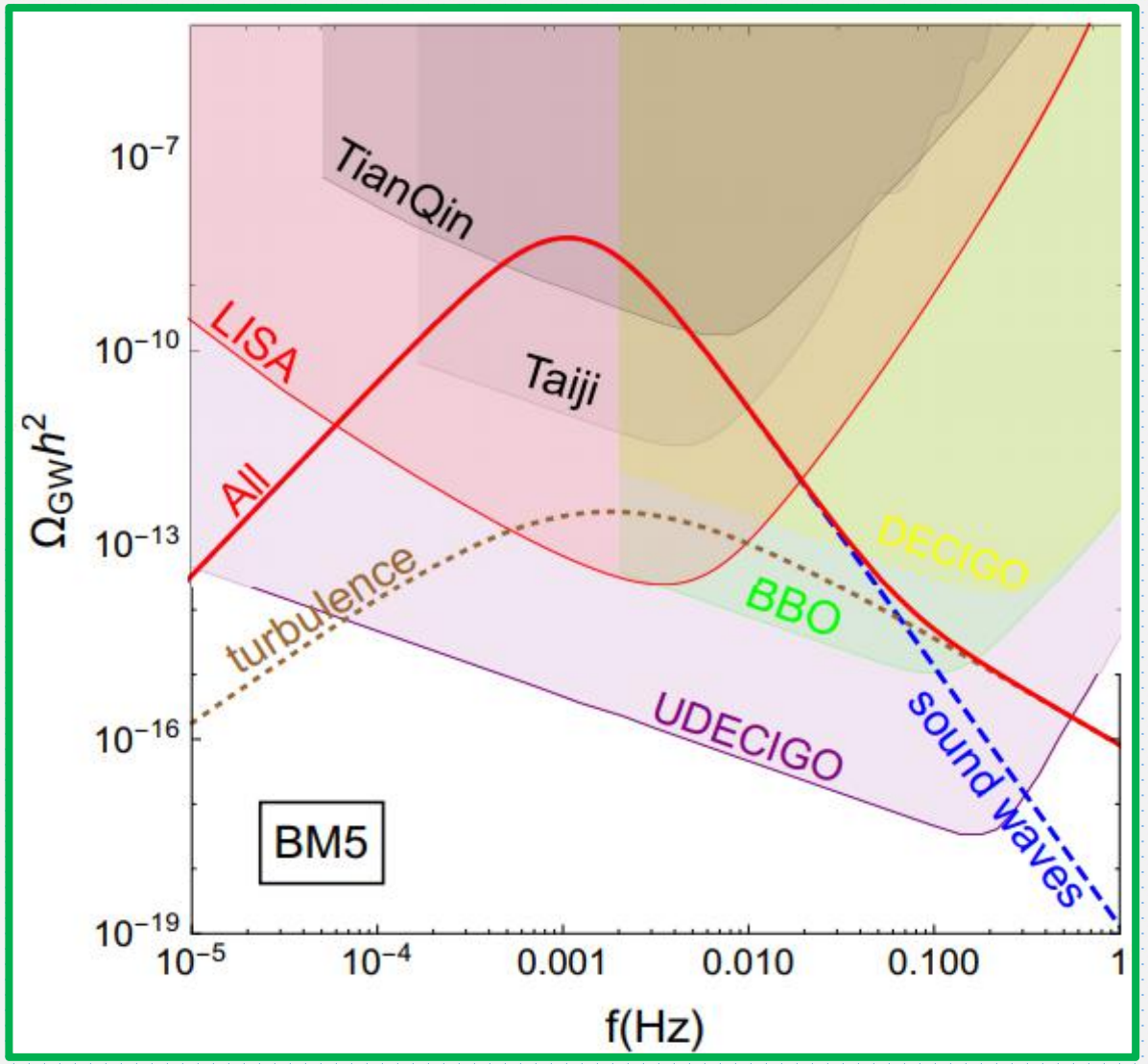
A. Alves, T.G., H. Guo, K. Sinha, arXiv:1808.08974



v_w ($v_+ = 0.05$)
0.766
0.345
0.861
0.770
0.774
0.274
0.164
0.078

A. Alves, T.G., H. Guo, K. Sinha, arXiv:1808.08974





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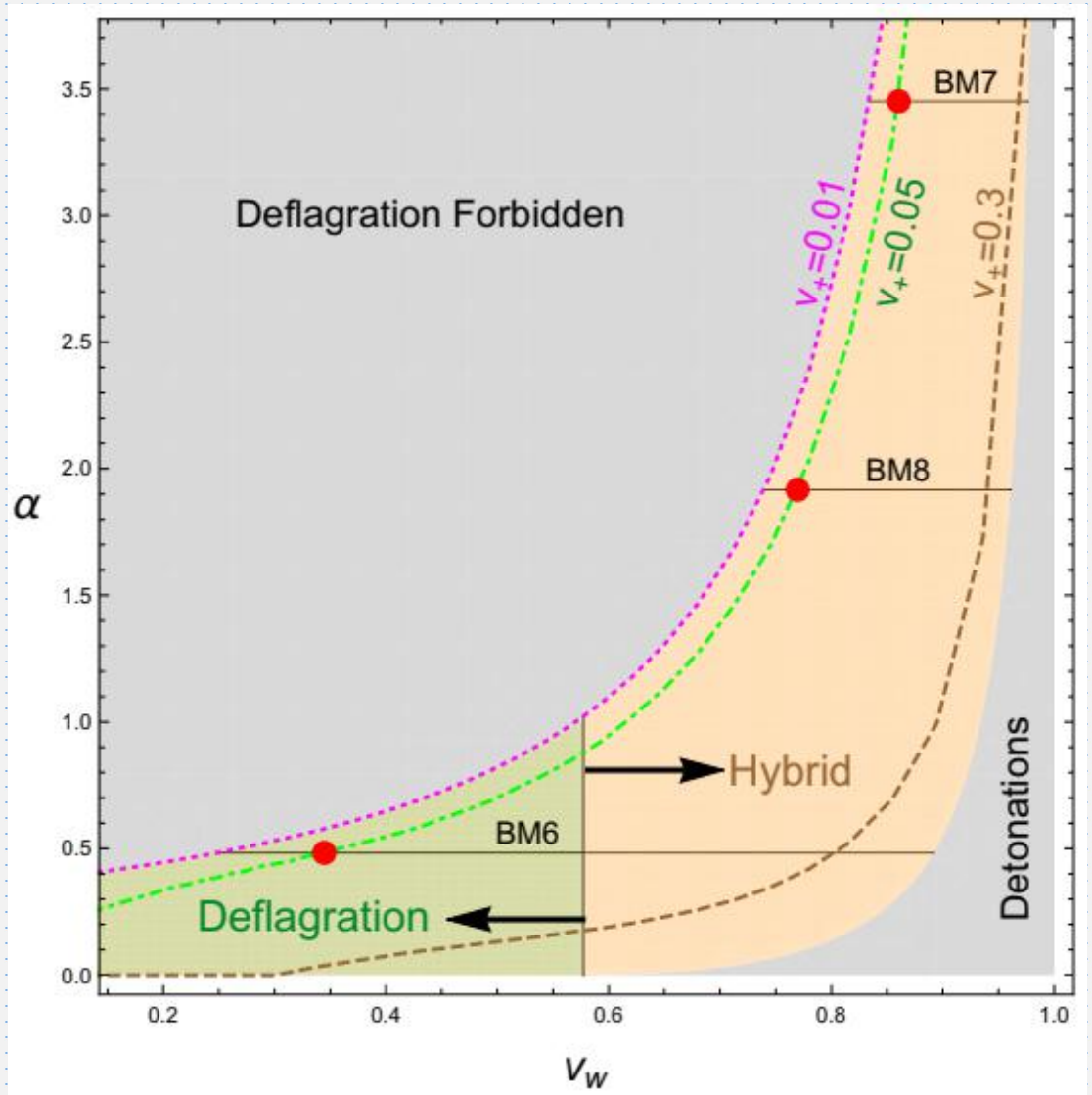

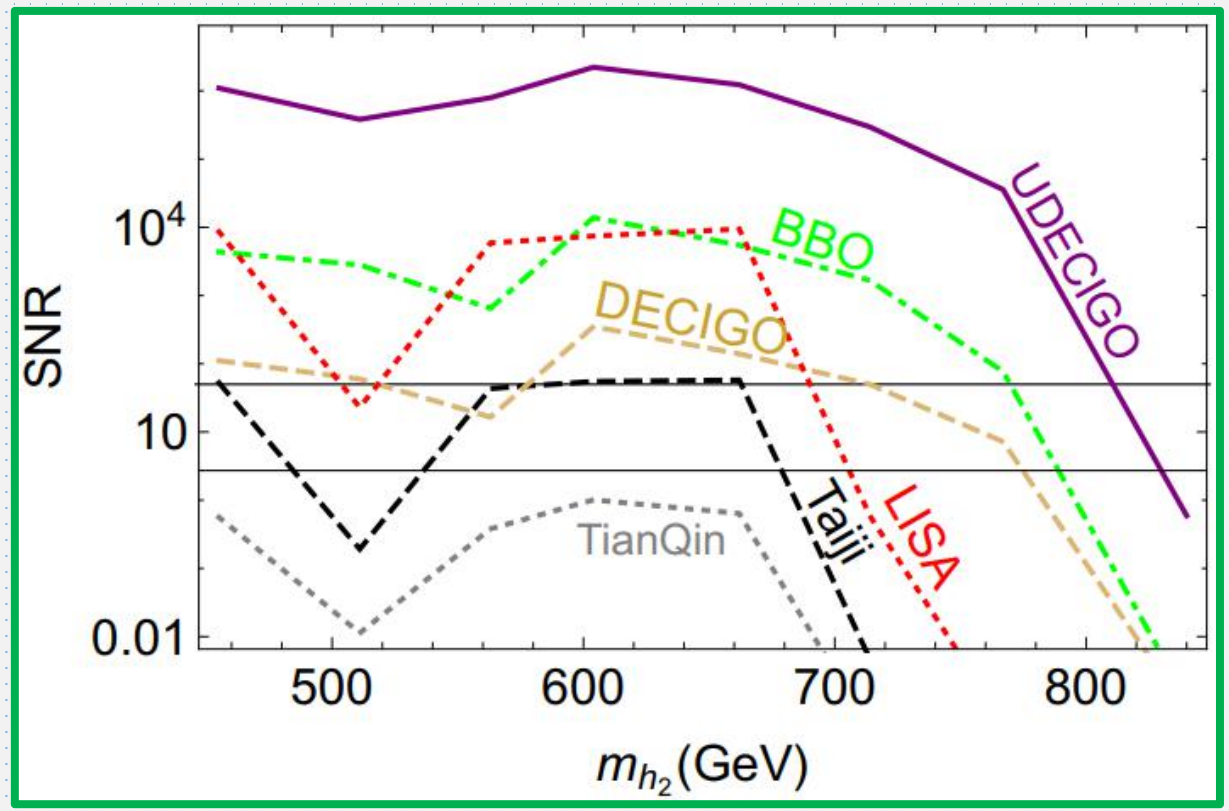

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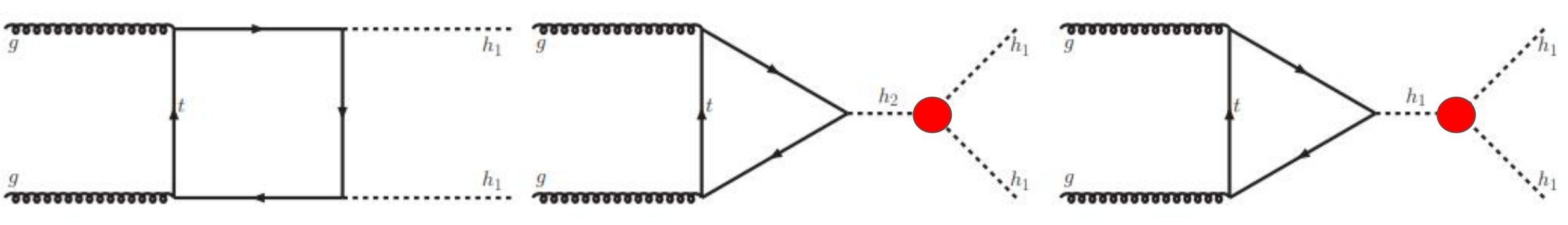
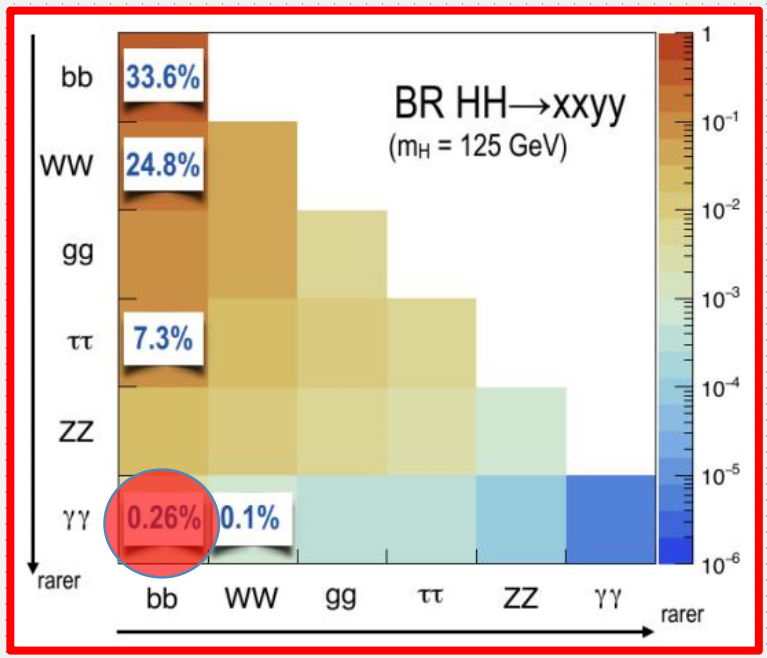


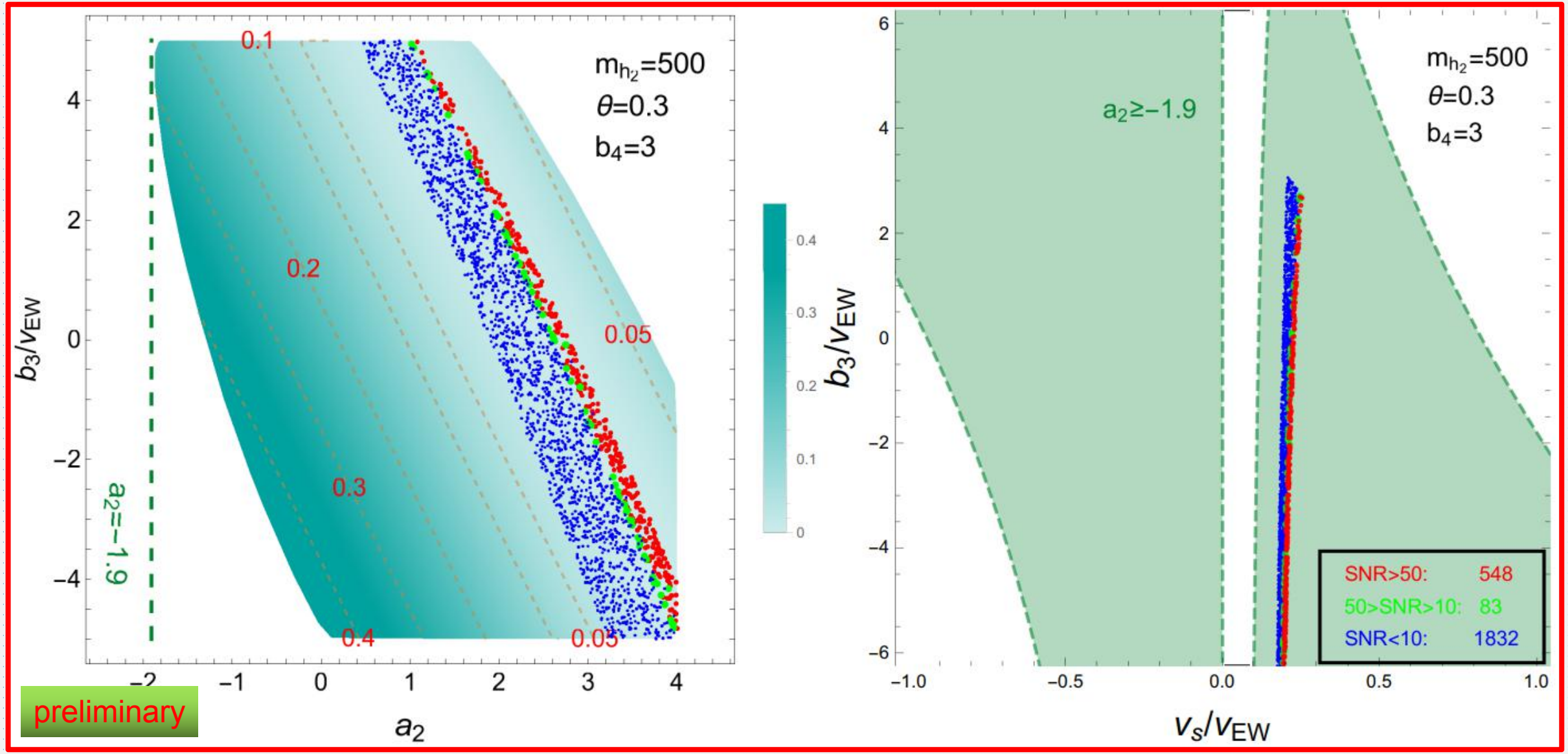
- With cross-checked realistic background simulations
- Taking systematics into account
- Jointly tuning cuts+BDT

Tathagata Ghosh, Fermilab, 2018

BM point	$\varepsilon_{sys}(\%)$	optimized cuts(σ)	S/B	BDT(σ)
BM5	5	3.4	0.9	6.3(6.4)
	10	3.2	1.2	6.1(6.4)
	15	2.9	1.4	5.9(6.4)
BM7	5	1.9	0.8	3.3(3.4)
	10	1.8	0.8	3.2(3.4)
	15	1.7	0.8	3.1(3.4)



While BM5 can be discovered, evidence of BM7 can be found @ 14TeV LHC with 3 ab^{-1}!



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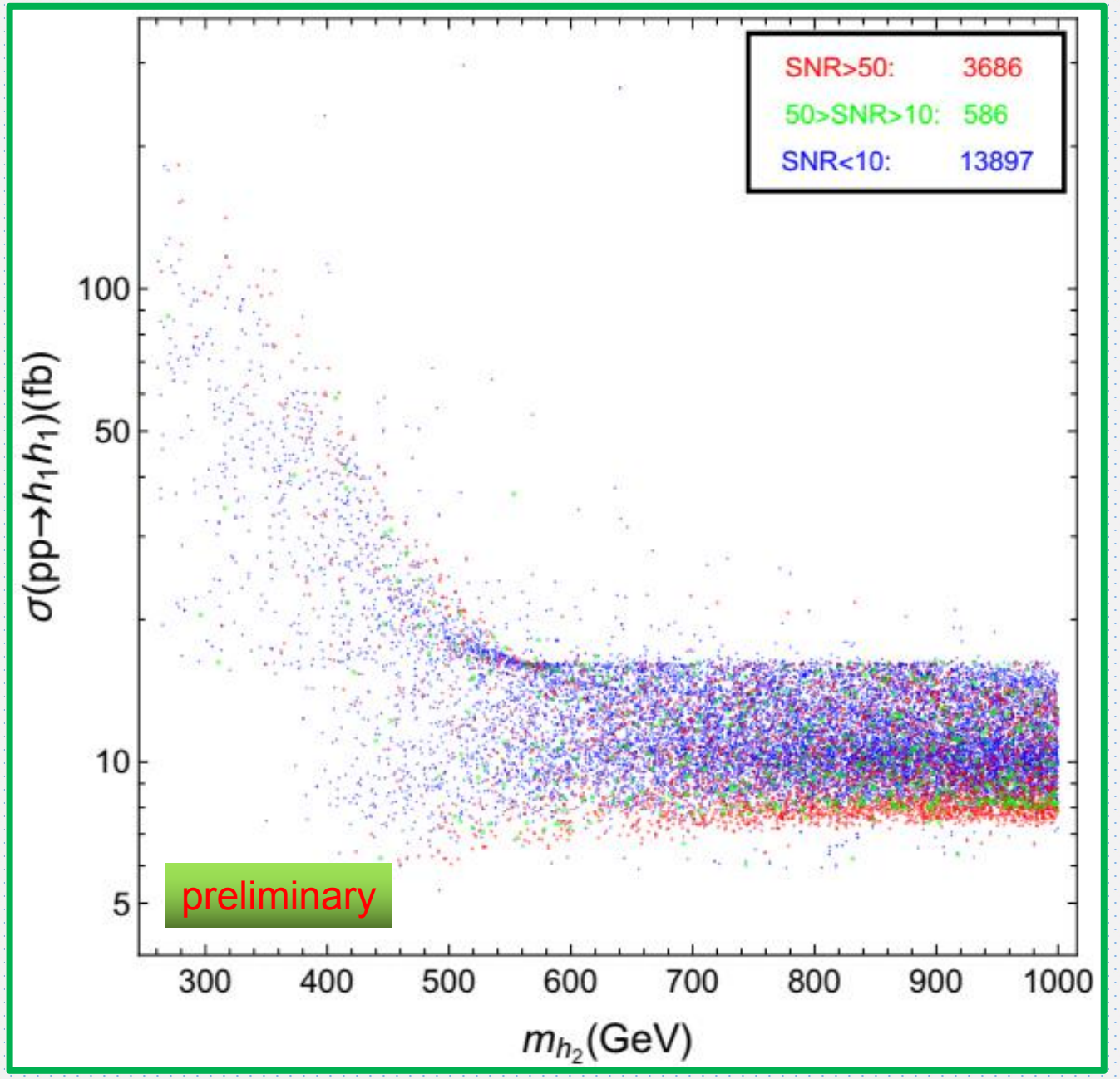

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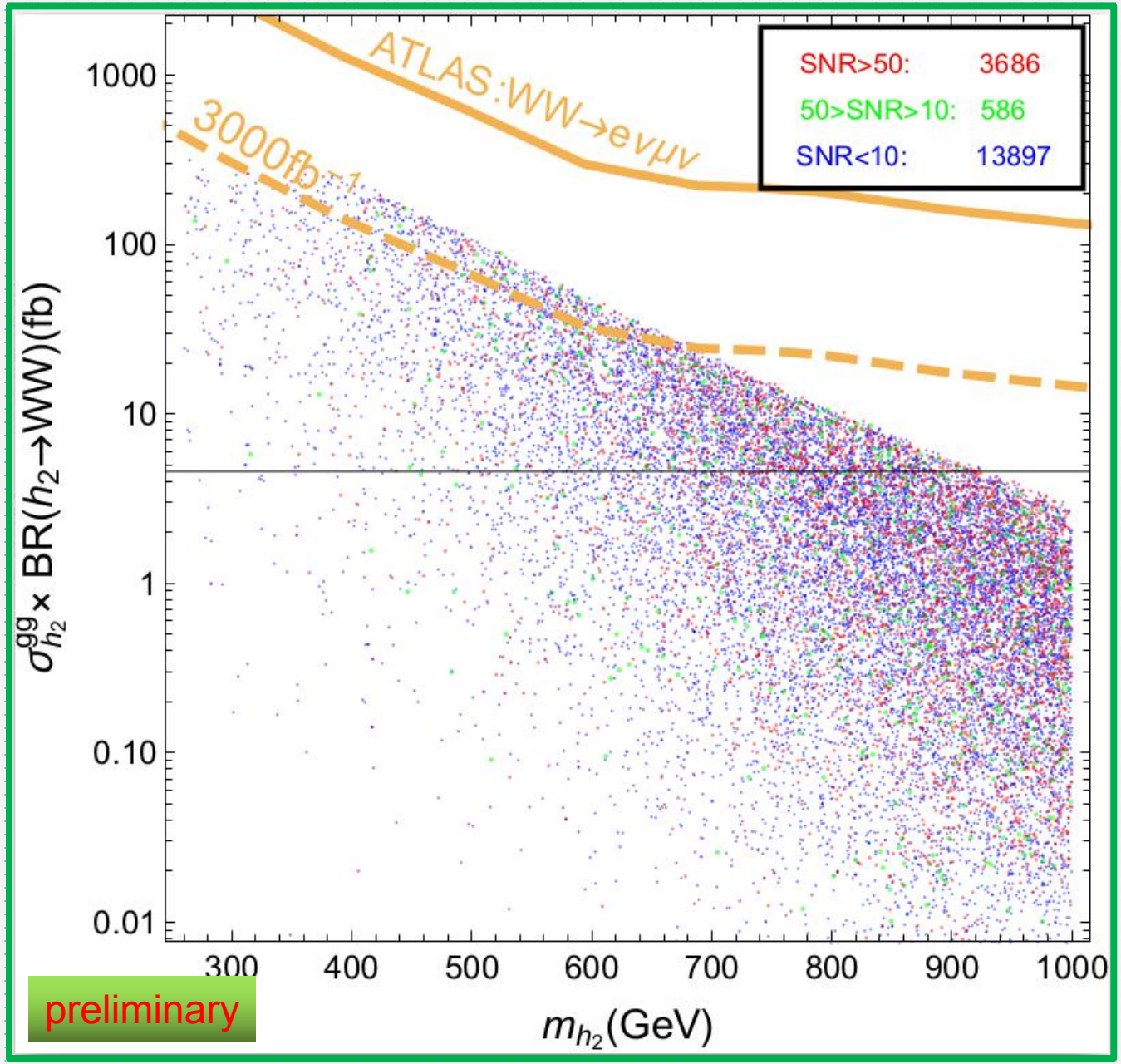

A. Alves, T.G., H. Guo, K. Sinha, D. Vagie [in progress]

Summary

- Gravitational waves from EWPT provides a new window to particle physics
- Hydrodynamic analysis plays an important role
- Theoretical uncertainties exist. More work to be done.

Thanks!