

# Sphalerons, Baryogenesis & Gravitational Waves

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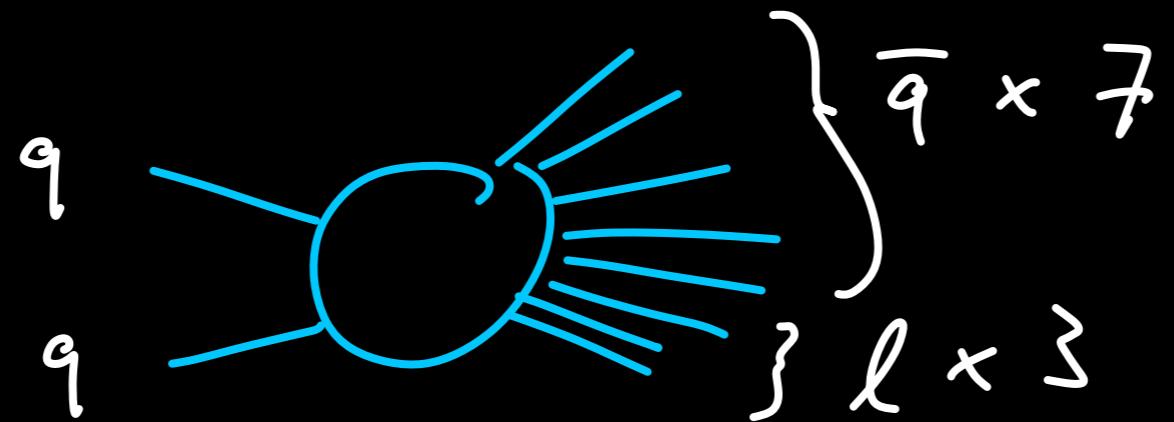
Mainz University

Workshop on topological effects in the SM  
CERN

December 17, 2020

# The Sphaleron

At zero Temperature



$$\Gamma \propto \exp\left(-\frac{E_{sp}}{v}\right) \sim \text{very small}$$

# The Sphaleron S



$$I_{\text{sym}} \propto \alpha^5 T^4$$

$$I_{\text{broken}} \propto \alpha_0^4 \exp\left(-\frac{\epsilon_{sp}}{T}\right)$$

$$\int_0 \sim \exp\left(-\frac{\epsilon_{sp}}{v}\right) \sim \exp\left(-\frac{4\pi}{\alpha_0}\right)$$

# High- $T$ Sphaleron

$$\Gamma_{\text{sph}} = (8.24 \pm 0.10) \left(\frac{N}{2}\right)^5 \frac{g^2 T^2}{m_D^2} \left( \log \frac{m_D}{g^2 T} + 3.041 \right) \alpha^5 T^4$$

Boedeker, hep-ph/9801430  
 Moore, hep-ph/0001216

In thermal equilibrium

below

$T_{\text{ss}}$	$2.4 \times 10^{13} \text{ GeV}$	strong sphaleron
$T_{\text{ws}}$	$1.8 \times 10^{12} \text{ GeV}$	weak sphaleron

Garbrecht, PS, 1404.2915

(high scale)

Affect washout rate in Leptogenesis

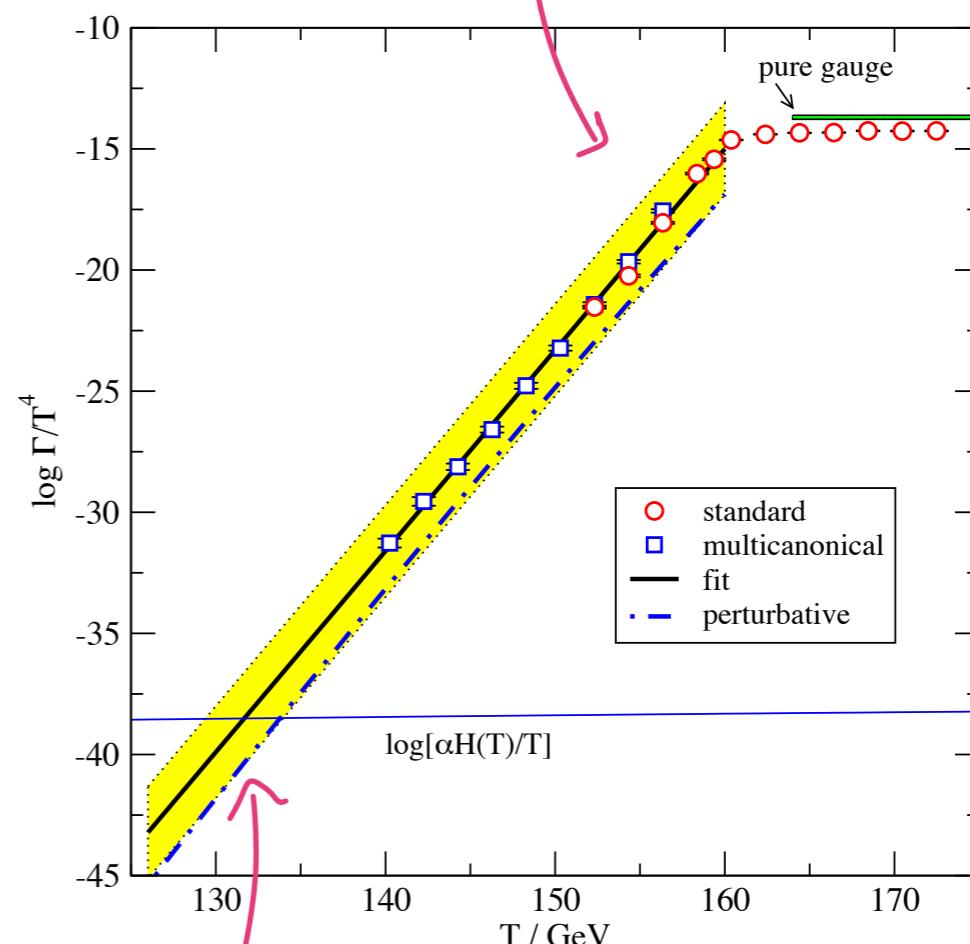
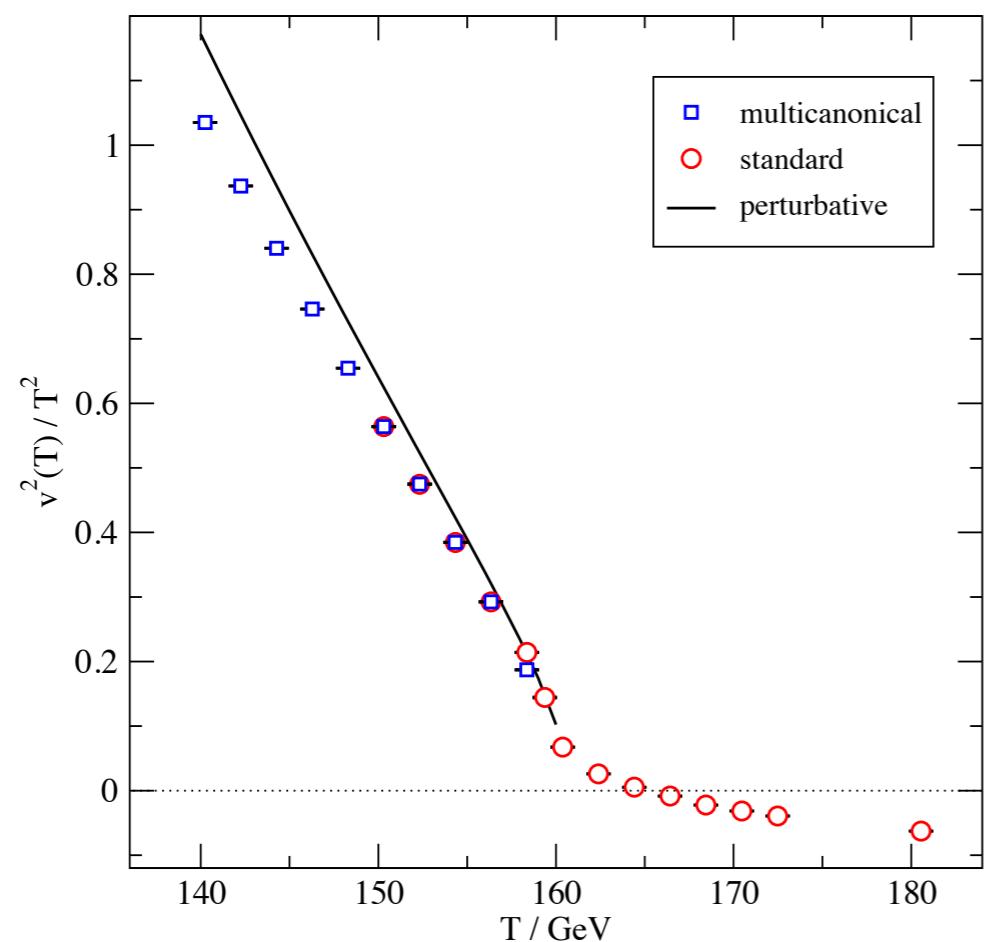
- strong  $q_L \leftrightarrow q_R$

"spectator effects"

- weak  $\beta \leftrightarrow L$

# Weak scale sphaleron

exponential suppression starts

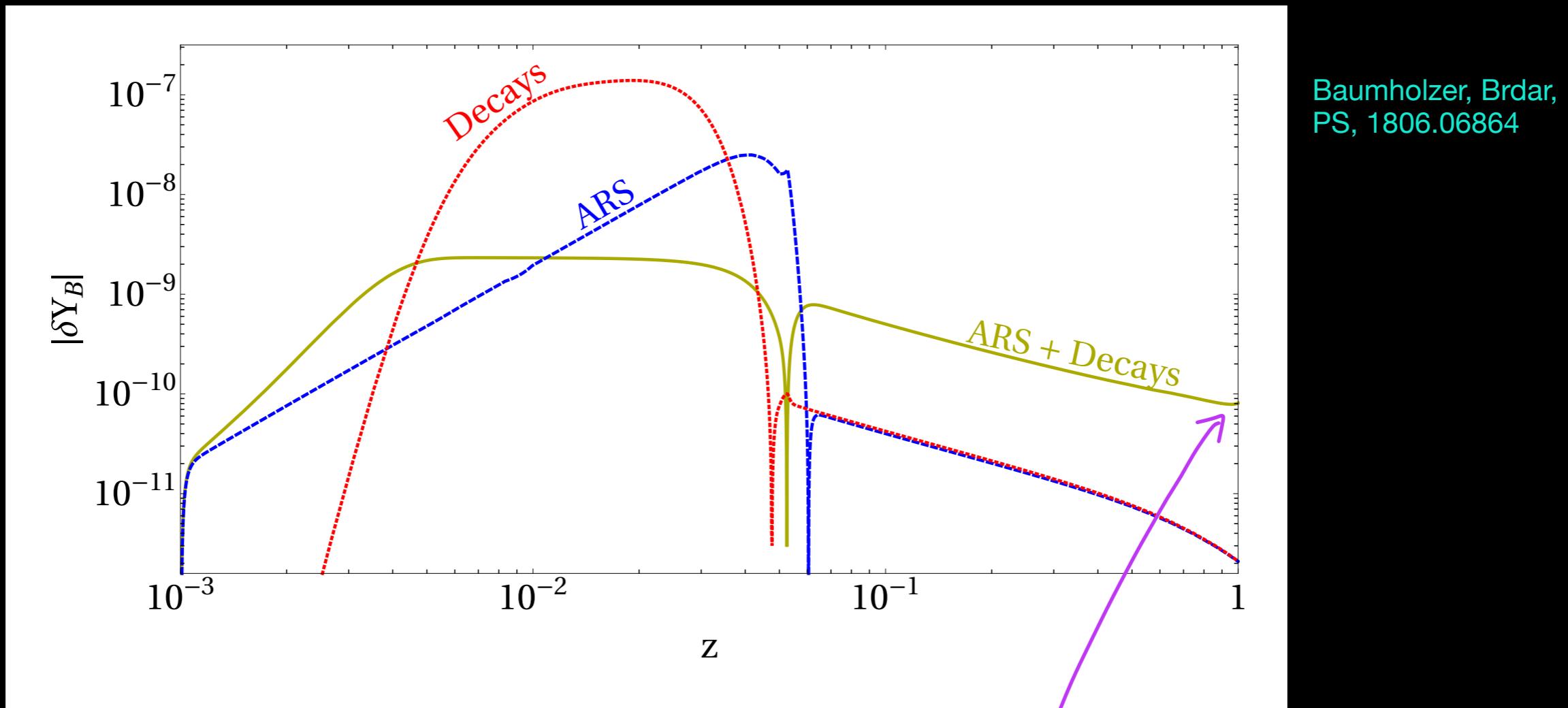


freeze-out  
 $\Gamma/H < 1$

D'Onofrio, Rummukainen,  
Tranberg, 1404.3565

# Weak scale sphaleron

Relevant e.g. for low scale leptogenesis scenarios  
& electroweak Baryogenesis



$$z = \frac{T_{\text{sph}}}{T}$$

this value of the baryon  
asymmetry frozen in?

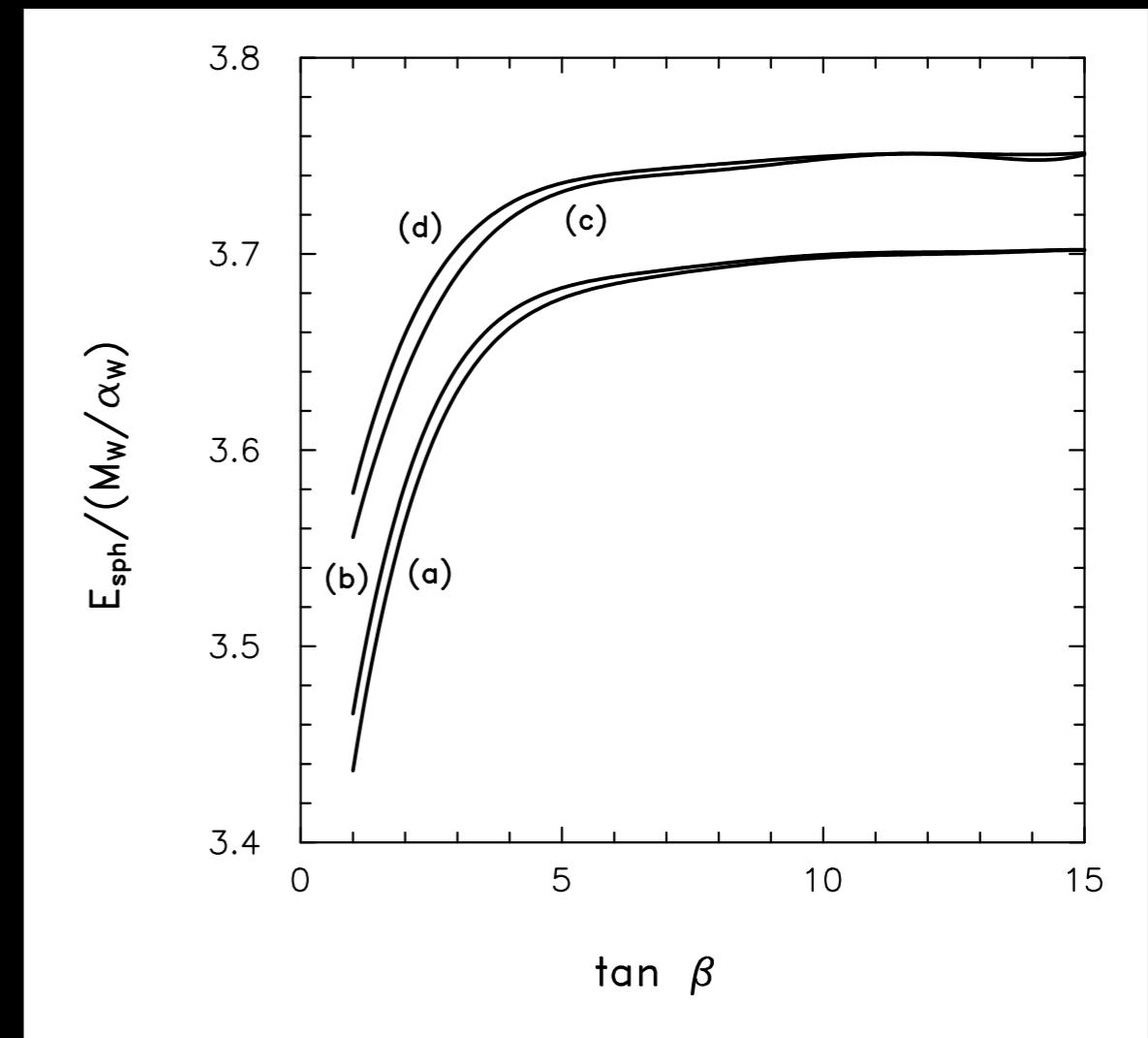
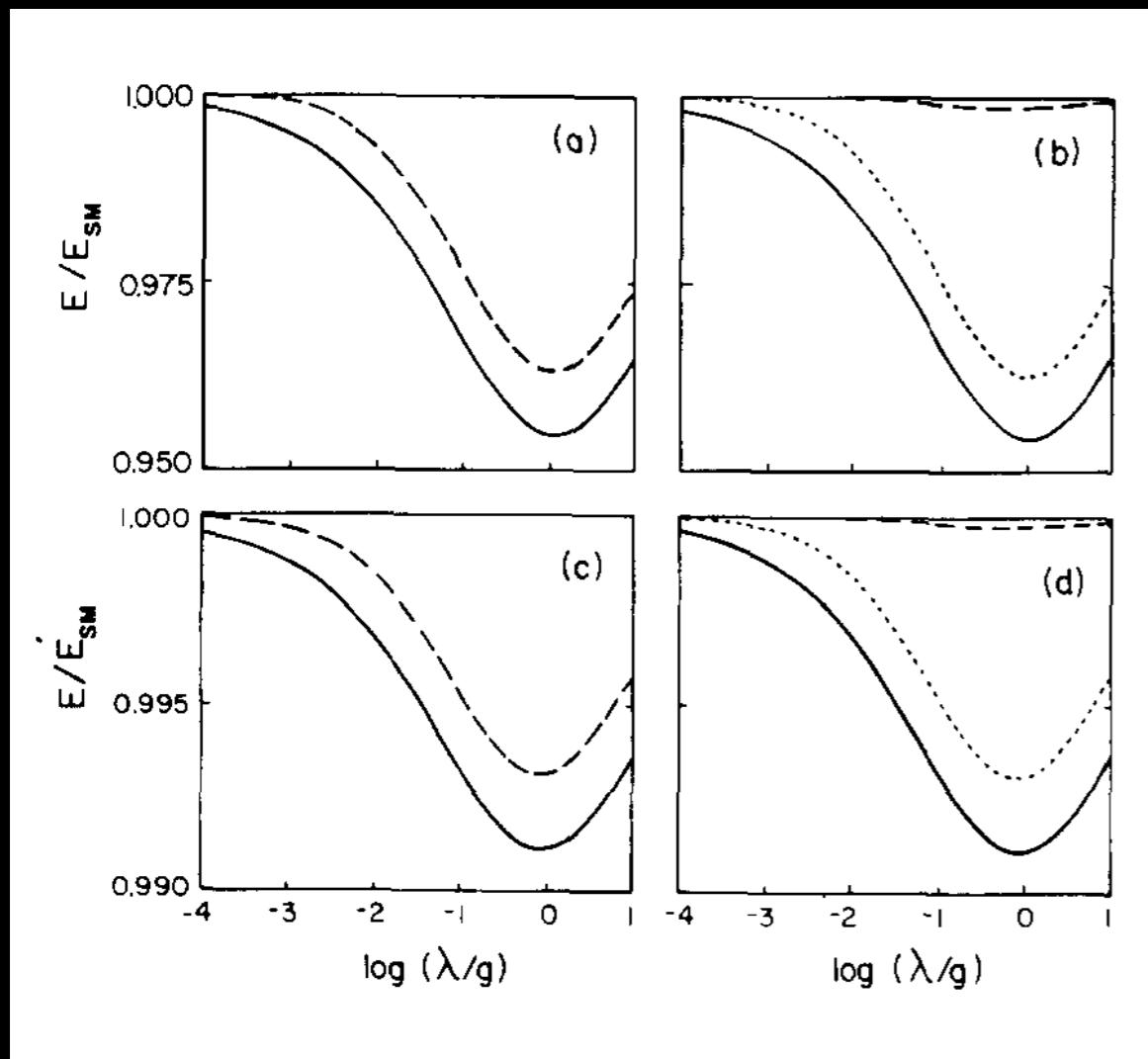
# Changing sphaleron

- High  $T$ : pure gauge theory
  - ↳ change RGE running
  - ↳ embed  $SU(2)$  in larger group
- Low  $T$ : modify Higgs potential
  - ↙ extend Higgs sector
  - change  $E_{\text{sph}}$   $\longrightarrow$  also affect zero  $T$  rate

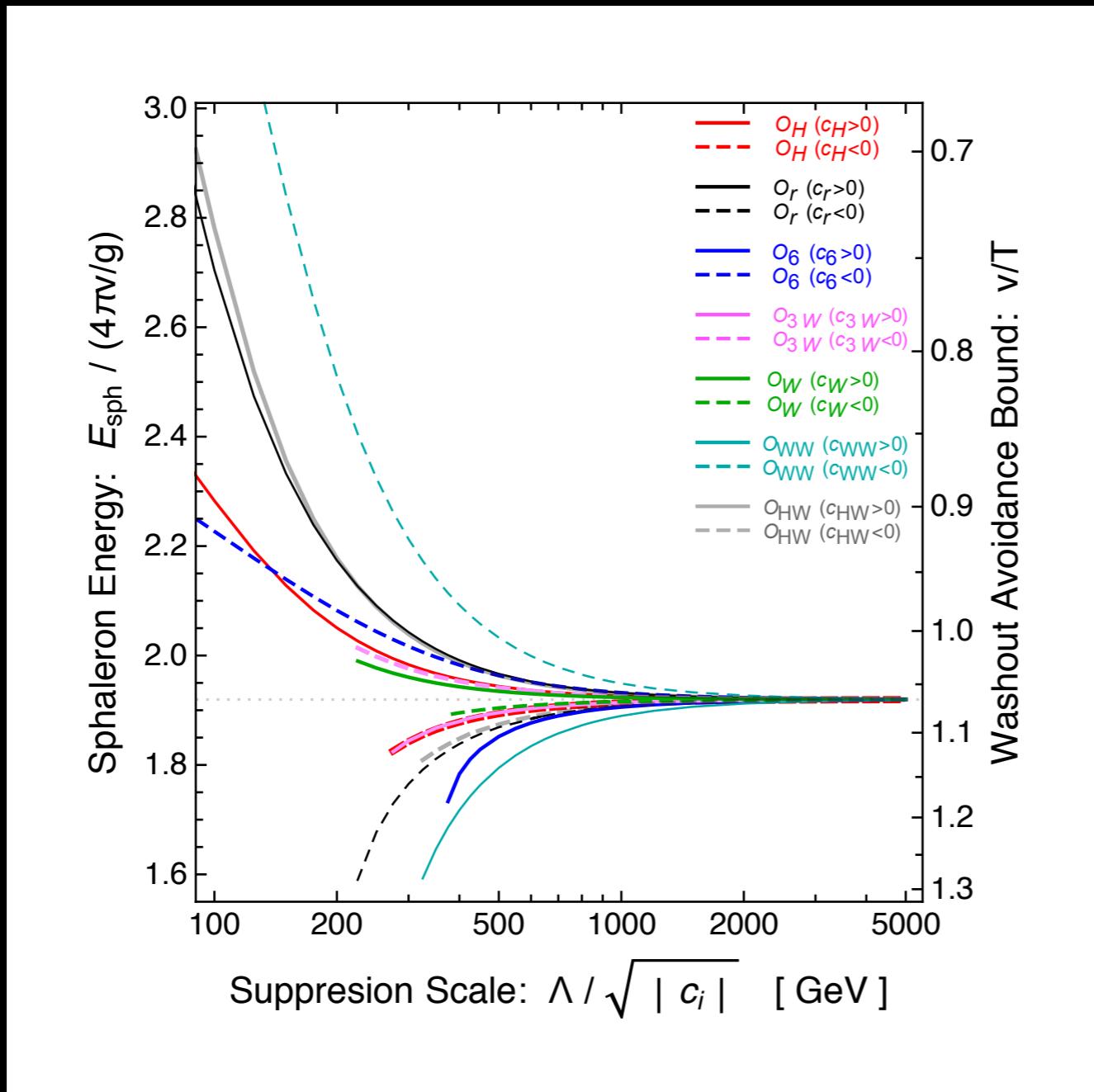
1990 S

singlet extension

MSSM

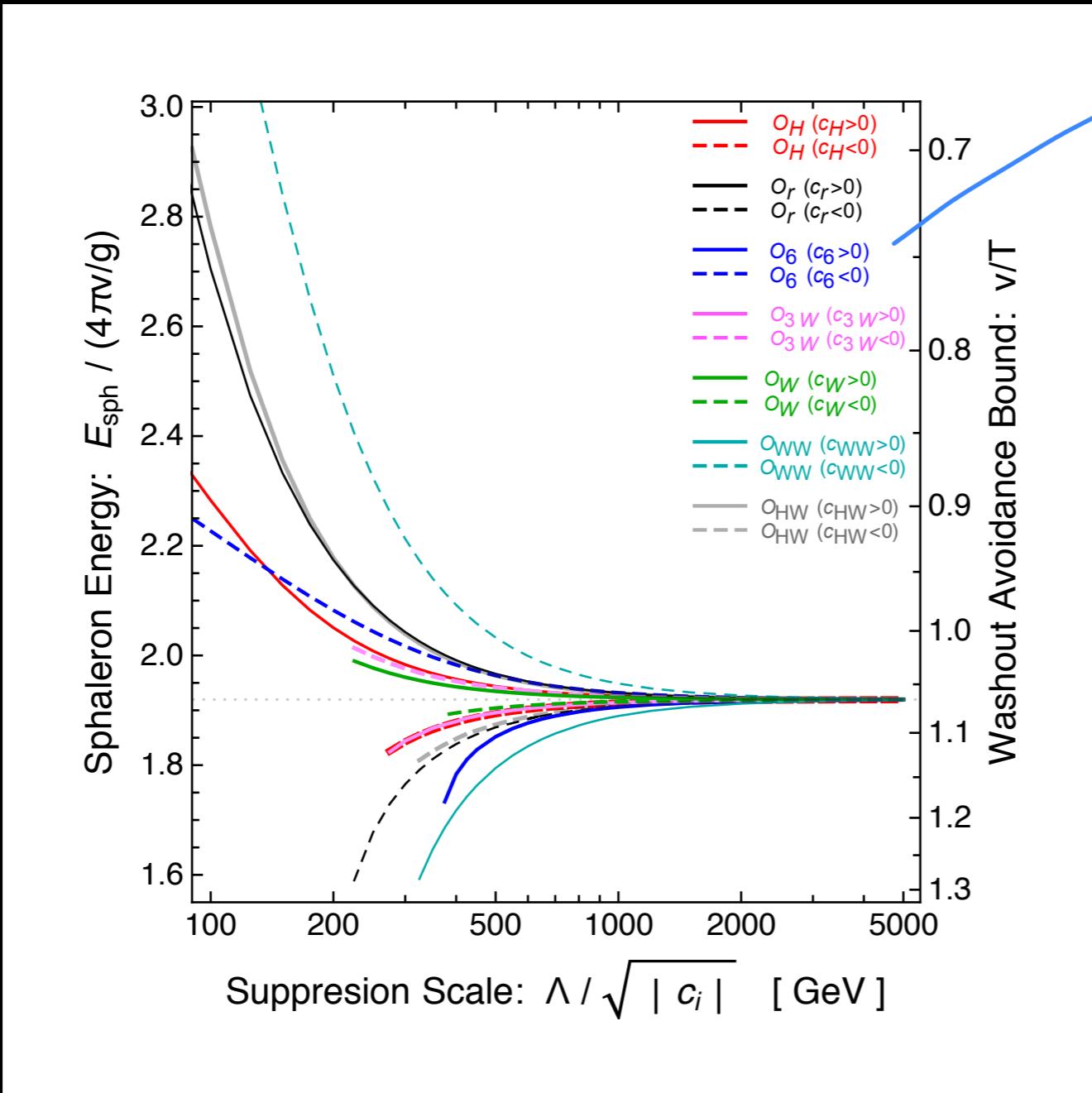


# 2010s - EFT



Gan, Long, Wang, 1708.03061

# 2010s - EFT



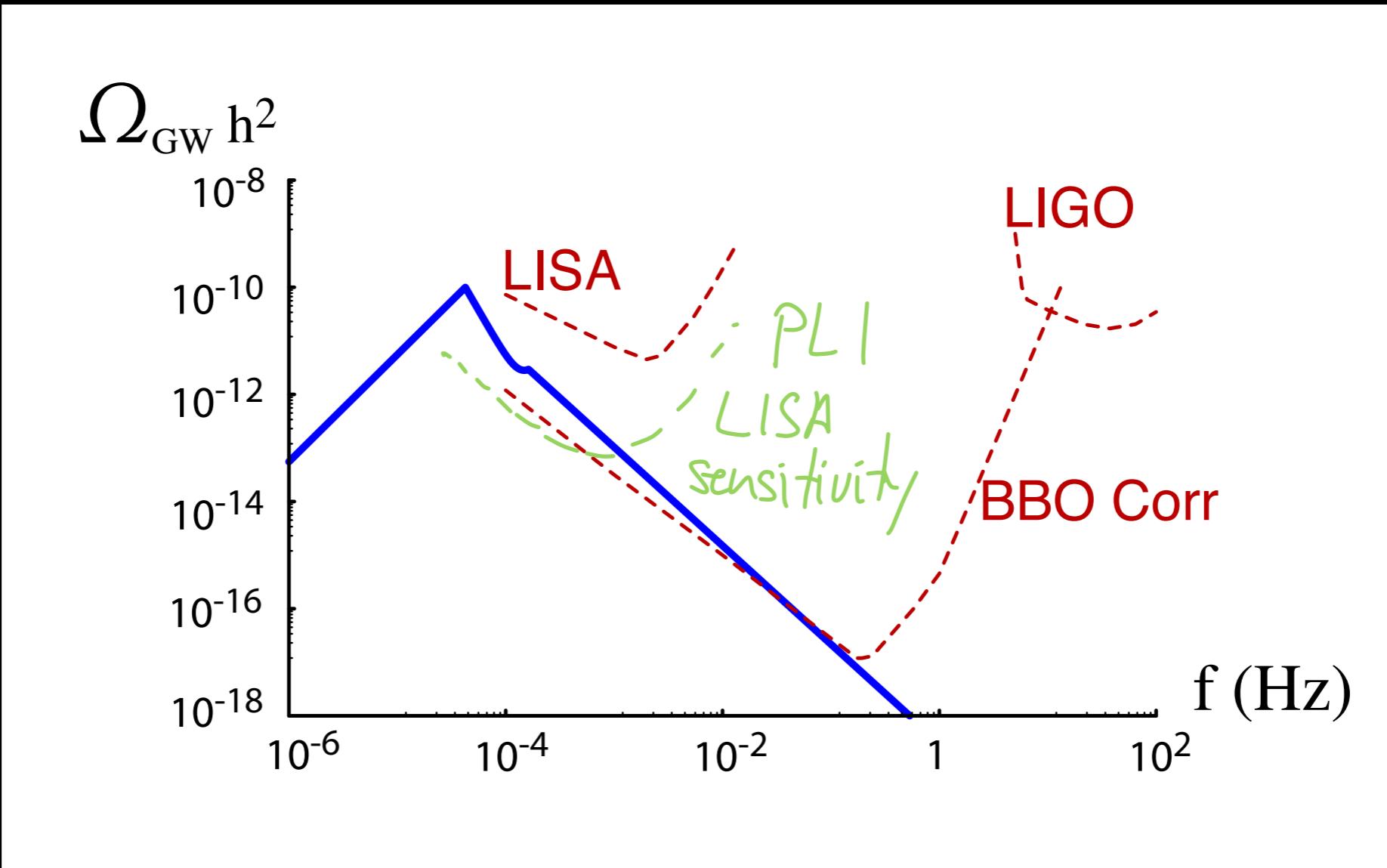
Gan, Long, Wang, 1708.03061

$$\frac{c_i}{\Lambda^2} (H^\dagger H)^3$$

For  
 $500 \text{ GeV} < \Lambda < 800 \text{ GeV}$   
 EWPT is first  
 order

Grojean, Servant, Wells,  
 hep-ph/0407019

# GW's in $SM + H^6$

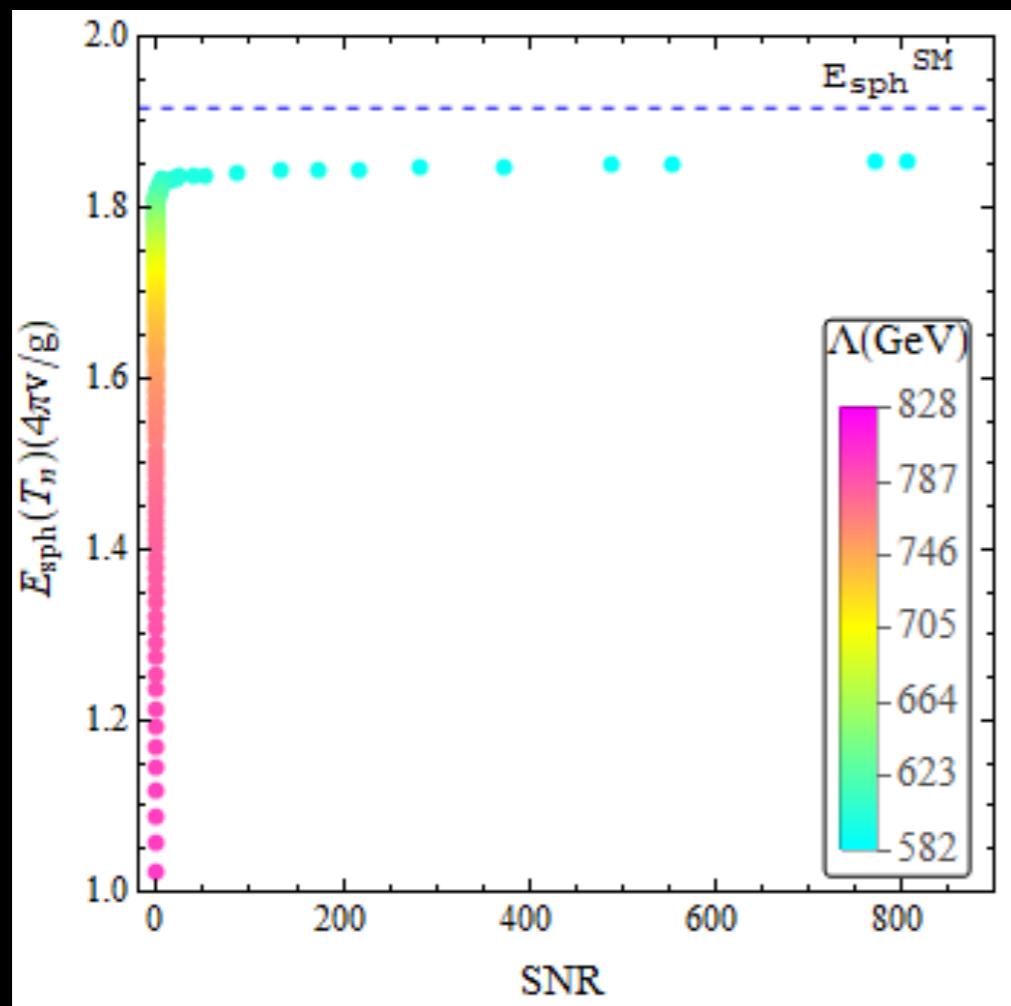


Delaunay, Grojean, Wells, 0711.2511

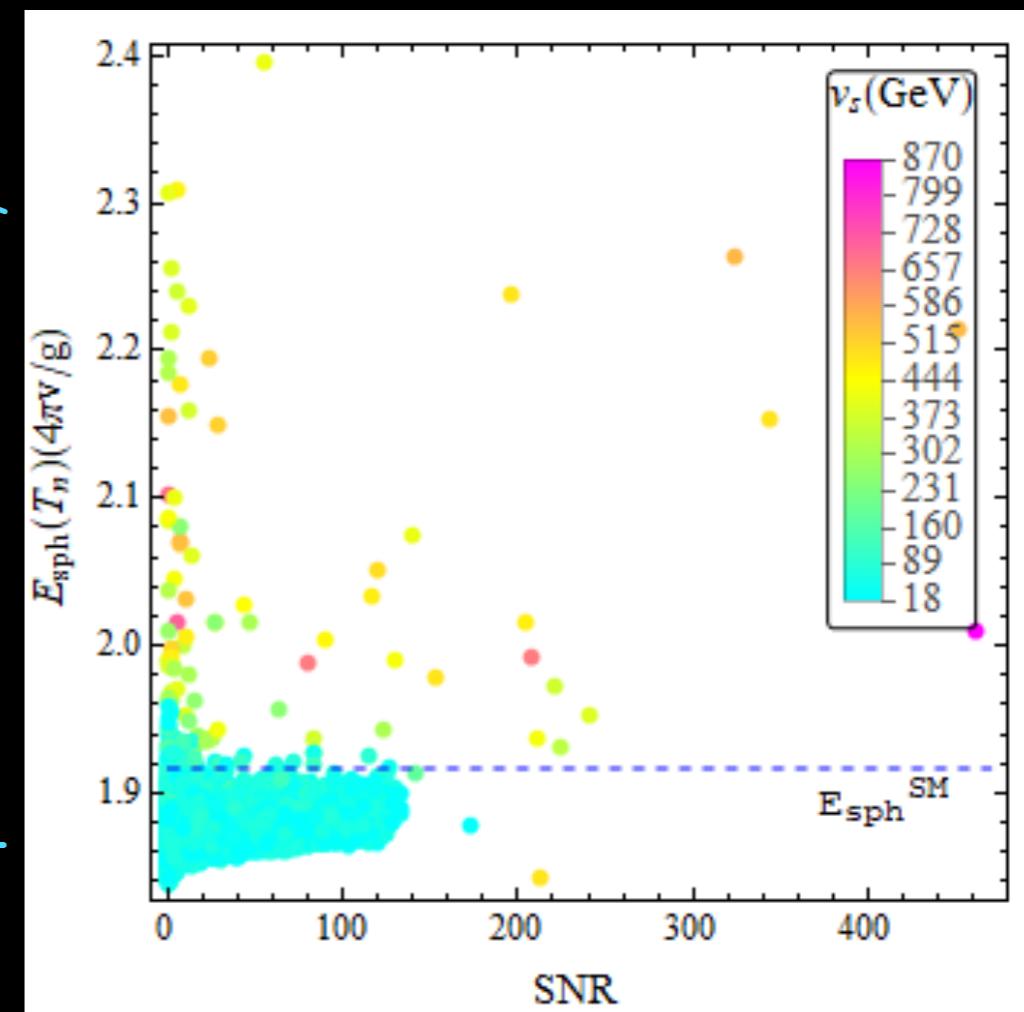
GW -  $E_{\text{sp}}$  correlation ?

$$\frac{1}{\Lambda^2} \left( H^+ H^- \right)^3$$

singlet with  $\langle \phi \rangle = v_s$



Sphaleron energy

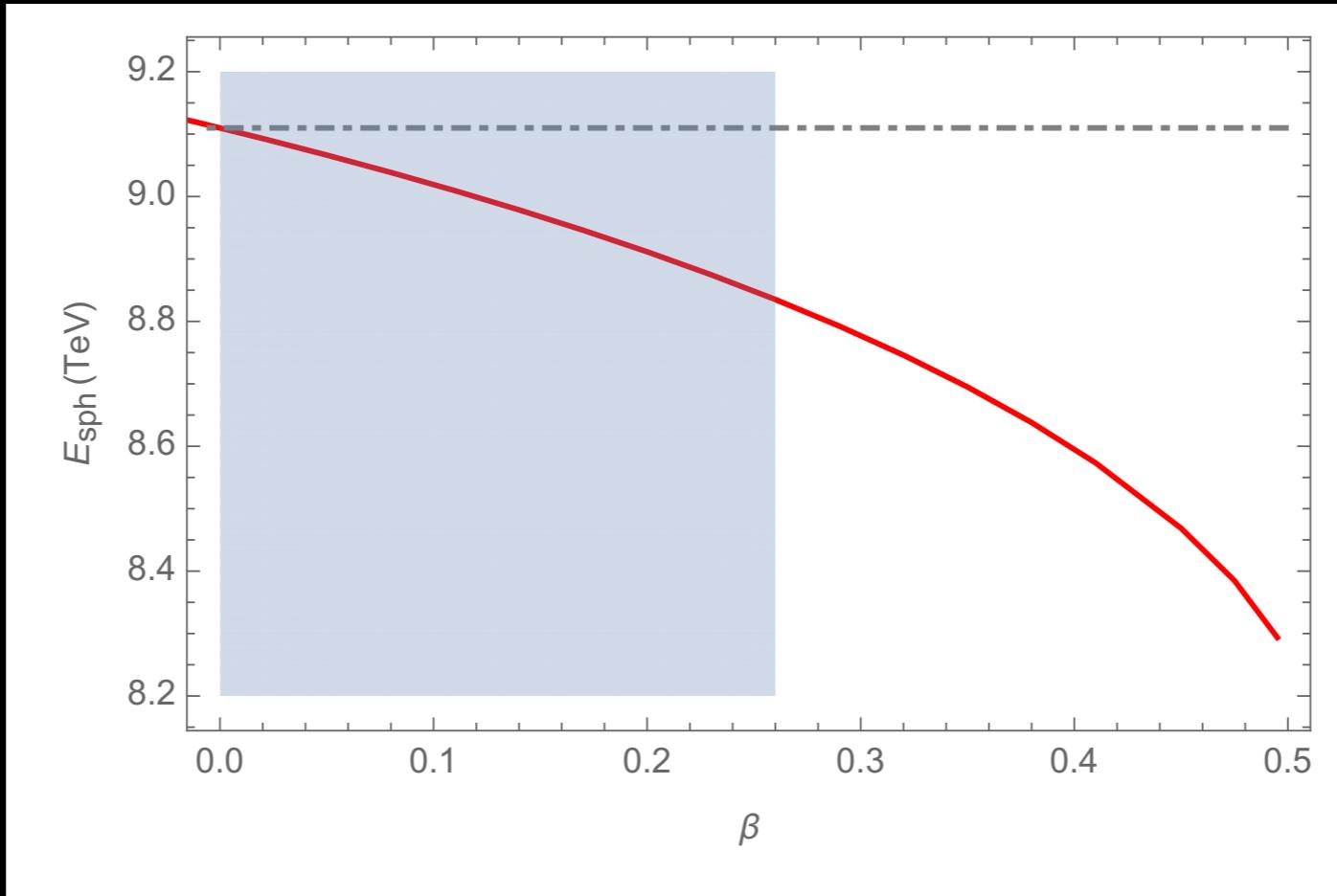


GW signal  
detectability @ LISA

(SNR > 10 (50))

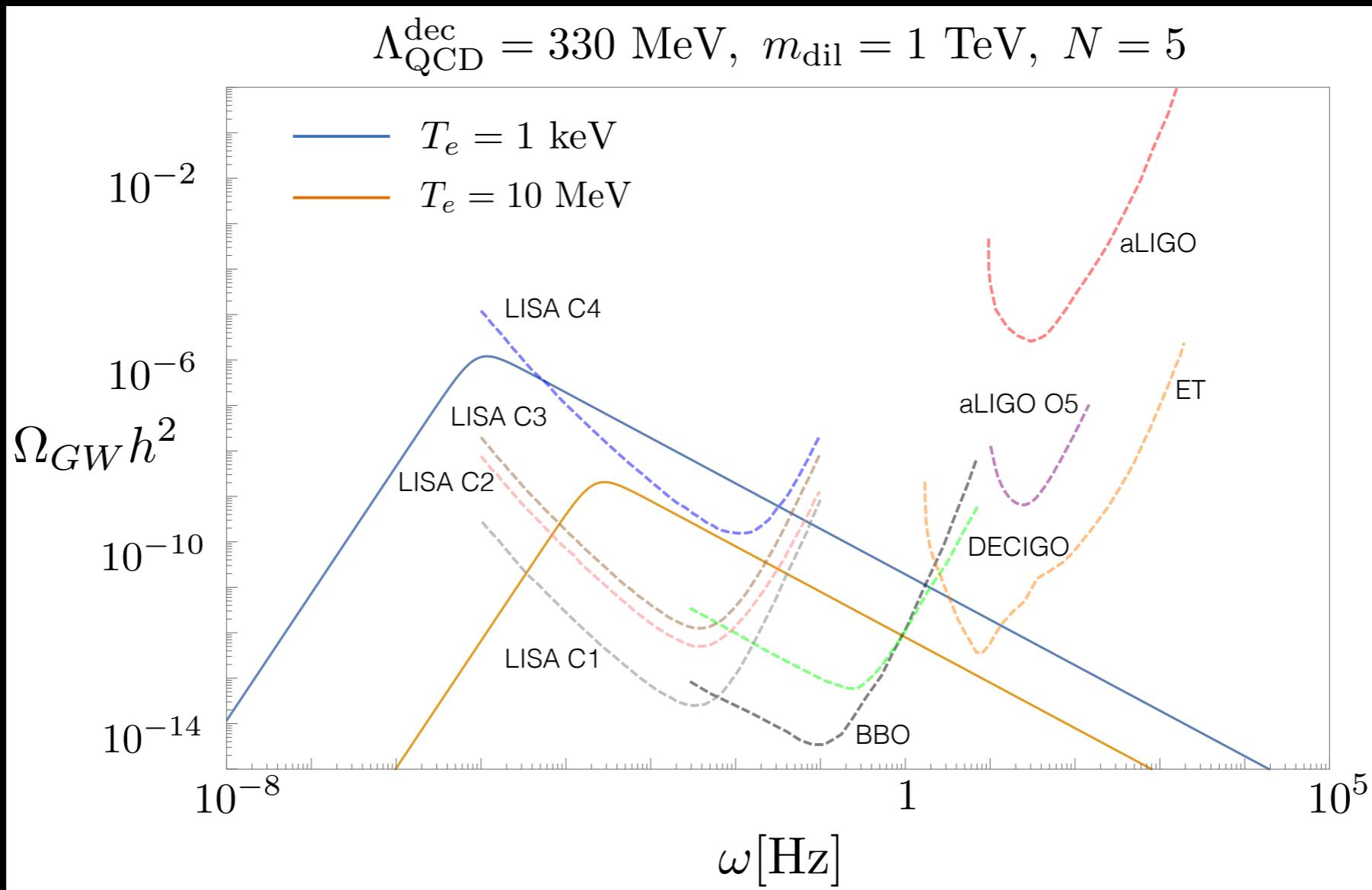
# Also : Composite Higgs

$$V(H) = V_0 + m_H^2 H^\dagger H + (H^\dagger H)^2 \left( -\lambda + \beta \log \left[ \gamma + \frac{2H^\dagger H}{\phi_0^2} \right] \right)$$



Spannowsky, Tamarit, 1611.05466

# Composite Higgs & GW's

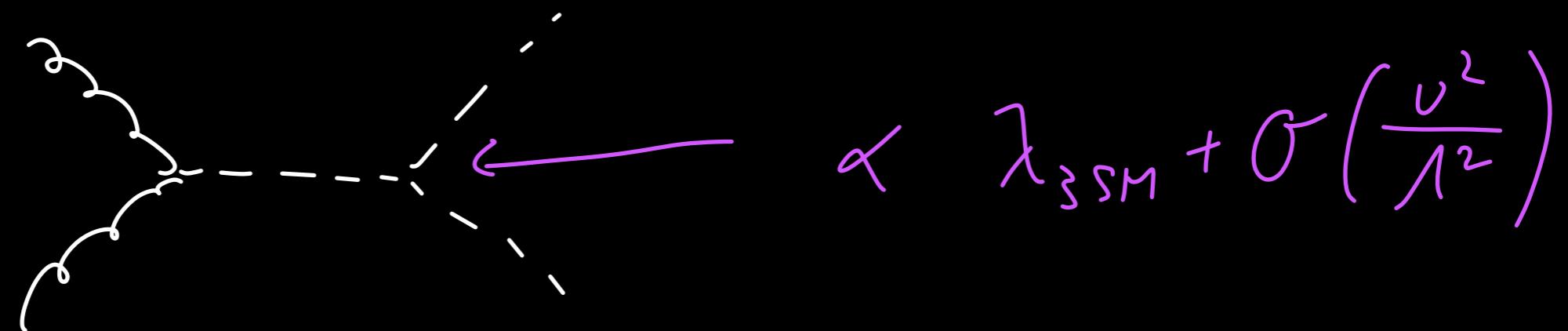


Baratella, Pomarol, Rompineve, 1812.06996

see also Bruggisser, von Harling, Matsedonskyi, Servant, ...

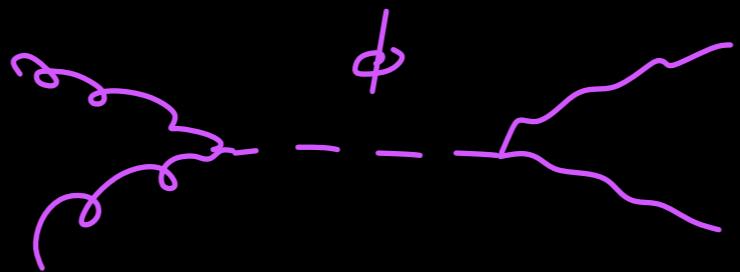
# Collider probes

$\frac{1}{\lambda^2} H^6$  double Higgs production



# Collider probes

singlet  
extension



di-photon , etc .

composite  
warped

- modified Higgs couplings  $(1 - \frac{v^2}{f^2})$
- light dilaton, radion

sphaleron directly ... unclear

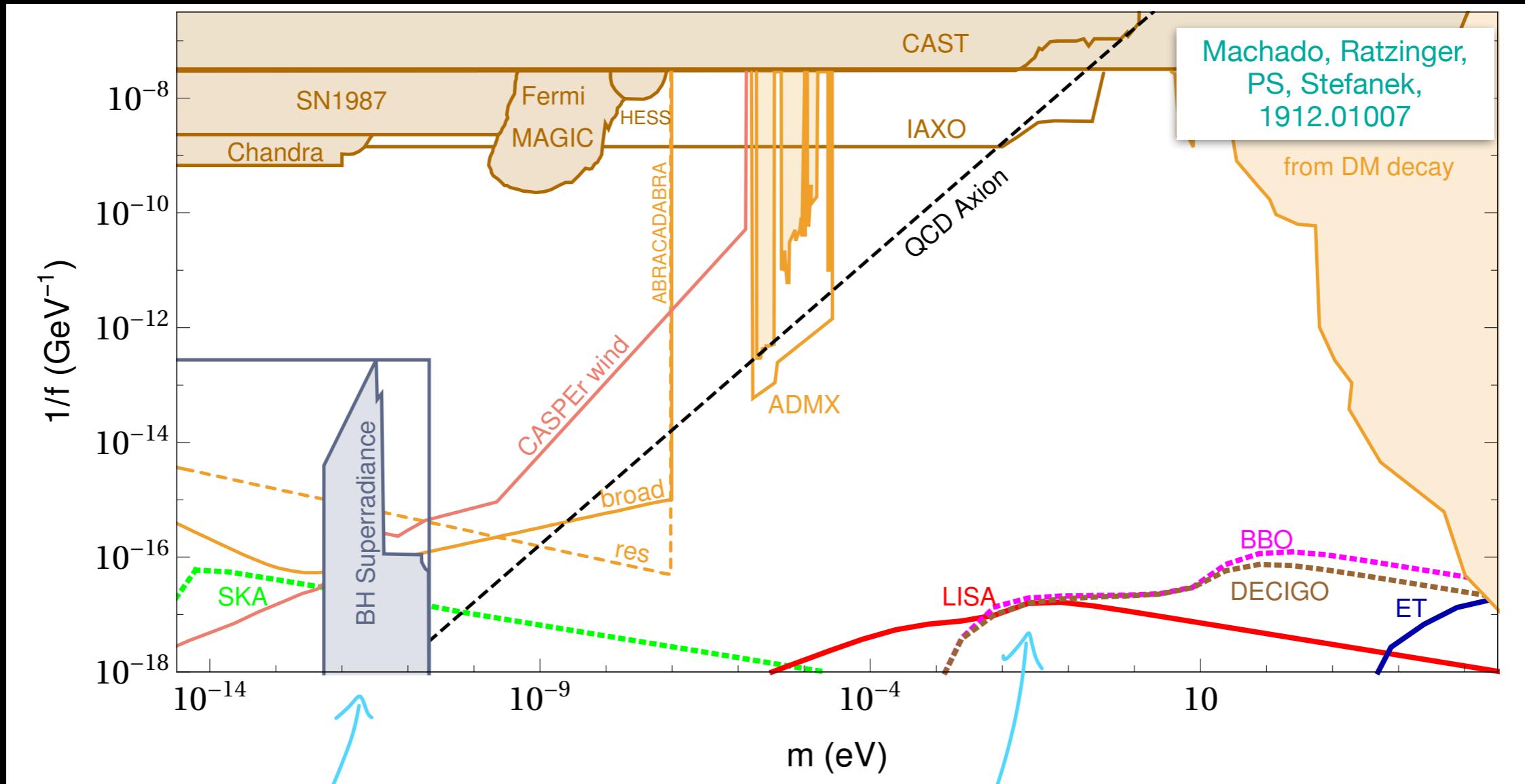
# Instantons

- unsuppressed at scales  $>$  few GeV
- axion couples to derivative of CS-current

$$\frac{a}{f} G \tilde{G}$$

- Any effect on instanton rates
  - ↳ what if we are in a coherent axion background?

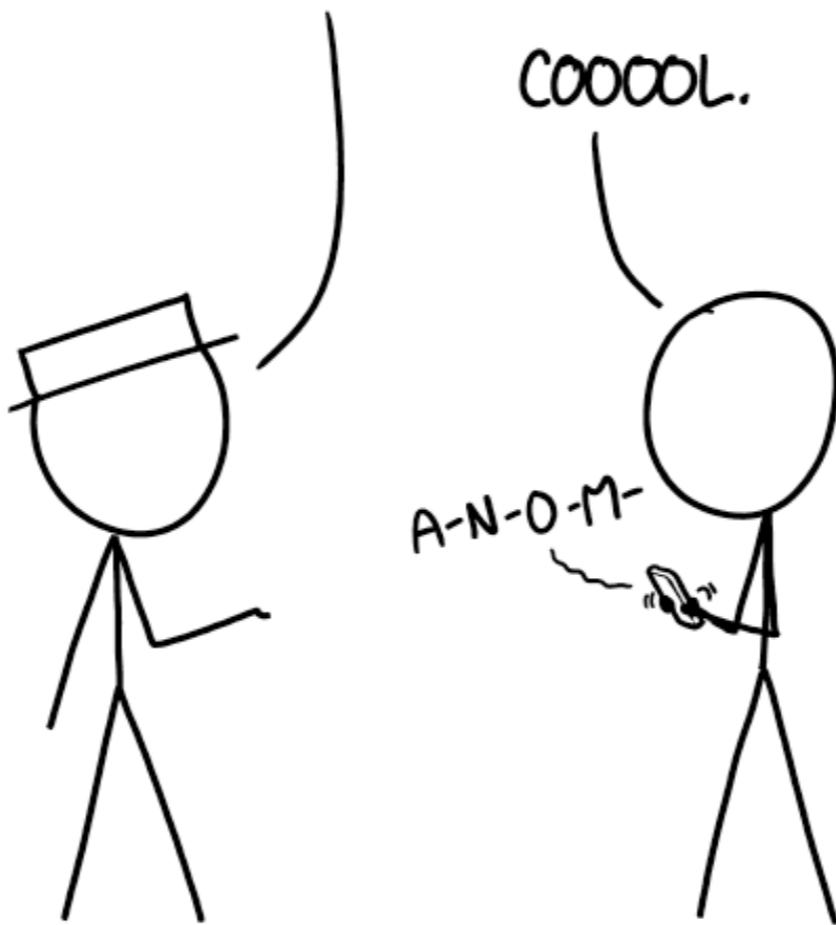
# Axion & GW's



Superradiance  
(Arvanitaki et al.)

GW's from axion coupled  
to dark photon

YEAH, I LEARNED ABOUT IT WHEN I WAS  
RESEARCHING ANOMALOUS ELECTROWEAK  
SPHALERON TRANSITION BARYOGENESIS.



MY HOBBY: COLLECTING REALLY SATISFYING-  
SOUNDING FIVE-WORD TECHNICAL PHRASES.

Topology is cool - let's find something