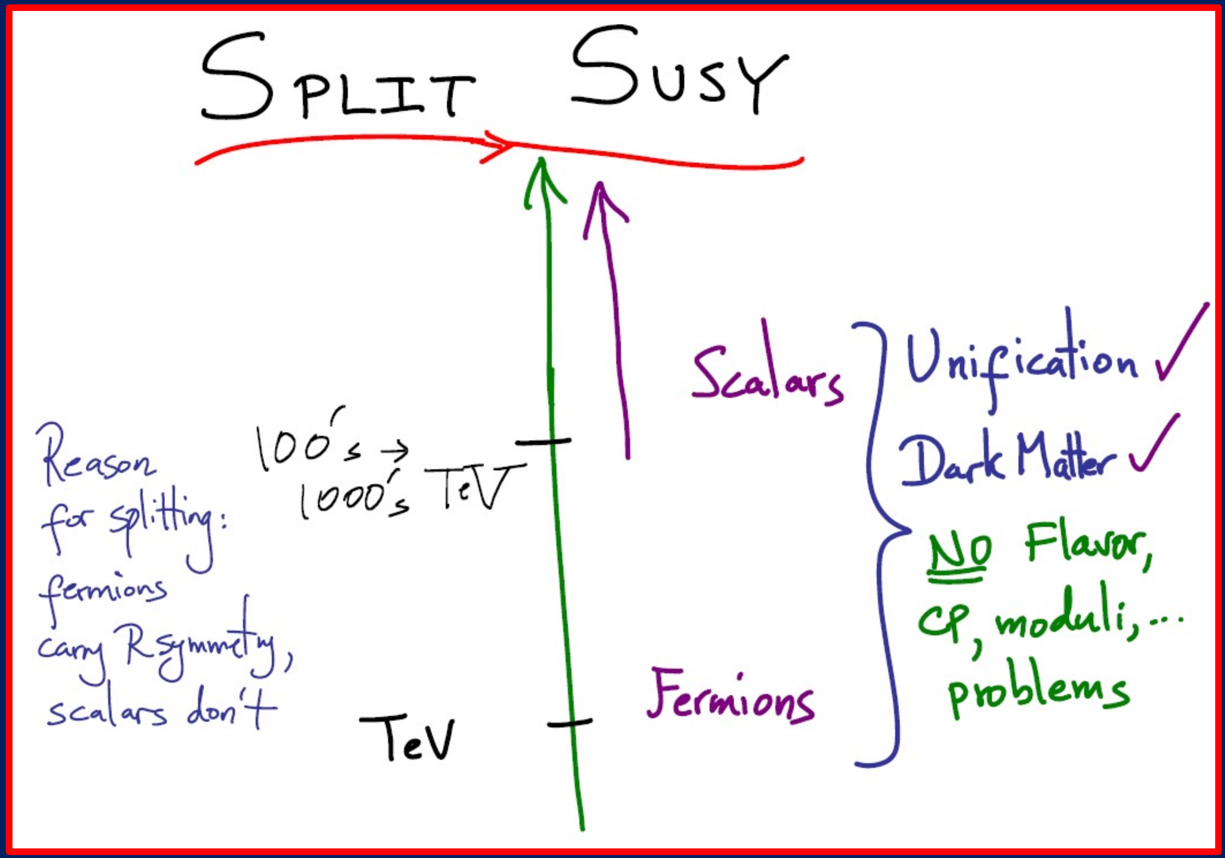
Gravitational Waves from Mini-Split SUSY

Bartosz Fornal

Barry University

XXVIII International Conference on Supersymmetry and Unification of Fundamental Interactions
Beijing, August 24, 2021

In collaboration with: ***Barmak Shams, Jiang-Hao Yu, Yue Zhao***

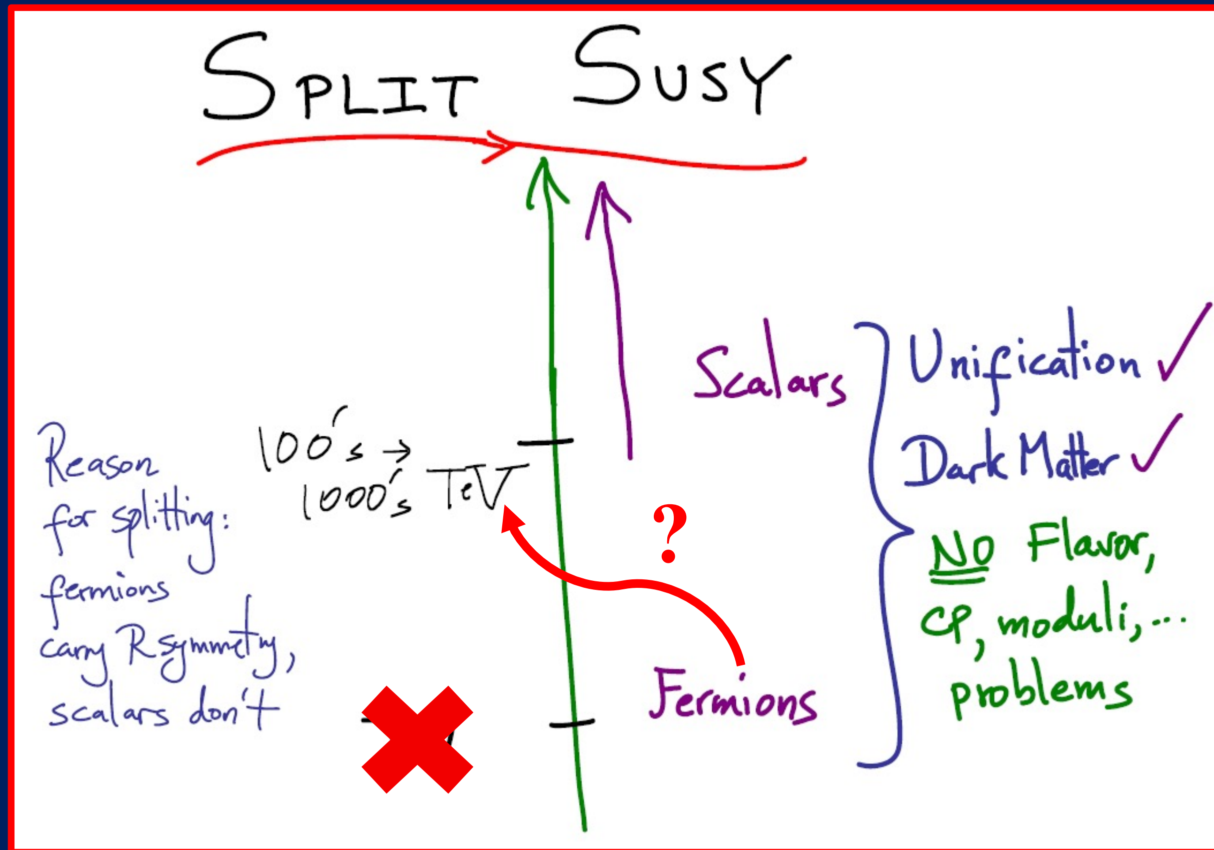


From Nima Arkani-Hamed's talk

(1) Arkani-Hamed, Dimopoulos, JHEP 06, 073 (2005)

(2) Arkani-Hamed, Dimopoulos, Giudice, Romanino, NPB 709, 3 (2005)

(3) Arvanitaki, Craig, Dimopoulos, Villadoro, JHEP 02, 126 (2013)



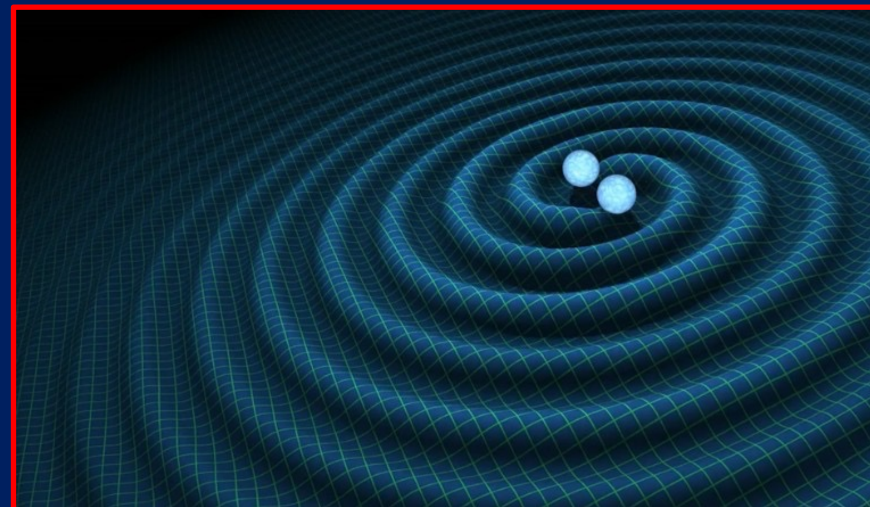
From Nima Arkani-Hamed's talk, modified

LHC

Gravitational wave detectors ?

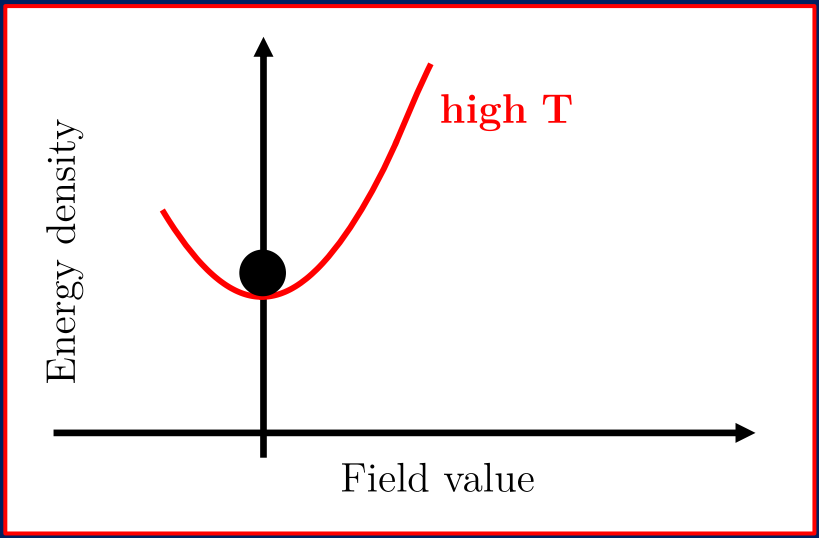
Indirect detection via gravitational waves

LIGO interferometer



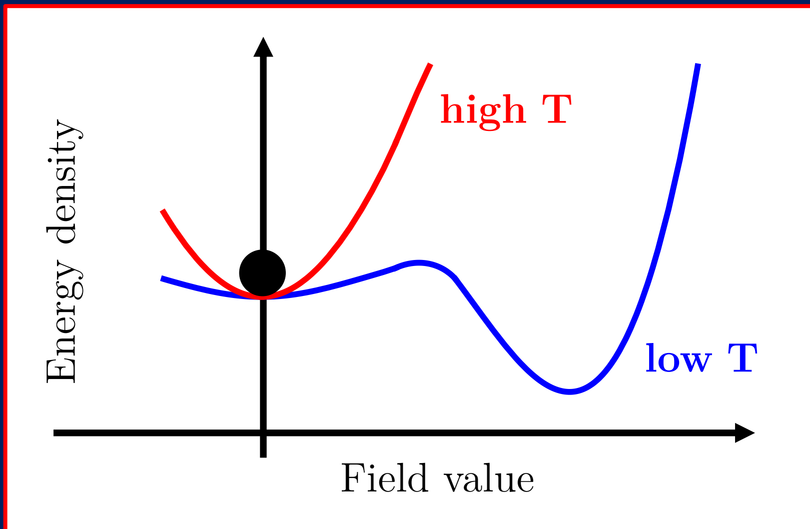
New frontier of probing particle physics models

Gravitational waves from the early Universe



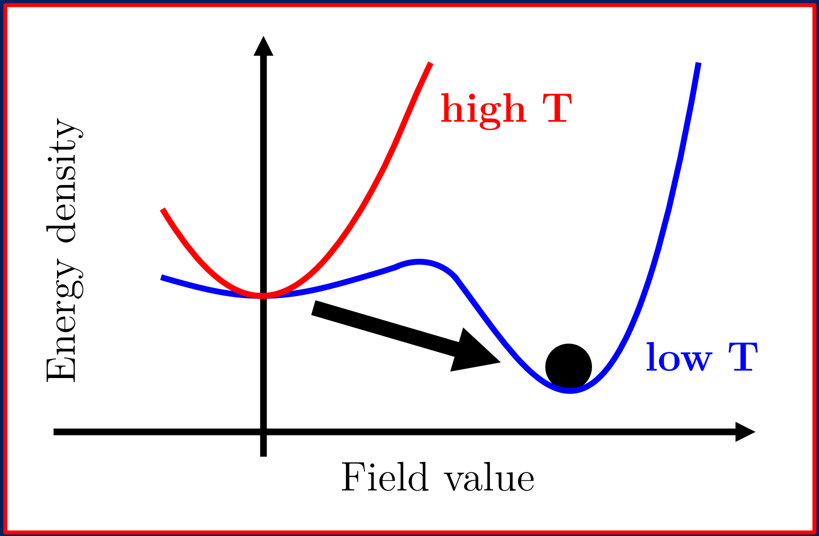
➡ **The energy at each point in space is determined by the minimum of the potential**

Gravitational waves from the early Universe



- The energy at each point in space is determined by the minimum of the potential
- As temperature decreases, a lower minimum can appear

Gravitational waves from the early Universe



- The energy at each point in space is determined by the minimum of the potential
- As temperature decreases, a lower minimum can appear
- First order phase transition (FOPT) to the lower minimum corresponds to forming a bubble
- The dynamics of the bubbles generates gravitational waves

Symmetry nonrestoration – toy model

$$-\mathcal{L} = -\mathcal{L}_{\rm SM} + \frac{\mu_s^2}{2} s^2 + \frac{\lambda_s}{4} s^4 + \frac{\lambda_{hs}}{2} h^2 s^2$$

Higgs thermal mass

$$m_h(T) \simeq \frac{1}{2}\left(\frac{\lambda_t^2}{2} + \lambda + N_s \frac{\lambda_{hs}}{6}\right) T^2$$

can become negative!

See, e.g., Meade and Ramani, PRL 122, 041802 (2019)

Formation of new vacuum states may result in a FOPT at high temperatures!

In the Mini-Split MSSM a similar feature occurs!

D-term contribution to the potential

$$\boxed{V_D = \frac{g_s^2}{6}\left(\sum_{\tilde{q}_L} |\tilde{q}_L|^2 - \sum_{\tilde{q}_R} |\tilde{q}_R|^2\right)^2}$$

Assuming that all the left-handed squarks and only the right-handed $\boxed{\tilde{d}_R}$ and $\boxed{\tilde{s}_R}$ are at the PeV scale, and all other right-handed squarks are heavy:

$$\boxed{V_D = \frac{g_s^2}{6}\left(\sum_{\tilde{q}_L} |\tilde{q}_L|^2 - |\tilde{d}_R|^2 - |\tilde{s}_R|^2\right)^2}$$

Effective potential

Tree-level

$$V_{\text{tree}} = \tfrac{1}{2} m_{\tilde{d}}^2 \phi_d^2 + \tfrac{1}{2} m_{\tilde{s}}^2 \phi_s^2 + \frac{g_s^2}{24} \left(\phi_d^2 + \phi_s^2\right)^2$$

$$\tilde{d}_{R1} = \frac{1}{\sqrt{2}} (\phi_d + i a_d)$$

$$\tilde{s}_{R1} = \frac{1}{\sqrt{2}} (\phi_s + i a_s)$$

One-loop

$$V_{\text{loop}} = \sum_i \frac{n_i}{64\pi^2} \left\{ m_i^4 \left[\log\left(\frac{m_i^2}{\mu^2} \right) - c_i \right] \right\}$$

$$m_{i,j}^2(\phi_d, \phi_s) = \frac{1}{2} \frac{\partial^2 V}{\partial \tilde{q}_i \partial \tilde{q}_j} \bigg|_{\phi_d, \phi_s}$$

Finite temperature:

$$V_{\text{temp}}^{(1)} = \frac{T^4}{2\pi^2} \sum_i n_i \int_0^\infty dy\, y^2 \log\left(1 \mp e^{-\sqrt{m_i^2/T^2 + y^2}} \right)$$

$$V_{\text{temp}}^{(2)} = -\frac{T}{12\pi} \sum_j n_j' \left\{ \left[m_j^2 + \Pi_j(T) \right]^{\frac{3}{2}} - m_j^3 \right\}$$

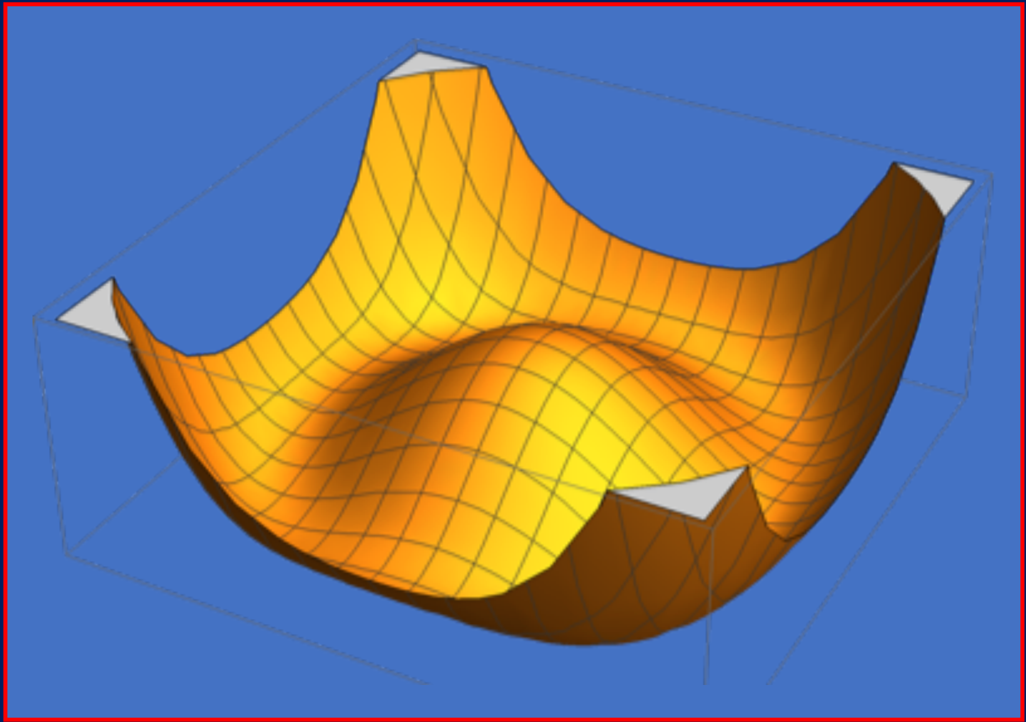
At temperatures ~ few PeV

Thermal contribution to the effective potential:

$$\Delta V_{\rm eff} = C\,(\phi_d^2 + \phi_s^2)T^2$$

with $C < 0$

results in $v(T) \sim T$



SO(2) symmetric vacuum

Lifting the SO(2) vacuum degeneracy

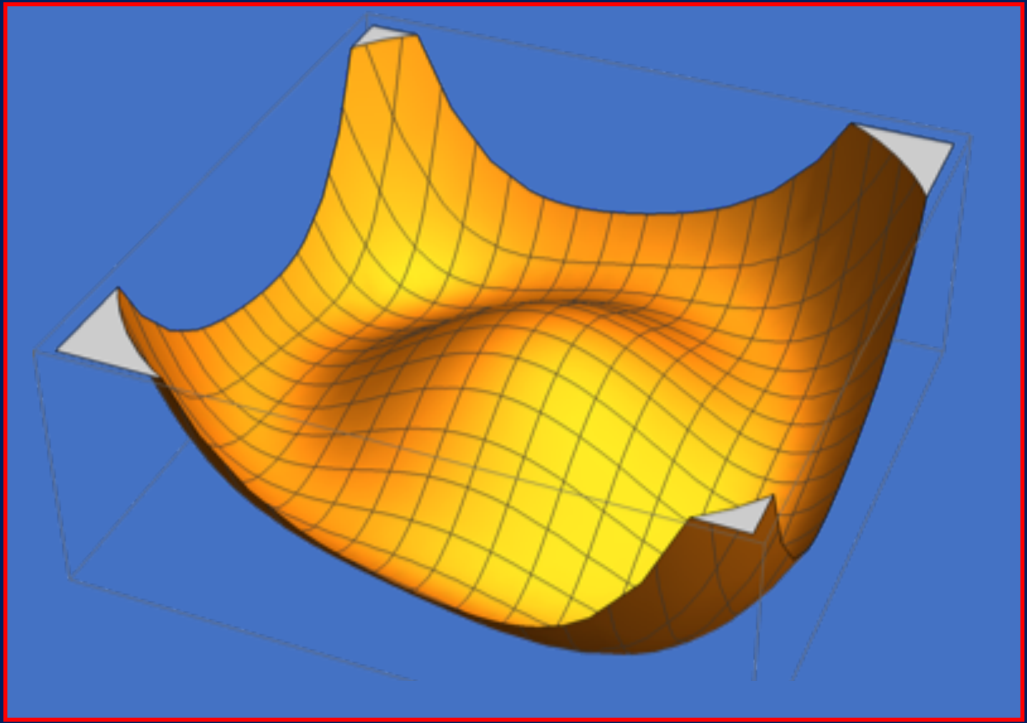
SO(2) breaking natural within the framework of MSSM alone via:

➡ ***A*-terms**

$$V_A = \left(\lambda_d |\tilde{d}_R|^4 + \lambda_s |\tilde{s}_R|^4\right)$$

➡ **Flavor-changing soft mass terms**

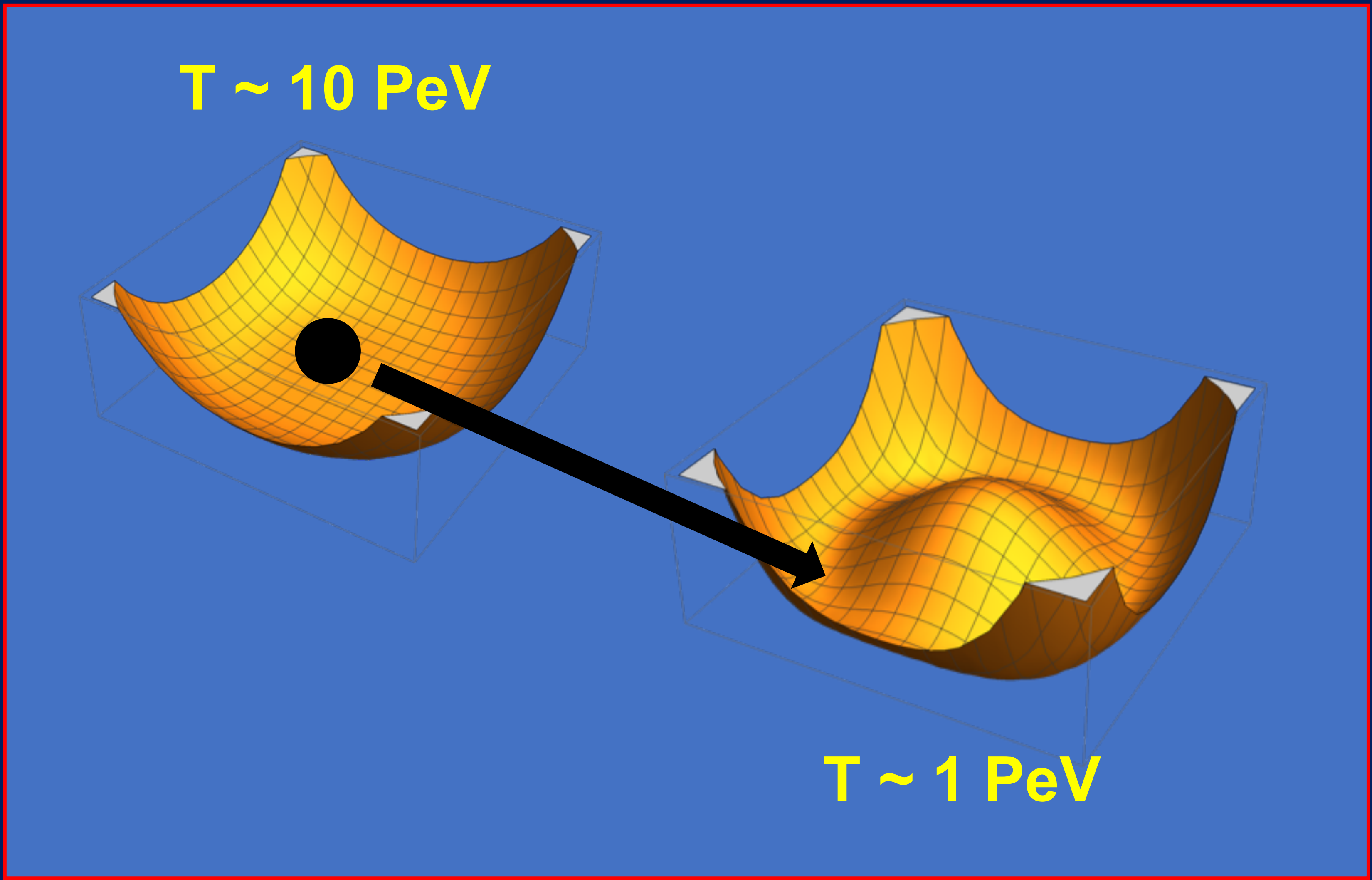
$$V_F = \widetilde{m}^2_{ds}\, \tilde{d}^\dagger_R \tilde{s}_R + \text{h.c.}$$



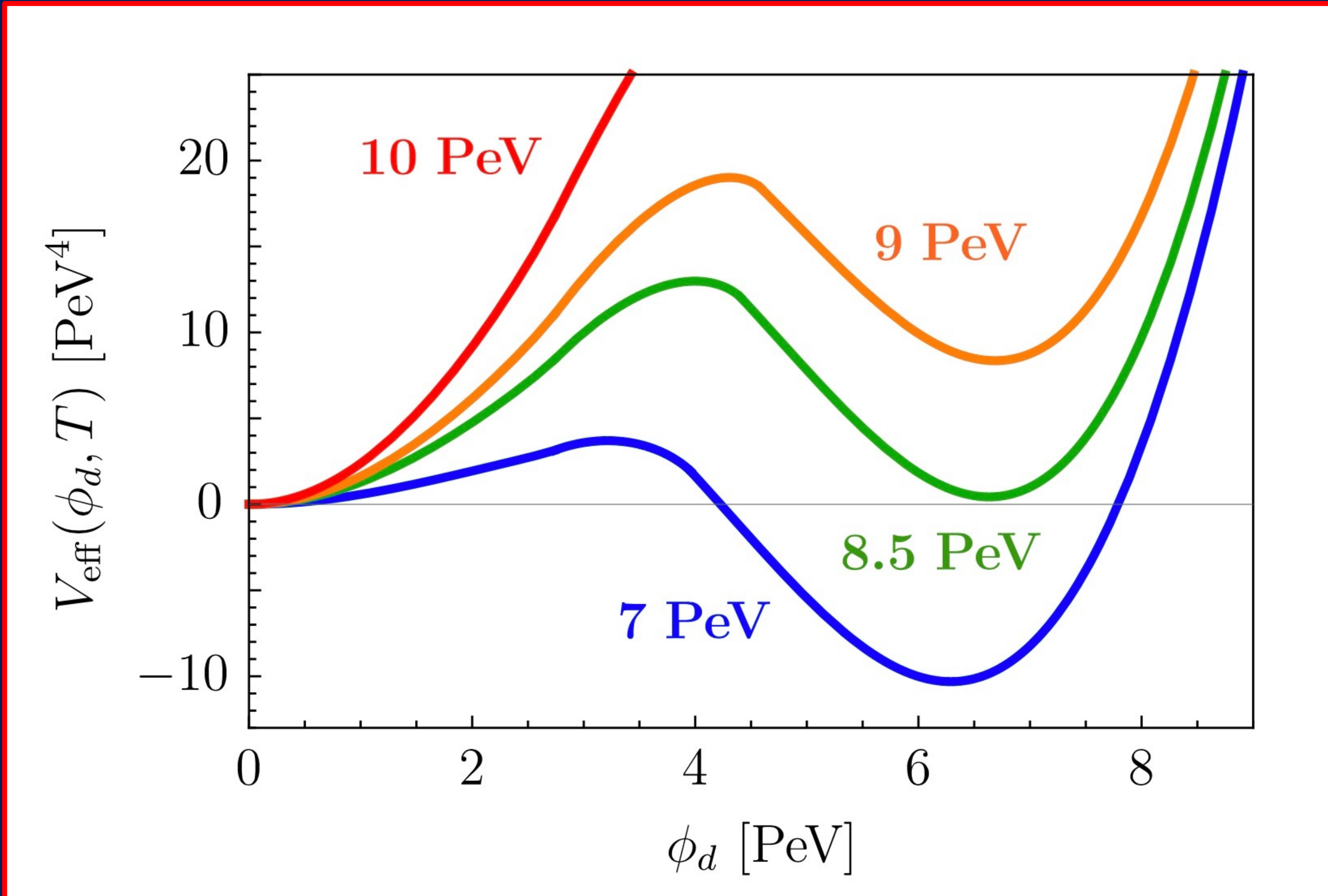
SO(2) symmetry broken

$$T_R > M_{\tilde{q}}$$

First order phase transition *(i)*



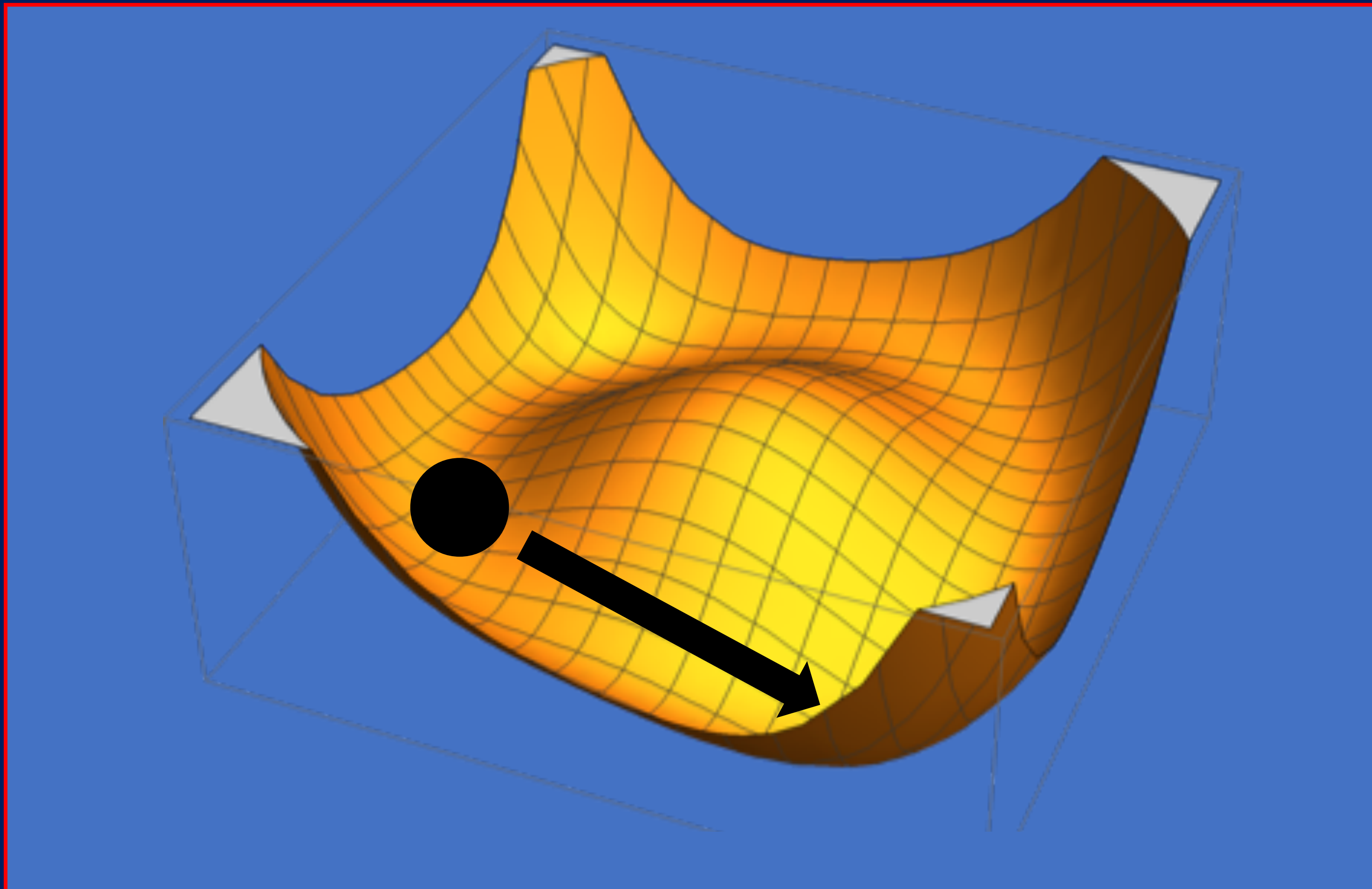
Effective potential



B.F. , B. Shams, J.-H. Yu, Y. Zhao, arXiv:2104.00747

$T_R < M_{\tilde{q}}$

First order phase transition *(ii)*



Relevant parameters

- Bubble wall velocity $\boxed{v_w}$
- Nucleation temperature $\boxed{T_*}$
- PT duration $\boxed{1/\tilde{\beta}}$ where $\boxed{\tilde{\beta} = T_* \frac{d}{dT}\left(\frac{S(T)}{T}\right)\Big|_{T=T_*}}$
- Strength of the transition $\boxed{\alpha = \frac{\rho_{\rm vac}(T_*)}{\rho_{\rm rad}(T_*)}}$

Gravitational waves from phase transition

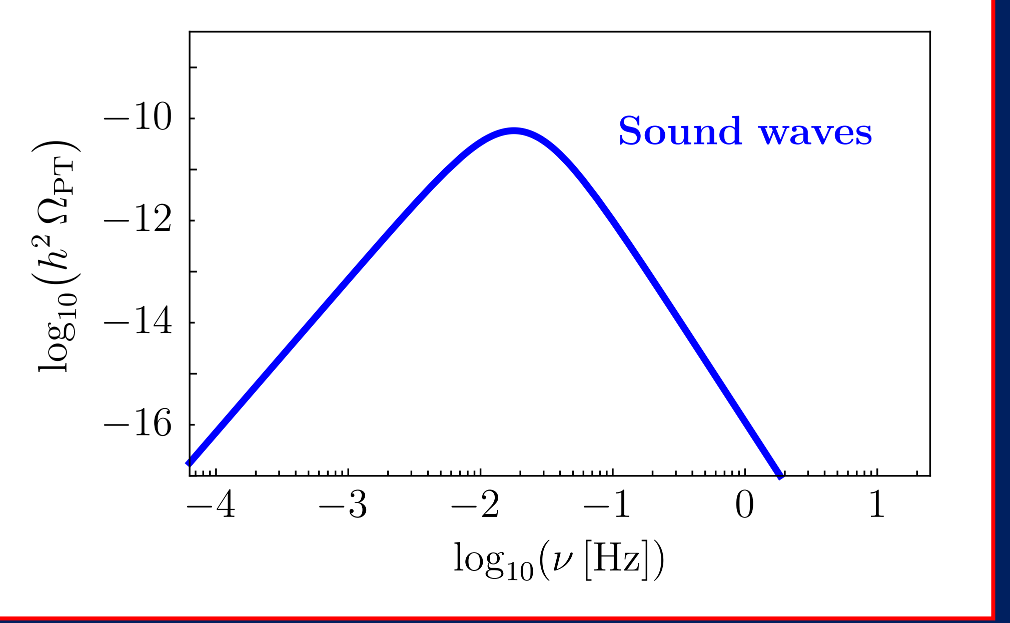
Sound waves provide the leading contribution

$$h^2\Omega_s(\nu) \approx \frac{(1.86\times 10^{-5})\left(\frac{\nu}{\nu_s}\right)^3}{\left[1+0.75\left(\frac{\nu}{\nu_s}\right)^2\right]^{\frac{7}{2}}}\frac{v_w}{\tilde{\beta}}\left(\frac{\kappa_s\,\alpha}{\alpha+1}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\Upsilon$$

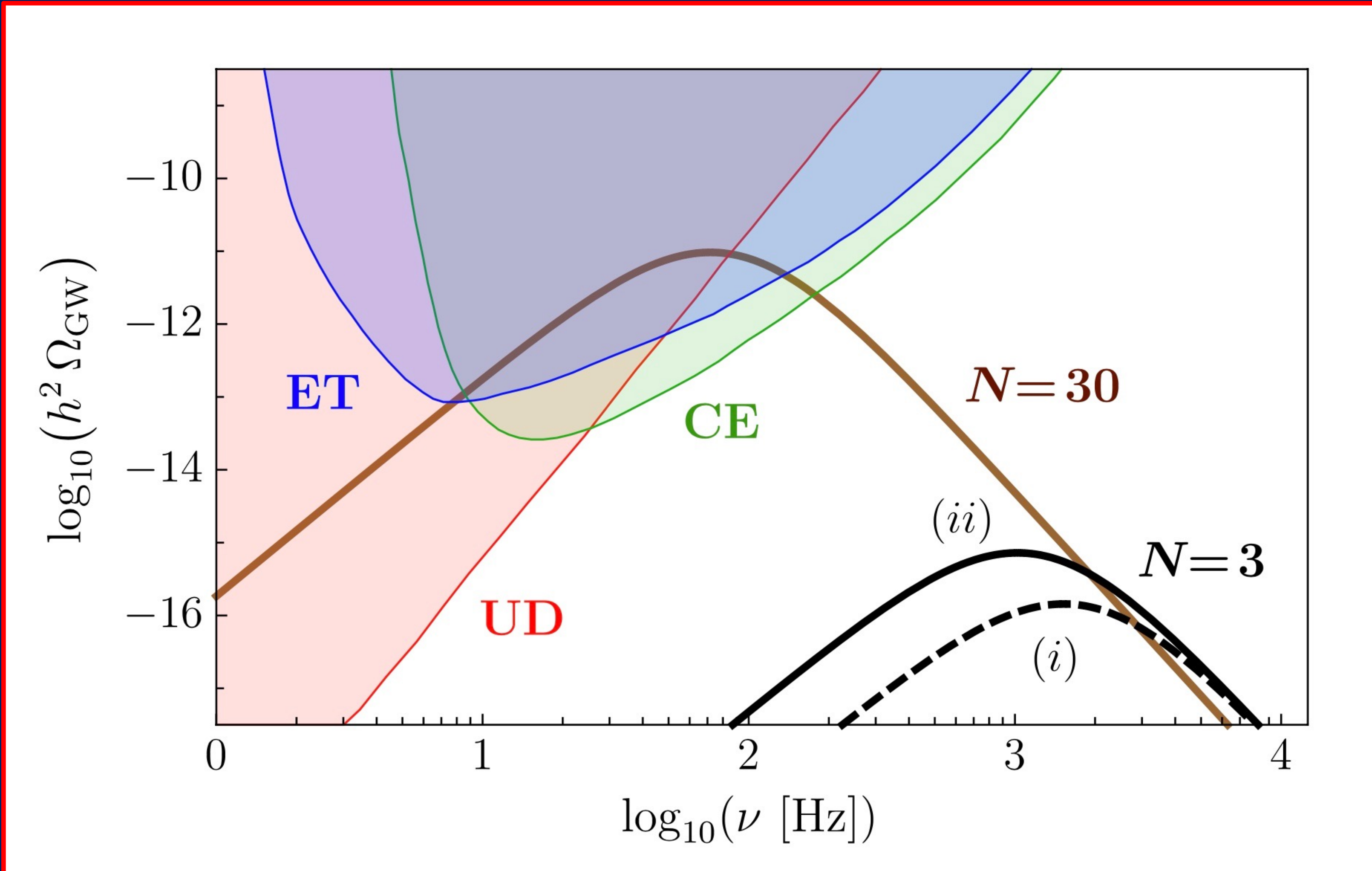
where

$$\kappa_s \approx \frac{\alpha}{0.73+0.083\sqrt{\alpha}+\alpha}$$

$$\nu_s \approx (1.9\times 10^{-4}\ \mathrm{Hz})\left(\frac{g_*}{100}\right)^{\frac{1}{6}}\frac{\tilde{\beta}}{v_w}\left(\frac{T_*}{1\ \mathrm{TeV}}\right)$$



Gravitational wave signature



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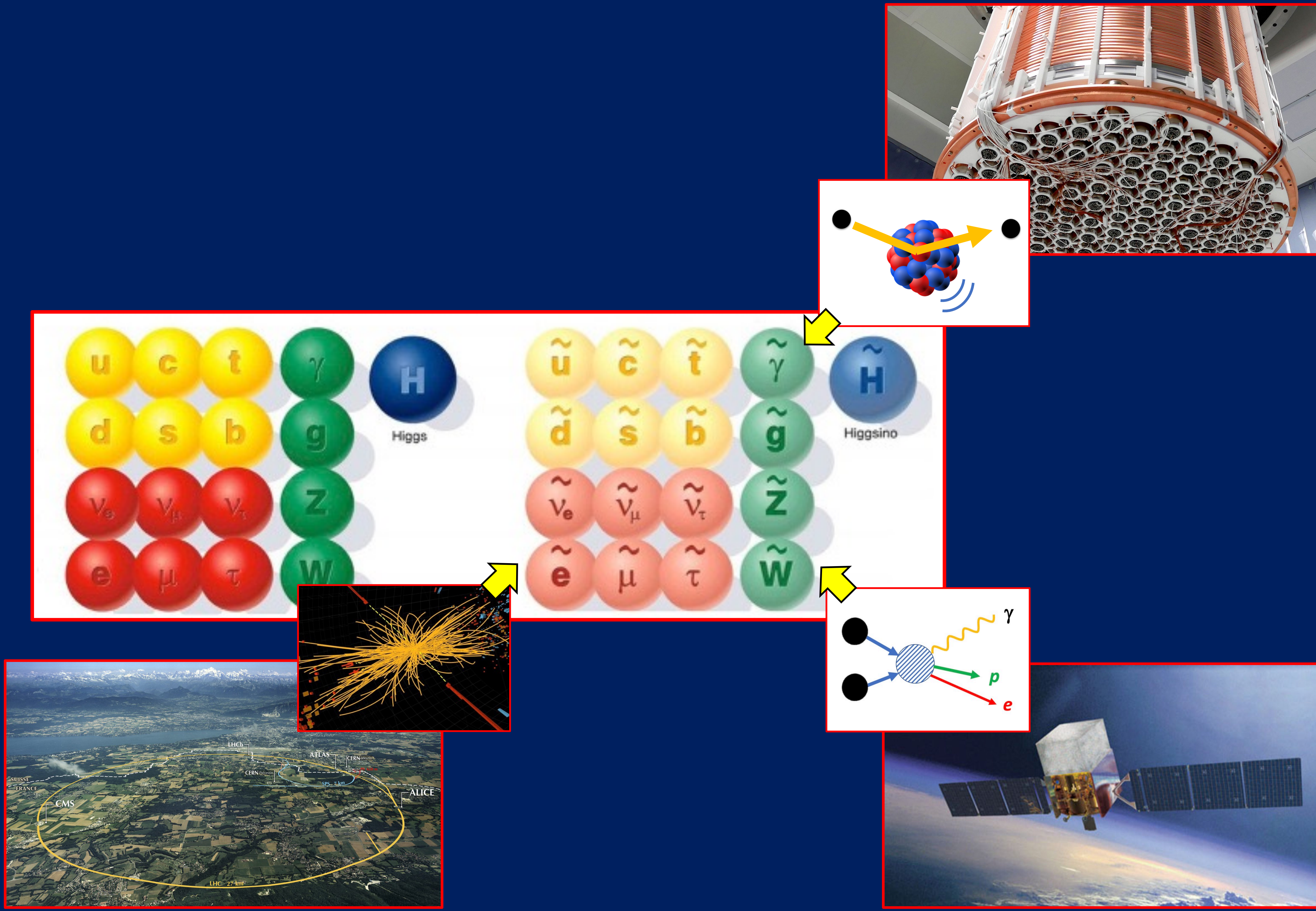

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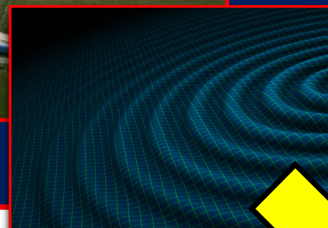
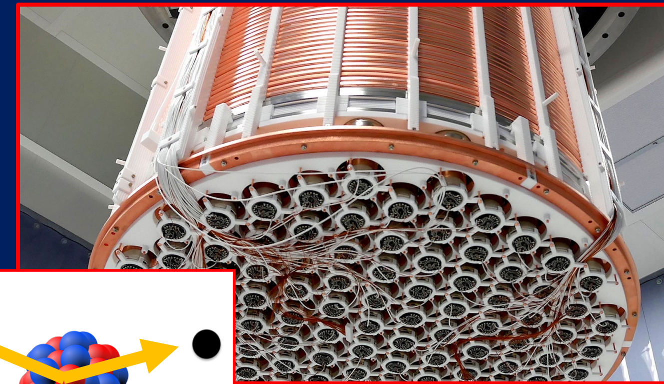
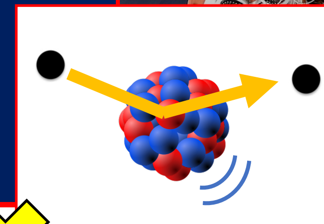
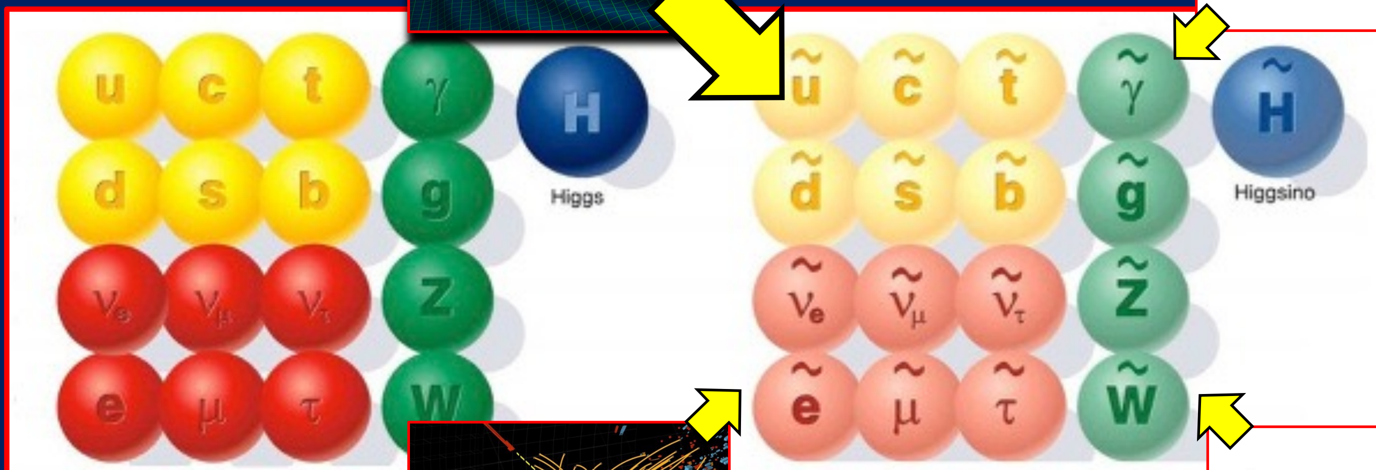
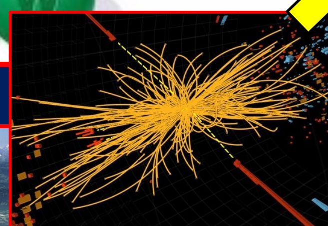
ALICE

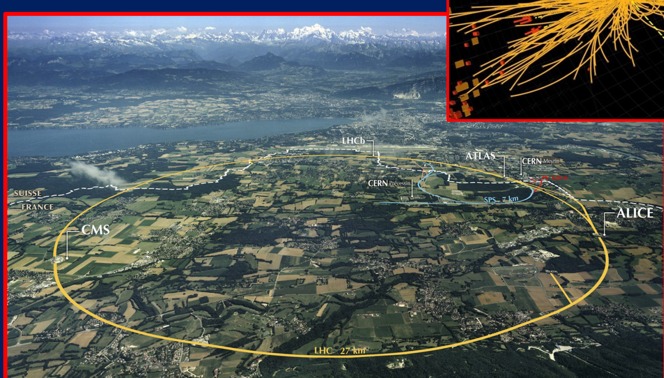


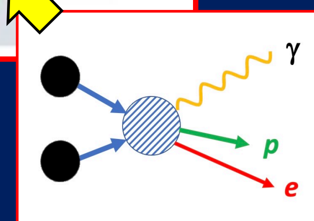












Thank you!