Cosmic Relics

Archil Kobakhidze

THE UNIVERSITY OF SYDNEY

Gordon Godfrey Workshop on Astroparticle Physics

Standard Model of the Universe

- The Standard Model – [Quantum Mechanics + Special Relativity] – accurately describes (almost) all physical phenomena down to miniscule scales $\sim 10^{-18}$ cm.

- The ΛCDM Model [aka the Standard Model of Cosmology] – [General Relativity +…] – accurately describes (almost) all phenomena up to cosmic scales $\sim 10^{29}$ cm.

It’s absolutely incredible how much physics at vastly disparate distance scales we know based on a few elegant laws of Nature!

Historical detour

- Several breakthroughs in particle physics since the second half of 20th century were driven by theoretical considerations: extrapolate a known theory to higher energies (= small distance scales); if not consistent expect new physics to replace old at those scale.

- Fermi theory of radioactivity -> theory breaks at ~100 GeV -> discovery of W and Z bosons, $M_W \approx 81 \text{ GeV}, \; M_Z \approx 90 \text{ GeV},$ (SPS, CERN, 1983) – principle of gauge invariance

- Standard Model (without Higgs) -> theory breaks at ~900 GeV -> discovery of the Higgs boson $M_h \approx 125 \text{ GeV}$ (LHC, CERN 2012) – spontaneous mass generation (Higgs mechanism)

What is the next energy scale to be probed?

Standard Model fails to accommodate:

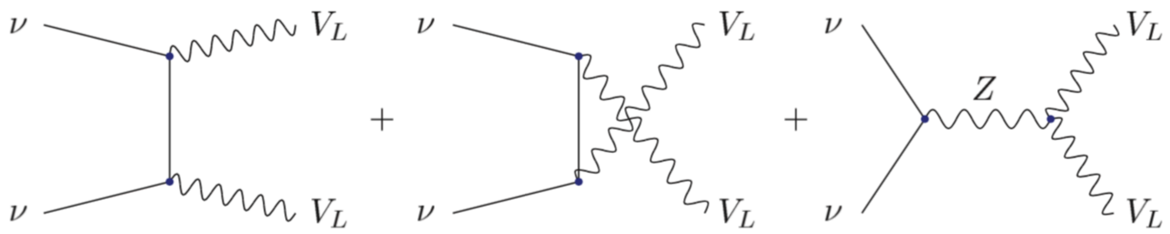
- Neutrino masses - robust evidence from particle physics (neutrino oscillation) experiments

Add neutrino mass to the SM Lagrangian (EW gauge invariance is still OK, but nonlinear):

$$\mathcal{L}_\nu = -\frac{1}{2} m_\nu \nu_L^T C \nu_L + h.c \equiv -\frac{1}{2} m_\nu \left[L^T \epsilon \Sigma\right] C \left[\Sigma^T \epsilon L\right]$$

$$L = (\nu, \ell),\ \Sigma = \exp\{i\sigma^a \pi^a(x)\}(0,1)$$

Consider in this theory neutrino scattering off longitudinal EW bosons:



Perturbative unitarity implies:

$$\Lambda \lesssim \frac{4}{\alpha_2} \cdot \frac{M_W^2}{m_\nu} \sim 10^{11}\ \mathrm{GeV}$$

Maltoni, Niczyporuk, and Willenbrock, 01’

What is the next energy scale to be probed?

- Dark Matter – robust, but only observed in gravitational interactions

Assuming non-relativistic DM is produced thermally via weak-strength scatterings with SM particles, we arrive at the 'WIMP miracle':

$$\Omega_X h^2 \sim \frac{3 \cdot 10^{-27} \mathrm{cm}^3/\mathrm{sec}}{\langle \sigma v_{\mathrm{rel}} \rangle}$$

Cross section is constrained from perturbative unitarity:

$$\sigma_J \le \pi(2J+1)/p_i^2 \approx 16\pi(2J+1)/(m_X^2 v_{\mathrm{rel}}) \Longrightarrow m_X^2 \le 16\pi/(\sigma_{J=0} v_{\mathrm{rel}}), \;\; [v_{\mathrm{rel}} \approx 1/4]$$

$$\boxed{\Lambda \sim m_X \lesssim 100 \ \mathrm{TeV}}$$

Griest and Kamionkowski, 90'

What is the next energy scale to be probed?

- EW vacuum has topologically non-trivial structure [SU(2) sector].

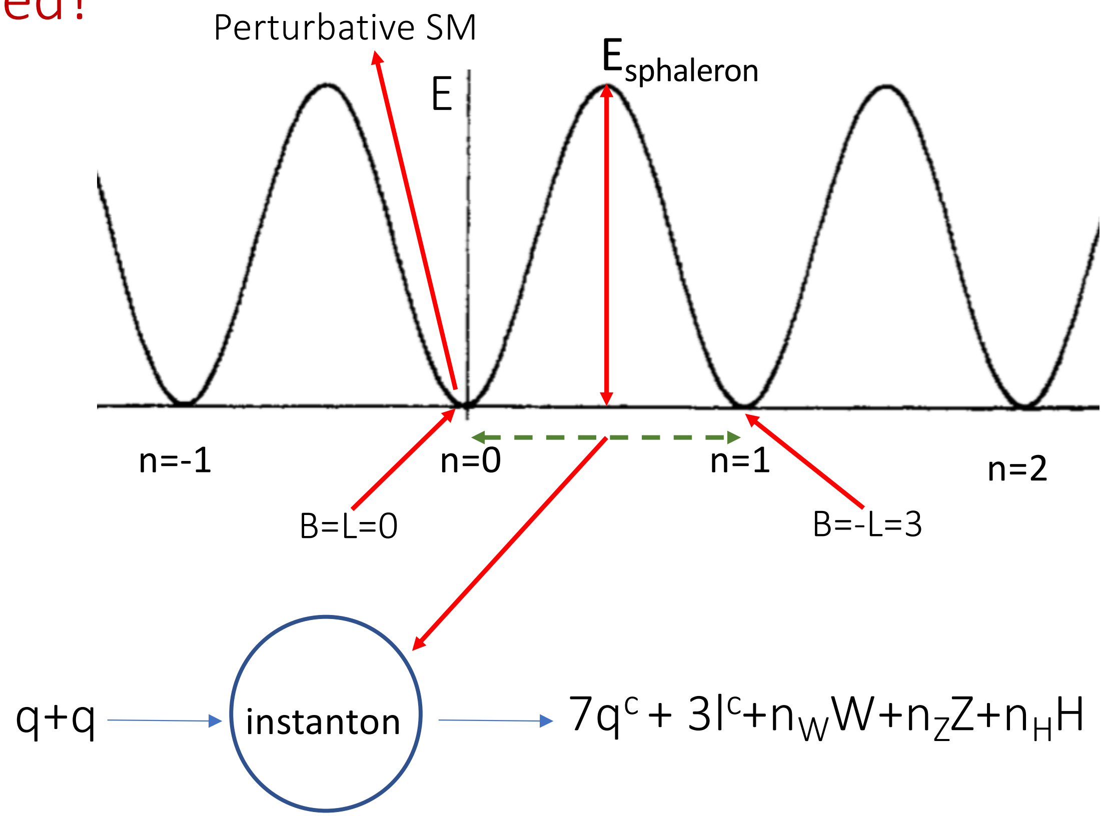
- Transition between vacua change B and L by 3 units: ΔB=-ΔL=3Δn (quantum anomaly); Δ(B-L)=0.

- EW instantons are classical solution of Euclidean e.o.m., with action, e.g., for Δn =1,

$$S_{\rm inst.} = \frac{2\pi}{\alpha_2}$$

(multiple of W,Z, H particles in a coherent state)

- describe vacuum-to-vacuum transitions)



$$\mathcal{A}_{\rm inst.} \sim \exp\{-S_{\rm inst}\} \approx 10^{-80}$$

$$\Lambda \sim E_{\rm sphaleron} \sim \frac{4M_W}{\alpha_2} \approx 10\ TeV$$

Going back in time

- Another way of probing consistency of theoretical models is to extrapolate them back in time; E.g.,

- 3 min ABB, $l_U \approx 10^{12}$ cm $\approx 0.01\ AU$ - light elements synthesized (BBN) [requires matter-antimatter asymmetry]

- 10^{-5}sec ABB, $l_U \approx 10^{5}$ cm - quarks gets combined into hadrons [QCD phase transition]

- 10^{-8} sec ABB, $l_U \approx 0.1$ cm - the instanton processes are thermally activated and matter-anti matter asymmetry gets nullified! [baryogenesis problem]

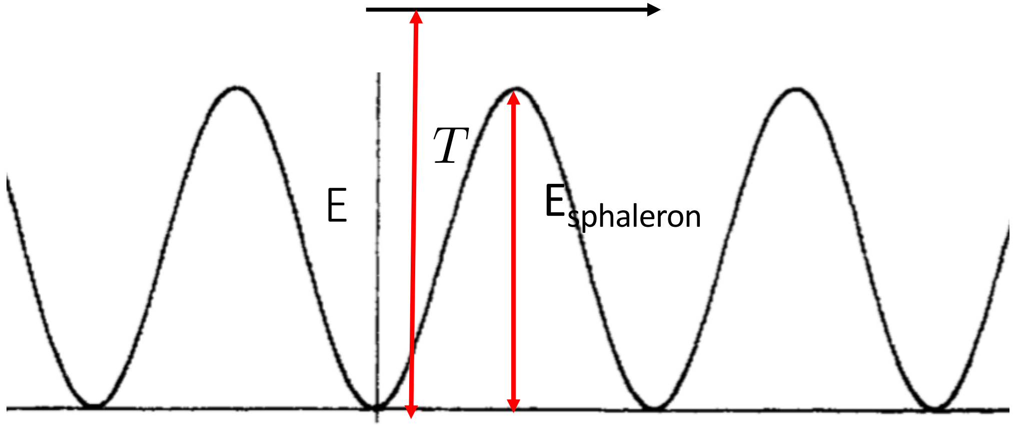
Going back in time

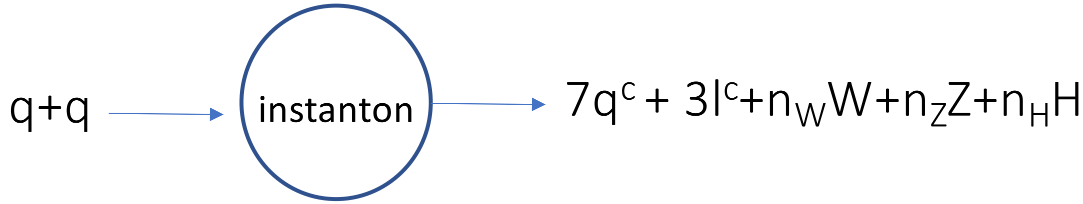
- Let's extrapolate our theory back in time, when the temperature of the universe was

  $T > E_{sphaleron}$

- Instanton mediated processes are rapid (thermally activated transitions) $\sim \alpha_2 T^4$

- <u>Problem</u>: any pre-existing matter-antimatter asymmetry gets washed-out and we end up in an inhabitable universe without matter.



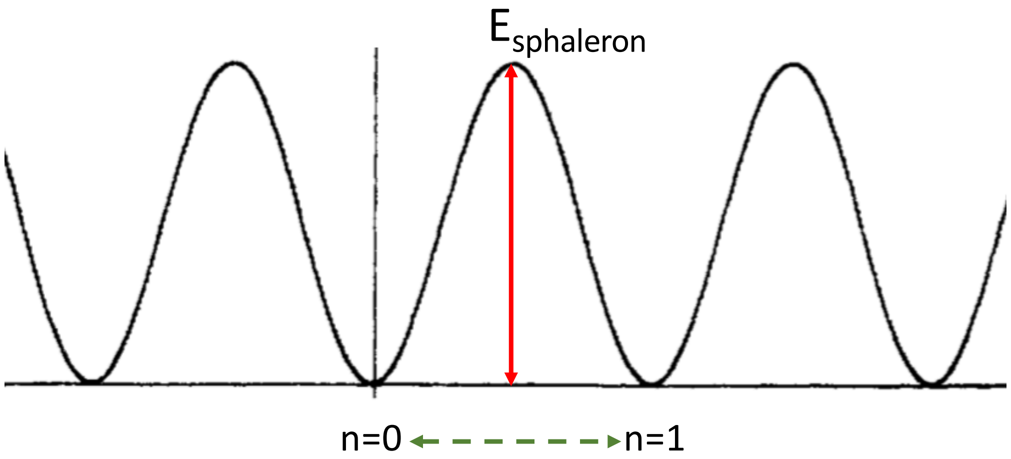


Standard Model of particle physics and Standard Model of Cosmology fail to describe the existence of matter in the Universe!

- <u>Alternatively</u>: In non-equilibrium and with extra CP violation these processes could explain the origin of matter in the visible universe! [Electroweak Baryogenesis]

Electroweak Avatars

(sphalerons, skyrmions, monopoles)



Shpalerons in high energy collisions?

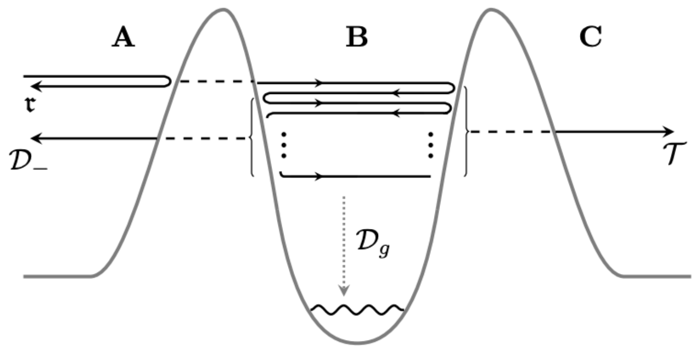
- Jump over barrier is described by production and subsequent decay of a sphaleron.

- Sphaleron is an unstable particle-like classical solution with a typical size ~$1/M_W$ and mass ~10 TeV.

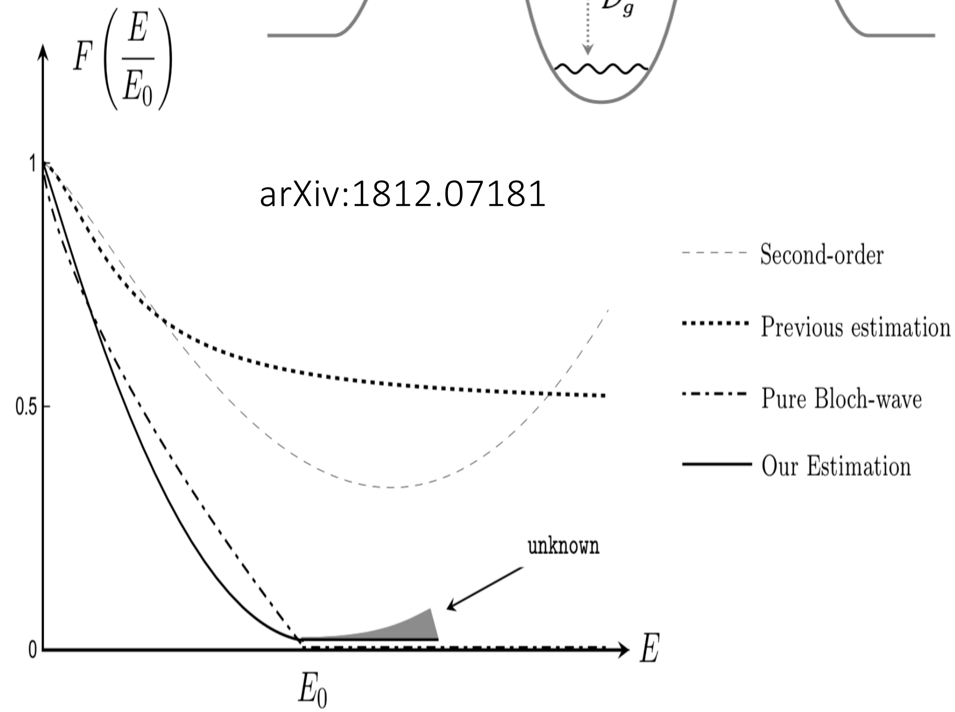
- Spectacular B+L – violating processes with multiple of W,Z and H (background-free!)

- Cross section:

$$\sigma \propto \exp\{-2S_{\rm ints.}F(E/E_0)\}, \quad [E_0 \equiv E_{\rm sphaleron}]$$



arXiv:1812.07181



Ringwald; McLerran, Vainstein and Voloshin 90'
Bezrukov and Levkov, 03'
Tye and Wong, 15'

Cosmic ray air showers from sphalerons

- Available energy transfer $E = \sqrt{E_{CR} m_N} \approx 500\ TeV!$

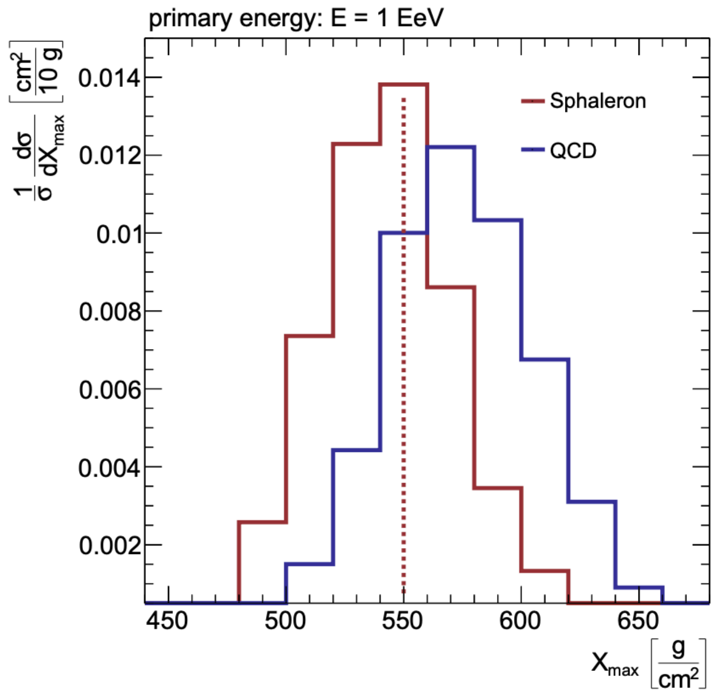
$$q + q \to 7q^c + 3l^c + n_W W + n_Z Z + n_H H$$

- At least one hard muon
- Different radial size of the air shower

Can be probed/constrained at Pierre Auger.

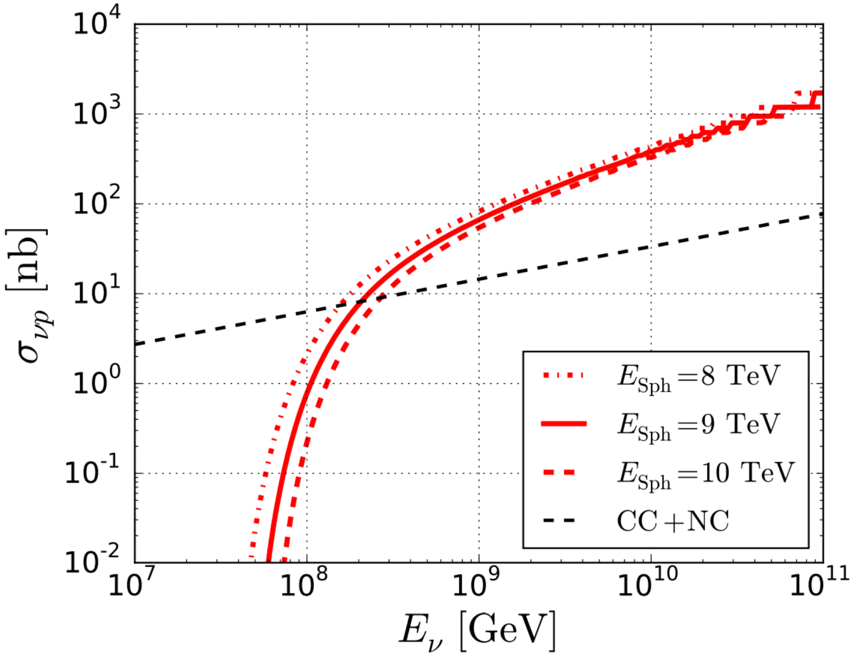
- Enhanced neutrino-nucleon scattering (IceCube)

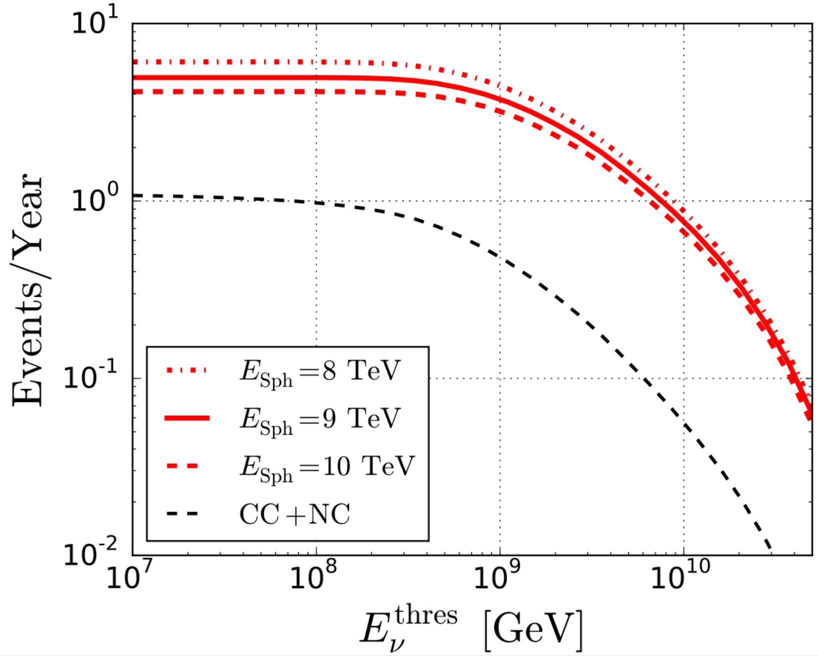
$$\nu + q \to 8q^c + 2l^c + n_W W + n_Z Z + n_H H$$



arXiv:1602.00647

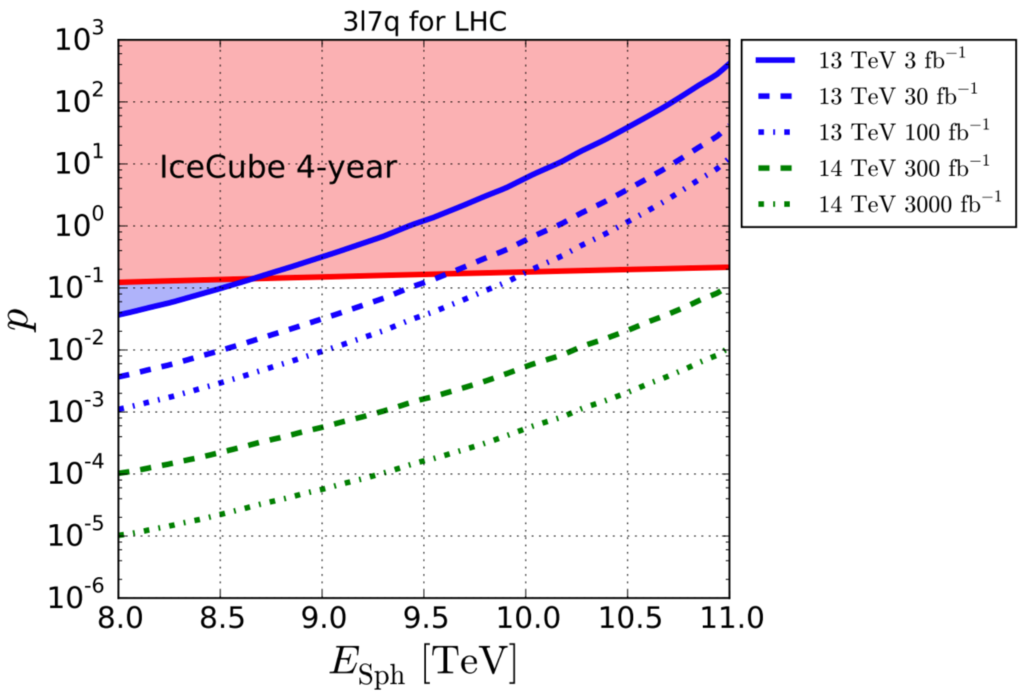
Sphaleron processes in HE cosmic rays

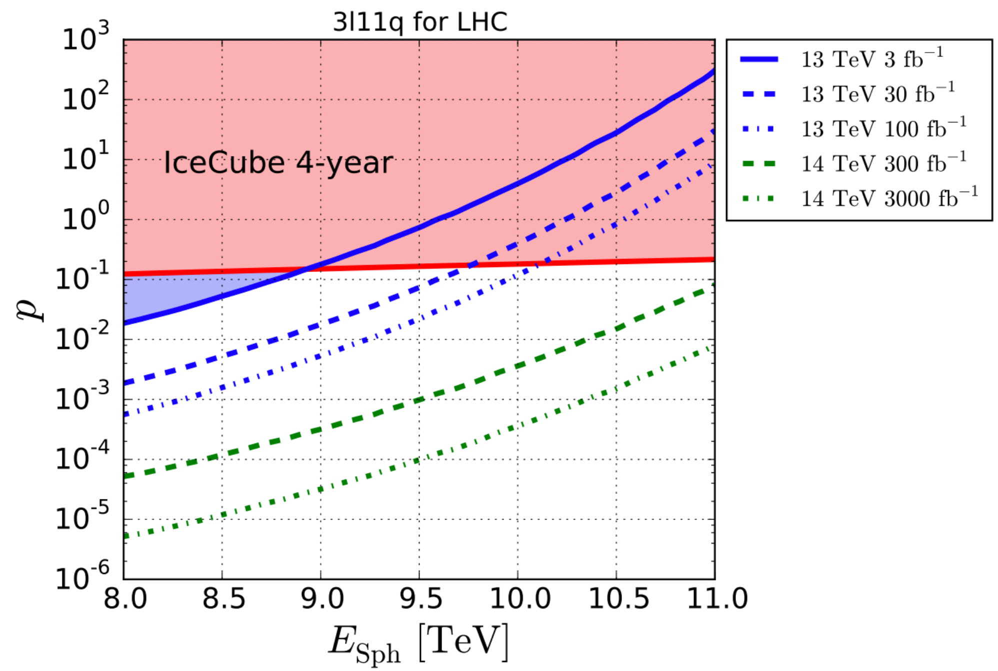




Ellis, Sakurai, Spannowsky, arXiv:1603.06573

Sphaleron processes in HE cosmic rays





Ellis, Sakurai, Spannowsky, arXiv:1603.06573

Electroweak monopoles

[Arunasalam, Collison, AK, 18']

- Standard (and incorrect) argument against electroweak monopoles:

$$H^\dagger H \equiv \phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 \overset{r\to\infty}{=} \rho_0^2$$

Map of S^2 (boundary at spatial infinity) onto the vacuum manifold S^3 . The map is trivial, hence topological ('t Hooft-Polyakov) monopoles do not exist.

- However, ϕ_i can be singular (gauge d.o.f.). In that case the vacuum manifold may not be S^3.

- Consider an ansatz:

Cho and Maison, 96'

$$H = \frac{1}{\sqrt{2}}\rho(r)\zeta, \quad \zeta = i\begin{pmatrix}\sin(\theta/2)e^{-i\phi} \\ -\cos(\theta/2)\end{pmatrix};$$

$$\mathbf{A}_\mu = -\frac{1}{g_2}A(r)\partial_\mu t\hat{r} + \frac{1}{g_2}(f(r)-1)\hat{r}\times\partial_\mu\hat{r},$$

$$B_\mu = -\frac{1}{g_1}B(r)\partial_\mu t - \frac{1}{g_1}(1-\cos\theta)\partial_\mu\phi.$$

Singular at θ = π/2

Electroweak monopoles

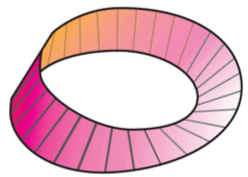
- Denote the components of doublet Higgs as: $z_1 \equiv \phi_1 + i\phi_2,\, z_2 \equiv \phi_3 + i\phi_4$

- Are defined up to hypercharge gauge transformations: $(z_1, z_2)^T \equiv (\lambda z_1, \lambda z_2)^T,\ \lambda \in U(1)_Y$;
Hence could be viewed as coordinates on a complex plane C^2 (modulo singularities).

- Remove singularities by using the gauge freedom and defining two monopole solutions on two different patches of space:

$$H_N = i\frac{\rho(r)}{\sqrt{2}}\begin{pmatrix}\sin(\theta/2)e^{-i\phi}\\ -\cos(\theta/2)\end{pmatrix}, \quad B_\phi^N = -\frac{1}{g'}\frac{1-\cos\theta}{r\sin\theta} \quad \text{for } 0 \le \theta \le \pi/2, \text{ and}$$

$$H_S = i\frac{\rho(r)}{\sqrt{2}}\begin{pmatrix}\sin(\theta/2)\\ -\cos(\theta/2)e^{i\phi}\end{pmatrix}, \quad B_\phi^S = \frac{1}{g'}\frac{1+\cos\theta}{r\sin\theta} \quad \text{for } \pi/2 \le \theta \le \pi.$$



- At the equator ($\theta = \pi/2$) the transition function $e^{i\phi}$ is a holomorphic function => (z_1, z_2) actually span a projective complex plane CP^1 .
- Hence, monopole solution is topologically nontrivial: $\pi_2(CP^1) = \pi_2(S^2) = Z$

Electroweak monopoles

- Considering, two monopole solutions on the whole space (with opposite magnetic charges), one gets monopole-antimonopole bound state, which actually is a sphaleron!

- Monopole – particle scattering is known unsuppressed (Rubakov 81'; Callan 82'). By crossing symmetry the process of production of monopole-antimonopole pair in two-particle collision must not be suppressed either. Monopole-antimonopole pair then can form sphaleron:

$$q + q \to M + M^c \to 7q^c + 3l^c + n_W W + n_Z Z + n_H H$$

- EW monopoles inevitably introduce new CP violating phase (Witten effect):

$$\mathcal{L}_\theta = \theta_2 F^a_{\mu\nu}\tilde{F}^{a\mu\nu} + \theta_1 B_{\mu\nu}\tilde{B}^{\mu\nu} \implies \mathcal{L}_\theta = \theta_{ew} F^a_{\mu\nu}\tilde{F}^{a\mu\nu}\ , \quad \theta_{ew} = \theta_2 - \theta_1$$

- Contribute to EDM of known particles
- Successful electroweak baryogenesis scenario [Arunasalam and AK, 17']

The electroweak monopole

- The mass of EW monopoles is divergent. Within the string theory inspired Born-Infeld-type extension of the Standard Model [Arunasalam, AK, 17']:

$$E_{\text{monopole}} \simeq 77.1\sqrt{\beta} + 2.8 \text{ TeV}, \quad \sqrt{\beta} \text{ is the Born-Infeld mass parameter}$$

- PVLAS measurements of nonlinearity in light propagation:

$$\sqrt{\beta} \gtrsim 5.0 \cdot 10^{-4} \text{ GeV} \implies E_{\text{monopole}} \gtrsim 2.8 \text{ TeV}$$

- Constraints from the light-by-light scattering data extracted from heavy ion collisions at LHC:

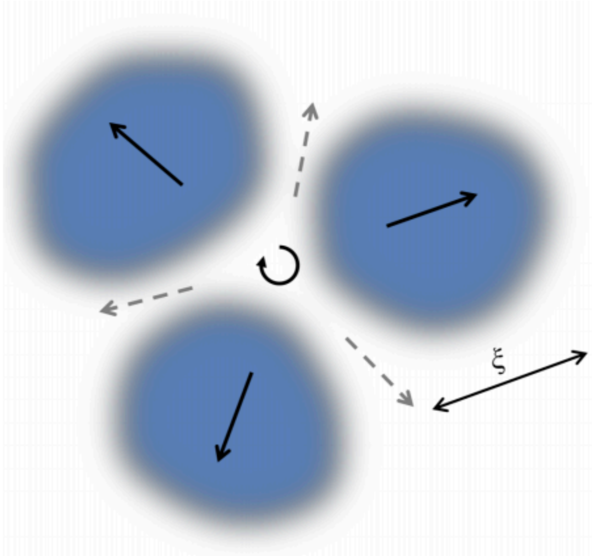
$$\sqrt{\beta} \gtrsim 88 \text{ GeV} \implies E_{\text{monopole}} \gtrsim 9.6 \text{ TeV}$$ Ellis, Mavromatos, You, 17'

- LHC is not capable to produce EW monopoles. Higher energy collider or search in cosmic rays!

- 'Sweet spot' value for EW monopole mass ~ 10^7 GeV (baryogenesis)

Cosmological production of EW monopoles

- The EW monopoles are produced during the electroweak phase transition when the temperature of the universe was T_{EW}~ 100 GeV (~10^{-32} s after Big Bang) via the Kibble mechanism.



- The estimated monopole number density today:

$$n_M \sim \frac{1}{\alpha_g^3}\left(\frac{M}{M_{\rm Pl}}\right) T_{\rm CMB}^3 \sim 10^{-26}\left(\frac{M}{10^7\ {\rm GeV}}\right)\ {\rm cm}^{-3}.$$

$\alpha_g = 1/2\alpha \simeq 68.5$ - the magnetic ‘fine structure’ constant

Astrophysics of EW monopoles

- While produced non-relativistic, (not very heavy) EW monopoles are easily accelerated in a galactic magnetic field B ~ 3μG:

$$v_{\rm mag} \sim \begin{cases} c, & M \lesssim 10^{11}{\rm GeV} \ , \\ 10^{-3} c \left(\frac{10^{17}\,{\rm GeV}}{M}\right)^{1/2}, & M \gtrsim 10^{11}{\rm GeV} \ . \end{cases}$$

- The flux of relativistic monopoles:

$$F = \frac{c n_M}{4\pi} \approx 2.3 \cdot 10^{-19} \left(\frac{M}{10^7 \ GeV}\right) \ {\rm cm}^{-2} \ {\rm sr}^{-1} \ {\rm s}^{-1}$$

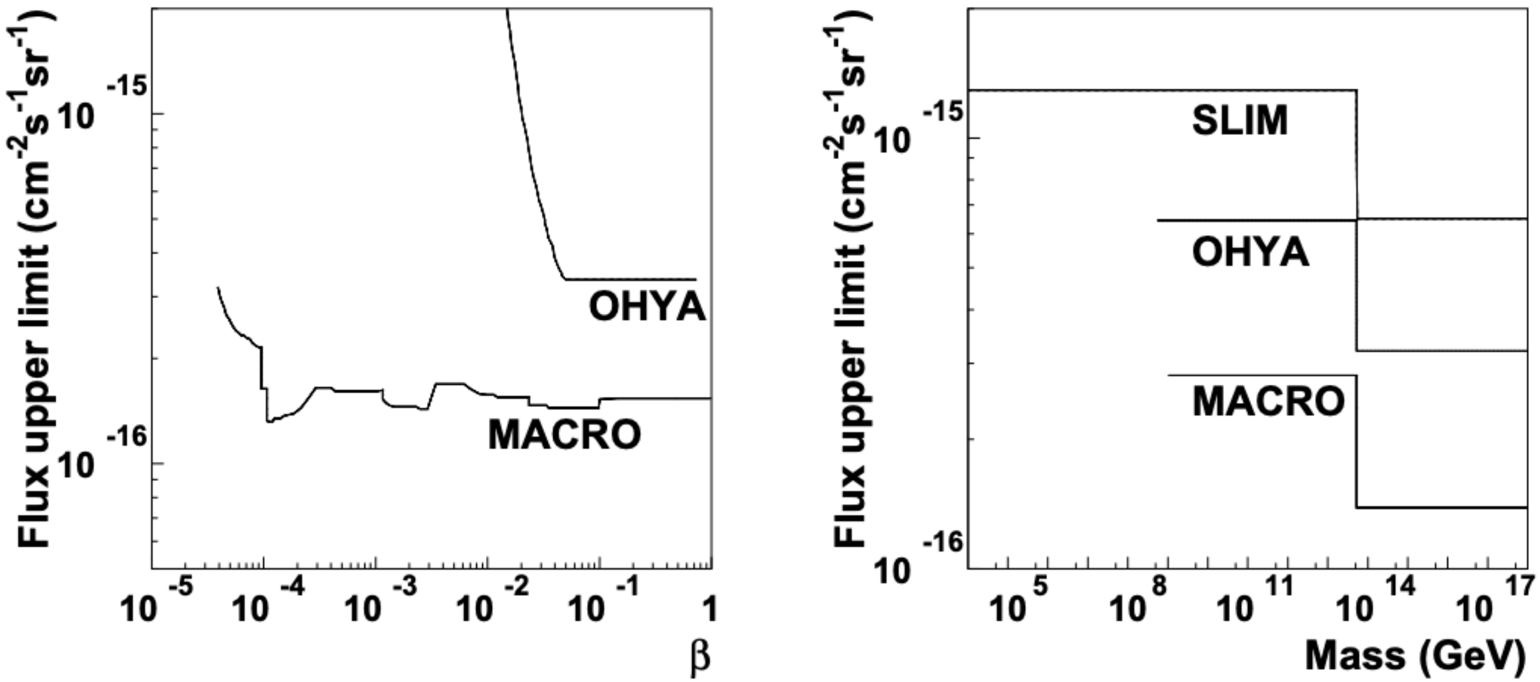
Astrophysics of EW monopoles

- Constraints from the survival of galactic magnetic field (the Parker bound):

$$F < \begin{cases} 10^{-15}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{sec}^{-1}\,, & M \lesssim 10^{17}\,\mathrm{GeV}\ , \\ 10^{-15}\left(\frac{M}{10^{17}\,\mathrm{GeV}}\right)\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{sec}^{-1}\,, & M \gtrsim 10^{17}\,\mathrm{GeV}\ . \end{cases}$$

- EW monopoles do not catalyze proton decay (like GUT monopoles). Therefore, bounds from the heating of compact objects do not directly apply. However, they mediate different B+L violating processes, requires careful study.

Summary of constraints



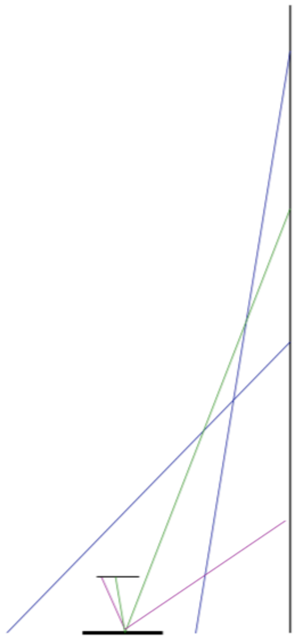
D. Mealsted & E.J. Weinberg, PDG 2017

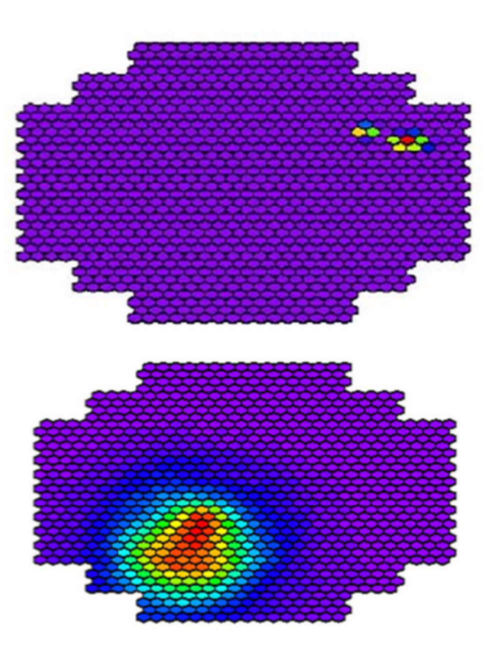
Cherenkov light from relativistic monopoles

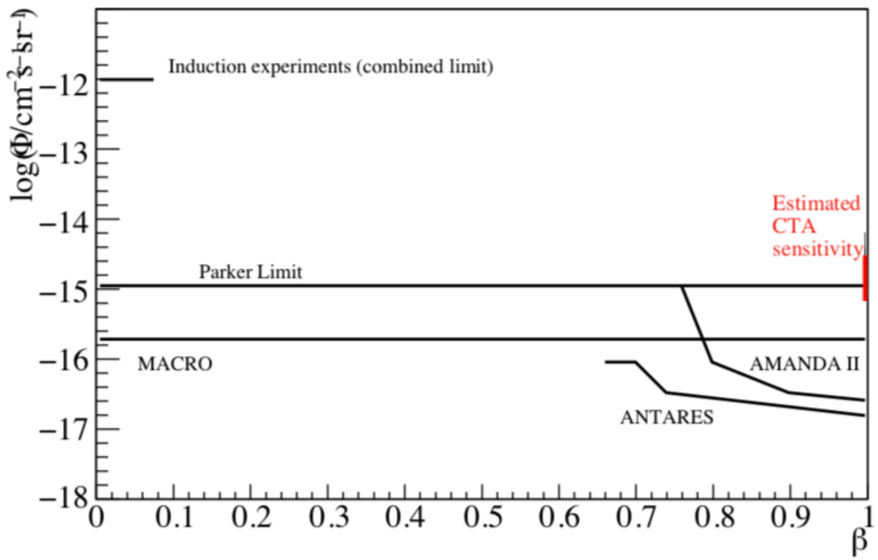
- Because much stronger electromagnetic interactions a relativistic monopole produces

$$\sim n^2 \left(\frac{g}{e}\right)^2 = 2n^2\alpha_g^2 \approx 9400$$ more photons than e.g., a relativistic muon.

- If no other interactions, very distinct image [Spengler, Schwanke, 11']:







M. Doro et al, 2012

More exotic signatures from EW monopoles and sphalerons

- B+L-violating electroweak scatterings:

$$M + N \to M + 6q^c + 3l^c + \ [\text{Higgses, W's, Z's}]$$

Much more brighter showers than usual hadronic ones.

- More theoretical work required
- Are we throwing them out as a ‘background’?
- A dedicated image cleaning? A dedicated analysis?

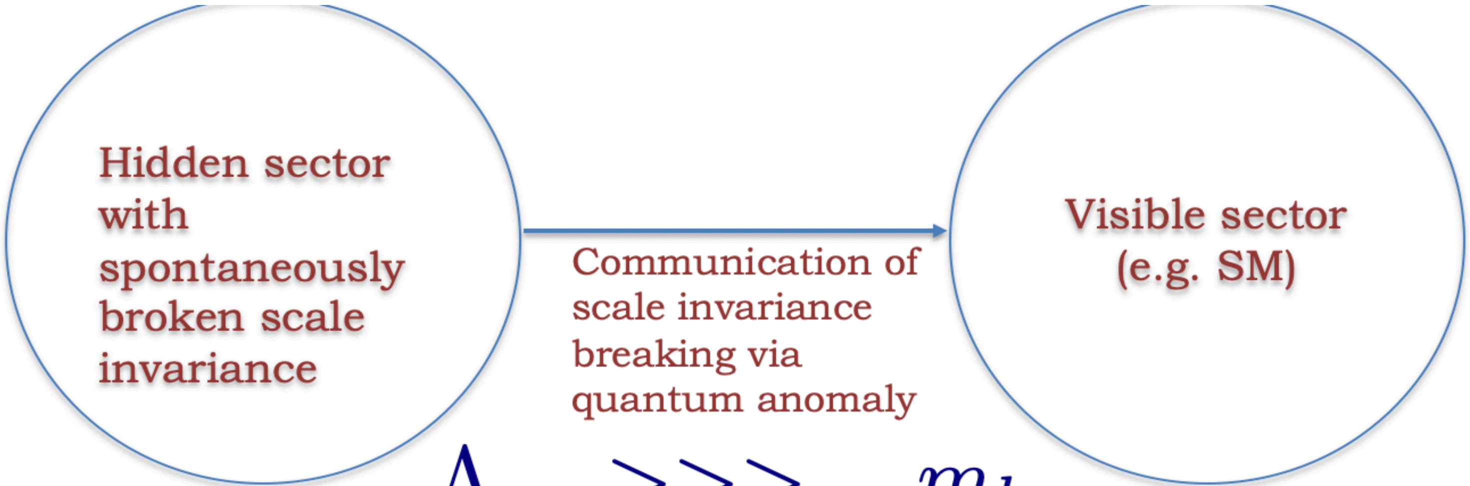
The origin of mass

(quark nuggets, gravitational waves, primordial black holes)

The origin of mass - Scale invariant paradigm

- We have not found yet anticipated new physics at the LHC => old problems remain unsolved

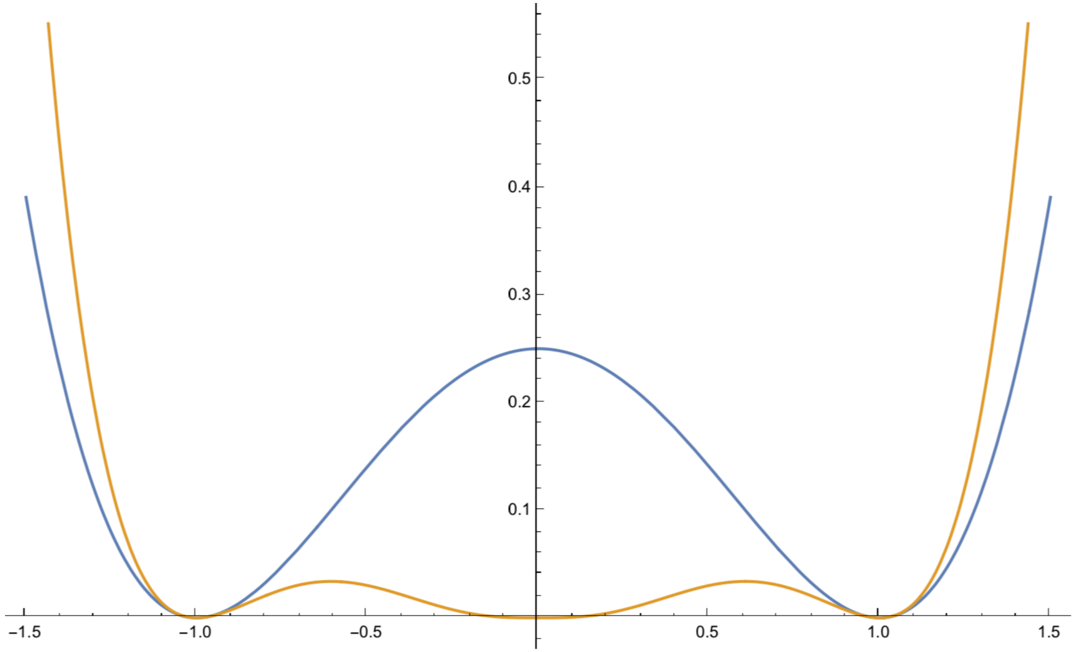
- Scale invariant paradigm for solving the electroweak scale stability (aka hierarchy, aka naturalness) problem [Wetterich 84’; Bardeen 95’; Meissner and Nicolai 07’; Foot, AK, Volkas 07’]



$$\Lambda \quad >>> \quad m_h$$

Scale invariant paradigm: Sydney version

- The minimal model is just SM with very feebly coupled dilaton of mass 10^{-8} eV (can be a dark matter).
- Almost indistinguishable from the SM in the perturbative sector, but…



- Can the model be probed through non-perturbative effects?

Cosmological electroweak phase transition

- The Higgs potential becomes:

$$V_T(h,\chi(h)) = \left[c(h)\pi^2 - \frac{\lambda(\Lambda)}{576}\frac{v_{ew}^2}{v_\chi^2}(2+v_{ew}^2/v_\chi^2)\right]T^4 + \frac{1}{48}\left[4\lambda(\Lambda)+6y_t^2(\Lambda)+\frac{9}{2}g^2(\Lambda)+\frac{3}{2}g'^2(\Lambda)\right]h^2T^2$$

$4\lambda(\Lambda)+6y_t^2(\Lambda)+\frac{9}{2}g^2(\Lambda)+\frac{3}{2}g'^2(\Lambda) > 0 \implies$ *h=0* is a local minimum for any T.

- If so, the universe would be trapped in symmetric vacuum *h=0*.

Cosmological electroweak phase transition

- In *h=0* vacuum all quarks are massless. *SU(6)xSU(6)* chiral symmetry is broken at T_c~132 MeV. The quark condensate break the electroweak symmetry as well.

$$\langle \bar{q}q \rangle_T = \langle \bar{q}q \rangle \left[1 - (N^2-1)\frac{T^2}{12Nf_\pi^2} - \frac{1}{2}(N^2-1)\left(\frac{T^2}{12Nf_\pi^2}\right)^2 + \mathcal{O}\left((T^2/12Nf_\pi^2)^3\right) \right]$$

$$\langle \bar{q}q \rangle \approx -(250\ \mathrm{MeV})^3$$

[Gasser & Leutwyler, 86']

- Higgs-quark Yukawa interactions: $y_q \langle \bar{q}q \rangle_T h/\sqrt{2}$

- $y_q \langle \bar{q}q \rangle_T/\sqrt{2} + \dfrac{\partial V_T}{\partial h} = 0 \rightarrow$ *h=0* is no more an extremum

Cosmological electroweak phase transition

- Quark condensate tips the Higgs field from the origin, which ‘runs down’ classically towards the electroweak minimum, smoothly and quickly completing the transition

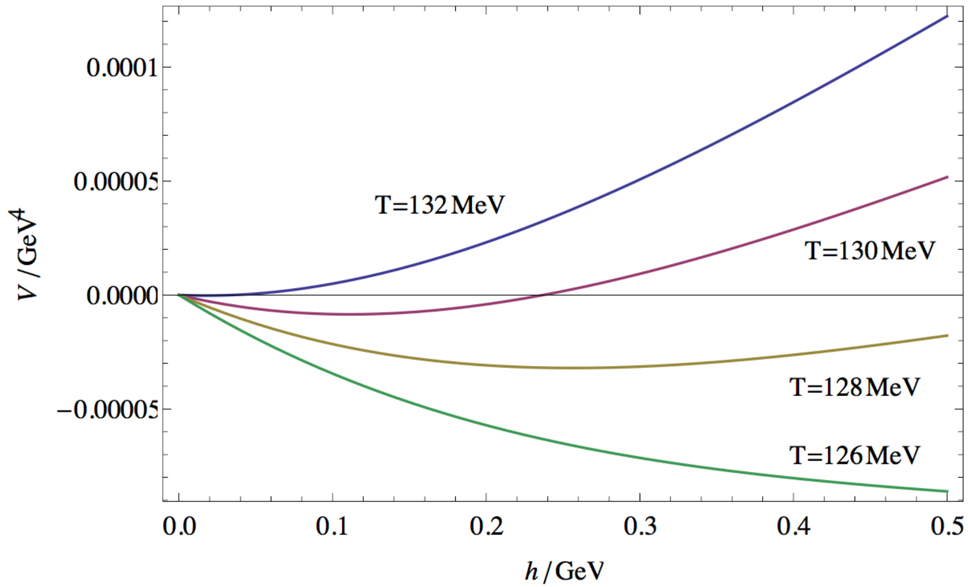


Figure 2: $V_T(h) - V_T(0)$ for different temperatures below the chiral phase transition.

Cosmological electroweak phase transition

- QCD with N=6 quarks undergoes first-order phase transition, unlike the standard case with N=3 [Pisarski, Wilczek 84'].

- Formation of 6 flavour quark matter nuggets of mass ~10^7 kg and size ~1 mm [Bai, Long 17', Witten 84']. Can constitute 100% dark matter.

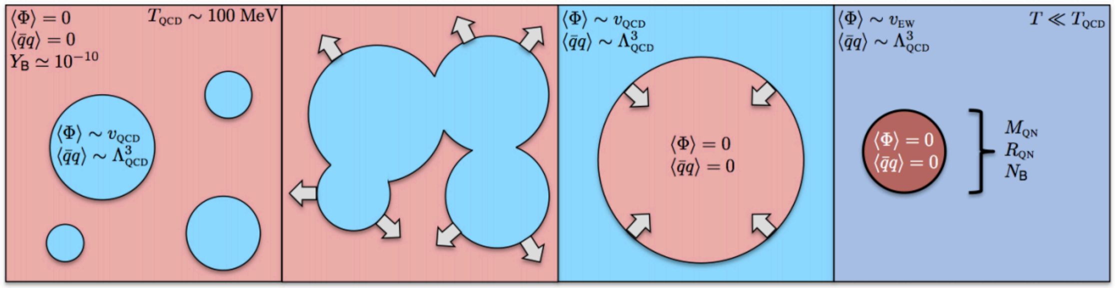


Figure 2: A cartoon illustrating the cosmological dynamics leading to the formation of nuggets of six-flavor quark matter. A first-order QCD phase transition causes the baryon number to accumulate into pockets of quark gluon plasma, which eventually cool to form 6FQM nuggets.

Taken from arXiv:1804.10249

Cosmological electroweak phase transition

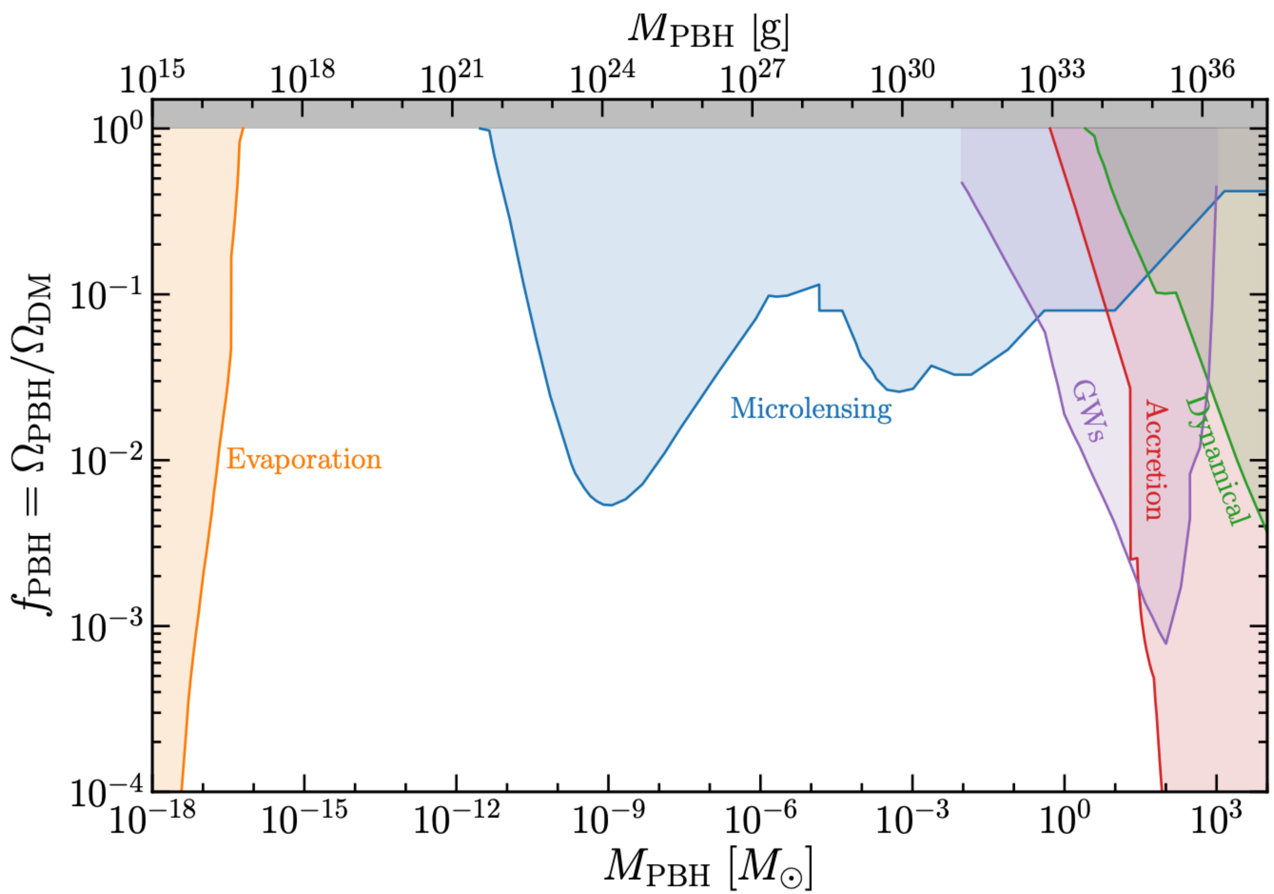
- Gravitational waves with peak frequency ~10^{-8} Hz, potentially detectable by means of pulsar timing (EPTA, SKA…) – (intriguing hint in recent NANOGRAV data)

- Production of primordial black holes with mass M_{bh}~$M_{\odot}$ – work in progress

$$R \sim 1/H_{\rm QCD} \sim M_P/T^2_{\rm QCD},$$
$$M_{bh} = R/2G \sim M_P^3/T^2_{QCD} \sim 10^{30}\ {\rm kg}$$

- QCD baryogenesis(?) – work in progress

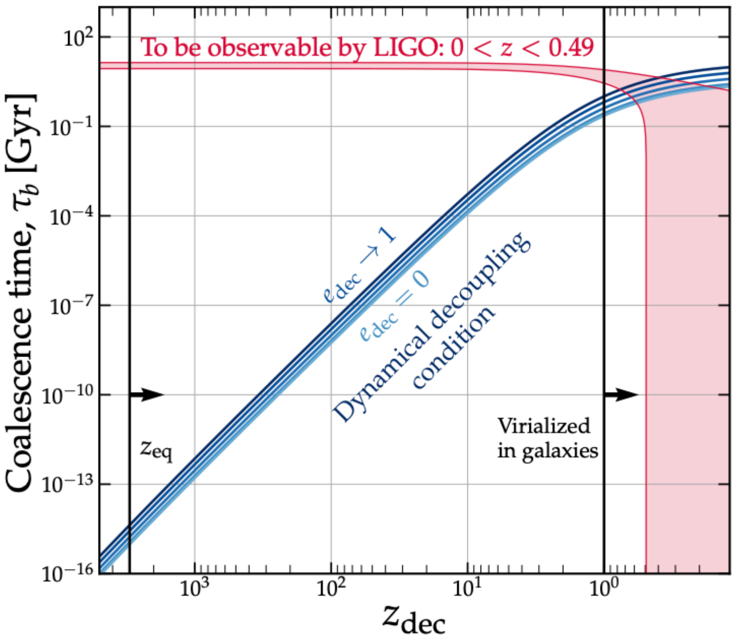
Primordial black holes as dark matter



A. M. Green, B. J. Kavanagh - arXiv:2007.10722

Primordial black holes as dark matter

- How do the black holes evolve in cosmological background?
- What is the mass of cosmological black holes? How do they evaporate? How do they form binaries?...



C. Boehm, AK, C. O'Hare, Z. Picker - arXiv:2008.10743

Conclusion

- The robust prediction for a new physics scale within SM is ~10 TeV.

- This scale is associated with a non-perturbative aspects of electroweak theory and potentially provides (less explored) portal to the BSM physics.

- Cosmic relics: sphalerons, monopoles, quarks nuggets, primordial black holes – can only be probed through astrophysical observations

- Tight connections with cosmology and fundamental questions on the origin of matter and mass

- Several theoretical/computational issues must be solved.