Boson Stars, Primary Photons & Phase Transitions

G. Kozlov

❑ Symmetries, PT & ***Boson Stars***

- Any phenomena in Universe are governed by **principles of symmetries /SSB**
- The scales in PP/Cosmology are the subjects of the light scalars (**the dilatons*)***

$\Rightarrow$ origin of ***BSs***

PT: Critical role on Evolving & Fluctuating of scalars in the early Universe

- PT corresponds to an initial thermal state (hidden sector) invariant under conf. group
- ***PT***: Cross-over influence, formation of bound states (scalars), approximately stable
- ***BEC*** of the dilatons into the ***BSs***

- PT @ finite T is identified through observables (measured quantities)

- ***Primary (direct) photons*** registration at the detector.

  "Primary" operator means not a derivative of another operator

❑ Boson stars

- $\left.\begin{matrix} self-interaction \\ gravitational\ equilibrium \end{matrix}\right\}$ Boson star *Colpi, Shapiro, Wasserman (1986)*

- $Repulsive\ \lambda_4\ in \sim \lambda_4\Phi^4 \Rightarrow rise\ to\ dense\ massive$ ***BS*** $(dilatons/"glueballs")$

➢ "Glueball" case. $m_G \sim O(\Lambda)$. **"Heavy"** ***BS***

$$M_{max}^{star} \sim \sqrt{\lambda_4}\left(\frac{m_p}{m_G}\right)^2 M_{wd} \sim M_{wd} \sim 1.7\cdot 10^{57} GeV, \quad \lambda_4 \sim O(1)$$

➢ Dilaton case. Boson star as *a dilaton garland mixed with the Higgs*

✓ $\boldsymbol{m_D \sim O(m_h), f}$ *are constrained by LHC data.* **"Light"** ***BS***

$$M^{star} < \sqrt{\frac{\lambda_{h\varphi}}{2\pi\zeta}\left(\frac{m_p}{f}\right)^2 \frac{v}{m_D}} M_{wd} \approx 1.7\cdot 10^{-6}\ M_{wd}$$

$GK\ (2022)$

❑ Boson star. Lifetime.

- ***BS*** *existence longevity in time* is governed by principles of symmetry

- Lifetime $\boldsymbol{\tau_{BS}}$ *depends on* $\boldsymbol{\tau_O}$ *in* $\sim \frac{\xi m^2}{\Lambda} H^+ H(x) O(x)$, $\quad O(x) = \sum_k c_k \varphi_k(x)$

- $\tau_H \ll \tau_O$, hidden scalar garland *GK (2022)*

- In the approximate $\mathbb{Z}_2$ *symmetry* $O(x)$ *is the* **LLP** if $\xi \ll \frac{\Lambda v}{m^2}$

➢ $\boldsymbol{\tau_{BS} \sim \tau_o = a_h^2 \tau_h}$, $\quad a_h = \frac{\xi m^2 v}{\Lambda m_h^2}$, $\qquad 7.7 \cdot 10^{-23} < \tau_h < 1.3 \cdot 10^{-21} s$

LLPs: $h \to \boldsymbol{OO} \to 2\tau^+ 2\tau^-$, $c\tau > 40\ m$, $m_{LLP} = 40\ GeV$ $\quad CMS$ (2021)

➢ $\boldsymbol{\tau_{BS} \sim \tau_O > 1.3 \cdot 10^{-7}\, s}$, $\quad \xi < 4 \cdot 10^{-2}$, $\quad \Lambda \sim O(M_{NP} \sim 10^5\ \mathrm{TeV})$

▪ Minimal model. Boson star.

○ ***BS*** is massive scalar in the asymptotic flat space-time

BS field $\boldsymbol{X(x)} \in \{h(x), O(x)\}$

$\downarrow$ Higgs

$\downarrow$ $\sum_{k=1}^{N} c_k \phi_k(x)$ *hidden scalar garland*

$$L = \frac{1}{2i}\left[(\partial_\mu X)^2 - (\partial_\mu X^*)^2\right] + D_\mu X (D^\mu X^*) + \frac{1}{2i}(v^{*2} X^{*2} - v^2 X^2)$$

$$D_\mu = \partial_\mu + ig B_\mu \; (DP)$$

$$\phi \to a\phi, \qquad h \to a^{-1} h$$

$$\boldsymbol{X(x)} = \frac{\omega\phi(x) + i\kappa h(x)}{\sqrt{2}}$$

$$h(x) = \frac{\omega}{\kappa}\frac{Im\,(a^2 v^2)}{Re(v^2)}\left[\phi(x) + f x_\mu \boldsymbol{B^\mu(x)}\right] + C(x), \quad (\Delta + Re v^2) C(x) = 0$$

✓ ADPM: ***DP*** $\boldsymbol{B_\mu(x) = m_{DP}^{-1}(const\, m_{DP}^{-2}\,\partial^2 - 1)\partial_\mu \phi(x)}$ *GK* (2021)

$$[P_\mu, \phi(x)] = -2iB_\mu(x); \quad [P_\mu, h(x)] = -i\partial_\mu h(x); \; \theta(k^0)\phi(k)|0\rangle = 0$$

vacuum

❑ *BS. Warm scenario*

○ ***BS*** *(N quantum states) in stat. equilibrium* $Z_N = Spe^{-H\beta},\ \beta = T^{-1}$

$H = \sum_{1 \le j \le N} H(j) = \sum_f F(f) b_f^+ b_f = \sum_f F(f)\, n_f$ (in f − representation)

$$F(f) = E(f) - \mu\, Q(f),\ \ b_f \to b_f = a_f + r_f$$

random fluctuation

➢ Probability to formation & evolution of ***BS*** *@ finite* ***T***

$$P(\bar{\mu}) = \sum_{N=1}^{\infty} Z_N \bar{\mu}^N, \qquad \bar{\mu} = \frac{\mu}{\mu_c}, \qquad @\ CP\ \mu_c < \frac{E(f)}{Q(f)}, \qquad \bar{\mu} \cong 1\ \boldsymbol{PT}!$$

BS *potential* $K = K_\phi + V_\phi + \lambda(f/2)^4,\ \ V_\phi = (\lambda/4)\phi^4[ln(\phi/f) - 1/4]$

$K_\phi(\bar{\mu}) = \beta^{-1} \int ln\left[1 - \bar{\mu} e^{-F(f)\beta}\right] df$ *thermochemical potential*

❑ *BS*. *Warm scenario (cont'd)*

- $K = \theta(\beta-\beta_c)K_\phi(\bar{\mu}) + \theta(\beta_c-\beta)K_{gH}^{eff}$, *"glueball" & gluons d.o.f.*

$$\downarrow$$

$$K_g + K_H(Haar\ measure, mod.-dep't)$$

➢ $K_g \approx \frac{m_g^2}{\pi^2\beta^2}\sum_{n=1}^{\infty}\frac{c_n}{n}K_2(n\beta\, m_g),\ m_g(\beta) = \frac{g(\beta)}{\beta},\ E_g = \sqrt{\vec{p}^2 + m_g^2}$

➢ Condition to condensed formation of ***BS*** in the early Universe

$$\sum_f \bar{n}_f = \sum_f \frac{1}{\bar{\mu}_0^{-1}e^{F(f)\beta} - 1} = N \quad \begin{cases} N \to \infty \Rightarrow \textbf{light dilaton}, \\ \text{"glueball"}\ \{gg\}_{s=0} \end{cases}$$

$$\downarrow$$

ground state of $\bar{\mu} = \mu/\mu_c$

$For\ n_f \to \infty \Rightarrow BEC \Rightarrow formation\ of\ BS$ ***bounded by self-gravity***

❖ *Warm & cold BSs*

Warm $BS \;\; \bar{\mu}_0 e^{\mu Q \beta} < 1 \; (T > T_c)$
Cold $BS \;\; \bar{\mu}_0 e^{\mu Q \beta} \sim 1 \; (T < T_c)$

$$\sum_f \bar{n}_f = \sum_f \frac{1}{\bar{\mu}_0^{-1} e^{F(f)\beta} - 1} = N$$

➢ Minimization of the probability to formation of the ***BS***

$$\frac{d}{d\bar{\mu}}[P(\bar{\mu})\bar{\mu}^{-N}]_{\bar{\mu}=\bar{\mu}_0} = 0, \qquad \bar{\mu} = \frac{\mu}{\mu_c}$$

Warm ***BS*** $\quad T_c = \frac{2\pi}{m_\phi}(2{,}612 \ldots \; v)^{-2/3}, m_\phi \neq 0, \quad v = \Omega/N$

✓ Correlation length $\quad \xi \sim \frac{\mu \, Q}{2\pi}(2{,}612 \ldots \; v)^{2/3} ln^{-1}(\bar{\mu}_0^{-1})$

- Fluctuation of m_ϕ *becomes more correlated*
- $non - mon. \xi \to \infty \;\; if \; the \; ground \; state \; \bar{\mu}_0 \to 1$ ***(indicator of PT)*** $\left(known \; from \; CP \; @ \; QCD_\beta\right)$ *Stephanov (2005)*
- For finite & small ***BS*** inverse density $v = \frac{\Omega}{N}$ *no PT caused by* ξ
- Short $\xi - length \; once \; T \ll T_c, \;\; \bar{\mu}_0 < 1.$

❖BS. Fluctuations of observables

*Event-by-event fluctuation of scalar's density @ T in **BS** volume V< Ω*

$$\frac{\langle (n_V - \langle n_V \rangle)^2 \rangle}{\langle n_V \rangle} - 1 = \frac{\sqrt{2}\, v}{\pi^2} (m_\phi T)^{\frac{3}{2}} \int_0^\infty \frac{x^2 dx}{\left(\bar{\mu}_0^{-1} e^{-\mu Q \beta} e^{x^2} - 1\right)^2}$$

$\langle n_V \rangle \hookrightarrow V/\Omega$

- *Increase sharply if* $T \to \mu Q / ln(1/\bar{\mu}_0)$

▪ ***PT** approached (vicinity of* **CP***)*

$$\frac{\langle (n_V - \langle n_V \rangle)^2 \rangle}{\langle n_V \rangle} - 1 \approx \frac{4}{\sqrt{\pi}\, 2{,}612 \ldots .} \int_0^\infty \frac{x^2 dx}{\left(z_c\, e^{x^2} - 1\right)^2}$$

❑ *No dependence of the scalar mass*

$$z_c = \bar{\mu}_0^{-1} e^{-a_c}, \quad a_c \approx \mu_c\, Q\, \Lambda\, (2{,}612 \ldots v)^{\frac{2}{3}} / (2\pi)$$

✓ **Non-monotonous rising if** $\bar{\mu}_0 \to 1$ ***with*** $v \to 0$ $(N \to \infty)$ **!**

❑ *Primary photons from* ***BS***

Primary (direct) *γ's radiated by* ***BS*** *through the decays of scalars*

- Indications? Observables? What's happed @ PT?

- In exact scale symmetry:

Hidden scalar – SM sector: $L = \frac{\phi}{f}\left(\Theta^{\mu}_{\mu\ tree} + \Theta^{\mu}_{\mu\ anom}\right)$

$-\sum_q m_q \bar{q} q + \cdots$ ↩ ↪ in contrast to SM

➢ Hidden scalars couple to $\gamma\gamma$ *or* gg ***even before*** *running any SM in the loop* $\Rightarrow$ *trace* $\Theta^{\mu}_{\mu\ anom}$ *DP* ↰

$$\sim -\alpha b_{EM} F^2_{\mu\nu} - \alpha_s \sum_i b_{oi} \left(G^a_{\mu\nu}\right)^2 - \bar{\varepsilon} F_{\mu\nu} B^{\mu\nu}$$

❑ BS by "glueballs"

If $\left.\begin{matrix} QCD \\ EM \end{matrix}\right\} \in conformal\ sector \rightarrow \sum_{light} b_o = -\sum_{heavy} b_o\ above\ \Lambda$

quark-lepton conformal condition

➢ **The "glueball" mass splits light and heavy states !**

$$\frac{\beta(g)}{2g}\left(G^a_{\mu\nu}\right)^2 \rightarrow \frac{\alpha_s}{8\pi} b_o^{light}\left(G^a_{\mu\nu}\right)^2, \qquad b_o^{light} = -11 + \frac{2}{3} n_L$$

$$m_\phi \sim O(\Lambda) \rightarrow n_L = 3:\ COUPLING\ STRENGTH \sim \frac{gg\phi}{ggh} \sim 14!\ increase$$

Low-energy eff. $\left\langle \gamma\gamma \middle| b_0^{light}\alpha_s\left(G^a_{\mu\nu}\right)^2 \middle| 0\right\rangle = -\left\langle \gamma\gamma \middle| b_{EM}\alpha\left(F_{\mu\nu}\right)^2 \middle| 0\right\rangle, \vec{q} \approx 0$

➢ Primary photons emission:

$-8/3$ ↰

$$\Gamma(\phi \rightarrow \gamma\gamma) \cong \left(\frac{\alpha F_{anom}}{4\pi}\right)^2 \frac{m_\phi^3}{16\pi f^2}, \quad F_{anom} = -\left(\frac{2n_L}{3}\right)\left(\frac{b_{EM}}{b_0^{light}}\right)$$

❑ *Primary photons. Observation.*

BSs unstable, showers of $\gamma\gamma,\ \bar{\gamma}\bar{\gamma},\ \bar{\gamma}\gamma, \ldots$ $\quad (conformal\ EM\ anomaly)$

- Measurement of $\gamma's\ escape\ -\ decisive\ way\ to\ observe$ & $differentiate\ primary\ \gamma's$ and ordinary $\gamma's$ $(\pi^0 \to \gamma\gamma, \ldots)$

- Fluctuation rate of $\gamma's\ production\ in\ approximate$ $conformal\ sector\ (proximity\ to\ PT)$ $\qquad f \sim O(\Lambda), f_\pi \approx 0.3\Lambda$

$$r_{\gamma\gamma} = 1 + \frac{BR(\pi^0 \to \gamma\gamma)}{BR(\phi \to \gamma\gamma)} = 1 + m_\pi^3 \left(\frac{6}{F_{anom}}\right)^2 \xi^3$$

❑ Abundant $\gamma's\ escape$: $r_{\gamma\gamma} \to \infty\ as\ \xi(T \to T_c) \to \infty$

with $n_L \to 0,\ \ and\ N_f \to N_f^c,\ m_\phi \approx \left(1 - \frac{N_f}{N_f^c}\right)^{\frac{1}{2}} \Lambda$

N_f^c separates conformal phase from the one with chiral symmetry

✓ **Result:** ***Fluctuation of the BSs in the proximity to IRFP***

❑ *SU(N) Hidden sector in the BS*

➢ *SU(N) hidden. Direct coupling. "Glueball" ϕ.*

Soni (2016)

$$\frac{1}{M_{cut}^4}\left(H_{\mu\nu}\right)^2\left(F_{\alpha\beta}\right)^2 \rightarrow \frac{N m_\phi^3}{M_{cut}^4}\phi\left(F_{\alpha\beta}\right)^2$$

$SU(N)_{hidden\ gauge\ group}$

❑ Primary $\gamma's\ emission\ (direct\ point - like\ in\ \boldsymbol{BS})$:

$$\Gamma(\phi \rightarrow \gamma\gamma) = \frac{1}{4\pi} m_\phi N^2 \left(\frac{m_\phi}{M_{cut}}\right)^8$$

the value N for a self-interacting ϕ: $N \approx Max\left[\left(0.1\,GeV/m_\phi\right)^{3/4}, 2\right]$

➢ **Combined result** $[conformal\ anomaly\ \leftrightarrow SU(N)_{hidden}]$:

$$M_{cut} > 3.4\,GeV, \qquad \Lambda = 330\,MeV$$

$m_\phi \sim O(\Lambda)$

$$M_{cut} > 5.2\,GeV, \qquad \Lambda = 500\,MeV$$

❑ Conclusions

1. DM: the lightest hidden scalar field likely dilaton or the "glueball"

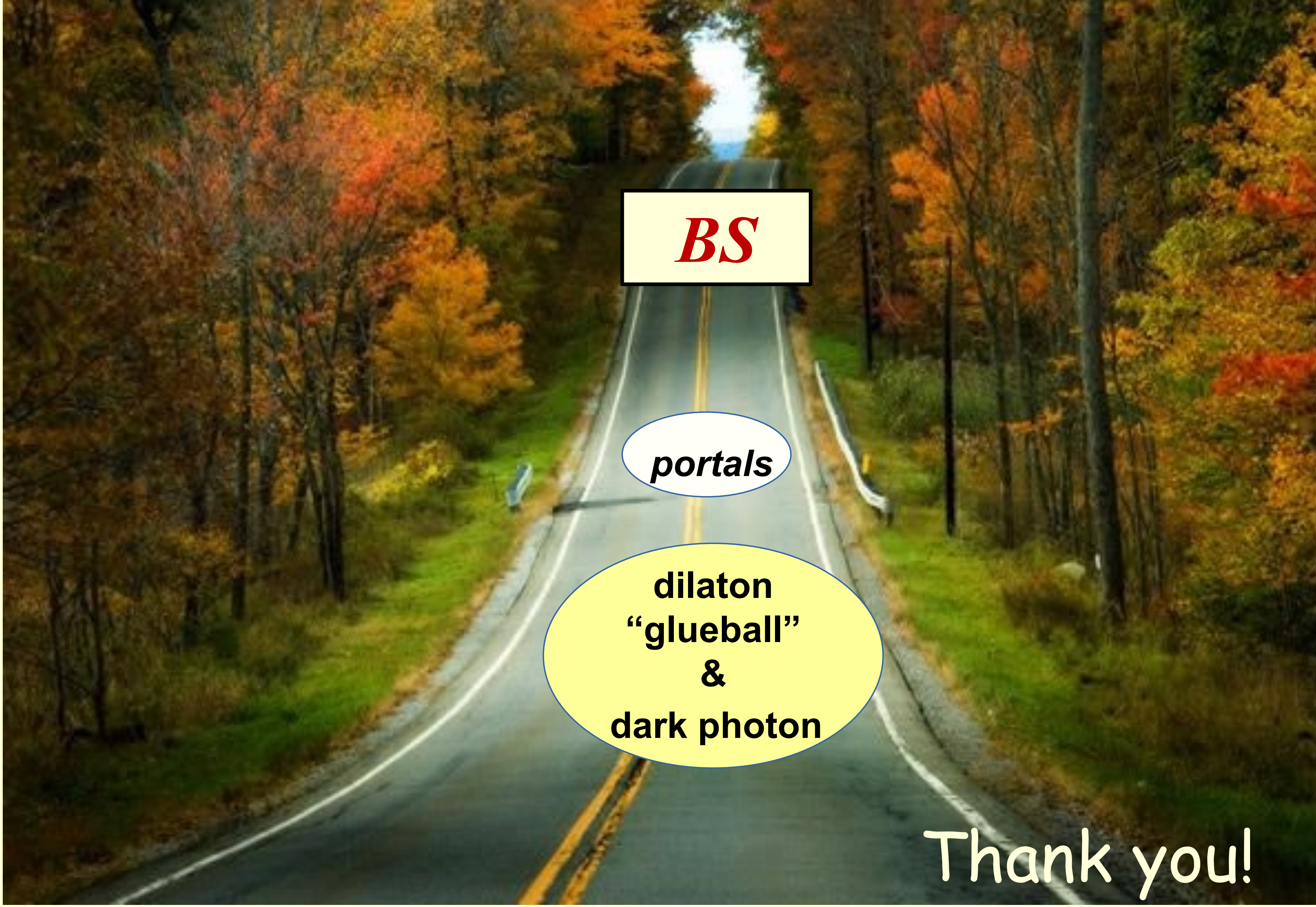
2. DM *cold*/*warm*, BEC into compact massive ***BS.*** CA cosmic rays.

3. ***BS*** hides a part of scalar DM from observations. After formation, becoming large, ***BS*** may *explode* into leptons via decays of ***DP***s or emit primary photons.

4. Energy scan, non-monotonous behavior $\gamma\gamma$ fluctuation at *PT/CP vicinity*

5. PT & CP signature: $\gamma's$ showers increase compared to π^0 $decays$

6. Observation: measuring $\gamma's$ yields, fitting with μ/T ***QFT*** models


BS
portals
dilaton
“glueball”
&
dark photon
Thank you!