(QCD) *axions* as CDM

1603.04249
1405.1139
1307.8024

how to distinguish from WIMPs?

Sacha Davidson T Schwetz, M Elmer
and thanks to Georg Raffelt
IN2P3/CNRS, France

1a. Reminder:
- the QCD axion
- PQPT after inflation $\Rightarrow$ axions from misalignment and string-network decay

1b. to compute dynamics of axion energy density?
...ask the Path Integral...
$\Rightarrow$ Einsteins Eqns with $T^{\mu\nu}(a_{cl}, f(x,p))$

2. growing Large Scale Structure ...is dynamical...+ non-linear

- initial conditions
- linear era
- $\delta\rho/\rho \gtrsim 1$: a **static** solution $\Leftrightarrow$ the halo of Andromeda today

We all know the QCD axion...

1. strong CP solution: can have $\delta\mathcal{L} \sim -\boldsymbol{\theta}\frac{g_s^2}{32\pi^2}G^A_{\mu\nu}\widetilde{G}^{\mu\nu A}$... To suppress $\theta \lesssim 10^{-10}$ (nedm: Pich-deRafael, Pospelov-Ritz) arrange fermions to transfer θ onto phase of scalar field Φ via chiral anomaly, $|\Phi|$ gets large ($\sim 10^{12}$ GeV) vev.

2. one new light dynamical field = phase of Φ = axion

Peccei Quinn
Kim , ShifmanVainshteinZakharov
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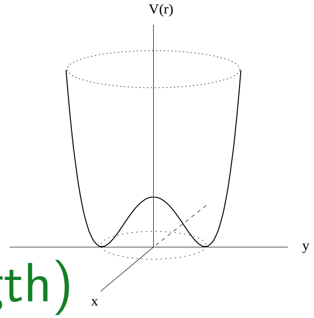
3. axion of **QCD** $\Rightarrow$ fix potential

$$V(a) \approx f_\pi^2 m_\pi^2[1-\cos(a/f)] \simeq \frac{1}{2}m^2a^2 - \frac{1}{4!}\frac{m^2}{f^2}a^4 + \frac{1}{6!}\frac{m^2}{f^4}a^6 + ...$$

$$m_a \sim \frac{m_\pi f_\pi}{f} \simeq 6\times 10^{-5}\frac{10^{11}\mathrm{GeV}}{f}\mathrm{eV} \qquad \lambda = \frac{m^2}{4!f^2} \simeq 10^{-49}\left(\frac{m}{.0001\mathrm{eV}}\right)^4$$

(but λ not small compared to grav: $\frac{1}{f^2} \sim 10^{16}G_N$, and attractive...keep in *field* equations?)

Cosmological history $\rightarrow$ fluctuation spectrum



1. *IF* first inflation, then the axion is born: $\Phi \rightarrow f e^{ia/f}$
   $*$ a random $-\pi f \leq a \leq \pi f$ in each horizon ($=$ correlation length)

$$\langle a^2 \rangle_{U\ today} \sim \pi^2 f^2/3$$

   $*$ ...one string/horizon

   ...wait loooong time til QCD PT (*notice* $\rho_a = 0$)

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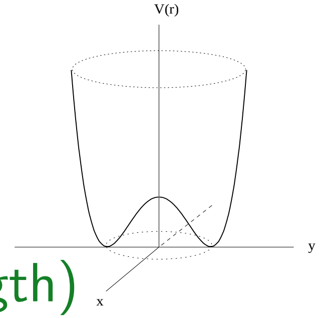

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2. QCD Phase Transition ($T \sim 200$ MeV): ...χ sym. breaks (tilt mexican hat)

$$m_a(t) : 0 \rightarrow f_\pi m_\pi / f \quad \Rightarrow \quad V(a) = f_{\rm PQ}^2 m_a^2 [1 - \cos(a/f_{\rm PQ})]$$

   $*$ ... at $H < m_a$, "misaligned" axion field starts oscillating around the minimum
   $*$ energy density $m_a^2 \langle a_0 \rangle^2 / R^3(t)$ density today higher for smaller mass
   $*$ strings go away (radiate cold axions, $\vec{p} \sim H \lesssim 10^{-6} m_a$)

$$\Omega_{axion} \sim \Omega_{CDM} \qquad \Leftrightarrow m_a \sim 10^{-4}\ {\rm eV}$$

Hiramatsu etal 1012.5502

Step back: how to compute what?

Two sources/populations of CDM axions: from misalignment and strings

classical field?
Bose Einstein Condensate? } ?same?
made of particles } ?different? ?? ???

no matter! I only need to know: *how do they evolve?*

⇒ **consult the path integral**/(delphic oracle)

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- variables $=$ expectation values of n-pt functions ($\phi \equiv$ axion)

$$\langle\phi\rangle \leftrightarrow \text{ classical field} = \text{misalignment axions } \phi_{cl}$$

$$\langle\phi(x_1)\phi(x_2)\rangle \leftrightarrow \text{ (propagator)} + \text{distribution of particles } f(x,p)$$

?put the string axions here?

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- get Eqns of motion for expectation values in Closed Time Path formulation

Einsteins Eqns with $T^{\mu\nu}(\phi_{cl}, f)$ + quantum corrections(λ, G_N)

(in 2 Particle Irreducible formulation, get EoM simultaneously for 1 , 2-pt fns)

$\Rightarrow$**simple @ leading order**(Saddle Pt of Path Int.): Einsteins Eqns with $T^{\mu\nu}(\phi_{cl}, f)$.
Quantum corrections as perturbative expansion in G_N, λ (both tiny)

do 2ParticleIrred, ClosedTimePath PI in CurvedSpaceTime?

Equations for CDM axions: Einstein with $T_{\mu\nu}(a_{cl}, f(x,p))$

$f(x,p)$ for non-rel. incoherent axion modes : like WIMPs (so ignore in remainder):

$$T_{\mu\nu} = \begin{bmatrix} \rho & \rho\vec{v} \\ \rho\vec{v} & \rho v_i v_j \end{bmatrix}$$

compare to perfect fluid: $T_{\mu\nu} = (\rho + P)U_\mu U_\nu - P g_{\mu\nu}$. $P_{int} \propto \lambda^2 \to 0$, nonrel $\Rightarrow P \ll \rho, U = (1, \vec{v}), |\vec{v}| \ll 1$

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Classical field in non-relativistic limit ($a \to \frac{1}{\sqrt{2m}}\sigma(x)e^{i\theta(x)}e^{-imt}$)

$$T_{\mu\nu} = [\nabla^\mu a \nabla^\nu a] - g^{\mu\nu}\left(\frac{1}{2}\nabla^\alpha a \nabla_\alpha a - V(a)\right)$$

$$= \begin{bmatrix} \rho & \rho\vec{v} \\ \rho\vec{v} & \rho v_i v_j + \Delta T_{ij} \end{bmatrix} \qquad \Delta T^i_j \sim \partial_i a \partial_j a \ , \ \lambda a^4$$

Sikivie

different pressures with classical field+ self-interactions at $\mathcal{O}(\lambda)$

$\equiv$ Bose Einstein condensate(1. field = order param in QFT. 2. is defn of cond. mat.)

Part II: Forming Large Scale Structure

with misalignment axions?

(and axion born after inflation $\Rightarrow$ miniclusters)

1. initial conditions for the field
2. assume linear growth is “standard”
3. not do dynamics ofminicluster collapse/ galaxy formation — requires numerics
4. statics for FIELD : stable axion + Newton configuration
5. observational bounds

Initial spectrum of axion density fluctuations

(QCDPT = complicated...start a bit after)

1a: misalignment axions spatially random on co-moving QCDPT-horizon scale

$\equiv$ **miniclusters**, white noise spectrum $\langle \frac{\delta M_a}{M_a} \rangle \sim \sqrt{\frac{M_{mini}}{M_a}}$

Hogan,Rees
Tkachev+Kolb

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$$M_{mini} \sim V_{osc} m_a n_{osc} E$$

$m(T_{osc}) = 3H(T_{osc})$, $E \sim 2 \rightarrow 8$ E: Turner86 Lyth92,BaeEtal08

curious variation by $\sim 10^3$ in E/V estimates in literature? +some include axions from strings

$$M_{mini} \sim \frac{\pi^2 m f_{PQ}^2}{H^2(T_{osc})} \simeq \begin{cases} 3 \times 10^{-14} M_\odot & \text{Etal + Villadoro} \\ 3 \times 10^{-13} M_\odot & \text{int. inst. liq.} \\ 3 \times 10^{-12} M_\odot & \text{Kitano, Yamada} \end{cases}$$

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1b: axion field(+string-decay-prods) inherit adiabatic $\delta\rho/\rho$ on LSS scales from bath

2. phase space distribution of NR axions from strings

??fluctuation spectrum?? $\frac{\delta\rho_a}{\rho_a} \sim 1$ on scale H^{-1}_{QCDPT}??

Linear Fluctuation Evolution

standard lore: matter fluctuations in horizon "frozen" in rad. fluid 'til $\rho_{mat} \gtrsim \rho_{rad}$

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G_N \overline{\rho}_a \delta + c_s^2 \frac{k^2}{R^2(t)} \delta = \text{non–lin–grav} \qquad \left(\delta \equiv \frac{\delta \rho_{mat}(\vec{k}, t)}{\overline{\rho}_{mat}(t)} \; , \; \delta_{rad} = 0 \right)$$

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1. For $\delta \sim 10^{-5}$ fluctuations on LSS scales:

⋆ pressure ($c_s^2 \sim \delta P / \delta \rho$) irrelevant because $k \to 0$

⋆ non-lin on LSS scales negligeable because $\delta \ll$. And $\delta \sim 1$ on small scales negligeable for large LSS scales because separation of scales

Peebles, LSS sec 28

(virial on small scales ⇒ cancellations among non-lin terms)

2. for the miniclusters ?

defn c_s
Peebles+Ratra

$$c_s^2 \sim \left(\frac{k}{mR(t)} \right)^2 - \lambda \frac{a^2(t)}{m^2}$$

∗ so neglect pressure for $\lambda_{comov} \gtrsim \sqrt{\frac{H_{HCD}}{m}} \frac{1}{H_{QCD}} \simeq$ Jeans

∗ are grav.non-linearities irrelevant? Hogan+ Rees said frozen til t_{eq}
⇒ suppose correct

∗ ...when $\delta\rho_a \sim \bar{\rho}_{rad+mat}$, decouples from Hubble + collapse
hierarchical process

Hogan+Rees
FairbairnEtal

⇒ to what?

Eqns to look for stable grav. bd solution

1. NR axion field (NB $[\phi] = m^{3/2}$),:

$$a = \frac{1}{\sqrt{2m}}(\phi e^{-imt} + \phi^* e^{imt})$$

2. EoM from $T^{\mu\nu}{}_{;\nu} = 0$,either
   1) Schrodinger-like (Gross Pitaevskii):

$$\dot{\phi} = -\frac{\nabla^2}{2m}\phi - |g|(\phi^\dagger\phi)\phi + mV_N\phi$$

with $$|g| = \frac{1}{8f^2} \quad , \ \nabla_x^2 V_N(x - x') = 4\pi G_N \rho(x'),$$

Eqns to look for stable grav. bd solution after collapse

1. NR axion field (NB $[\phi] = m^{3/2}$),:

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with $\quad |g| = \frac{1}{8f_{\rm PQ}^2},\ \nabla_x^2 V_N(x - x') = 4\pi G_N \rho(x'),$

   2) write $\phi = \sqrt{\frac{\rho}{m}} e^{-iS}$ and $v^j = -\partial_j S/m$, get *fluid* eqns:

$$\begin{aligned} \partial_t \rho &= -\nabla \cdot \rho\vec{v} && \text{continuity} \\ \rho\partial_t\vec{v} + \rho\vec{v}\cdot\nabla\vec{v} &= \rho\nabla\left(\frac{\nabla^2\sqrt{\rho}}{2m^2\sqrt{\rho}} + |g|\frac{\rho}{m^2} - V_N\right) && \text{Euler} \quad , \end{aligned}$$

Stable solution that could occur after collapse

1 recall *fluid* eqns (with $\phi = \sqrt{\frac{\rho}{m}} e^{-iS}$ and $v^j = -\partial_j S/m$),

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* eqns for dust extra terms for axion field, $|g| \sim 1/f^2 \sim \lambda/m^2$

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$*$ eqns for dust extra terms for axion field, $|g| \sim 1/f^2 \sim \lambda/m^2$
$*$ self-interaction pressure *inwards*: $\frac{\partial}{\partial r} r^{-n} < 0$
$*$ fluid parameters single-valued (no shell-crossing $\Rightarrow$ shocks, etc.) ... *different* from $f(x,p)$

"Bose Stars" in GR, Rindler-Daller+Shapiro, Chavanis, ... Broadhurt etal (numerics)

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2 Set LHS of Euler $\simeq 0$ (stable soln), dim analysis:

$$\left(\frac{1}{2m^2 R^2} - |g| \frac{M}{m^2 R^3} - G_N \frac{M}{R} \right) \simeq 0 \quad \Rightarrow \quad R \sim \frac{m_{pl}^2}{4m^2 M} \left(1 \pm \sqrt{1 \mp \frac{m^2 M^2}{2 f^2 m_{pl}^2}} \right)$$

$M_\odot \simeq 10^{57}$ GeV $\sim 2 * 10^{30}$ kg
$kpc \simeq 3 * 10^{21}$ cm

Stable solutions

BarrancoBernal
Rindler-DallerShapiro
Chavanis+
DavidsonSchwetz
...

approx stationary soln to *Euler* , with self-int sign from $\mathcal{L}_a \supset \pm\frac{\lambda}{4!}a^4$

$$R \sim \frac{m_{pl}^2}{4m^2}\frac{1}{M}\left(1 \pm \sqrt{1 \pm \lambda\frac{48M^2}{m_{pl}^2}}\right)$$

the QCD axion, $m \sim 10^{-4}$ eV, $\lambda \sim -\frac{m^2}{f^2} \sim -10^{-45}$,

$$\Rightarrow \quad R \sim \frac{m_{pl}^2}{4m^2 M} \quad , \quad M \lesssim \frac{m_{pl} f}{m} \, .$$

$$R \sim 100 \text{ km} \quad , \quad M_{max} \sim 10^{-(14\to 13)} M_\odot \left(\frac{10^{-4}\text{eV}}{m}\right)^2 \simeq \begin{cases} \text{asteroid!} \\ \lesssim \text{minicluster} \end{cases}$$

Andromeda : $M \sim 10^{12} M_\odot$, flat rotn curves to 100s kpc. ...halo not composed of oscillating axion field?

(numerical ansätz for the radial fn, allowing breathing mode Chavanis)
heavier, smaller solutions, if account for $1 - \cos(a)$ potential BraatenMohapatraZhang

arXiv:1603.04249
with Thomas Schwetz
Rindler-DallerShapiro,
ALP halos, $m \ll$, repulsive SI.

If allow for rotation, can we get a bigger object?

• Include rotation via Virial thm:

$$E_{grav} + 2E_{cin} + 3E_{si} = 0$$

$$E_{grav} = \int dV \frac{\rho}{2} V_N \,, \qquad E_{si} = g \int dV \frac{\rho^2}{2m^2} \,, \qquad E_{cin} = \frac{1}{2} \int dV \left[\frac{(\nabla \rho)^2}{4\rho m^2} + \rho |\vec{v}|^2 \right] .$$

assume applies for rotating axion drop.

• Implement rotn in field Eqns, because simple to impose continuity of phase

$$\phi(r, \theta, \varphi) \simeq \mathrm{top} - \mathrm{hat} \times \sin^l \theta e^{il\varphi}$$

• See that $E_{grav}, E_{SI} \sim \sqrt{l+1}$ (drop flattens to disk for large l)
$E_{cin} \sim l^2$ (angular momentum + gradient in θ)

$$M \lesssim \frac{m_{pl} f}{m} \frac{1 + 4l(l+1)}{\sqrt{l+1}} \lesssim \frac{1 + 4l(l+1)}{\sqrt{l+1}} \times 10^{-13} \, M_\odot \, .$$

• Asteroids have masses, radii $\sim$ non-rotating axion drops, rotation periods ~ 6 hours. Equatorial rotation frequency of drop at r_c, $\omega \simeq l/(r_c^2 m) \simeq 6l/$day, $\Rightarrow$ (?) low l are realistic.

$\Rightarrow M_{max}$ grows by $\sim$ order of mag (confirmed numerics)

Dynamics !

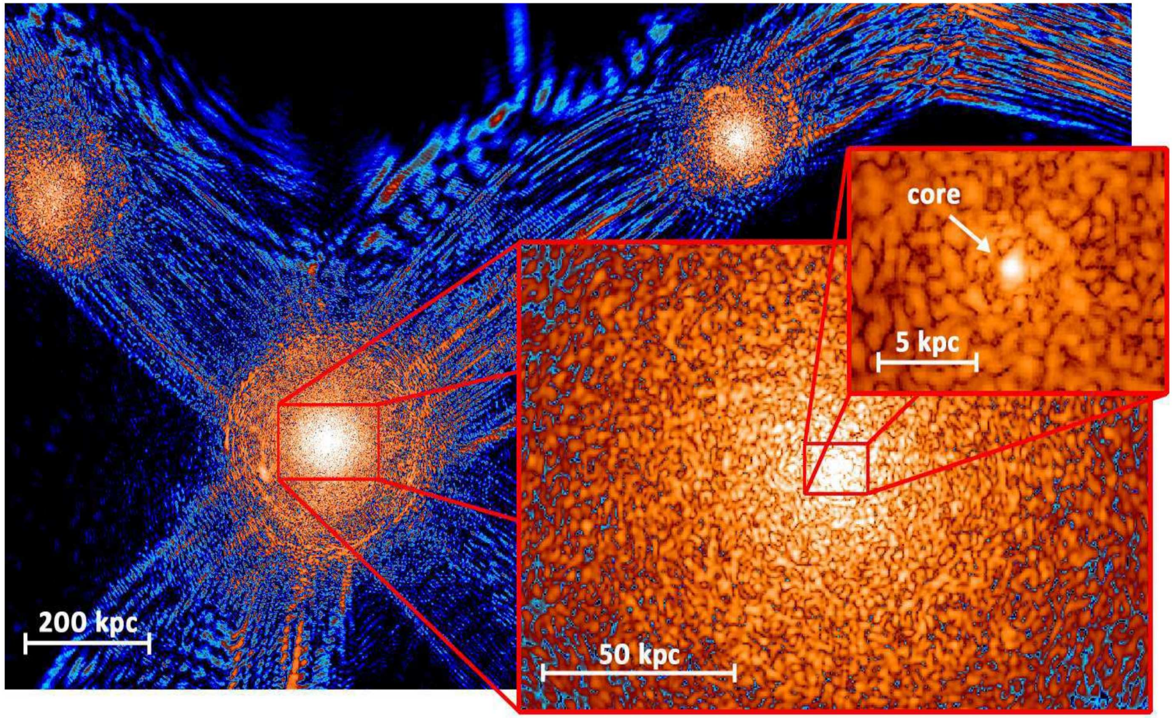

Figure 2: A slice of density field of ψDM simulation on various scales at $z = 0.1$. This scaled sequence (each of thickness 60 pc) shows how quantum interference patterns can be clearly seen everywhere from the large-scale filaments, tangential fringes near the virial boundaries, to the granular structure inside the haloes. Distinct solitonic cores with radius $\sim 0.3 - 1.6$ kpc are found within each collapsed halo. The density shown here spans over nine orders of magnitude, from 10^{-1} to 10^{8} (normalized to the cosmic mean density). The color map scales logarithmically, with cyan corresponding to density $\lesssim 10$.

SchiveChiuehBroadhurst, Nature , $m \sim 10^{-22}$ eV

Constraints on DM of the size of asteroids?

Jacobs Starkman Lynn
Zurek etal
FairbairnMarshQuevillon

window where Primordial Black Holes can contribute $\Omega_{BH} \sim .1$:

$$\text{(femtolensing) } 10^{-13} M_\odot \lesssim M_{PBH} \lesssim 10^{-9} M_\odot \text{ (microlensing)}$$

(PBH $\lesssim 10^{-18} M_\odot$ evaporate)

Micro-lensing:halo object amplifies light from nearby stars (LMC)

Femtolensing: source = GRBs, lensing objects in intervening space, signal = oscillation in energy spectrum (interference between light that took two different paths round the lensing object)

BATSE: exclude $\Omega \sim 0.2$ for $10^{-16} \to 10^{-13} M_\odot$

(+ picolensing bounds = 1 σ sensitivity to $\Omega \sim 1$ of compact objects in the mass range $10^{-12.5} M_\odot \to 10^{-9} M_\odot$.)

FERMI :GRBs at measured redshift, exclude $\Omega > 0.03$ in compact objects of mass between

$$5 \times 10^{-17} \to 5 \times 10^{-15} M_\odot$$

BarnackaGlicensteinModerski

(assumes GRB = point source. Is GRB projected onto lens plane smaller than Einstein radius?)

$\Rightarrow$ axion asteroids allowed as (at least part of) DM

? hierarchical clustering ? (need more coherence among analyses before excluding :))

Other constraints?

1. Do the drops evaporate due to self-interactions?

   Tkachev,Riotto

2. Do axion drops drops shine like comets (could be bound on $\lesssim 10^{-14} M_{\odot}$)?

3. What is cross-section in CMB? geometric ? (Starkmann et al argue for "collisional damping" constraints if yes. Might depend on whether drops accumulate baryons?

4. One can ask what happens if a drop meets an ordinary star, a white dwarf, a neutron star, or a black hole?

   disk stars
   Dokuchaev Eroshenko Tkachev

5. The "explosion" of axion drops was recently proposed as a possible source for Fast Radio Bursts.

   Tkachev

(Summary), Speculations + Provocations

Suppose PQ phase transition after inflation...two axion contributions to CDM. (Assume) linear fluctuation growth like WIMPs.

1. "particles" from strings: cluster like WIMPS/N-body (?). $\Rightarrow$ in our galaxy, a non-rel. maxwellian distribution, approximate as axion field

2. misalignment axions ...have "miniclusters"...similar size (?) to stable grav. bound configuration, which is size of an asteroid (not galactic halo, *field* cannot support itself with velocity dispersion...). Asteroid density $\sim f \times 10^{-5}/AU^3$.
$\Rightarrow$ "not even an estimate" that misalignment axion contribution to CDM in our galaxy is an oscillating backgrd field at our planet. ? what is assumed in direct detection sensitivity plots?

$*$ *need to study*: galaxy formation with axion field $\Leftrightarrow$ what does field look like in galaxy today?

...? and what if axion born before inflation: all axions in the field, no miniclusters. ...what is small scale $\delta\rho/\rho$? How collapses to what?

Do asteroids evaporate?

Backup

From the chiral anomaly to axion models

Peccei Quinn
Kim , ShifmanVainshteinZakharov
DineFischlerSrednicki,Zhitnitsky
Srednicki NPB85

1. the chiral anomaly says can remove it by a chiral phase rotn on massless quarks
$$q_L \to e^{-i\theta/4} q_L \quad , \quad q_R \to e^{i\theta/4} q_R \quad \Rightarrow \quad \theta \frac{g_s^2}{32\pi^2} G\widetilde{G} \to 0 \times \frac{g_s^2}{32\pi^2} G\widetilde{G}$$
In classical theory of massless quarks, chiral phase rotns are a sym:
$$\delta\mathcal{L} \propto \theta \partial_\mu J_5^\mu = 0$$
but not in quantum theory due to mass scale introduced for renormalisation
$$\delta\mathcal{L} \propto \theta \partial_\mu J_5^\mu = \theta \frac{g_s^2 N}{8\pi^2} G\widetilde{G}$$
(true, because predicts $\pi_0 \to \gamma\gamma$)

2. but SM quarks are not massless :(
$$m\overline{q_L} q_R \to e^{i\theta/2} m\overline{q_L} q_R$$

3. add ... quarks with a mass invariant under chiral rotns!
$\Rightarrow$ introduce new quarks, and new complex scalar $\Phi = |\Phi| e^{ia/f}$, such that $\Phi \to e^{-i\theta/2}\Phi$, whose vev ($\sim 10^{11}$ GeV) gives mass to new quarks
$$\mathcal{L} = \mathcal{L}_{SM} + \partial_\mu \Phi^\dagger \partial^\mu \Phi + i\overline{\Psi} \not{D} \Psi + \{\lambda \Phi \overline{\Psi} \Psi + h.c.\} + V(\Phi)$$

4. θ is gone, $|\Phi|$ and new quarks are heavy...remains at low energy a, the axion.

What is a Bose Einstein Condensate?

1. all the particles in the zero mode?
   - but that was undergrad stat. mech. definition, before learned QFT
   - neccessarily homogeneous + isotropic

2. expectation value of a field
   - consistent with QFT defn of a phase transition; expectation value = order parameter
   - definition in etal+ Pitaevskii stat mech review about BECs of cold atoms
   - the misalignement axions are this...

Above defns are inequivalent...but no need to worry(words don't matter)...instead, let focus on what we want to know: how axions are born and evolve in U.

Can't do the path integral, why bother thinking about it?

1. no need to worry about definitions and dynamics of Bose Einstein Condensates

2. gives recipe for computing quantum corrections: perturbative expansion in G_N, λ (both tiny)

   Ramond, A FT Primer chapter 3.3

   $$\text{Defn of previous slide :} \qquad \phi_{cl} = \frac{\int \mathcal{D}\phi\phi \exp i \int d^4x(\mathcal{L} - \mathcal{J}\phi)}{\int \mathcal{D}\phi e^{iS[\phi,J]}}$$

   $\star$ ϕ_{cl} is "observable" classical field, all quantum stuff summed.
   ϕ_{cl} arg of $\Gamma_{eff}[\phi_{cl}] = \ln\{PI\} - \int d^4xJ\phi$ = effective action, generator of 1PI diagrams... $= S + \mathcal{O}(\hbar)$ in saddle-pt approx $\Rightarrow$ EoM $\frac{\delta\Gamma_{eff}}{\delta\phi_{cl}} = 0$ Alternate defn: saddle-pt of the PI $\equiv$ solution of classical Eqn of Motion.
   Path Integral $\propto \int \mathcal{D}\phi e^{-i(S - \int J\phi)}$, with $S = \int d^4x\mathcal{L}$, so
   $\phi_0 \ni \frac{\delta\mathcal{S}}{\delta\phi} = \frac{\delta\mathcal{L}}{\delta\phi} - \partial_\mu\frac{\delta\mathcal{L}}{\delta\partial_\mu\phi} = \mathcal{J}$
   Then distribute $\hbar$ in $\mathcal{L}$ such that absent from Eqn of Motion.

3. Path Integral defn gives recipe for including $\mathcal{O}(\hbar)$ corrections = field evaporation, interaction with particles
   $\star$ timescale for axion-particles-from-strings to scatter axions out of field $\gg \tau_U$ D+Elmer
   $\star$ timescale for $4 \to 2$ evaporation $\gg \tau_U$ PreskillWiseWilcek, Dvali

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