Distinguishing axions from WIMPs
as
Cold Dark Matter

using Large Scale Structure data?

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1405.1139
1307.8024)

Sacha Davidson (IN2P3/CNRS), (M Elmer, T Schwetz)

1. the QCD axion...
   ...as dark matter

- two scenarios for production (born before/after inflation)
- why is the $m_a \sim m_\nu$ called CDM?

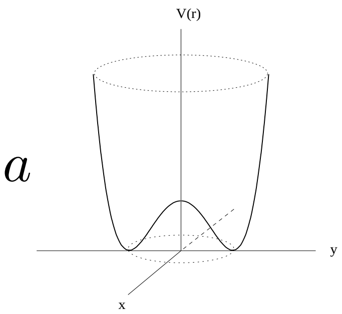
2. to distinguish axions from WIMPS as CDM?

- (direct detection)
- **from LSS data?** axion field has pressure, unlike WIMPS...

PecceiQuinn,Weinberg
Kim , ShifmanVainshteinZakharov
DineFischlerSrednicki,Zhitnitsky
Srednicki NPB85

At low energy... remains the axion

- can trade CPV parameter θ (of $\mathcal{L}_{QCD}$) for a dynamical field a
  who is phase of $\Phi \sim f e^{ia/f}$, $\langle \Phi \rangle \sim f \gtrsim 10^{11}$ GeV.



$\Rightarrow$ only new particle at low-energy is the (pseudo-) goldstone a

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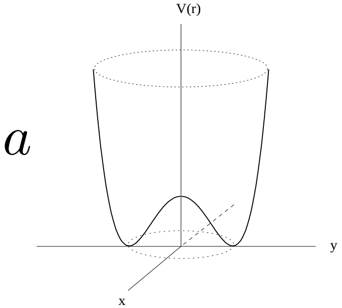

- chiral symmetry broken below $\sim \Lambda_{QCD} \Rightarrow$ tilt mexican hat:

etal+ Villadoro

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

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

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

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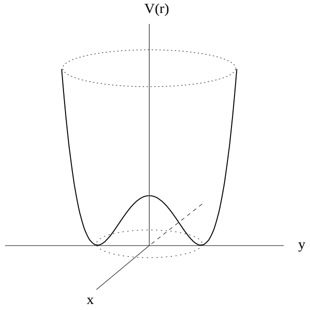

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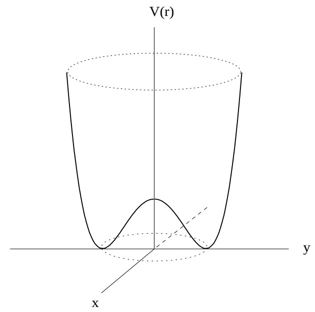
- couplings to SM $\propto \frac{1}{f} \propto m_a$ (!! one-parameter NP model, almost) Srednicki NPB85

upper bound on $\frac{1}{f}$ to avoid rapid stellar energy loss:

$$\boldsymbol{m_a \lesssim 10^{-2}}\ \mathrm{eV} \qquad\qquad (f_{PQ} \gtrsim 10^9\ \mathrm{GeV})$$

Raffelt...

The axion in cosmology: non-thermal production $\Rightarrow$ CDM



The axion is born: $\Phi \to f e^{ia/f}$ ($f \sim 10^{12}$ GeV)

$*$ a massless, random $-\pi f \leq a_0 \leq \pi f$ in each horizon

Laaaater: QCD Phase Transition ($T \sim 200$ MeV): (tilt hat)

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

$*$ ...after $H < m_a$, "misaligned" a oscillates, energy density $\sim m_a^2 \langle a_0 \rangle^2 / R^3(t)$

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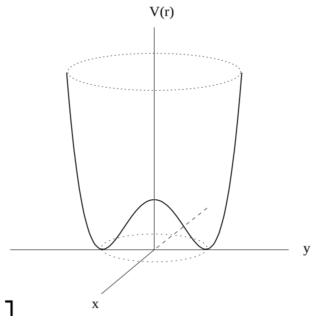

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if born BEFORE inflation
$*$ *unknown* a_0 inflated across U, grows classical fluctuations: $\frac{\delta a}{a} \sim \frac{H_I}{2\pi f}$

isocurvature density fluctuations: $\Rightarrow H_I \lesssim 10^7 \sqrt{f/10^{12}}$ GeV
? or non-canonical kin.terms for a? ...

Planck
WantzShellard
HanannHRW
FolkertsCristianoRedondo

$\Rightarrow$ **field** redshifts like CDM, Ω_{dm} for $m_a \lesssim 10^{-5}$eV (tune a_0)

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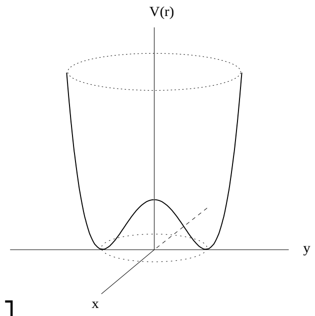

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if AFTER inflation

$*$ many PQPT horizons in U today: $\langle a_0^2 \rangle_{U\ today} \sim \pi^2 f^2 / 3$

$*$ ...one string/horizon :(

$*$ strings go away @ QCD PT (radiate cold axion particles, $\vec{p} \sim H \lesssim 10^{-6} m_a$)

Hiramatsu etal 1012.5502
Klaer+Moore, 2017

$\Rightarrow$ **field + cold particles** redshift like CDM, Ω_{dm} for $m_a \sim 10^{-4}$eV

To distinguish Axions from WIMPs using Large Scale Structure Data?

Need equations of motion.

$$= \text{Einsteins Equations} \Leftrightarrow T_{\mu\nu} \text{ for the axion field}$$
$$+ T_{\mu\nu} \text{ for the cold particles } (= \text{dust}).$$

Need initial conditions/spectrum of fluctuations

Initial spectrum of axion density fluctuations

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

1: adiabatic $\delta\rho/\rho$ on L$_{\text{arge}}$S$_{\text{cale}}$S$_{\text{tructure}}$ scales imprinted on axion field(+particles)
(born before/after inflation)

Initial spectrum of axion density fluctuations

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

1: adiabatic $\delta\rho/\rho$ on LargeScaleStructure scales imprinted on axion field(+particles)
(born before/after inflation)

2: axion born after inflation:

field spatially random on QCDPT-horizon scale ≡ **miniclusters**

$\frac{\delta\rho}{\rho} \sim \mathcal{O}(1)$ on comoving scale $1/H_{QCD}$

fall off like random walk on larger scales (white noise)

Hogan,Rees
Tkachev+Kolb

$$M_{mini} \sim V_{osc} m_a n_{osc} E \sim \begin{cases} 3 \times 10^{-13} M_\odot \\ 10^{-10} M_\odot \end{cases}$$

where $m(T_{osc}) = 3H(T_{osc})$, $E \sim 2-8$

: Turner86
Lyth92,BaeEtal08

These collapse before LSS — if to dense objects, then on larger scales, "phase space distribution" of objects could behave like CDM?

2b. what fluctuations on QCD-horizon for axions particles from strings? $\frac{\delta\rho_a}{\rho_a} \sim 1$ on scale H^{-1}_{QCDPT}??

To use Einsteins' Eqns ... need stress-energy tensors

non-rel axion particles are dust, like WIMPs (so not consider further):

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

...stress-energy tensors

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

Classical field $T_{\mu\nu} = \partial_\mu a \partial_\nu a - g_{\mu\nu}(\partial^\alpha a \partial_\alpha a - V(a))$
...in non-relativistic limit:

$$T_{\mu\nu} \to \begin{bmatrix} \rho & \rho\vec{v} \\ \rho\vec{v} & \rho v_i v_j + \Delta T_{ij} \end{bmatrix}$$

$$\Delta T^i_j \sim \partial_i a \partial_j a \ , \ \lambda a^4$$

Sikivie

$\Rightarrow$ classical field has different pressure + self-interactions at $\mathcal{O}(\lambda)$

??do extra pressures distinguish axions from WIMPs in structure formation??

Einsteins Equations for axion field

- E Eqns inside horizon $\Rightarrow$ Poisson for Newtonian V_N, and $T^{\mu}{}_{\nu;\mu} = 0$

$$\partial_t \rho = -\nabla \cdot \rho \vec{v} \qquad \text{continuity}$$

$$\partial_t \vec{v} + \vec{v} \cdot \nabla \vec{v} = -\nabla V_N + \nabla \left(\frac{\nabla^2 \sqrt{\rho}}{2m^2 \sqrt{\rho}} + |\lambda| \frac{\rho}{m^4} \right) \qquad \text{Euler} \quad ,$$

$*$ eqns for dust

Equations of motion

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$$\begin{aligned} \partial_t \rho &= -\nabla \cdot \rho \vec{v} && \text{continuity} \\ \partial_t \vec{v} + \vec{v} \cdot \nabla \vec{v} &= -\nabla V_N + \nabla \left(\frac{\nabla^2 \sqrt{\rho}}{2m^2 \sqrt{\rho}} + |\lambda| \frac{\rho}{m^4} \right) && \text{Euler} \quad , \end{aligned}$$

$*$ eqns for dust

$*$ equivalent to axion field eqns (not course-graining approx like for $f(x,p)$).

(for non-rel axion $= \phi = \sqrt{\frac{\rho}{m}} e^{-iS}$ and $v^j = -\partial_j S/m$)

extra terms for axion field

self-interaction pressure *inwards*: $\frac{\partial}{\partial r} r^{-n} < 0$

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$\Rightarrow$ *to see if extra pressures affect structure formation:*

1. Simple: are stable/stationary solutions different for axion-field vs dust? Rindler-Daller+Shapiro Chavanis, ...

2. Analytic dynamics: WIMP-axion diffs on scales where fluctuations are small Hwang+Noh+

3. Numerically solve with extra pressures and compare to N-body (= dust)? EtalBroadhurt, Niemeyer etal MoczVogelsangerEtal

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

Stable solution that could occur after collapse

BarrancoBernal
Rindler-DallerShapiro
Chavanis+
...
DavidsonSchwetz

1 look for *time-independent* solution to eqns

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find (set $\vec{v}, \partial_t = 0$ and do dim analysis):

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

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2 Allow breathing mode(Chavanis) + rotation(DavidsonSchwetz): for($m \sim 10^{-4}$ eV, $\lambda \sim 10^{-45}$ of QCD axion born after inflation)

$$\Rightarrow \quad R \sim \frac{m_{pl}^2}{4m^2 M} \lesssim 100 \text{ km} \quad , \quad M \lesssim \frac{m_{pl} f}{m} \sim 10^{-(13 \pm 1)} M_\odot \simeq \begin{cases} \text{asteroid!} \\ \lesssim \text{minicluster} \end{cases}$$

3 allowed: (picolens.)$10^{-13} \to 10^{-9} M_\odot$(microlens.) =Black Holes ok galactic DM

4 ... do miniclusters collapse to lumps of these asteroids? (numerical problem)

Analytic evolution of small fluctuations

• inside horizon, but conformal time, $T^{\mu}_{\nu;\mu} = 0$, with $\rho(\vec{x},\tau) = \bar{\rho}(\tau)(1+\delta(\vec{x},\tau)),\ \theta = \nabla\cdot\vec{v}$ gives

$$\partial_\tau\delta + \nabla\cdot\vec{v} = \qquad -\nabla\cdot[\delta\vec{v}] \qquad \text{continuity}$$

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• in fourier space (used Poisson : $\nabla^2 V_N = \frac{3\mathcal{H}^2}{2}\widetilde{\delta}, \Omega_{cdm} = 1$)

$$\partial_\tau\widetilde{\delta}_{\vec{k}} + \widetilde{\theta}_{\vec{k}} \quad = \quad -\int \frac{d^3q}{(2\pi)^3}\alpha_{WIMP}(\vec{q},\vec{k})\widetilde{\delta}_{\vec{q}}\widetilde{\theta}_{\vec{k-q}}$$

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• for small δ (small k/large dist.), physics/numerics says non-linearities negligeable :

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G_N\overline{\rho}_a\delta + c_s^2\frac{k^2}{R^2(t)}\delta \simeq 0$$

($c_s^2 \sim \delta P/\delta\rho$) irrelevant because $k \to 0$
$\Rightarrow$ axion DM : grows linear/small density fluctuations like WIMPs

Zaldarriaga+...
Senatore+...

To calculate beyond linear approx...an EFT

$\star$ including 1st non-lin terms for WIMPs extends k range where soln $\approx$ data

$\Rightarrow$ calculate effect of axion non-linearities?

Zaldarriaga+...
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— but...higher order diverge from data, integrals are divergent/cut-off dependent...no small parameter: $\tilde{\delta}$ large on short distance/high energy, $(\tilde{\theta} = \vec{k} \cdot \tilde{v})$

$$\partial_\tau \widetilde{\delta}_{\vec{k}} + \widetilde{\theta}_{\vec{k}} \;\; = \;\; -\int \frac{d^3q}{(2\pi)^3} \alpha_{WIMP}(\vec{q}, \vec{k}) \widetilde{\delta}_{\vec{q}} \widetilde{\theta}_{\vec{k}-\vec{q}} \quad \ldots \text{ if } |q|, |q-k| \gg |k| \;\; ?$$

Zaldarriaga+...
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EFT$\Rightarrow$ choose distance $R \approx \frac{1}{\Lambda}$ (with $\widetilde{\delta}_\Lambda < 1$), and "integrate out" shorter-distance

$\Rightarrow$ get Eqns for smoothed $\widetilde{\delta}$

$=$ continuity$+$ Euler $+$ extra terms $\propto (k/\Lambda)^X$

(UV theory $=$ gravity$\Leftrightarrow$coefficients calculable,

but non-lin gravity ... N-body!)

$\Rightarrow$ without knowing high-energy behaviour,, can calculate "low-energy" physics that is independent of "higher dimensional operators" (=short distance)

$\Rightarrow$ do axions induce differences in "low energy"/calculable observables?

In mildly non-lin gravity where can compute, do axion extra-terms give significant deviation from WIMPs?

...more later... (dim reg in $3-d$ is different)

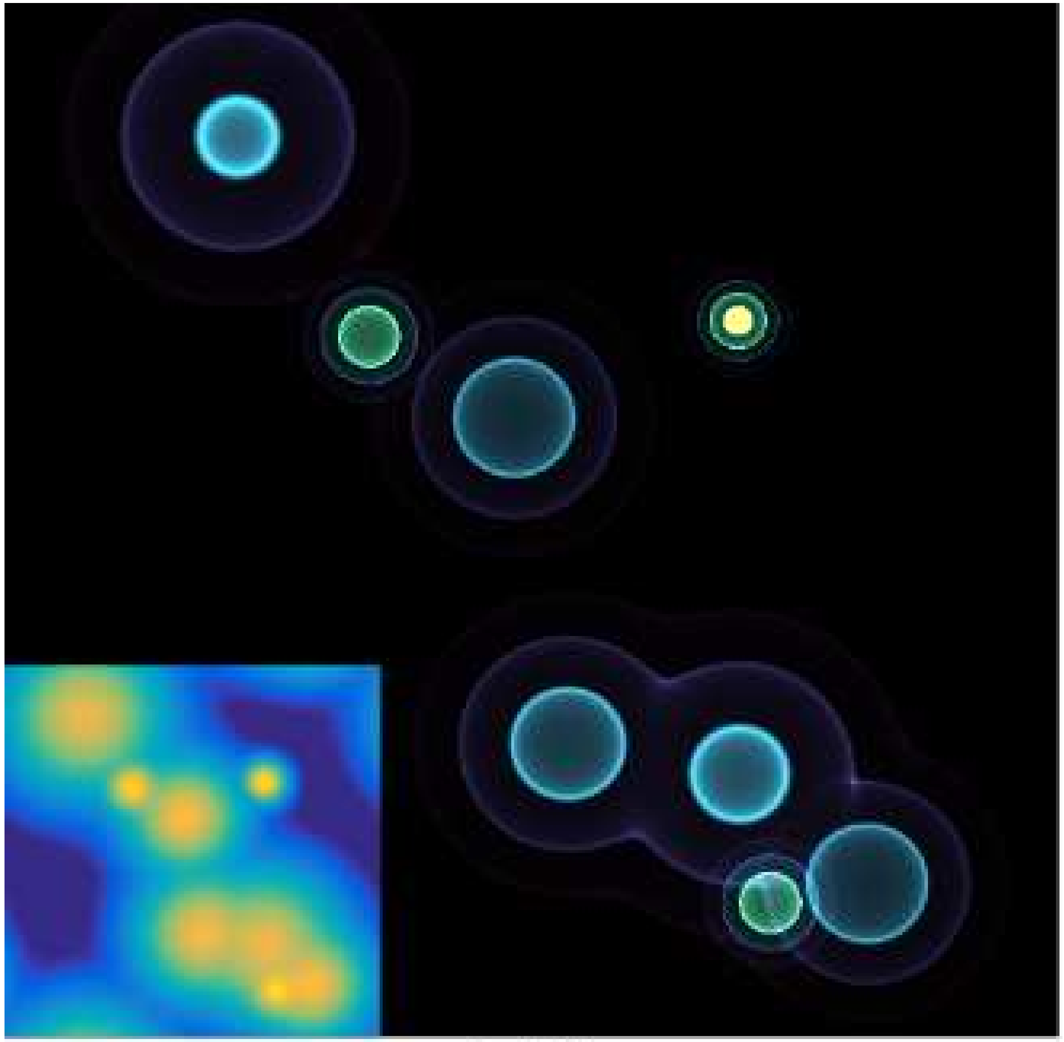
but I think not :
calculate power spectrum (fourier tran of 2pt fn) $\mathcal{P} = \mathcal{P}_{\rm lin} + \mathcal{P}_{\rm non-lin}$
(where $\mathcal{P}_{\rm lin}$ same for axion+WIMP).
By dim analysis :

$$\frac{\Delta \mathcal{P}^{axion}_{\rm non-lin}}{\mathcal{P}^{WIMP}_{\rm non-lin}} \sim \tilde{\delta}^2_\Lambda < 1$$

where $\tilde{\delta}_\Lambda =$ density fluctuation smoothed on scale $1/\Lambda$

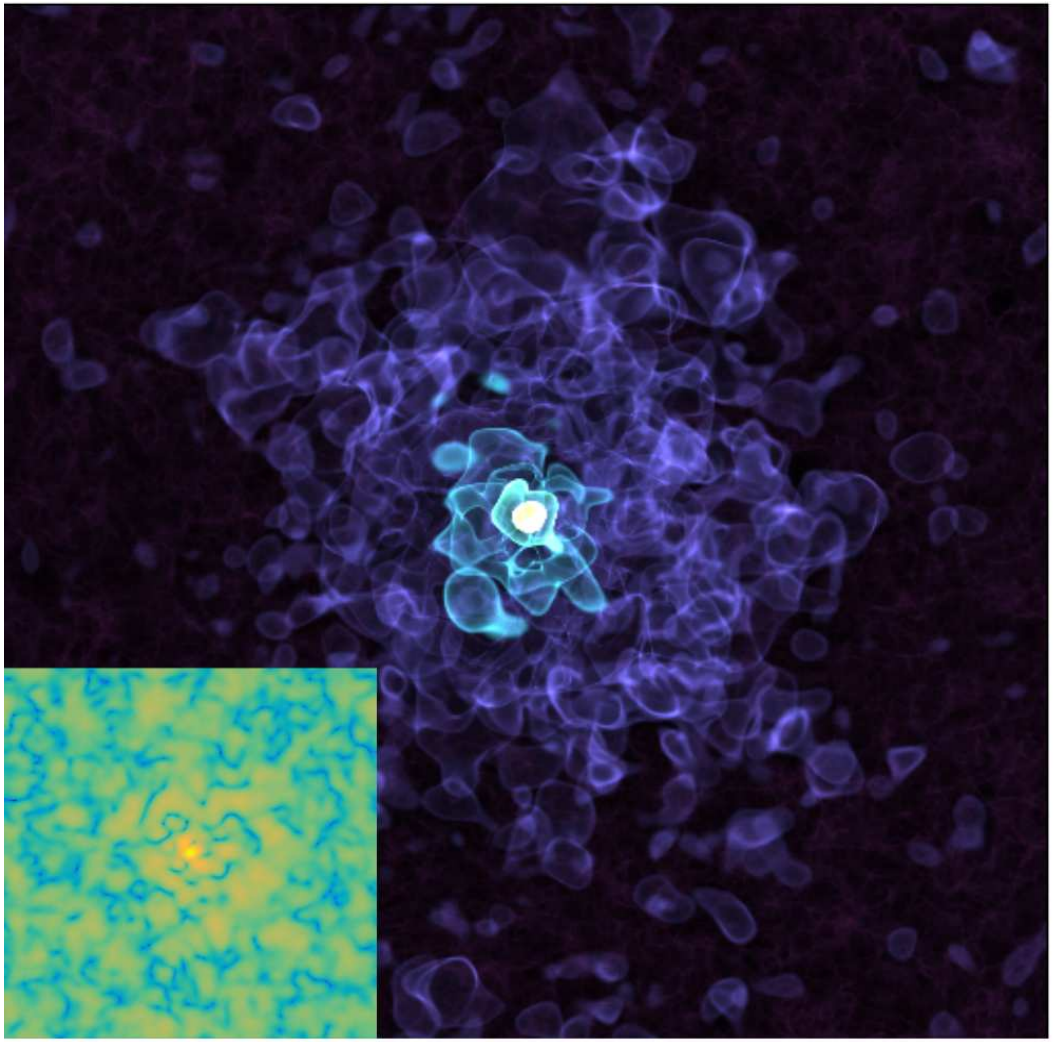
? whether is cutoff indep is tbc...

arXiv:1705.05845 Mocz, Vogelsberger,etal: initial conditions for a halo



scalar field, $m \sim 10^{-21}$ eV, no self-interaction
picture = lines of constant density, insert = density in log

arXiv:1705.05845 Mocz, Vogelsberger,etal: ALP halo



scalar field, $m \sim 10^{-21}$ eV, no self-interaction
picture = lines of constant density, insert = density distribution in log
dark blue falls off as $\sim r^{-3} \sim$ NFW

Summary and Speculations

The QCD axion is a a motivated CDM candidate. It is born, massless, around the time of inflation. At the QCDPT, the axion mass turns on; afterwards the energy density in axion field oscillations redshifts as $1/R(t)^3$.

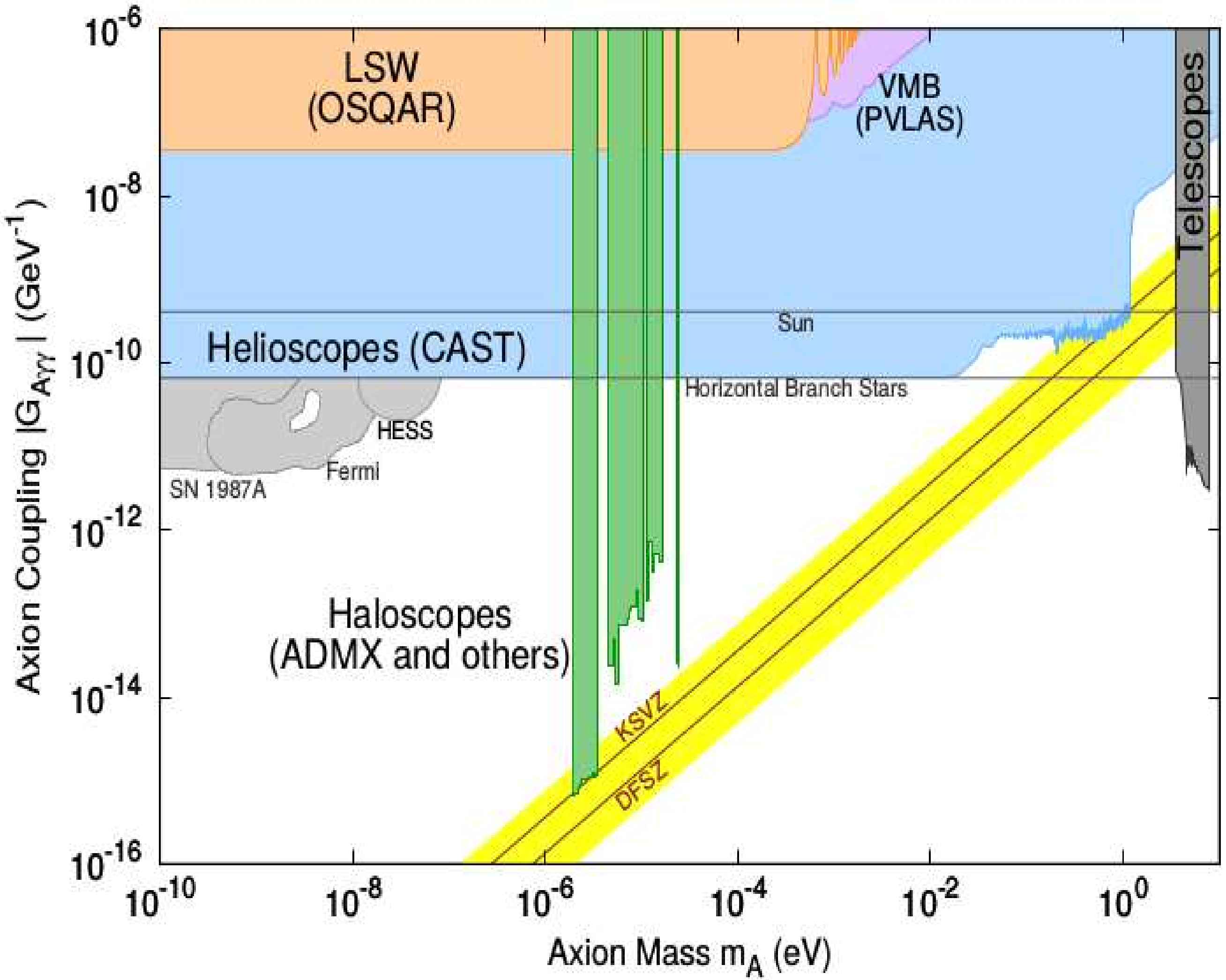
The axion *field* has extra pressures compared to WIMPs. These have negligeable effects in the linearised equations for fluctuation growth.

In non-linear structure formation, it remains to be seen whether these could give detectable effects in observables (non-linear corrections to the power spectrum? Bispectrum?)

These extra pressures imply that the QCD axion has a stable gravitationally bound configuration the size of an asteroid.
Is galaxy formation different between axions and WIMPs? (numerical problem?)
Does the axion field fragment into asteroids as the proto-galaxy collapses?

Backup

PDG ALP plot

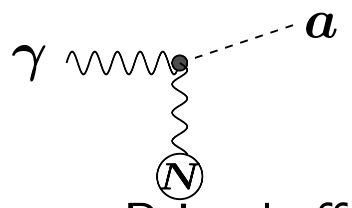


LSW
(OSQAR)
VMB
(PVLAS)
Telescopes
Helioscopes (CAST)
Sun
Horizontal Branch Stars
HESS
Fermi
SN 1987A
Haloscopes
(ADMX and others)
KSVZ
DFSZ
Axion Coupling $|G_{A\gamma\gamma}|$ (GeV^{-1})
Axion Mass m_A (eV)
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}

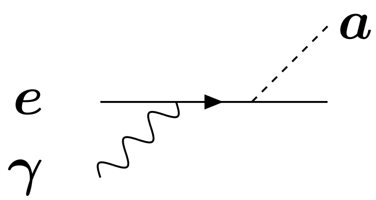
Astrophysical bounds

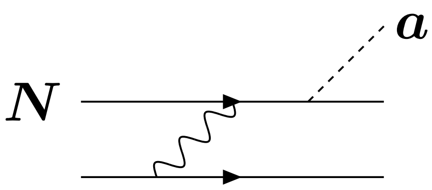
axion light and (feebly) coupled to SM $\propto \frac{1}{f_{PQ}} \propto m_a$

$\Rightarrow$ produce in sun, He-burning stars(g_{ae}), supernovae(g_{aN})...



Primakoff





(axion couplings to e vs N vary across models by ~ 10)

upper bound on coupling to avoid rapid stellar energy loss:

$$\boldsymbol{m_a \lesssim 10^{-2}} \text{ eV} \qquad\qquad (f_{PQ} \gtrsim 10^9 \text{ GeV})$$

...or, are some/many astro objects observed to cool a wee bit faster than theory predicts?
??? hint for an Axion-Like-Particle just beyond current bounds on the coupling?
GiannottiIrastorzaRedondoRingwaldSaikawa

(This talk interested in lighter, more weakly coupled QCD-axion)

Dynamics !

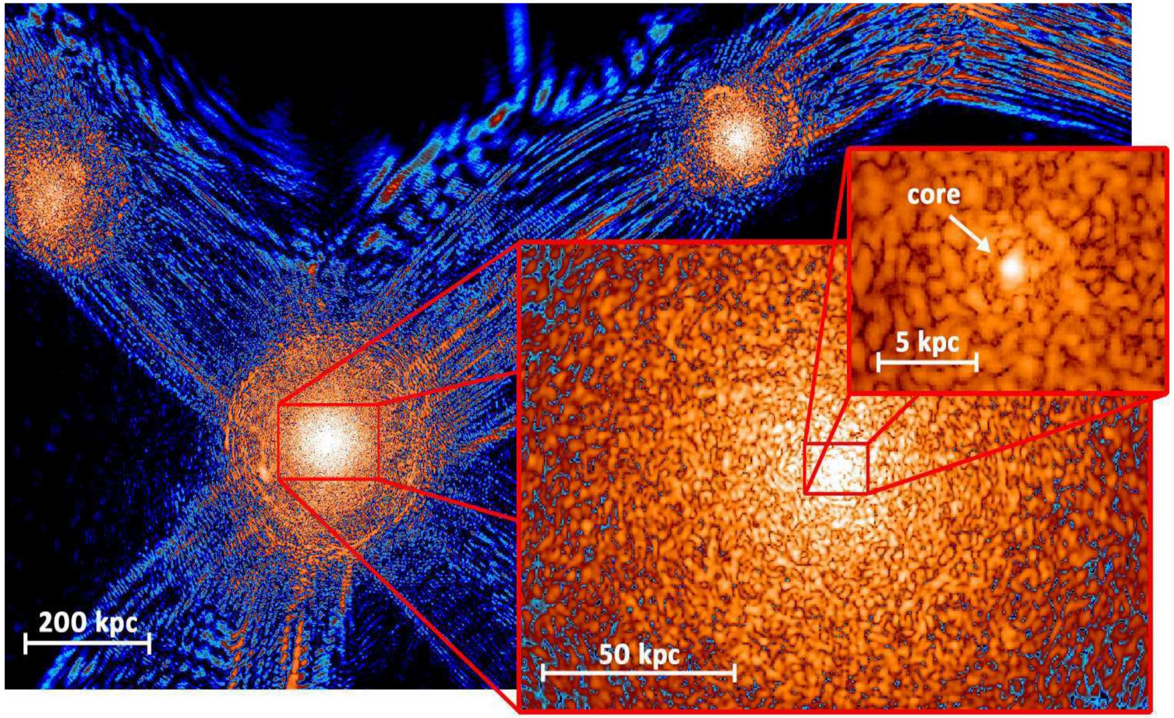


Figure 2: A slice of density field of ψDM simulation on various scales at $z = 0.1$. This scaled sequence (each of thickness 60 pc) shows how quantum interference patterns can be clearly seen everywhere from the large-scale filaments, tangential fringes near the virial boundaries, to the granular structure 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 $\Omega_{BH} \sim .1$:

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

Using $T^{\mu\nu}{}_{;\nu} = 0$ vs Eqns of motion of the field a

Eqns of motion for axion field cpled to gravity studied by Sikivie et al, Saikawa etal:

$$(\Box - m^2)a \sim G_N a^3 \qquad \Rightarrow \qquad i\frac{\partial n}{\partial t} \sim G_N \int a^4$$

Both obtained from $T^{\mu\nu}{}_{;\nu} = 0$ and Poisson Eqn ($\rightarrow$ dynamics is equivalent?)

$$\begin{aligned} T^{\mu\nu}{}_{;\nu} &= \nabla_\nu[\nabla^\mu a \nabla^\nu a] - \nabla_\nu[g^{\mu\nu}\left(\frac{1}{2}\nabla^\alpha a \nabla_\alpha a - V(a)\right)] \\ &= (\nabla_\nu \nabla^\mu a)\nabla^\nu a + \nabla^\mu a(\nabla_\nu \nabla^\nu a) - g^{\mu\nu}\nabla_\nu \nabla^\alpha a \nabla_\alpha a + g^{\mu\nu} V'(a)\nabla_\nu a \\ 0 &= \nabla^\mu a[(\nabla_\nu \nabla^\nu a) + V'(a)] \end{aligned}$$

1. eqns for $T_{\mu\nu} \sim a^2$ solvable during linear structure formation. Find $\delta \equiv \delta\rho(\vec{k}, t)/\overline{\rho}(t)$ in dust or axion field has same behaviour on LSS scales ($c_s \simeq \partial P/\partial\rho \rightarrow 0$):

   Ratra, Hwang+Noh

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G_N \overline{\rho}\delta + c_s^2 \frac{k^2}{R^2(t)}\delta = 0$$

2. "better" handle on IR divs: ensures that long-wave-length gravitons see large objects (like MeV photons see the proton, and not quarks inside)