Dark Matter Minihalos from Early Matter Domination

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based on 1905.06952, 20xx.xxxxx with Matthew Dolan, Patrick Draper and Jonathan Kozaczuk

Outline

- Cosmology before nucleosynthesis
- Abundance of axion-like particles (ALPs)
- Growth of ALP structures
- Clump Detection

Early Matter Domination (EMD)

- No observations of pre-BBN universe

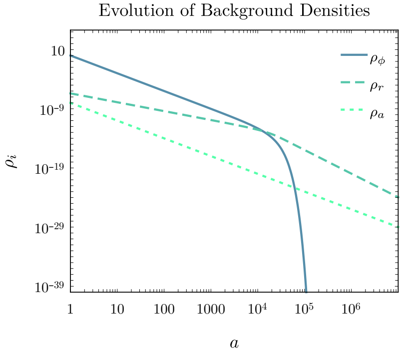
  Universe must be radiation-dominated (RD) for $T \gtrsim 5$ MeV

  de Salas et al (2015)

- UV completions feature non-RD evolution at early times: moduli, frozen-out hidden sectors

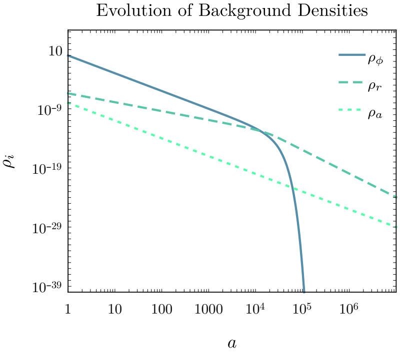
  Acharya et al (2008), Berlin, Hooper and Krnjaic (2016)++

- Out-of-equilibrium reheating interesting: DM production, baryogenesis



Early Matter Domination (EMD)

- Pre-BBN universe dominated by non-relativistic field ϕ
- Transition from EMD to RD (reheating – RH) happens at $T_{\rm RH}$
- Evolution of the dominant component (both b/g and perturbations) is the same as DM: $\rho_\phi/\rho_a \sim \texttt{const}$.



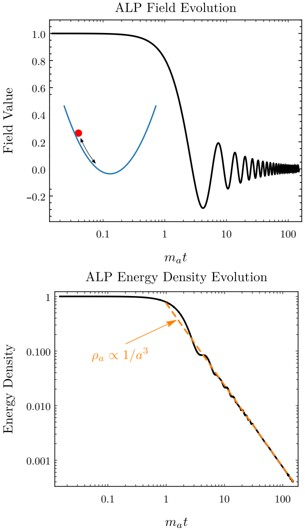
Production of ALPs: Misalignment

- Generic mechanism for light bosonic DM, a (axions, ALPs, moduli,...)
- Scalar displaced from the origin of its potential with $a_i = \theta_0 f_a$
- Oscillations about origin begin when

$$m_a \sim H$$

- Energy density redshifts as matter:

$$\rho_a \propto 1/a^3$$

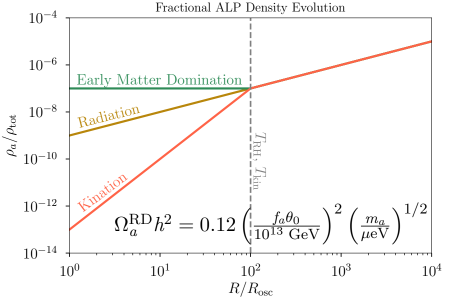


Sensitivity to Early Cosmology

- Final abundance depends on evolution of the total energy density
- Evolution before nucleosynthesis $T \gtrsim 5\,\mathrm{MeV}$ unknown:

$$\rho_{\rm tot} \propto \begin{cases} a^{-4} & \text{radiation} \\ a^{-3} & \text{matter} \end{cases}$$

- correct abundance obtained for different values of m_a, f_a depending on cosmology



Visinelli & Gondolo (2009)+
NB, Dolan, Draper & Kozaczuk (2019)

Smaller $f_a \Rightarrow$ larger coupling to SM $g_{a\gamma\gamma} \propto 1/f_a$

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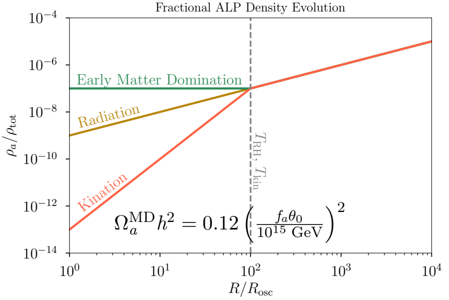

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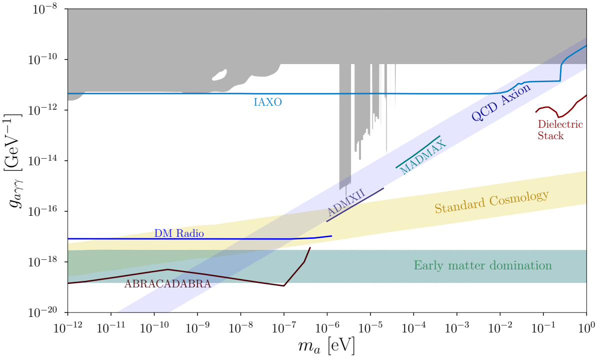
Plentitude of Targets for ALP Searches

Since $g_{a\gamma\gamma} \propto 1/f_a$, early matter domination is challenging to test directly



NB, Dolan, Draper & Kozaczuk (2019)

Non-cosmological modifications can lead to easier-to-reach targets

Farina *et al* (2017); Agrawal *et al* (2017)

Initial Conditions and Substructure

Two qualitatively different initial conditions for the ALP field:

1. Post-inflationary PQ breaking

   Field values different in Hubble patches, $\mathcal{O}(1)$ initial density fluctuations

   "Automatic" minicluster formation in ΛCDM and modifications

   Kolb and Tkachev (1994)+, Enander et al (2017), Fairbairn et al (2017)++

   See Malte Buschmann's and Javier Redondo's talks on Thurs.

2. Pre-inflationary PQ breaking:

   Same ($\delta\phi = 0$) field value across our Hubble patch, no initial density fluctuations

   No (or few) miniclusters in ΛCDM, but generic in EMD

   Nelson and Xiao (2018), Visinelli and Redondo (2018)

Structure Growth During EMD

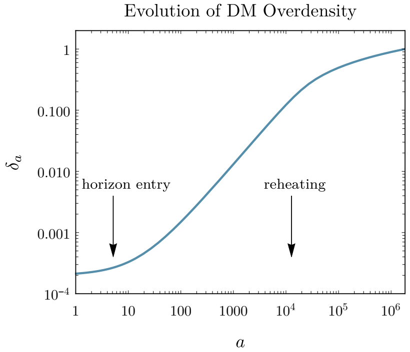
Evolution of a **CDM** density perturbation $\delta = [\rho(x) - \bar{\rho}]/\bar{\rho}$ governed by energy/momentum conservation+gravity

$$\ddot{\delta} + \mathcal{H}\dot{\delta} \approx -k^2\Psi$$

Growth of δ depends on background expansion through $H = 2/[3(1+w)t]$

$$\delta \propto \begin{cases} a & \text{MD} \\ \ln a & \text{RD} \end{cases}$$

EMD enhances growth by a factor $\sim (a_{\rm RH}/a_{\rm hor}) \sim (k/k_{\rm RH})^2$



Erickcek and Sigurdson (2011)

The Sound of ALPs

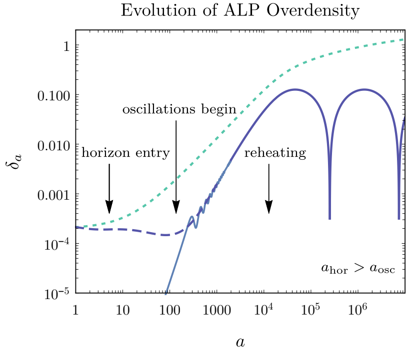
Rapid **ALP** oscillations introduce additional "pressure" terms

$$\ddot{\delta} + \mathcal{H}\dot{\delta} + c_s^2 k^2 \delta \approx -k^2\Psi \quad \text{with an effective sound speed} \quad c_s^2 \approx \frac{k^2}{4m_a^2 a^2}$$

Hu, Barkana & Gruzino (2004), Arvanitaki *et al* (2009), Hlozek *et al* (2014)++

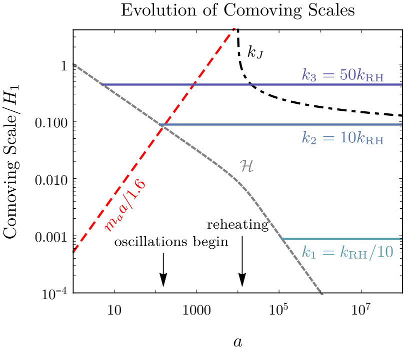
The effective pressure slows or prevents structure growth for scales smaller than a "Jeans" length k_J^{-1}:

$$k_J^2 \sim \frac{a_{\mathrm{RH}} m_a H(a_{\mathrm{RH}})}{\ln(a/a_{\mathrm{RH}})}$$



Small-Scale Power Spectrum

- $k > m_a a,\ k_J$: effective pressure important, perturbation growth suppressed
- $k_{\rm RH} < k < m_a a,\ k_J$: effective pressure not important, perturbation growth enhanced by EMD
- $k < k_{\rm RH}$: perturbation enters horizon after RH, no EMD enhancement



Small-Scale Power Spectrum

Our universe is a realization of the primordial density distribution

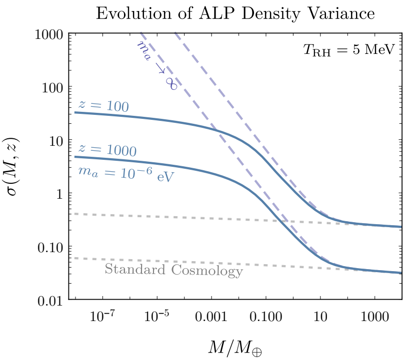
$$\sigma^2(z, R \leftrightarrow M) = \int \frac{d^3k}{(2\pi)^3} \langle \delta(a,k)^2 \rangle \, W(kR)^2$$

- ansatz: probability of forming a minihalo of mass M is equal to the probability of δ exceeding a critical overdensity $\delta_c \sim 1$:

$$P \propto \int_{\delta_c}^{\infty} d\delta \exp\left(-\frac{\delta^2}{2\sigma^2}\right)$$

Press and Schechter (1974)++

- σ is a growing function of a



Typical Clumps

If a clump grows dense enough, it decouples from Hubble flow and collapses at redshift z to create a virialized minihalo

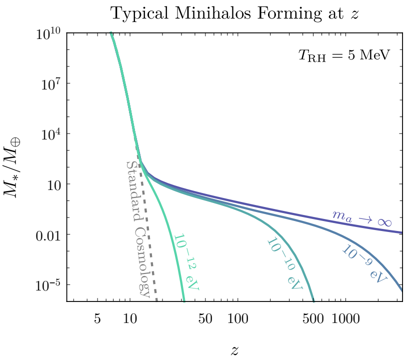
$$\sigma(z_c, M_*(z_c)) \sim 1$$

For $z > 20$ and $m_a \gtrsim 10^{-6}$ eV

$$M_*(z_c) \approx M_{\rm RH} \left(\frac{2.6}{1+z_c}\right)^{6/(n_s+3)}$$

where $M_{\rm RH}$ is the mass contained within a horizon at $T_{\rm RH}$

$$M_{\rm RH} \approx 250 M_\oplus \left(\frac{5\ \mathrm{MeV}}{T_{\rm RH}}\right)^3$$



Typical Clumps

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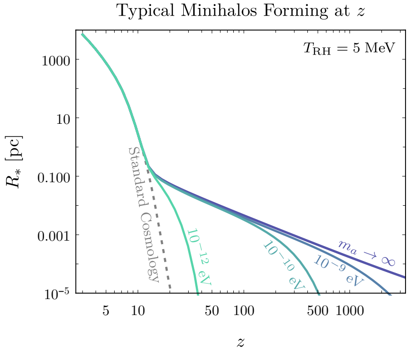
$$\text{spherical collapse} \Rightarrow \rho_{\text{clump}} \approx 178\bar{\rho}(z_c)$$

Average clump density

$$\rho(z_c) \approx 230 \text{ GeV/cm}^3 \left(\frac{1+z_c}{100}\right)^3$$

gives a characteristic size of

$$R_*(z_c) \sim 4 \times 10^{-3} \text{ pc} \times \left(\frac{5 \text{ MeV}}{T_{\text{RH}}}\right)\left(\frac{100}{1+z_c}\right)^{\frac{(5+n_s)}{(3+n_s)}}$$



Clump Disruption

Not all clumps survive until today. Clumps can become disrupted by

- Merging with other clumps in the early universe
- Clump-clump encounters in the late universe (seem to be less important)

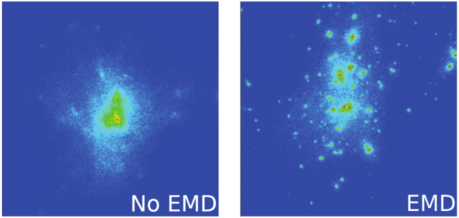
van den Bosch et al (2017)

- Encounters with baryonic objects: the galactic disk and individual stars

Berezinsky, Dokuchaev and Eroshenko (2014), Dokuchaev, Eroshenko and Tkachev (2017)

Detailed properties of the clumps (including density profiles) must be obtained from simulation

Clump Disruption



Erickcek and Waldstein (2017), Sten Delos et al (2018)++

Impact on Direct Detection

- couplings $\sim 1/f_a$ favored by EMD are already difficult

  other cosmologies can favor couplings that are easier to detect, e.g. pre-BBN kination

- Direct detection prospects further reduced by the time between Earth-clump encounters

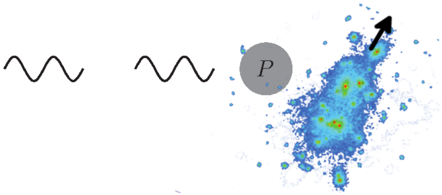
$$\tau = \frac{1}{n_{\rm mc}\sigma_{\rm mc} v},$$

- Distruption can create DM streams that increase encounter probability, but are less dense than the progenitor clumps

Tinyakov, Tkachev and Zioutas (2015)

Astrophysical Probes

- EMD-grown clumps are dense, but much more diffuse than compact objects like PBHs
- Standard searches for compact objects (e.g., microlensing) provide no constraints for microhalos with concentrations $c \sim 10^3 -$ few $\times 10^4$
- EMD-motivated clump densities and masses can be probed with pulsar timing:



Dror, **Ramani**, Trickle & Zurek (2019)

See Hari's talk on Wed.

Conclusion

- Non-thermal production sensitive to *early* universe cosmology
- Several high-value targets accessible to direct detection, that are easier or harder to reach compared to the conventional scenario
- Substructure provides a window into pre-nucleosynthesis universe

Thank you!

Backup

DM Substructure in Non-Thermal Cosmology

Are non-thermal models distinguishable in principle?

- Non-thermally produced DM can feature enhanced sub-structure
- Early matter domination and kination have a period of early perturbation growth

  Erickcek & Sigurdson (2011); Redmond, Trezza & Erickcek (2018);Visinelli & Redondo (2019)

- Inflationary production of dark photons makes clumps with a characteristic size

  Graham, Mardon and Rajendran (2016), Planck (2018)

- DM clumps enhance or worsen DD prospects

  Higher ρ_{cdm}, but less frequent encounters

- Can be searched for in astrophysical data

  Gaia: Van Tilburg, Taki & Weiner (2018); Pulsar timing: Dror *et al* (2019)