Kinetic isocurvature perturbation

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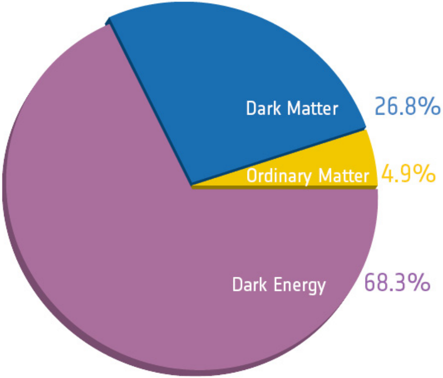
Based on Bae, Cheong, JG, Harigaya and Shin, 2603.22394

Outline

1. Introduction
2. Basic idea
3. A simple model
4. Possible observational signatures
5. Conclusions

Back then, Summer Institute 2010

What do we know about the composition of the universe?



We do not know 95% of the universe

Why dark matter?

- Confirmed by many independent observations

  N.B. Dark energy?

- Indispensable for structure formation
- Yet (seemingly) no candidate within SM
- A number of well-motivated candidates

DM is a key probe to study BSM

Why isocurvature perturbations?

- In simple case, every component fluctuates identically
- “Adiabatic”: Everything comes from the same source
- Any independent source makes deviations, “isocurvature”
- Isocurvature can tell the composition of the universe

Isocurvature contains important information

Current status of isocurvature perturbations

- Isocurvature perturbations = everything else from simplicity
- Planck parametrizes $\beta_{\rm iso} \equiv \dfrac{P_{\rm iso}}{P_{\rm adi} + P_{\rm iso}}$
- Specific scenarios are more stringent ($\beta_{\rm iso} < 0.001$)
- General isocurvature are less constrained ($\beta_{\rm iso} \lesssim 0.01$)

Still ample room for isocurvature

What are we going to do?

We suggest a generic class of possible isocurvature perturbation

- Main source is the perturbation in kinetic energy
- Easily realized in simple setup
- Interesting observational signatures

Within observational reach within next decades

Energy density perturbation of DM

DM species with mass $m_{\rm DM}$ and momentum $p_{\rm DM}$

$$\rho_{\rm DM} = E_{\rm DM} n_{\rm DM} \quad \text{with} \quad E_{\rm DM} = \sqrt{m_{\rm DM}^2 + p_{\rm DM}^2}$$

The perturbation of $\rho_{\rm DM}$

$$\frac{\delta\rho_{\rm DM}}{\rho_{\rm DM}} = \frac{\delta n_{\rm DM}}{n_{\rm DM}} + \frac{p_{\rm DM}^2}{E_{\rm DM}^2}\frac{\delta p_{\rm DM}}{p_{\rm DM}}$$

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As DM becomes non-rel, $v_{\rm DM} = p_{\rm DM}/E_{\rm DM} \propto a^{-1}$, usually irrelevant

What survives with kinetic isocurvature perturbation

But the distance traveled = integrated effect survives

$$\lambda_{\rm FS} = \int_{a_i}^{a_{\rm eq}} \frac{da}{a^2 H(a)} \frac{p_{\rm DM}(a)}{E_{\rm DM}(a)}$$

W/ $\delta p_{\rm DM}$, patch by patch $\delta_\lambda \equiv \delta\lambda_{\rm FS}/\lambda_{\rm FS}$ induces **modulated cutoff**

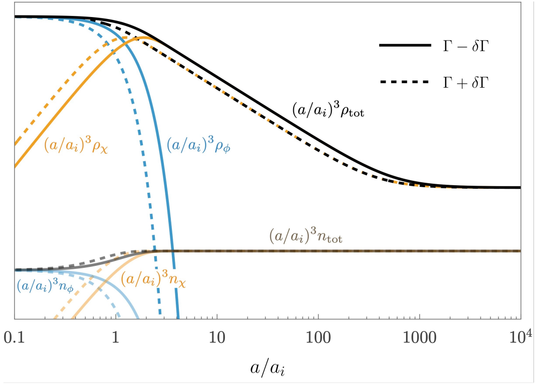
Fluctuating $\lambda_{\rm FS} \longleftrightarrow$ fluctuating $P_m(k)$

A concrete model: Decaying scalar → light DM

A decaying massive scalar ϕ to scalar/fermion light DM particle χ

$$\mathscr{L} \supset A(\sigma)\phi\chi^2 \quad \text{or} \quad y(\sigma)\phi\bar{\chi}\chi$$

$\delta\sigma$ leads to δA or δy, which leads to $\delta\Gamma$ ($m_\chi = 10^{-3} m_\phi$, $\delta\Gamma/\Gamma = 0.2$)



δ_λ from $\delta\rho$

With sudden-decay approximation the relation bet δ_λ from $\delta\rho$ is

$$\delta_\lambda \simeq \frac{\delta\rho_\chi}{\rho_\chi}\left\{1+1.56g_*^{-1/2}\left(\frac{1\,\mathrm{Mpc}}{\lambda_{\mathrm{FS}}}\right)^2\left[1+0.27\log\left(\frac{1\,\mathrm{Mpc}}{\lambda_{\mathrm{FS}}}\right)\right]\left(\frac{6.7\,\mathrm{Mpc}^{-1}}{k}\right)^2\right\}$$

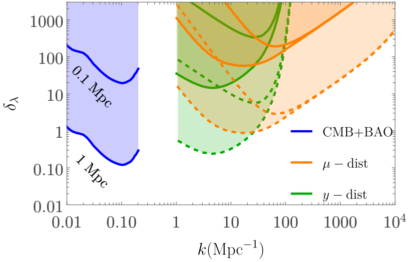
Upper bound on δ_λ come from the associated constraints on $\delta\rho_\chi$

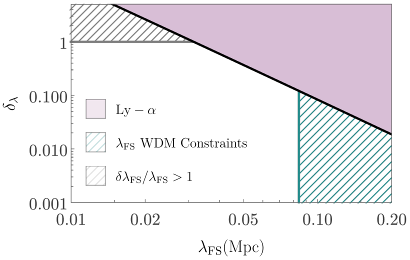
How do existing iso constraints translate into that on δ_λ?

Existing constraints into bounds on δ_λ

2 limiting spectrum profiles of δ_λ: Delta-function one & flat one

(Reinterpretation of Buckley et al. 2502.20434)

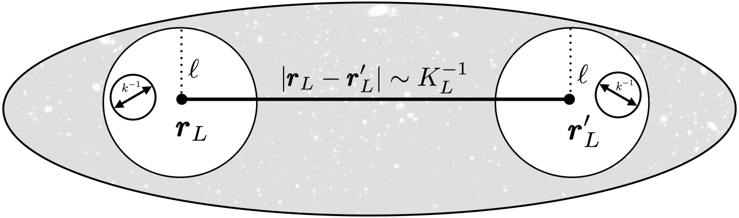




$\delta_\lambda = \mathcal{O}(0.1 - 1)$ **is allowed**

Modulation in free streaming length

λ_{FS} fluctuates patch by patch, so that the cutoff scale $\sim 1/\lambda_{\text{FS}}$



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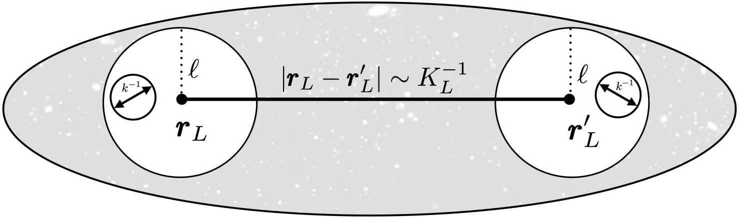


$$\Delta P_m \equiv P_m(\boldsymbol{k}, \lambda_{\rm FS}(\boldsymbol{r}_L)) - P_m(\boldsymbol{k}, \bar{\lambda}_{\rm FS}) \simeq \lambda_{\rm FS} \left.\frac{dP_m}{d\lambda_{\rm FS}}\right|_{\lambda_{\rm FS}=\bar{\lambda}_{\rm FS}} \delta_\lambda(\boldsymbol{r}_L)$$

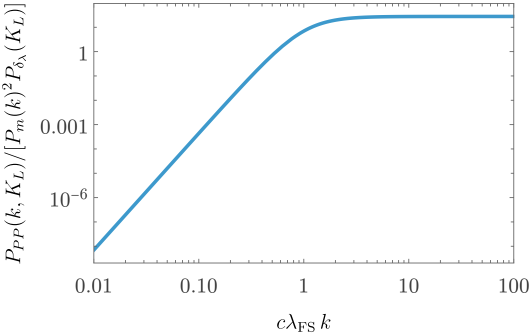
Correlation of ΔP_m is governed by P_{δ_λ}

$$P_{PP}(\boldsymbol{k}, \boldsymbol{K}_L) = \lambda_{\rm FS}^2 \left(\frac{dP_m}{d\lambda_{\rm FS}}\right)^2 P_{\delta_\lambda}(\boldsymbol{K}_L)$$

Estimates for modulating power spectrum

W/ $P_m(k) = T_{\rm FS}^2(k,\lambda_{\rm FS})P_{\mathscr{R}}(k)|W_s(k)|^2$, the fitting transfer function is

$$T_{\rm FS}(k,\lambda_{\rm FS}) = \left[1+(c\lambda_{\rm FS}k)^\beta\right]^\gamma \quad (\beta = 2.4\,,\, \gamma = -1.1)$$



$\mathscr{O}(1)$ **fluctuation in normalized correlation – detectable!**

Conclusions

- Kinetic isocurvature perturbation: A new class of isocurvature
  - Governed by momentum fluctuation
  - Evades CMB constraints
- Explicit models can be constructed
- $\mathcal{O}(1)$ modulations in the perturbation of $\lambda_{\rm FS}$
- Most sensible estimator? UV completion?