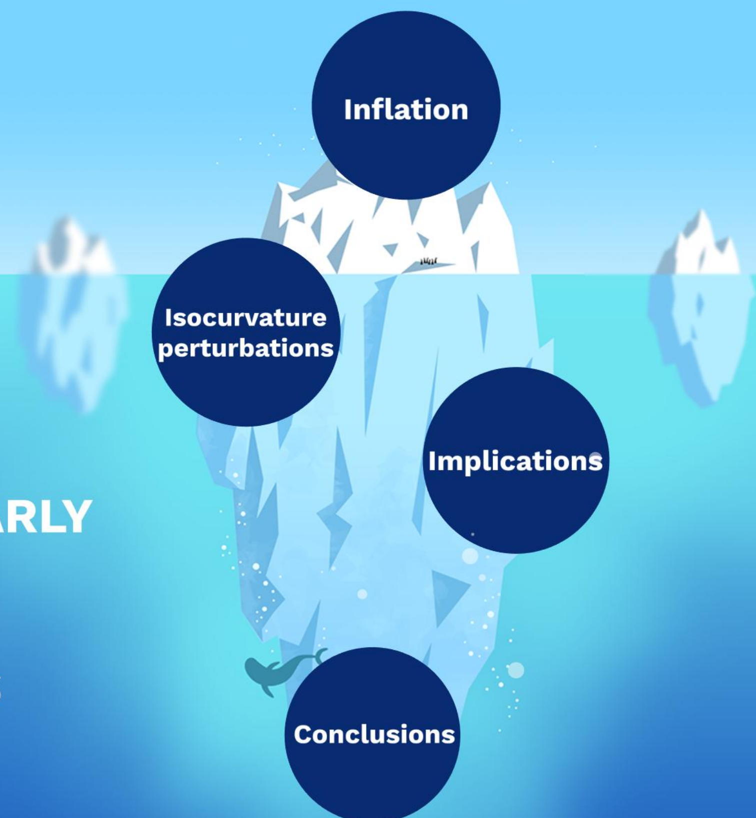
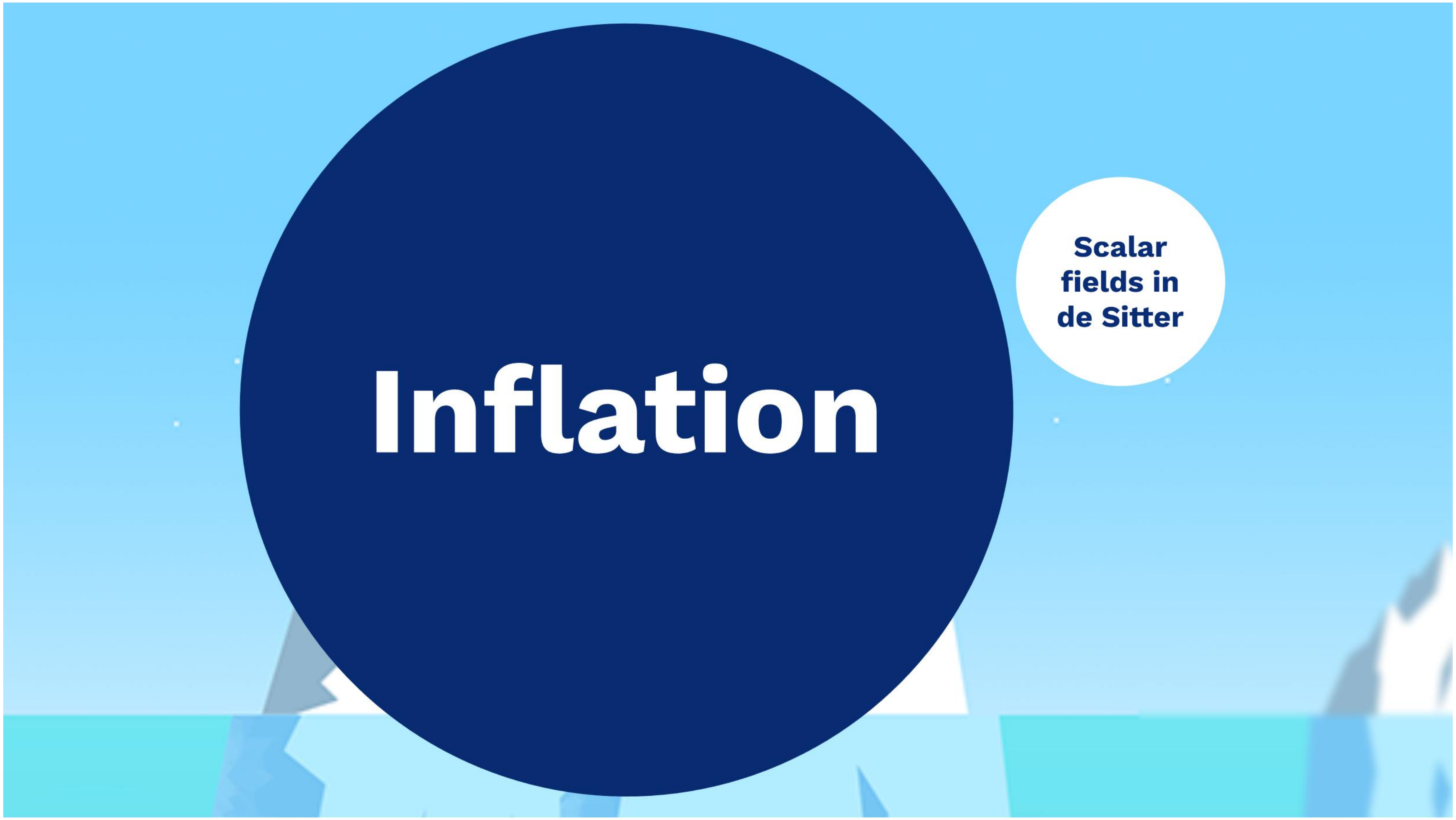


PROBING THE EARLY UNIVERSE WITH ISOCURVATURE PERTURBATIONS

Tommi Tenkanen
ttenkan1@jhu.edu

Talk based on
PRL 123, 061302 (2019)
1905.01214


Inflation
Scalar
fields in
de Sitter

Scalar fields in de Sitter space

- Assume standard cosmology (inflation, reheating, hot Big Bang as usual)

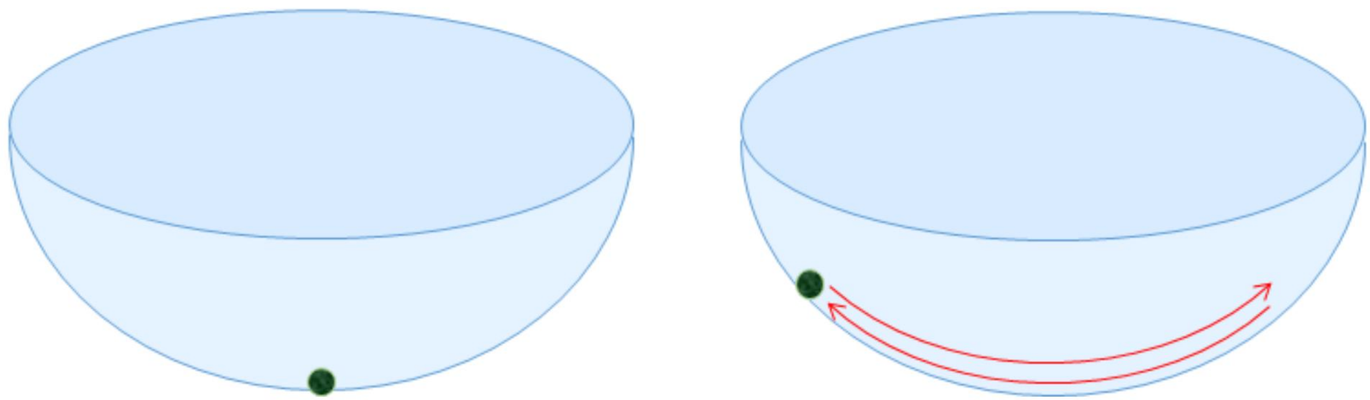
- Assume there is a scalar field with the Lagrangian

$$\mathcal{L} = \frac{1}{2}\partial^\mu\chi\partial_\mu\chi - \frac{1}{2}m^2\chi^2$$

- Assume the field is not the inflaton but a **spectator field**

Scalar fields in de Sitter space

- If the field was light (m<H), it acquired fluctuations during inflation



Scalar fields in de Sitter space

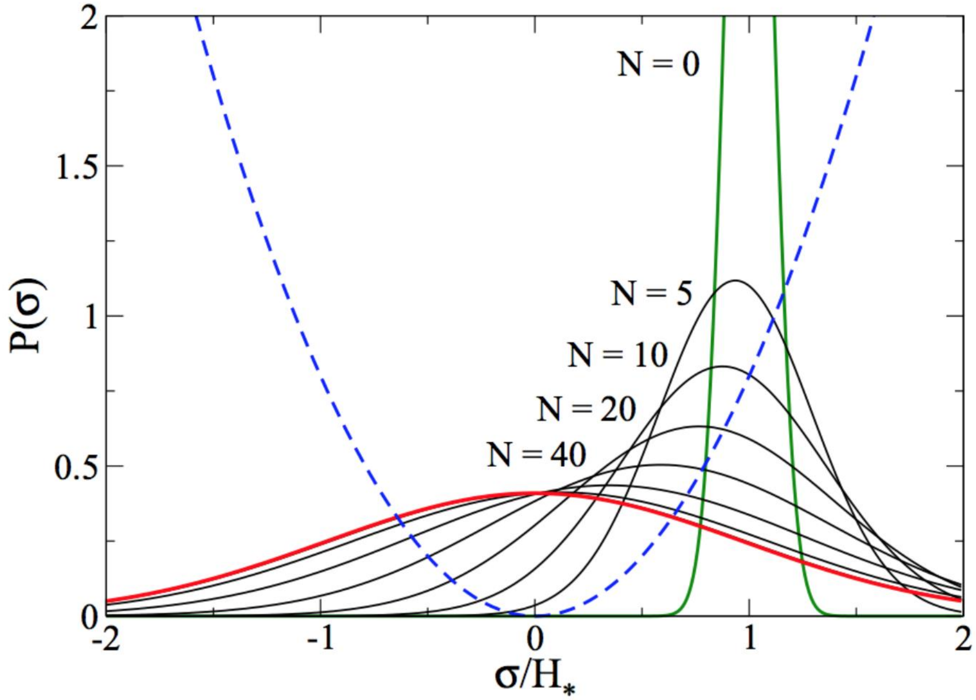


Figure from Enqvist et al. (1205.5446)

Scalar fields in de Sitter space

- Using the stochastic approach* it can be shown that the distribution of field values is**

$$P(\chi) = N \exp\left(-\frac{8\pi^2}{3H^4}V(\chi)\right)$$

- Typical displacement: $\langle\chi^2\rangle \sim \frac{H^4}{m^2}$

*) Starobinsky & Yokoyama (9407016), see also Markkanen, Rajantie, Stopyra, TT (1904.11917)

**) Relaxation time-scale: $N \sim H^2/m^2$

Evolution after inflation

- At the end of inflation, there was a non-zero condensate of the scalar field

- The field had the energy density

$$\rho_\chi^{\rm end}(x) = \frac{1}{2} m^2 \chi_{\rm end}^2(x)$$

Note that this is a position-dependent quantity

Evolution after inflation

- At the end of inflation, there was a non-zero condensate of the scalar field

- The field had the energy density

$$\rho_\chi^{\mathrm{end}}(x) = \frac{1}{2} m^2 \chi_{\mathrm{end}}^2(x)$$

This is a generic initial condition for non-thermal DM models with scalar fields

Evolution after inflation

- Soon, the field started to oscillate about its minimum with

$$\rho_\chi(a) \propto a^{-3}$$

- If the field did not decay, the present abundance is

$$\frac{\Omega_\chi h^2}{0.12} = 3.5 \times 10^{17} g_*^{-1/4} \left(H_{\rm osc}\right) \left(\frac{\chi_{\rm end}}{M_{\rm P}}\right)^2 \sqrt{\frac{m}{\rm GeV}}$$

Evolution after inflation

- Soon, the field started to oscillate about its minimum with

$$\rho_\chi(a) \propto a^{-3}$$

The simplest possible dark matter model

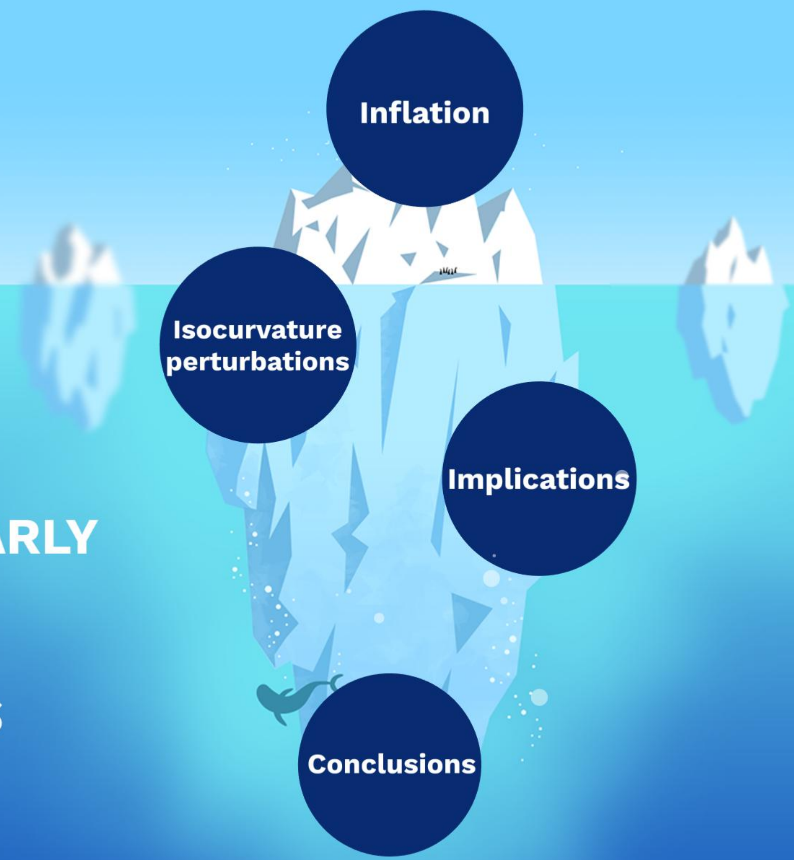
$$\frac{\Omega_\chi h^2}{0.12} = 3.5 \times 10^{17} g_*^{-1/4} \left(H_{\rm osc}\right) \left(\frac{\chi_{\rm end}}{M_{\rm P}}\right)^2 \sqrt{\frac{m}{\rm GeV}}$$

Evolution after inflation

- If the field did decay into stable particles, their present abundance is

$$\frac{\Omega_\psi h^2}{0.12} = 1.2 \times 10^9 g_*^{-1/4} \left(H_{\rm osc}\right) \left(\frac{m}{\Gamma_\chi}\right)^{3/8} \left(\frac{\chi_{\rm end}}{M_{\rm P}}\right)^{3/2} \left(\frac{m_\psi}{\rm GeV}\right)$$

- Other sources (such as freeze-in) can contribute to the final DM abundance, too



JOHNS HOPKINS UNIVERSITY

PROBING THE EARLY UNIVERSE WITH ISOCURVATURE PERTURBATIONS

Tommi Tenkanen
ttenkan1@jhu.edu

Talk based on
PRL 123, 061302 (2019)
1905.01214


Isocurvature perturbations
Observational consequences

Dark matter perturbations

- It was noted that the DM energy density is a position-dependent quantity

$$\rho_\chi^{\text{end}}(x) = \frac{1}{2} m^2 \chi_{\text{end}}^2(x)$$

Do the perturbations overlap with those in radiation?

(Are the DM perturbations **adiabatic** or **isocurvature?**)

Dark matter isocurvature

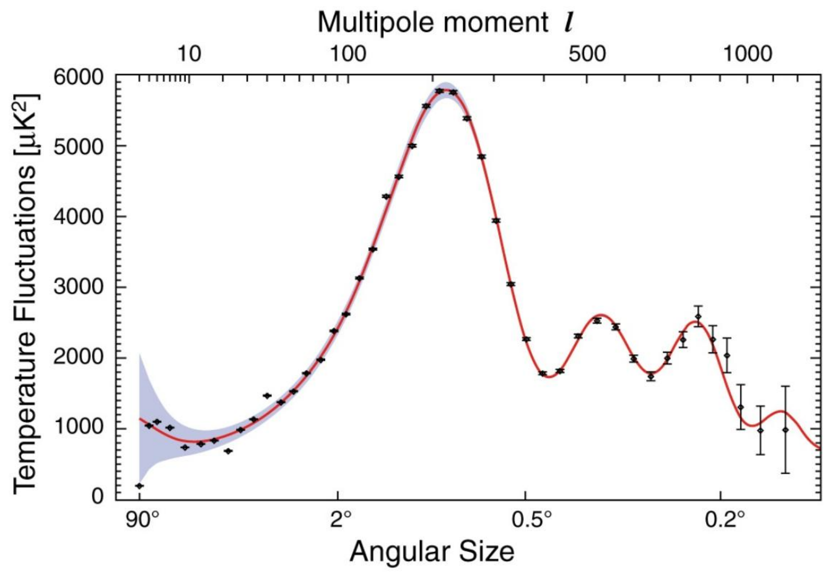
- Isocurvature between CDM and radiation is

$$S \equiv \frac{\delta\rho_{\rm c}}{\rho_{\rm c}} - \frac{3}{4}\frac{\delta\rho_\gamma}{\rho_\gamma}$$

- This quantity describes how much the CDM perturbations differ from those in radiation

DM isocurvature vs. observations

- Non-observation of DM isocurvature places stringent constraints on this type of scenarios



DM isocurvature spectrum

- The CMB constraints require

$$\mathcal{P}_S(k_*) \lesssim 0.04\mathcal{P}_\zeta(k_*)$$

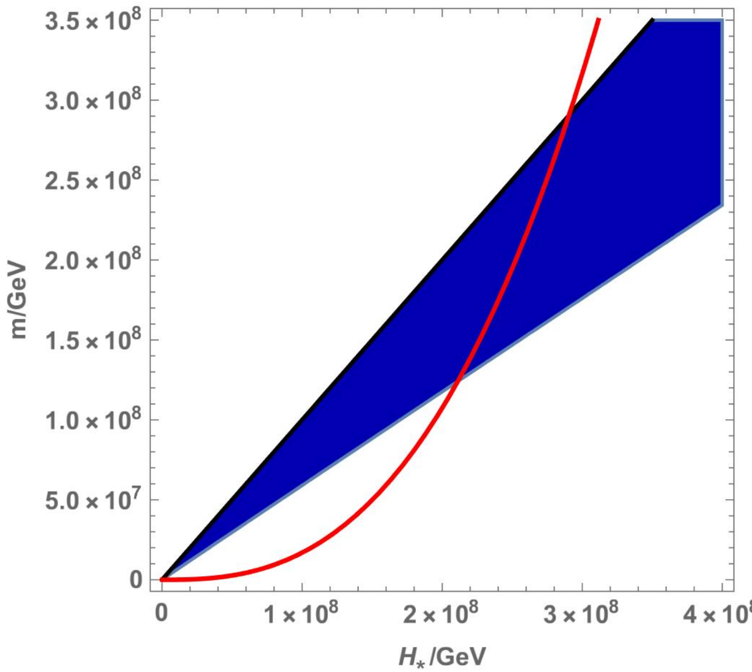
- The spectator field generates a spectrum

$$\mathcal{P}_S(k_*) = \mathcal{A}_{\rm iso}\left(\frac{k}{k_*}\right)^{n_{\rm iso}-1}$$

$$\mathcal{A}_{\rm iso} = 4(n_{\rm iso}-1)e^{-2N(k_*)(n_{\rm iso}-1)} \qquad n_{\rm iso}-1 = \frac{2}{3}\frac{m^2}{H^2}$$

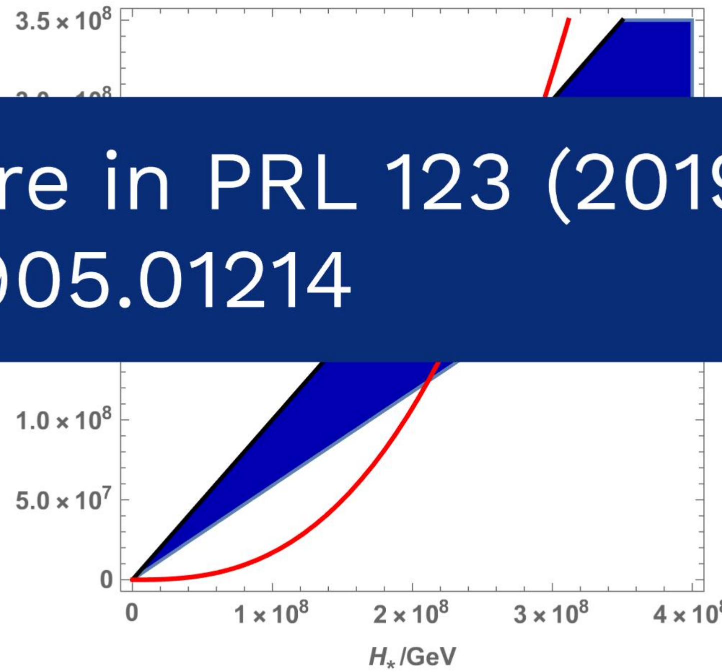
The simplest DM model vs. observations

- The constraints can be evaded



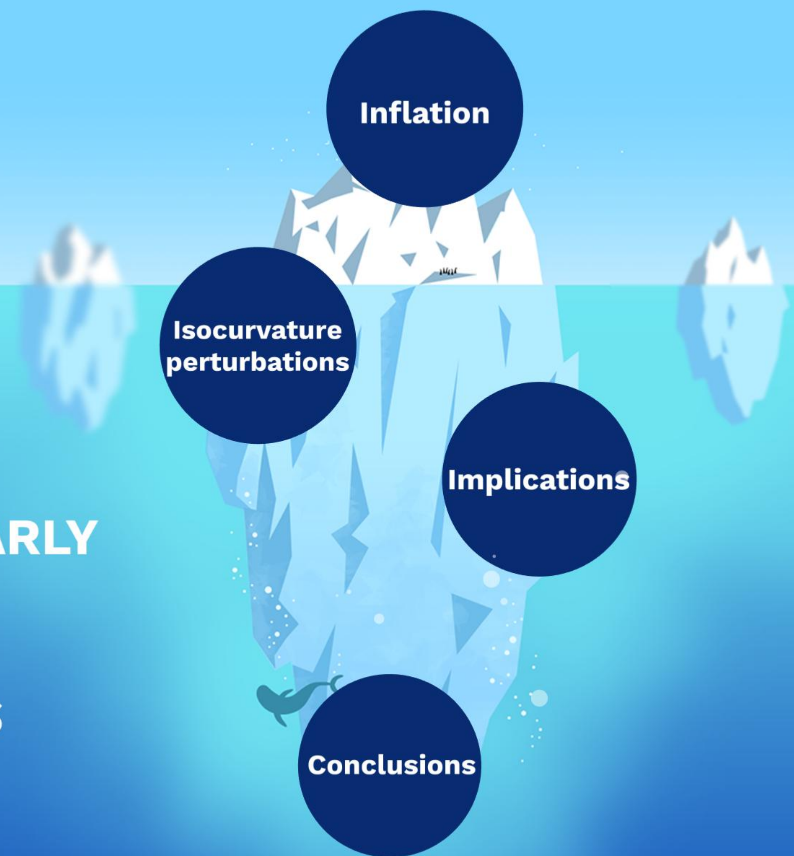
The simplest DM model vs. observations

- The constraints can be evaded



See more in PRL 123 (2019) 061302
arXiv: 1905.01214

PROBING THE EARLY UNIVERSE WITH ISOCURVATURE PERTURBATIONS



Tommi Tenkanen
ttenkan1@jhu.edu

JOHNS HOPKINS UNIVERSITY

Talk based on
PRL 123, 061302 (2019)
1905.01214

Implications

Structure formation

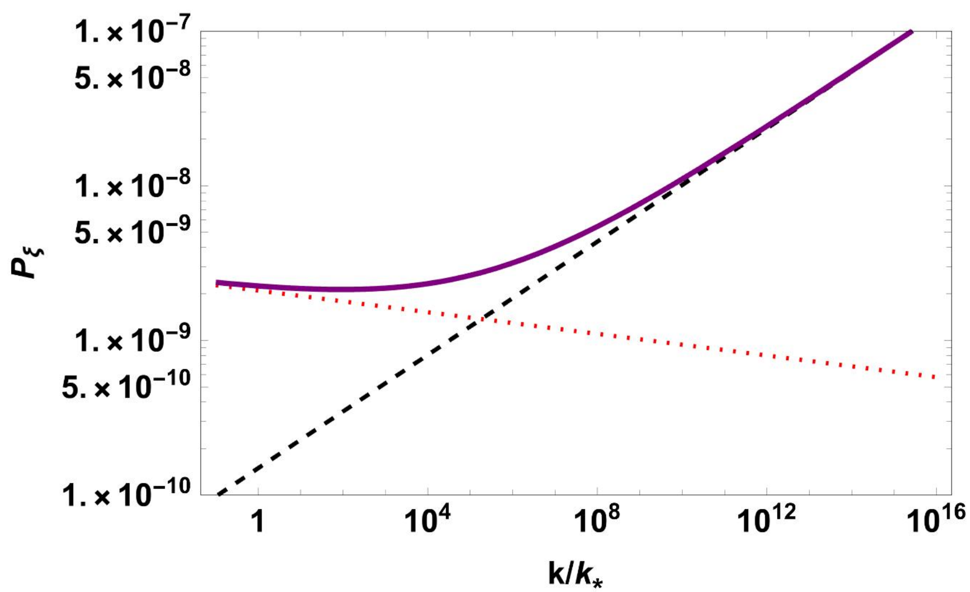
Testability

- Dark matter isocurvature affects the curvature perturbation

$$\zeta = \zeta_{\rm inf} + \frac{1}{3}S$$

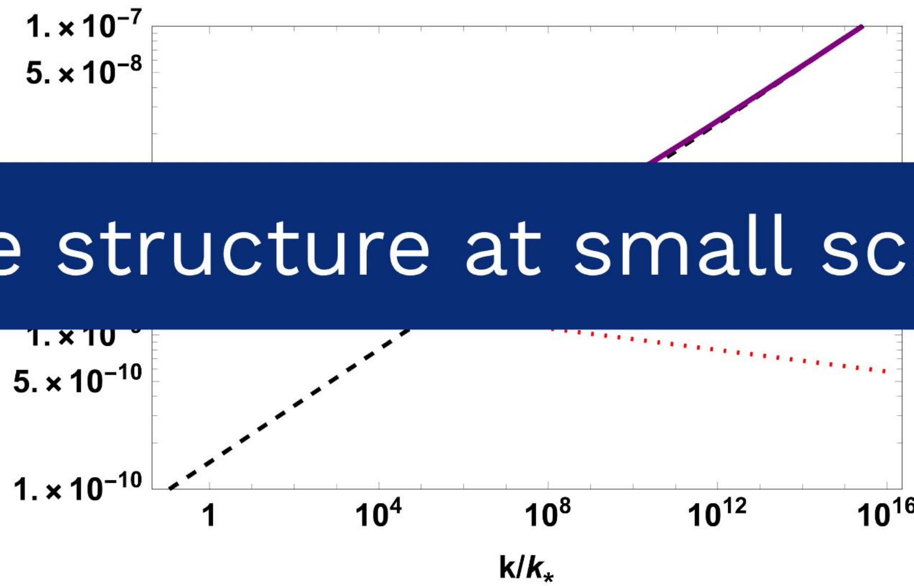
Testability

- Dark matter isocurvature affects the curvature perturbation



Testability

- Dark matter isocurvature affects the curvature perturbation



More structure at small scales!

Matter power spectrum

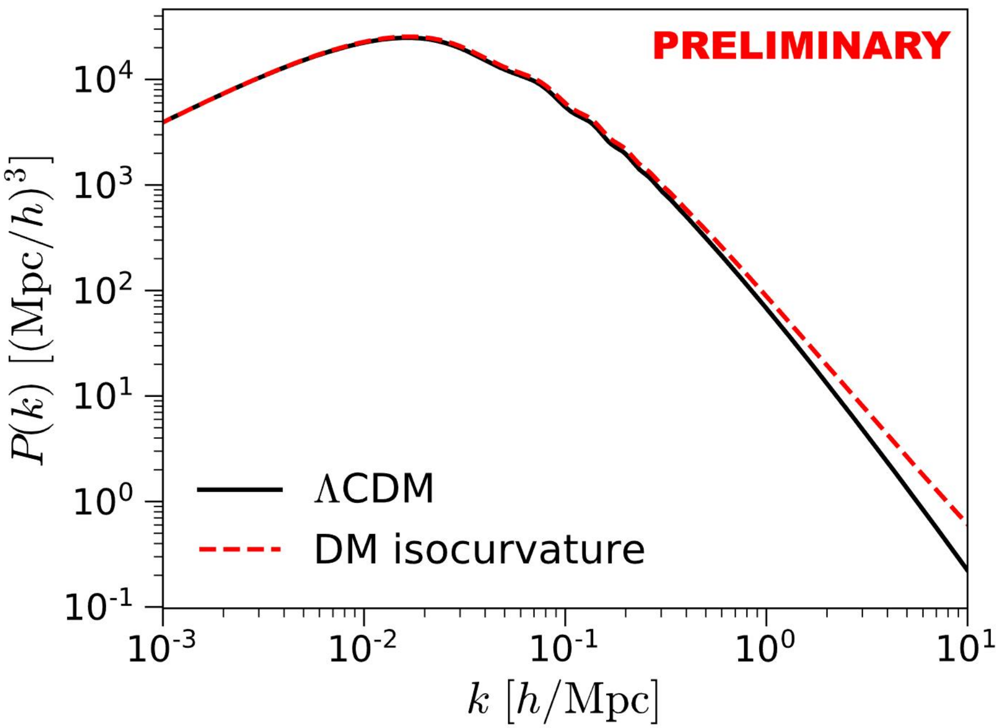
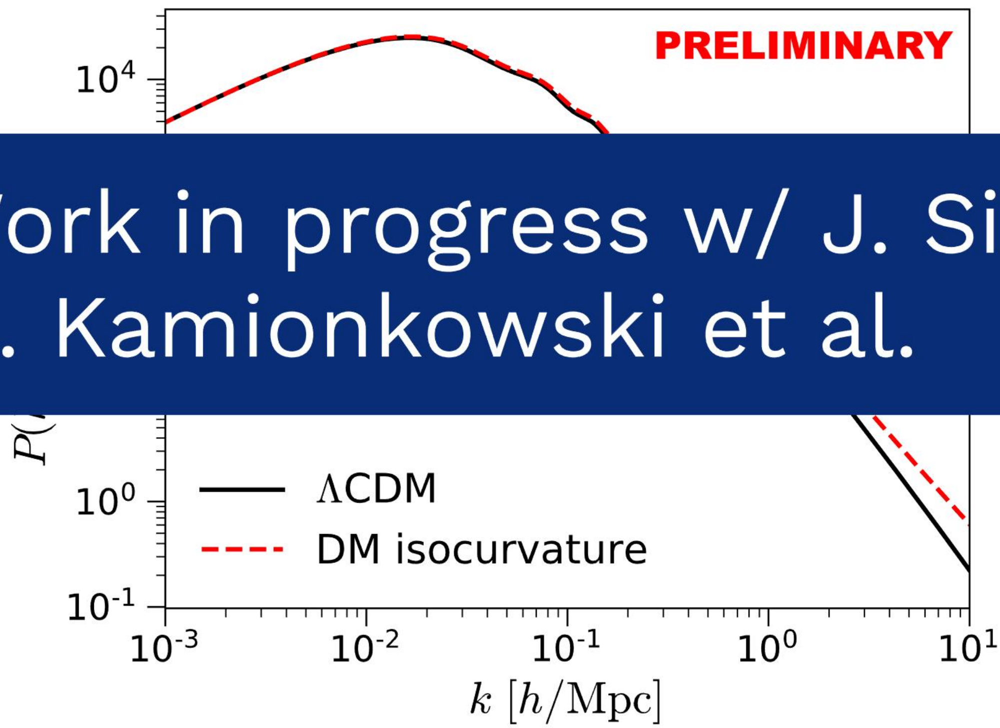


Figure by K. Boddy

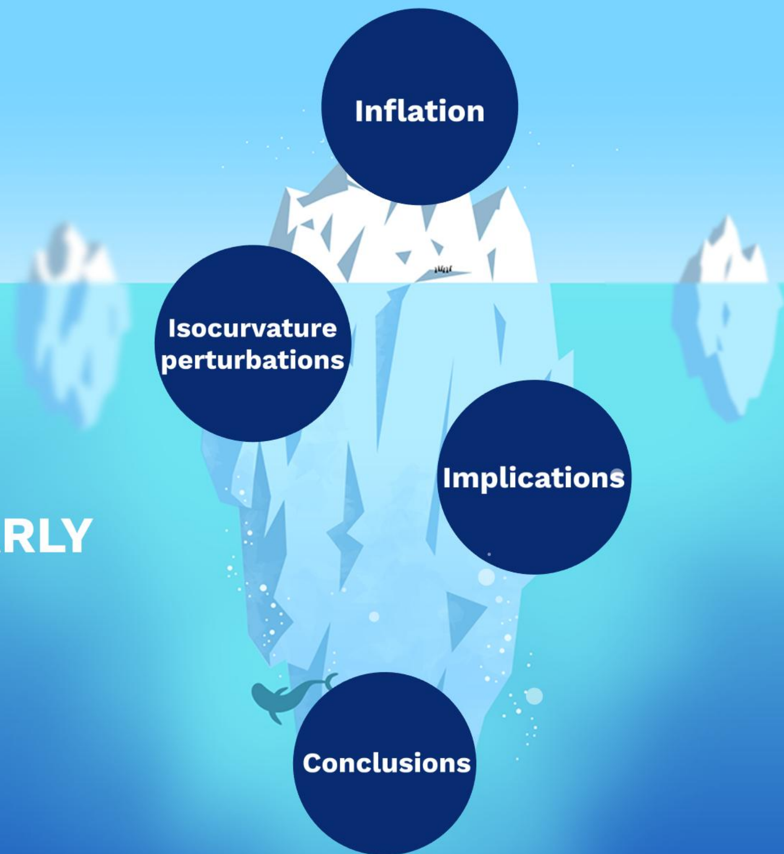
Matter power spectrum



Work in progress w/ J. Silk, M. Kamionkowski et al.

Figure by K. Boddy

JOHNS HOPKINS UNIVERSITY



PROBING THE EARLY UNIVERSE WITH ISOCURVATURE PERTURBATIONS

Tommi Tenkanen
ttenkan1@jhu.edu

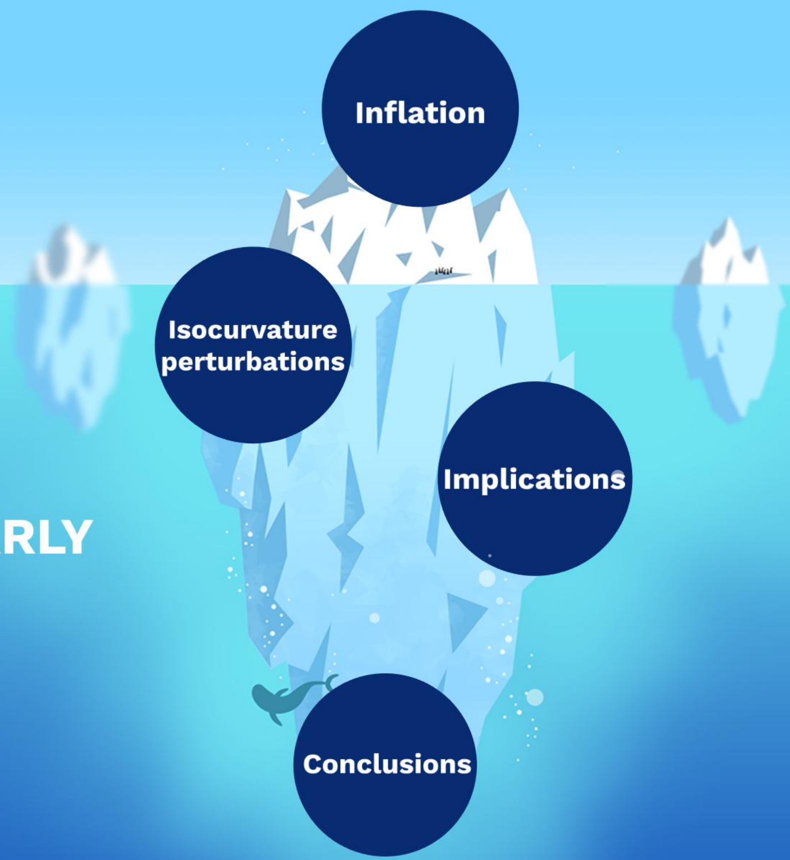
Talk based on
PRL 123, 061302 (2019)
1905.01214

Conclusions

- Inflation provides generic initial conditions for scalar fields

- Such scalars can constitute all DM

- The scenario can be tested with observations of the large scale structure



PROBING THE EARLY UNIVERSE WITH ISOCURVATURE PERTURBATIONS

Tommi Tenkanen
ttenkan1@jhu.edu

Talk based on
PRL 123, 061302 (2019)
1905.01214