Generalized Neutrino Isocurvature

Wolfram Ratzinger

With Christopher Gerlach and Pedro Schwaller

Based on 2504.17047 and to appear

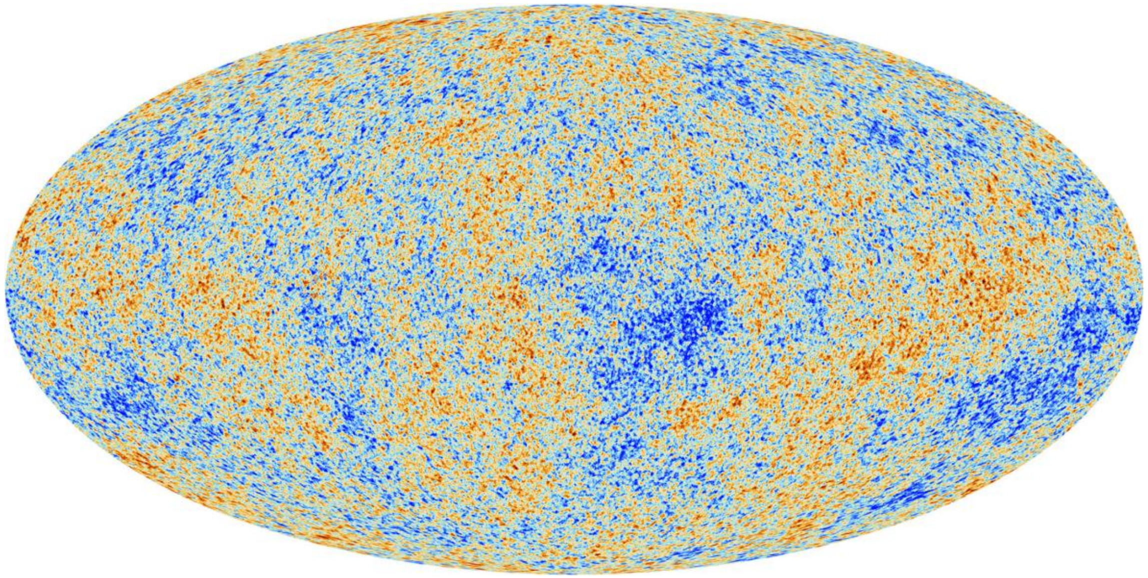
COSMO Fondue

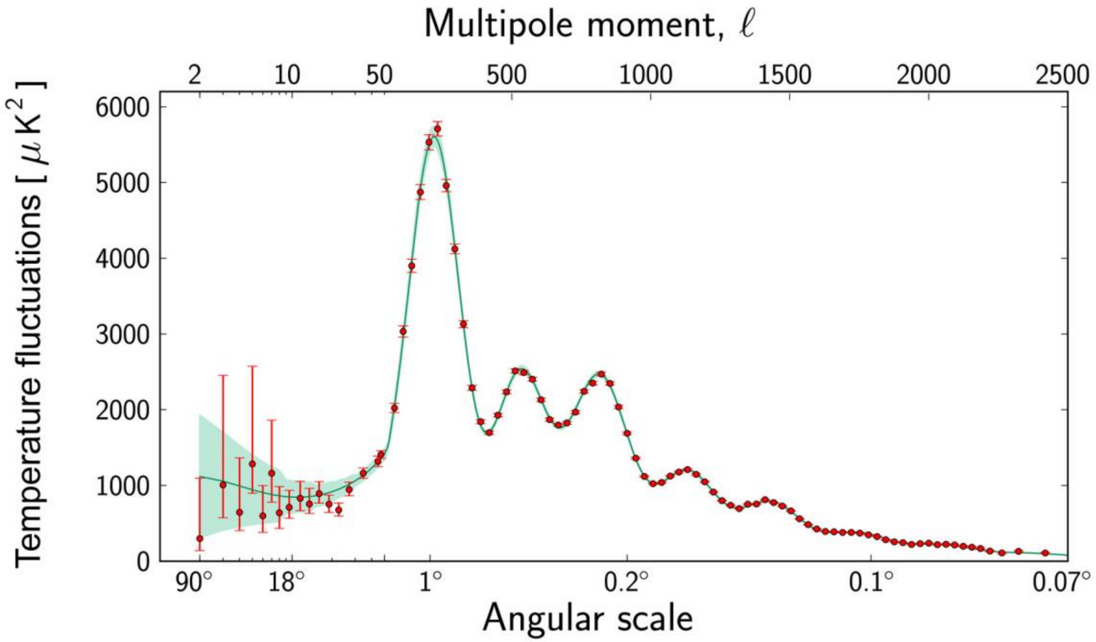
מכון ויצמן למדע

WEIZMANN INSTITUTE OF SCIENCE

The CMB so far:

- Adiabatic/curvature perturbations
  - Strict relation between overdensities in different fluids





Search for isocurvature

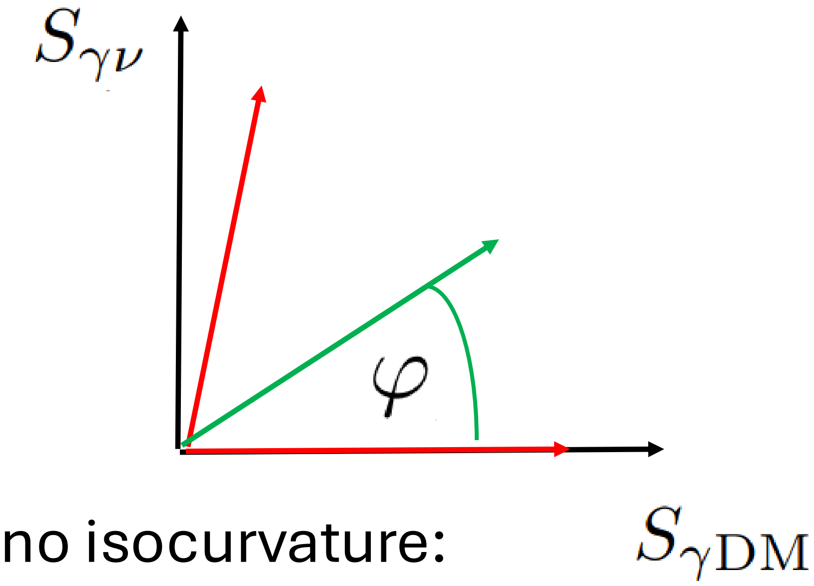
- Additional initial condition, with constant total density
- 2 (3) combinations:
  - Relative to photons DM, neutrino or baryon overdense $S_{\gamma \mathrm{DM}}, \ S_{\gamma\nu}, \ S_{\gamma \mathrm{b}}$
- Need to generalize curvature power spectrum to 3x3 matrix

$$\langle\zeta\zeta\rangle \rightarrow \left\langle \begin{matrix} \zeta\zeta & \zeta S_{\gamma\mathrm{DM}} & \zeta S_{\gamma\nu} \\ \zeta S_{\gamma\mathrm{DM}} & S_{\gamma\mathrm{DM}} S_{\gamma\mathrm{DM}} & S_{\gamma\mathrm{DM}} S_{\gamma\nu} \\ \zeta S_{\gamma\nu} & S_{\gamma\mathrm{DM}} S_{\gamma\nu} & S_{\gamma\nu} S_{\gamma\nu} \end{matrix} \right\rangle$$

- Very difficult to fit, no one has done it

Search for isocurvature

- Instead pick one additional combination



So far people considered:
-one "random" combination
-DM isocurvature only

Generalized neutrino isocurvature:
-consider all ratios out of neutrino and DM isocurvature

Outline

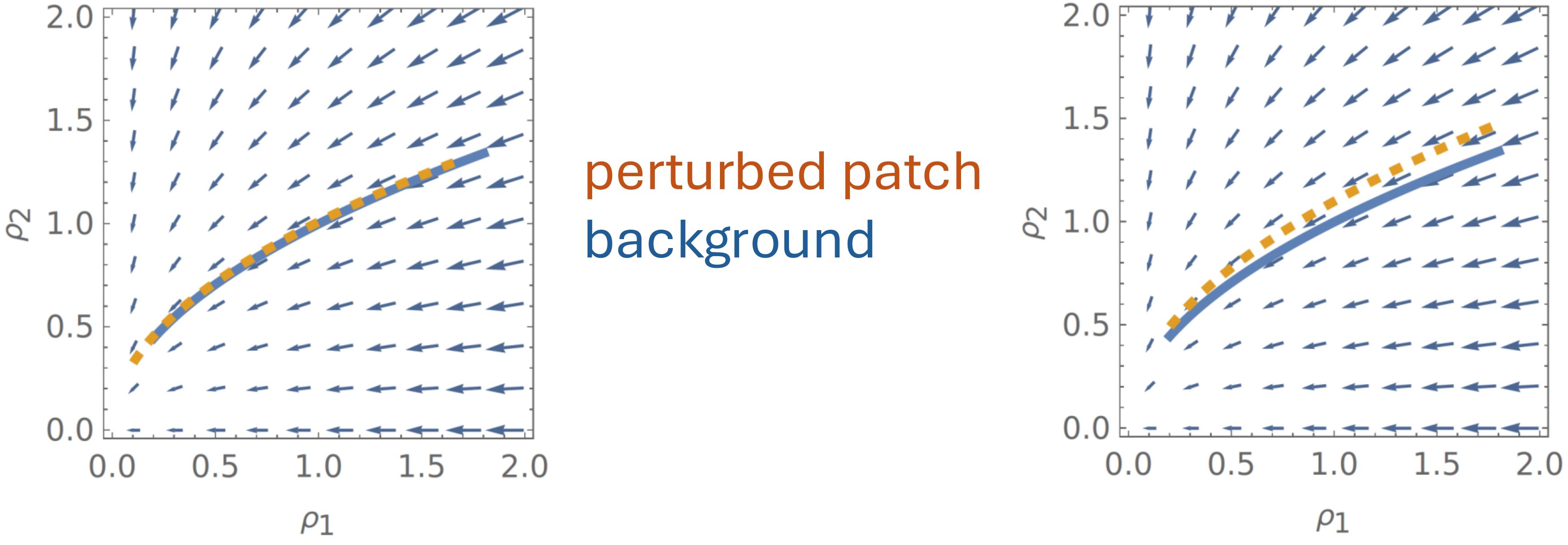
I Part: Neutrino isocurvature comes generically with DM isocurvature

II Part: CMB observables with general isocurvature

Adiabatic vs. Isocurvature perturbation

Wands, Malik, Lyth, Liddle 2000

- Perturbation on super-horizon scale correspond to patches perturbed relative to background evolution



Adiabatic: Perturbed patch only ahead of background

Isocurvature: Perturbed patch goes through different history

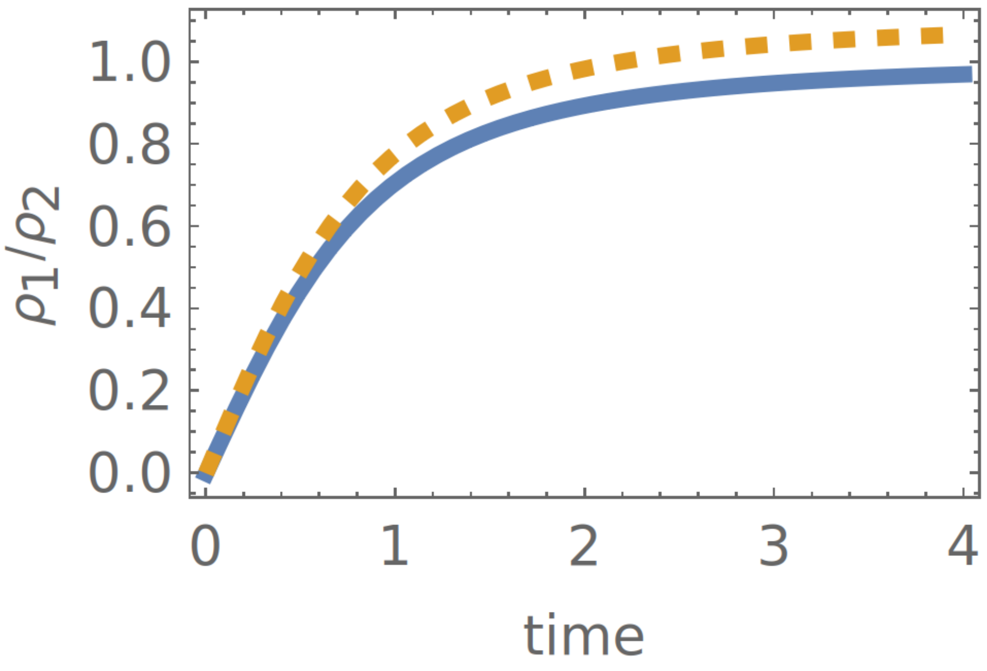
Isocurvature: Special case

- Consider conserved number densities
- If ρ_i is conserved number density

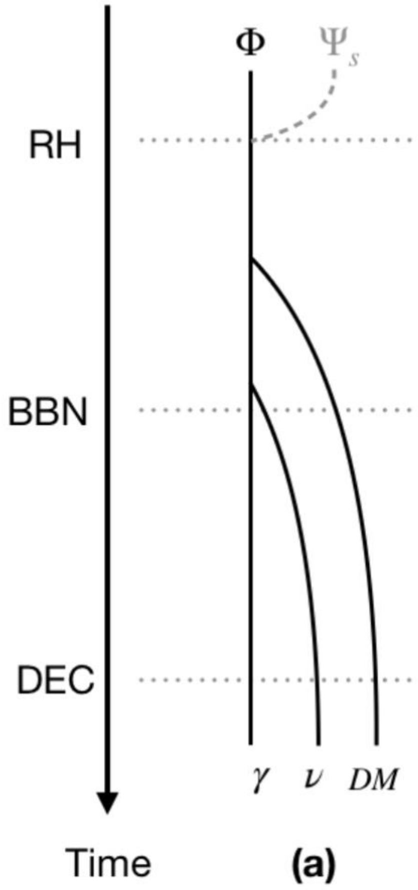
$$\dot{\rho}_i = -3H\rho_i$$

may define isocurvature as

$$S_{ij} = \delta\left(\frac{\rho_i}{\rho_j}\right) / \frac{\rho_i}{\rho_j}$$



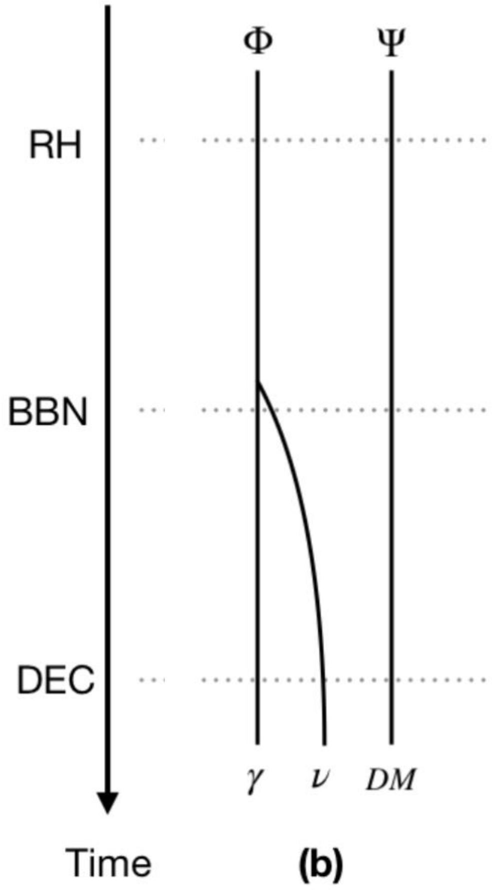
Cosmological histories



Only adiabatic perturbation

Weinberg 2004

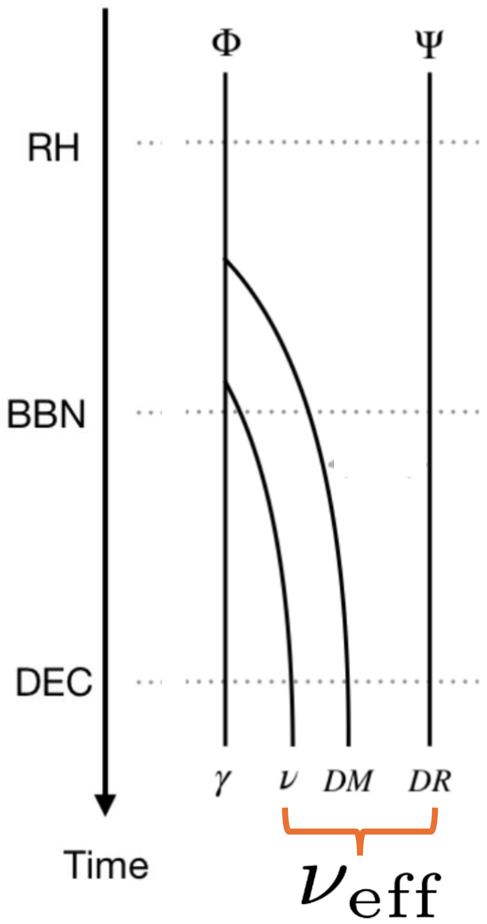
Cosmological histories



Curvature + DM Isocurvature

e.g. ultra light DM from misalignment mechanism

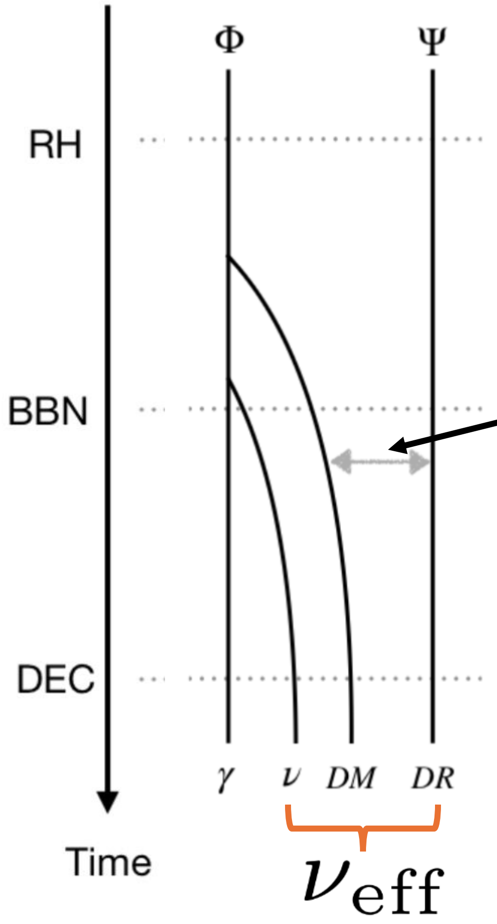
Cosmological histories



Neutrinos are just free-streaming dark radiation for CMB

Curvature + neutrino Isocurvature
-> naively no DM Isocurvature

Cosmological histories

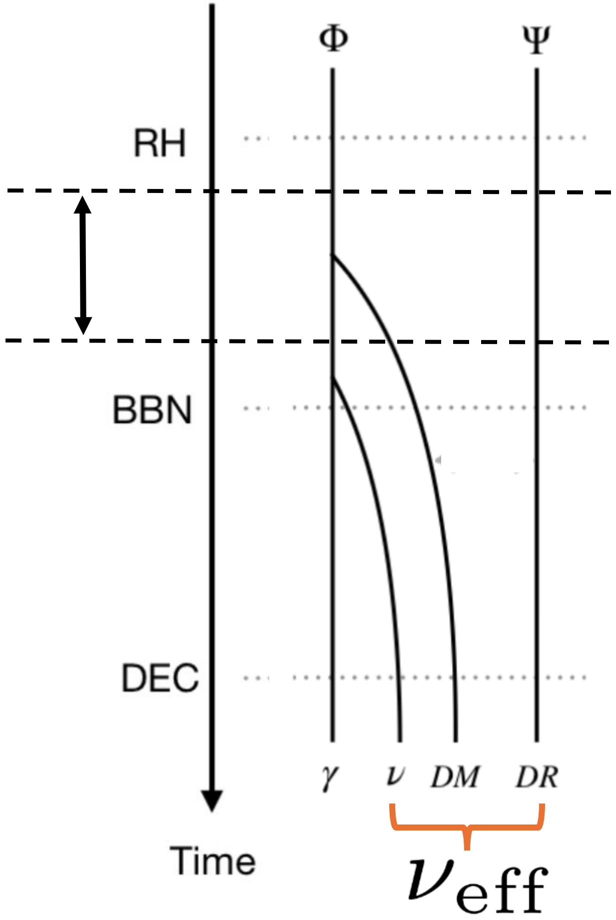


Additional, weak interaction

Curvature + neutrino Isocurvature
Also generates DM Isocurvature

Cosmological histories

Only consider this period
- freeze-in
- freeze-out
- ...

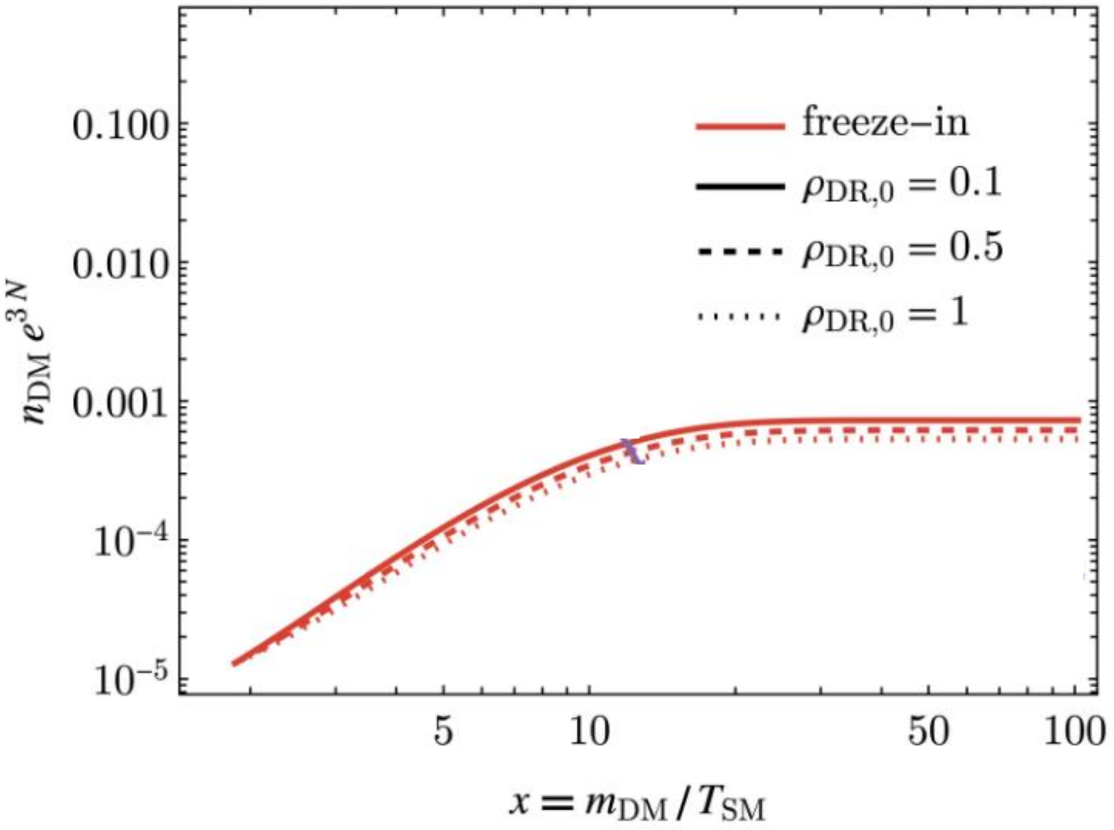


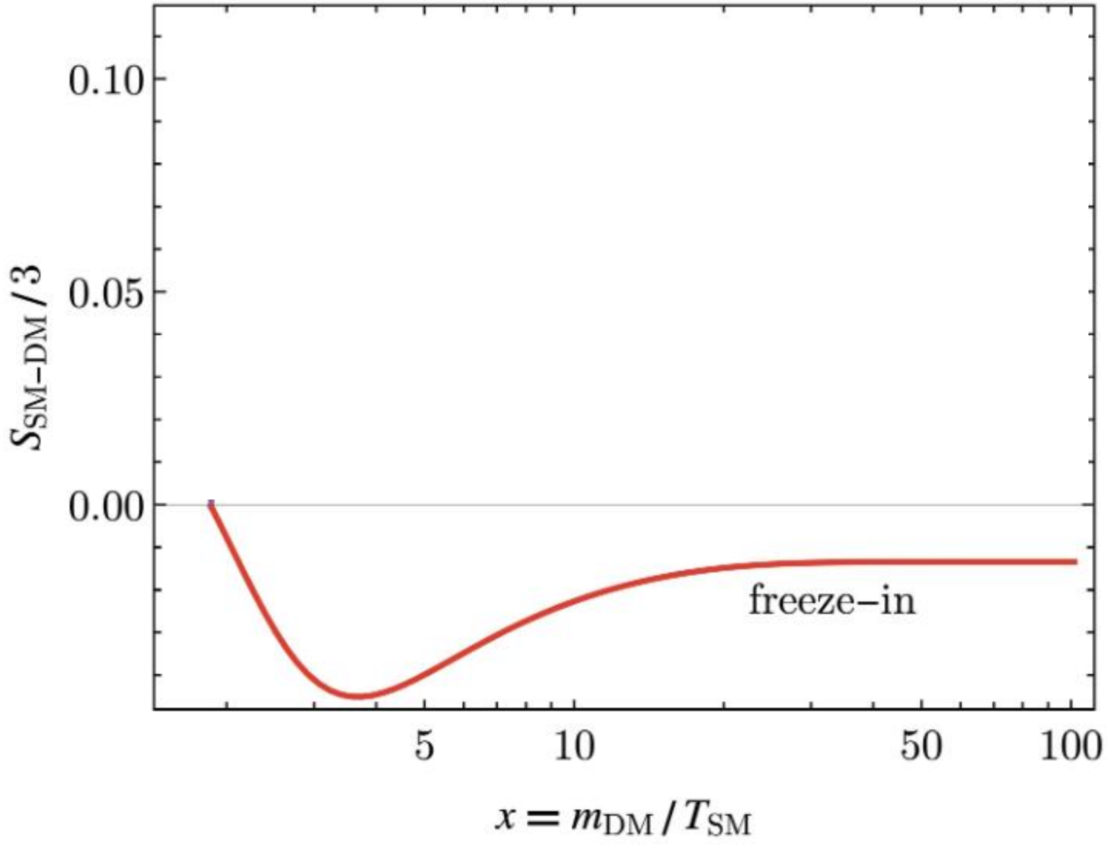
Curvature + neutrino Isocurvature
-> gravitationally induce DM Isocurvature

Curvaton case: Lyth, Ungarelli, Wands 2018
BBN relics: Adshead, Holder, Ralegankar 2020

Freeze-in

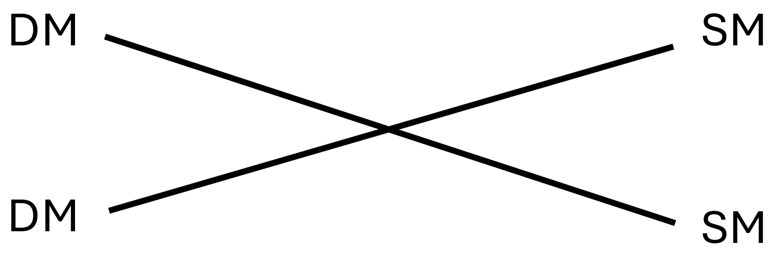
Yield $Y = \frac{n_{\mathrm{DM}}}{n_{\mathrm{SM}}} \sim \frac{\Gamma(T_{\mathrm{SM}} = m)}{H(T_{\mathrm{SM}} = m)}$



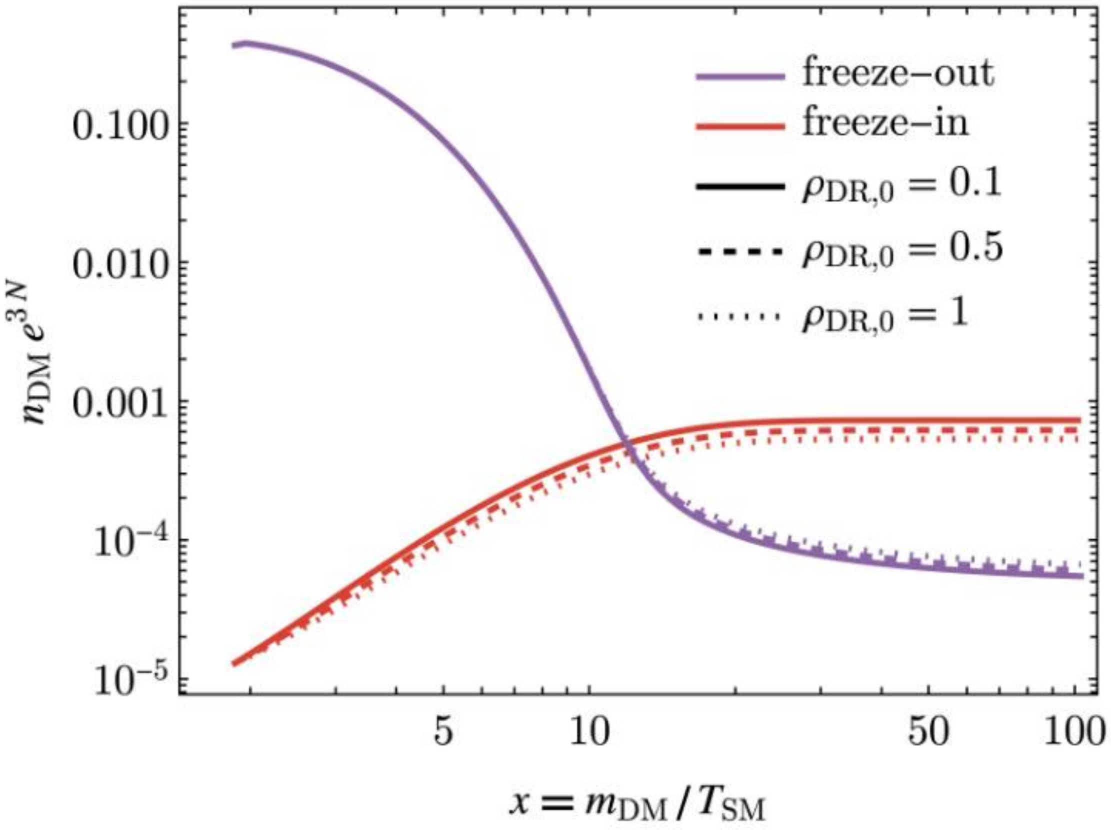


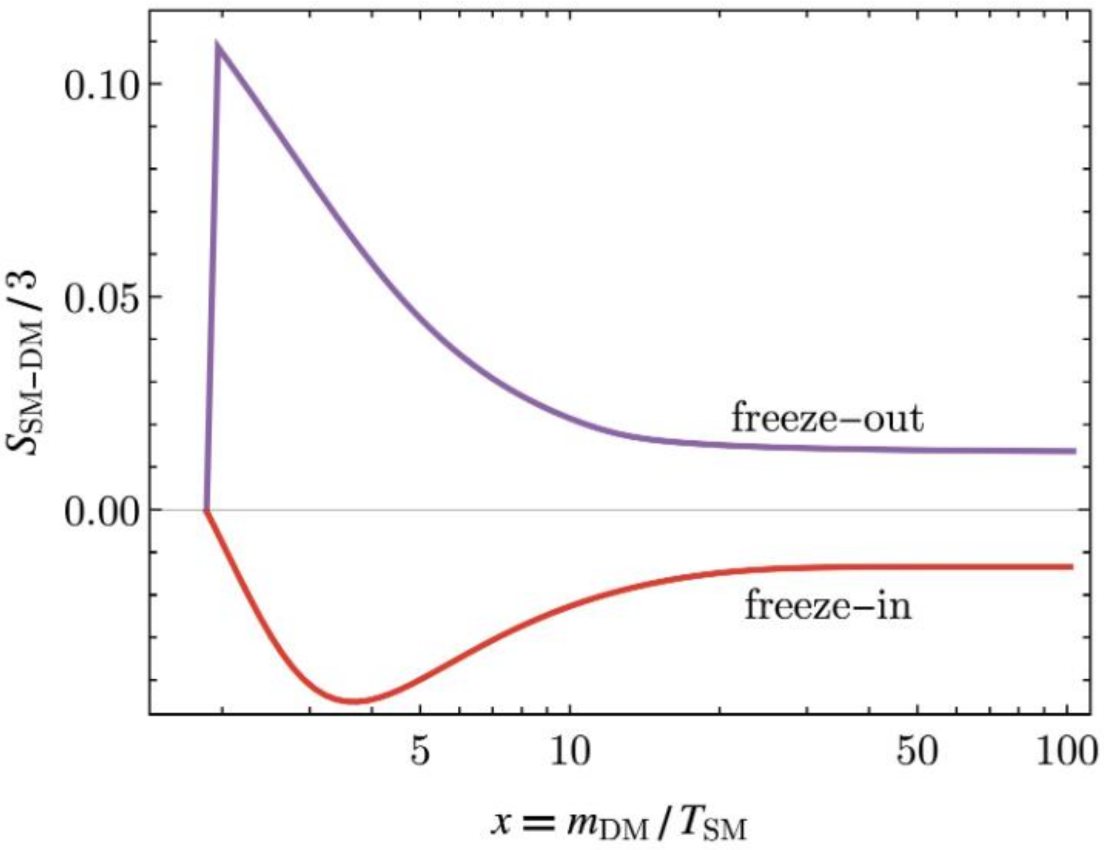
Curvaton case: Lyth, Ungarelli, Wands 2018
BBN relics: Adshead, Holder, Ralegankar 2020

Freeze-out



Yield $Y \sim Y_{\text{eq}}(T^*),\ \Gamma_{\text{an}}(T^*) = H(T^*)$

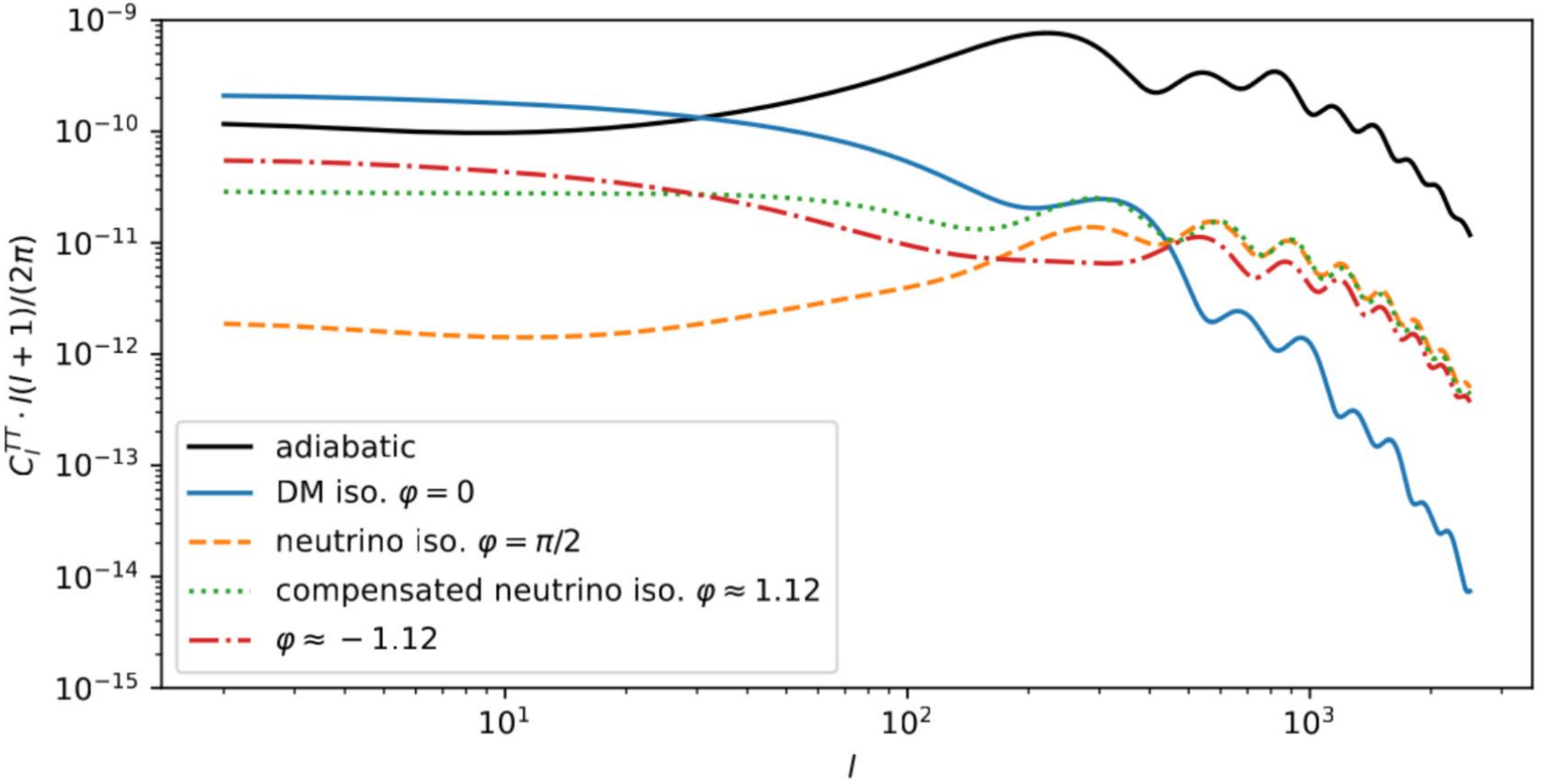




II Part: CMB observables

The CMB spectrum

Observables depend on $\tan(\varphi) = \frac{S_{\gamma\nu}}{S_{\gamma \mathrm{DM}}}$

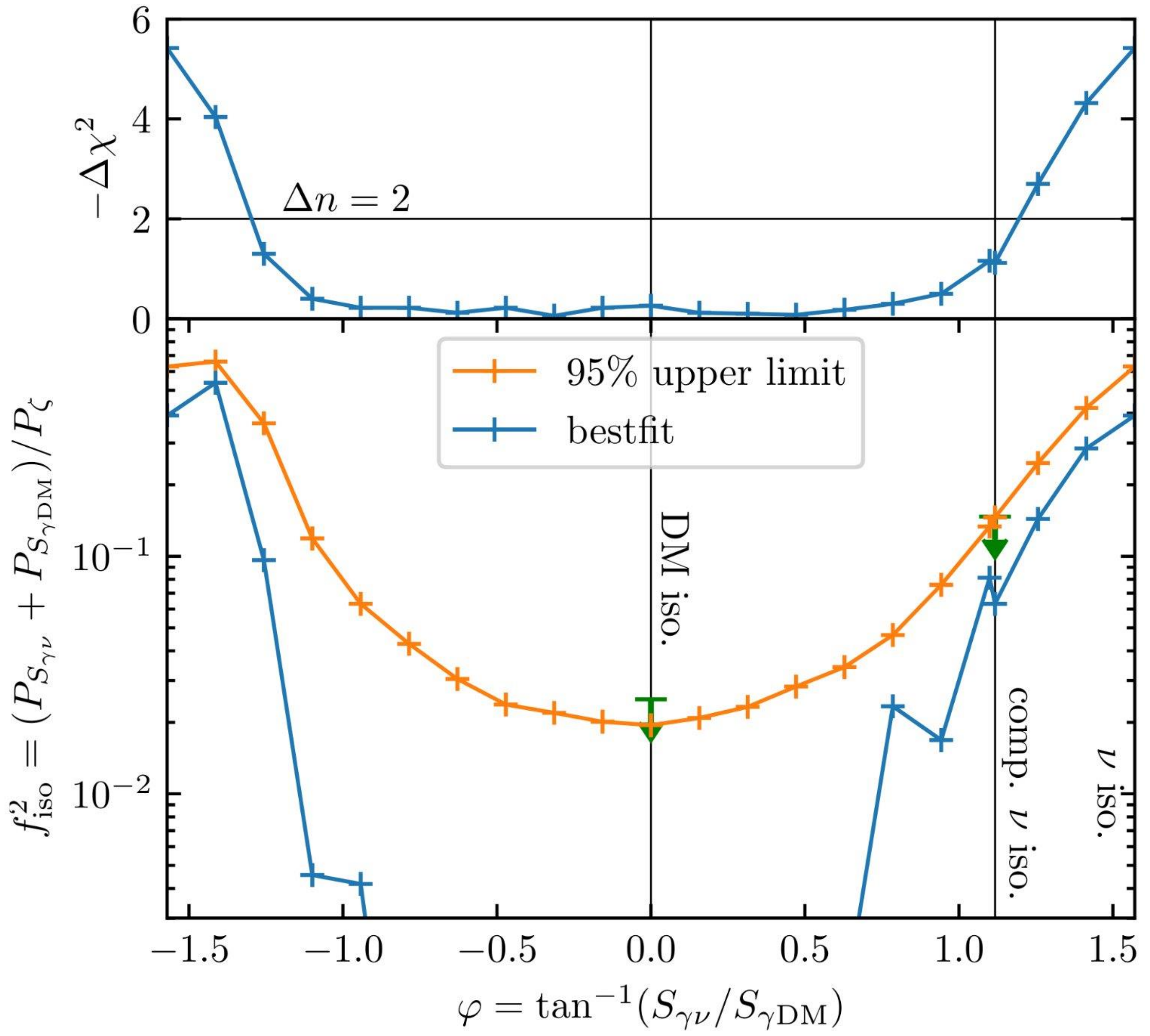


Result of CMB and LSS fit

-Fit to Planck and BAO data

-Varying isocurvature amplitude and correlation

-Fixed spectral index
$n_{\text{iso}} = 1$

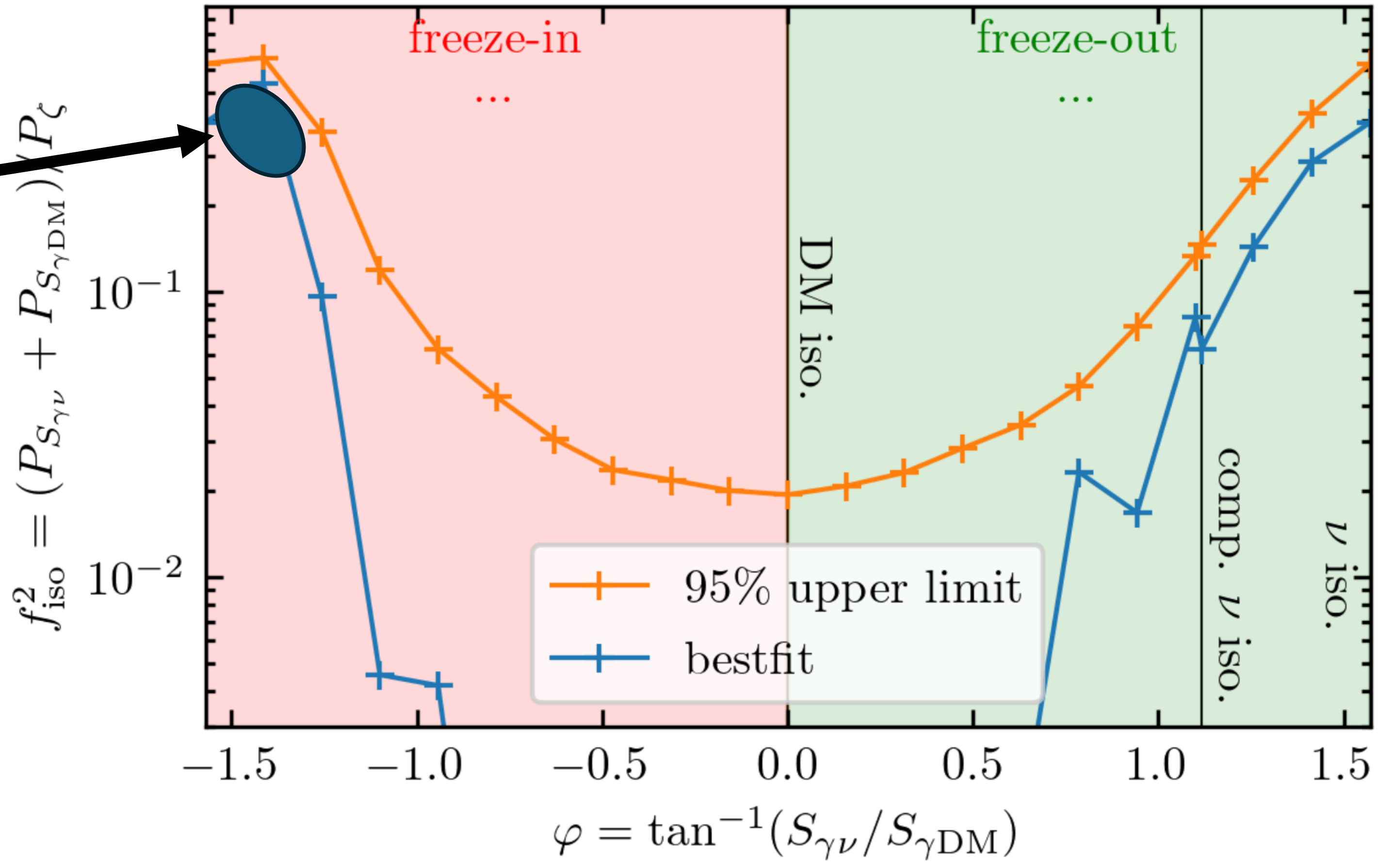


Future searches

Staying optimistic:

Let's assume CMB stage 4 finds isocurvature here
-> DM is produced via freeze-in

Requires assumptions:
-> No direct interaction
-> baryogenesis unaffected
->...



Cosmological archaeology

A few more hints...

$$\frac{S_{\gamma\nu}}{S_{\gamma \mathrm{DM}}}$$

Full cosmological history

Conclusion

- Cosmologies with neutrino isocurvature generically feature fully correlated DM isocurvature

  -> Should included general case in searches

- If detected, this provides valuable information about the entire history

Thanks