SUPERHORIZON ISOCURVATURE AS A WINDOW INTO DARK MATTER PRODUCTION

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Cosmo 2026

Universiteit Leiden
August 24, 2026

Motivation

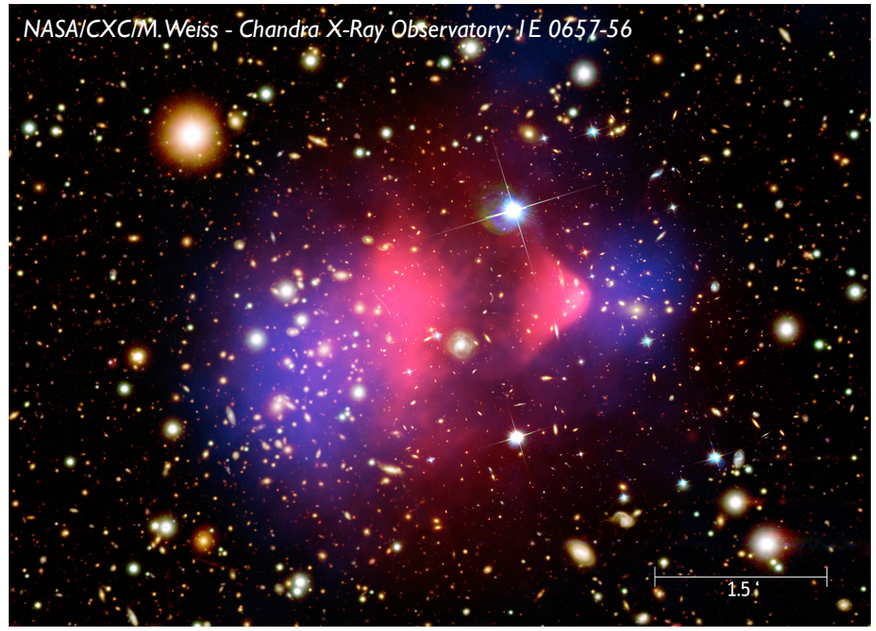
There is probably a dark sector with

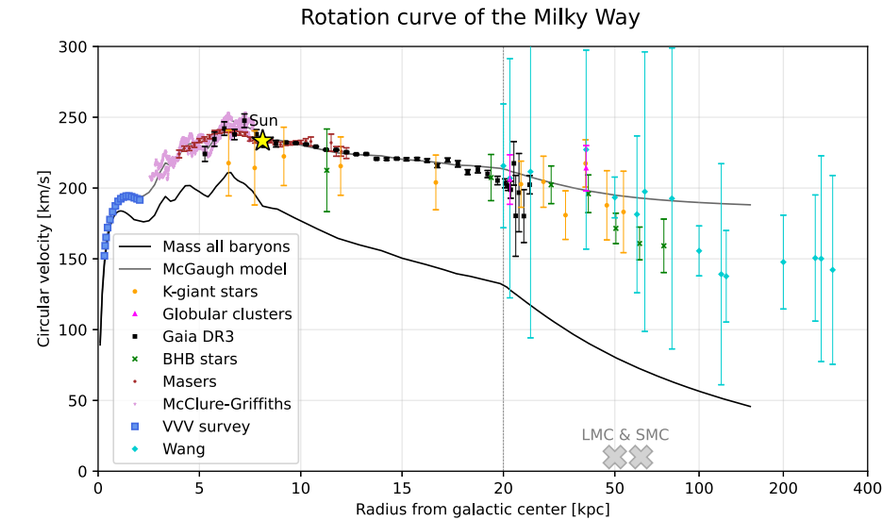
- Dark matter
- Dark radiation?
- …

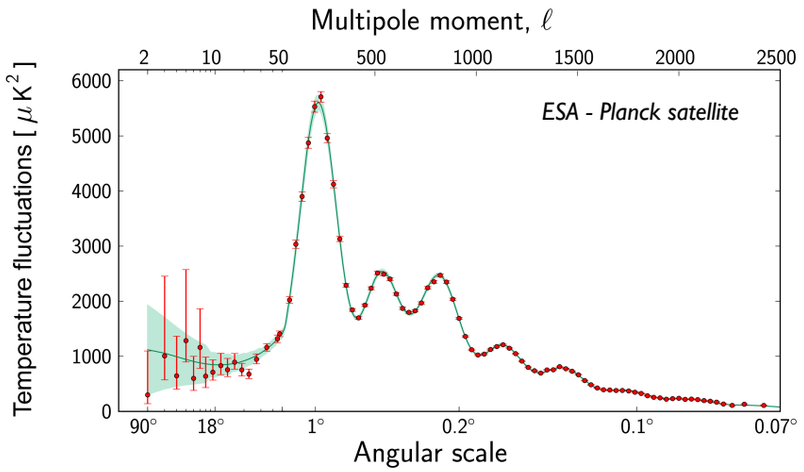
We don’t know much else

Today: What can we learn from isocurvature

- Minimal isocurvature scenarios
- Probes of DM production







Cosmic perturbation theory

Universe is almost homogeneous and isotropic

$$ds^2 = -\left[1+2\phi(t,\mathbf{x})\right]dt^2 + a^2(t)\left[1-2\psi(t,\mathbf{x})\right]d\mathbf{x}^2$$

$$\rho_\alpha(t,\mathbf{x}) = \rho_\alpha(t)+\delta\rho_\alpha(t,\mathbf{x}) \qquad \alpha = \gamma,\nu,\mathrm{DM},\mathrm{b}$$

Gauge invariant combinations:

$$\zeta_\alpha = -\psi - H\frac{\delta\rho_\alpha}{\dot\rho_\alpha}$$

"curvature perturbation"

Adiabatic vs. Isocurvature

Total curvature perturbation:

$$\zeta = \sum_{\alpha} \frac{\dot{\rho}_\alpha}{\dot{\rho}} \zeta_\alpha$$

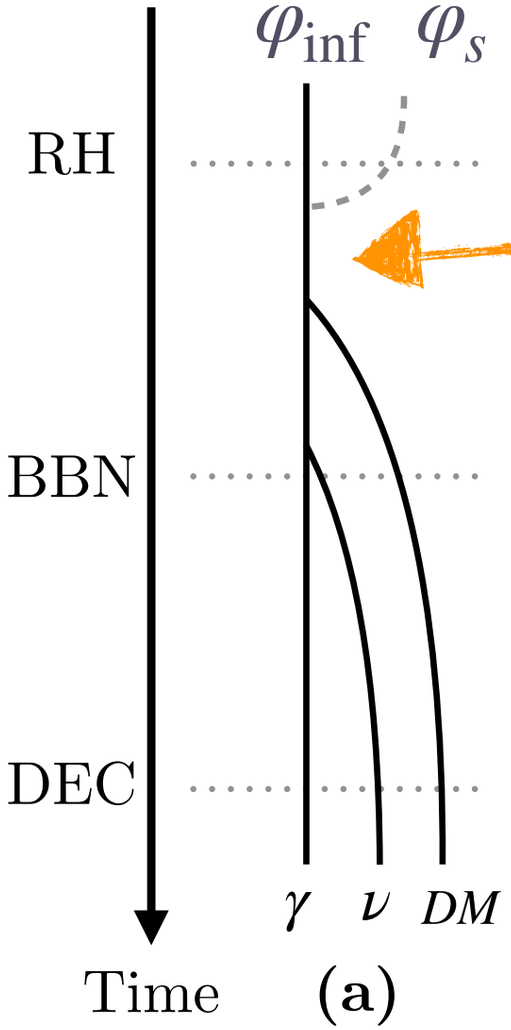
Relative (isocurvature) perturbations:

$$S_{\alpha\beta} = 3(\zeta_\alpha - \zeta_\beta) = -3H\left(\frac{\delta\rho_\alpha}{\dot{\rho}_\alpha} - \frac{\delta\rho_\beta}{\dot{\rho}_\beta}\right)$$

Adiabatic perturbations $\Leftrightarrow S_{\alpha\beta} = 0 \quad \forall \alpha, \beta$

“All fluctuations described by a common time shift”

How to (not) get isocurvature initial conditions



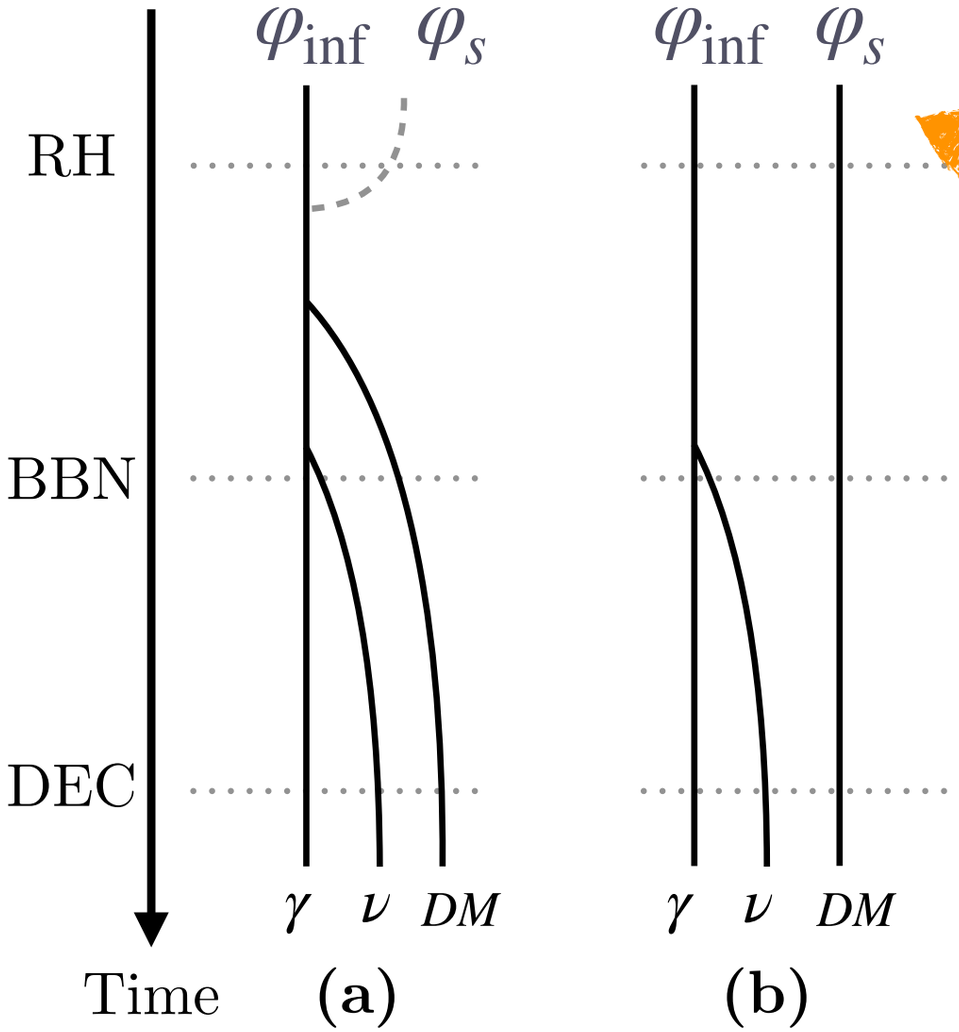
(Effective) single field inflation

Single clock

- No isocurvature
- ever!*

* (superhorizon)

How to get DM isocurvature



Two field inflation

Second (spectator) field has independent fluctuations

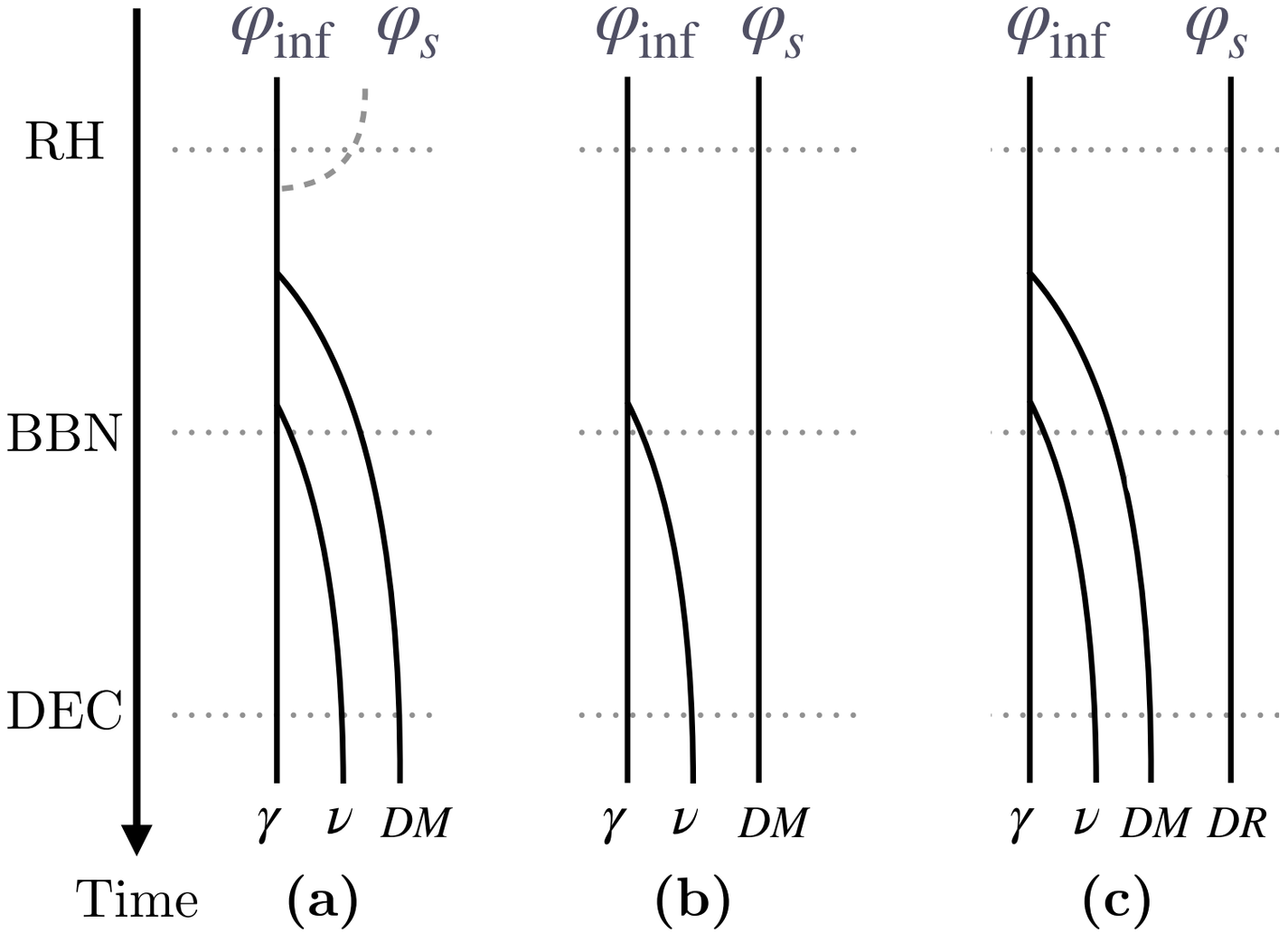
Becomes DM

- $S_{\gamma \rm DM} \neq 0$

Example: Axion misalignment

Gerlach, Ratzinger & PS, 2504.17047

How to get neutrino isocurvature



CMB cannot (yet) distinguish neutrinos from other dark radiation

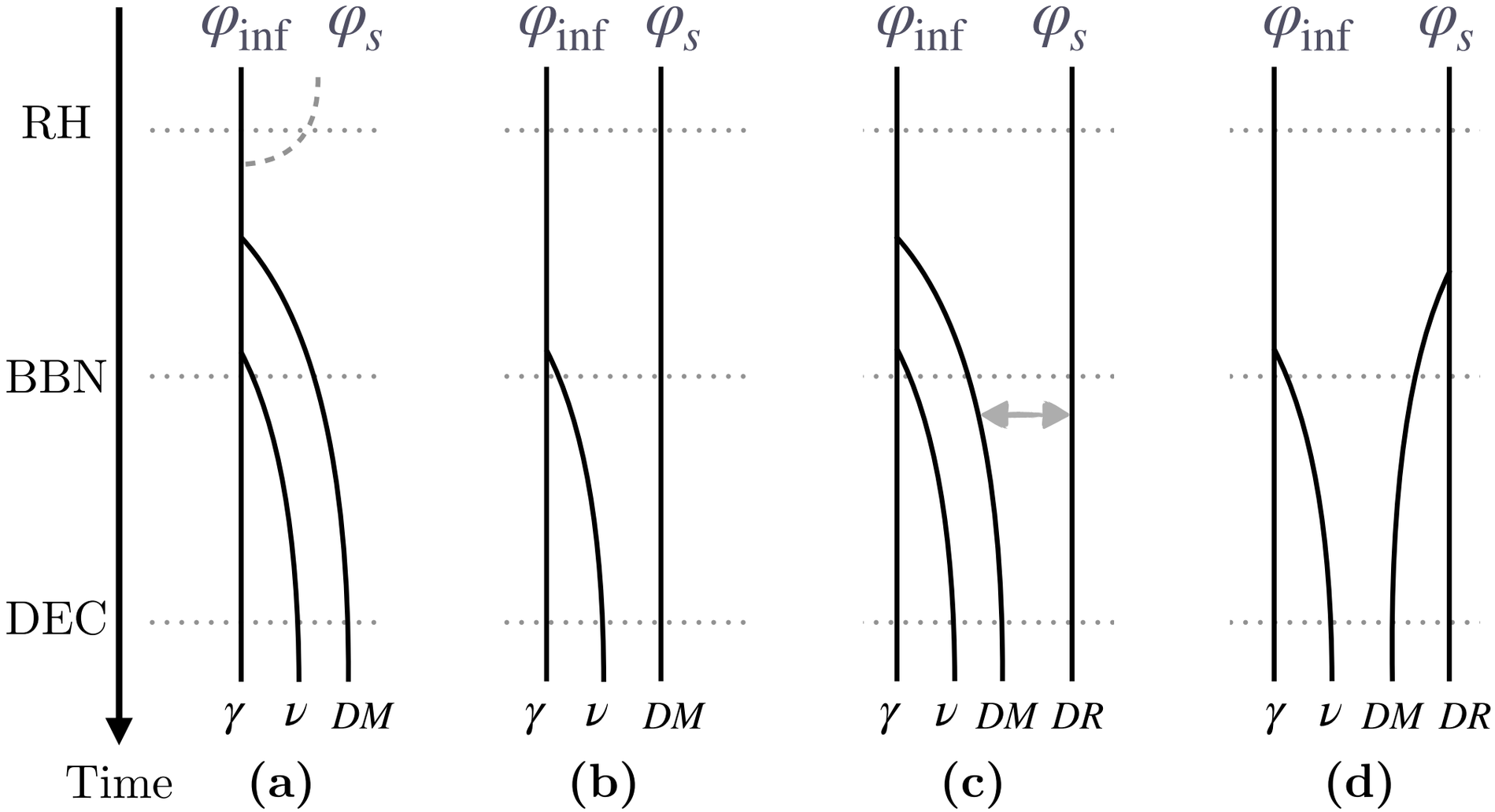
$$\rho_{\nu_{\rm eff}} = \rho_\nu + \rho_{\rm DR}$$

$$S_{\gamma\nu_{\rm eff}} = \frac{\rho_{\rm DR}}{\rho_{\nu_{\rm eff}}} S_{\gamma{\rm DR}}$$

$$S_{\gamma DM} = 0 \ \ (?)$$

Gerlach, Ratzinger & PS, 2504.17047

How to get all isocurvatures :)



Finally: DM and DR from φ_s: $S_{\gamma\nu_{\rm eff}} \neq 0\,, \quad S_{\gamma DM} \neq 0$

Gerlach, Ratzinger & PS, 2504.17047

General expectation:

Both DM and neutrino isocurvature (relative to the photons) are present

Ratio of the two depends on cosmological model

Simplest parameterisation:

mixing angle $$\tan(\varphi) = \frac{S_{\gamma\nu}}{S_{\gamma\mathrm{DM}}}$$

Ok it is never that easy. In a fit, need also:

$$f^2_{\mathrm{iso}} = \frac{\langle S^2_{\gamma\nu}\rangle + \langle S^2_{\gamma\mathrm{DM}}\rangle}{\langle \zeta^2_{\mathrm{tot}}\rangle} \qquad c_{\zeta S} = \frac{\langle S_{\gamma\mathrm{DM}}\zeta_{\mathrm{tot}}\rangle}{\sqrt{\langle S^2_{\gamma\mathrm{DM}}\rangle\langle \zeta^2_{\mathrm{tot}}\rangle}} \qquad n_{\mathrm{iso}} = 1$$

Gerlach, Ratzinger & PS, 2504.17047

What Planck fits

DM isocurvature

"Neutrino" isocurvature

Model and data	Δn	$100\beta_{\rm iso}$ at $k_{\rm low}$	$k_{\rm mid}$	$k_{\rm high}$	$100\cos\Delta$	$100\alpha_{\rm non-adi}$	$\Delta\chi^2$	$\ln B$
General models (*three* isocurvature parameters):								
CDI *Planck* TT,TE,EE+lowE+lensing	3	2.5	[1 : 26]	47	[−12 : 15]	[−0.25 : 1.31]	−2.8	−12.8
CDI CamSpec TT,TE,EE+lowE+lensing	3	3.0	19	33	[−16 : 18]	[−0.38 : 1.54]	−0.9	−14.1
CDI *Planck* TT,TE,EE+lowP+lensing	3	2.2	[1 : 27]	50	[−11 : 16]	[−0.16 : 1.36]		
CDI WMAP-9	3	20.1	[2 : 50]	66	[−38 : 34]	[−1.79 : 6.46]	−0.2	−9.6
NDI *Planck* 2015 TT+lowP+lensing	3	15.8	[2 : 24]	[2 : 29]	[−32 : 0]	[−4.04 : 1.37]	−2.8	
NDI *Planck* TT+lowE+lensing	3	15.3	17	21	[−36 : 4]	[−4.20 : 1.53]	−1.9	−10.8
NDI *Planck* TT,TE,EE+lowE+lensing	3	7.4	[3 : 17]	[2 : 23]	[−13 : 8]	[−0.76 : 1.74]	−5.3	−10.9

[Planck Collaboration 1807.06211]

In our notation

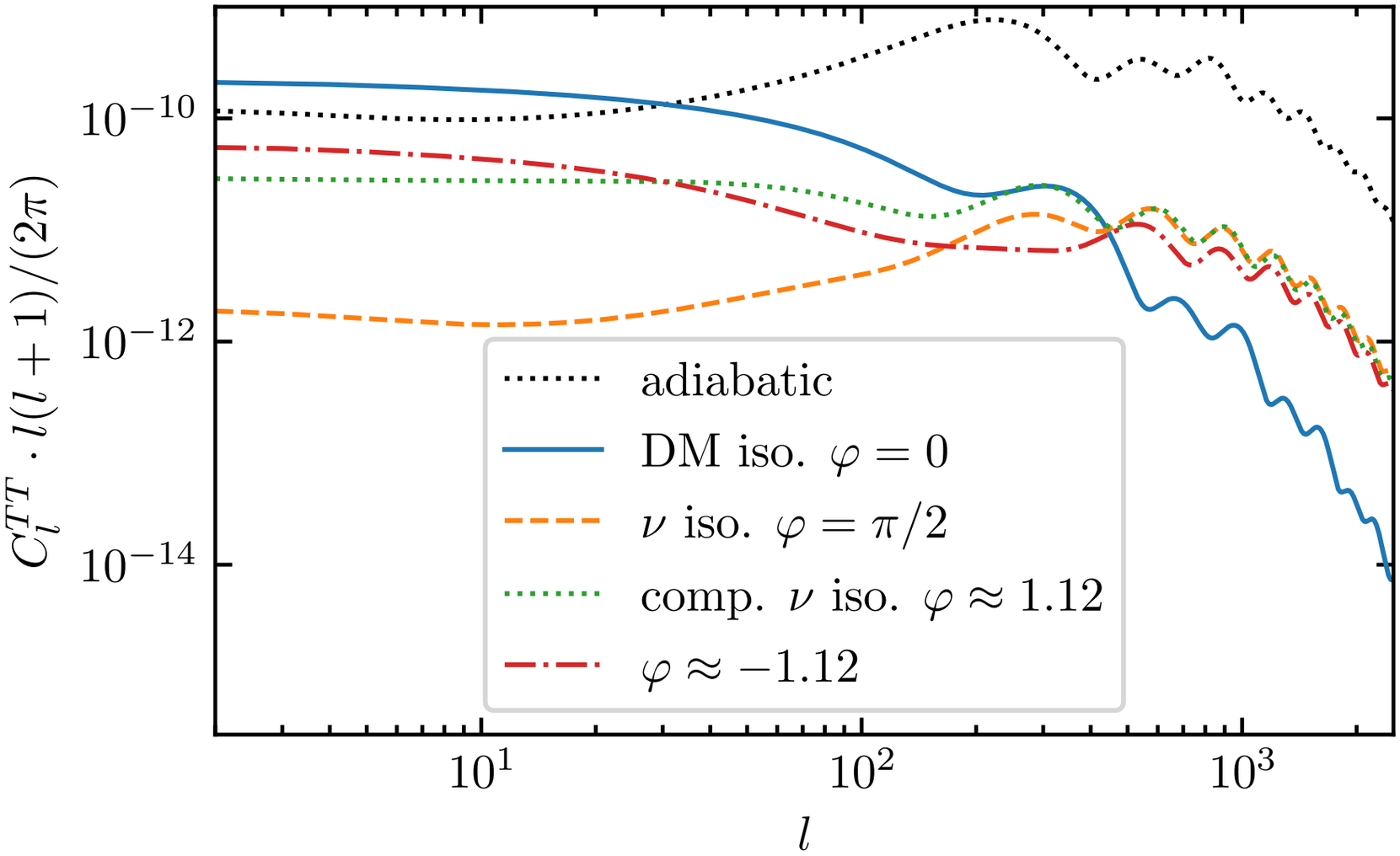
DM isocurvature: $\phi = 0$

Neutrino isocurvature (NDI): $\phi \approx 1.12$???

(this has $\delta\rho_\gamma + \delta\rho_\nu = 0$)

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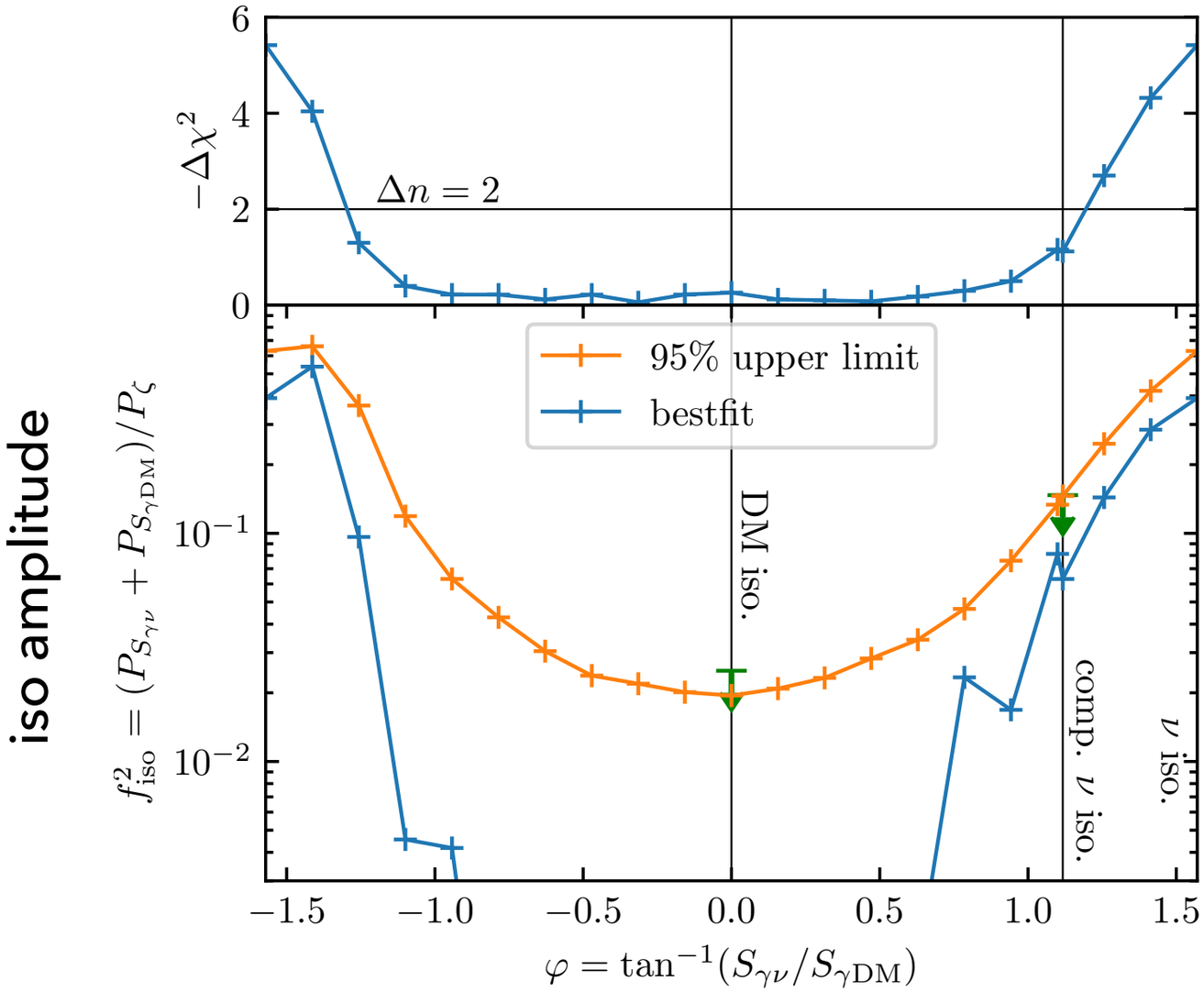
Can the CMB distinguish this?



Yes :)

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Limits on generalised neutrino isocurvature from CMB & LSS[2,3]



Green arrows:
Planck limits

[2][Brinckmann, Lesgourgues 1804.07261]

[3][Audren et al. 1210.7183]

mixing angle ⟵ fixed for each fit

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DM production and matter isocurvature

DM production with DR isocurvature

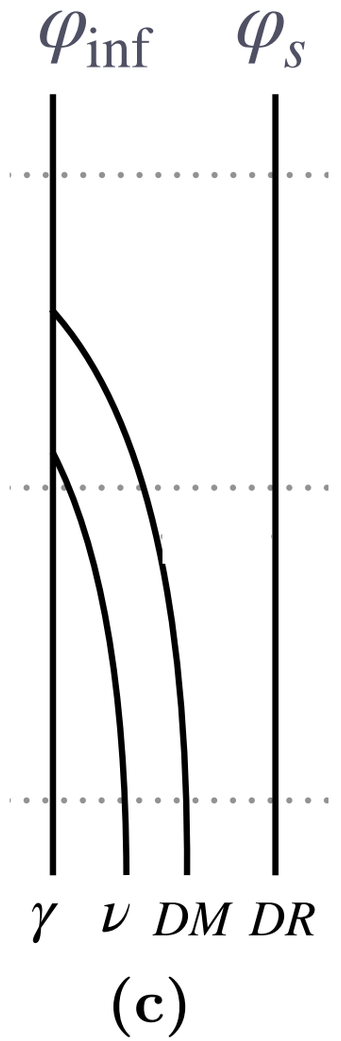
Assumptions:

- DR with isocurvature
- DM produced from SM (photon) bath

Initially:

- $S_{\gamma \mathrm{DM}} = 0$

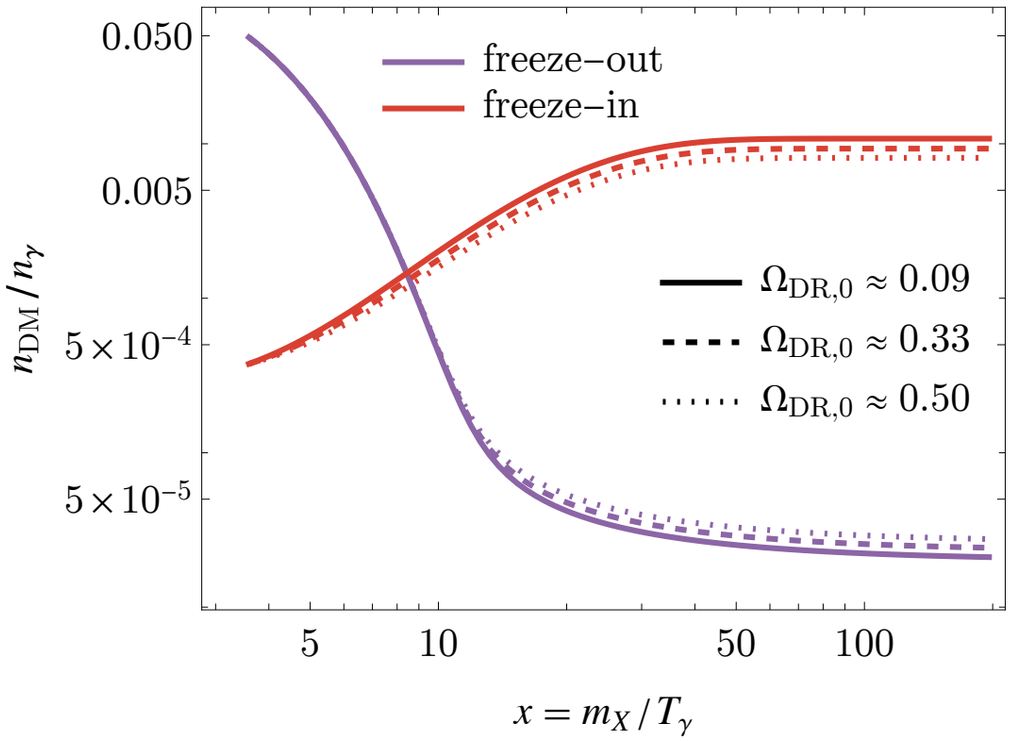
But freeze-in/freeze out is sensitive to local Hubble rate, which depends on the density fluctuations in dark radiation



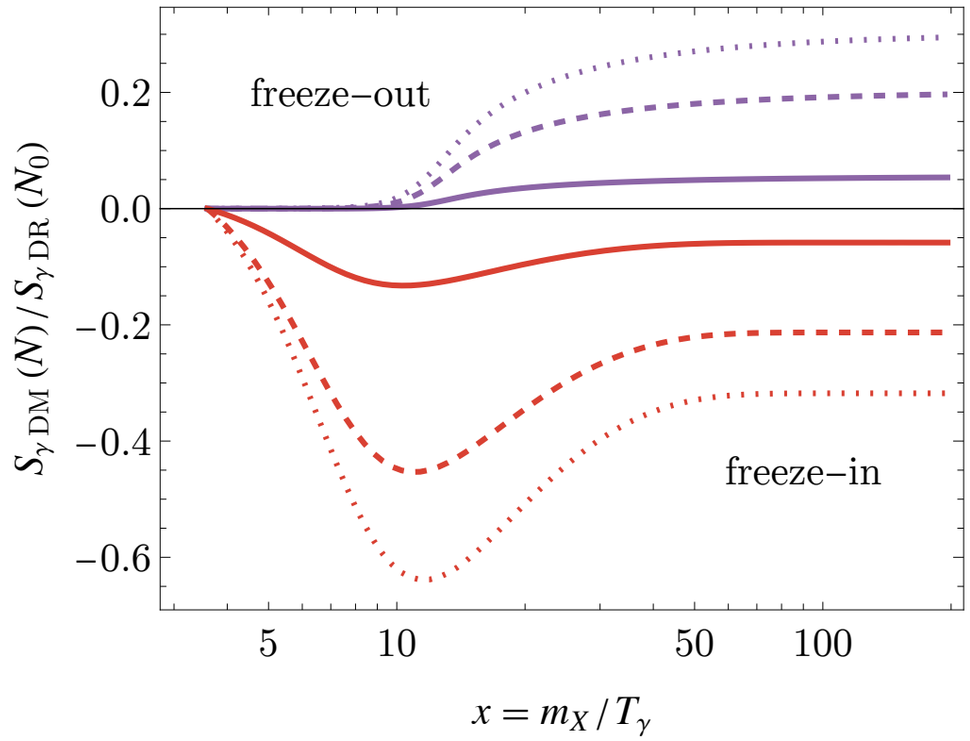
(c)

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DM production with DR isocurvature



(a) Yield of dark matter component.



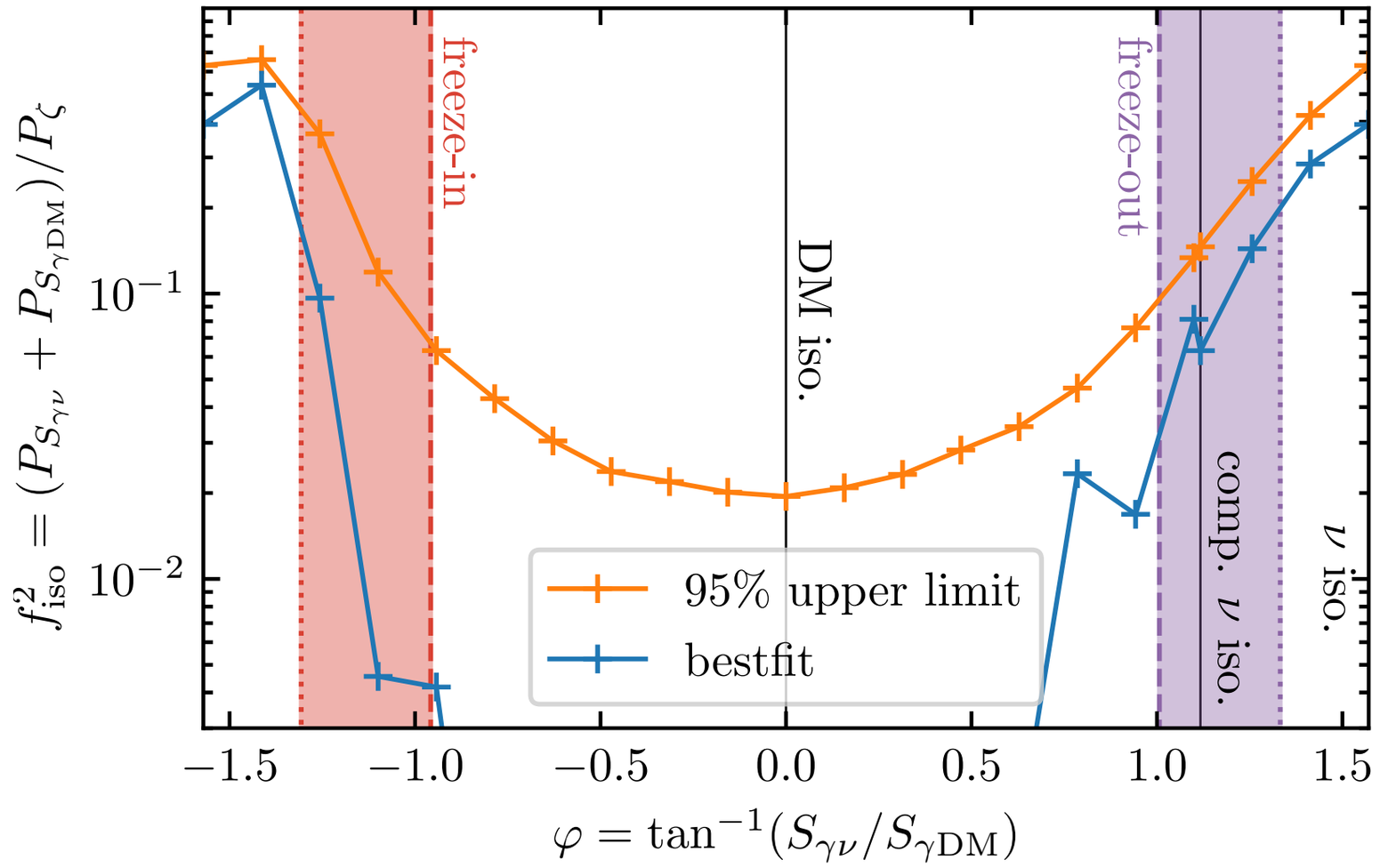
(b) Curvature perturbation evolution.

Non-zero $S_{\gamma\nu}$ generates non-zero $S_{\gamma\rm DM}$, even without direct interactions

Relative sign depends on DM production mechanism!

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Predictions for freeze-in/out

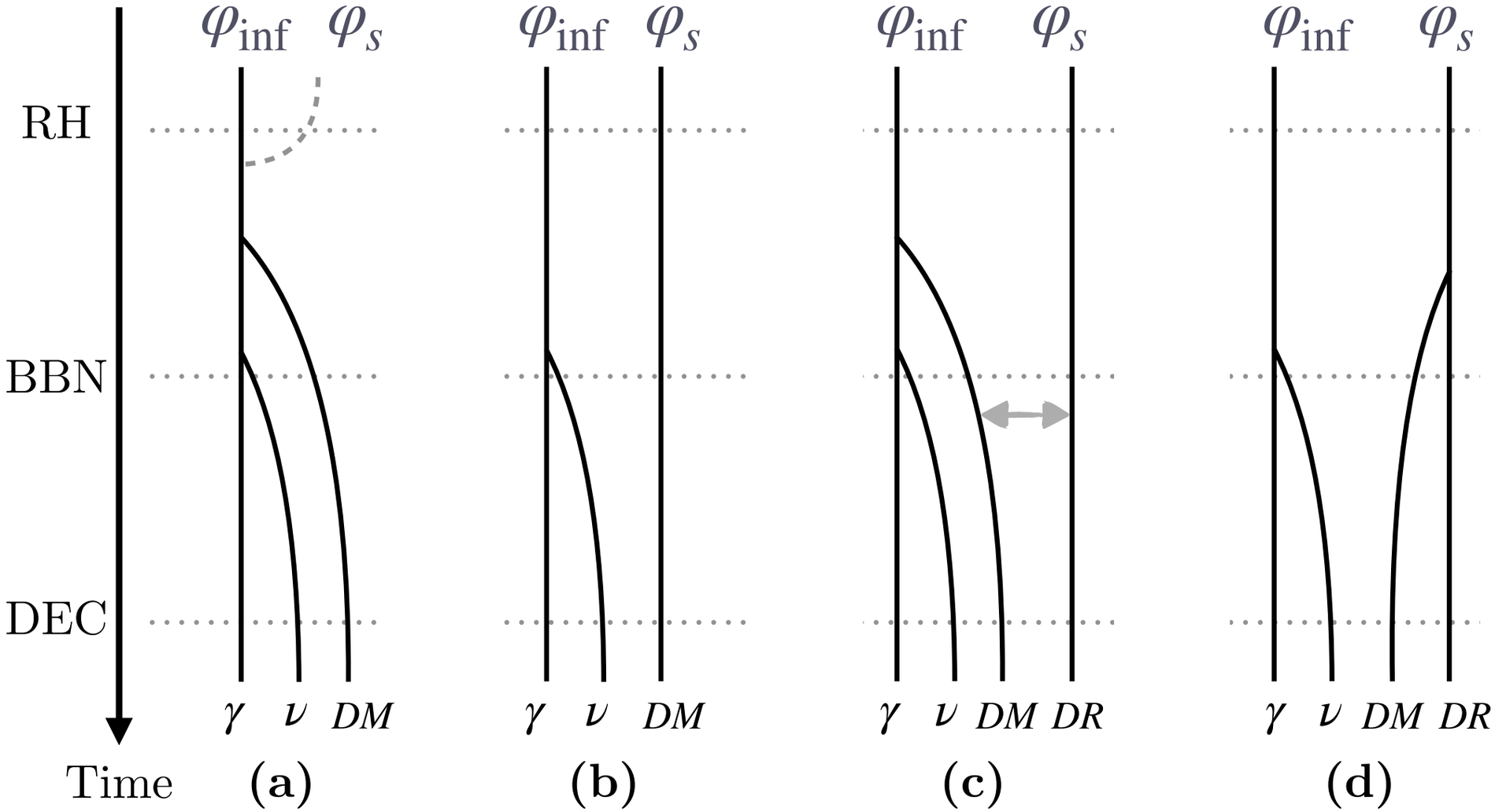


Almost model independent:

$$S^{\rm FI}_{\gamma\rm DM} = -\,0.67\Omega_{\rm DR}S_{\gamma\rm DR} \qquad S^{\rm FO}_{\gamma\rm DM} \approx 0.55\Omega_{\rm DR}S_{\gamma\rm DR}$$

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How about that last case?

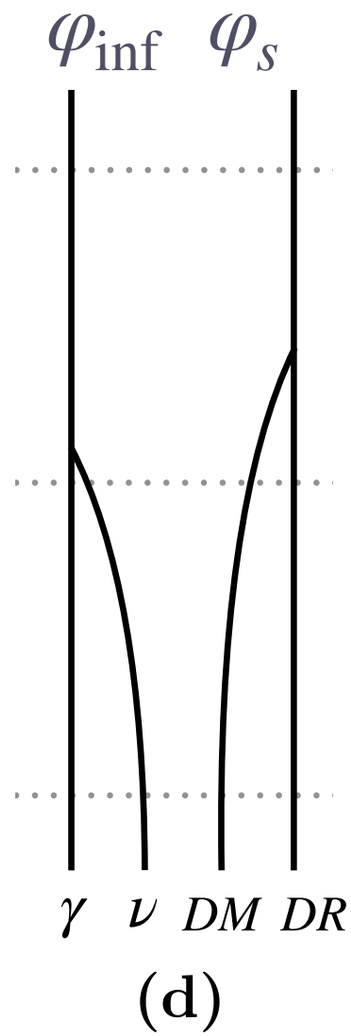


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Dark matter from dark radiation

Considered 3 simple models

	Model 1	**Model 2**	**Model 3**
Dark Matter	Scalar	Dirac fermion	Dirac fermion
Mediator	Scalar	Scalar	Pseudoscalar
Coupling	[GeV]	Dimensionless	Dimensionless
Cross section	s- + p-wave	p-wave	p-wave
Degrees of Freedom	2	4.5	4.5



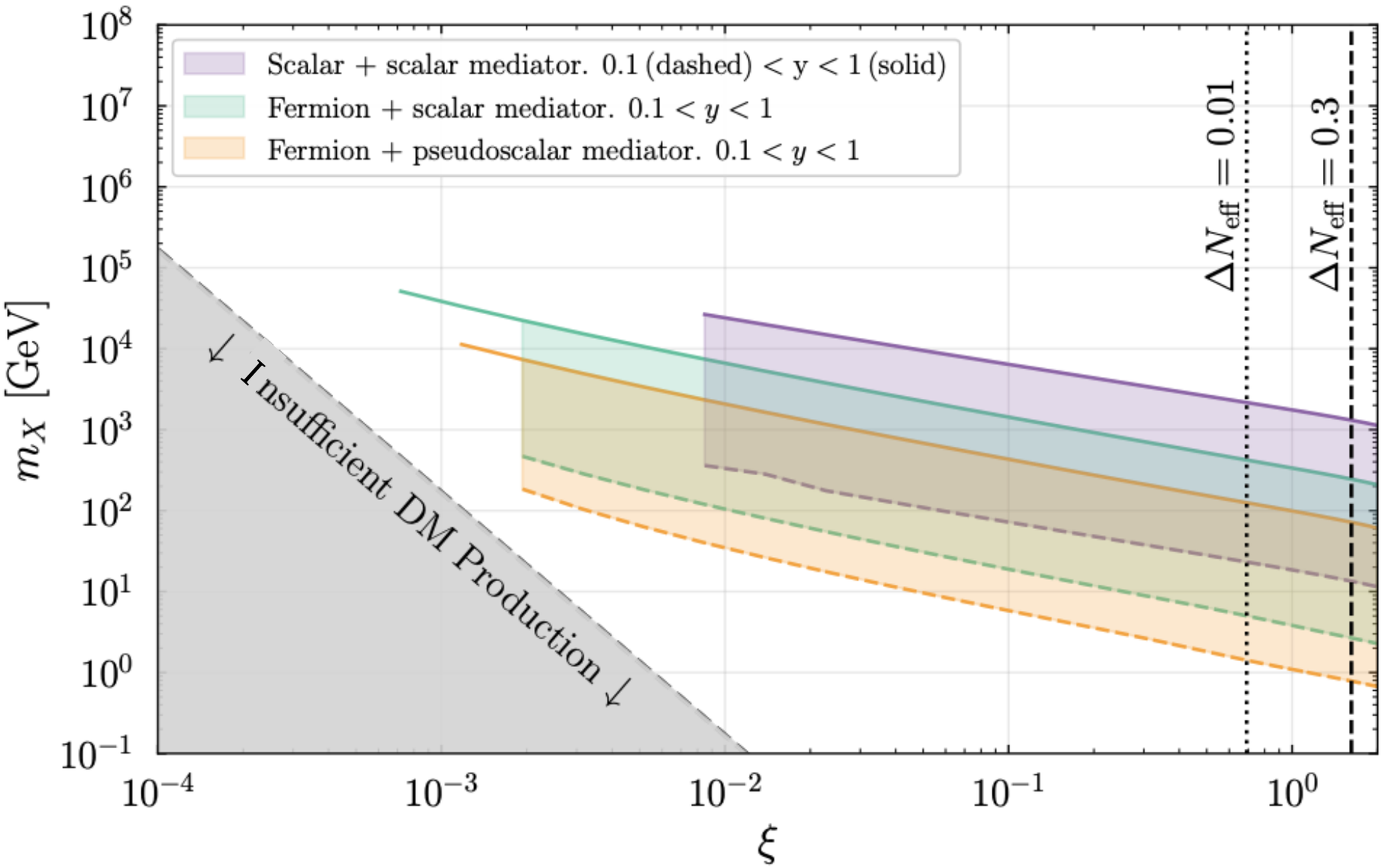
(d)

Parameters:

$$m_{\mathrm{DM}} \qquad y \qquad \xi = \frac{T_{\mathrm{DR}}}{T_{\mathrm{SM}}} \leftrightarrow \Delta N_{\mathrm{eff}}$$

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Dark matter from dark radiation



Gerlach, Saul, PS, in preparation

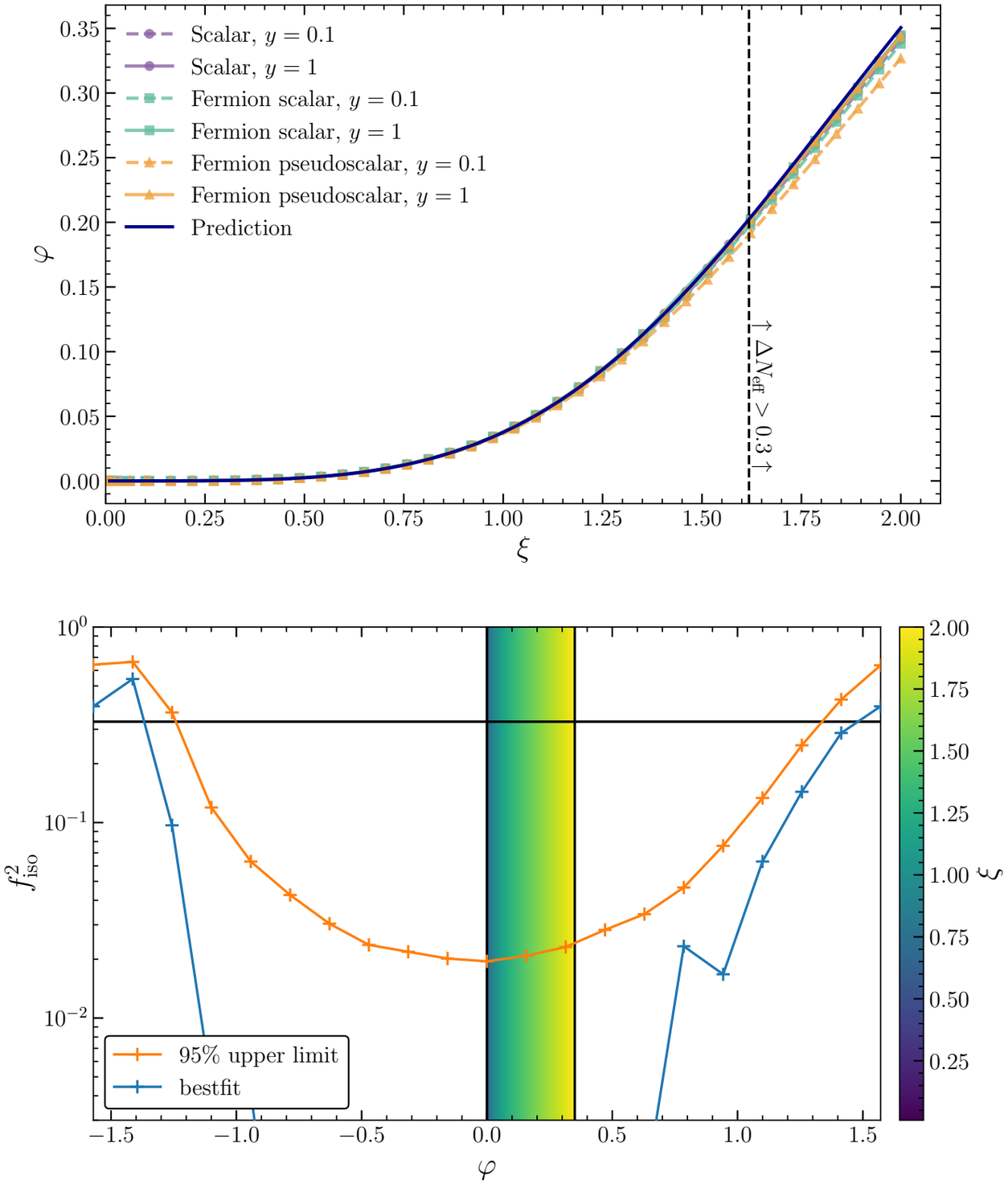
Dark matter from dark radiation

How to probe?
Isocurvature!

Freeze-out suppresses DM isocurvature

DR isocurvature unsuppressed, but weighted by $\Delta N_{\rm eff}$

Distinct from SM freeze-in/out



Summary

There is probably a dark sector,
we should find out what is inside

If everything fails, need to rely on gravity!

Today:

- Neutrino (dark radiation) isocurvature can probe realistic inflationary scenarios
- Isocurvature is sensitive to DM production mechanism
- Could probe DM production from dark radiation

Extra slides

Superhorizon evolution of perturbations: Some fun for the enthusiasts

Fluctuations at CMB scales are far outside the horizon at early times (e.g. during DM production)

Each patch evolves independently

- Separate universe approach

Consider evolution of energy densities $\boldsymbol{\rho} = (\rho_1, \rho_2, \dots)$

EOM: $$\dot{\boldsymbol{\rho}} = \boldsymbol{F}(\boldsymbol{\rho})$$

Example: Single fluid

$$F(\rho) = -3(1+\omega)H\rho \quad \text{with} \quad H^2 = \rho/(3M_{\rm Pl}^2)$$

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Superhorizon evolution of perturbations: Some fun for the enthusiasts

EOM: $$\dot{\boldsymbol{\rho}} = \boldsymbol{F}(\boldsymbol{\rho})$$

Autonomous equation! No explicit time dependence!

All possible values of $\boldsymbol{\rho}$ form phase space

- Solutions for given $\boldsymbol{\rho}_0(t_0)$ are trajectories in phase space:

$$\boldsymbol{\rho}(t) = \boldsymbol{\rho}(\boldsymbol{\rho}_0, t - t_0)$$

Now consider a patch with perturbed initial conditions: $\boldsymbol{\rho}_0 + \delta\boldsymbol{\rho}_0$. Solution becomes

$$\boldsymbol{\rho}(t) + \delta\boldsymbol{\rho}(t) = \boldsymbol{\rho}(\boldsymbol{\rho}_0 + \delta\boldsymbol{\rho}_0, t - t_0)$$

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Superhorizon evolution of perturbations: Some fun for the enthusiasts

Expand $\boldsymbol{\rho}(t) + \delta\boldsymbol{\rho}(t) = \boldsymbol{\rho}(\boldsymbol{\rho}_0 + \delta\boldsymbol{\rho}_0, t - t_0)$:

$$\delta\rho_\alpha(t) = \sum_\beta \frac{\partial\rho_\alpha(t)}{\partial\rho_{0,\beta}}\delta\rho_{0,\beta}$$

Evolution of fluctuations known once the evolution of the homogeneous background is solved!

- Much easier than solving ODE system for the fluctuations themselves (and you need to solve the background anyways)

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More details

Must include fluctuations of metric, gauge dependence…

$$\zeta_\alpha(t) = \sum_\beta \left[\frac{H(t)}{\dot\rho_\alpha(t)} \frac{\partial \rho_\alpha(t)}{\partial \rho_{0,\beta}} - \frac{\partial N(t)}{\partial \rho_{0,\beta}} \right] \frac{\dot\rho_\beta(t_0)}{H(t_0)} \, \zeta_\beta(t_0)$$

Or, if we choose e-folds N as time variable:

$$\zeta_\alpha(N) = \sum_\beta \frac{1}{\rho'_\alpha(N)} \frac{\partial \rho_\alpha(N)}{\partial \rho_{0,\beta}} \rho'_\beta(N_0) \, \zeta_\beta(N_0)$$

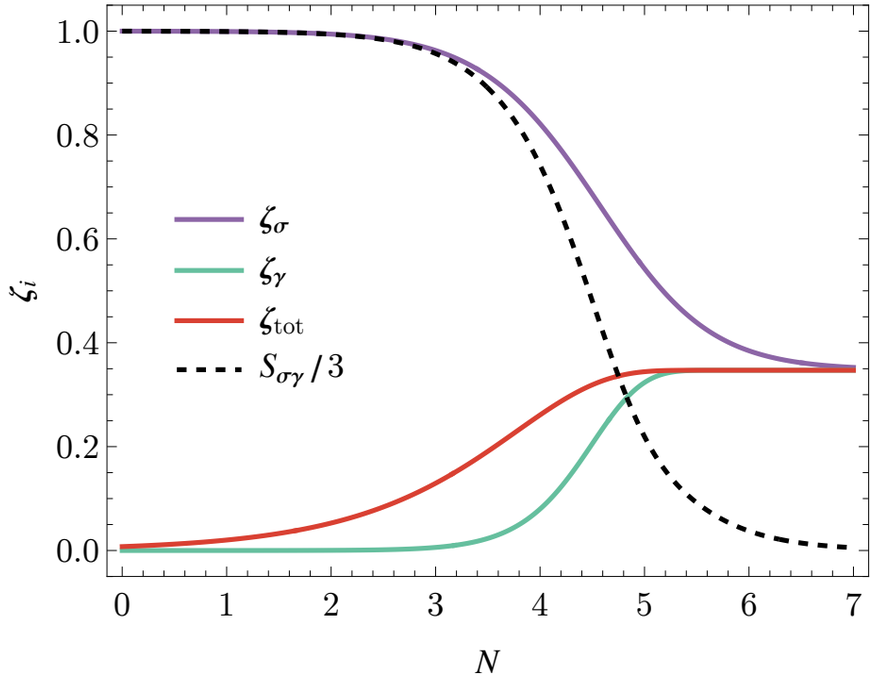
Just solve the usual homogeneous problem (e.g. freeze-out of DM, decay of a curvaton), get evolution of fluctuations for free!

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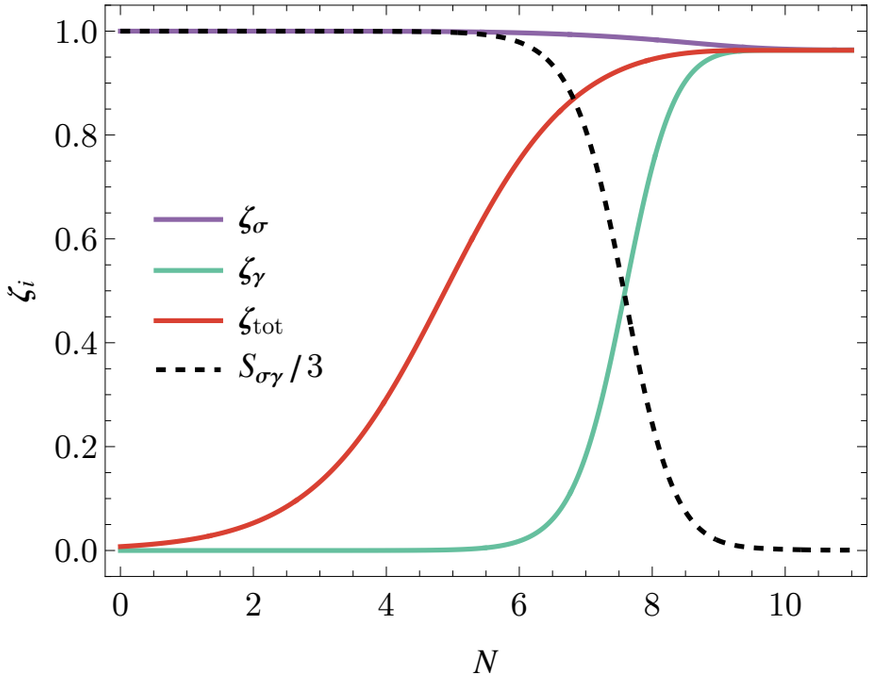
Check: Curvation decay

Background evolution: $$\rho'_\sigma = -(3+\tilde{\Gamma})\rho_\sigma\,,$$
$$\rho'_\gamma = -4\rho_\gamma + \tilde{\Gamma}\rho_\sigma\,,$$

Initial conditions: $\zeta_\gamma(N_0) = 0\,, \quad \zeta_\sigma(N_0) = \zeta_{\sigma,0}$



(a) $\tilde{\Gamma}_0 = 10^{-3}$.



(b) $\tilde{\Gamma}_0 = 10^{-6}$.

Agrees with Malik, Wands, Ungarelli, PRD 2003

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A technical note

Simple expression for of superhorizon fluctuations:

$$\zeta_\alpha(t) = \sum_\beta \left[\frac{H(t)}{\dot\rho_\alpha(t)} \frac{\partial \rho_\alpha(t)}{\partial \rho_{0,\beta}} - \frac{\partial N(t)}{\partial \rho_{0,\beta}} \right] \frac{\dot\rho_\beta(t_0)}{H(t_0)} \, \zeta_\beta(t_0)$$

With e-folds N as time variable:

$$\zeta_\alpha(N) = \sum_\beta \frac{1}{\rho'_\alpha(N)} \frac{\partial \rho_\alpha(N)}{\partial \rho_{0,\beta}} \rho'_\beta(N_0) \, \zeta_\beta(N_0)$$

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