Axing minimal pre-inflationary axion models

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Work in progress

in collaboration with…

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DESY

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DESY

The aim:

We revisit the **cosmological history** of **pre-inflationary axion models** with a **standard inflationary sector**, whose compatibility with **axion isocurvature bounds** requires **axion-inflaton interactions**.

The novelty:

We **discard invalid assumptions** on the dynamics of isocurvature perturbations

Detailed simulations of the evolution of **super-horizon axion isocurvature** modes, including nonperturbative effects with **lattice** computations

The plan:

Motivation of pre-inflationary axion models

The trouble with isocurvature fluctuations

Improved calculations

Motivating pre-inflationary axion models

Why the axion?

QCD admits a CP violating interaction

$$\int d^4x\,\mathcal{L}_\theta = \int d^4x\,\bar{\mathrm{Tr}}\,\frac{g^2\theta}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma} = \theta n_{\mathrm{top}},$$

θ is an angle, and unphysical, yet there is a physical CP - violating phase

$$\theta_{\mathrm{phys}} = \theta + \mathrm{Arg}\ \mathrm{det} M_q$$

Measurements of the neutron's dipole moment imply $|\theta_{\mathrm{phys}}| < 10^{-11}$ [Kim 09]

Can be explained if θ_{phys} becomes a dynamical field -the axion [Peccei & Quinn, Weinberg, Wilczek]

Need a spontaneously broken U(1) with QCD anomaly, the axion A is pseudo-Goldstone:

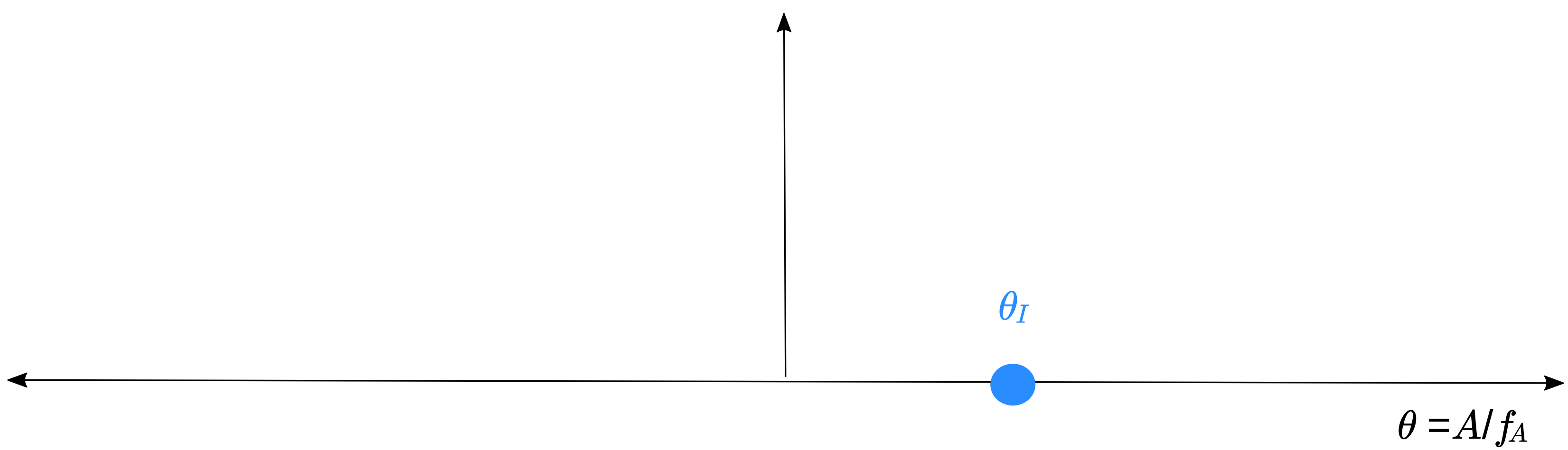
$$\theta_{\mathrm{phys}}(x) = \theta + \frac{A(x)}{f_A} + \mathrm{Arg}\ \mathrm{det} M'_q$$

Nonperturbative QCD effects generate an even potential for θ_{phys}(x), stabilized at 0!

Getting dark matter from the axion

The nonperturbative potential only arises at low temperatures. Axion field can end up oscillating, and the **time-averaged oscillations** interact with gravity like **presureless dark matter**!

[Preskill et all, Abbott and Sikivie, Dine and Fischler]



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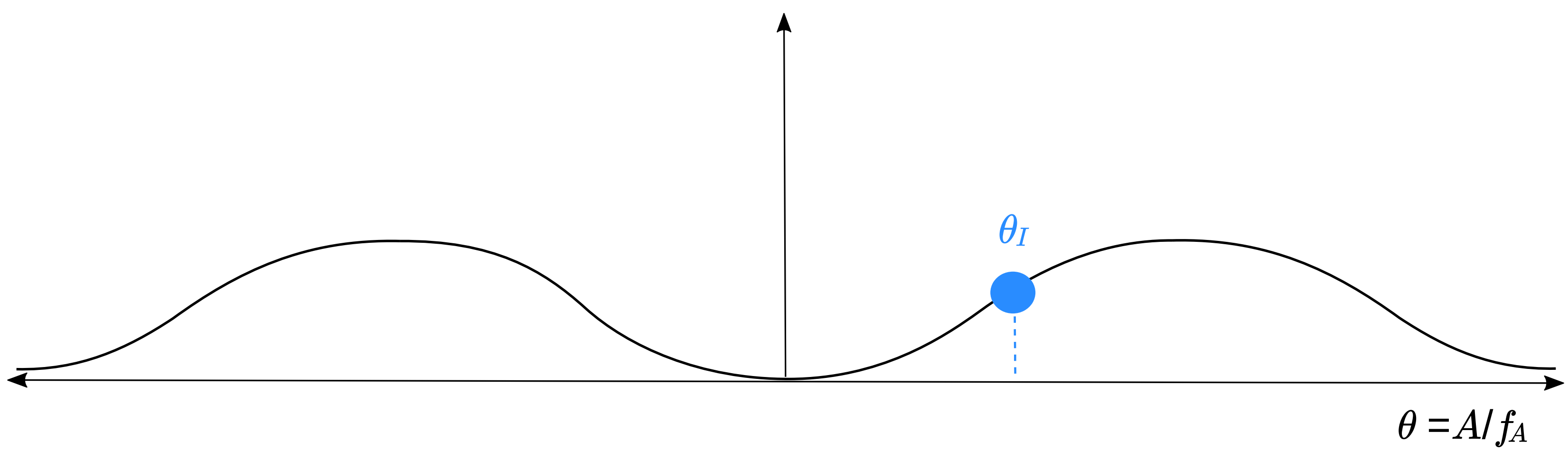

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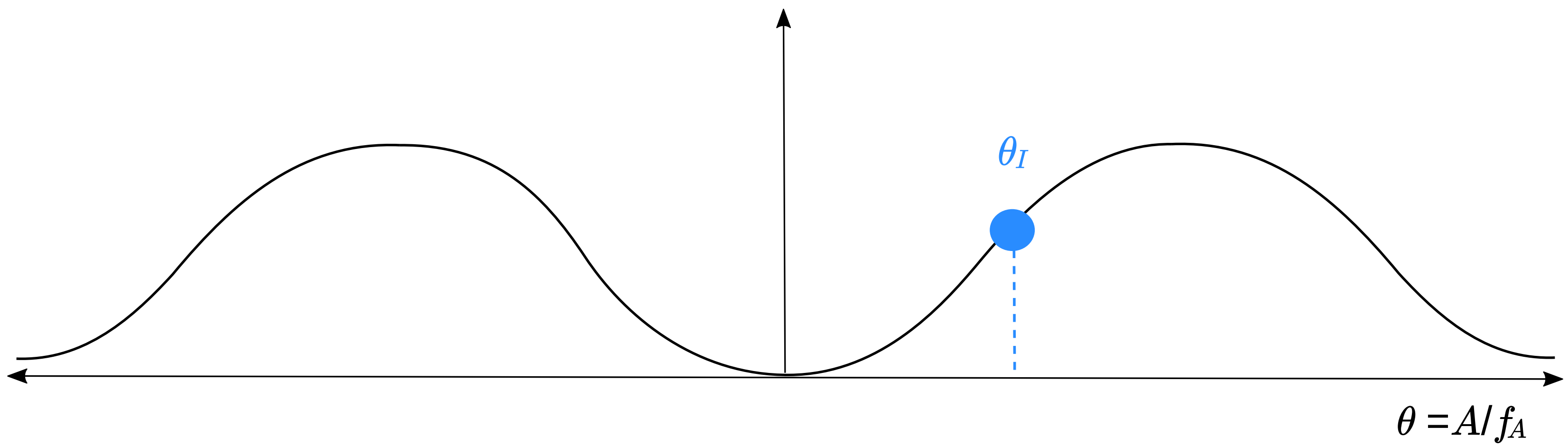

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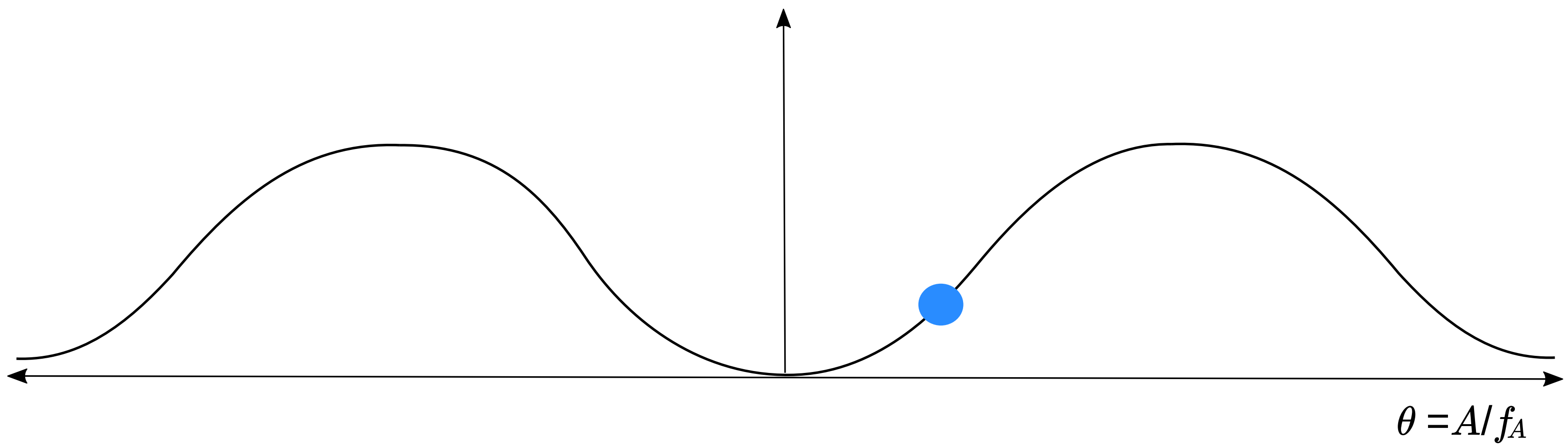

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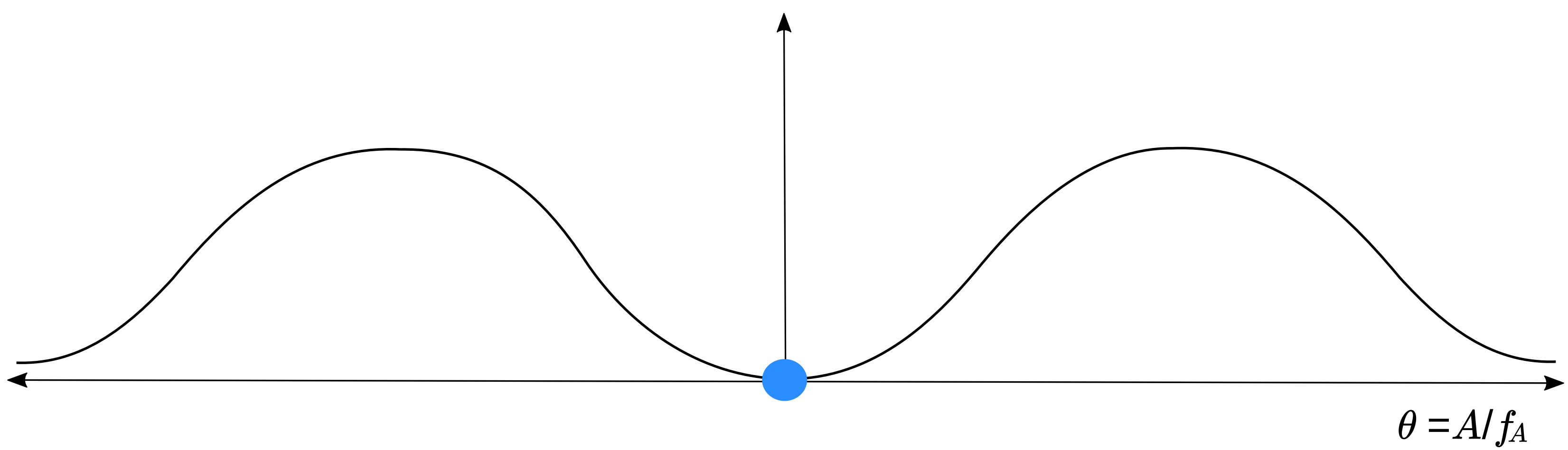

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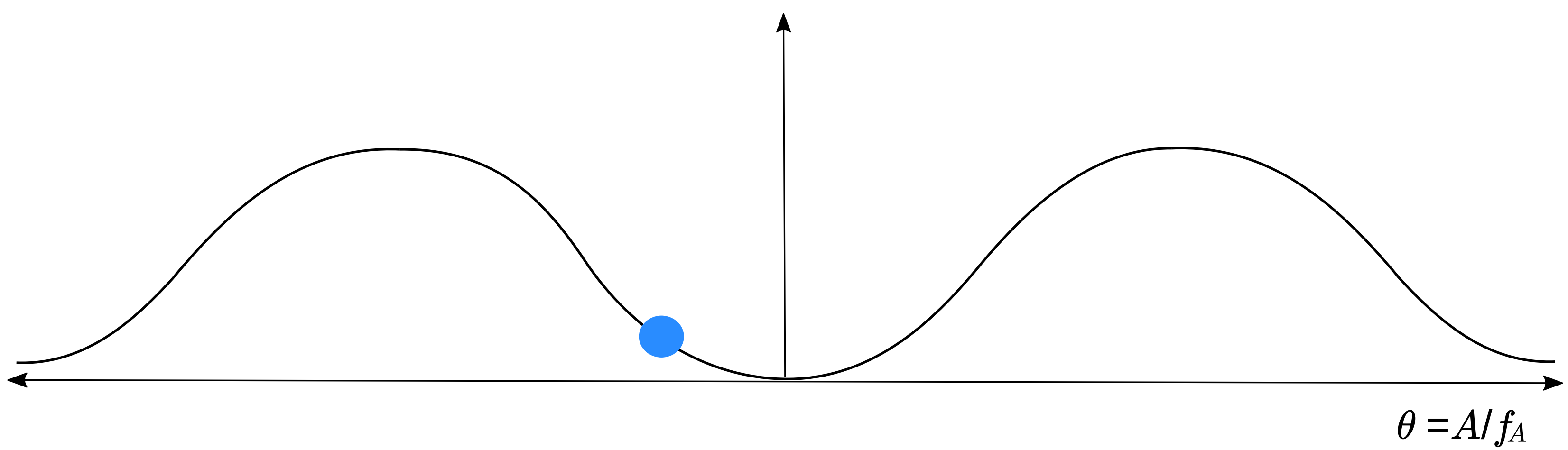

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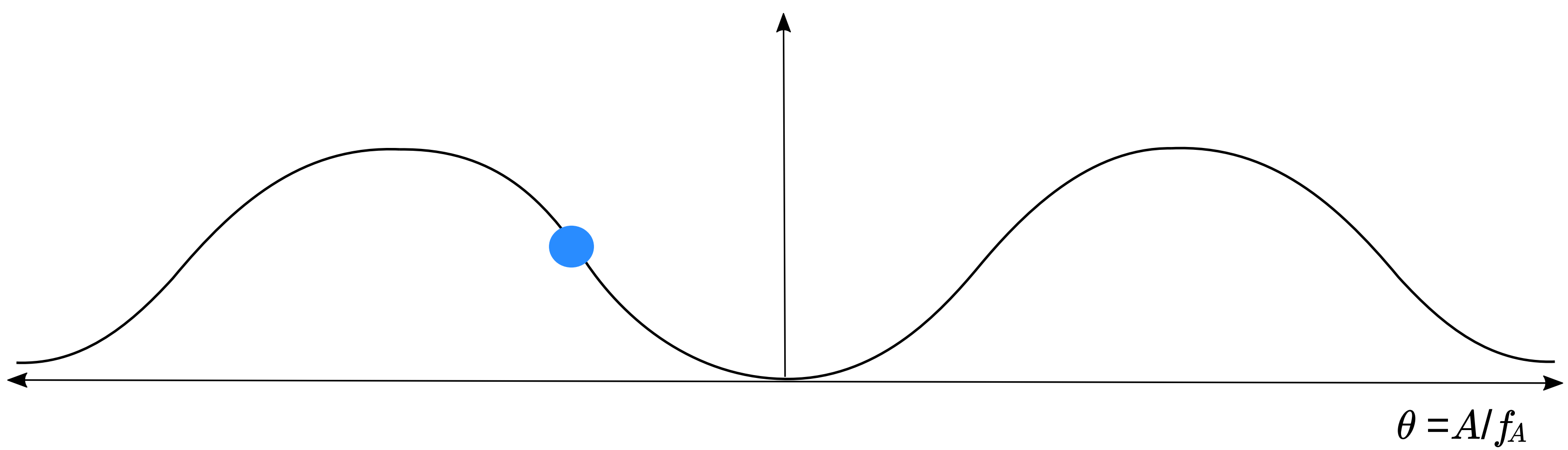

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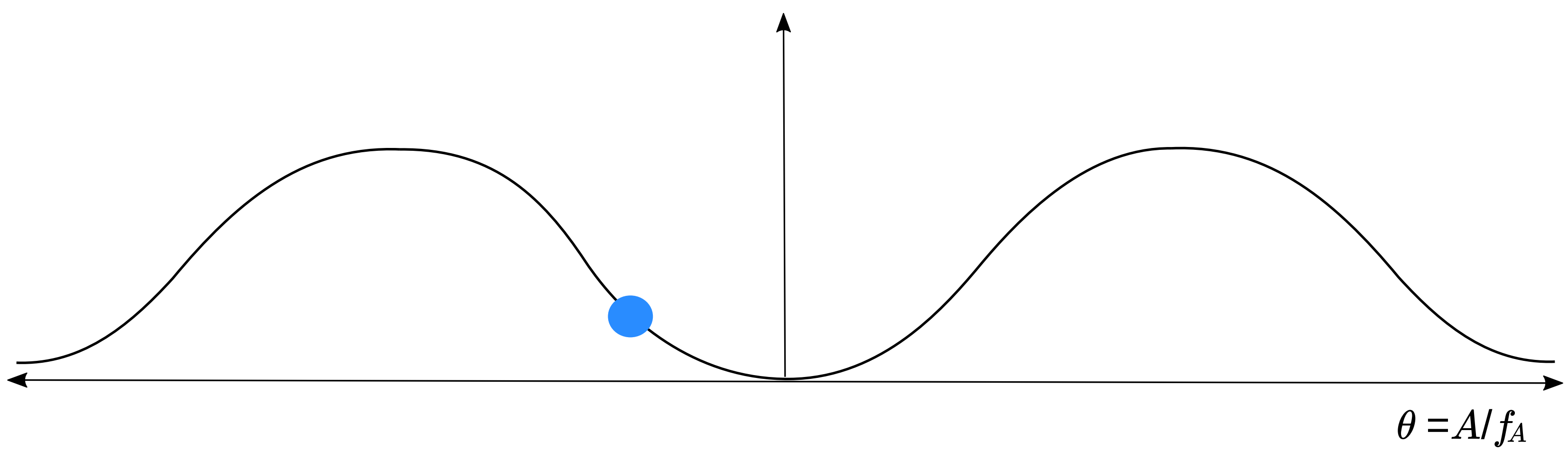
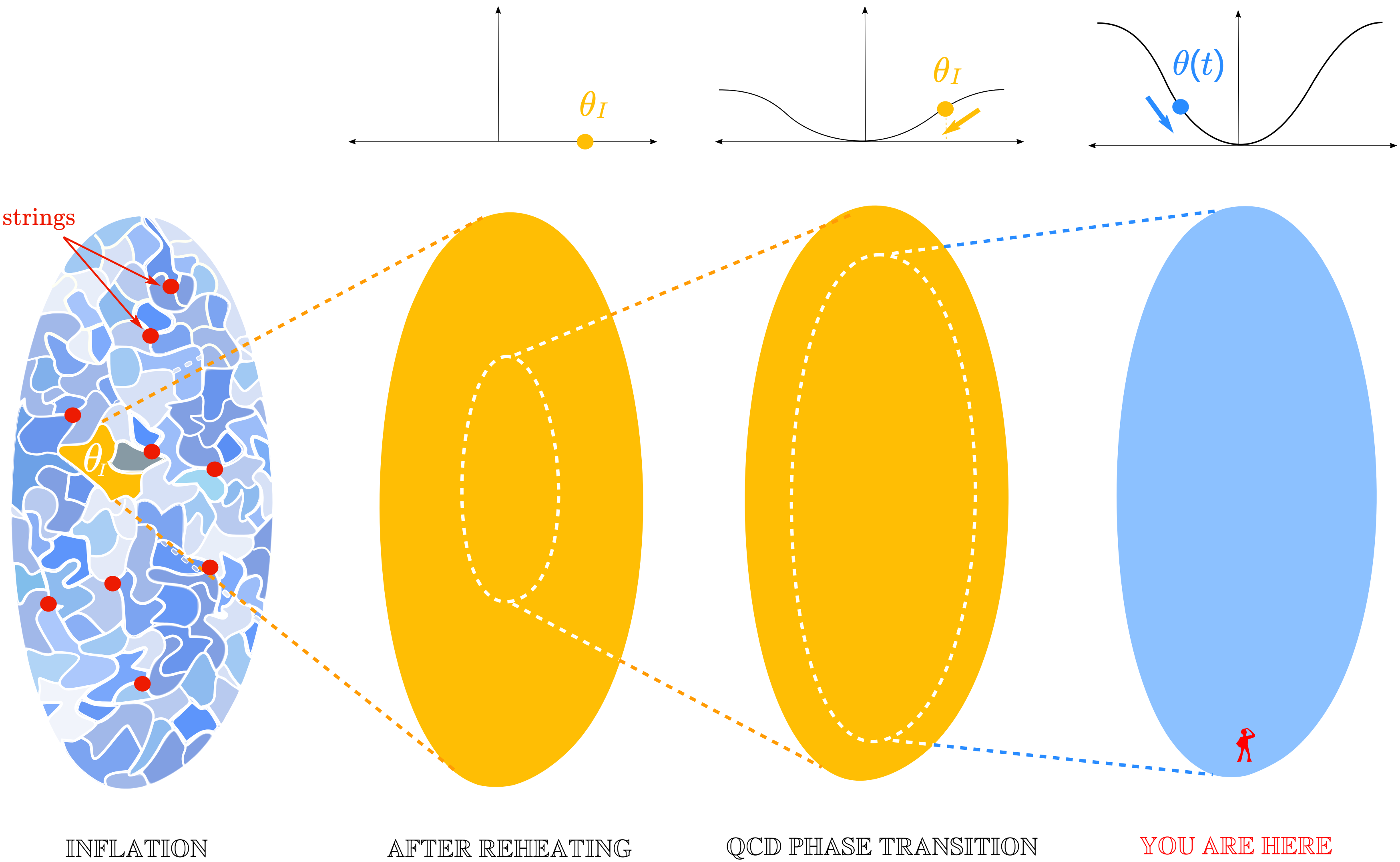


Pre-inflationary scenarios



For illustration purposes only. Resemblance to the actual product might be limited

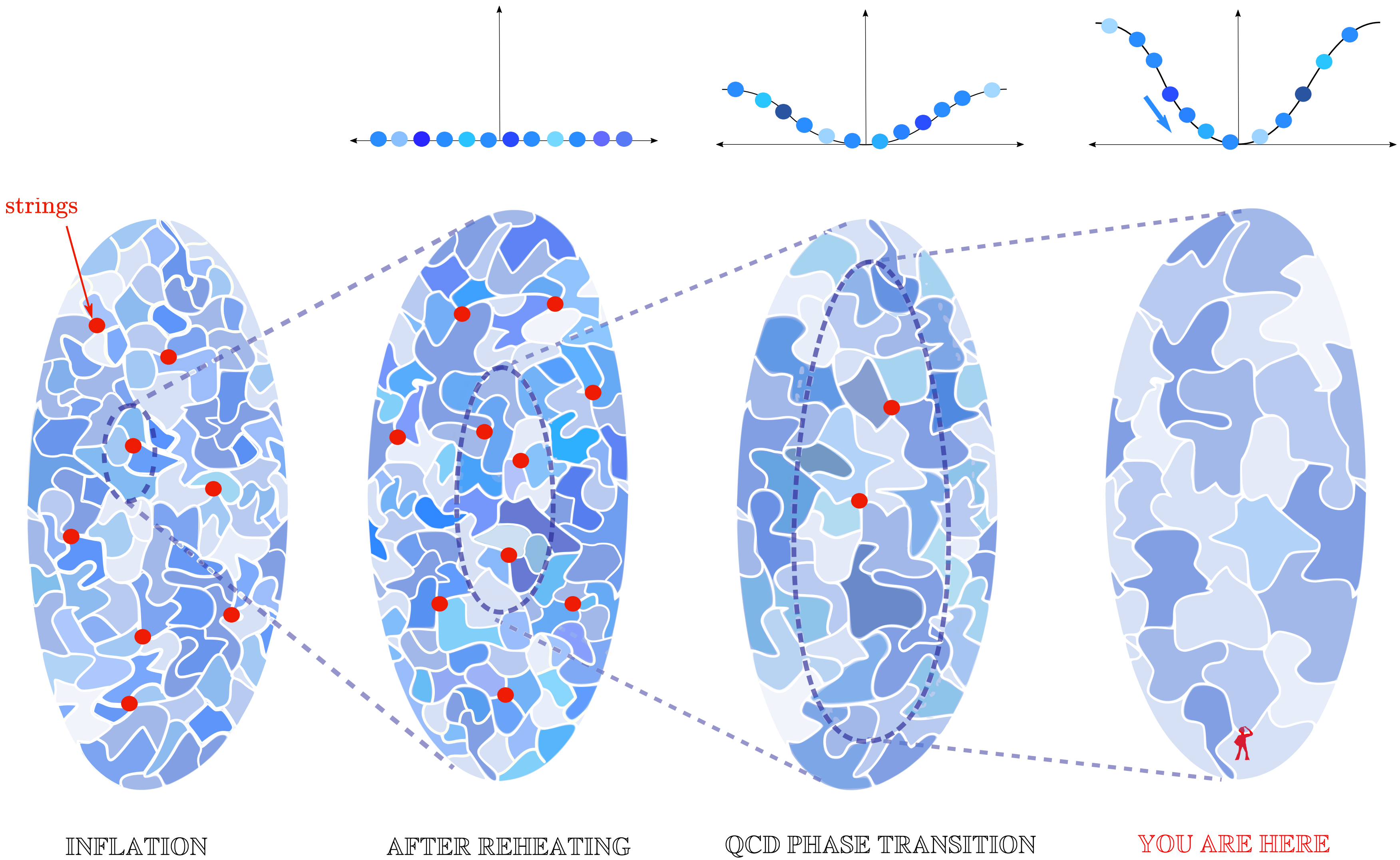
Pre-inflationary axion dark matter

For a given axion mass/f_A the DM abundance depends on the misalignment angle θ_I

$$\theta_I^2 = 3.4 \times 10^{-7} \left(\frac{\Omega_{DM} h^2}{0.12}\right) \left(\frac{f_A}{3 \times 10^{17} \mathrm{GeV}}\right)^{-1.165}$$

[Borsanyi et al]

Post-inflationary scenarios



For illustration purposes only. Resemblance to the actual product might be limited

Post-inflationary axion dark matter

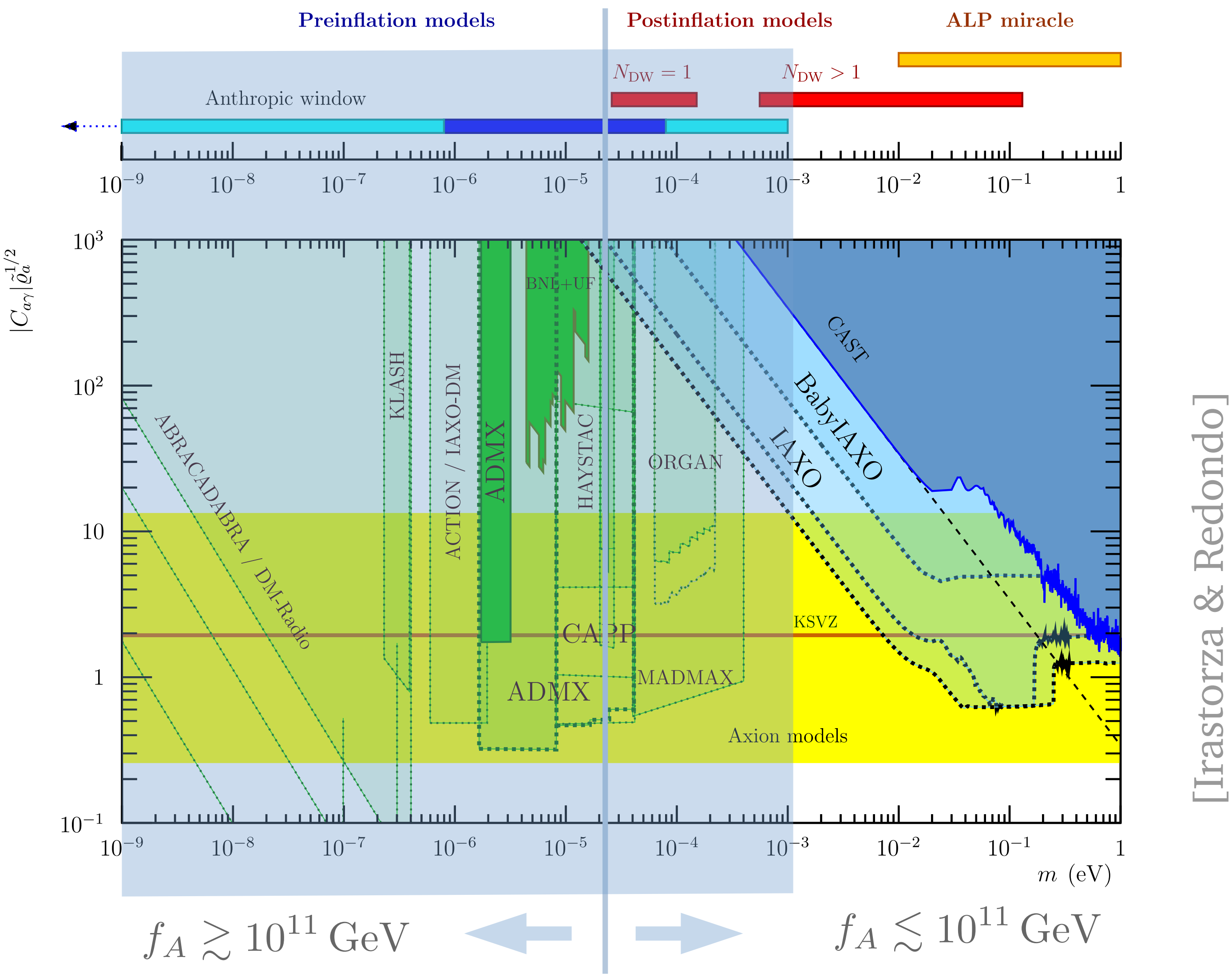
For a given axion mass/f_A the DM abundance is predicted!

$$\boxed{\Omega_A h^2 \approx 0.12 \Rightarrow 3\times 10^{10}\,\mathrm{GeV} \lesssim f_A \lesssim 1.2\times 10^{11}\,\mathrm{GeV} \quad ; \quad 50\,\mu\mathrm{eV} \lesssim m_A \lesssim 200\,\mu\mathrm{eV}}$$

[Borsanyi et al][Redondo et al][Villadoro et al][Hindmarsh et al][Safdi et al][Kawasaki et al]...

(String decay contribution still under debate)

Mass windows and experiments



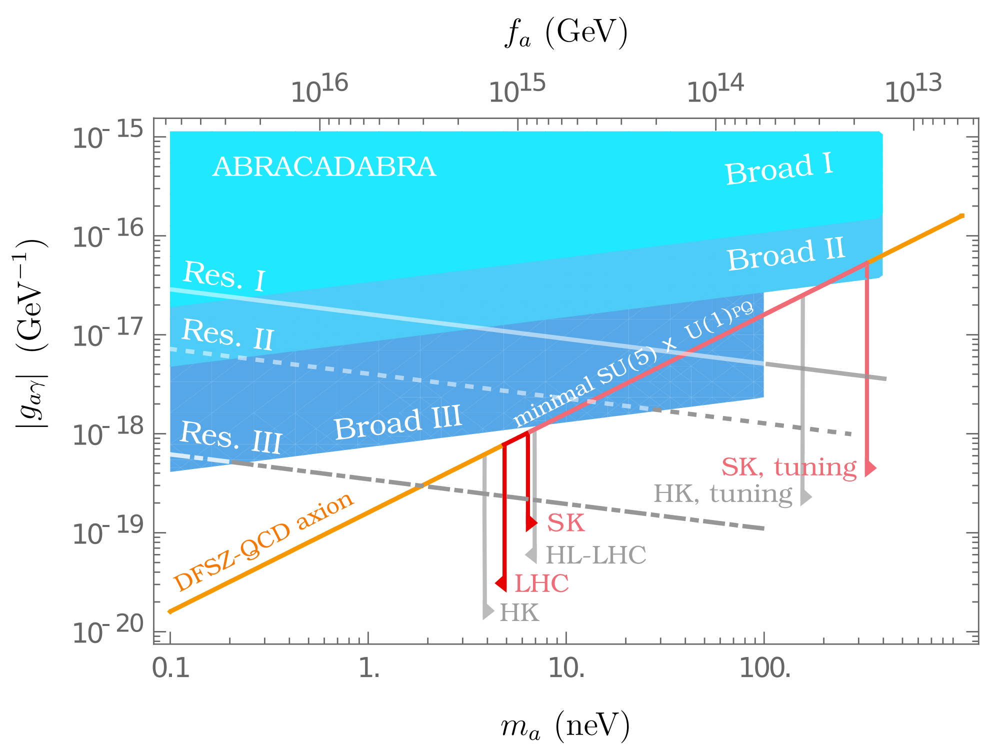
How can one theoretically motivate the large values of f_A in pre-inflationary models?

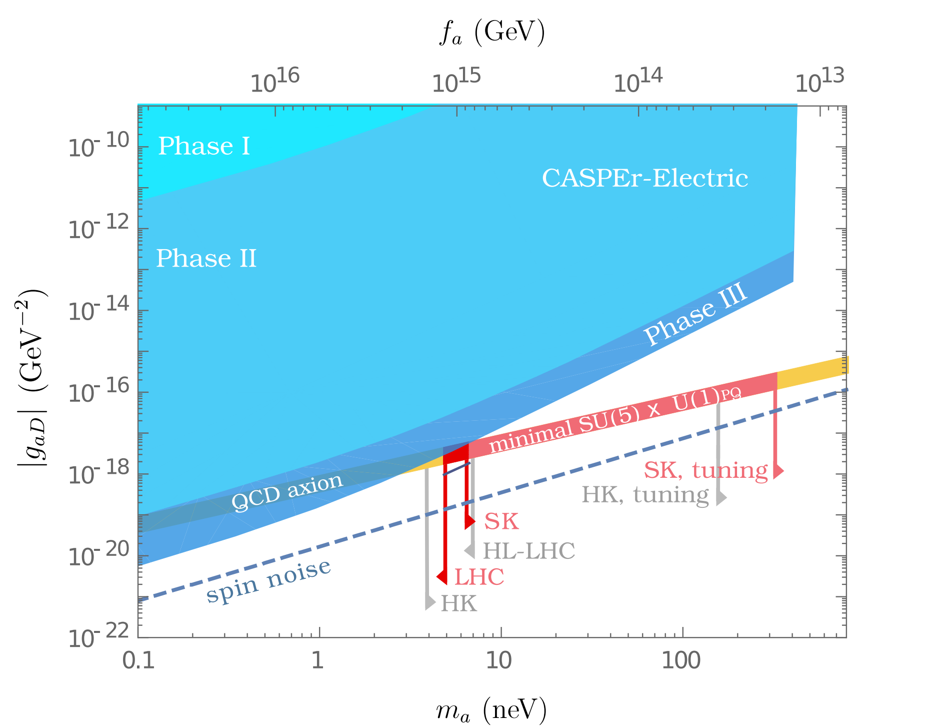
Pre-inflationary models from axion GUTs

Axion GUTs can offer an intriguing **connection** between the **axion scale f_A** and the **grand unification scale**.

This can result in **complementarities** between **axion searches** and **proton decay** experiments.

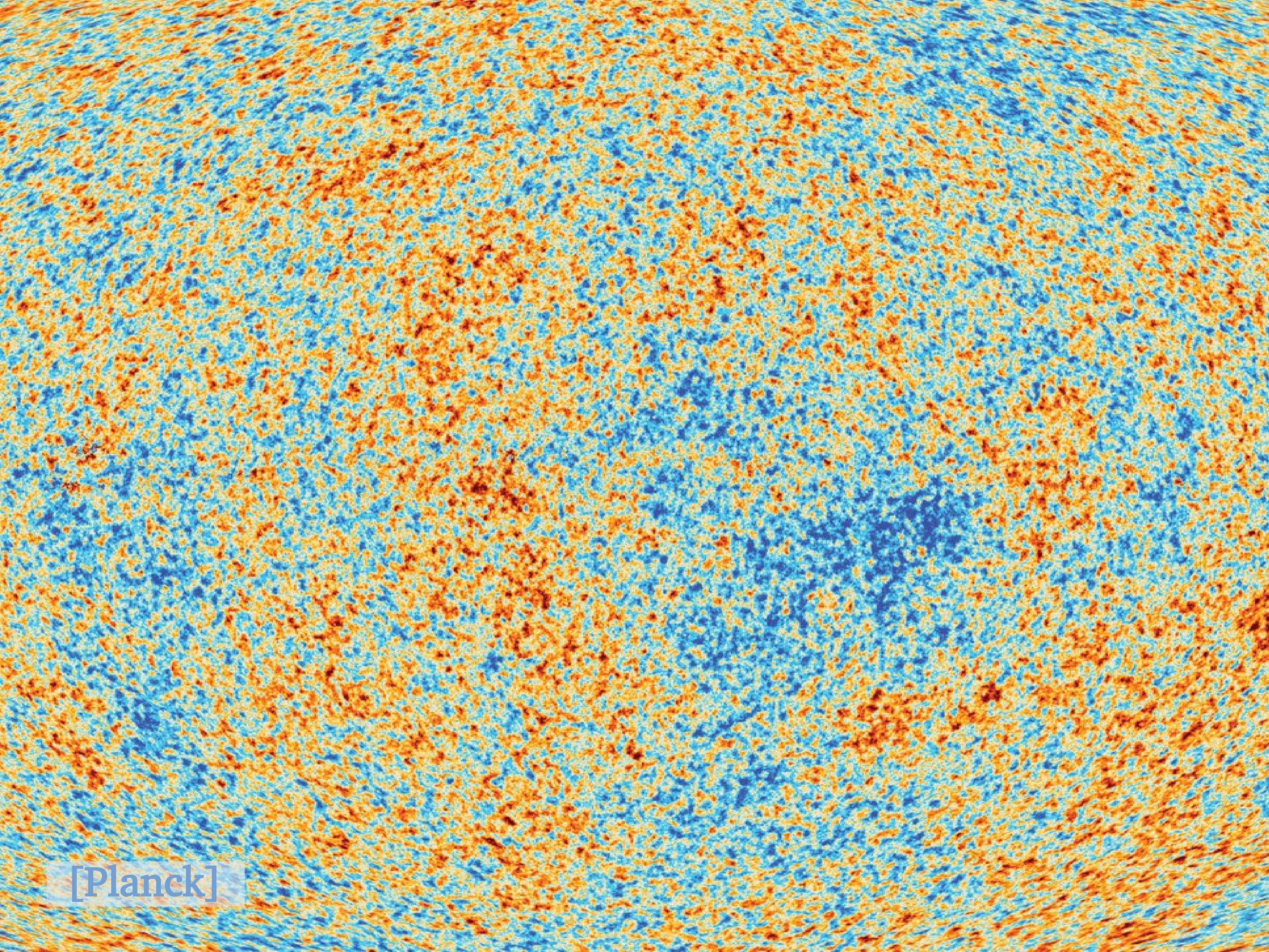
Motivates **targets for low-mass axion experiments** like ABRACADABRA and CASPER.



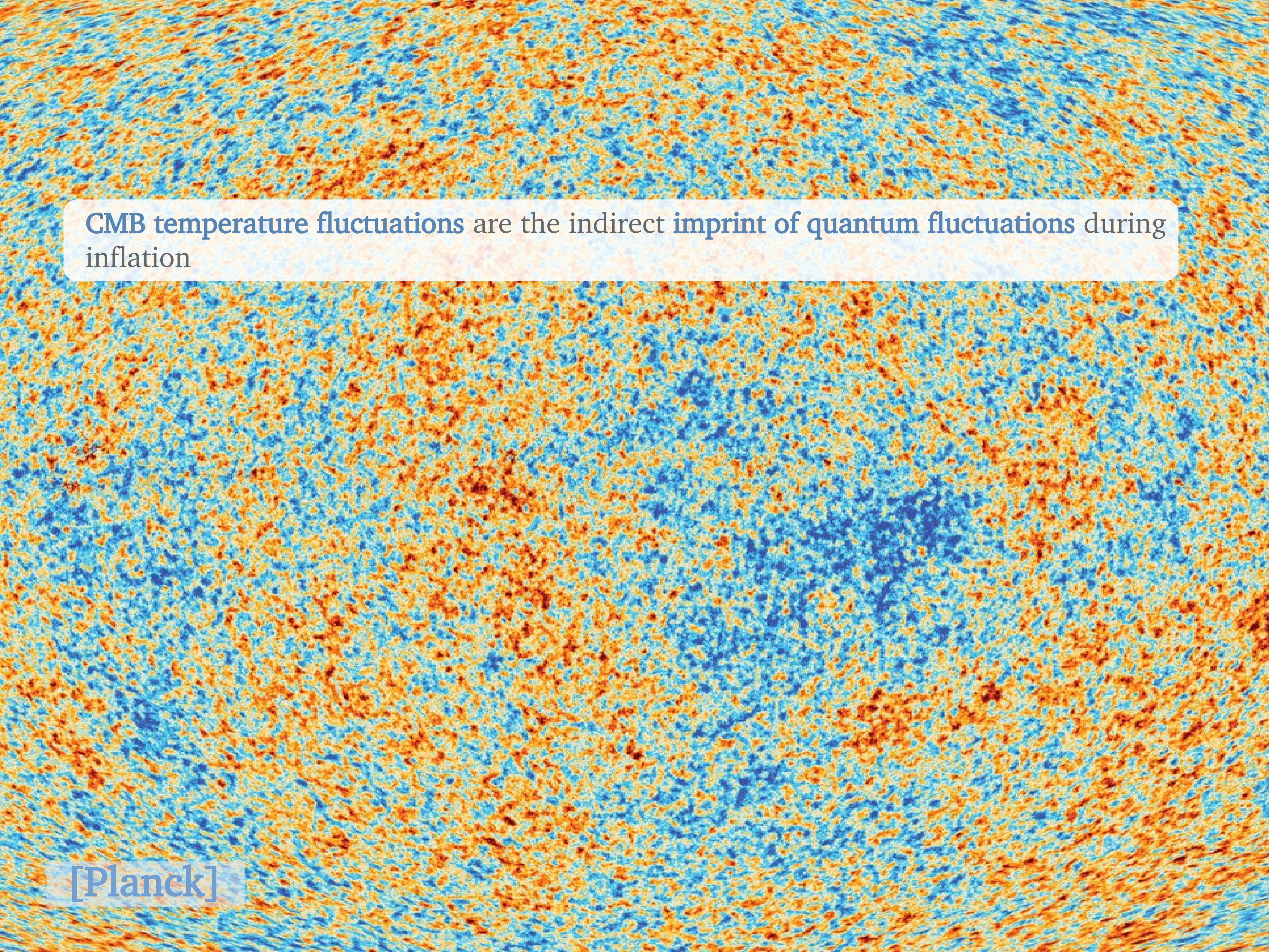


[Di Luzio, Ringwald, CT]

The trouble with isocurvature


[Planck]

CMB temperature fluctuations are the indirect **imprint of quantum fluctuations** during inflation



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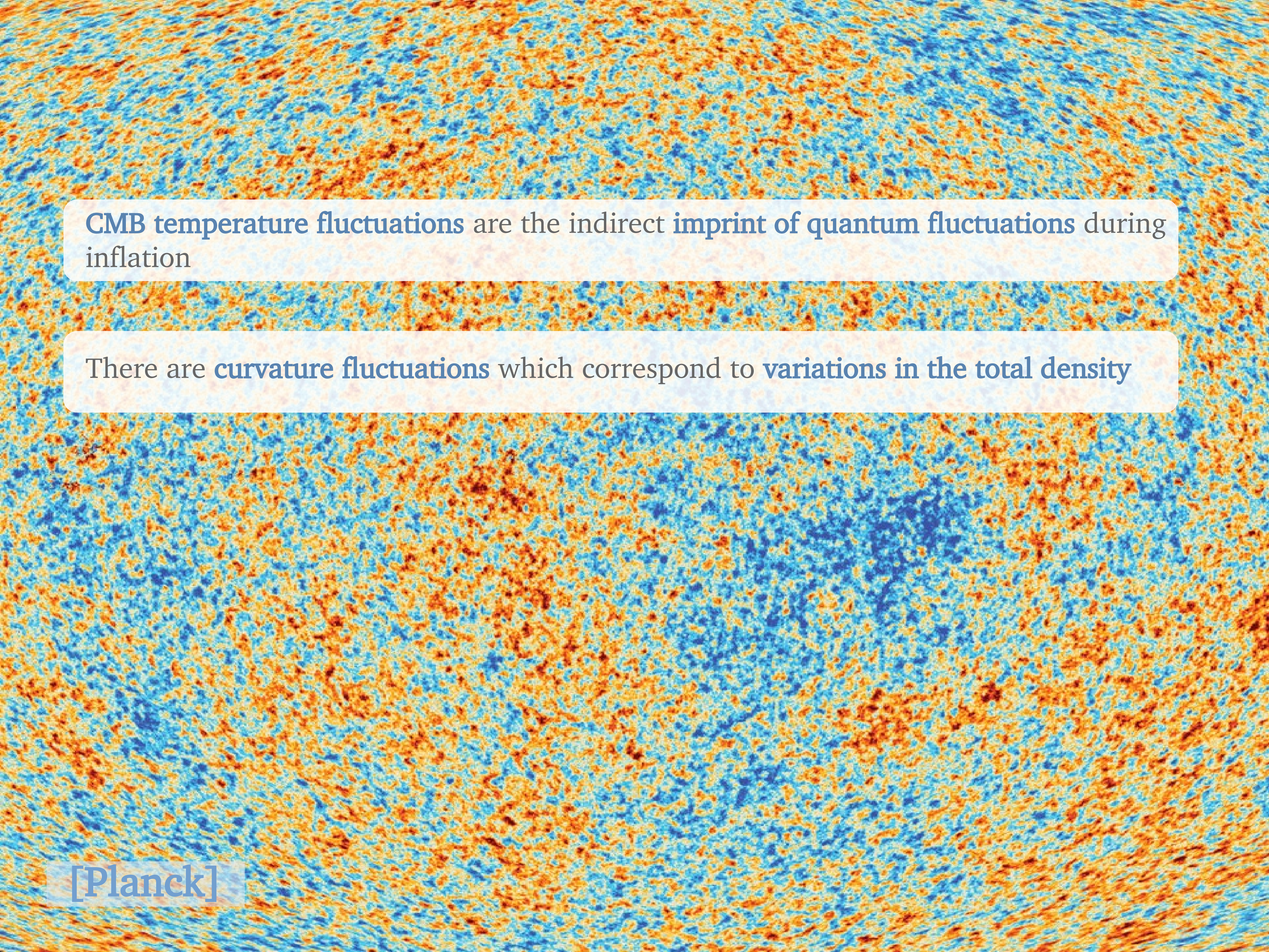

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There are **curvature fluctuations** which correspond to **variations in the total density**

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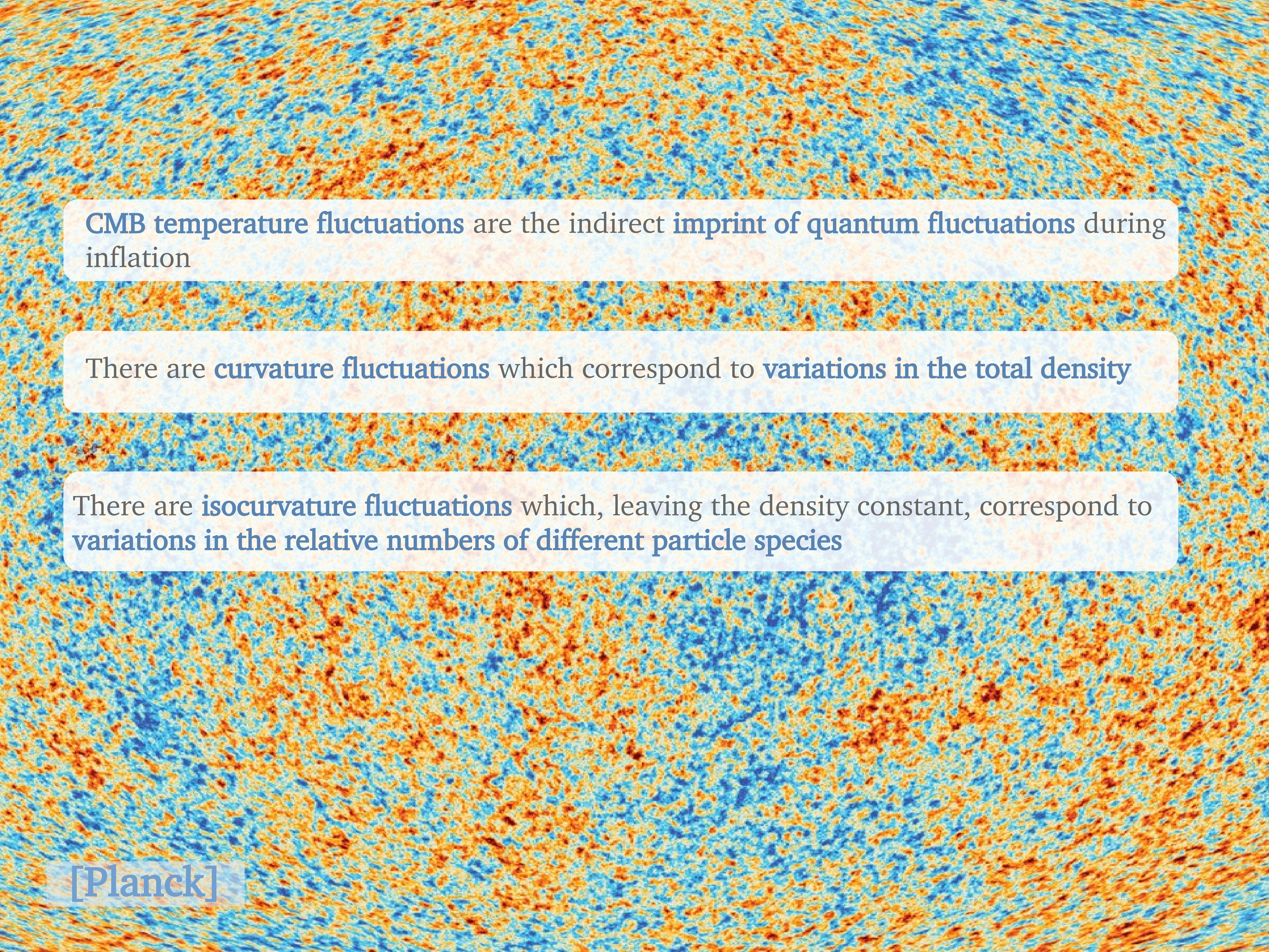
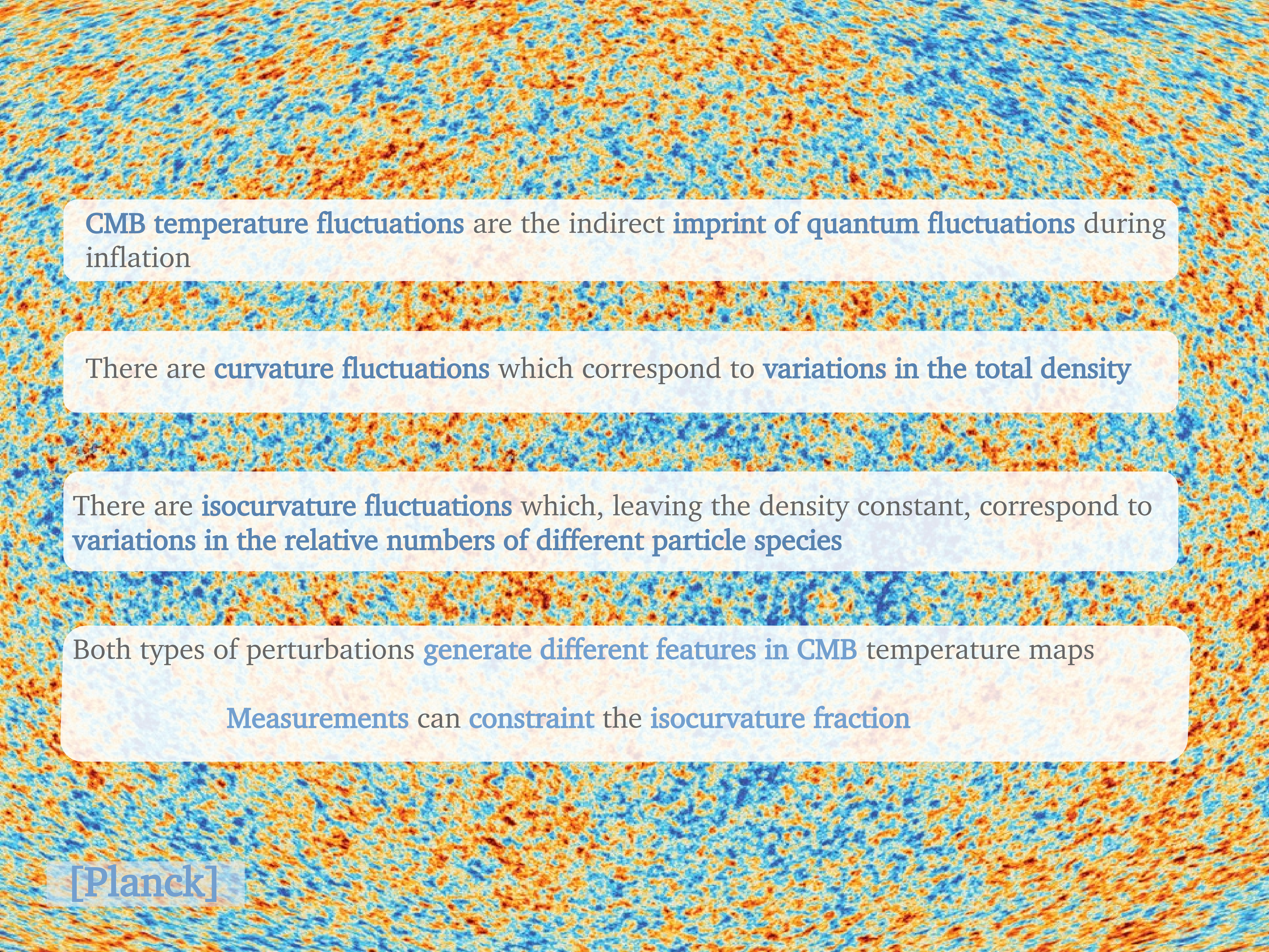
There are **isocurvature fluctuations** which, leaving the density constant, correspond to **variations in the relative numbers of different particle species**



[Planck]



CMB temperature fluctuations are the indirect **imprint of quantum fluctuations** during inflation

There are **curvature fluctuations** which correspond to **variations in the total density**

There are **isocurvature fluctuations** which, leaving the density constant, correspond to **variations in the relative numbers of different particle species**

Both types of perturbations **generate different features in CMB** temperature maps

Measurements can **constraint** the **isocurvature fraction**

[Planck]

Axion isocurvature perturbations

With the universe comprising axions and radiation, one can define the **isocurvature perturbation**

$$S_{A\gamma} = \frac{\delta n_A}{n_A} - \frac{\delta n_{\rm rad}}{n_{\rm rad}}\bigg|_{\delta\rho=0} = \frac{\delta n_A}{n_A} - 3\frac{\delta T}{T}\bigg|_{\delta\rho=0}, \quad n_A \propto \theta^2$$

This is to be contrasted with the **density or curvature perturbation** R.

One can define **power spectra** and an **isocurvature fraction**

$$\langle S_{A\gamma}(\mathbf{k})\mathbf{S}_{\mathbf{A}\gamma}(\mathbf{k}')\rangle = (2\pi)^3\delta(\mathbf{k}+\mathbf{k}')\mathbf{P}_{\mathbf{A}\gamma}(|\mathbf{k}|)$$
$$\langle R(\mathbf{k})\mathbf{R}(\mathbf{k}')\rangle = (2\pi)^3\delta(\mathbf{k}+\mathbf{k}')\mathbf{P}_{\mathbf{R}}(|\mathbf{k}|)$$

$$P_X(|\mathbf{k}|) \equiv \frac{\mathbf{2\pi^2}}{|\mathbf{k}|^\mathbf{3}}\mathbf{\Delta_X}(|\mathbf{k}|)$$

$$\boxed{\beta_{\rm iso}(|\mathbf{k}|) = \frac{\mathbf{P}_{\mathbf{A}\gamma}(|\mathbf{k}|)}{\mathbf{P}_{\mathbf{A}\gamma}(|\mathbf{k}|)+\mathbf{P}_{\mathbf{R}}(|\mathbf{k}|)} = \frac{\mathbf{\Delta}_{\mathbf{A}\gamma}(|\mathbf{k}|)}{\mathbf{\Delta}_{\mathbf{A}\gamma}(|\mathbf{k}|)+\mathbf{\Delta}_{\mathbf{R}}(|\mathbf{k}|)}}$$

CMB measurements imply

$$\boxed{\beta_{\rm iso}(0.002{\rm Mpc}^{-1}) < 0.035}$$

[Planck 2018]

Dark matter has dark consequences

Axion field A a combination of scalar phases. With a single complex scalar:

$$\phi = \frac{f}{\sqrt{2}} e^{i\theta} = \frac{f}{\sqrt{2}} e^{iA/f}. \quad n_A \propto A^2 = f^2\theta^2$$

Deep in the radiation era, the **isocurvature** is **dominated by the axion**

$$\rho_{\rm rad} \gg \rho_A \Rightarrow S_{A\gamma} \approx \frac{\delta n_A}{n_A} \qquad \theta = \langle\theta\rangle + \delta\theta \Rightarrow \langle S_{A\gamma} S_{A\gamma}\rangle \approx \frac{4}{\langle\theta\rangle^2}\langle\delta\theta\delta\theta\rangle = \frac{4}{\theta_I^2}\langle\delta\theta\delta\theta\rangle = \frac{4}{\theta_I^2}\Delta_{\delta\theta}$$

If the axion is a **massless field during inflation**, power spectrum freezes for $k < aH$

Power spectrum fixed by the only relevant dimensionful scale, H

$$\Delta_{\delta\theta} = \frac{1}{f^2}\Delta_{\delta A} = \frac{1}{f^2}\left(\frac{H}{2\pi}\right)^2 \qquad \Delta_{A\gamma} \approx \frac{4}{\theta_I^2}\Delta_{\delta\theta} = \frac{4}{f^2\theta_I^2}\left(\frac{H}{2\pi}\right)^2$$

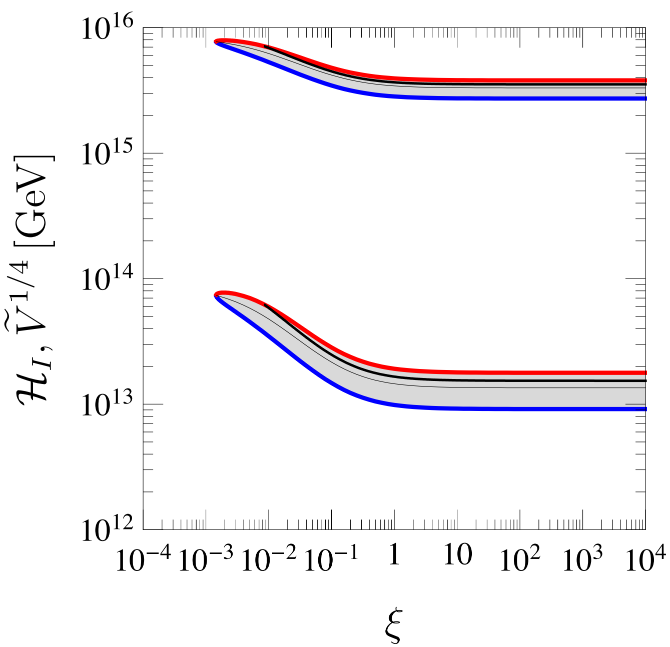
Substituting **relic abundance** constraint and imposing **CMB bound**,

$$H \lesssim \frac{5\times 10^{13}\,\mathrm{GeV}}{(f(\mathrm{GeV}))^{0.165}}$$

e.g. $H < 7\times 10^{11}$ GeV for $f > 10^{11}$ GeV

Dark matter has dark consequences

But the simplest inflationary models favour larger values of H during inflation!



[Ballesteros, Redondo, Ringwald, CT]

Non-standard inflation?

f or mass dynamical (and large) during inflation?

Need inflaton-axion interactions

Dark matter has dark consequences

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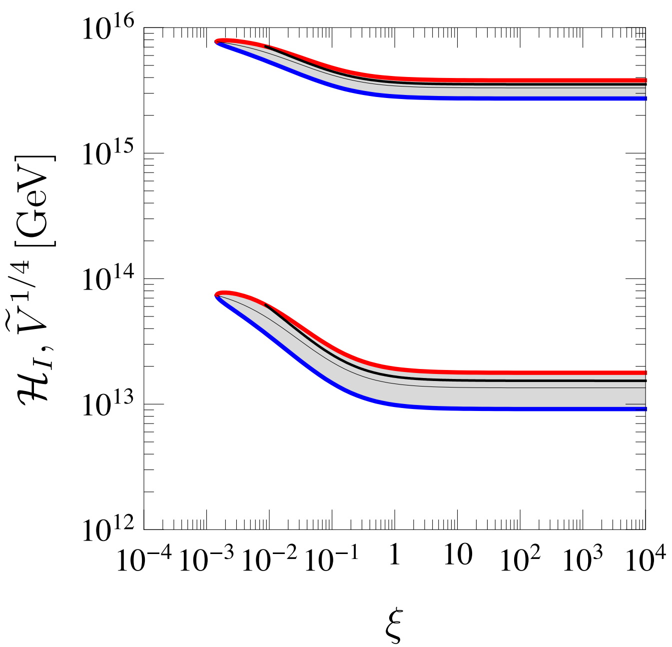


[Ballesteros, Redondo, Ringwald, CT]

Non-standard inflation?

f or mass dynamical (and large) during inflation?

Need inflaton-axion interactions

Model A: Axion embedded into inflaton

1 complex scalar with PQ charge, containing axion and inflaton

[Fairbairn & Marsh]

Axion still treated as massless, but f becomes Planckian inflaton value

$$\Delta_{A\gamma} \approx \frac{4}{f^2\theta_I^2}\left(\frac{H}{2\pi}\right)^2 \to \frac{4}{\rho_{\rm inf}^2\theta_I^2}\left(\frac{H}{2\pi}\right)^2$$

$$\boxed{f_A < 1.4 \times 10^{14}\mathrm{GeV}}$$

[Fairbairn & Marsh][Ballesteros, Redondo, Ringwald, CT]

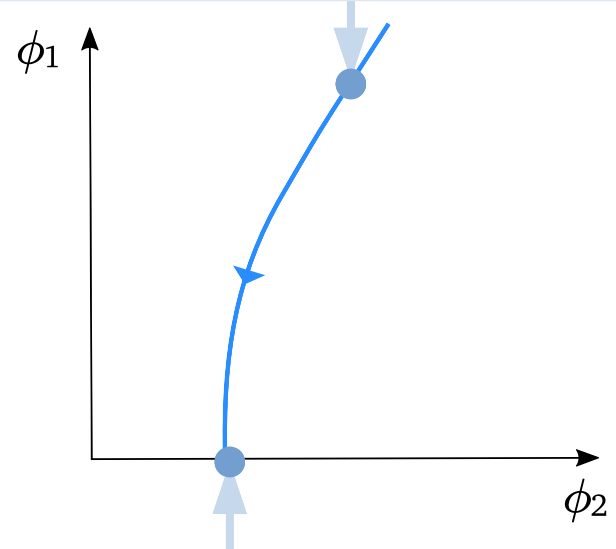
Incompatible with GUTs?

Model B: Axion very massive during inflaton

2 complex scalars with PQ charges, inflaton mostly in ϕ_1, axion contained in ϕ_2

[Nakayama, Takimoto]

During inflation, lightest direction mostly aligned with ϕ_1: axion isocurvature fluctuations suppressed



(Pre-inflationary scenario requires negative portal coupling)

After inflation: Avoid ϕ_1 VEV so that QCD axion contained in ϕ_2, which had suppressed fluctuations.

Compatible with GUTs?

Invalid assumptions?

For model A it was assumed:

$\boxed{\text{Axion field is massless during inflation}}$

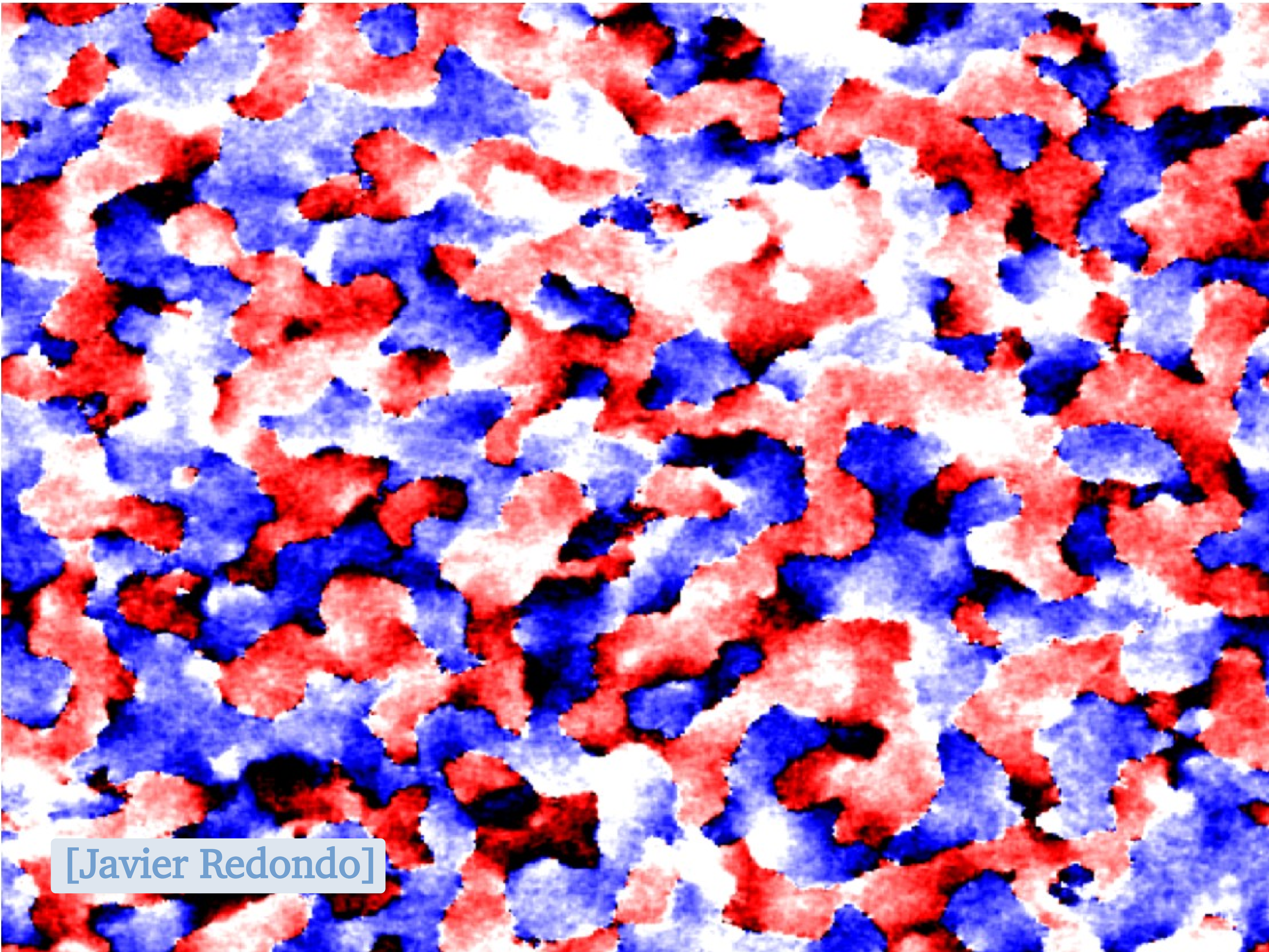
If axion interacts with inflaton, the field is not at its minimum during inflation: **Goldstone theorem does not apply and the axion is massive**

For models A, B it was assumed

$\boxed{\text{Primordial angular perturbations fixed after horizon crossing during inflation}}$

Not true for massive fields or with inflaton interactions!

Non-perturbative phenomena during reheating are known to affect angular perturbations


[Javier Redondo]

In previous work we showed that the PQ symmetry is restored by nonperturbative effects for type A models with low f.

We hypothesized that PQ could remain broken for $f > 10^{16}$ GeV, but did not confirm this with dedicated simulations

[Ballesteros, Redondo, Ringwald, CT]

Improved calculations

To-do list

For models A and B

Solve numerically the **evolution of inflationary perturbations**, accounting for nonzero masses

Use the above as initial conditions for **multi-field lattice simulations** for complex scalars + Higgs) including effects of **Higgs decays** and **SM radiation**

Derive power spectra for isocurvature perturbation and extrapolate to CMB scales

Model A setup

$$\sqrt{-g}\mathcal{L} \supset \sqrt{-g}\left\{\left(\frac{M_P^2}{2} + \xi\left(\phi^\dagger\phi - \frac{v_\phi^2}{2}\right)\right)R - \lambda_\phi\left(\phi^\dagger\phi - \frac{v_\phi^2}{2}\right) - \lambda_h\left(h^2 - \frac{v_h^2}{2}\right) - 2\lambda_{h\phi}\left(\phi^\dagger\phi - \frac{v_\phi^2}{2}\right)\left(h^2 - \frac{v_h^2}{2}\right)\right\}$$

$\phi = \phi_1 + i\phi_2$ **Inflaton field, containing axion**

$h :$ **Higgs field**

Evolution of perturbations during inflation

With $\delta\phi = \delta\phi_1 + i\delta\phi_2$ we separate the fluctuations components into

$\delta\phi_{\|}$ aligned with inflationary background

$\delta\phi_{\perp}$ orthogonal to background

Potential admits **straight inflationary trajectories**, with **misalignment angle** θ_I

$$\delta\phi_{\|} = \cos\theta_I \delta\phi_1 + \sin\theta_I \delta\phi_2, \quad \delta\phi_{\perp} = \cos\theta_I \delta\phi_2 - \sin\theta_I \delta\phi_1$$

For straight trajectories, perturbations in flat spatial curvature gauge satisfy

$$\delta\ddot{\phi}_{\|} + 3H\delta\dot{\phi}_{\|} + \left(\frac{\mathbf{k^2}}{a^2} + m_{\|}^2 - \frac{1}{M_P^2 a^3}\frac{d}{dt}\left(\frac{a^3\dot{\phi}_{\|}^{\,2}}{H}\right)\right)\delta\phi_{\|} = 0$$

$$\delta\ddot{\phi}_{\perp} + 3H\delta\dot{\phi}_{\perp} + \left(\frac{\mathbf{k^2}}{a^2} + m_{\perp}^2\right)\delta\phi_{\perp} = 0$$

[Gordon et al]

Power spectra at the end of inflation

Boundary conditions: match result in in the local Minkowski frame well below the horizon:

$$\phi_{i,\mathbf{k}}(t) \to \frac{e^{-i\omega\tau(t)}}{(2\omega)^{1/2}}, \; t \to -\infty, \quad \omega = \sqrt{\mathbf{k}^2 + a(t)^2 m_i^2}$$

These solutions with this normalization are associated with quantized fields

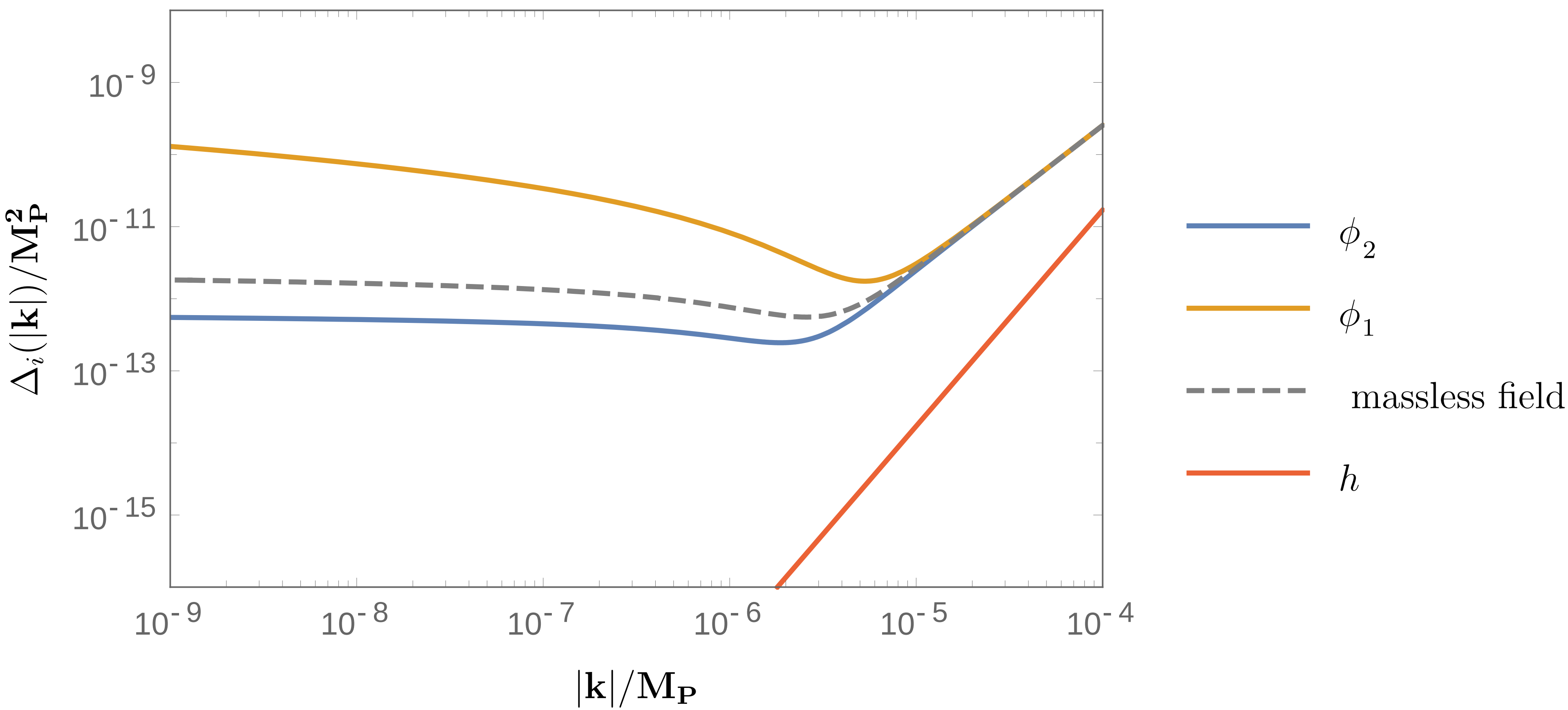
$$\hat{\phi}_i(\mathbf{k},\mathbf{t}) = \phi_{\mathbf{i},\mathbf{k}}(\mathbf{t})\mathbf{a}_\mathbf{k} + \phi_{\mathbf{i},\mathbf{k}}(\mathbf{t})^*\mathbf{a}_\mathbf{k}^\dagger, \quad [\mathbf{a}_{\mathbf{ik}}, \mathbf{a}_{\mathbf{ik}'}^\dagger] = (\mathbf{2}\pi)^\mathbf{3}\delta(\mathbf{k}-\mathbf{k}')$$

such that the corresponding power spectra are determined by the $\phi_{i,\mathbf{k}}(t)$

$$\left\langle \hat{\phi}_i(\mathbf{k},\mathbf{t})\hat{\phi}_\mathbf{i}(\mathbf{k}'.\mathbf{t}) \right\rangle = (2\pi)^3\delta(\mathbf{k}+\mathbf{k}')\mathbf{P}_{\phi_\mathbf{i}}(|\mathbf{k}|.\mathbf{t}), \quad \mathbf{P}_{\phi_\mathbf{i}}(|\mathbf{k}|.\mathbf{t}) = |\phi_{\mathbf{i},\mathbf{k}}(\mathbf{t})|^\mathbf{2}$$

We can infer power spectra from properly normalized solutions of the equations of motion

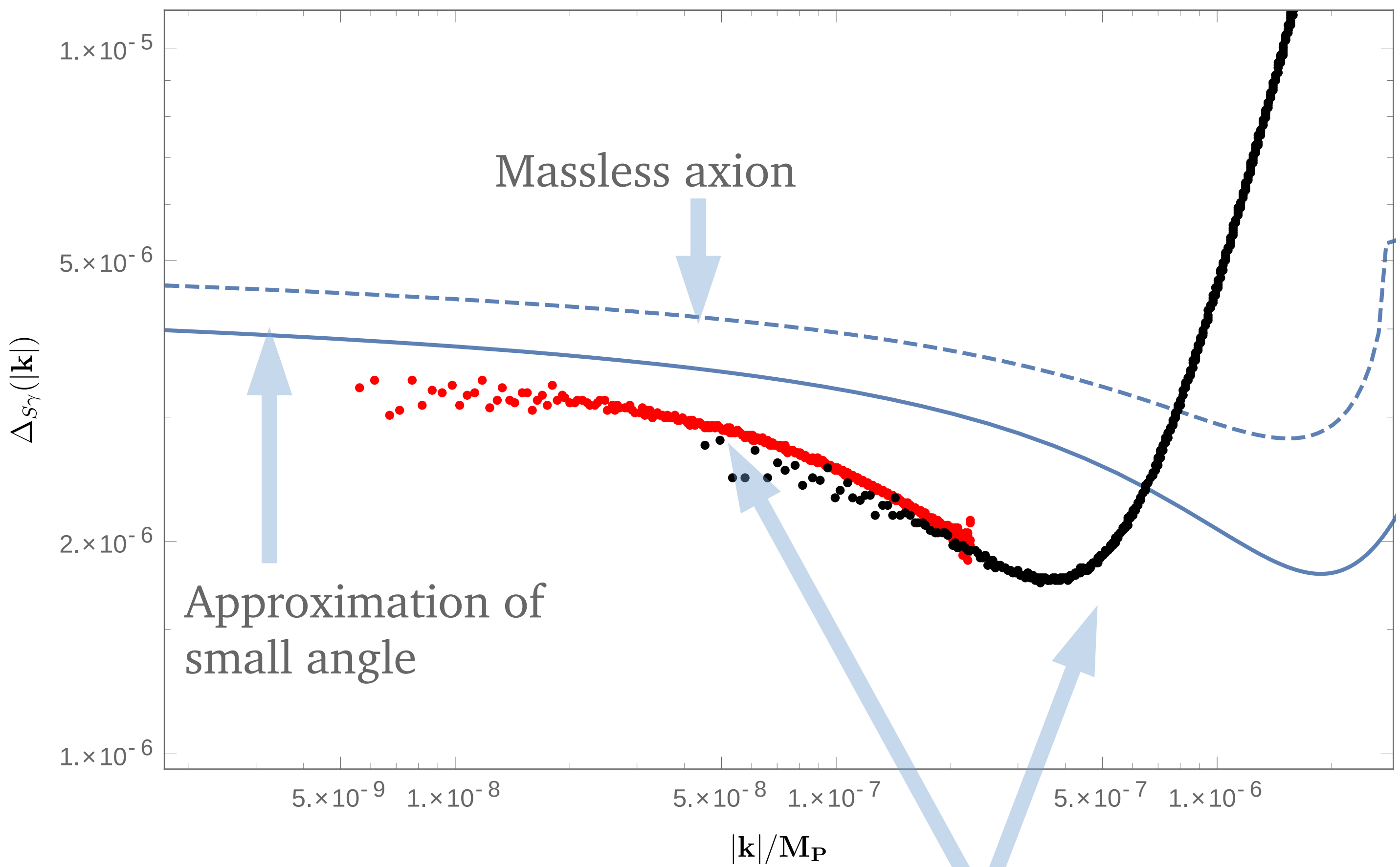
Power spectra at the end of inflation



Assumed: $\xi = 0.1, \quad \lambda_{h\phi} = 10^{-6}$

Isocurvature power spectrum at the end of inflation

From the previous result we can estimate the **power spectrum of the isocurvature perturbation** at the **end of inflation**



Assumed: $f_A = 5 \times 10^{17}\mathrm{GeV}, \quad \xi = 0.1$

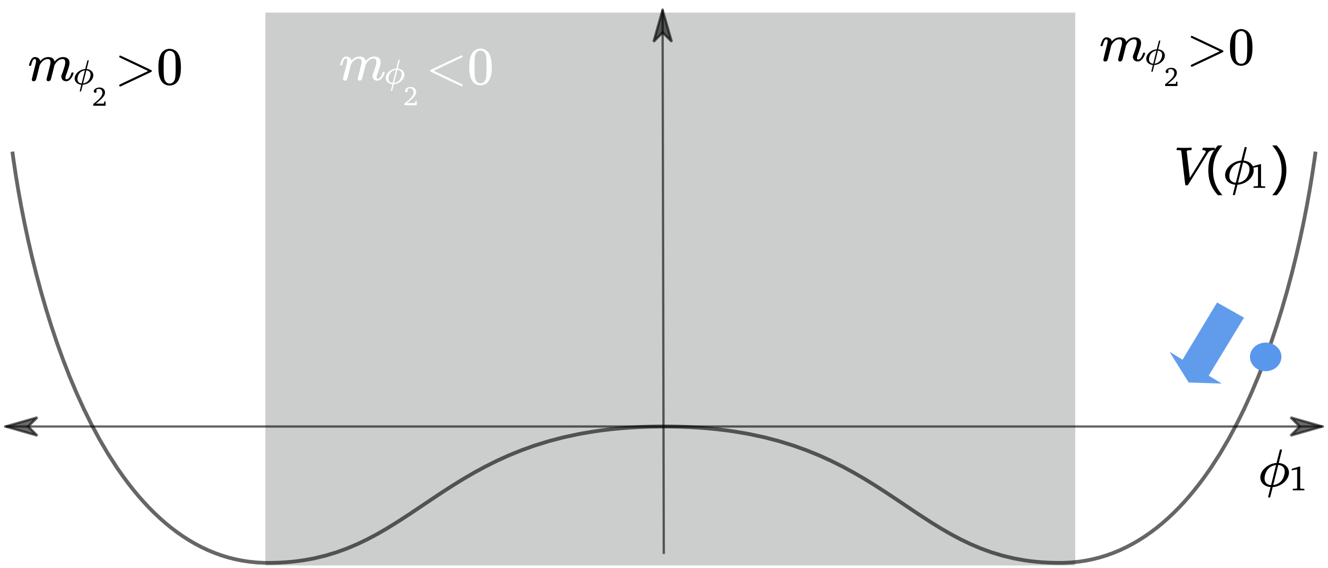
2 different lattices with 512^3 points

Isocurvature power spectrum at the end of inflation

The previous results show that the **(small) axion mass suppresses the power spectrum at super-horizon scales,** but the effect is very mild

Do the isocurvature modes decay further after inflation?

What happens when the background crosses the origin and the ϕ_2 **mass becomes negative**? Is there any **instability/growth**?



Lattice simulations of model A

We simulate **3 real scalars** $\phi_1(t,\mathbf{x}), \phi_2(t,\mathbf{x}), h(t,\mathbf{x})$ with h decaying into a **relativistic bath of SM particles** with density $\rho_{SM}(t)$, in an **expanding universe** with scale factor $a(t)$

$$\ddot{\phi}_k + 3\frac{\dot{a}}{a}\dot{\phi}_k - \frac{1}{a^2}\vec{\nabla}^2\phi_k + \frac{\partial V(\phi_l)}{\partial \phi_k} = 0, \;\; k = 1, 2,$$

$$\ddot{h} + 3\frac{\dot{a}}{a}\dot{h} - \frac{1}{a^2}\vec{\nabla}^2 h + \frac{\partial V(\phi_l)}{\partial h} + \Gamma_h \dot{h} = 0,$$

$$\dot{\rho}_{SM} + 4\frac{a}{a}\rho_{SM} = \Gamma_h \dot{h}^2,$$

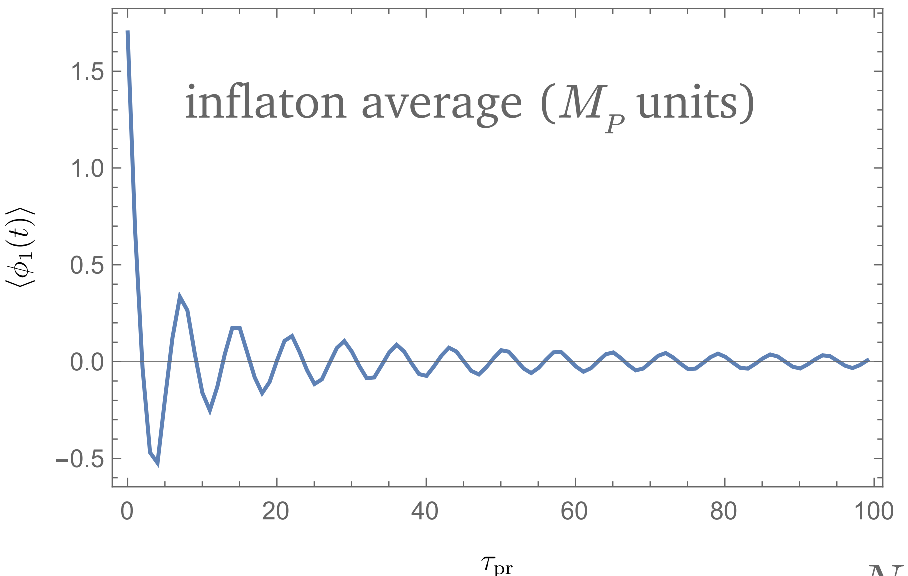
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3M_P^2}\left(\rho_{SM} + V + \frac{1}{2}(\dot{\phi}_1^2 + \dot{\phi}_2^2 + \dot{h}^2) + \frac{1}{2a^2}\left((\nabla\phi_1)^2 + (\nabla\phi_2)^2 + (\nabla h)^2\right)\right)$$

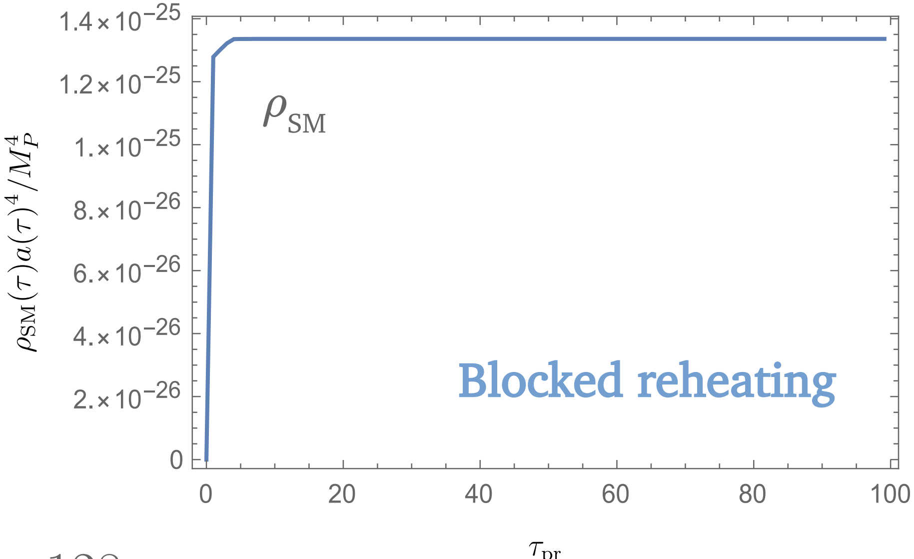
We use a modified version of “latticeeasy” [Felder,Tkachev]. Changes account for:

- Higgs decays
- SM radiation and impact on scale factor evolution
- Modified initial conditions for super-horizon modes

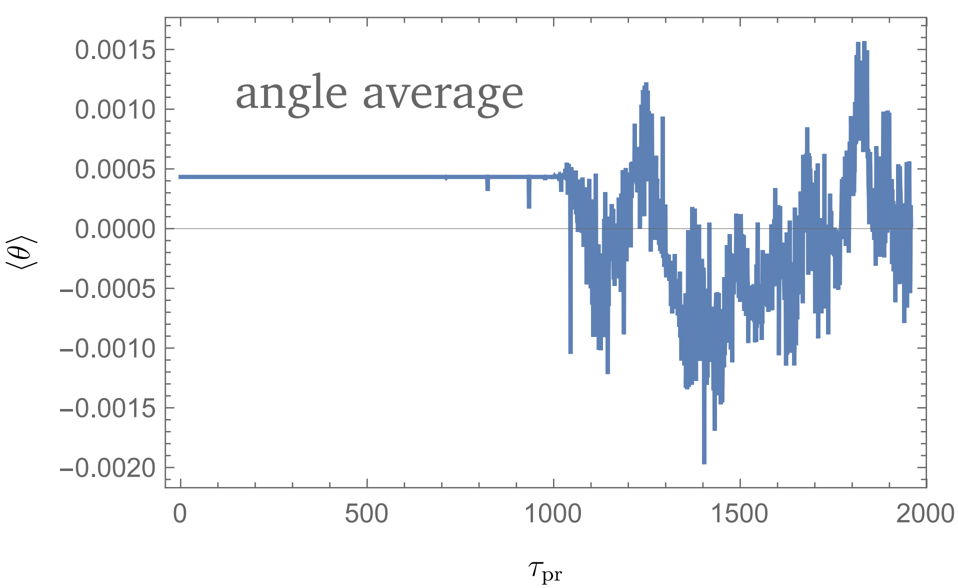
We fix $\xi = 0.1$, $\lambda_\phi = 1.27 \times 10^{-11}$ and vary f_A, $\lambda_{h\phi}$

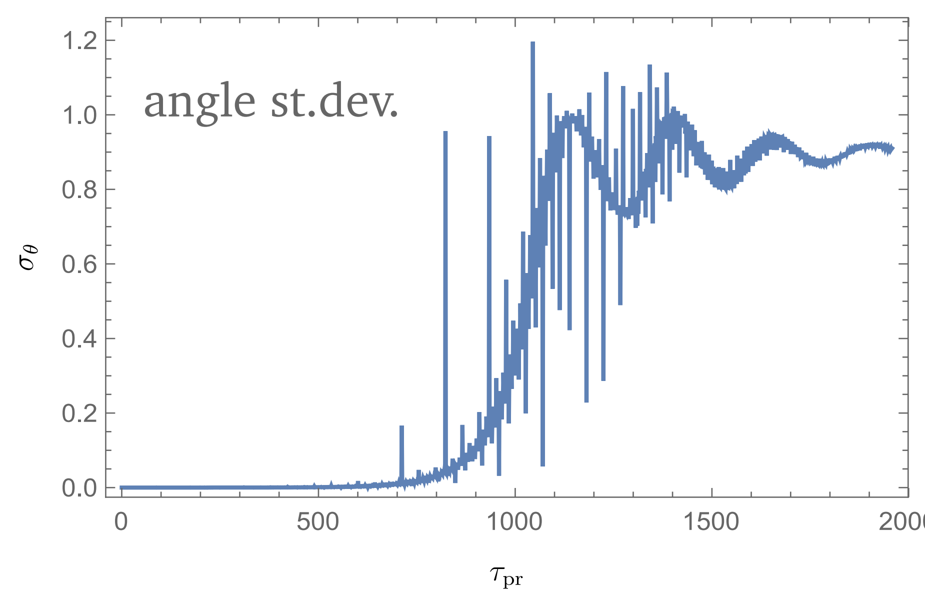
Relevant results for $f = 10^{11}$ GeV



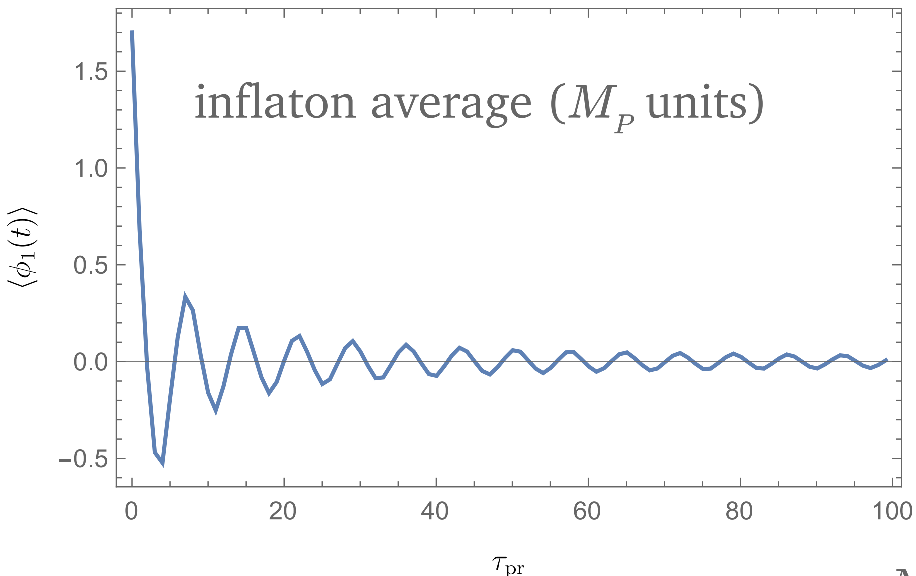


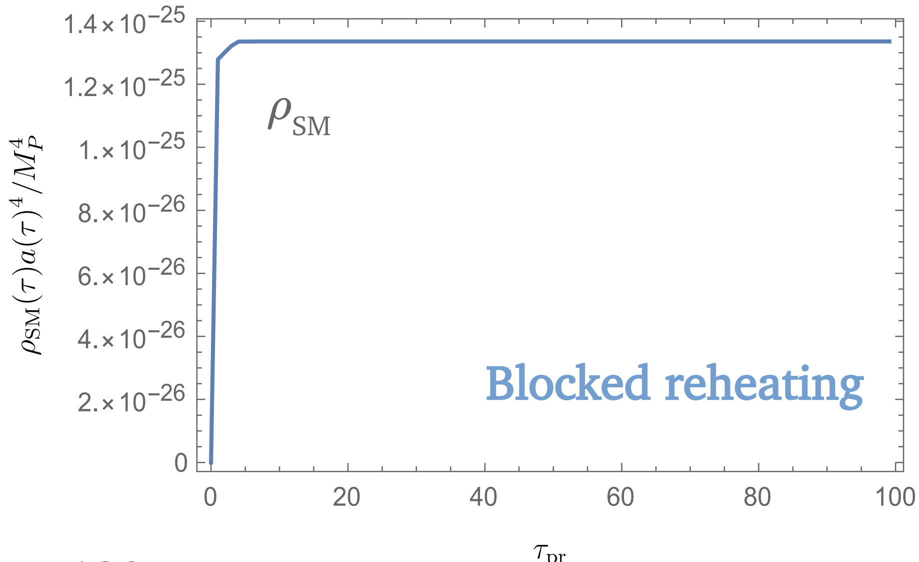
$N = 128$



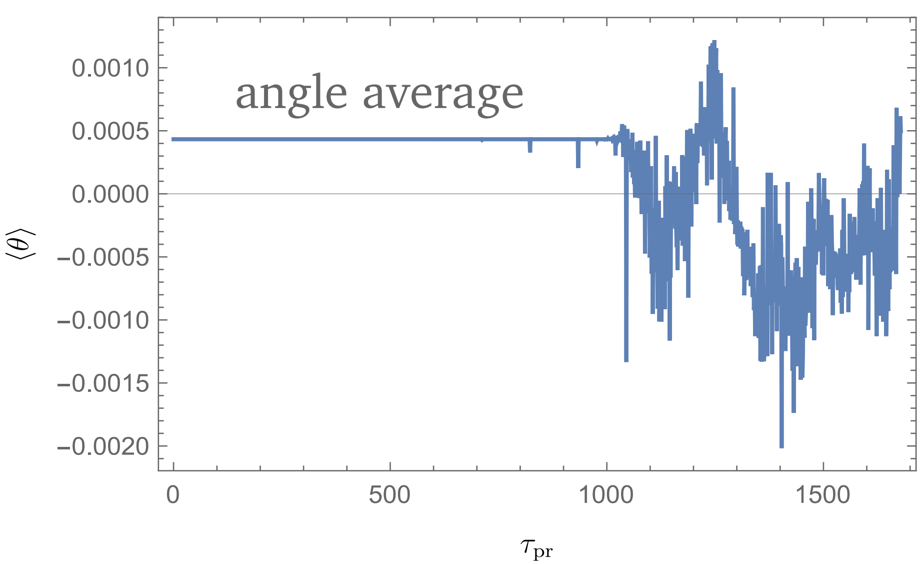


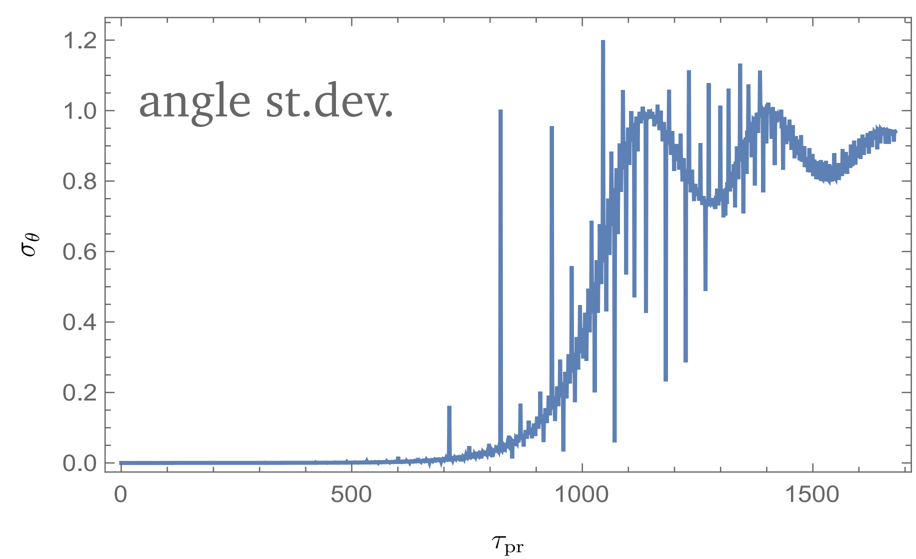
Relevant results for $f = 10^{13}$ GeV



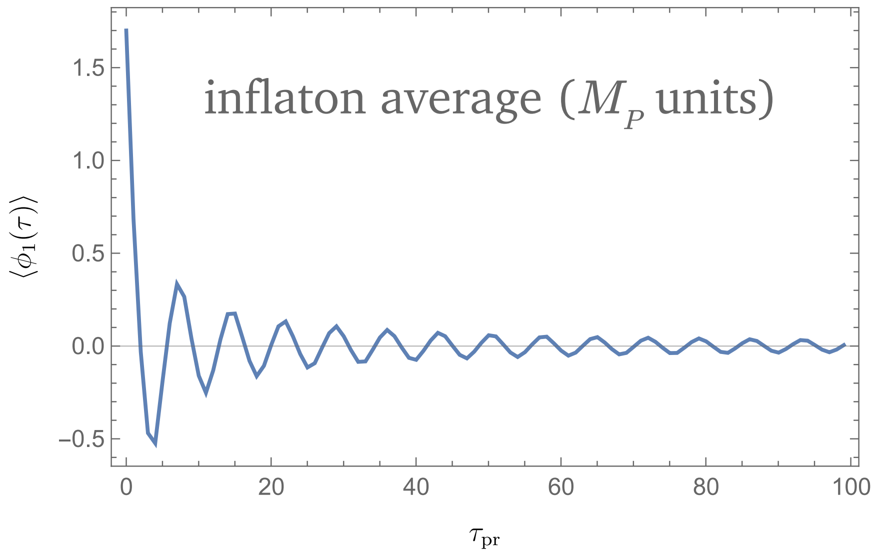


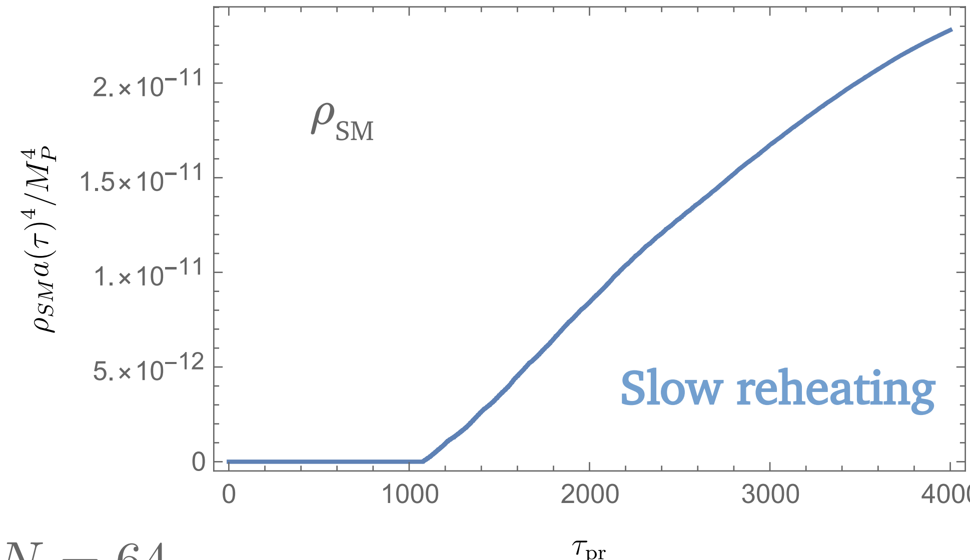
$N = 128$



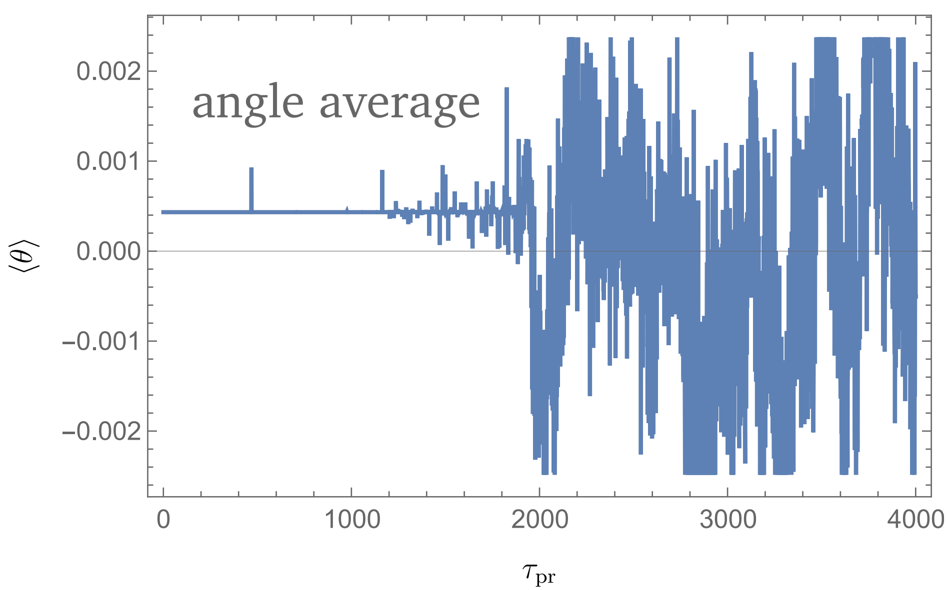


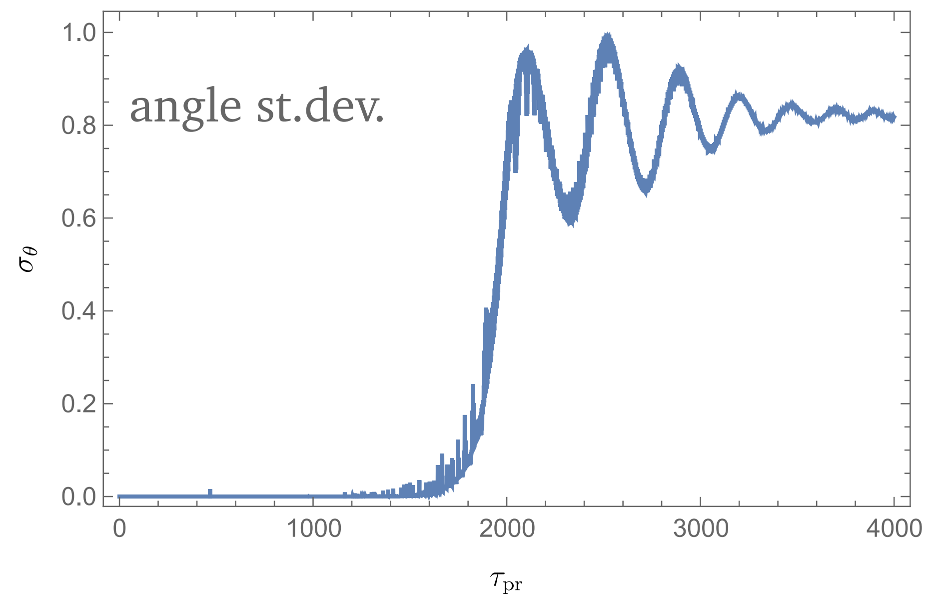
Relevant results for $f = 10^{15}$ GeV





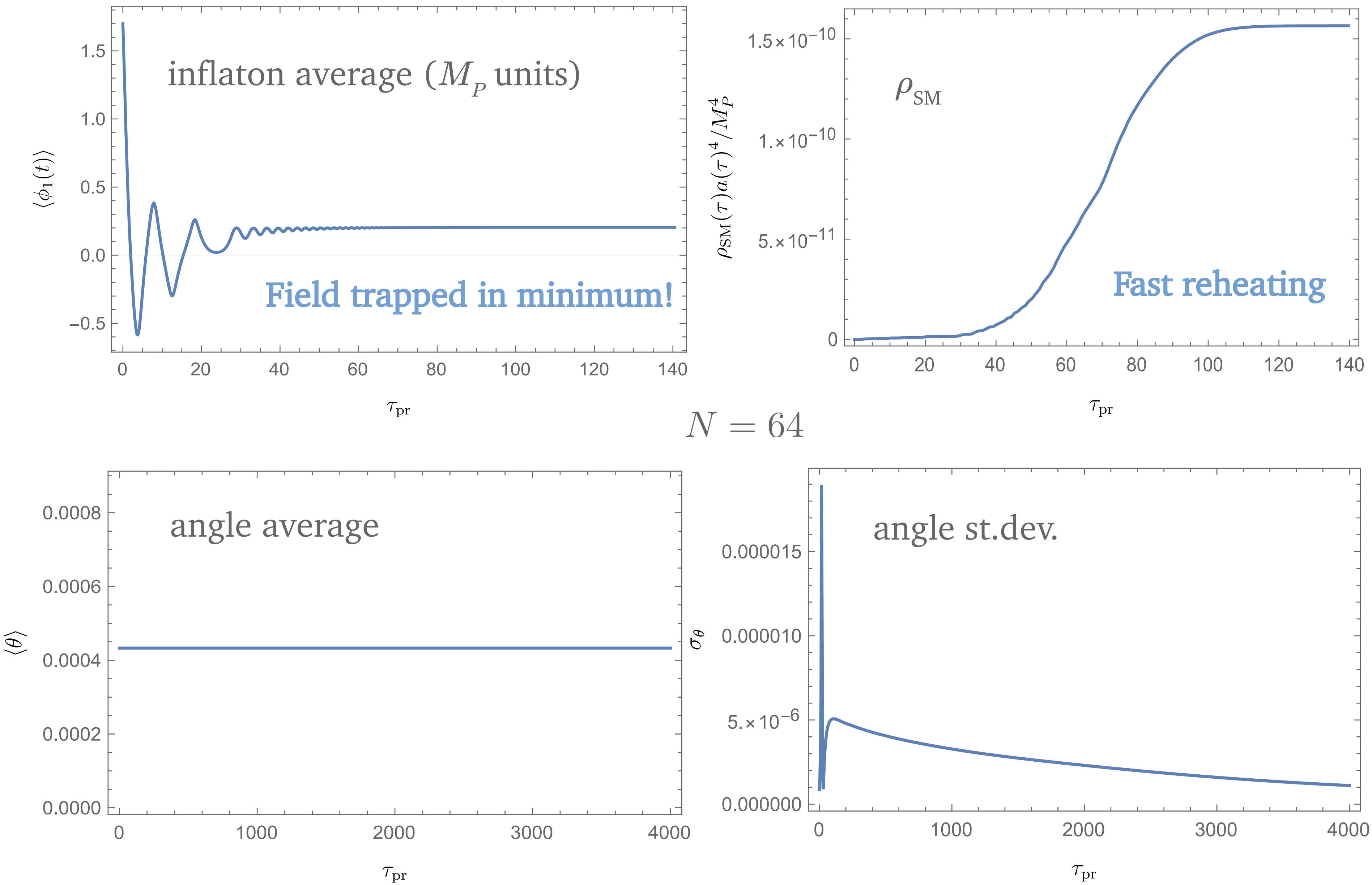
$N = 64$





similar results for f_A all the way up to...

Relevant results for f=5x10^{17} GeV



First conclusions

The **avoidance** of the **restoration of the PQ symmetry** from short-range fluctuations **favours GUT-scale** values for f_A

As hypothesized by [Ballesteros, Redondo, Ringwald, CT], the **trapping** of inflaton **in potential well** is key, but one needs larger f_A than initially thought

Still to do

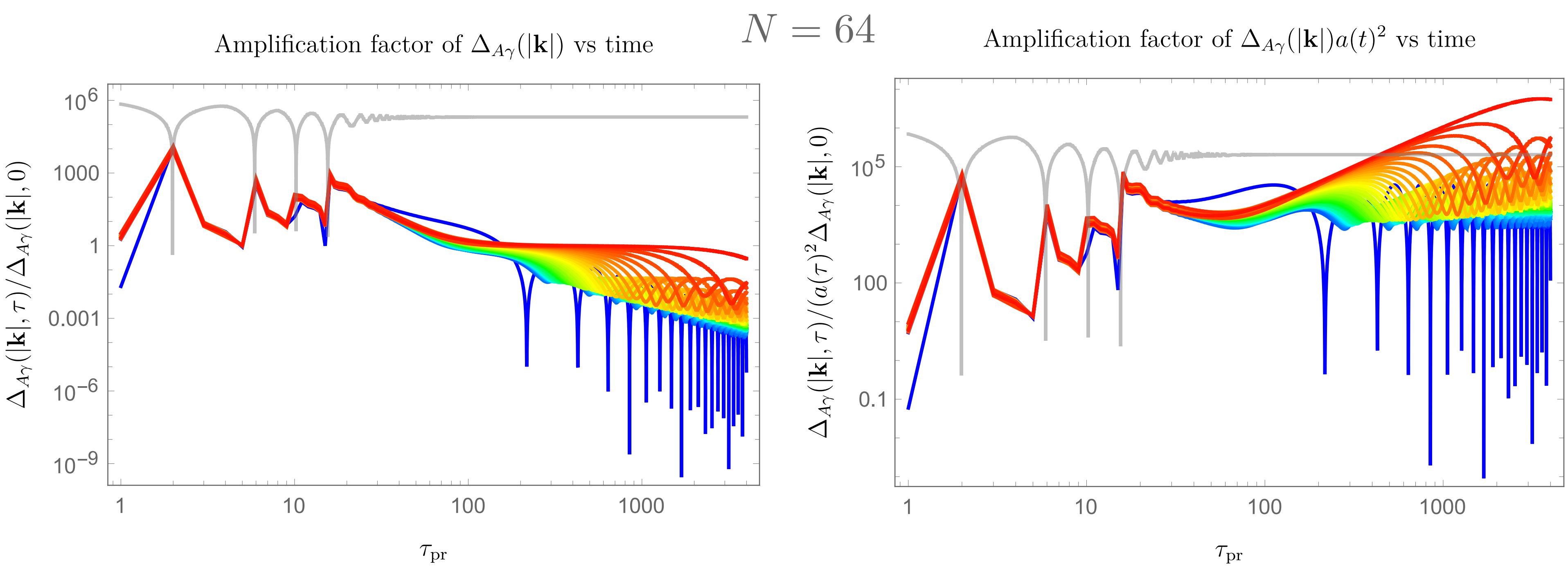
Estimate isocurvature fraction at CMB reference scale. Need:

Power spectra of isocurvature

Extrapolation to low scales

Results for isocurvature spectra

Super-horizon isocurvature modes have an initial exponential growth but then decay as $1/a(t)^2$!



Lower momenta in red, higher momenta in blue
In gray: $10^6\,\phi_1(\tau_{\rm pr})/M_P$

Note correlation of isocurvature peaks with crossings of the origin by the inflaton

Why the $1/a(t)^2$ decay?

Follows when the fields become **small fluctuations around the VEV** of the PQ field.

Massless **perturbations in $\mathrm{Im}\,\phi$** see a negligible potential and **redshift as 1/a(t)**

$$\mathrm{Im}\phi \propto \frac{1}{a(t)}$$

$$\theta \sim \tan\theta = \frac{\mathrm{Im}\,\phi}{\mathrm{Re}\,\phi} \sim \frac{\mathrm{Im}\,\phi}{f}$$

$$\Delta_{A\gamma} \approx \frac{4}{\theta_I^2}\Delta_{\delta\theta} \propto \frac{4}{f^2\theta_I^2}\Delta_{\mathrm{Im}\phi\mathrm{Im}\phi} \propto \frac{1}{a(t)^2}$$

…but it could not be so easy, could it?

The **initial exponential growth is larger for even lower modes**

Power spectrum at CMB scales and times will be a result of the **competition between initial amplification and later decay**

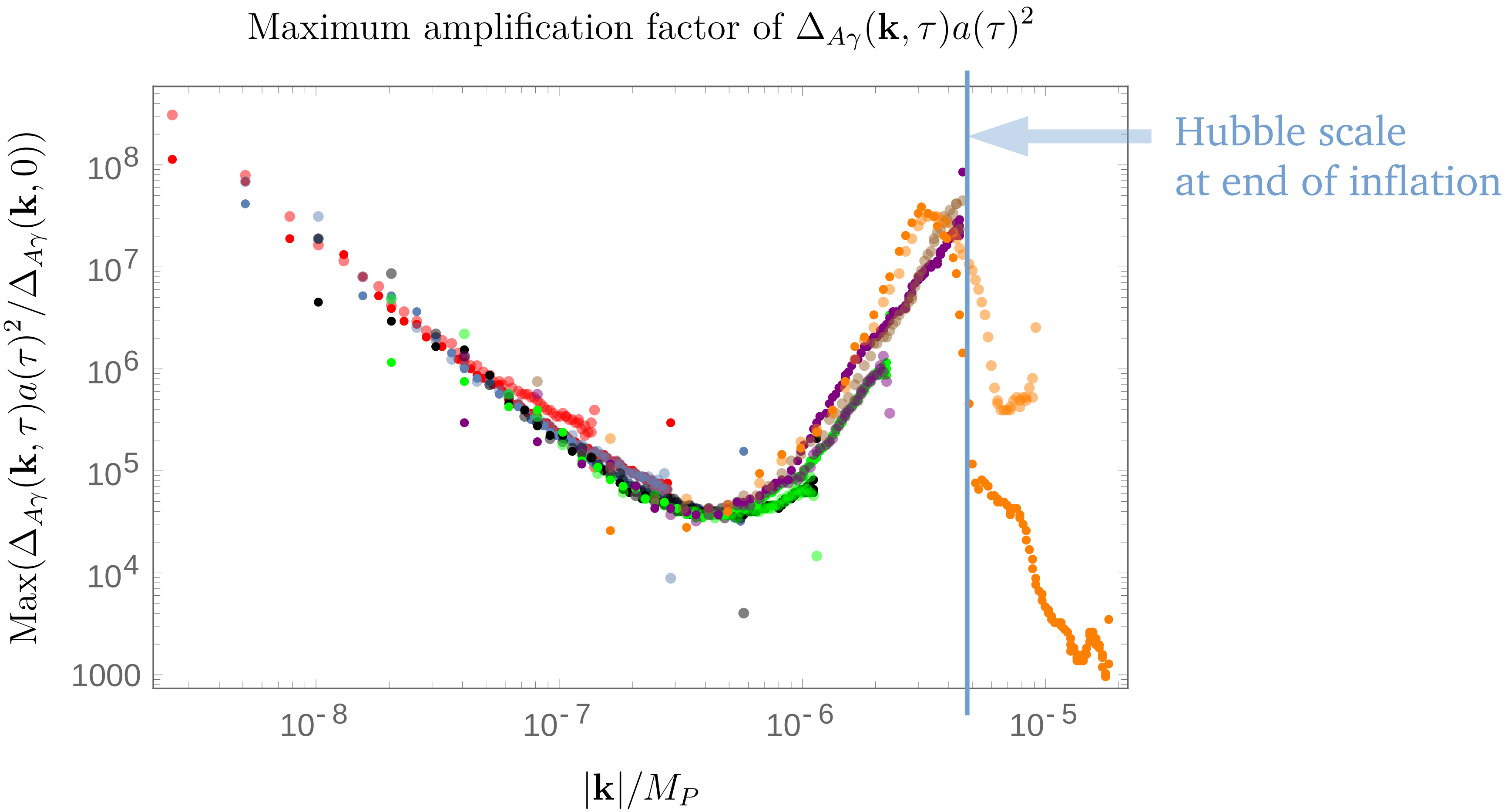
As $\Delta_{A\gamma}(|\mathbf{k}|,\tau)a(\tau)^2/\Delta_{A\gamma}(|\mathbf{k}|,0)$ seems to always peak and then oscillate around a constant value, we can estimate a bound

$$\Delta_{A\gamma}(|\mathbf{k}|,\tau) \lesssim \frac{\Delta_{A\gamma}(|\mathbf{k}|,0)}{a(\tau)^2}\mathrm{Max}\left(\frac{\Delta_{A\gamma}(|\mathbf{k}|,\tau)a(\tau)^2}{\Delta_{A\gamma}(|\mathbf{k}|,0)}\right)$$

From initial conditions

Amplification factor
estimated from lattice simulations

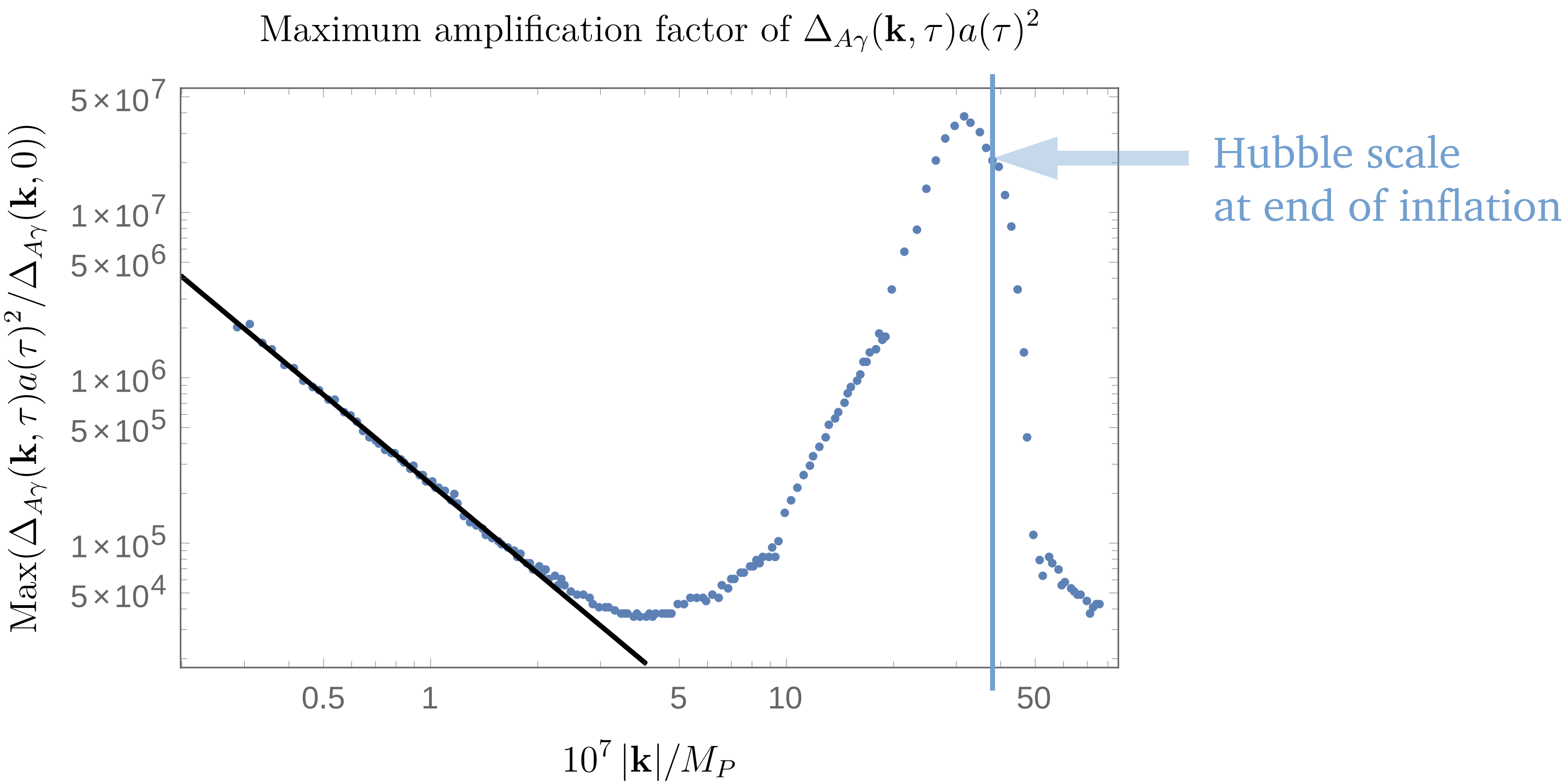
...but it could not be so easy, could it?



The plot shows **13 lattice simulations** with different grid (N=64, 128) and box sizes.

Now we only have to extrapolate along ~51 orders of magnitude to reach CMB scales :)!

...but it could not be so easy, could it?

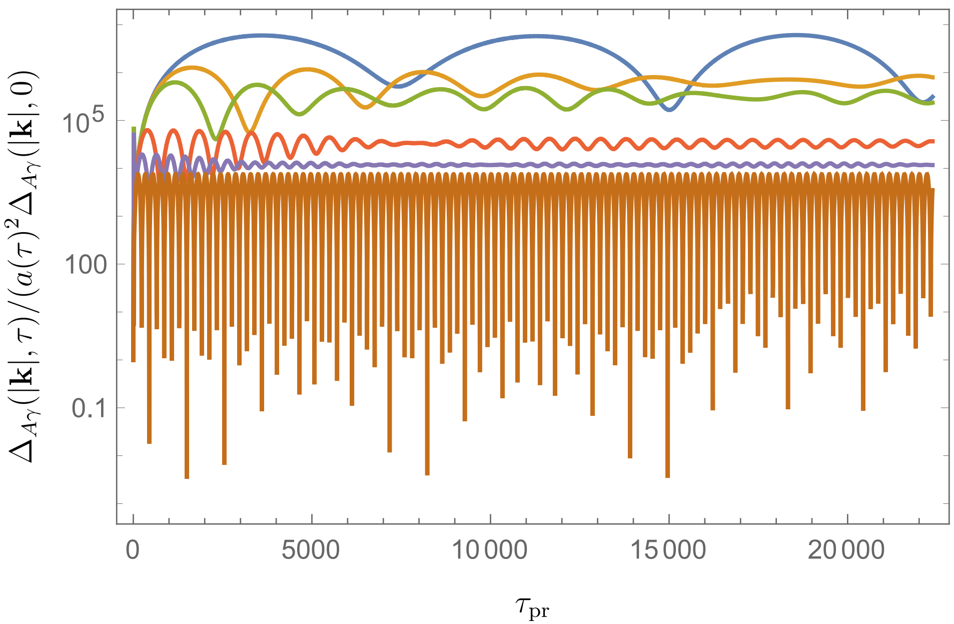


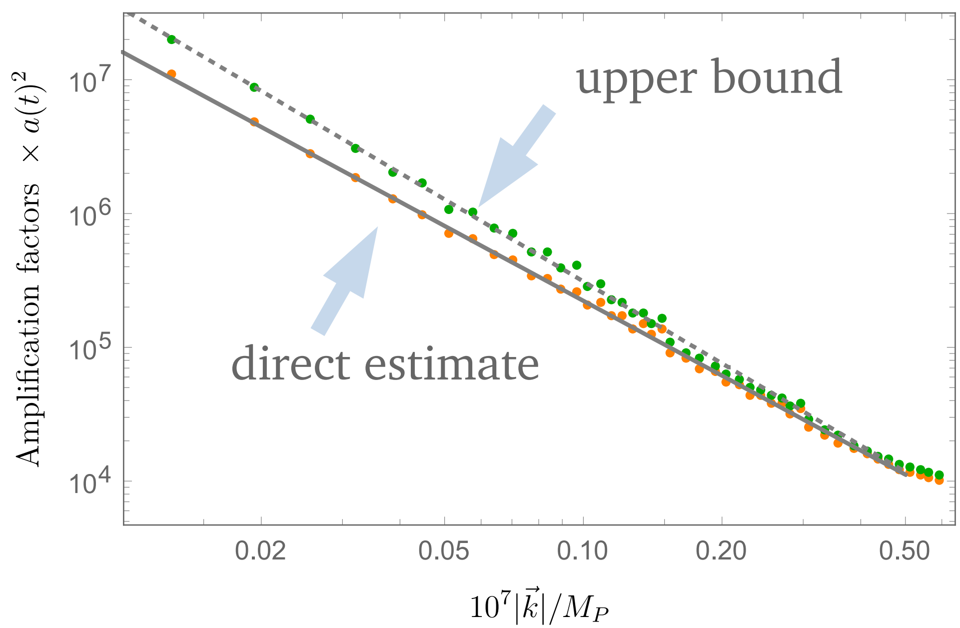
Cleanup: retain only larger grids, remove high and low momenta of each simulation, average over simulations with overlapping momenta.

For chosen parameters this **gives upper bound on isocurvature power spectrum at CMB scale/time of O(1) x (value at end of inflation). Ruled out by Planck!**

…but it could not be so easy, could it?

Can go **beyond upper bounds** by simulating for longer times, and computing averages of enhancement factors.

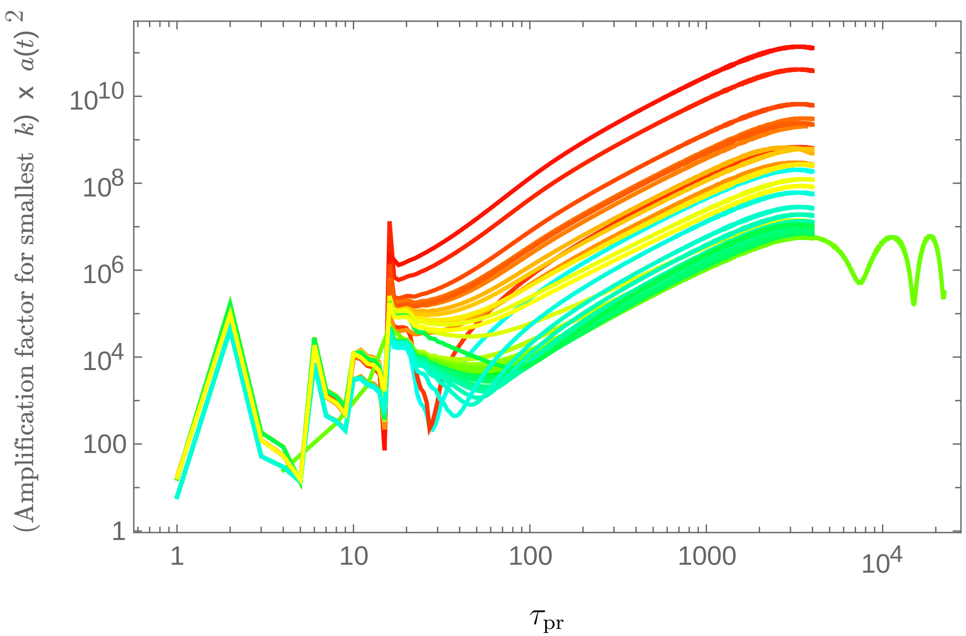




Have **found no viable model**, though it is hard to scan parameter space…

Effect of Higgs portal coupling

Amplification factor of lowest mode, from small to large values of Higgs portal.



Sweetspot

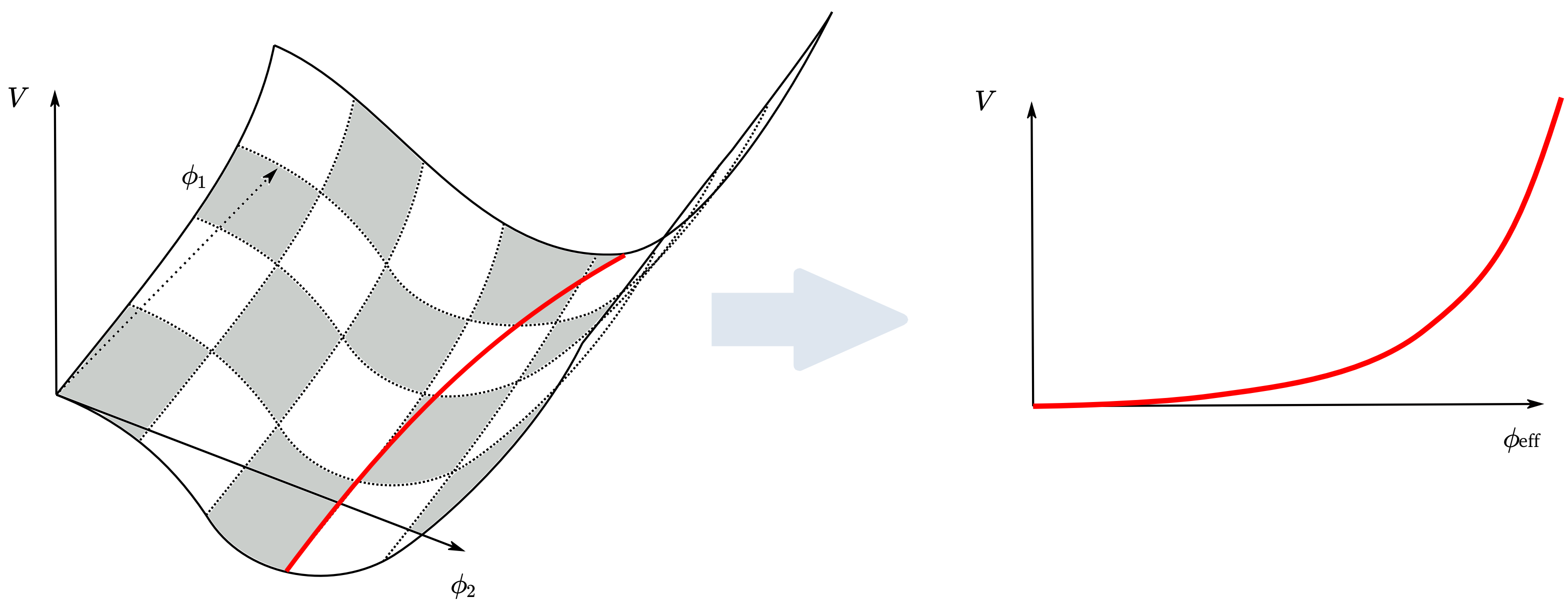
$\lambda_{h\phi} = 9.3 \times 10^{-7}$

Portal coupling can source axion fluctuations at intermediate times

Have **found no viable model**, though it is hard to scan parameter space...

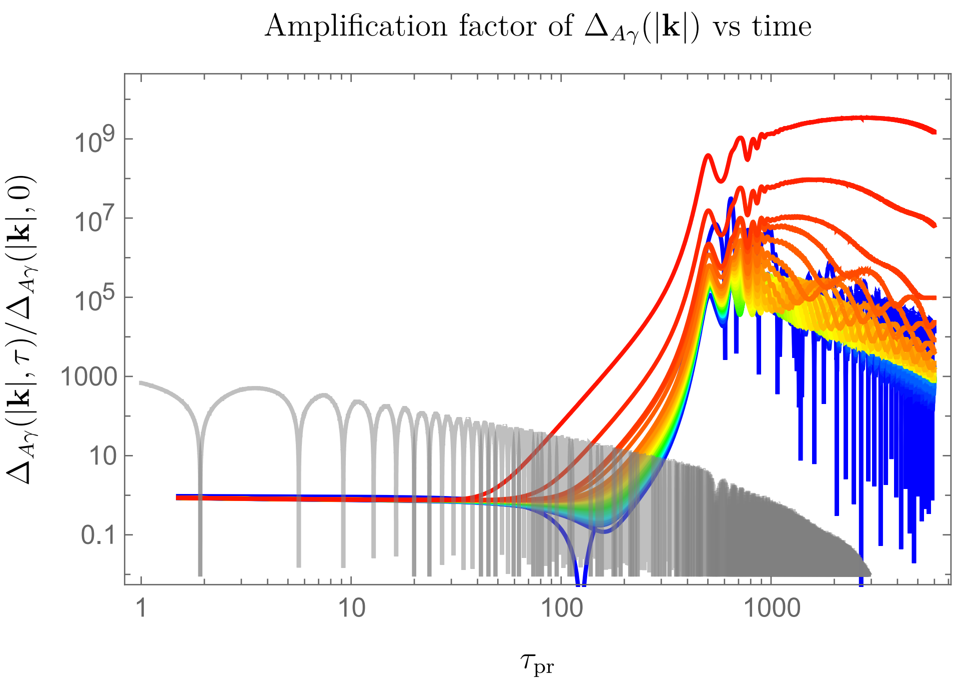
Model B

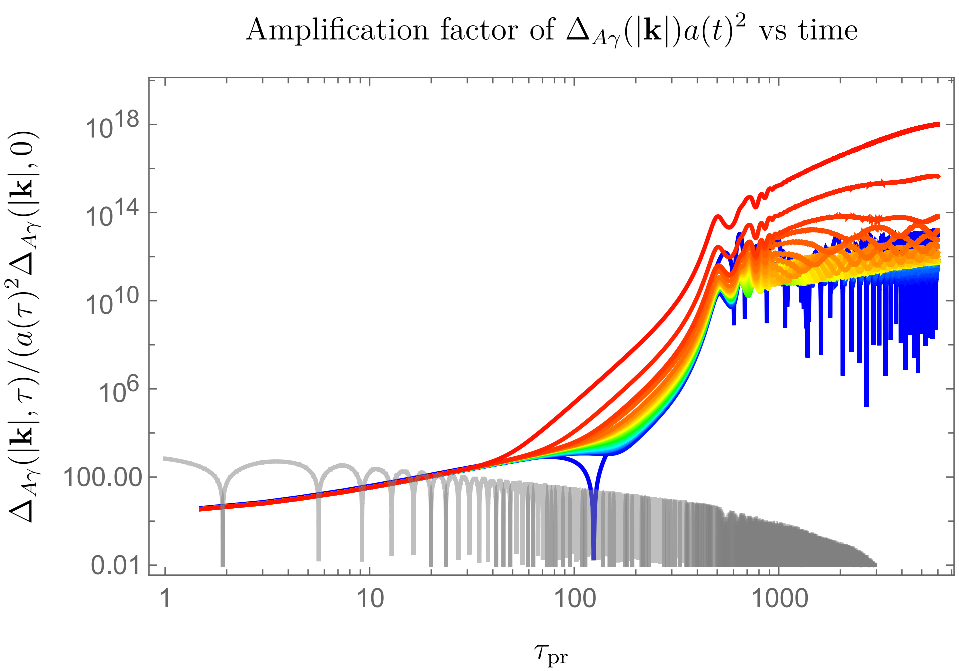
In model B, requiring axion to be aligned with field 2 gives potential energy valley with positive effective mass → **no effective potential well**!



With **no well**, **enhancement of fluctuations** can be more efficient than for model A…
Adding a VEV for ϕ_1 would give back an axion-inflaton model of type A.

Model B





Much higher amplification than in model A

Conclusions

The life of an axion isocurvature mode is richer than it was thought.

Traditional arguments for computing axion isocurvature perturbations are based on **invalid assumptions** of **masslessness** and **freezout** at horizon crossing

The axion **isocurvature** perturbation can evolve rather dramatically after inflation, with **early exponential growth and late-time decay**

GUT-scale f_A helps in avoiding restoration of PQ symmetry

The **simplest models don't seem to work** as the extrapolation of the isocurvature power spectrum to CMB scales gives values incompatible with Planck bounds

We are axing simple pre-inflationary axion models