SM*A*S*H
H
A
ρ
u d e ν1
Q
N1
c s μ ν2
N2
t b τ ν3
N3
g W Z γ

based on

Articles:

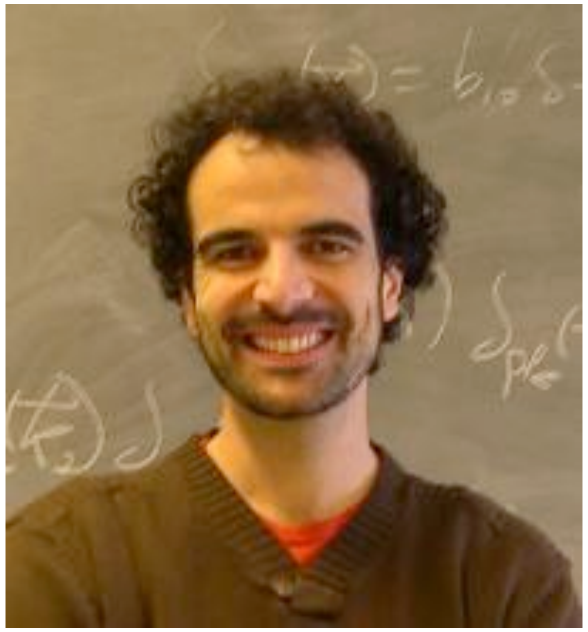
- Unifying Inflation with the Axion, Dark Matter, Baryogenesis, and the Seesaw Mechanism PRL 118, 071802 (2017)

- Standard Model-Axion-Seesaw-Higgs Portal Inflation. Five problems of particle physics and cosmology solved in one stroke e-Print: arXiv:1610.01639 [hep-ph] | PDF (submitted to JCAP)

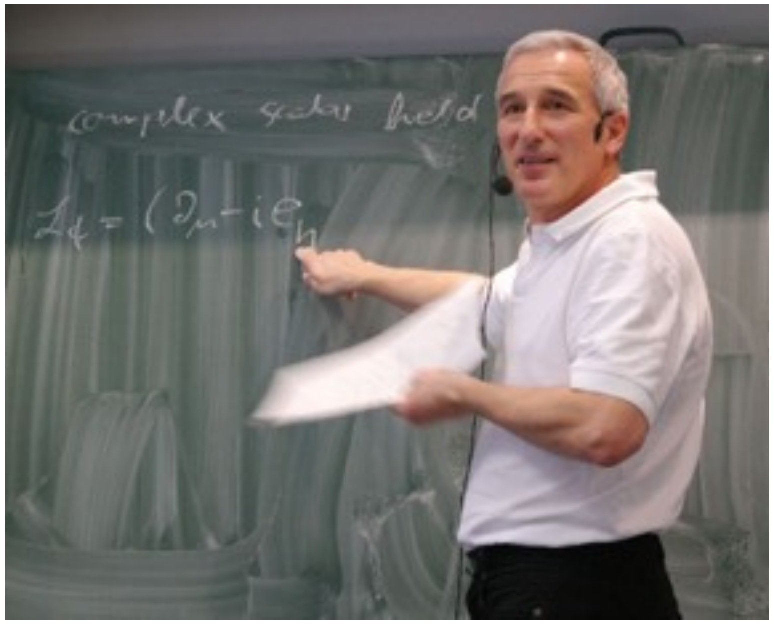
In collaboration with:

Carlos Tamarit
(IPPP Durham)

Guillermo Ballesteros
(Saclay)



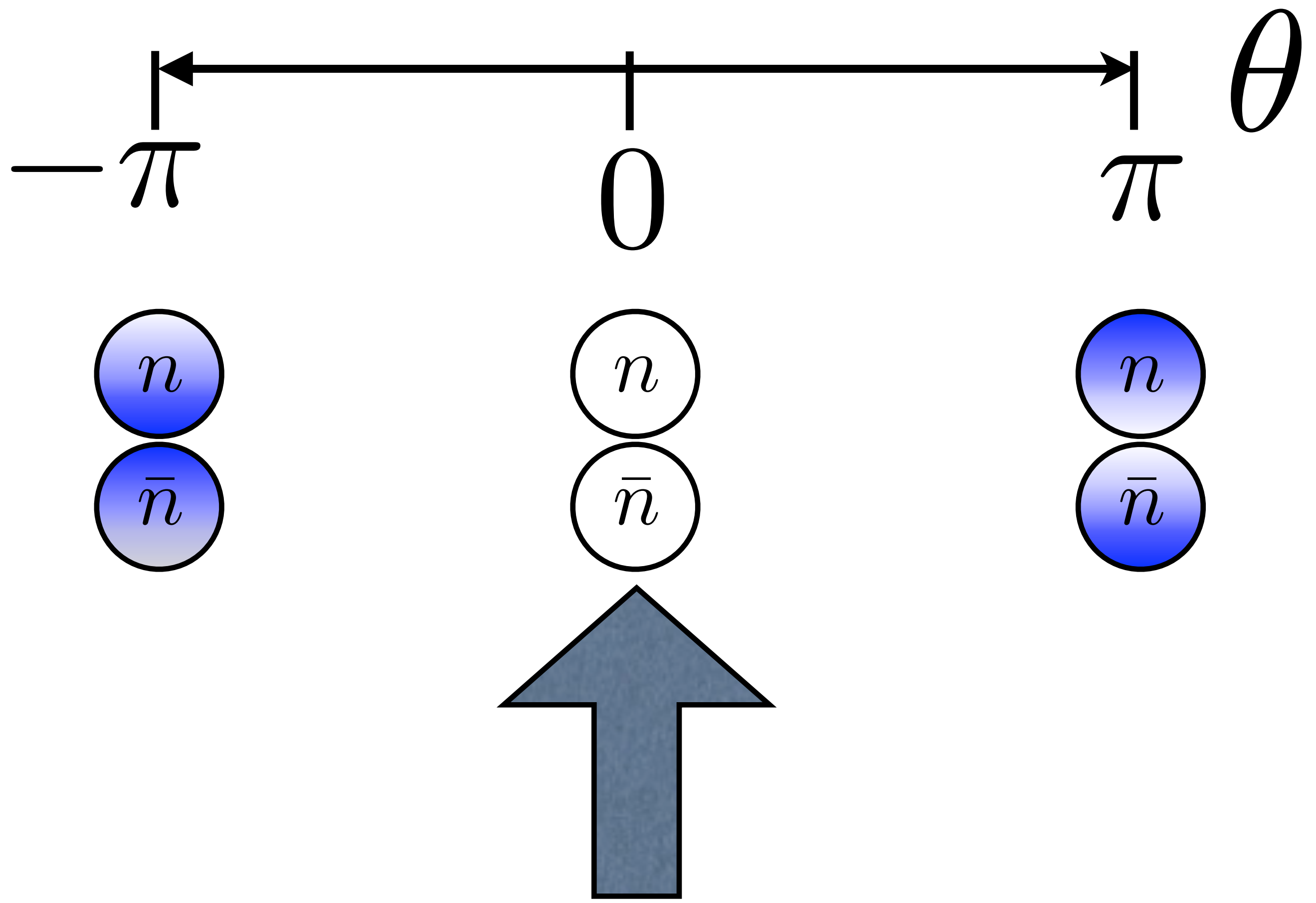
Andreas Ringwald
(DESY)



Javier Redondo
(Zaragoza U.)

The theta angle of the strong interactions

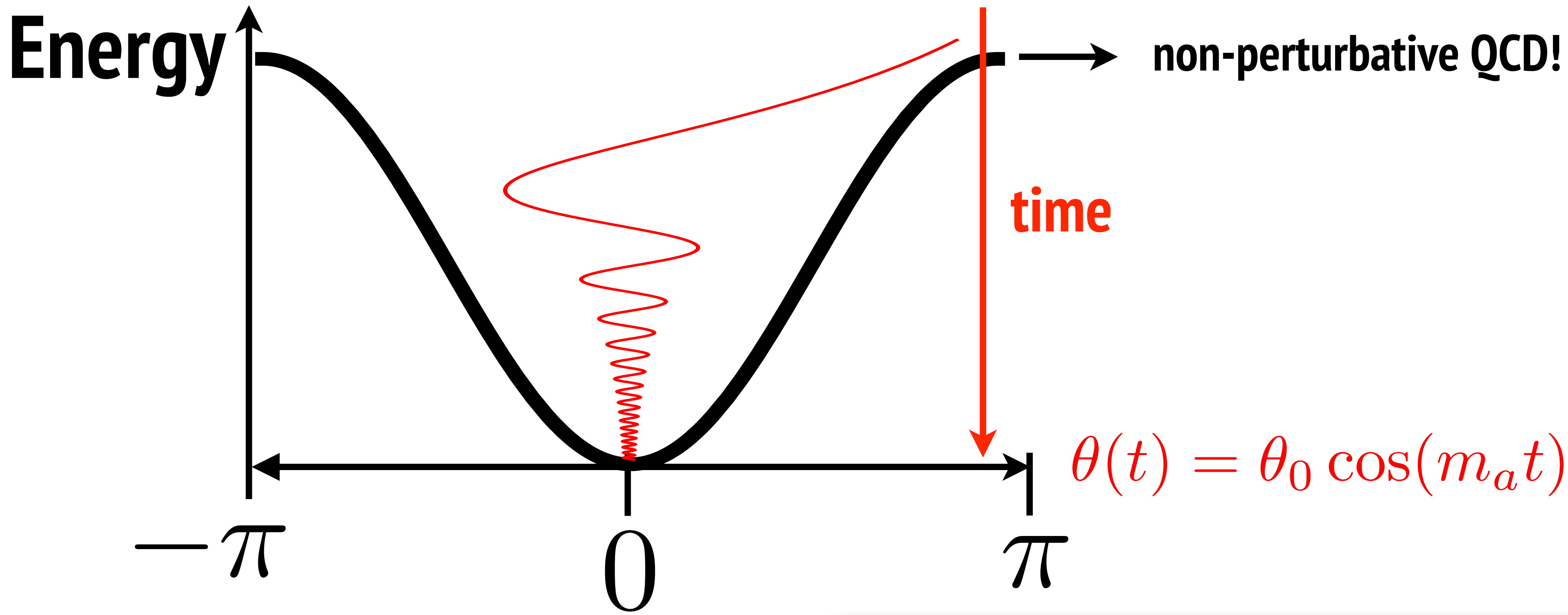
- The value of θ controls matter-antimatter differences in QCD



Measured today $|\theta| < 10^{-10}$ **(strong CP problem)**

Axions are necessarily dark matter

- is it a dynamical field? $\theta(t, \mathbf{x})$

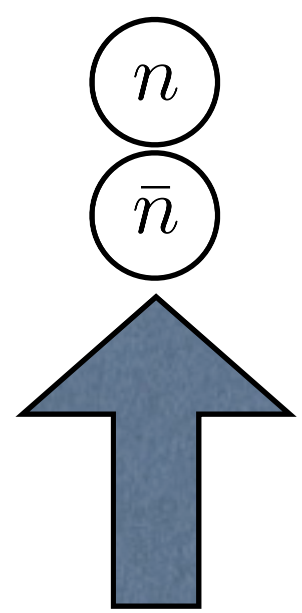


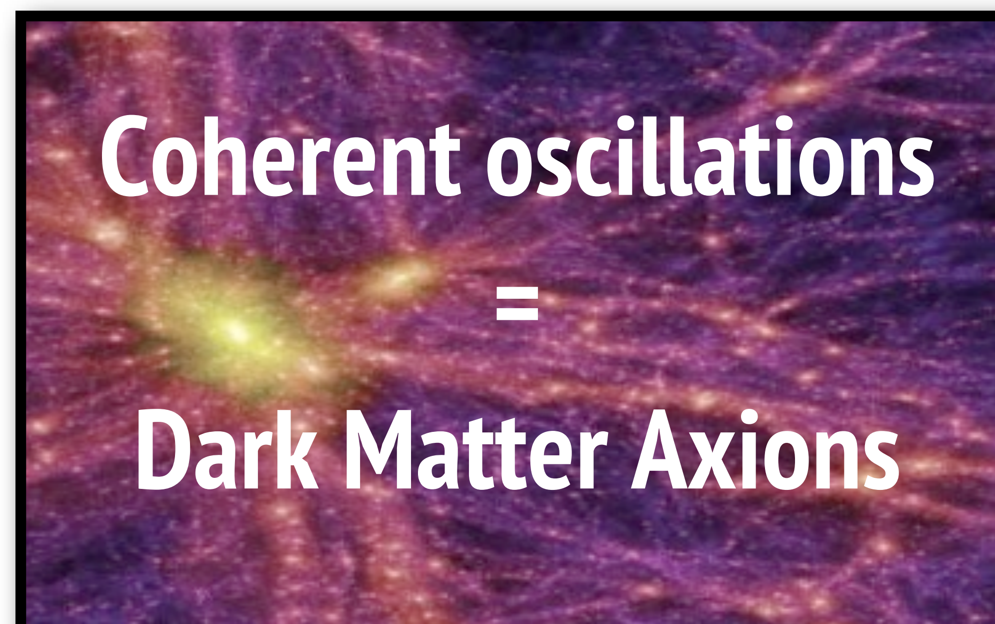
~ One parameter theory

$$\theta(t, x) = a(t, x)/f_a$$

axion mass

$$m_a = 6\,\mathrm{meV}\,\frac{10^9\,\mathrm{GeV}}{f_a}$$



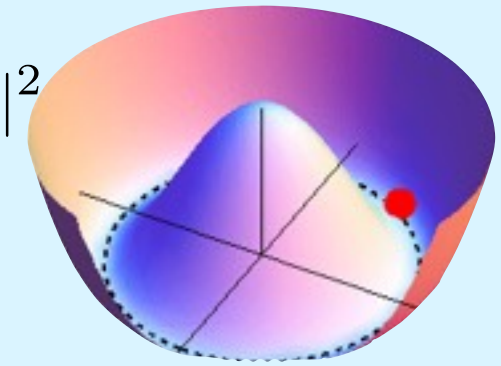


Measured today $|\theta| < 10^{-10}$ **(strong CP problem)**

Simple model KSVZ

- Peccei-Quinn symmetry, color anomalous, spontaneously broken at f_a

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{Q}DQ + \frac{1}{2}(\partial_\mu\sigma)(\partial^\mu\sigma^*) - (y\bar{Q}_L Q_R\sigma + {\rm h.c}) - \lambda|\sigma|^4 + \mu^2|\sigma|^2$$



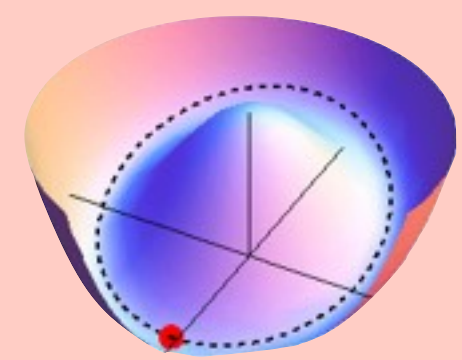
$$\sigma(x) = \rho(x)e^{i\frac{a(x)}{f_a}} \qquad f_a = \sqrt{\mu^2/2\lambda}$$

- At energies below f_a **(SSB)**

$$\mathcal{L} \in \frac{1}{2}(\partial a)^2 + \frac{\alpha_s}{8\pi}G\widetilde{G}\frac{a}{f_a}$$

- At energies below $\Lambda_{\rm QCD}$**,** $a - \eta' - \pi^0 - \eta - \ldots$ **mixing**

axion mass $m_a \simeq \frac{m_\pi f_\pi}{f_a} \sim 6{\rm meV}\frac{10^9{\rm GeV}}{f_a}$



couplings $\mathcal{L}_{a,I} = \sum_N c_{N,a}\bar{N}\gamma^\mu\gamma_5 N\frac{a}{f_a} + c_{a\gamma}\frac{\alpha}{2\pi}F_{\mu\nu}\widetilde{F}^{\mu\nu}\frac{a}{f_a} + \ldots$

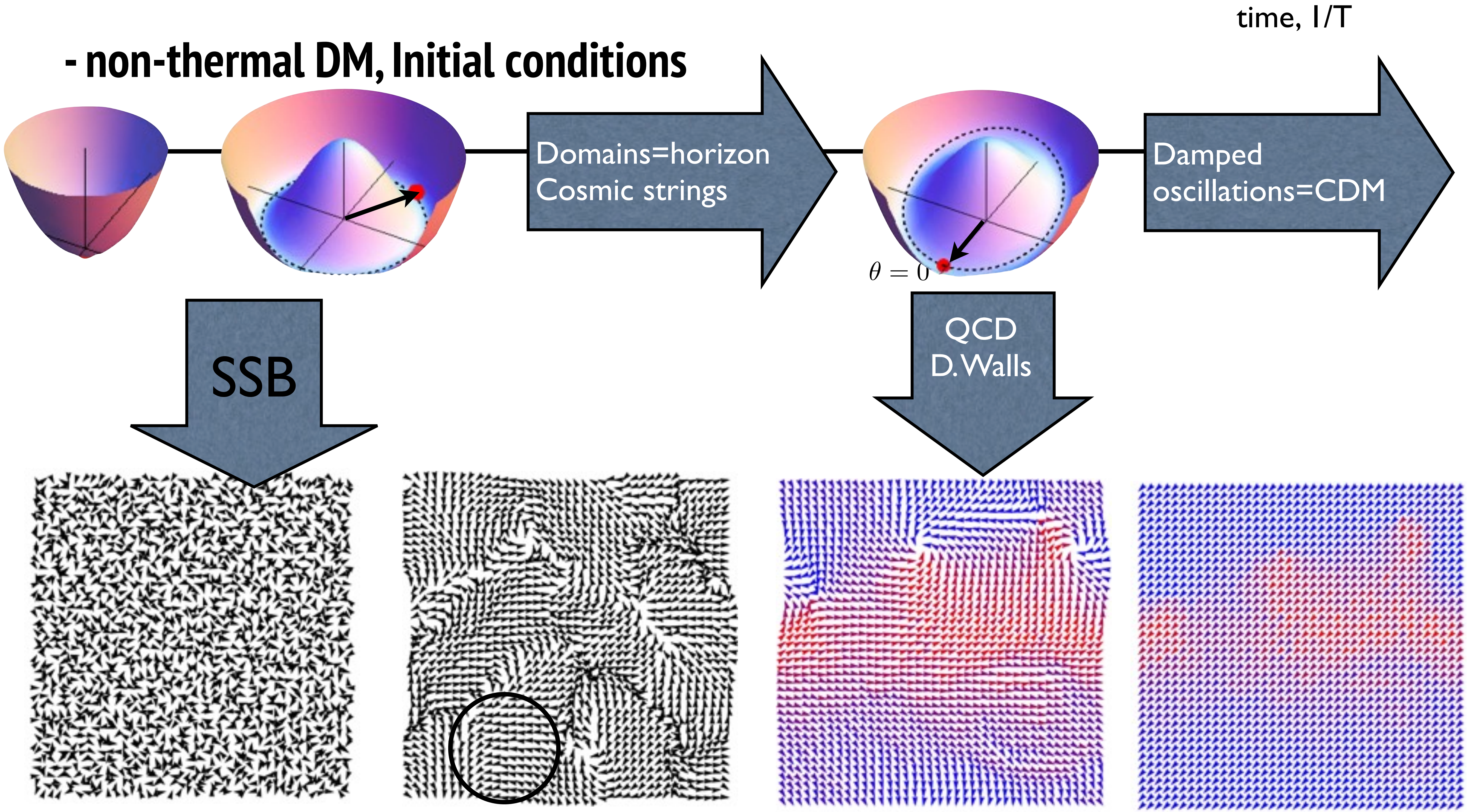
nucleons ... photons ... mesons ...

ENERGY (axis: $\sim f_a$, **~GeV**)

Vacuum realignment, strings, walls...

- **Axions: small mass, small interactions, ~~thermal DM~~**

- **non-thermal DM, Initial conditions**



Vacuum realignment, strings, walls...

- Axions: small mas

- non-thermal DM,

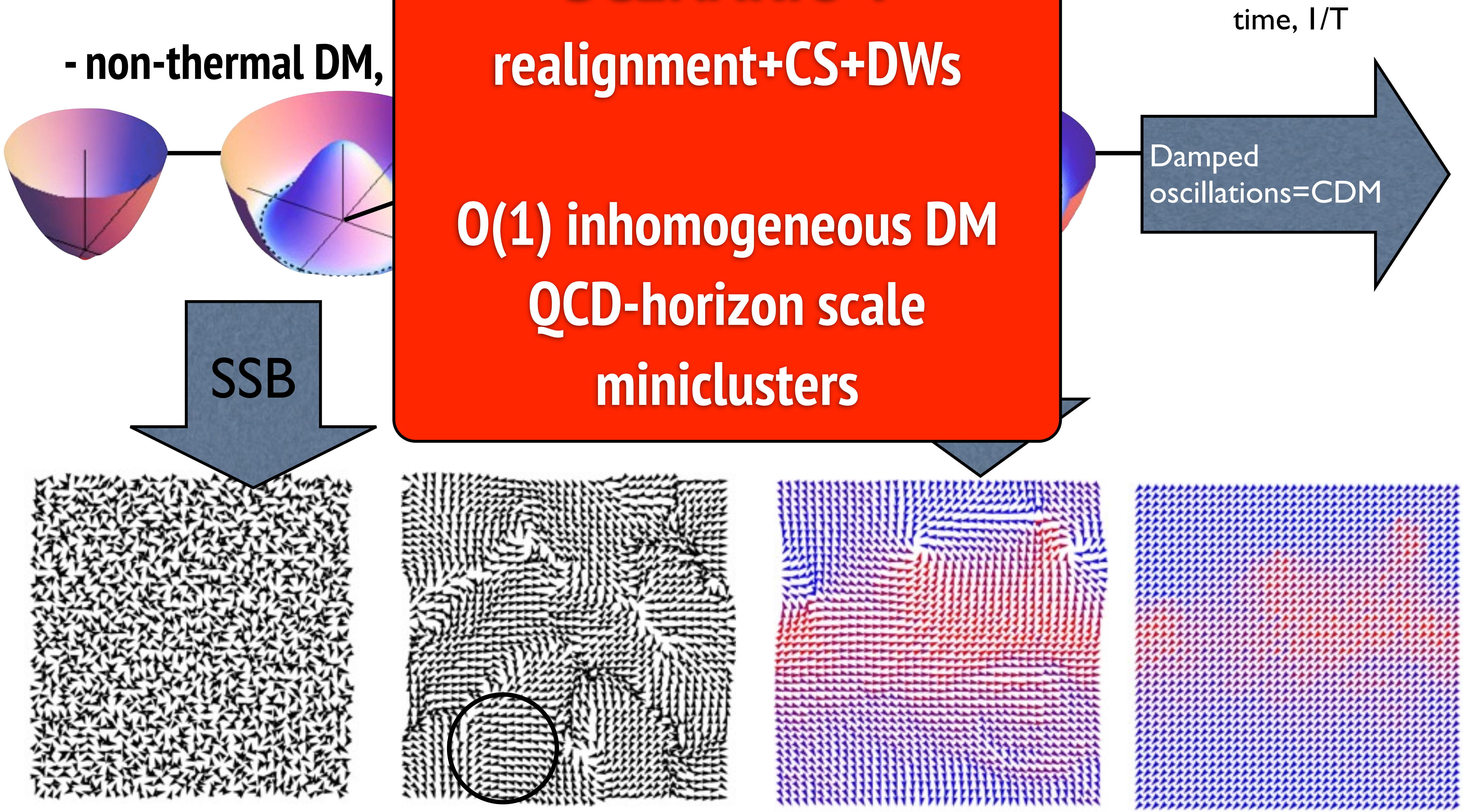
SCENARIO-I

realignment+CS+DWs

O(1) inhomogeneous DM

QCD-horizon scale

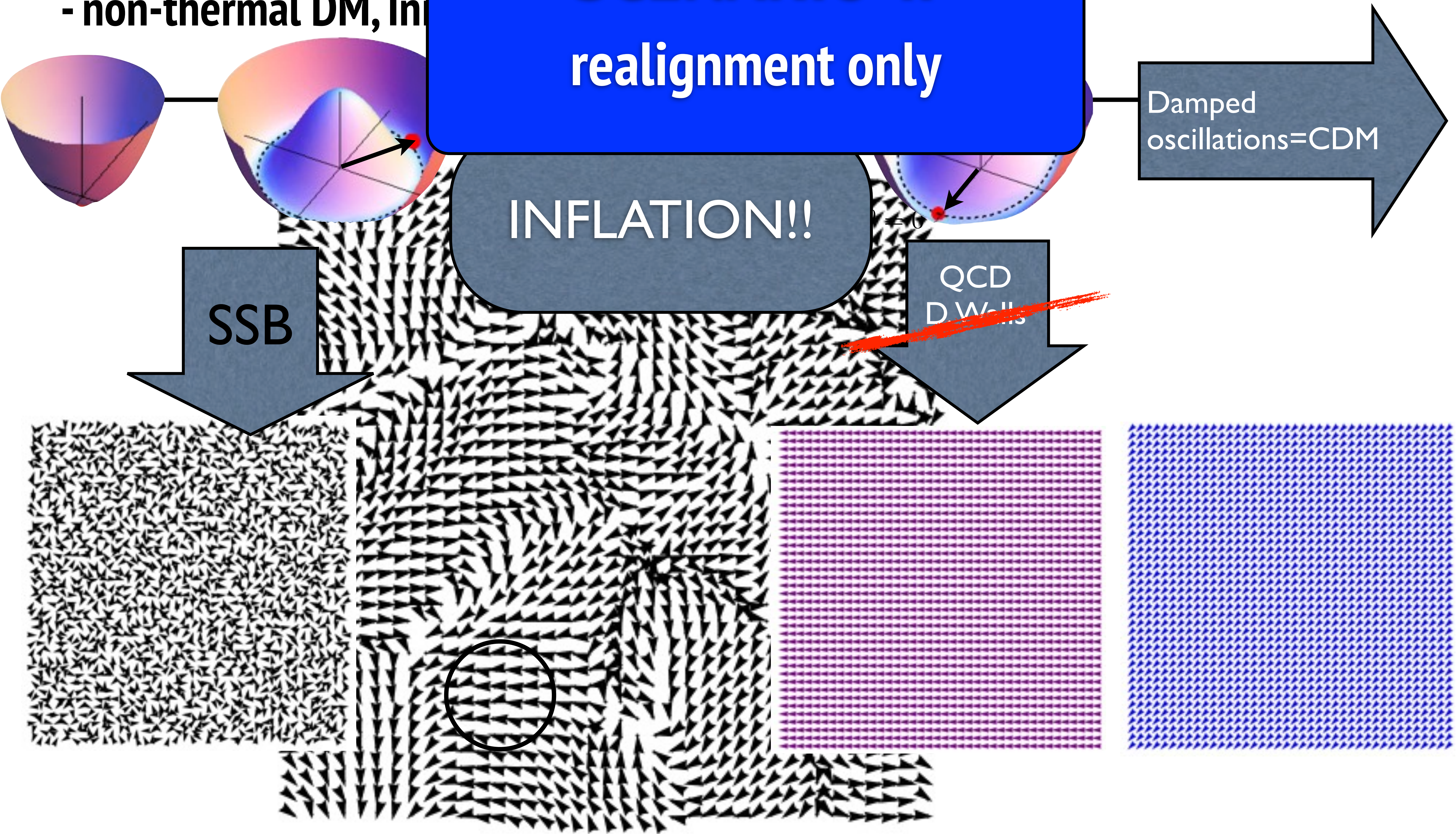
miniclusters



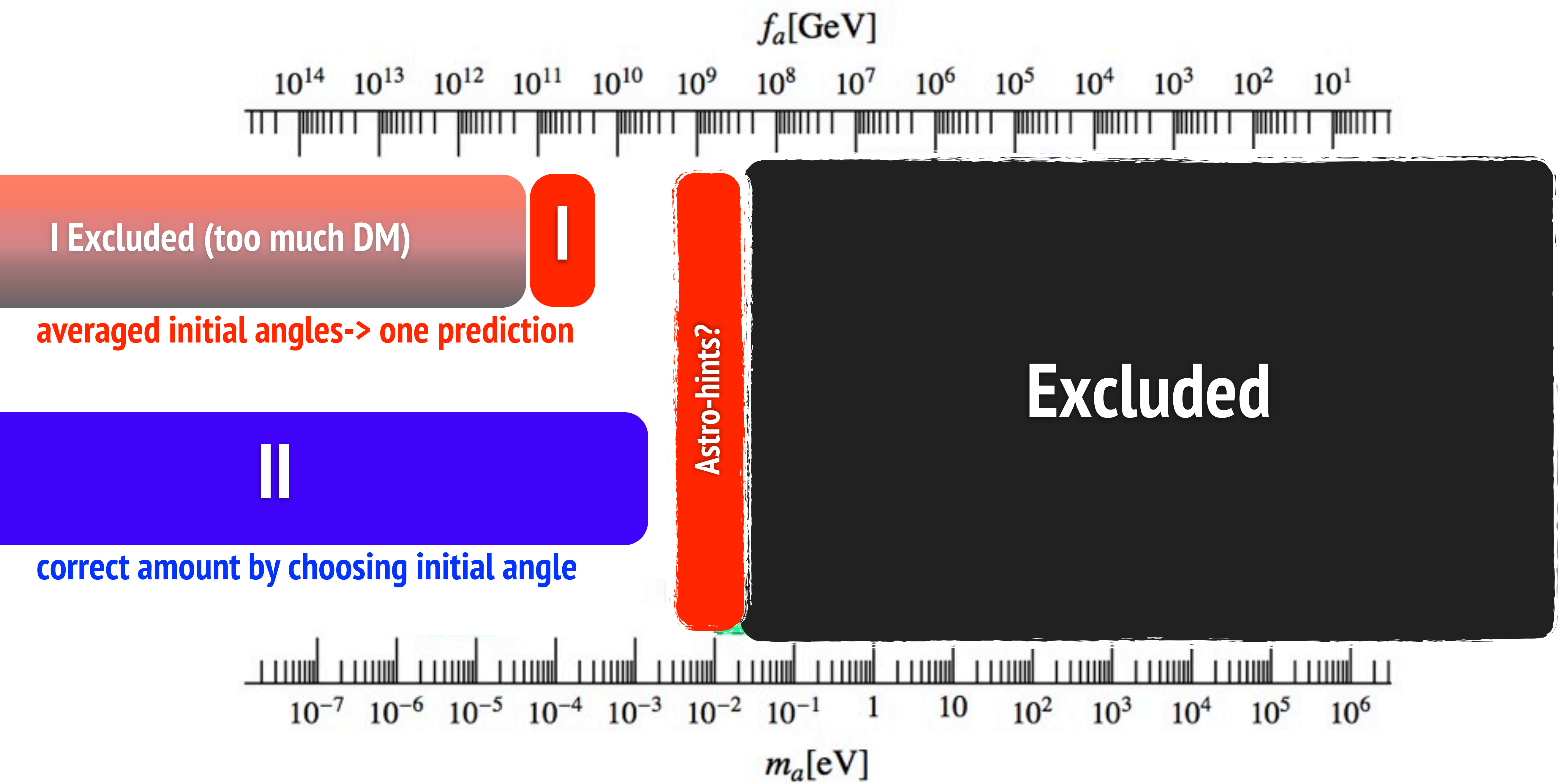
Vacuum realignment, strings, walls...

- Axions: small mass, small interactions thermal DM

- non-thermal DM, Ini



Axion dark matter

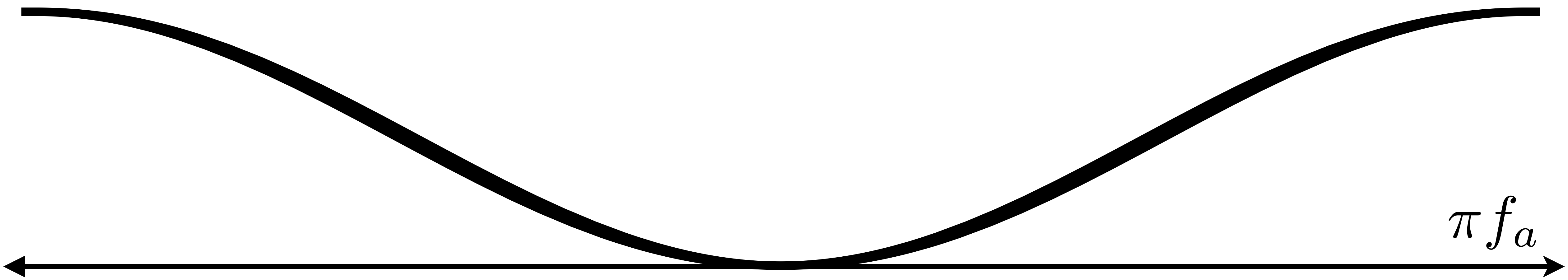


If axions exist, they are very light and VERY weakly interacting!

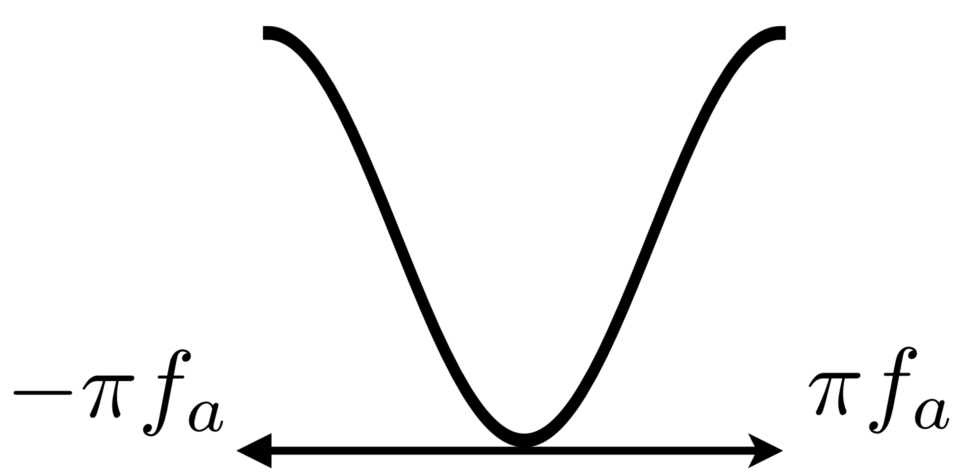
Axion dark matter

- The amount of axion DM produced depends on fa

- large fa, small curvature, oscillations start later->more DM



- small fa, large curvature, oscillations start earlier -> less DM



I or II ?

- Completely model dependent

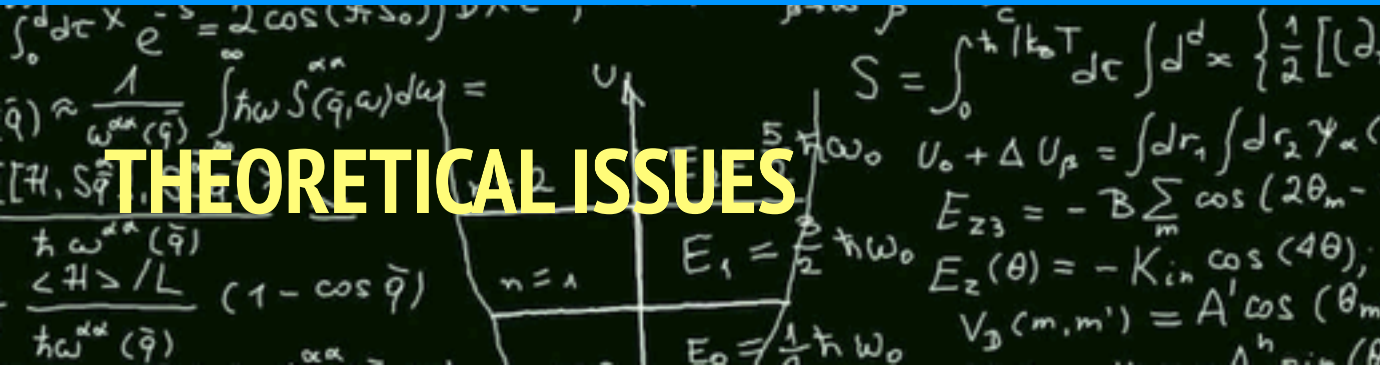
- what about the minimal model?

The minimal model is constrained by its embedding in a consistent picture of particle physics and cosmology

SMASH!

SM Axion See saw Hidden-scalar-Inflation

Beyond the Standard model of Particle Physics ...

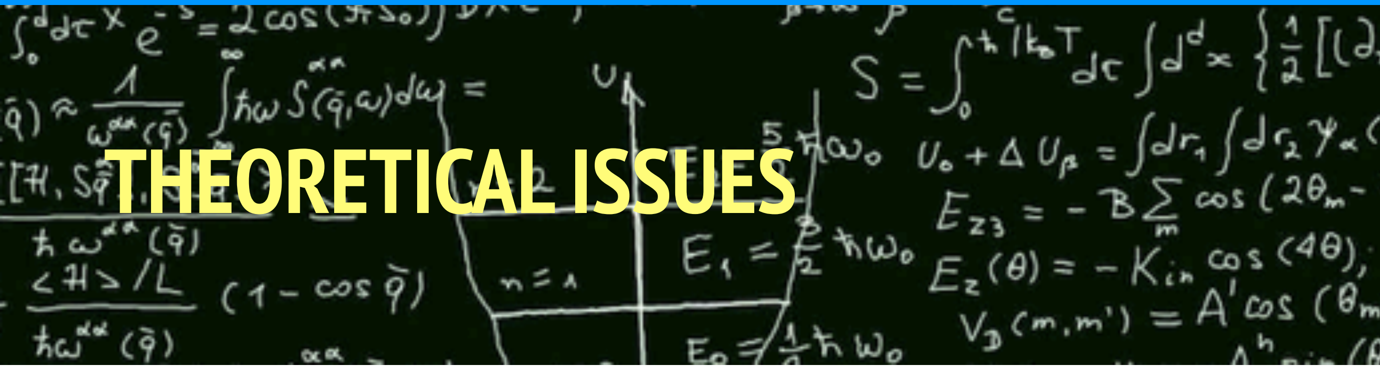


- quantum gravity?
- hierarchy issue/problem
- strong CP issue/problem
- neutrino masses
- why three generations?

- unification of forces?
- supersymmetry?

- dark matter
- dark energy
- baryon asymmetry
- inflation
- Higgs potential instability

SMASH: the power of a new scalar



THEORETICAL ISSUES

- quantum gravity? (postponed to Mp scales)
- hierarchy issue/problem
- strong CP issue/problem (axion)
- neutrino masses (RH neutrinos)
- why three generations?
- unification of forces?
- supersymmetry?

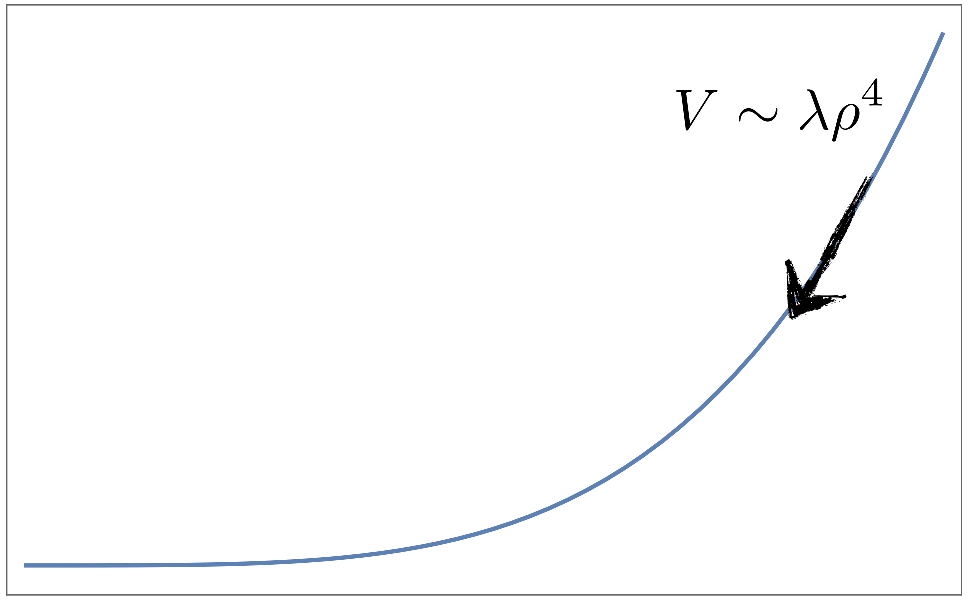
COSMOLOGY ISSUES

- dark matter (axion)
- dark energy $(\ldots\Lambda)$
- baryon asymmetry (RH nu)
- inflation (new scalar)
- Higgs potential instability (new scalar)

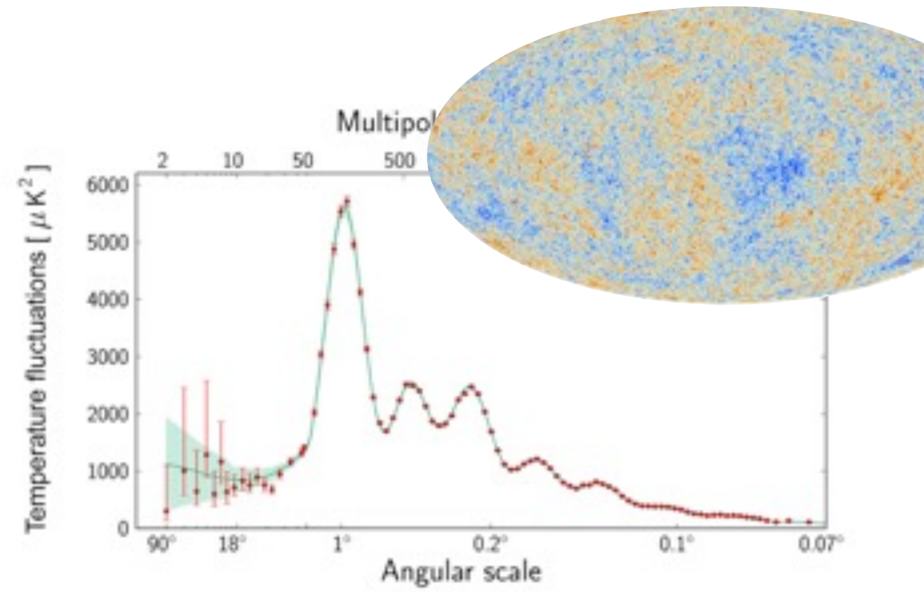
Objective:
built a <u>consistent</u>, <u>predictive</u>, <u>testable</u> <u>~minimal</u> model of HEP and cosmology
try to solve the most pressing problems, allow fine-tunings,

Inflation

- **Explains the flatness, homogeneity and <u>inhomogeneity</u> of the Universe**
- **Based on a period of exponential expansion of the Universe, driven by potential energy** $R \propto e^{\sqrt{V}t}$



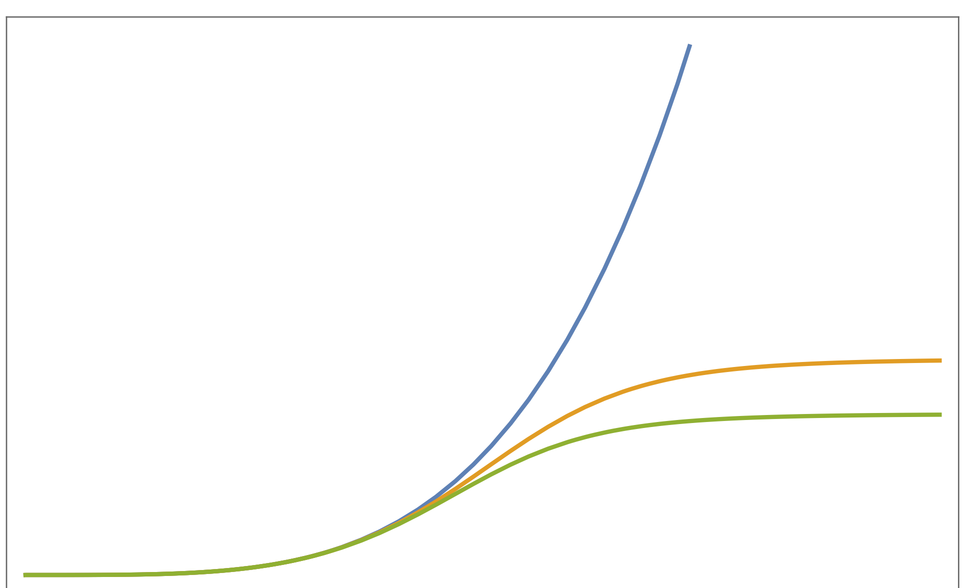
quantum fluctuations ⟶



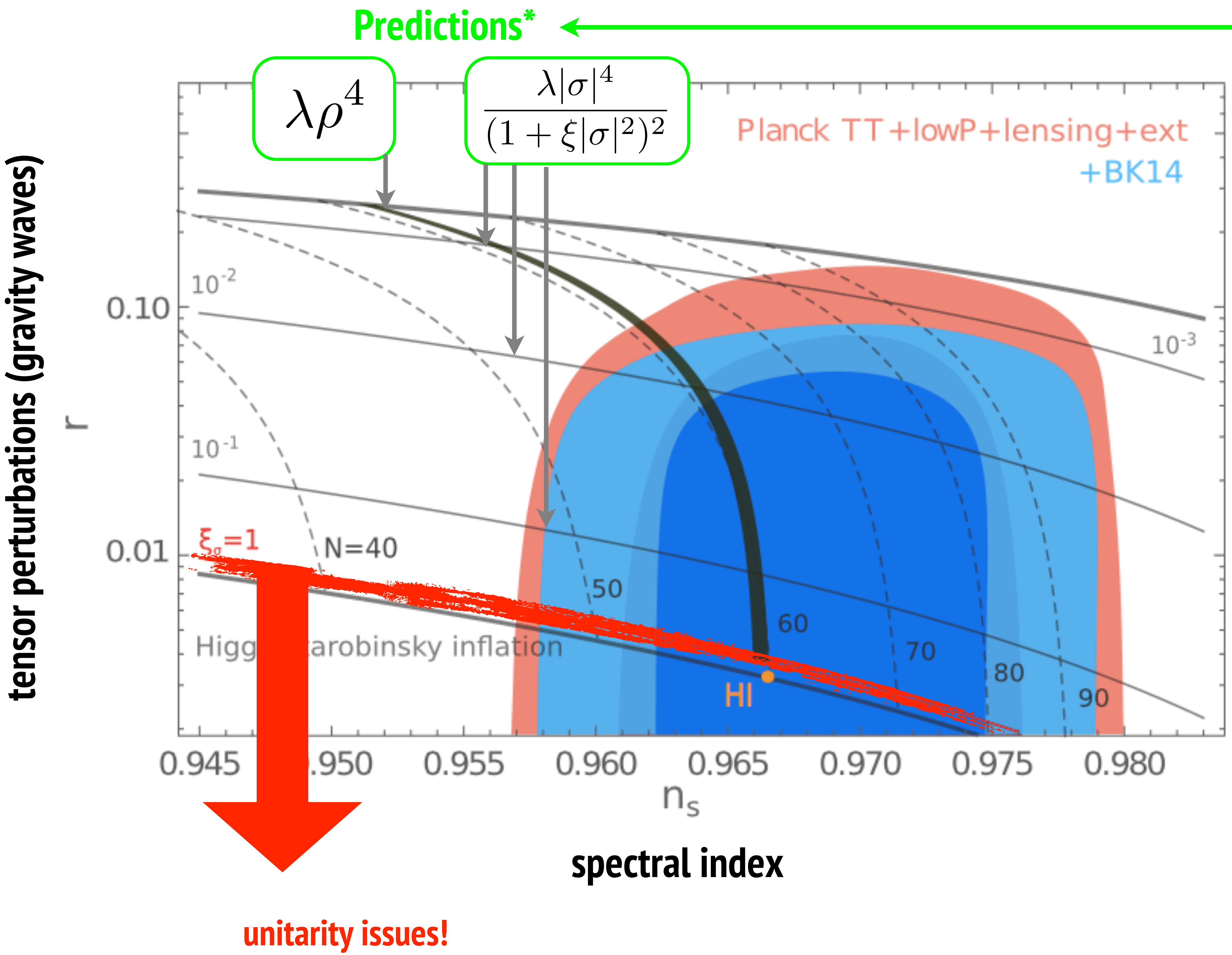
We need* to introduce a non-minimal coupling to gravity

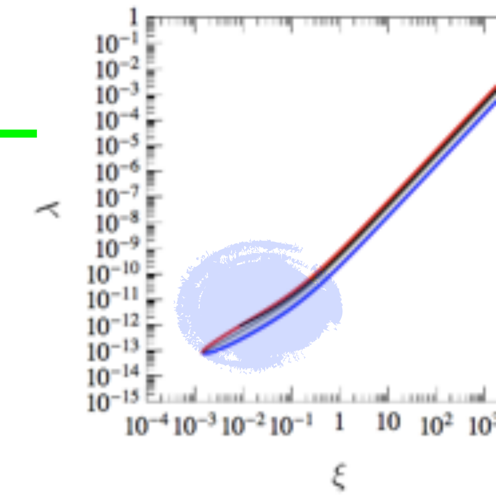
$$\mathcal{L} \ni \left(\frac{M_p^2}{2} + \xi|\sigma|^2 \right) R - \lambda|\sigma|^4 \longrightarrow \textbf{coordinate change} \longrightarrow \mathcal{L}' \ni -\frac{\lambda|\sigma|^4}{(1+\xi|\sigma|^2)^2}$$

flatter potentials, less gravity waves

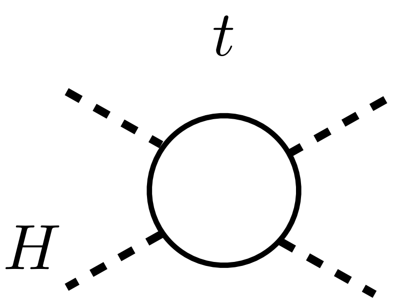


Fitting the CMB I

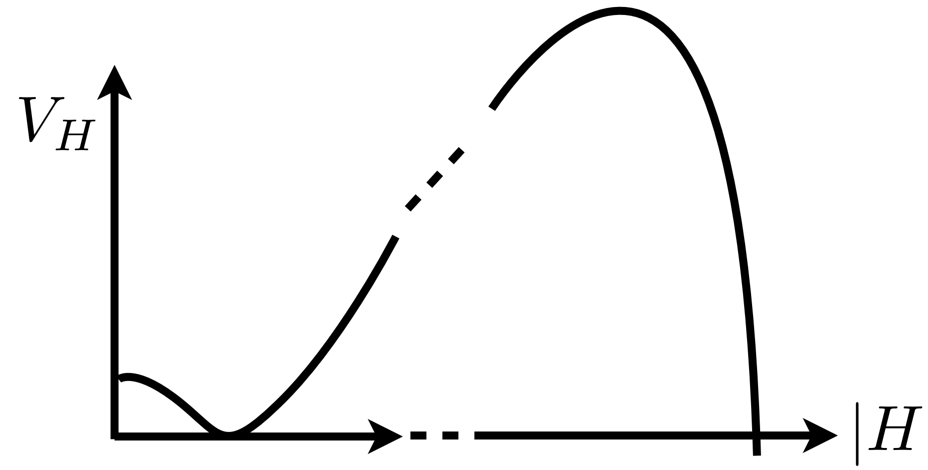




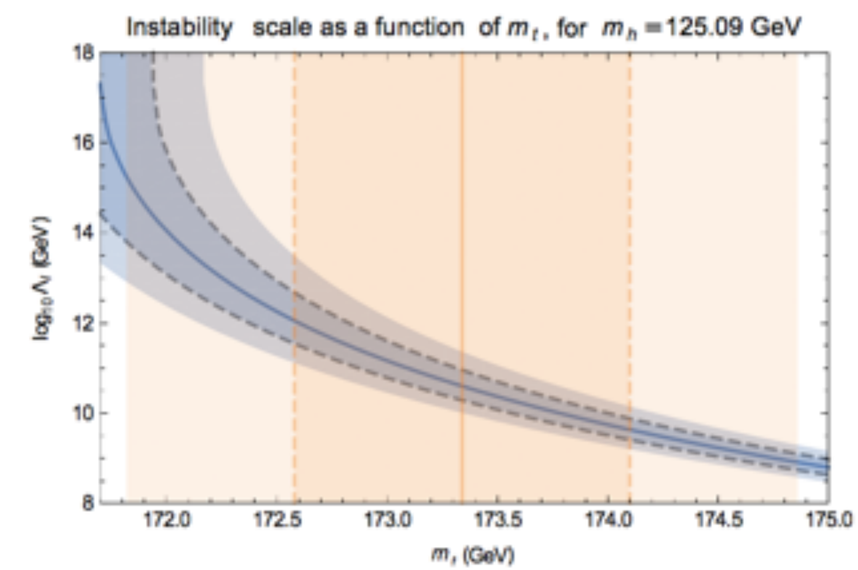
Higgs potential instability



makes λ_H run negative at large energies



$\Lambda_I \sim 10^{11}\mathrm{GeV}$



Portal coupling $\mathcal{L} \ni \lambda_{H\sigma}|\sigma|^2|H|^2$ has stabilizing effect

$$V_{\rm SMASH} = \lambda_H(|H|^2 - v^2)^2 + \lambda_{H\sigma}(|H|^2 - v^2)(|\sigma|^2 - f_a^2) + \lambda_\sigma(|\sigma|^2 - f_a^2)^2$$

at low energies, $\rho = \rho(|H|)$

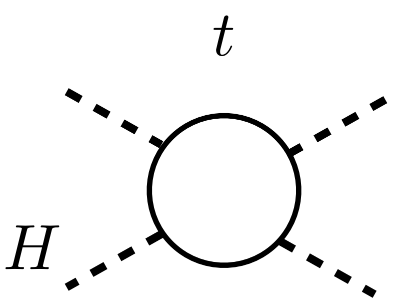
$$V_{\rm SM} = \left(\lambda_H - \frac{\lambda_{H\sigma}^2}{\lambda_\sigma}\right)(|H|^2 - v^2)^2$$

$$m_h \sim \sqrt{\bar{\lambda}_H} v = 125\,\mathrm{GeV}$$

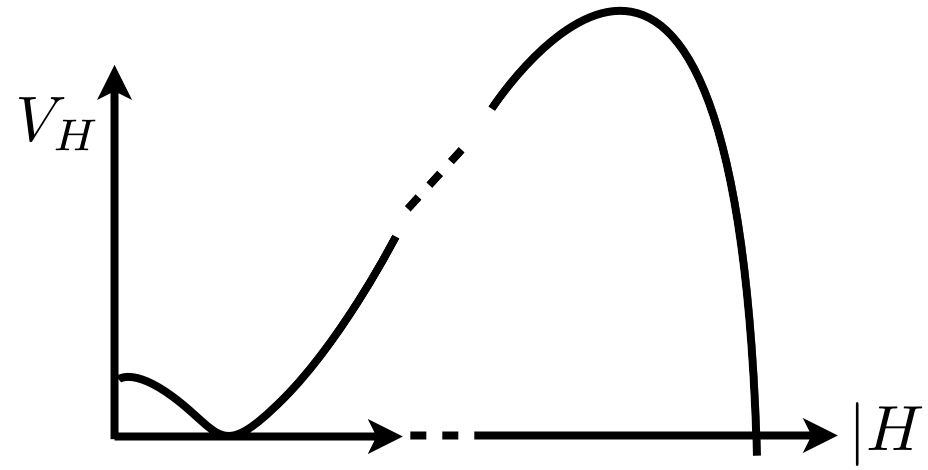
$$\bar{\lambda}_H = \lambda_H - \frac{\lambda_{H\sigma}^2}{\lambda_\sigma} = 0.132$$

λ_H in SMASH is larger than the SM measurement implies!

Higgs potential instability



makes λ_H run negative at large energies



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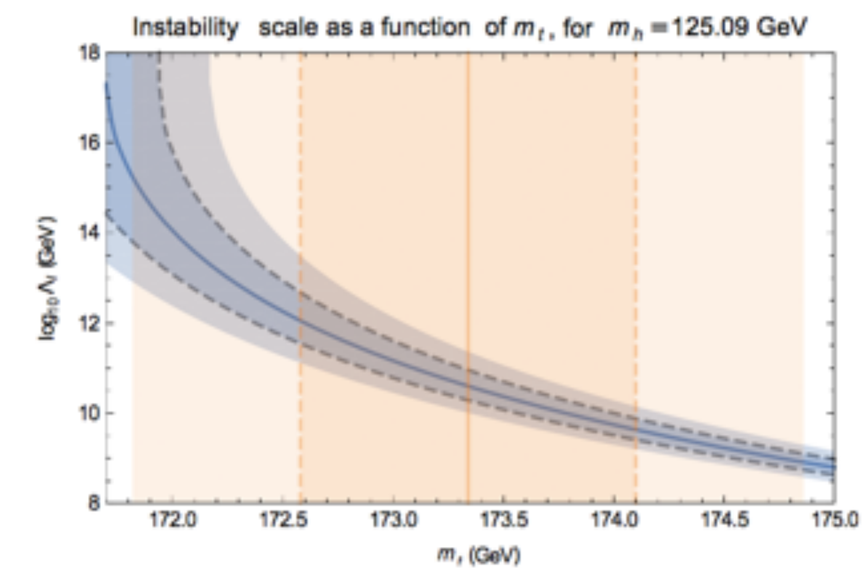
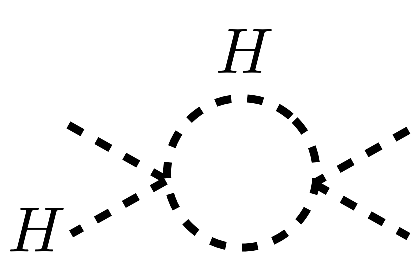


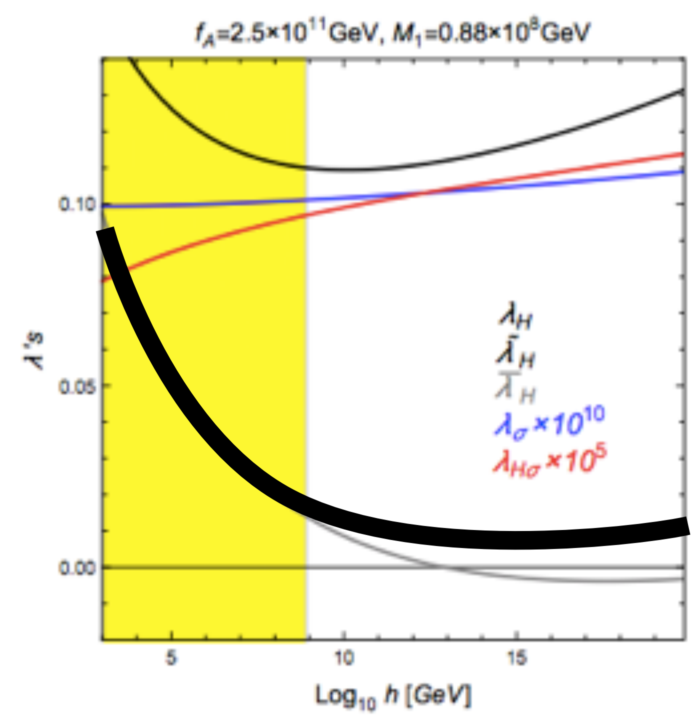
Portal coupling $\mathcal{L} \ni \lambda_{H\sigma}|\sigma|^2|H|^2$ **has stabilizing effect**

Higgs self-coupling in SMASH is larger



has positive sign

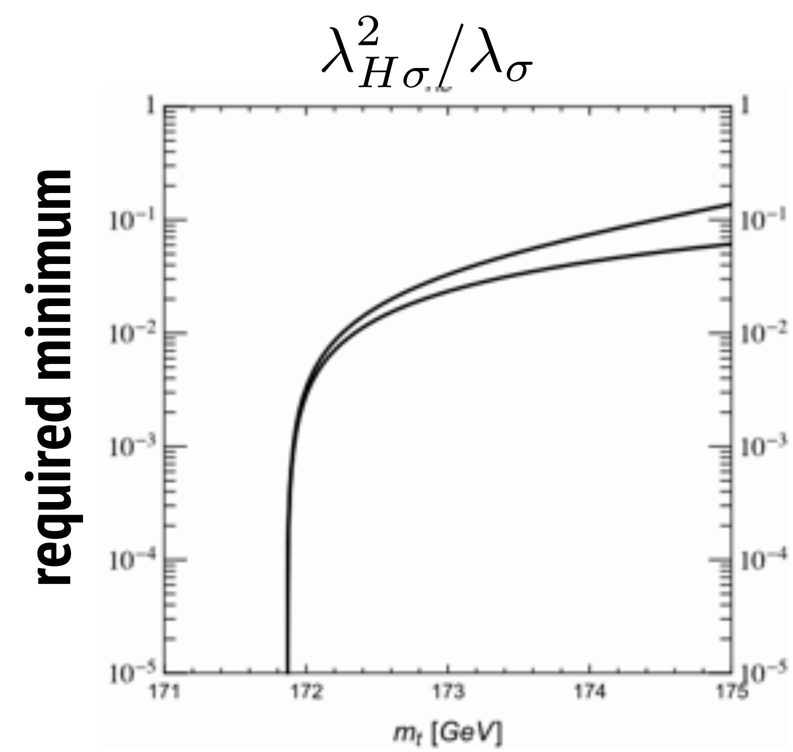
(non-linear effects larger!)



SMASH

SM

example



Neutrino masses, leptogenesis*

- Add 3 RH neutrinos, Majorana mass from Yukawas with new scalar!

$$\mathcal{L} \supset -\left[Y_{uij} q_i \epsilon H u_j + Y_{dij} q_i H^\dagger d_j + G_{ij} L_i H^\dagger E_j + F_{ij} L_i \epsilon H N_j + \boxed{\frac{1}{2} Y_{ij} \sigma N_i N_j}\right.$$

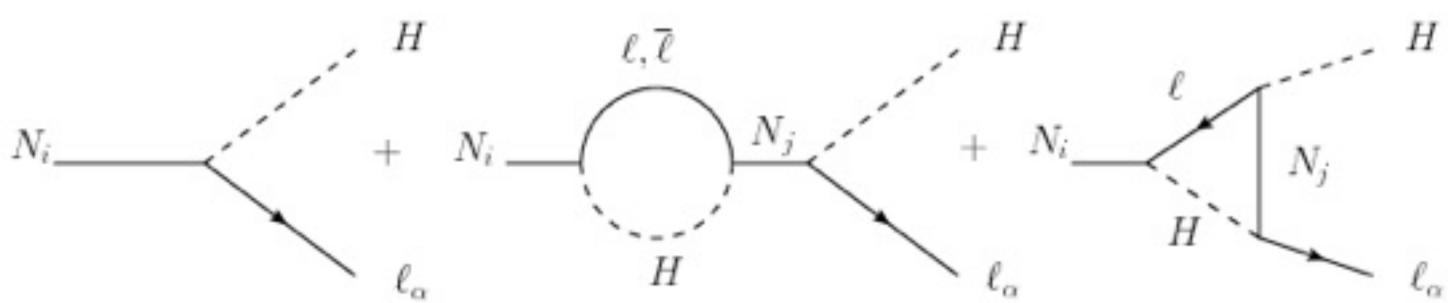
- See-saw mechanism

Neutrino mass matrix $$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & Fv \\ F^T v & Y v_\sigma \end{pmatrix}$$

Light (majorana) neutrinos without necessity of extremely small Dirac masses (F's)

$$m_\nu = -M_D M_M^{-1} M_D^T = -\frac{F Y^{-1} F^T}{\sqrt{2}} \frac{v^2}{v_\sigma} = 0.04\,\mathrm{eV} \left(\frac{10^{11}\,\mathrm{GeV}}{v_\sigma}\right) \left(\frac{-F Y^{-1} F^T}{10^{-4}}\right)$$

- Leptogenesis from heavy RH neutrinos $\Delta L \to \Delta B$



- Axion = majoron (PQ symmetry + Lepton number)

I or II ? SMASH cosmology

- **We have all ingredients and some freedom ...**

$$10^{-13} \lesssim \lambda \lesssim 10^{-9}$$

$(r < 0.1)$ $(\xi < 1)$

(CMB) **(unitarity)**

$$\lambda_{H\sigma}^2 \gtrsim 0.1\lambda$$

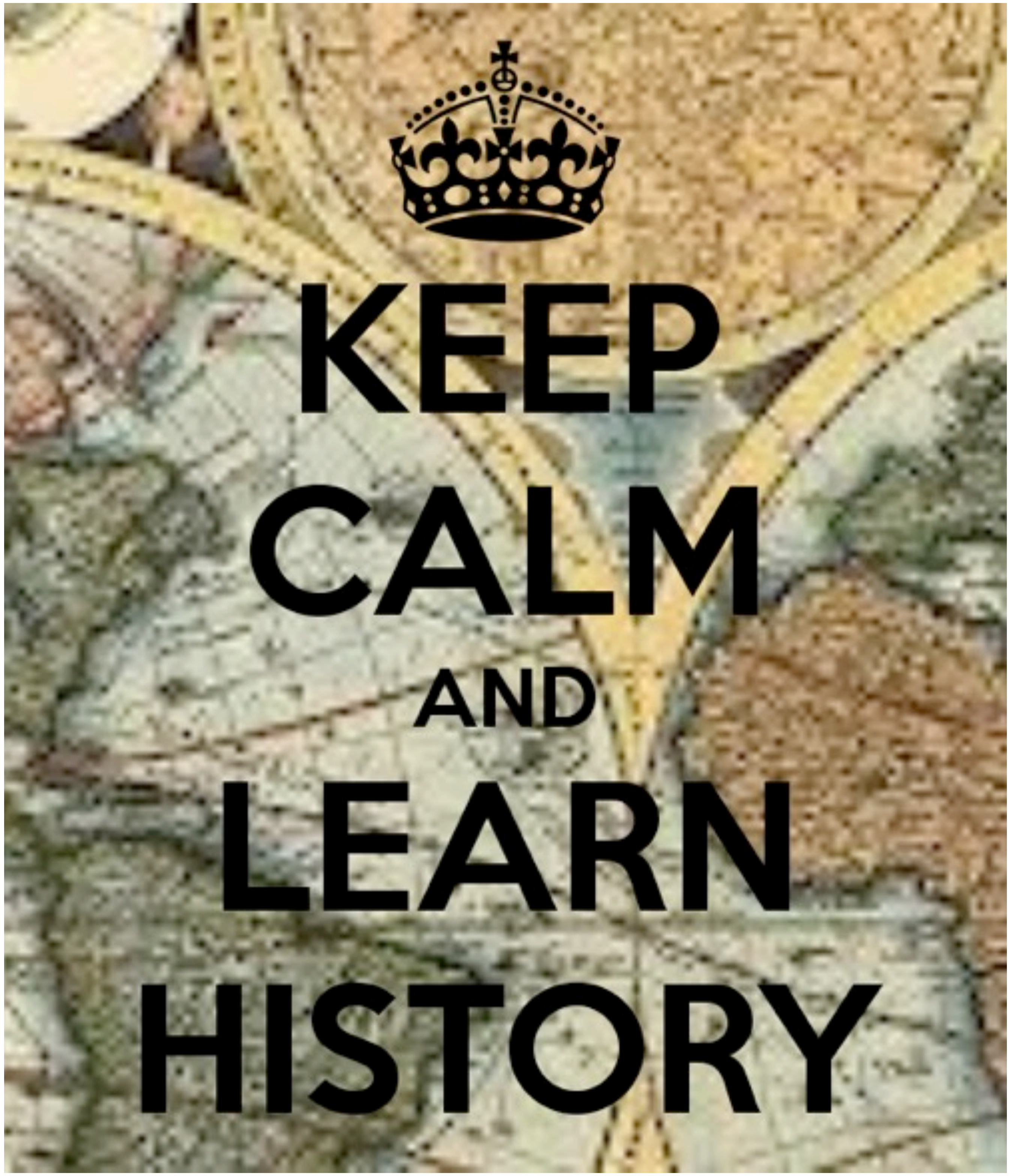
(stability)

$$F's, f_a$$

(nu masses and leptogenesis)

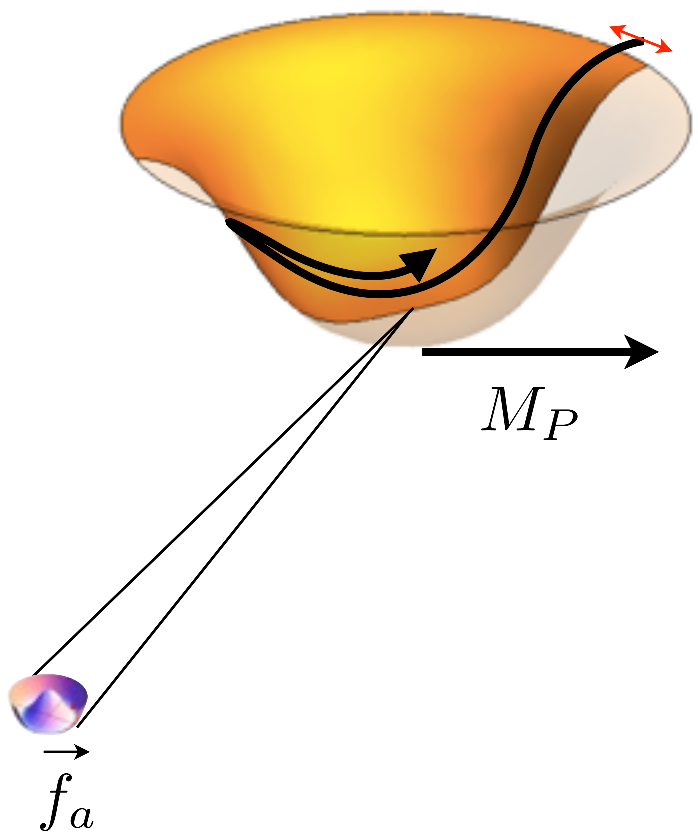
- **what f_a ? what scenario?**

SMASH history

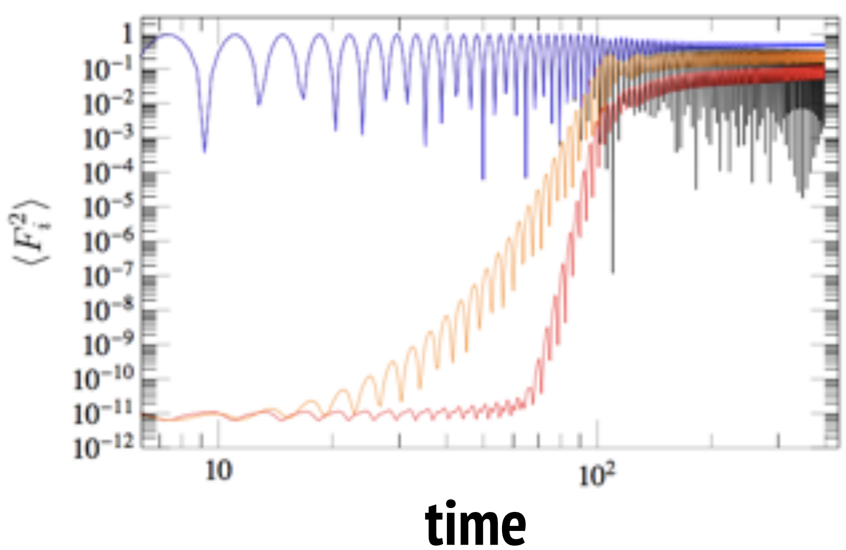


Reheating I : Non-thermal PQ restauration

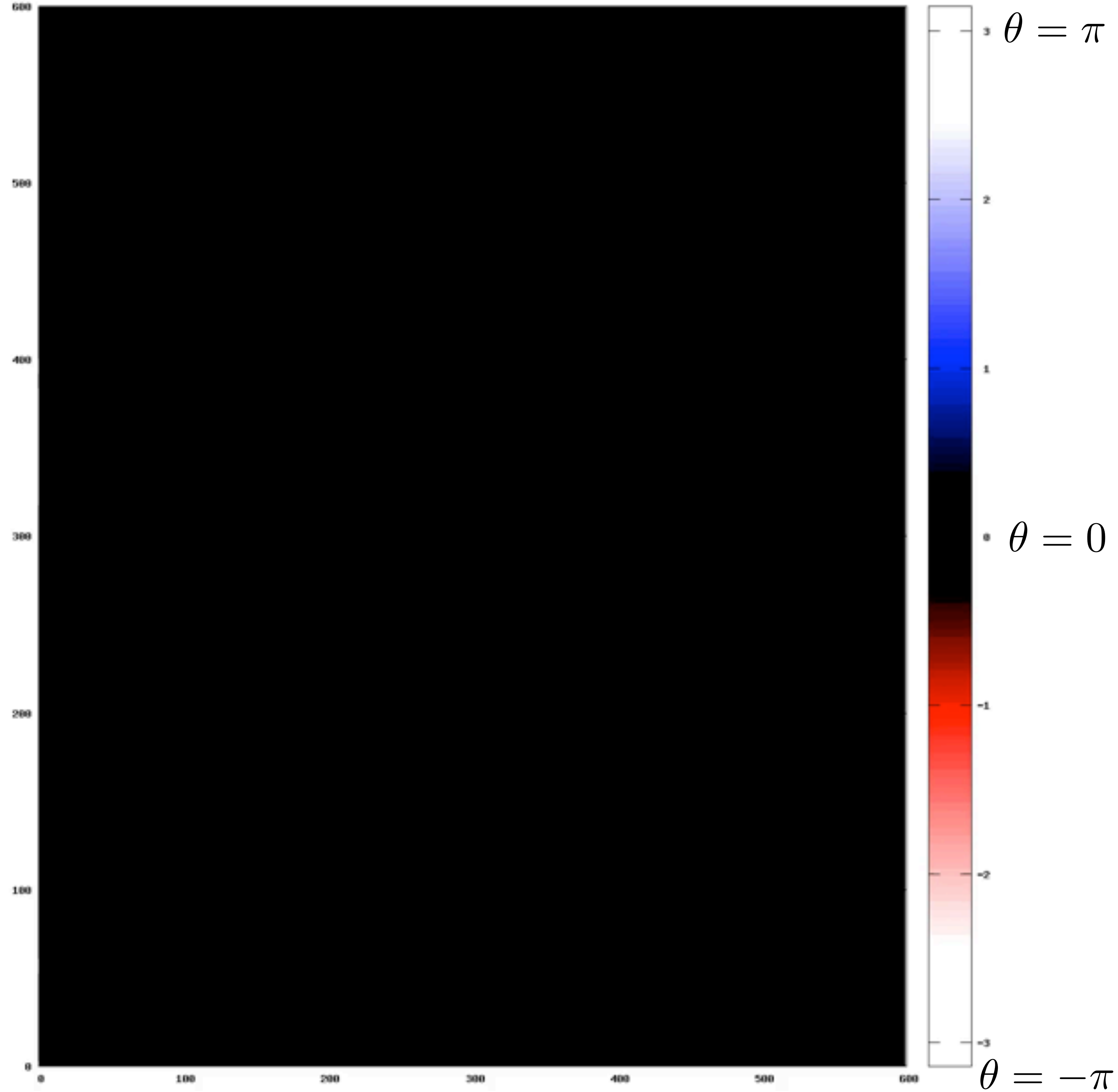
Quartic oscillations After inflation



fluctuations are amplified around $\rho \sim 0$ by parametric resonance



$\theta = \arg(\sigma)$ **in a slice of the Universe**



Reheating I : Non-thermal PQ restauration

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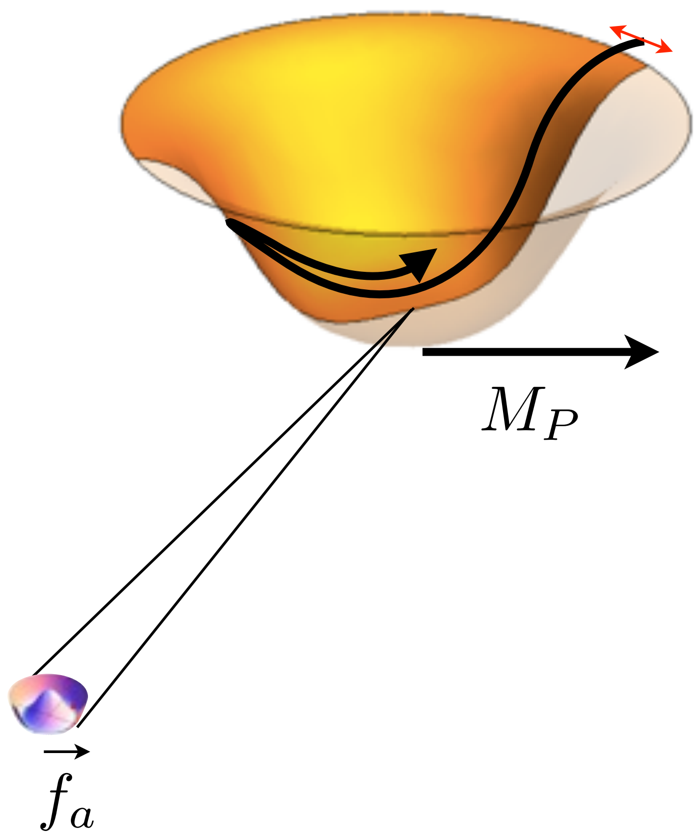

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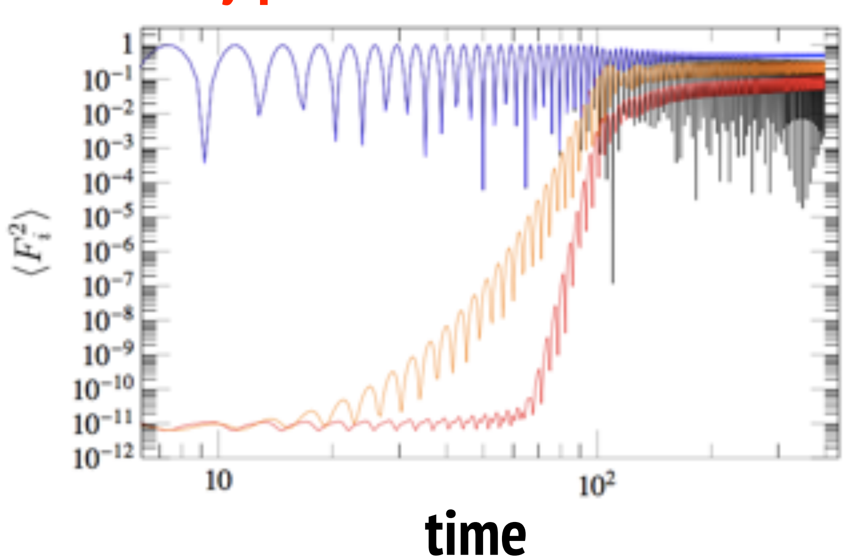
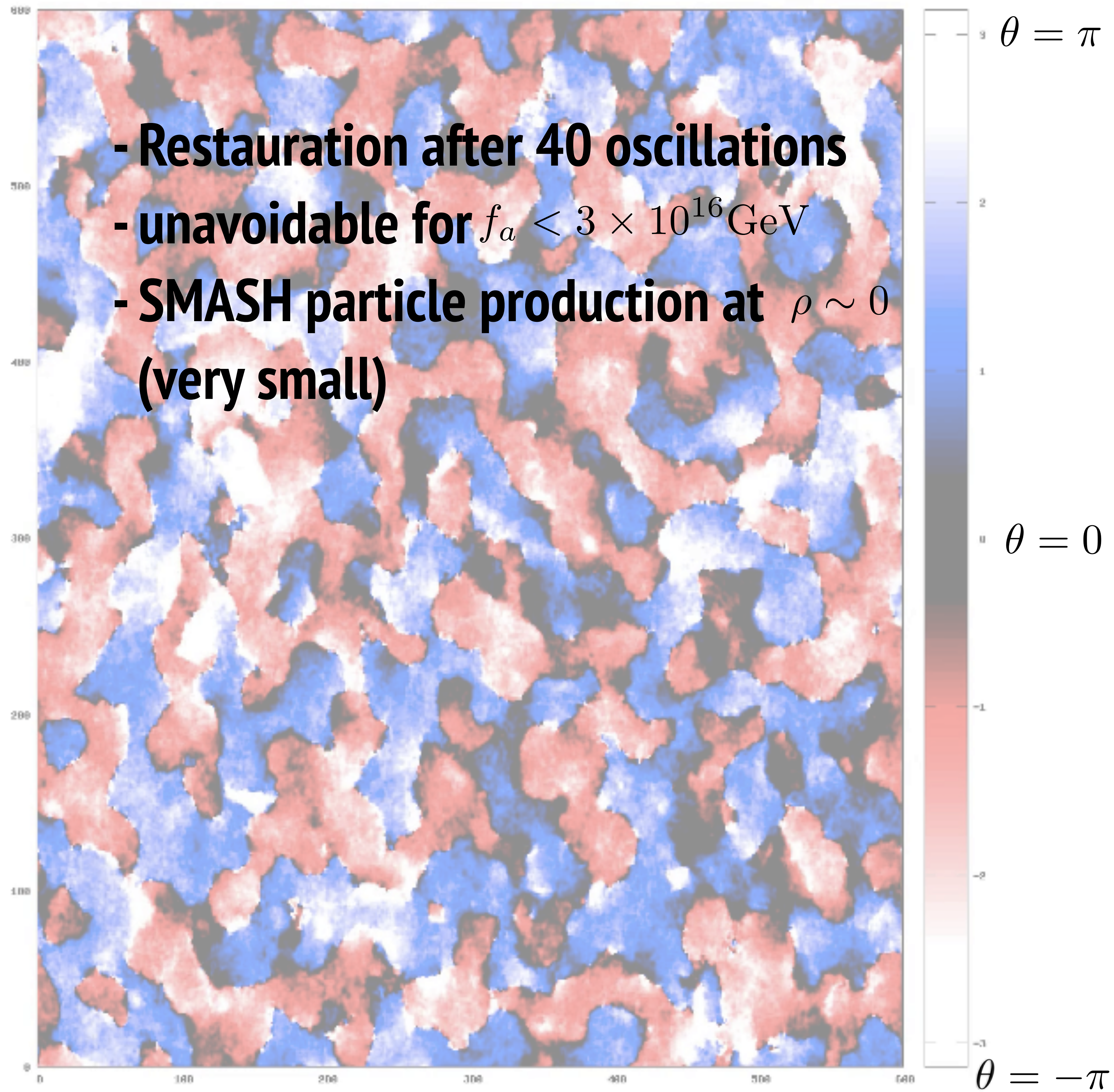


$\theta = \arg(\sigma)$ **in a slice of the Universe**

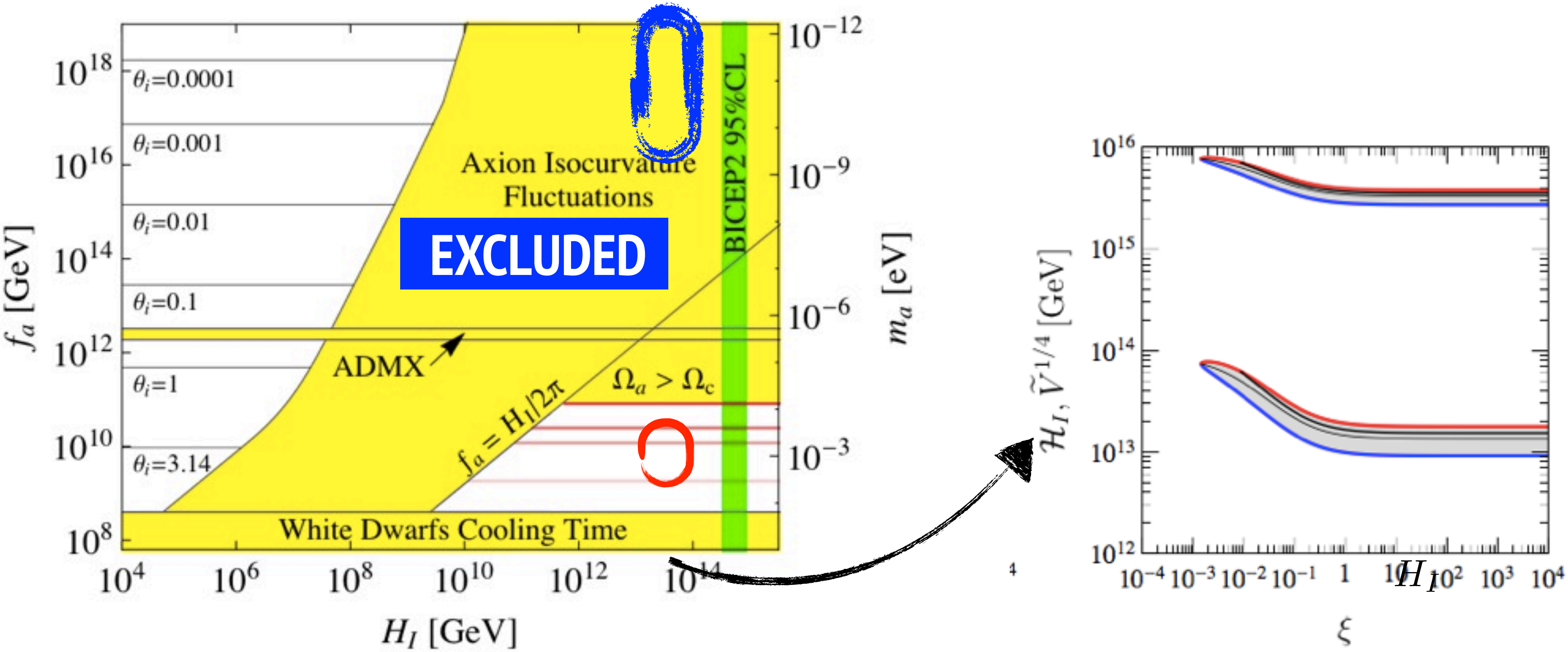


- **Restauration after 40 oscillations**
- **unavoidable for** $f_a < 3 \times 10^{16} \mathrm{GeV}$
- **SMASH particle production at** $\rho \sim 0$ **(very small)**

Scenario II ruled out

- Axion fluctuations during inflation imprinted in CMB (isocurvature)

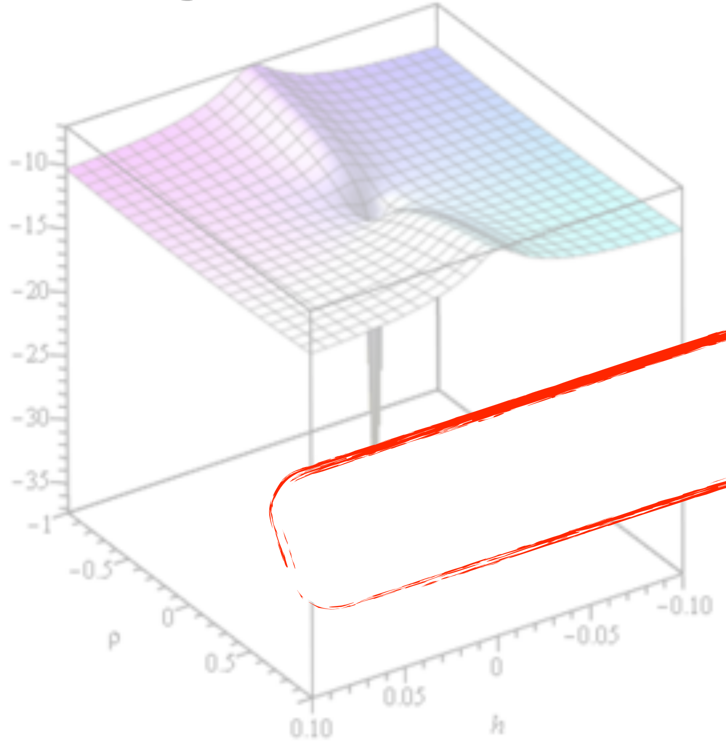
$$P_{\rm iso} = \frac{d\langle n_a\rangle}{n_a} \sim \frac{d\langle a^2\rangle}{a_I^2} = \frac{H_I^2}{\pi^2 a_I^2} = \frac{H_I^2}{\pi^2 f_a^2 \theta_I^2}$$



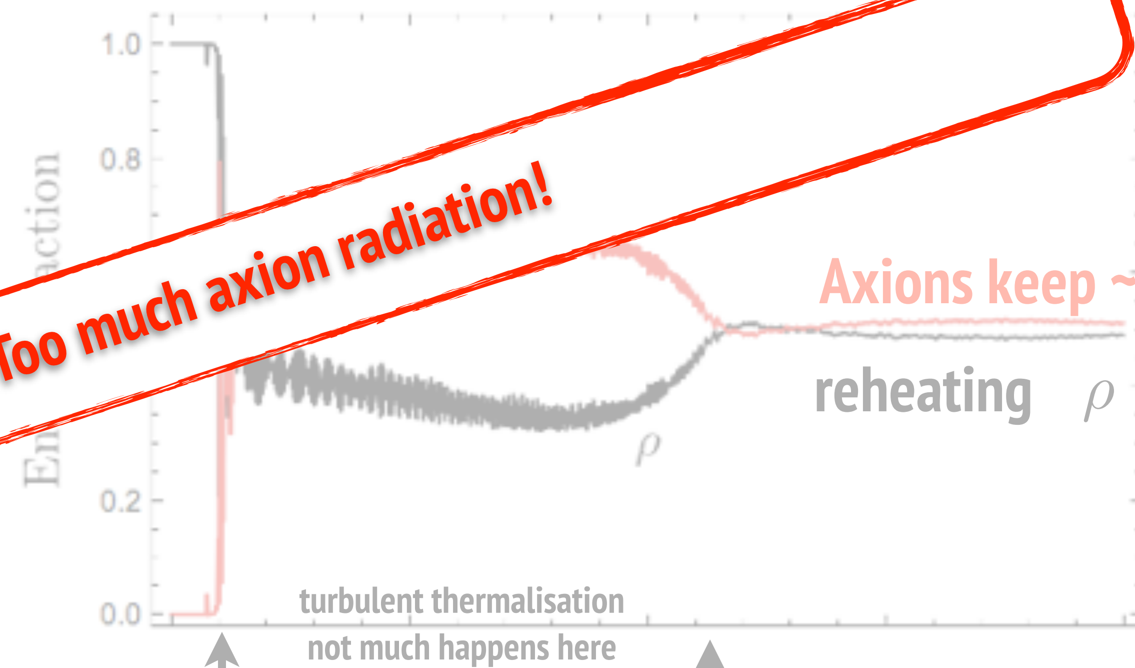
- SMASH II ruled out by CMB (isocurvature fluc)
- SMASH (sigma inflation) REQUIRES scenario I and DM $f_a \sim 10^{11}\,\mathrm{GeV}$

Reheating II : SM thermal bath

Pure sigma inflation $\lambda_{H\sigma} > 0$



Time, Universe expansion



Axions keep ~50% of energy

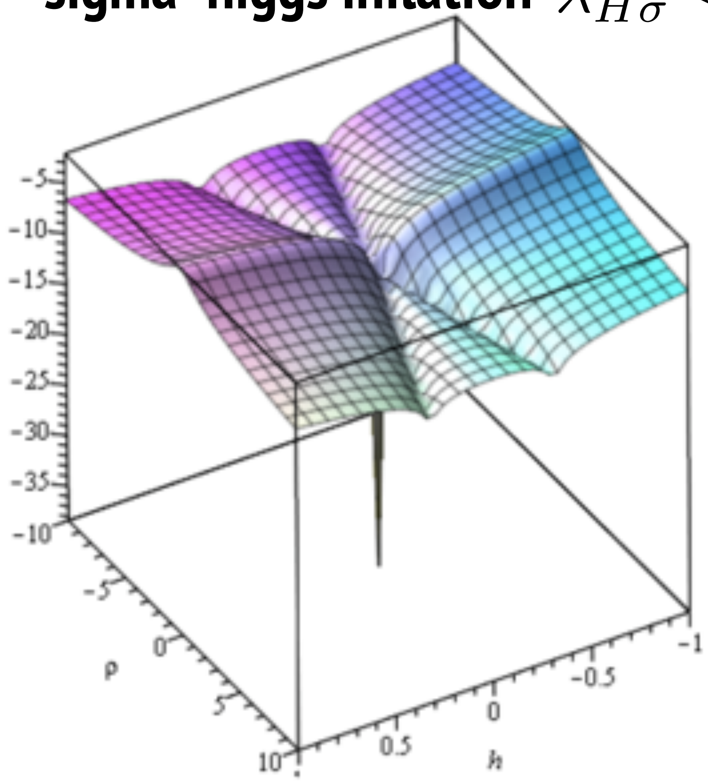
reheating $\rho \to HH, gg, \ldots$

PQ Restauration

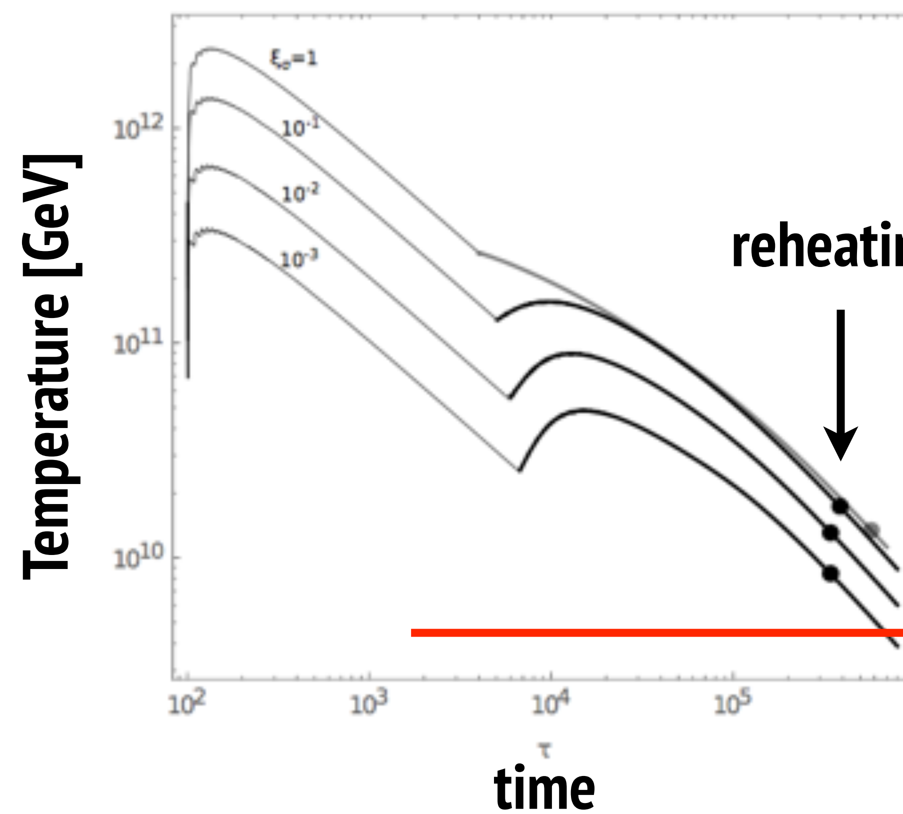
Energy~f_a

PQ SSB

sigma+higgs inflation $\lambda_{H\sigma} < 0$



$|\sigma|, |H| \to W \to \bar{f} f$

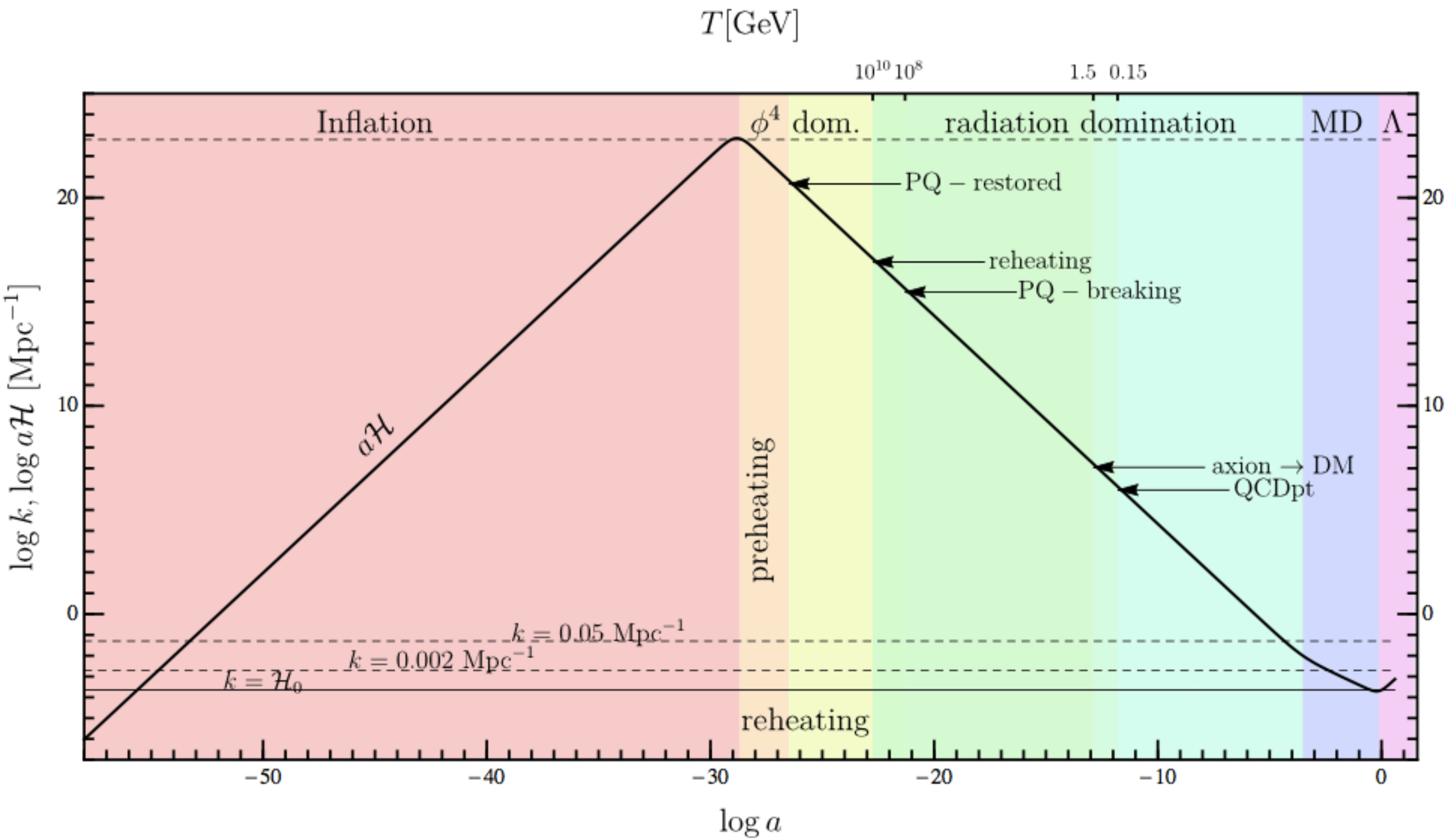


relatistic axions in thermal eq.

rel. axions decouple

$\Delta N_\nu^{\rm eff} \simeq 0.027$

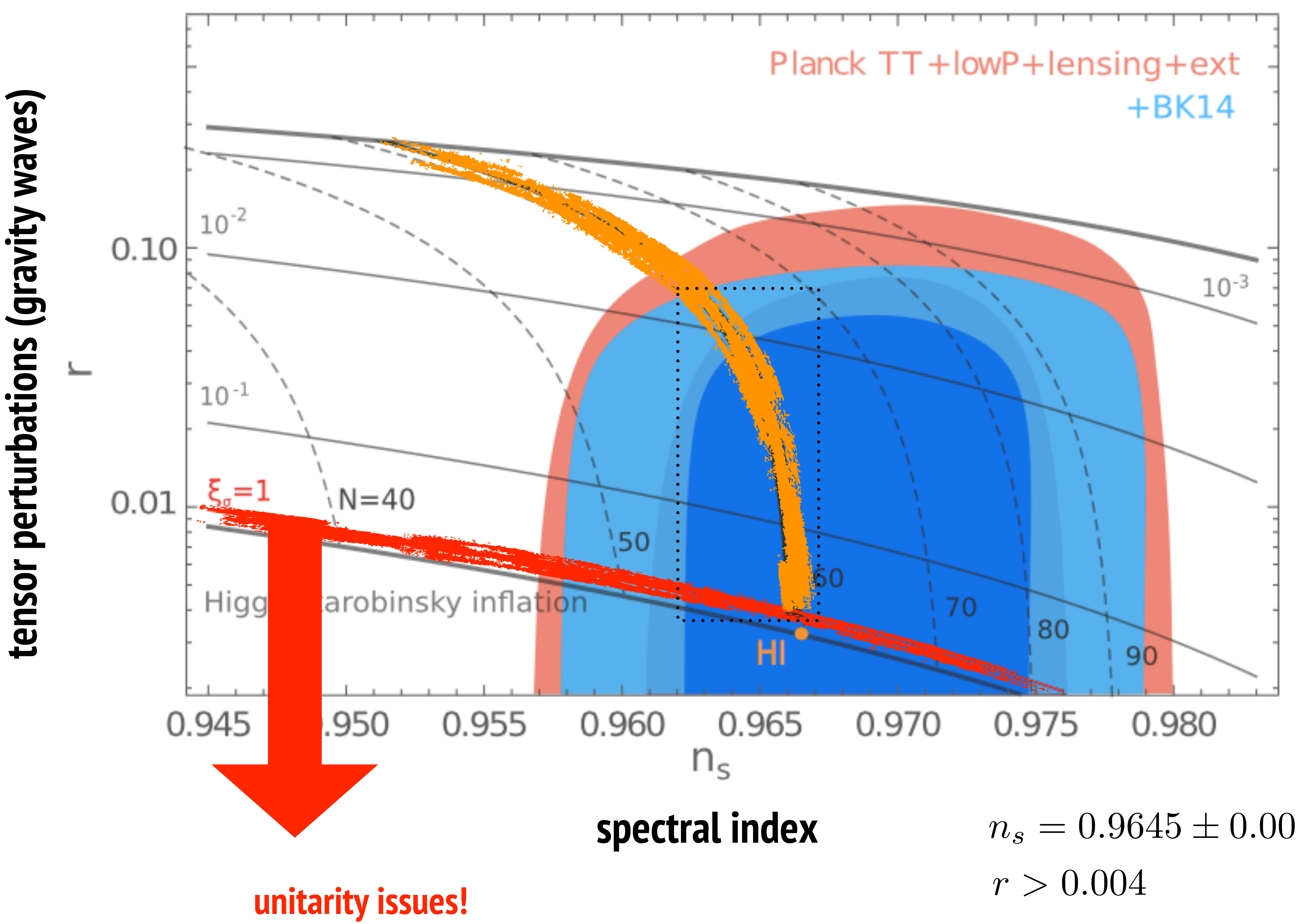
The whole picture



- **As a plus, reheating happens as in RD so we fix the scale of inflation**

Fitting the CMB ++

MUCH NARROW PREDICTION!!!!



$$n_s = 0.9645 \pm 0.0015$$

$$r > 0.004$$

Predictions/conclusions

- SMASH: SM Axion See saw Hidden-scalar-Inflation
- Minimal model of Axion dark matter, HEP and cosmology

- Predictions:

CMB : $r > 0.004$ $n_s = 0.9645 \pm 0.0015$ $\Delta N_\nu^{\rm eff} \simeq 0.03$ $P_{\rm iso} = 0$

$\alpha \sim -7 \times 10^{-4}$

Axion Dark Matter (scenario I: post inflation) : $m_a \sim 100\,\mu{\rm eV}$, miniclusters

Neutrinos : majorana, typically $M_2 \sim M_3$

top mass : $m_t < 175\,{\rm GeV}$