Prospects to scrutinise or smash SM*A*S*H

Andreas Ringwald
1st General Meeting of COST Action COSMIC WISPERS
Bari, Italy
Sep 5-8, 2023

Standard Model*Axion*Seesaw*Higgs-Portal Inflation

Minimal model of particle physics and cosmology [Ballesteros, Redondo, AR, Tamarit, arXiv:1608.05414; 1610.01639]

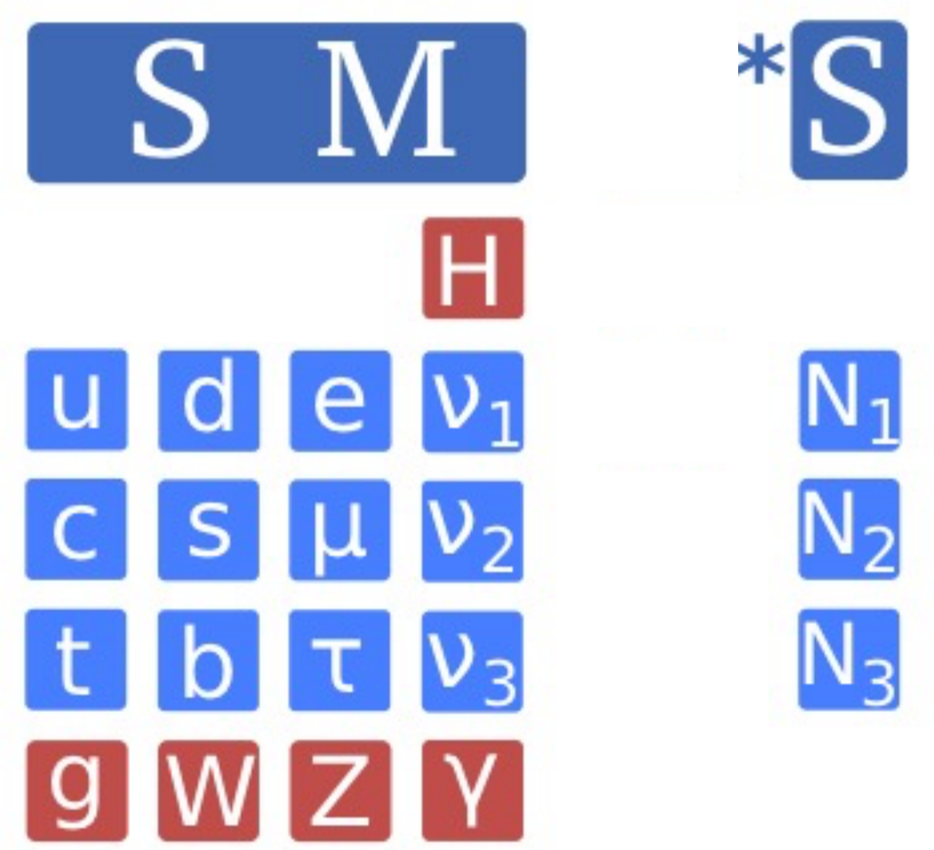
SM*A*S*H extends the SM

Standard Model*Axion*Seesaw*Higgs-Portal Inflation

Minimal model of particle physics and cosmology [Ballesteros, Redondo, AR, Tamarit, arXiv:1608.05414; 1610.01639]

SM*A*S*H extends the SM by

- 3 right-handed SM singlet neutrinos N_i

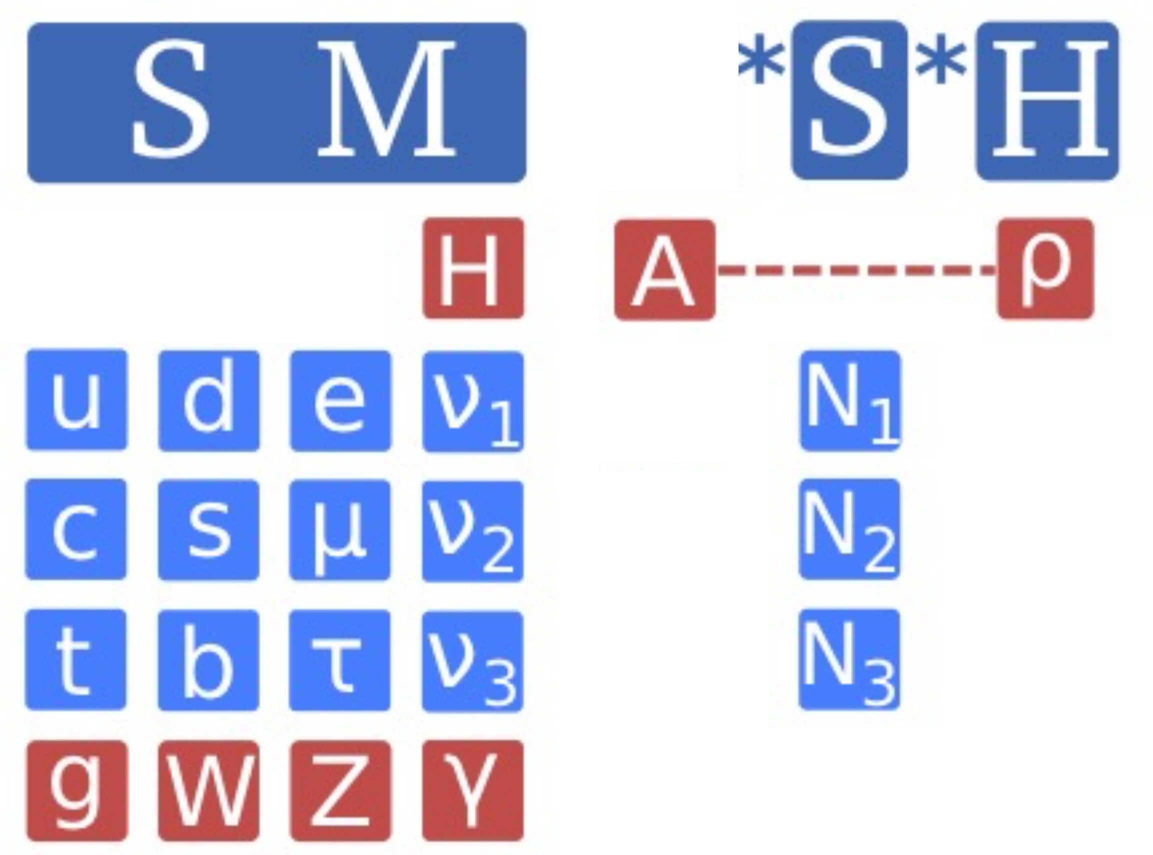


Standard Model*Axion*Seesaw*Higgs-Portal Inflation

Minimal model of particle physics and cosmology [Ballesteros, Redondo, AR, Tamarit, arXiv:1608.05414; 1610.01639]

SM*A*S*H extends the SM by

- 3 right-handed SM singlet neutrinos N_i
- a SM singlet complex scalar field σ



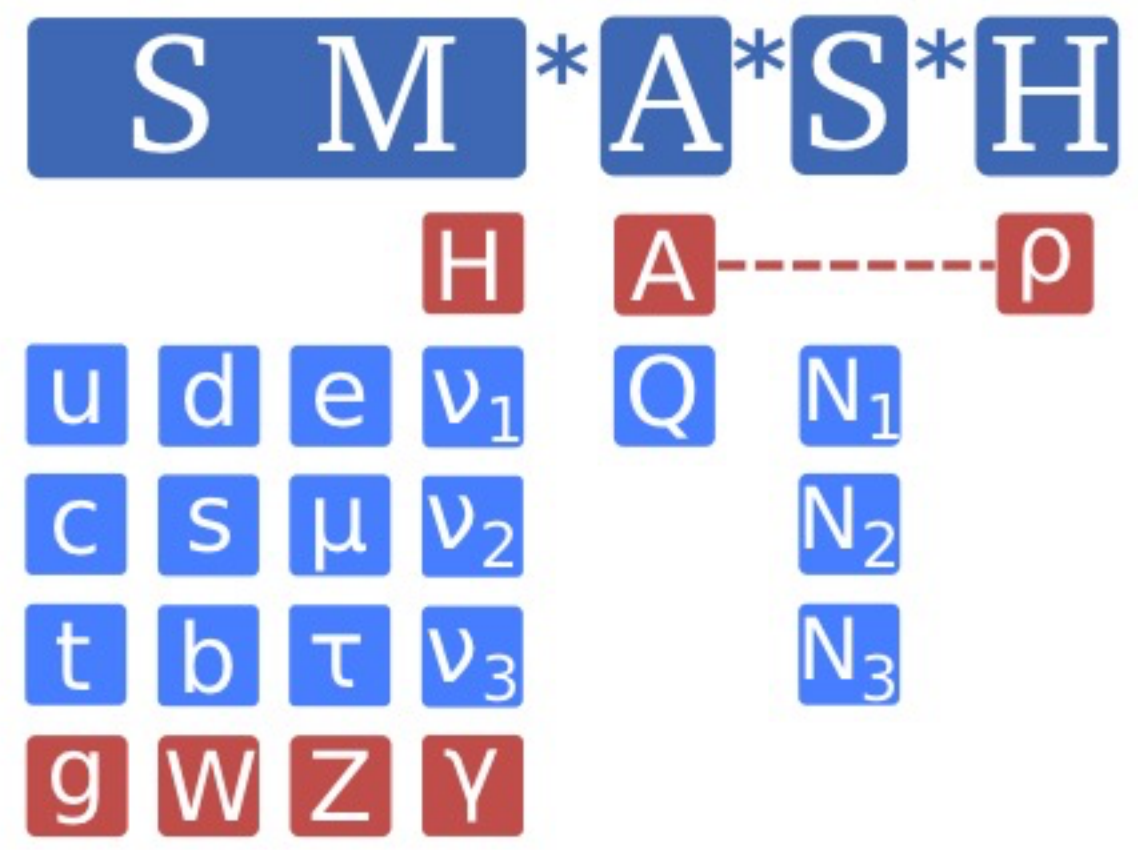
Standard Model*Axion*Seesaw*Higgs-Portal Inflation

Minimal model of particle physics and cosmology

[Ballesteros, Redondo, AR, Tamarit, arXiv:1608.05414; 1610.01639]

SM*A*S*H extends the SM by

- 3 right-handed SM singlet neutrinos N_i
- a SM singlet complex scalar field σ
- a vector-like quark Q



Standard Model*Axion*Seesaw*Higgs-Portal Inflation

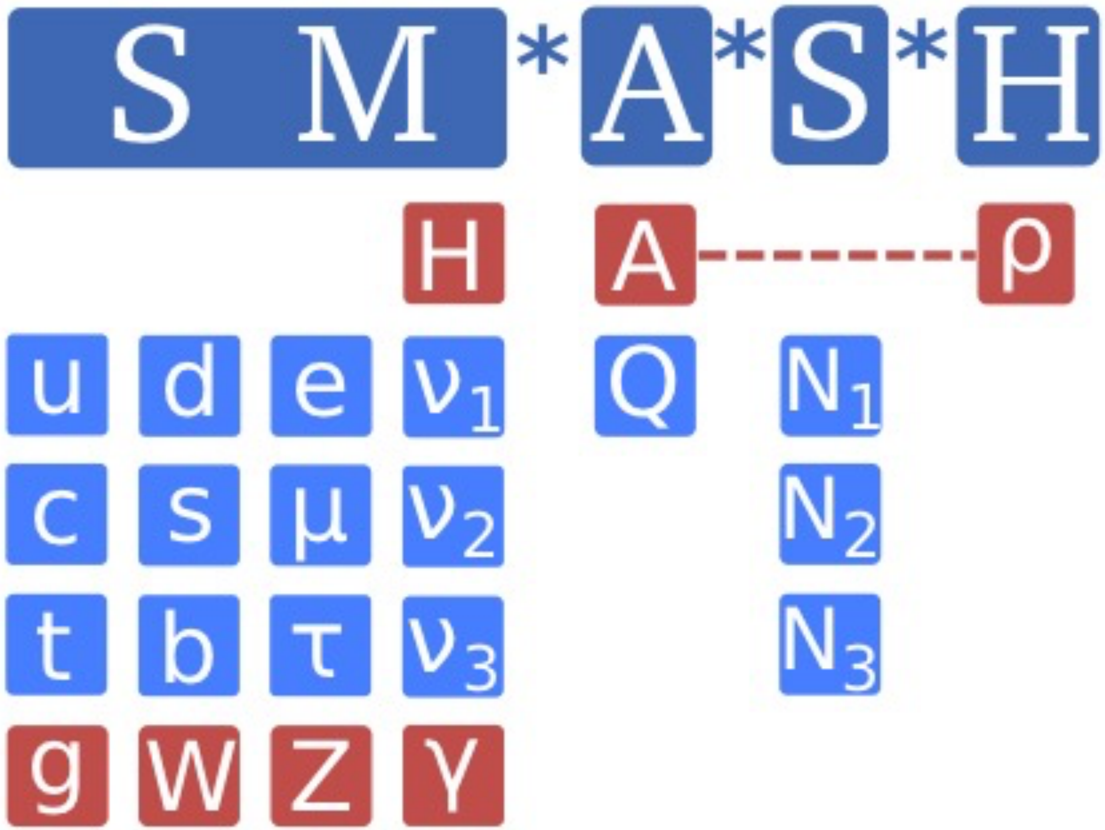
Minimal model of particle physics and cosmology

[Ballesteros, Redondo, AR, Tamarit, arXiv:1608.05414; 1610.01639]

SM*A*S*H extends the SM by

- 3 right-handed SM singlet neutrinos N_i
- a SM singlet complex scalar field σ
- a vector-like quark Q

all charged under a new global $U(1)_{PQ}$ symmetry, that is spontaneously broken by vev $\langle|\sigma|\rangle = v_\sigma/\sqrt{2} \sim 10^{11}\,\mathrm{GeV}$



Standard Model*Axion*Seesaw*Higgs-Portal Inflation

Minimal model of particle physics and cosmology

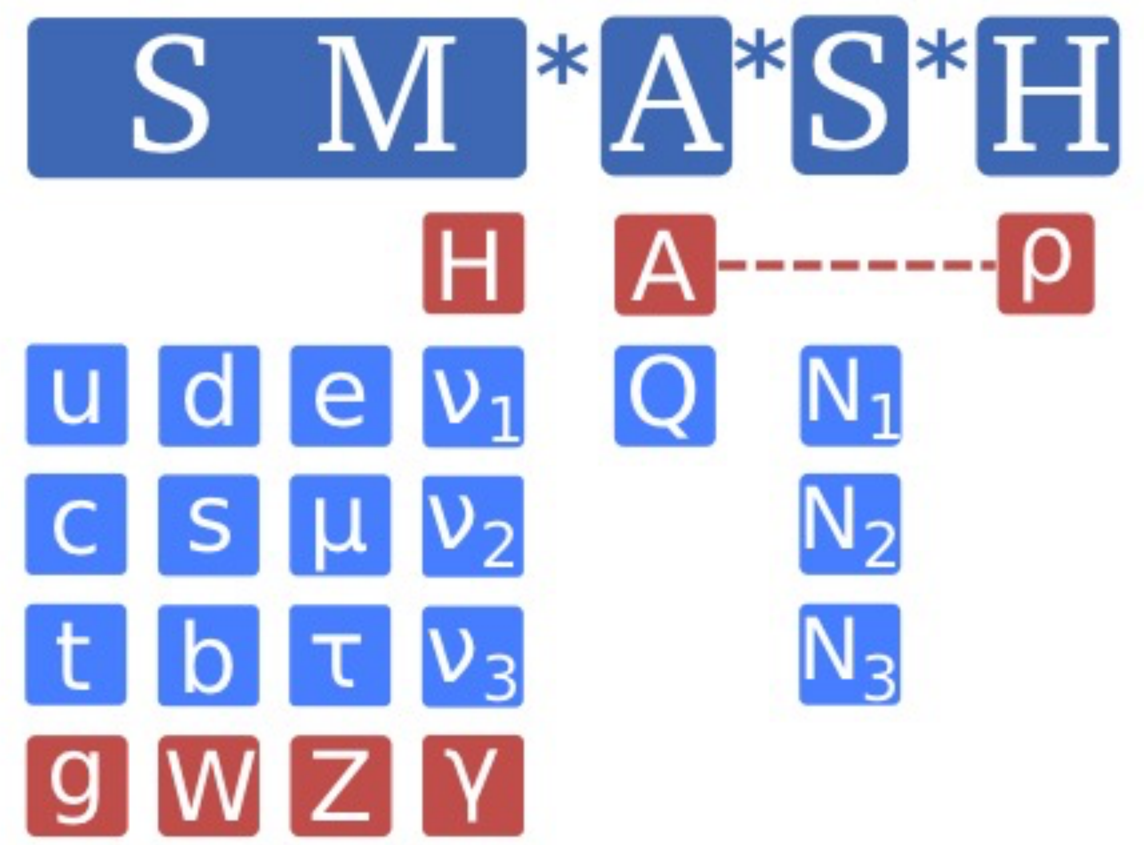
[Ballesteros, Redondo, AR, Tamarit, arXiv:1608.05414; 1610.01639]

SM*A*S*H extends the SM by

- 3 right-handed SM singlet neutrinos N_i
- a SM singlet complex scalar field σ
- a vector-like quark Q

all charged under a new global $U(1)_{PQ}$ symmetry, that is spontaneously broken by vev $\langle|\sigma|\rangle = v_\sigma/\sqrt{2} \sim 10^{11}\,\mathrm{GeV}$

It solves six puzzles in particle physics and cosmology in one smash



Standard Model*Axion*Seesaw*Higgs-Portal Inflation

Minimal model of particle physics and cosmology

[Ballesteros, Redondo, AR, Tamarit, arXiv:1608.05414; 1610.01639]

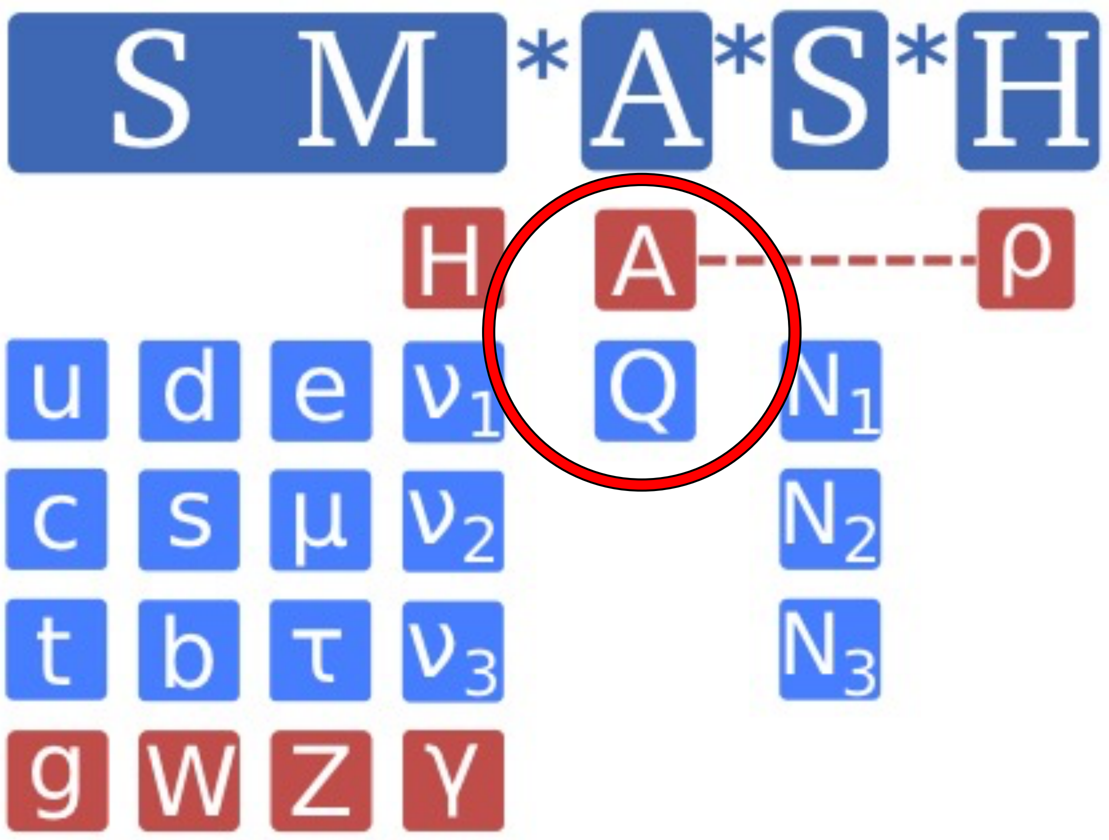
SM*A*S*H extends the SM by

- 3 right-handed SM singlet neutrinos N_i
- a SM singlet complex scalar field σ
- a vector-like quark Q

all charged under a new global U(1)$_{PQ}$ symmetry, that is spontaneously broken by vev $\langle|\sigma|\rangle = v_\sigma/\sqrt{2} \sim 10^{11}\,\mathrm{GeV}$

It solves six puzzles in particle physics and cosmology in one smash:

1. **Strong CP problem** (Peccei-Quinn (PQ) mechanism)
2. **Dark matter** (Axion)



Standard Model*Axion*Seesaw*Higgs-Portal Inflation

Minimal model of particle physics and cosmology [Ballesteros, Redondo, AR, Tamarit, arXiv:1608.05414; 1610.01639]

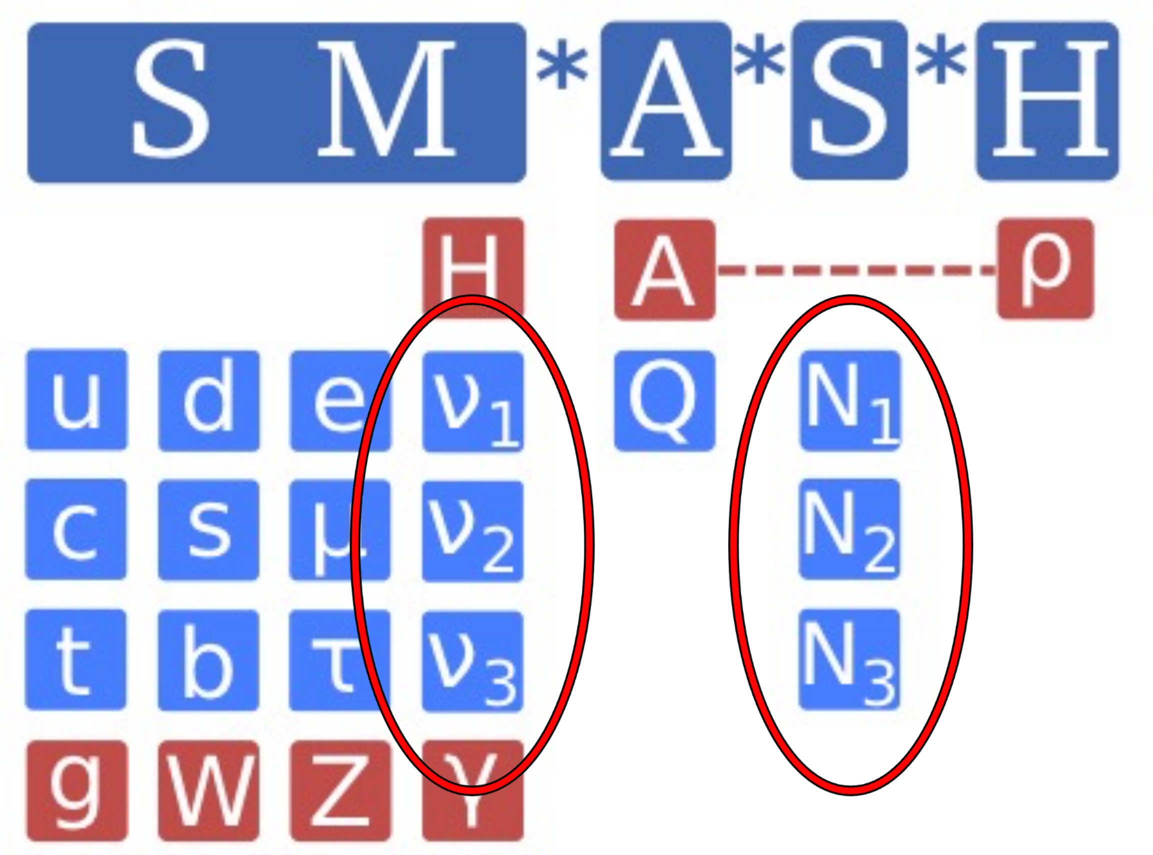
SM*A*S*H extends the SM by

- 3 right-handed SM singlet neutrinos N_i
- a SM singlet complex scalar field σ
- a vector-like quark Q

all charged under a new global $U(1)_{PQ}$ symmetry, that is spontaneously broken by vev $\langle|\sigma|\rangle = v_\sigma/\sqrt{2} \sim 10^{11}\,\mathrm{GeV}$

It solves six puzzles in particle physics and cosmology in one smash:

1. Strong CP problem (Peccei-Quinn (PQ) mechanism)
2. Dark matter (Axion)
3. **Neutrino masses and mixing** (Typ I seesaw mech.)
4. **Baryon asymmetry** (Thermal leptogenesis)



Standard Model*Axion*Seesaw*Higgs-Portal Inflation

Minimal model of particle physics and cosmology

[Ballesteros, Redondo, AR, Tamarit, arXiv:1608.05414; 1610.01639]

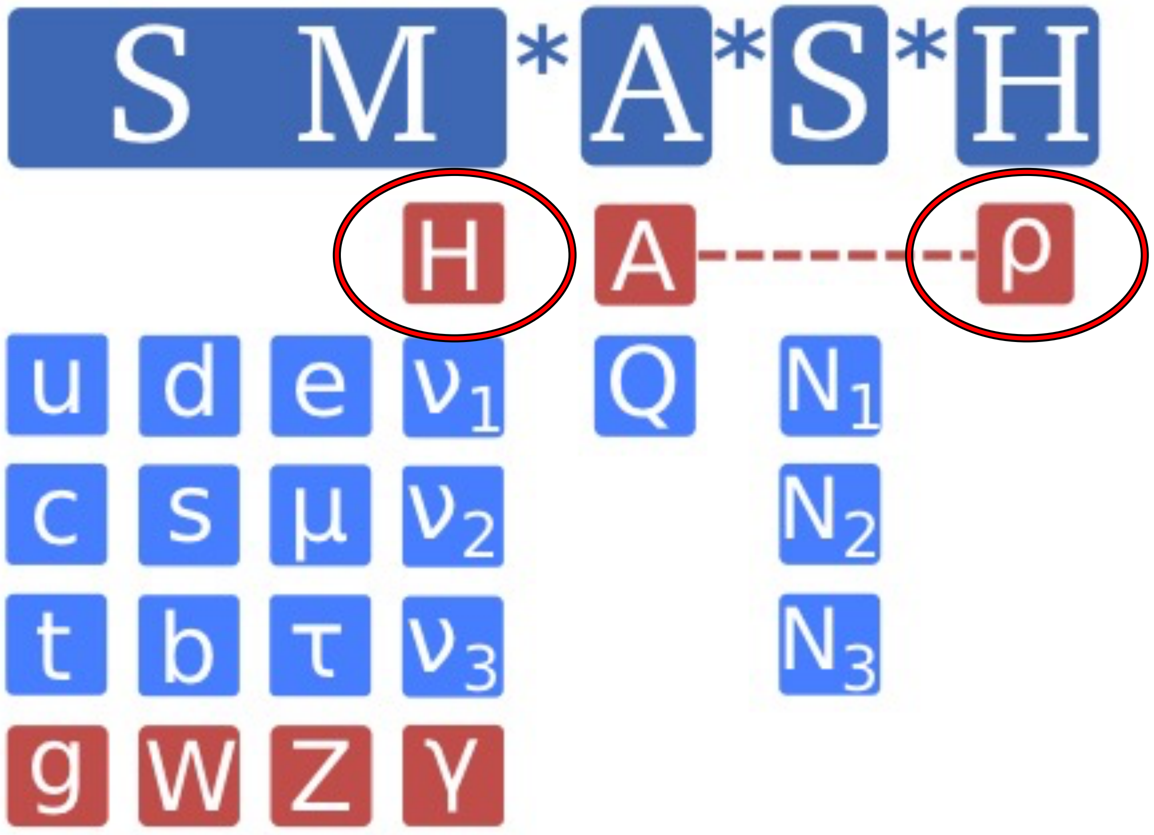
SM*A*S*H extends the SM by

- 3 right-handed SM singlet neutrinos N_i
- a SM singlet complex scalar field σ
- a vector-like quark Q

all charged under a new global $U(1)_{PQ}$ symmetry, that is spontaneously broken by vev $\langle|\sigma|\rangle = v_\sigma/\sqrt{2} \sim 10^{11}\,\mathrm{GeV}$

It solves six puzzles in particle physics and cosmology in one smash:

1. Strong CP problem (Peccei-Quinn (PQ) mechanism)
2. Dark matter (Axion)
3. Neutrino masses and mixing (Typ I seesaw mech.)
4. Baryon asymmetry (Thermal leptogenesis)
5. **Inflation** (Higgs-portal inflation)



Standard Model*Axion*Seesaw*Higgs-Portal Inflation

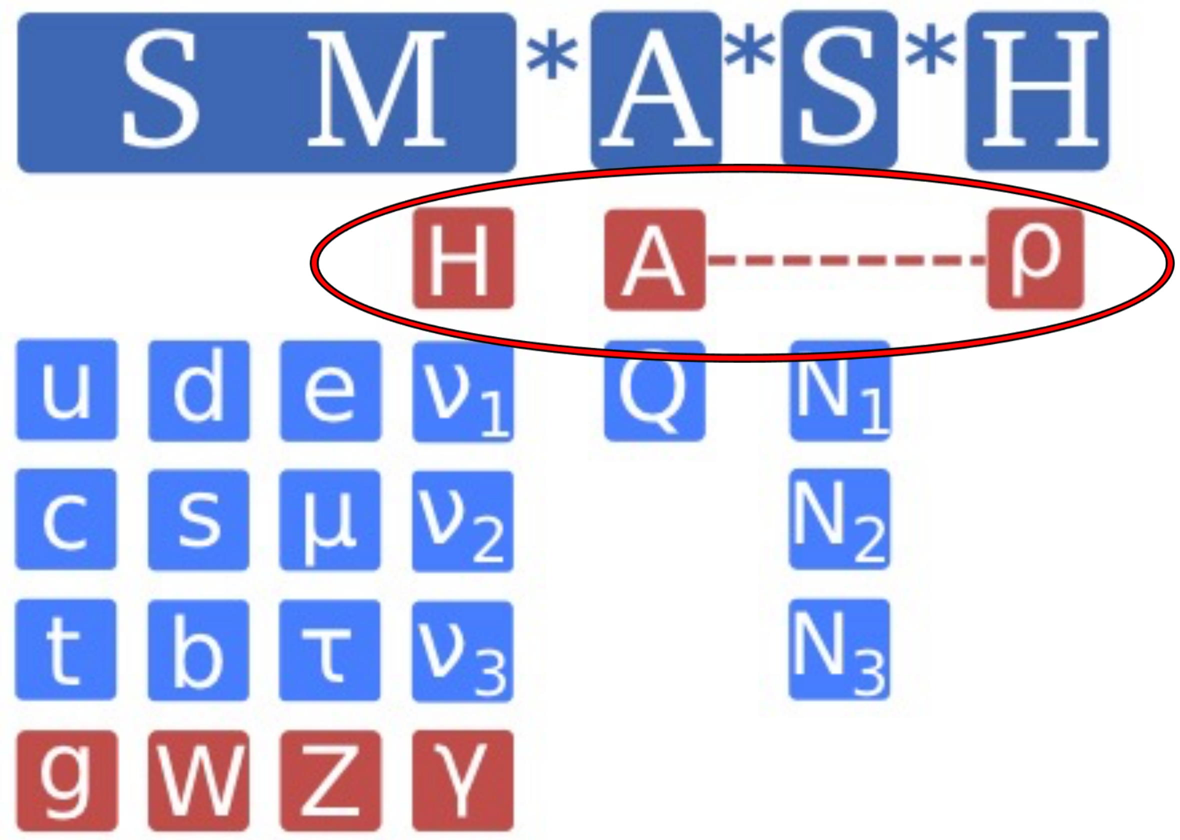
Minimal model of particle physics and cosmology

[Ballesteros, Redondo, AR, Tamarit, arXiv:1608.05414; 1610.01639]

SM*A*S*H extends the SM by

- 3 right-handed SM singlet neutrinos N_i
- a SM singlet complex scalar field σ
- a vector-like quark Q

all charged under a new global $U(1)_{PQ}$ symmetry, that is spontaneously broken by vev $\langle|\sigma|\rangle = v_\sigma/\sqrt{2} \sim 10^{11}\,\mathrm{GeV}$



It solves six puzzles in particle physics and cosmology in one smash:

1. Strong CP problem (Peccei Quinn (PQ) mechanism)
2. Dark matter (Axion)
3. Neutrino masses and mixing (Typ I seesaw mech.)
4. Baryon asymmetry (Thermal leptogenesis)
5. Inflation (Higgs-portal inflation)
6. **Vacuum stability**

Standard Model*Axion*Seesaw*Higgs-Portal Inflation

Parameters and their values constrained by symmetries and requirements to solve puzzles

- Peccei-Quinn charge assignments:

[Shin 88; Dias et al. 14; Ballesteros et al. 16]

q	u	d	L	N	E	Q	$\tilde{Q}$	σ
$1/2$	$-1/2$	$-1/2$	$1/2$	$-1/2$	$-1/2$	$-1/2$	$-1/2$	1

- PQ-invariant Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\rm kin} + \mathcal{L}_{\rm yuk}^{SM}$$

$$- \left[\frac{M^2}{2} + \xi_H \, H^\dagger H + \xi_\sigma \, |\sigma|^2 \right] R$$

$$-\lambda_H \left(H^\dagger H - \frac{v^2}{2} \right)^2 - 2\lambda_{H\sigma} \left(H^\dagger H - \frac{v^2}{2} \right) \left(|\sigma|^2 - \frac{v_\sigma^2}{2} \right)$$

STABILITY

$$-\lambda_\sigma \left(|\sigma|^2 - \frac{v_\sigma^2}{2} \right)^2 - [y \sigma \tilde{Q} Q + y_{Q_{d_i}} \sigma Q d_i + c.c]$$

INFLATION

CP PROBLEM

$$-[F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j + c.c.]$$

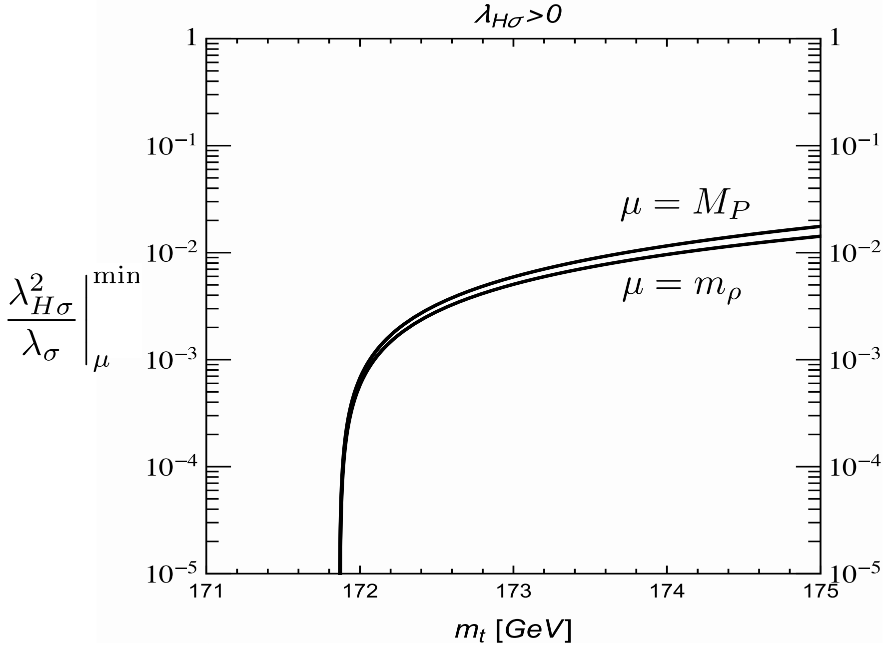
SEESAW AND LEPTOGENESIS

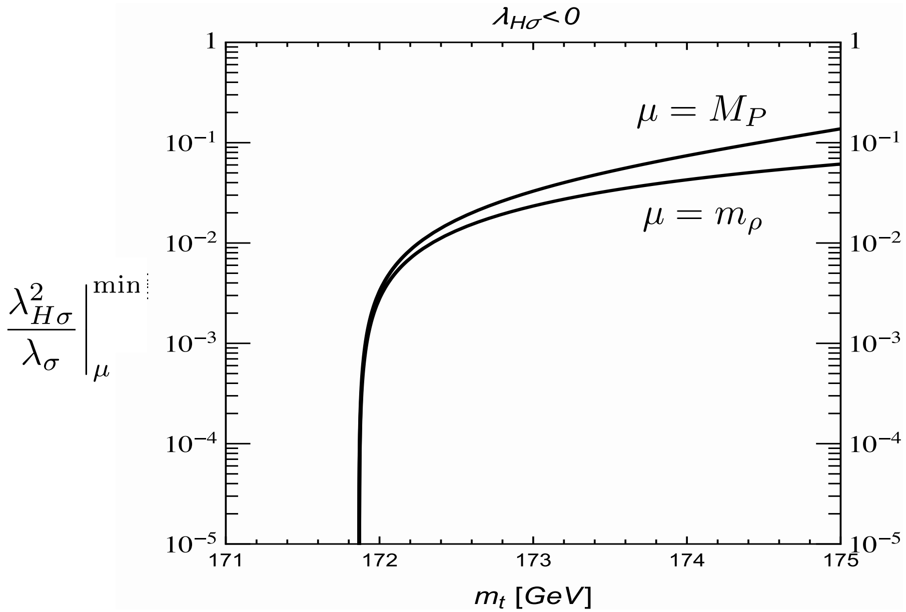
Vacuum Stability in SM*A*S*H

Constraints on scalar and Yukawa couplings

- Stability in Higgs direction:
  - SM-singlet scalar σ helps to stabilize scalar potential in Higgs direction through threshold effect associated with Higgs portal
  - Stability up to Planck scale ensured if $\delta = \lambda_{H\sigma}^2/\lambda_\sigma\big|_\mu$ exceeds a minimum value dependent on top mass
- Stability in ρ direction:
  - imposes upper limit on the Yukawas of the right-handed neutrinos and the exotic quark:

$$\sum Y_{ii}^4 + 6y^4 \lesssim 16\pi^2\lambda_\sigma/\log\left(M_P/\sqrt{2\lambda_\sigma}v_\sigma\right)$$



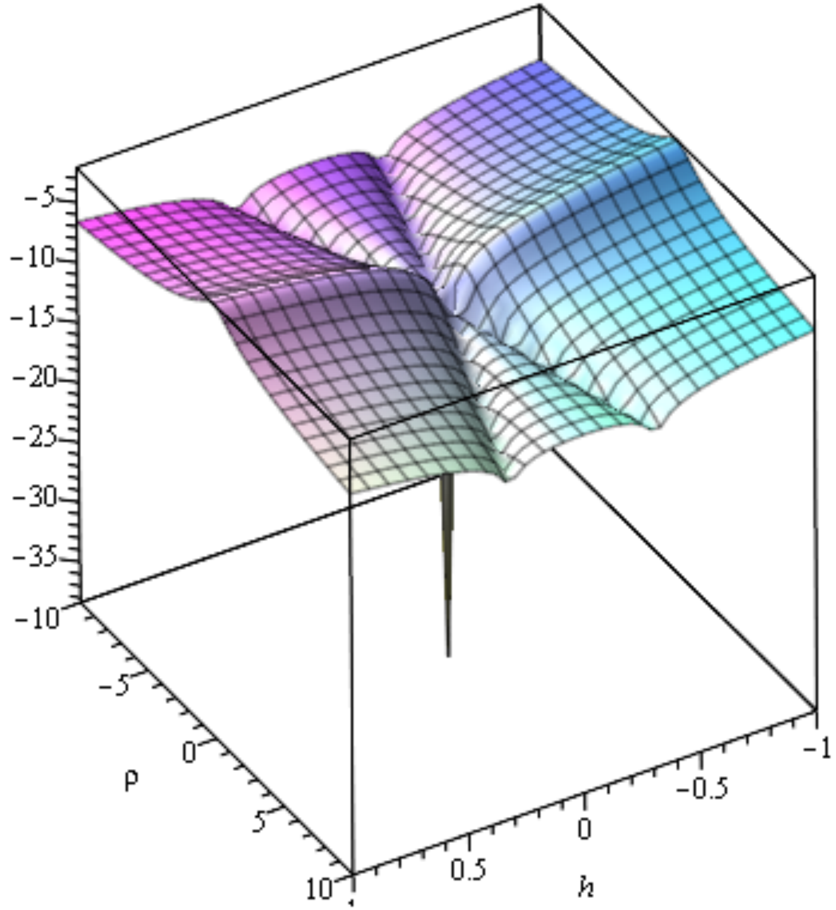


[Ballesteros,Redondo, AR,Tamarit, 1610.01639]

Inflation in SM*A*S*H

Higgs-portal inflation

- The scalar potential in the Einstein frame has a valley = attractor at large field values along the line $h/\phi = \sqrt{-\lambda_{H\sigma}/\lambda_H}$, $\phi = \sqrt{2}\,\mathrm{Re}\sigma$, provided that $\xi_\sigma \gg \xi_H \geq 0$ and $\lambda_{H\sigma} < 0$



[Ballesteros, Redondo, AR, Tamarit, arXiv:1610.01639]

Inflation in SM*A*S*H

Higgs-portal inflation

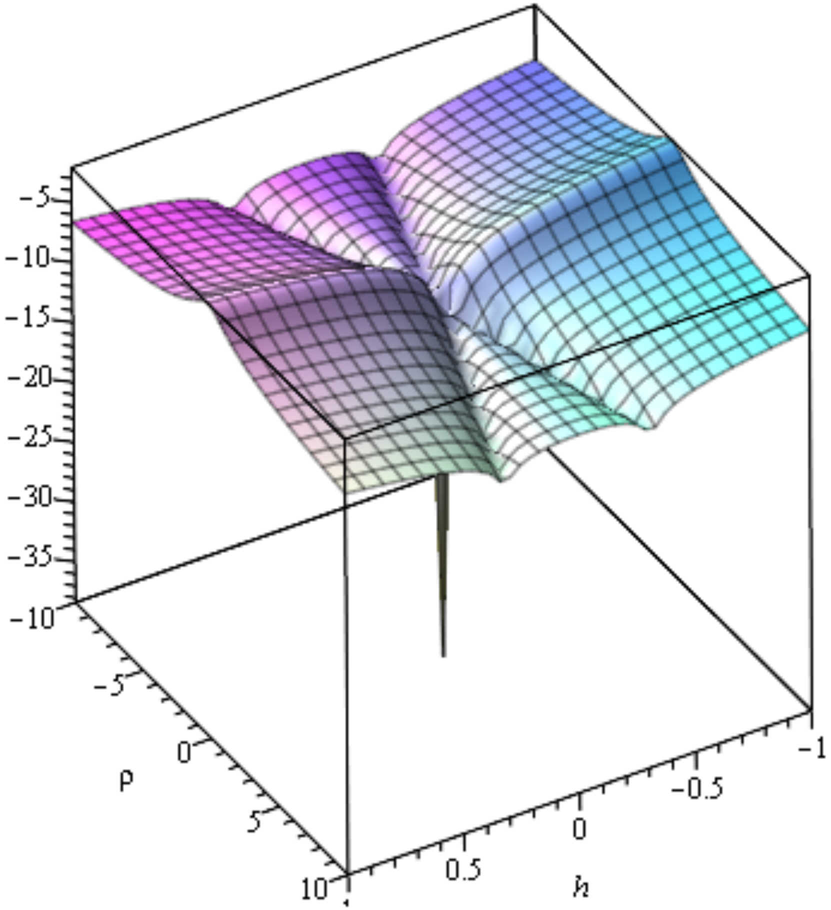
- The scalar potential in the Einstein frame has a valley = attractor at large field values along the line $h/\phi = \sqrt{-\lambda_{H\sigma}/\lambda_H}$, $\phi = \sqrt{2}\,\mathrm{Re}\sigma$, provided that $\xi_\sigma \gg \xi_H \geq 0$ and $\lambda_{H\sigma} < 0$
- Results in effectively single field inflation along that field direction with potential (in Einstein frame)

$$\tilde{V}(\chi) = \frac{1}{4}\tilde{\lambda}_\sigma \phi(\chi)^4 \left(1 + \xi_\sigma \frac{\phi(\chi)^2}{M_P^2}\right)^{-2}, \quad \tilde{\lambda}_\sigma \equiv \lambda_\sigma \left(1 - \frac{\lambda_{H\sigma}^2}{\lambda_\sigma \lambda_H}\right)$$

where canonically normalized inflaton field χ and ϕ are related by

$$\Omega^2\, d\chi/d\phi \simeq (b\,\Omega^2 + 6\,\xi_\sigma^2\,\phi^2/M_P^2)^{1/2}$$

with $\Omega^2 = 1 + \xi_\sigma \frac{\phi(\chi)^2}{M_P^2}$ and $b = 1 + |\lambda_{H\sigma}/\lambda_H|$



[Ballesteros, Redondo, AR, Tamarit, arXiv:1610.01639]

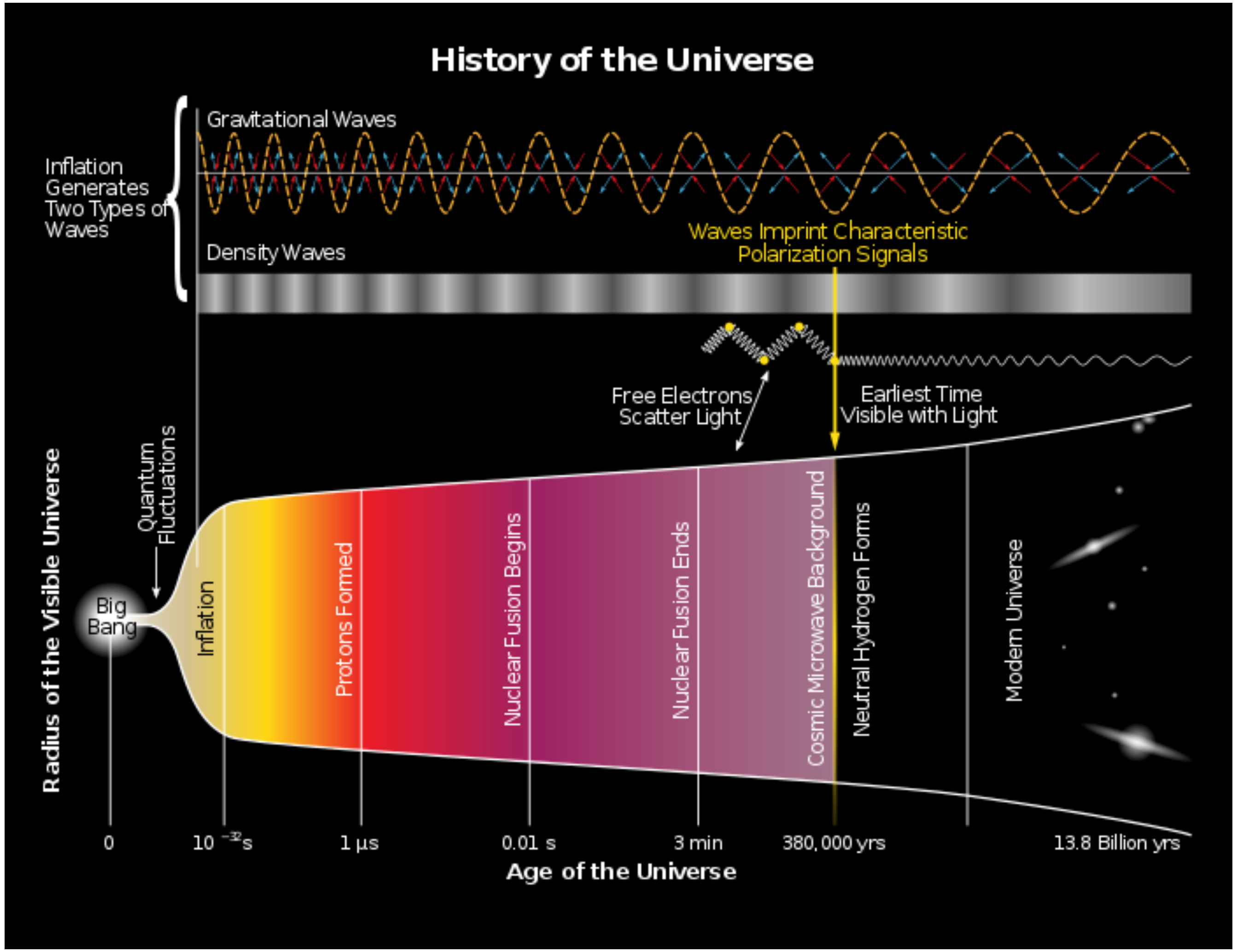
Inflation in SM*A*S*H

Confronting with CMB data

$$\tilde{V}(\chi) = \frac{1}{4}\tilde{\lambda}_\sigma \phi(\chi)^4 \left(1 + \xi_\sigma \frac{\phi(\chi)^2}{M_P^2}\right)^{-2}$$

- Quantum fluctuations during slow-roll inflation along this potential produce power spectra of density waves (scalar metric perturbations) and gravitational waves (tensor metric perturbations) which can be parametrized as

$$\Delta^2_{s/t}(k) = A_{s/t}(k_*)\,(k/k_*)^{n_{s/t}(k_*)-1+\cdots}$$



Inflation in SM*A*S*H

Confronting with CMB data

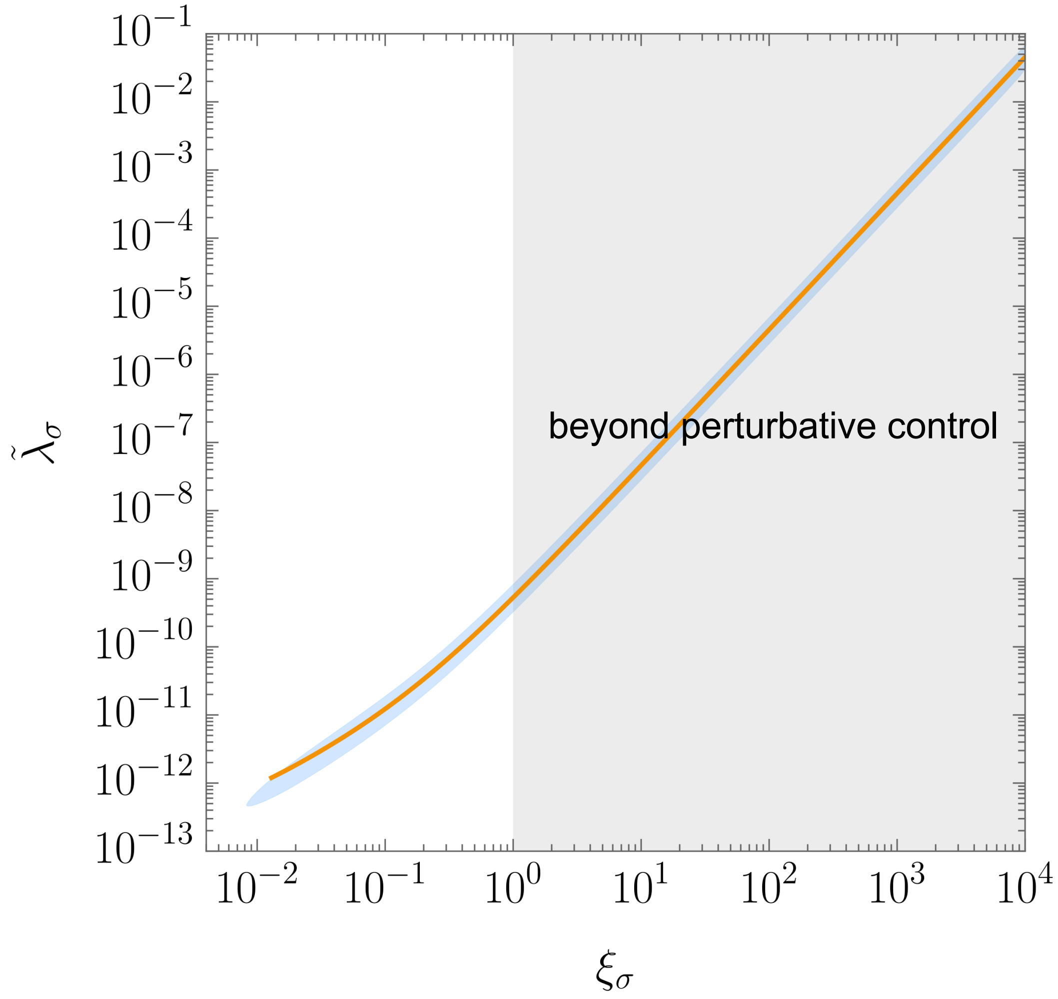
$$\tilde{V}(\chi) = \frac{1}{4}\tilde{\lambda}_\sigma \phi(\chi)^4 \left(1 + \xi_\sigma \frac{\phi(\chi)^2}{M_P^2}\right)^{-2}$$

- Quantum fluctuations during slow-roll inflation along this potential produce power spectra of density waves (scalar metric perturbations) and gravitational waves (tensor metric perturbations) which can be parametrized as

$$\Delta^2_{s/t}(k) = A_{s/t}(k_*)\,(k/k_*)^{n_{s/t}(k_*)-1+\cdots}$$

- Predicted spectral index $n_s(k_*)$ and tensor-to-scalar ratio $r(k_*) \equiv A_t(k_*)/A_s(k_*)$ consistent with newest constraints from CMB temperature and polarization data for

$$7 \times 10^{-3} \lesssim \xi_\sigma \simeq 4 \times 10^4 \sqrt{\tilde{\lambda}_\sigma} \lesssim 1$$



[AR,Tamarit, arXiv:2203.00621]

Inflation in SM*A*S*H

Confronting with CMB data

$$\tilde{V}(\chi) = \frac{1}{4}\tilde{\lambda}_\sigma \phi(\chi)^4 \left(1 + \xi_\sigma \frac{\phi(\chi)^2}{M_P^2}\right)^{-2}$$

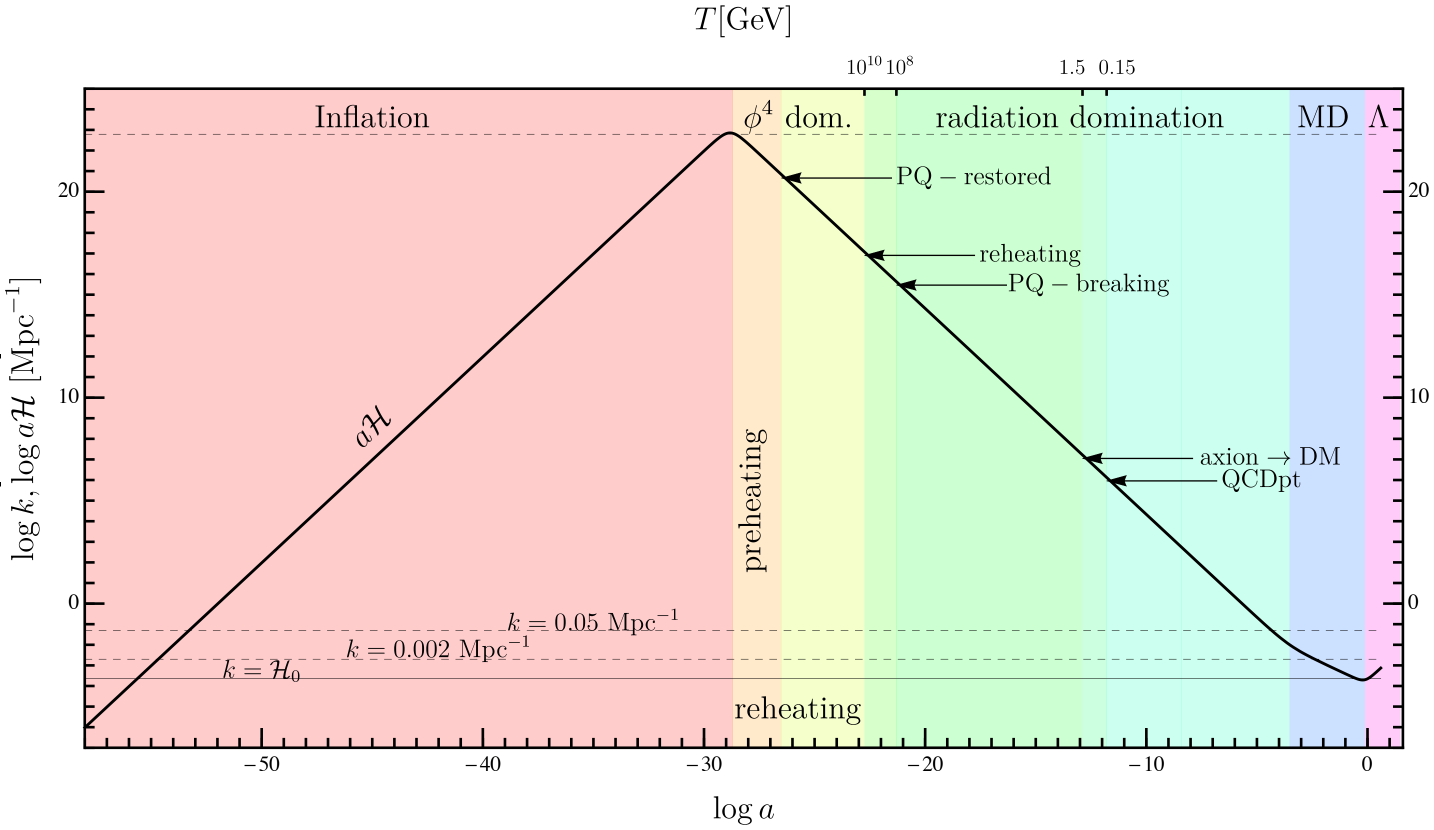
- Quantum fluctuations during slow-roll inflation along this potential produce power spectra of density waves (scalar metric perturbations) and gravitational waves (tensor metric perturbations) which can be parametrized as

$$\Delta^2_{s/t}(k) = A_{s/t}(k_*)\,(k/k_*)^{n_{s/t}(k_*)-1+\cdots}$$

- Predicted spectral index $n_s(k_*)$ and tensor-to-scalar ratio $r(k_*) \equiv A_t(k_*)/A_s(k_*)$ consistent with newest constraints from CMB temperature and polarization data for

$$7\times 10^{-3} \lesssim \xi_\sigma \simeq 4\times 10^4 \sqrt{\tilde{\lambda}_\sigma} \lesssim 1$$

- Taking into account complete expansion history predicted in SM*A*S*H



[Ballesteros, Redondo, AR, Tamarit, arXiv:1610.01639]

Inflation in SM*A*S*H

Confronting with CMB data

- Quantum fluctuations during slow-roll inflation along this potential produce power spectra of density waves (scalar metric perturbations) and gravitational waves (tensor metric perturbations) which can be parametrized as

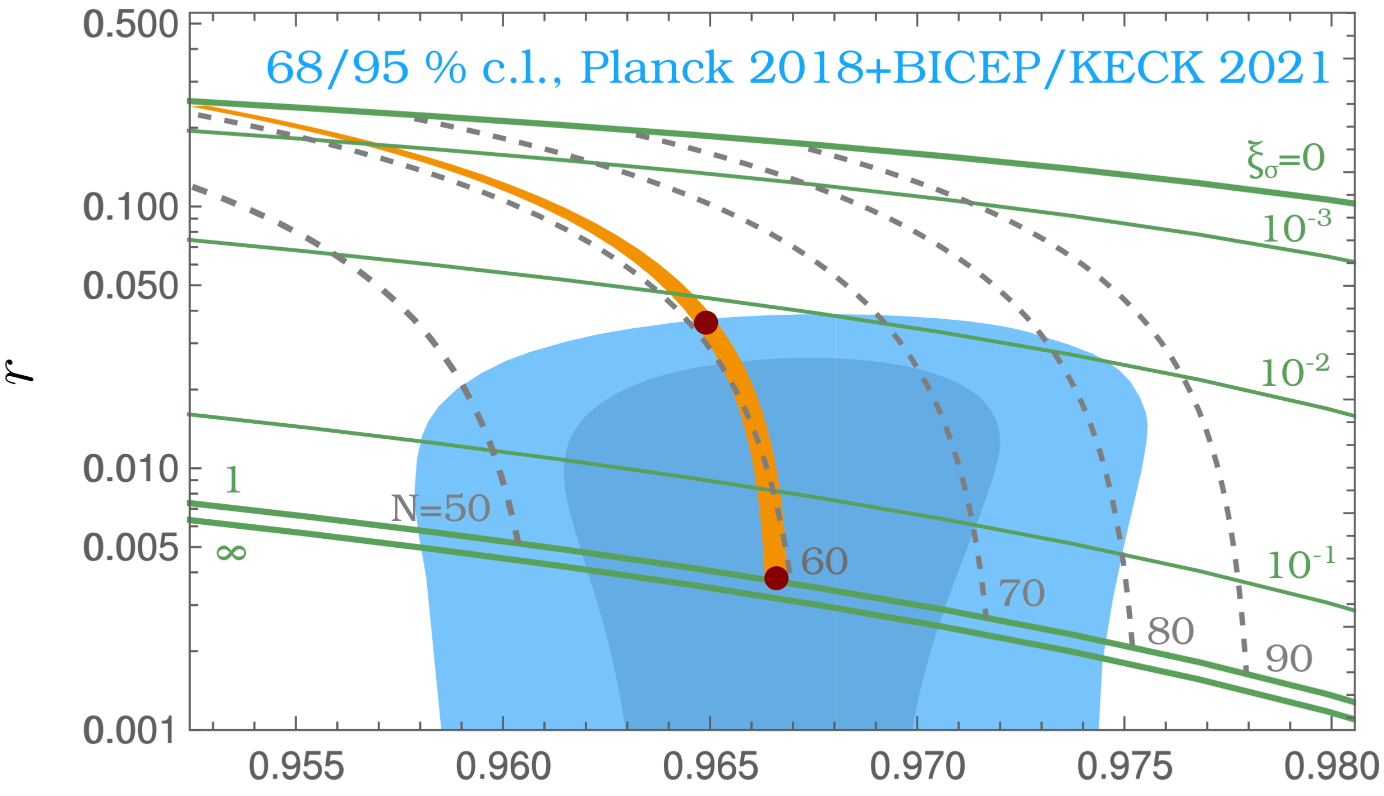
$$\Delta^2_{s/t}(k) = A_{s/t}(k_*)\,(k/k_*)^{n_{s/t}(k_*)-1+\cdots}$$

- Predicted spectral index $n_s(k_*)$ and tensor-to-scalar ratio $r(k_*) \equiv A_t(k_*)/A_s(k_*)$ consistent with newest constraints from CMB temperature and polarization data for

$$7\times 10^{-3} \lesssim \xi_\sigma \simeq 4\times 10^4 \sqrt{\tilde\lambda_\sigma} \lesssim 1$$

- Taking into account complete expansion history predicted in SM*A*S*H provides a sharp prediction of $r(k_*)$ vs. $n_s(k_*)$

$$\tilde V(\chi) = \frac{1}{4}\tilde\lambda_\sigma \phi(\chi)^4 \left(1+\xi_\sigma \frac{\phi(\chi)^2}{M_P^2}\right)^{-2}$$



[AR,Tamarit, arXiv:2203.00621]

n_s

Inflation in SM*A*S*H

Confronting with CMB data

$$\tilde{V}(\chi) = \frac{1}{4}\tilde{\lambda}_\sigma \phi(\chi)^4 \left(1 + \xi_\sigma \frac{\phi(\chi)^2}{M_P^2}\right)^{-2}$$

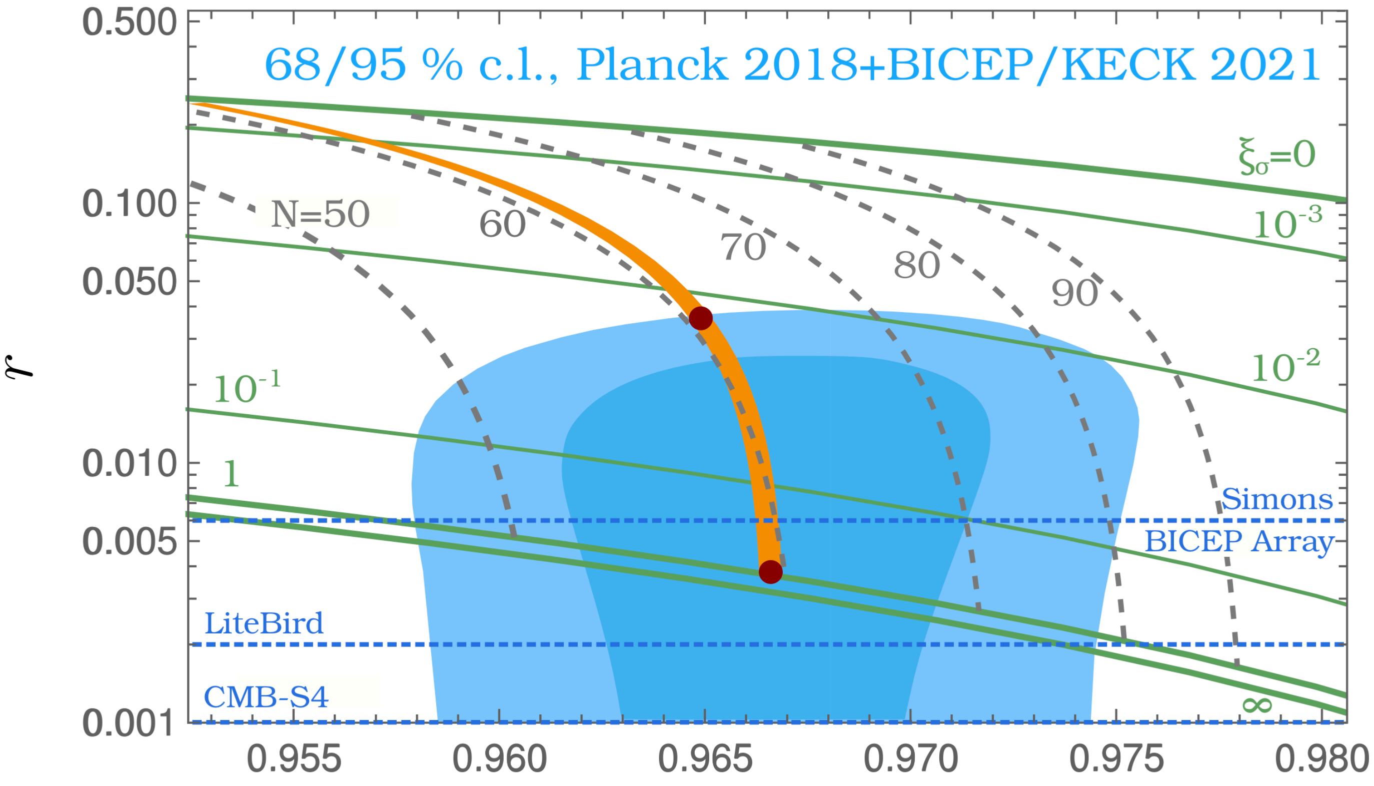
- Quantum fluctuations during slow-roll inflation along this potential produce power spectra of density waves (scalar metric perturbations) and gravitational waves (tensor metric perturbations) which can be parametrized as

$$\Delta^2_{s/t}(k) = A_{s/t}(k_*)\,(k/k_*)^{n_{s/t}(k_*)-1+\cdots}$$

- Predicted spectral index $n_s(k_*)$ and tensor-to-scalar ratio $r(k_*) \equiv A_t(k_*)/A_s(k_*)$ consistent with newest constraints from CMB temperature and polarization data for

$$7\times 10^{-3} \lesssim \xi_\sigma \simeq 4\times 10^4 \sqrt{\tilde{\lambda}_\sigma} \lesssim 1$$

- Taking into account complete expansion history predicted in SM*A*S*H provides a sharp prediction of $r(k_*)$ vs. $n_s(k_*)$ that can be entirely explored with the upcoming generation of CMB polarization experiments



n_s

[AR,Tamarit, arXiv:2203.00621]

Inflation in SM*A*S*H

Confronting with CMB data

$$\tilde{V}(\chi) = \frac{1}{4}\tilde{\lambda}_\sigma \phi(\chi)^4 \left(1 + \xi_\sigma \frac{\phi(\chi)^2}{M_P^2}\right)^{-2}$$

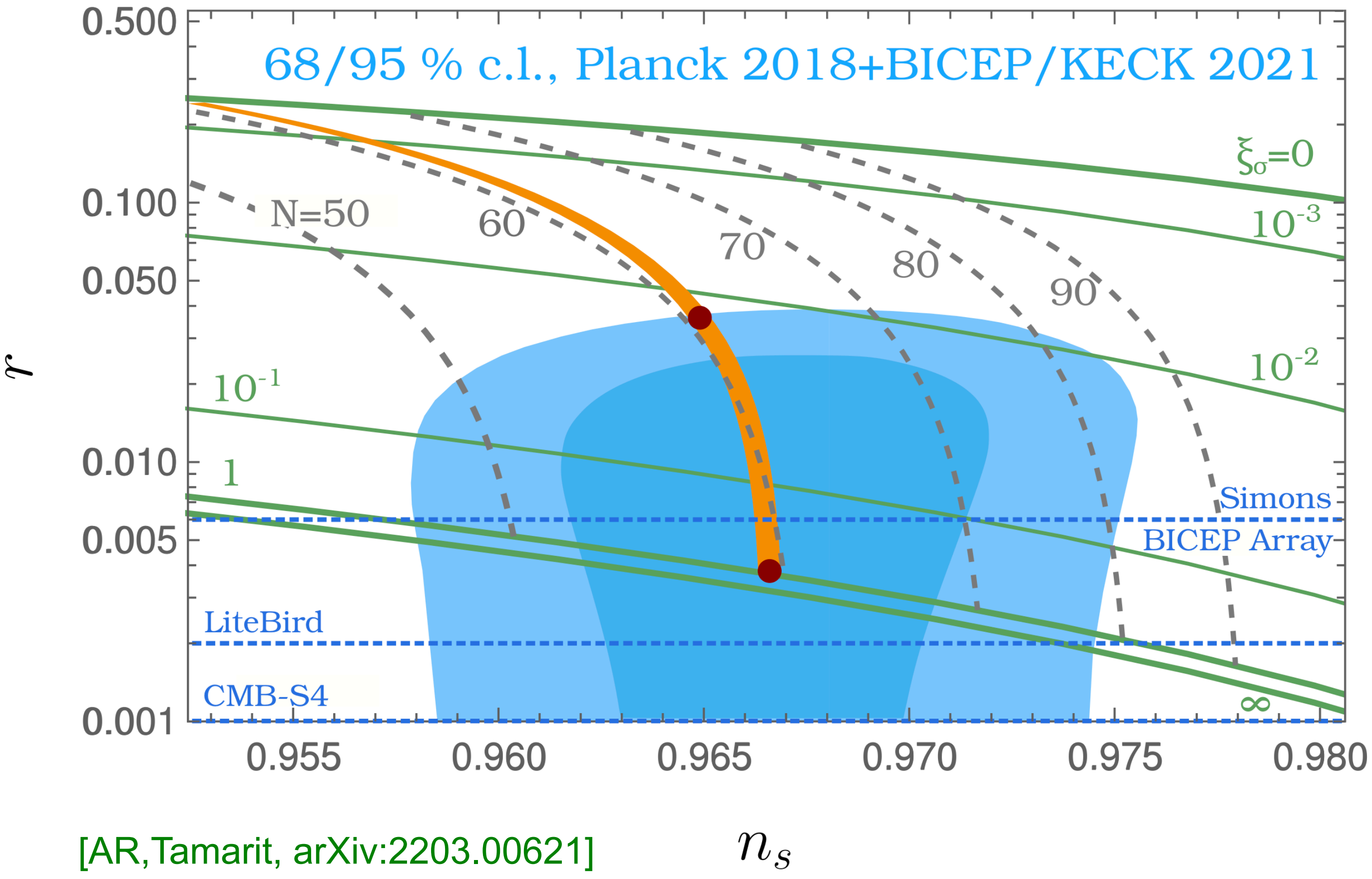
- Quantum fluctuations during slow-roll inflation along this potential produce power spectra of density waves (scalar metric perturbations) and gravitational waves (tensor metric perturbations) which can be parametrized as

$$\Delta^2_{s/t}(k) = A_{s/t}(k_*)\,(k/k_*)^{n_{s/t}(k_*)-1+\cdots}$$

- Predicted spectral index $n_s(k_*)$ and tensor-to-scalar ratio $r(k_*) \equiv A_t(k_*)/A_s(k_*)$ consistent with newest constraints from CMB temperature and polarization data for

$$7\times 10^{-3} \lesssim \xi_\sigma \simeq 4\times 10^4 \sqrt{\tilde{\lambda}_\sigma} \lesssim 1$$

- Taking into account complete expansion history predicted in SM*A*S*H provides a sharp prediction of $r(k_*)$ vs. $n_s(k_*)$ that can be entirely explored with the upcoming generation of CMB polarization experiments



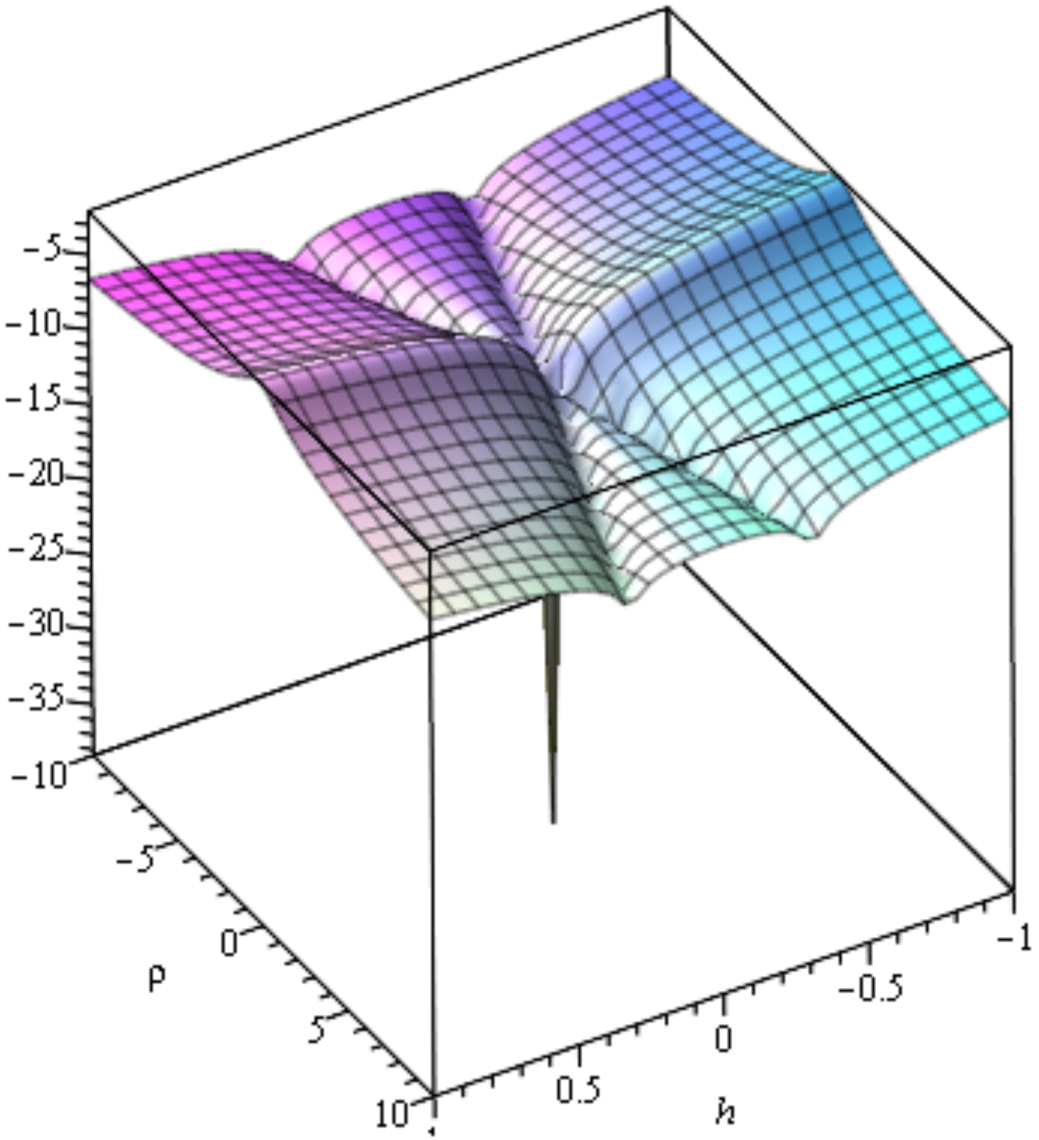
[AR,Tamarit, arXiv:2203.00621]

SM*A*S*H smashed if CMB-S4 or LiteBird do not discover B-modes from inflation!

Reheating in SM*A*S*H

PQ symmetry restoration

- Inflation ends at a value of $\phi \sim M_P$

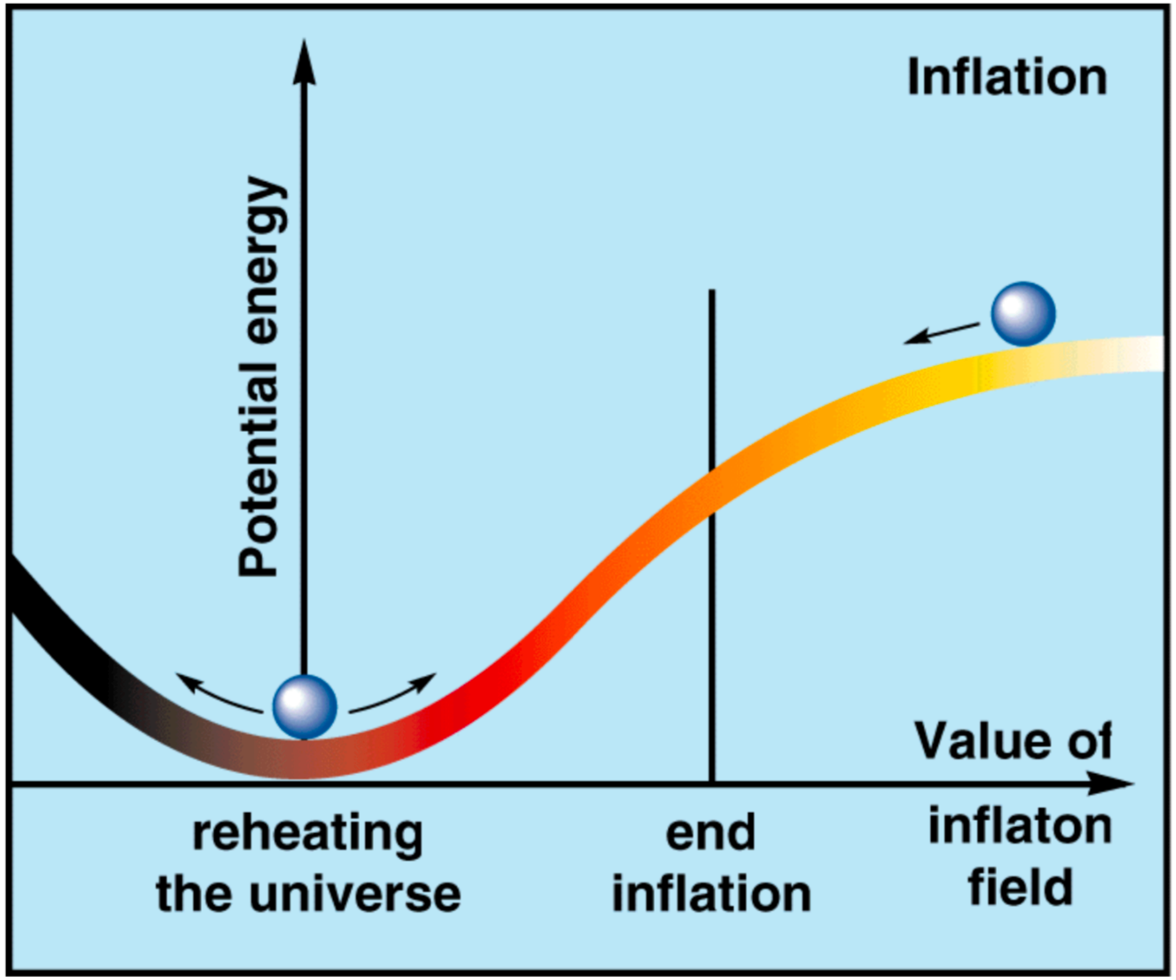


[Ballesteros, Redondo, AR, Tamarit, arXiv:1610.01639]

Reheating in SM*A*S*H

PQ symmetry restoration

- Inflation ends at a value of $\phi \sim M_P$
- Inflaton starts to undergo Hubble-damped oscil-lations in a quasi-quartic potential, with universe expanding as in a radiation-dominated era

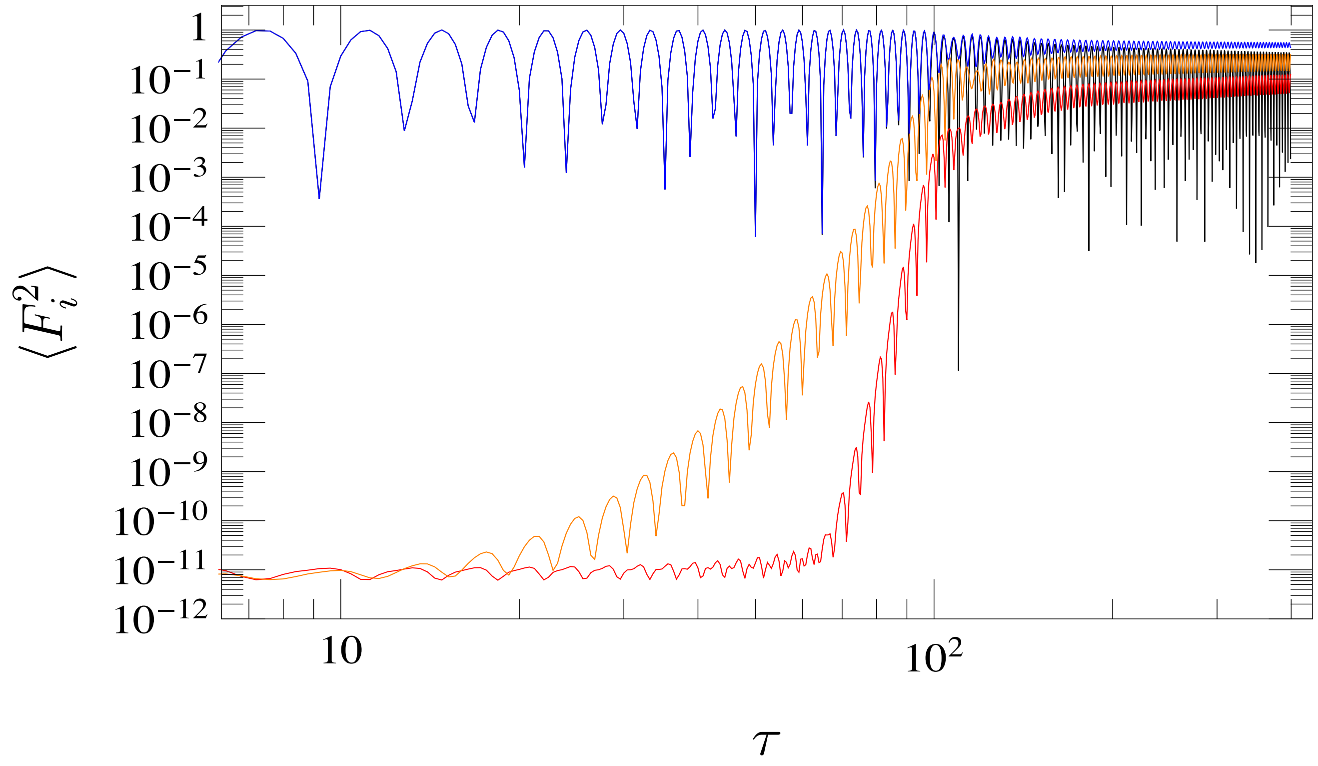


[Garcia-Bellido 99]

Reheating in SM*A*S*H

PQ symmetry restoration

- Inflation ends at a value of $\phi \sim M_P$
- Inflaton starts to undergo Hubble-damped oscillations in a quasi-quartic potential, with universe expanding as in a radiation-dominated era
- Copious production of fluctuations of bosonic fluctuations from parametric resonance (preheating) restores PQ symmetry after few oscillations

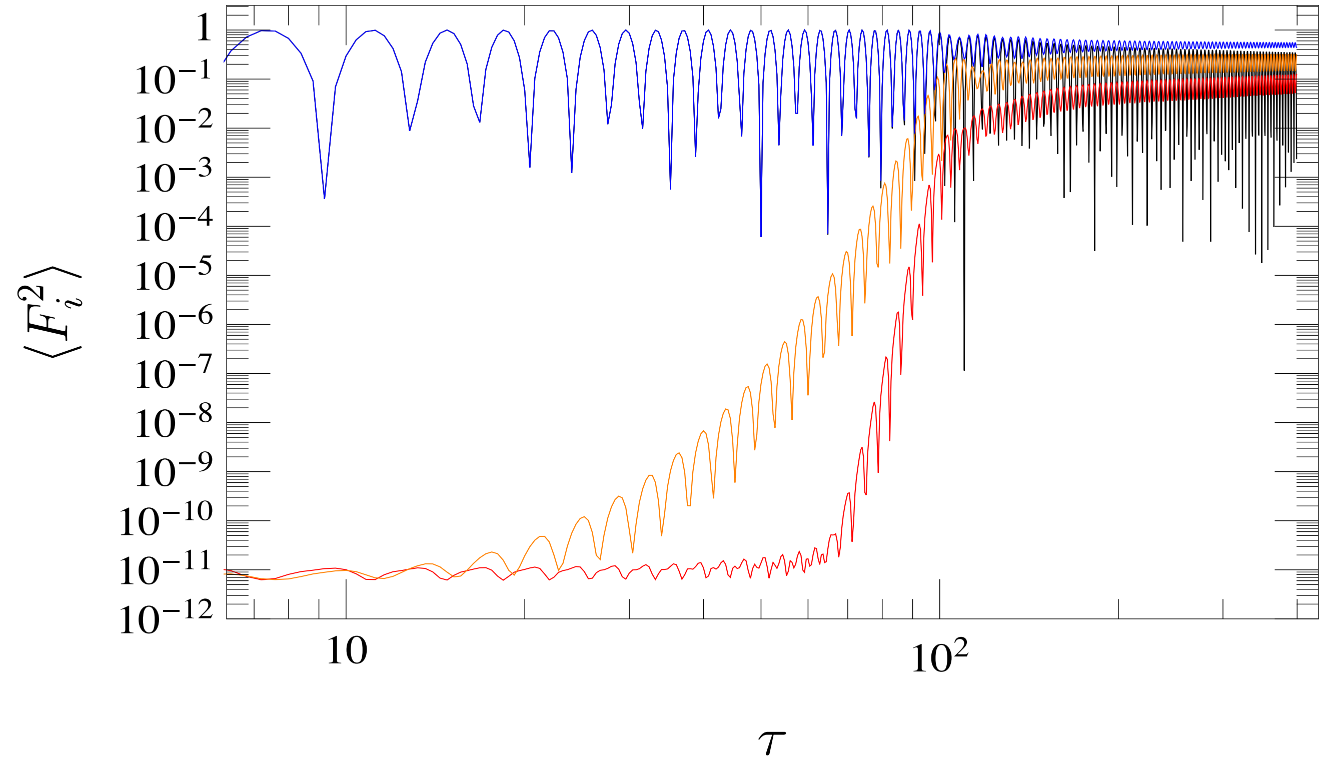


[Ballesteros, Redondo, AR, Tamarit, arXiv:1610.01639]

Reheating in SM*A*S*H

PQ symmetry restoration

- Inflation ends at a value of $\phi \sim M_P$
- Inflaton starts to undergo Hubble-damped oscillations in a quasi-quartic potential, with universe expanding as in a radiation-dominated era
- Copious production of fluctuations of bosonic fluctuations from parametric resonance (preheating) restores PQ symmetry after few oscillations
- Decays of Higgs component of inflaton into SM particles (mainly top quarks) reheats universe efficiently



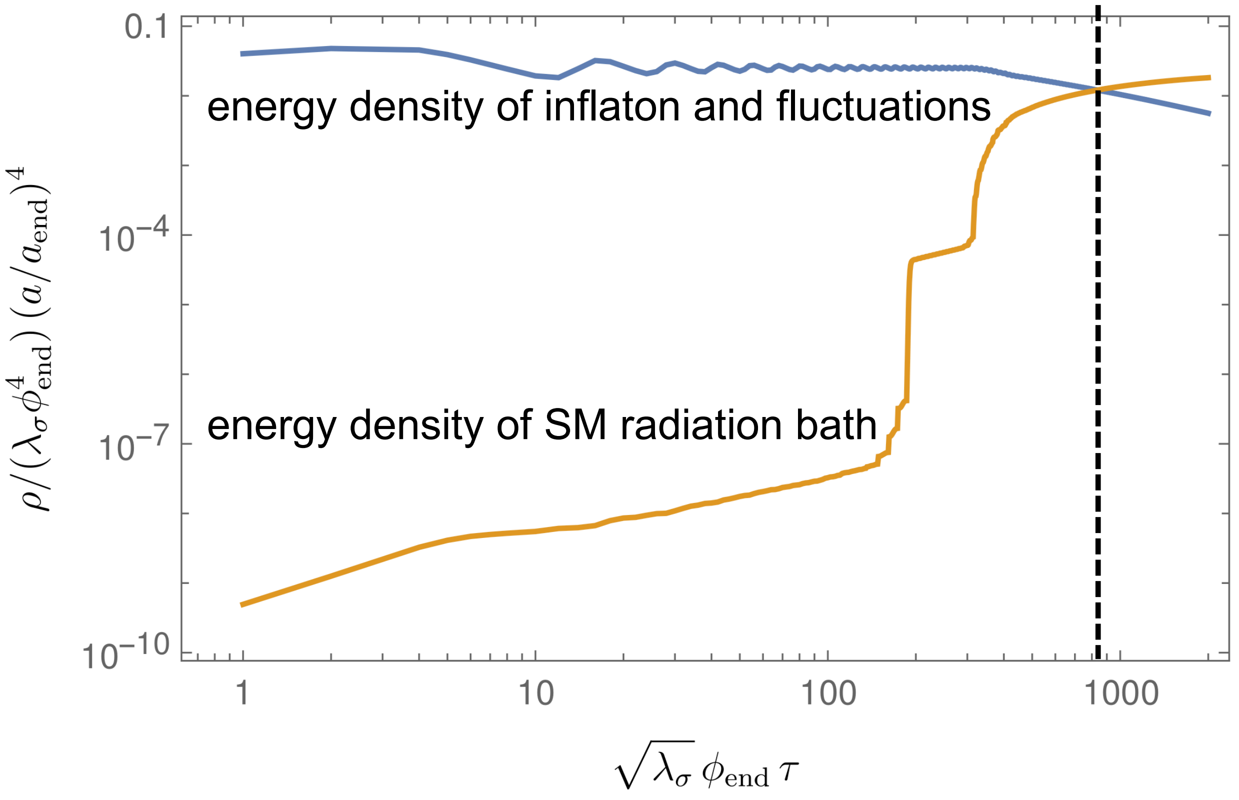
[Ballesteros, Redondo, AR, Tamarit, arXiv:1610.01639]

Reheating in SM*A*S*H

PQ symmetry restoration

- Inflation ends at a value of $\phi \sim M_P$
- Inflaton starts to undergo Hubble-damped oscillations in a quasi-quartic potential, with universe expanding as in a radiation-dominated era
- Copious production of fluctuations of bosonic fluctuations from parametric resonance (preheating) restores PQ symmetry after few oscillations
- Decays of Higgs component of inflaton into SM particles (mainly top quarks) reheats universe efficiently
- Reheating temperature from lattice simulations:

$$T_{\rm rh} = (30\,\rho_{\rm rad}(\tau_{\rm rh})/(\pi^2 g_{\star\rho}(T_{\rm rh}))^{1/4} \approx 10^{12-13}\,{\rm GeV}$$

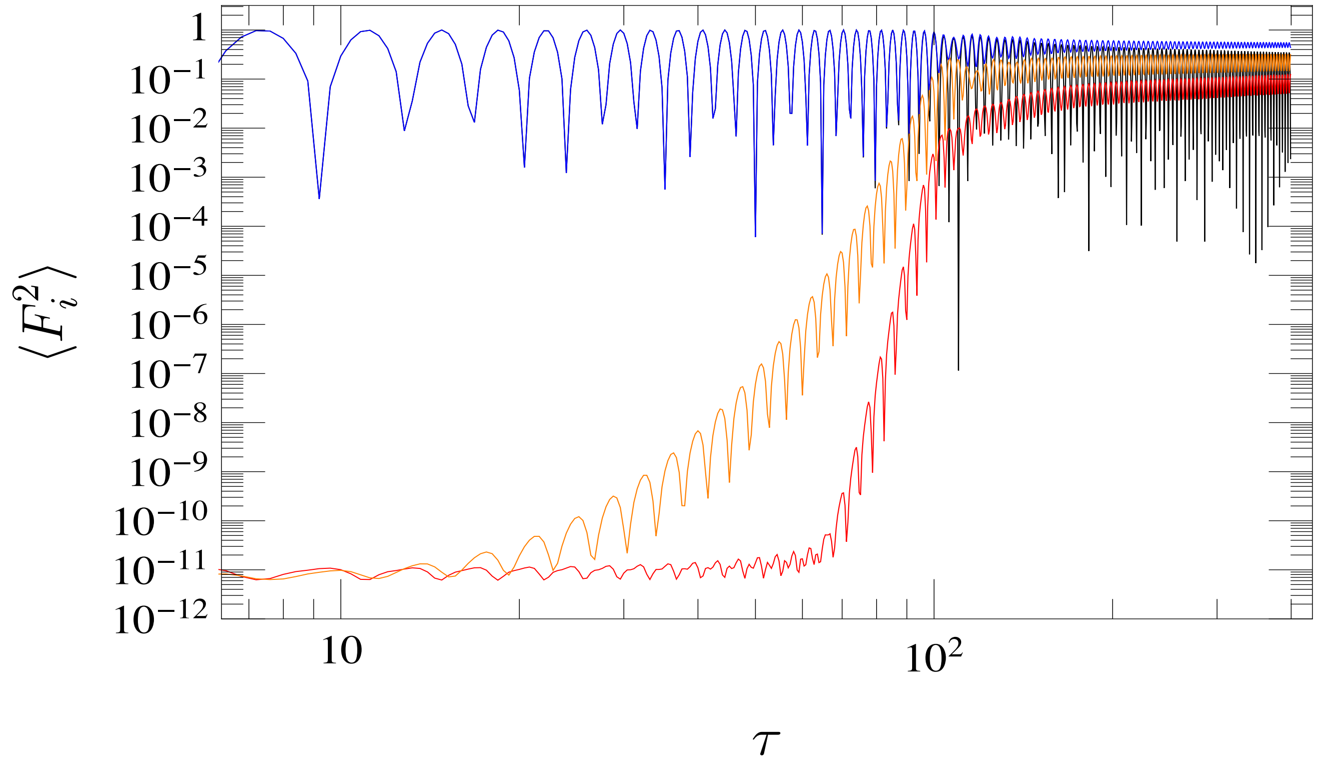


[AR,Tamarit, arXiv:2203.00621]

Dark Matter in SM*A*S*H

PQ symmetry breaking scale / axion mass

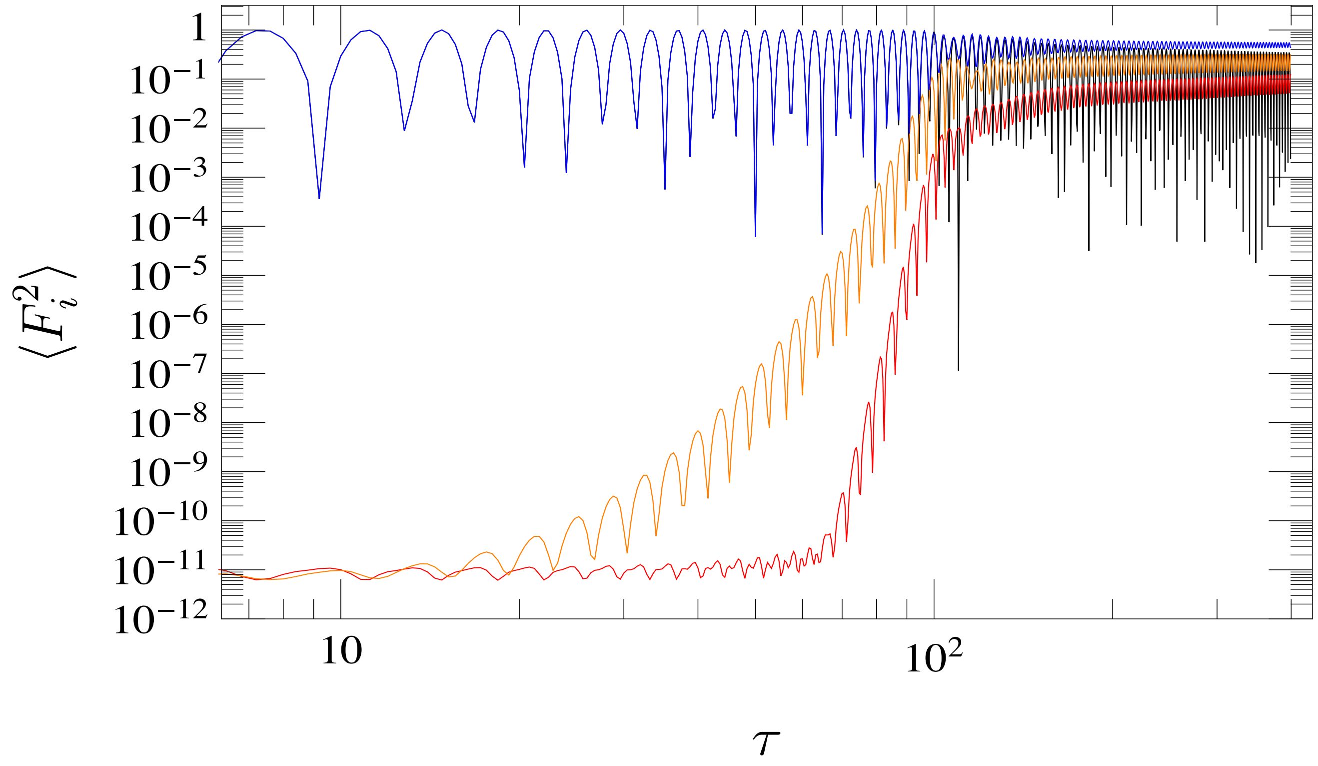
- PQ symmetry restored in preheating



Dark Matter in SM*A*S*H

PQ symmetry breaking scale / axion mass

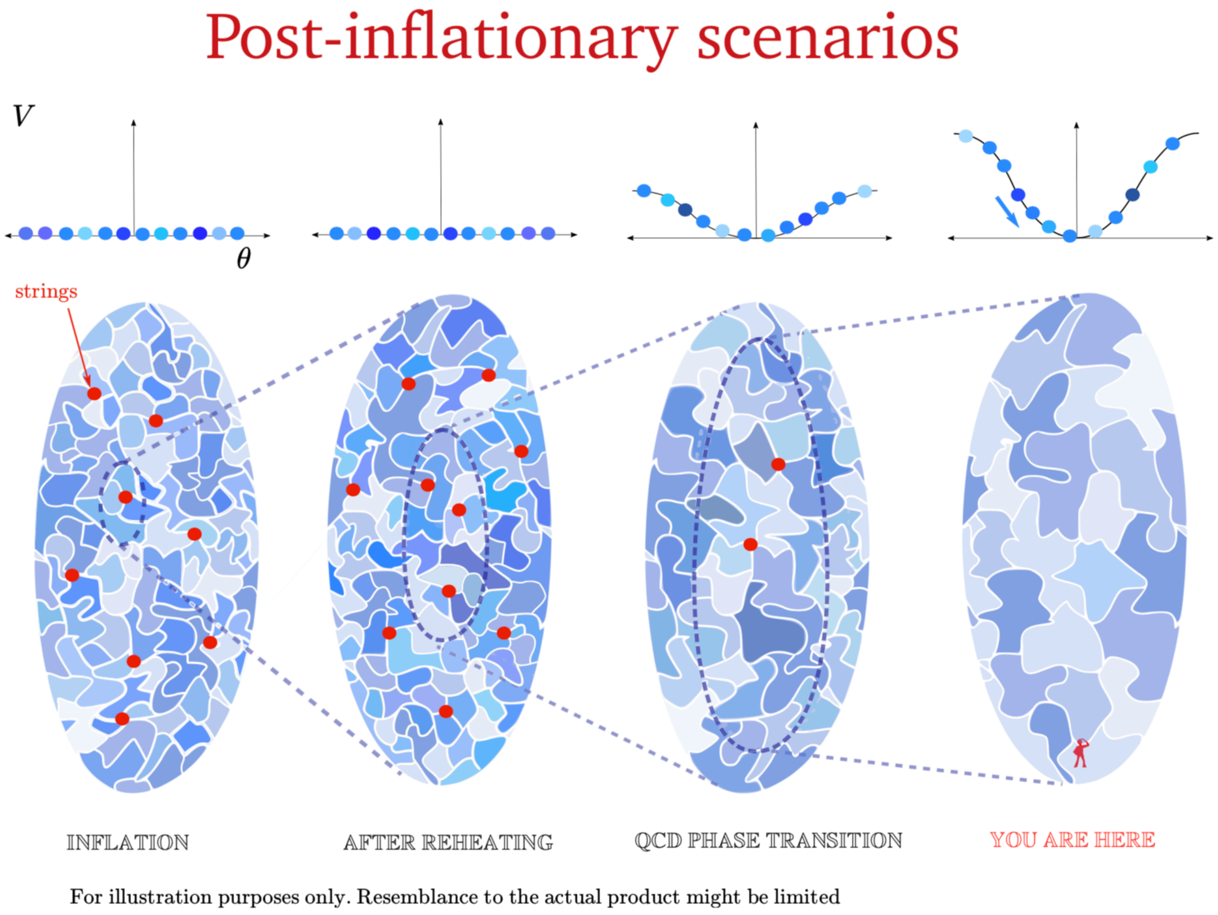
- PQ symmetry restored in preheating
- Latest PQ symmetry breaking occurs during the radiation-dominated hot big bang phase



Dark Matter in SM*A*S*H

PQ symmetry breaking scale / axion mass

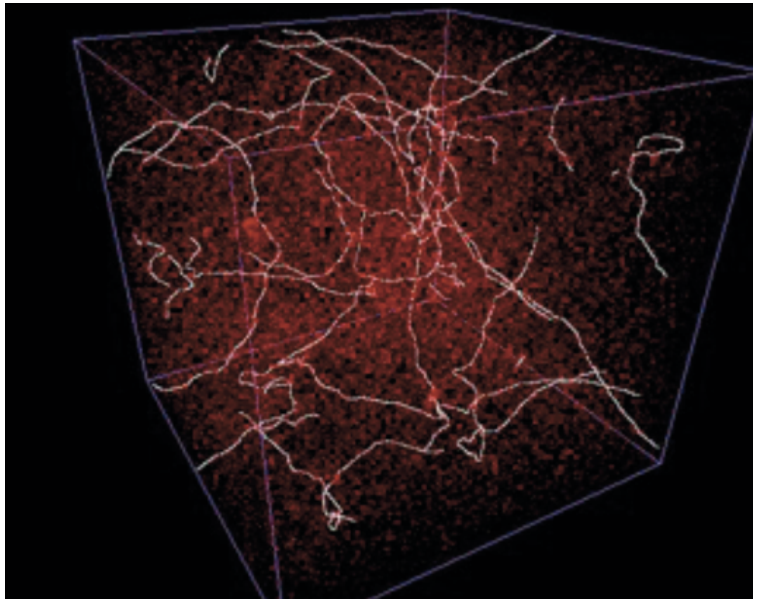
- PQ symmetry restored in preheating
- Latest PQ symmetry breaking occurs during the radiation-dominated hot big bang phase
- Axion dark matter produced by misalignment and the collapse of network of strings



Dark Matter in SM*A*S*H

PQ symmetry breaking scale / axion mass

- PQ symmetry restored in preheating
- Latest PQ symmetry breaking occurs during the radiation-dominated hot big bang phase
- Axion dark matter produced by misalignment and the collapse of network of strings

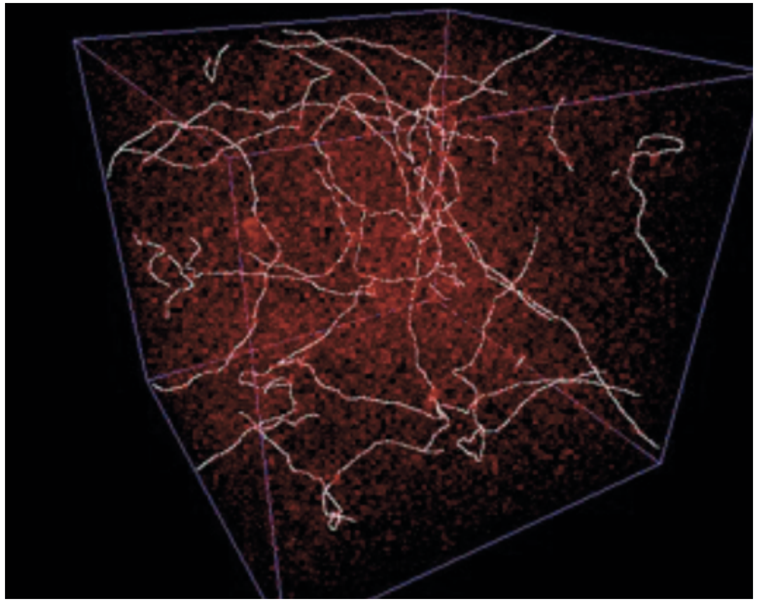


[Hiramatsu et al.]

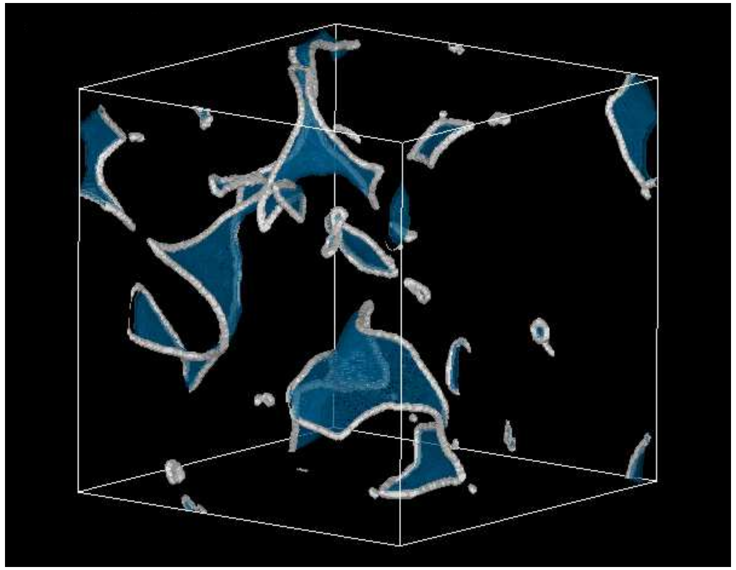
Dark Matter in SM*A*S*H

PQ symmetry breaking scale / axion mass

- PQ symmetry restored in preheating
- Latest PQ symmetry breaking occurs during the radiation-dominated hot big bang phase
- Axion dark matter produced by misalignment and the collapse of network of strings and domain walls



[Hiramatsu et al.]



Dark Matter in SM*A*S*H

PQ symmetry breaking scale / axion mass

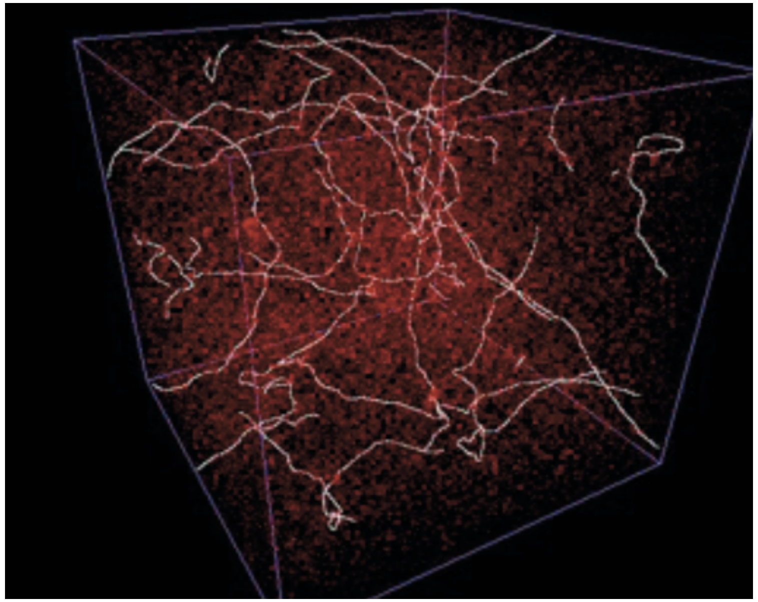
- PQ symmetry restored in preheating
- Latest PQ symmetry breaking occurs during the radiation-dominated hot big bang phase
- Axion dark matter produced by misalignment and the collapse of network of strings and domain walls
- Contribution of the latter determined by lattice simulations and extrapolations – still large uncertainties in predicted decay constant or mass to explain DM

cf. Ciaran O'Hare, WG2 (plenary)

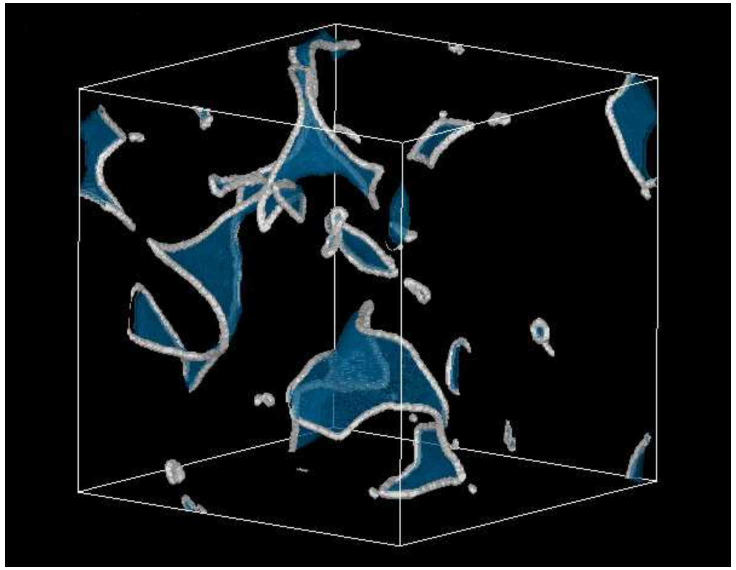
$$1.1 \times 10^{10}\,\mathrm{GeV} \lesssim f_a = v_\sigma < 2.2 \times 10^{11}\,\mathrm{GeV}$$

$$26\ \mu\mathrm{eV} < m_a \lesssim 0.5\ \mathrm{meV}$$

[Hiramatsu et al. 11,12,13; Kawasaki,Saikawa,Segikuchi 15; AR,Saikawa `16; Borsanyi et al. `16; Klaer,Moore `17; Gorghetto,Hardy,Villadoro `18; Buschmann et al. 19; Hindmarsh 19; Gorghetto,Hardy,Villadoro '20; Buschmann et al. 21;...]



[Hiramatsu et al.]



Dark Matter in SM*A*S*H

PQ symmetry breaking scale / axion mass

- PQ symmetry restored in preheating
- Latest PQ symmetry breaking occurs during the radiation-dominated hot big bang phase
- Axion dark matter produced by misalignment and the collapse of network of strings and domain walls
- Contribution of the latter determined by lattice simulations and extrapolations – still large uncertainties in predicted decay constant or mass to explain DM **cf. Ciaran O'Hare, WG2 (plenary)**

$$1.1 \times 10^{10}\,\text{GeV} \lesssim f_a = v_\sigma < 2.2 \times 10^{11}\,\text{GeV}$$

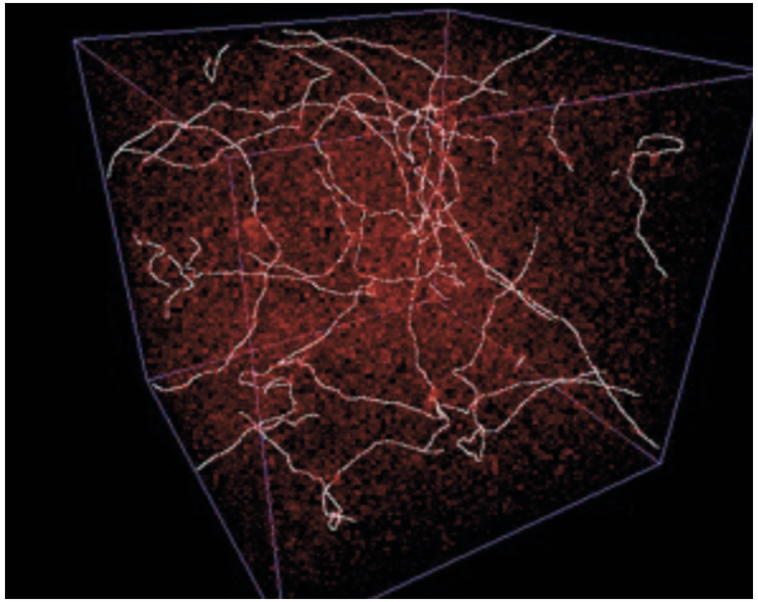
$$26\ \mu\text{eV} < m_a \lesssim 0.5\ \text{meV}$$

  - Conservative upper (lower) bound on $f_a(m_a)$ obtained by exploiting QCD lattice results on topological susceptibility and using only the misalignment contribution, i.e. neglecting axions from strings

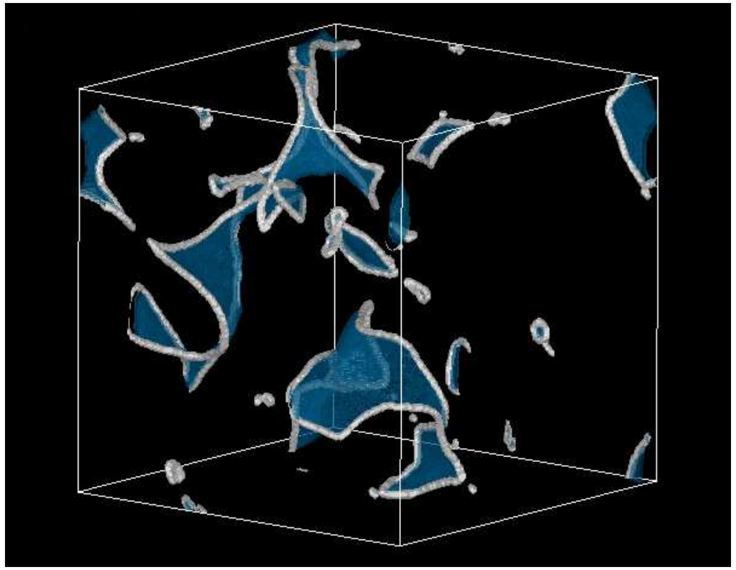
[Hiramatsu et al. 11,12,13; Kawasaki,Saikawa,Segikuchi 15; AR,Saikawa `16; Borsanyi et al. `16; Klaer,Moore `17; Gorghetto,Hardy,Villadoro `18; Buschmann et al. 19; Hindmarsh 19; Gorghetto,Hardy,Villadoro '20; Buschmann et al. 21;...]

[Borsanyi et al., Nature `16 [1606.0794]]

cf. Maria Lombardo, WG2 (parallel)



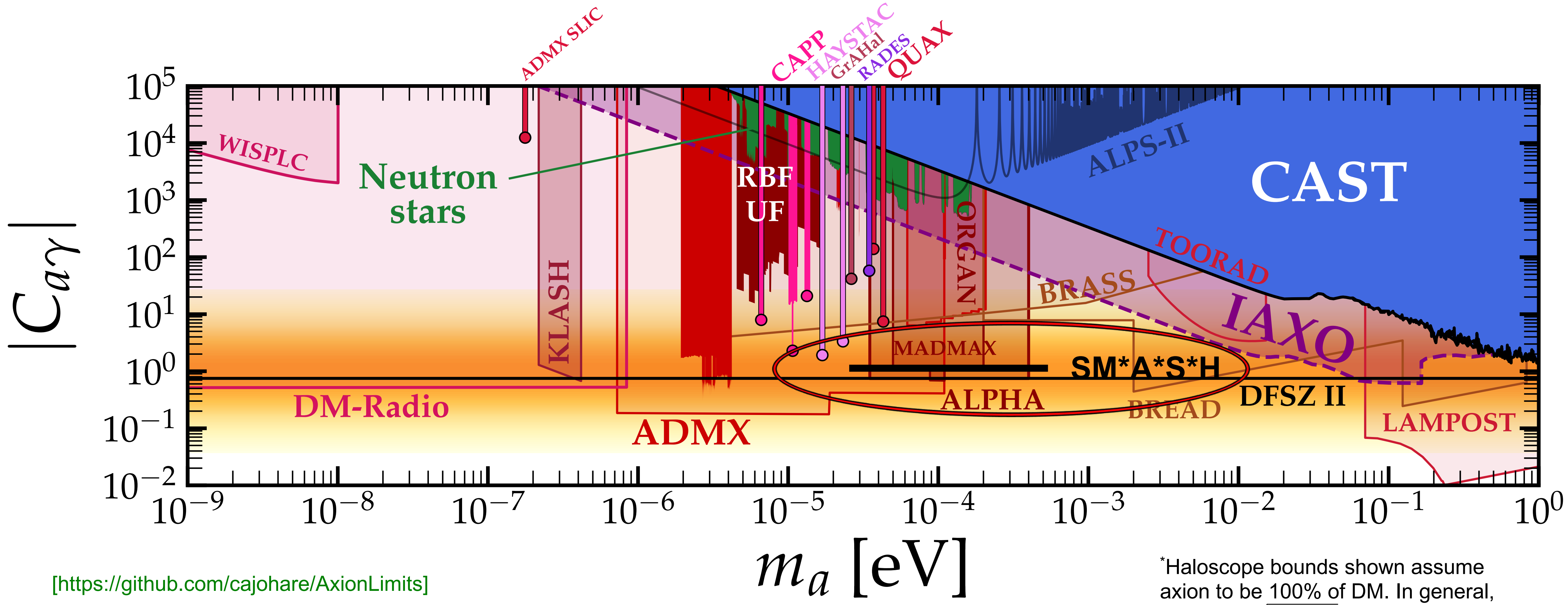
[Hiramatsu et al.]



Dark Matter in SM*A*S*H

PQ symmetry breaking scale / axion mass

- Will be probed in the upcoming generation of axion haloscopes:



[https://github.com/cajohare/AxionLimits]

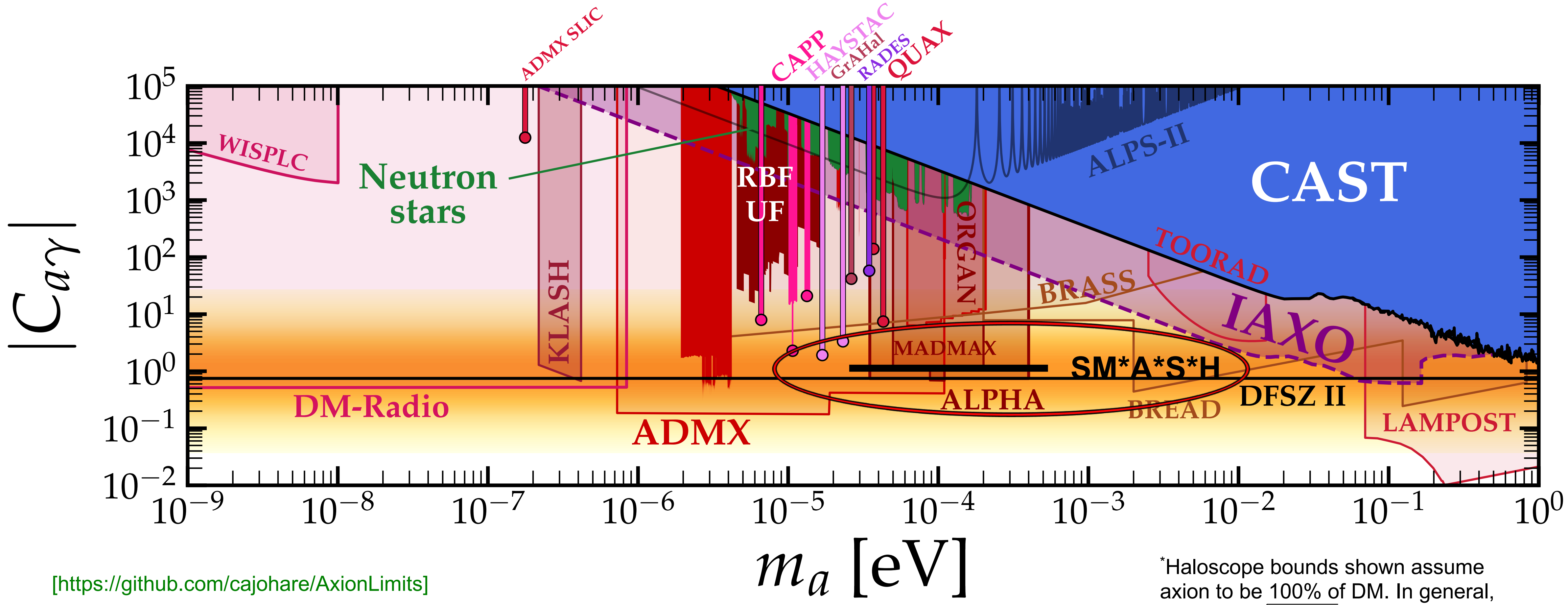
*Haloscope bounds shown assume axion to be 100% of DM. In general, scale as $\sqrt{\rho_{DM}/\rho_a}$

Dark Matter in SM*A*S*H

PQ symmetry breaking scale / axion mass

SM*A*S*H smashed if axion dark matter experiments
- **discover an axion with a mass below 26 micro-eV or**
- **do not discover axion dark matter in the mass range between 26 micro-eV and 500 micro-eV!**

- Will be probed in the upcoming generation of axion haloscopes:



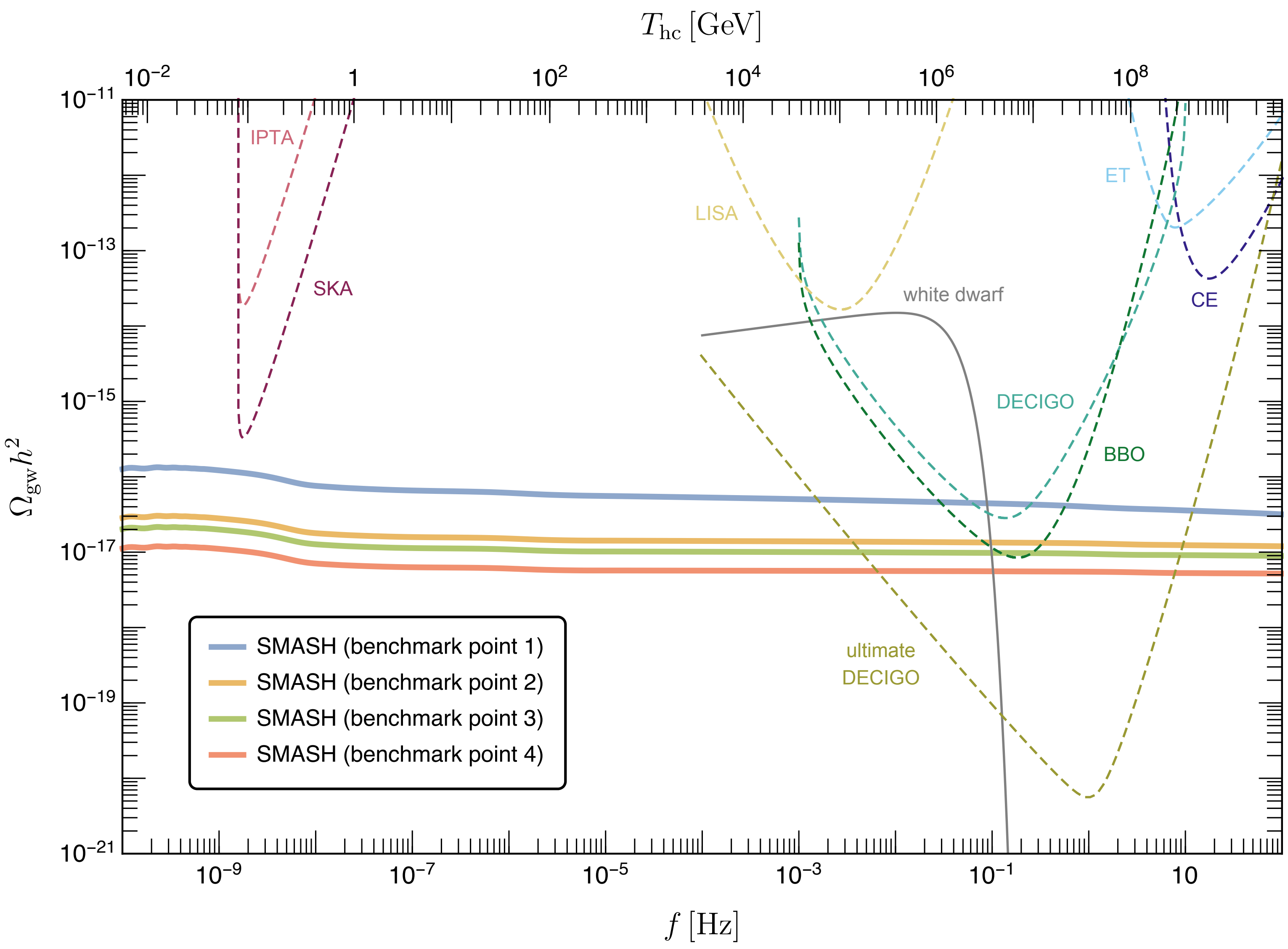
[https://github.com/cajohare/AxionLimits]

*Haloscope bounds shown assume axion to be 100% of DM. In general, scale as $\sqrt{\rho_{\rm DM}/\rho_a}$

Stochastic GW Background from Inflation in SM*A*S*H

Can be probed directly by future space-born interferometer

[AR, Saikawa, Tamarit, arXiv:2009.02050]

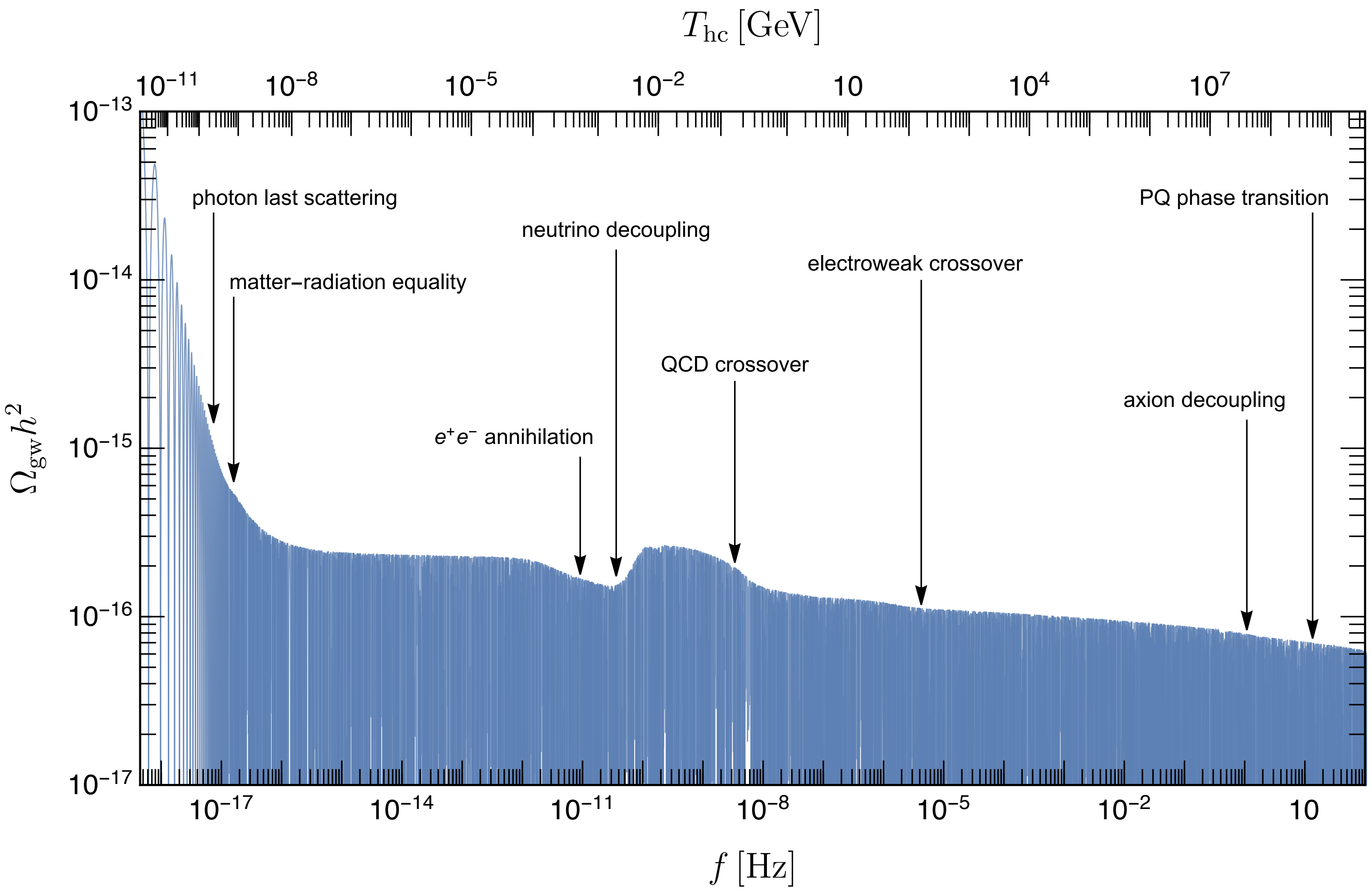


Benchmark point	1	2	3	4
$r(0.002\ \mathrm{Mpc}^{-1})$	0.048	0.0096	0.0068	0.0037
$n_s(0.002\ \mathrm{Mpc}^{-1})$	0.9642	0.9663	0.9665	0.9666
ϕ_*/M_P	22	18	16	8.4
$\xi_\sigma(\phi_*)$	0.0096	0.079	0.14	1.0
$\tilde{\lambda}_\sigma(\phi_*)$	9.1×10^{-13}	9.0×10^{-12}	2.0×10^{-11}	5.3×10^{-10}
$\lambda_\sigma(M_P)$	4.4×10^{-12}	1.4×10^{-10}	5.0×10^{-11}	4.4×10^{-9}
$\lambda_{H\sigma}(M_P)$	-1.5×10^{-6}	-6.0×10^{-6}	-6.5×10^{-6}	-2.9×10^{-5}
$\lambda_H(M_P)$	0.63	0.26	1.2	0.21
$y(M_P)$	0.00056	0.0014	0.00086	0.0027
$Y_{ii}(M_P)$	0.0011	0.0025	0.0016	0.0045

Stochastic GW Background from Inflation in SM*A*S*H

Cosmic history of SMASH imprinted on SGWB

[AR, Saikawa, Tamarit, arXiv:2009.02050]



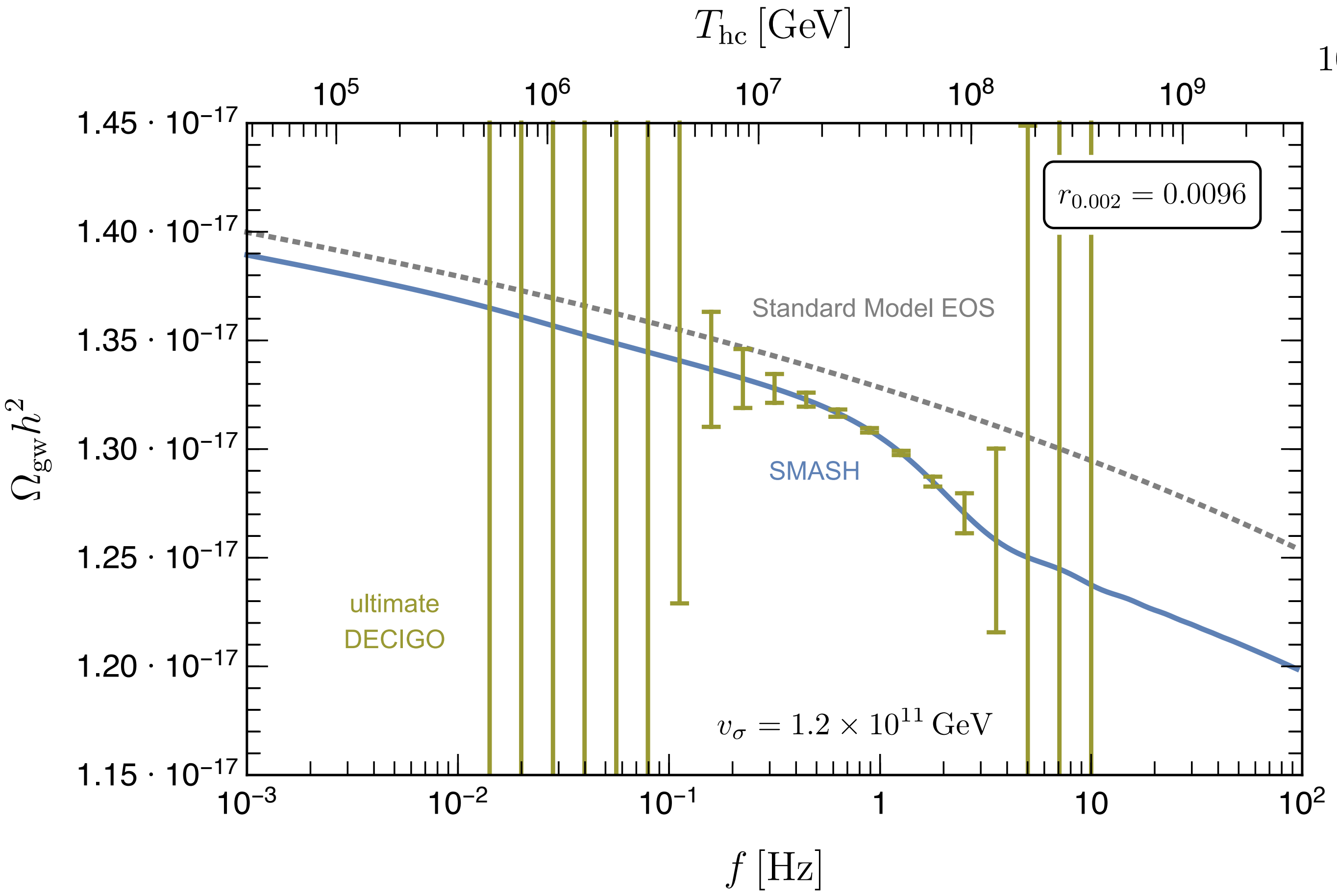
Stochastic GW Background from Inflation in SM*A*S*H

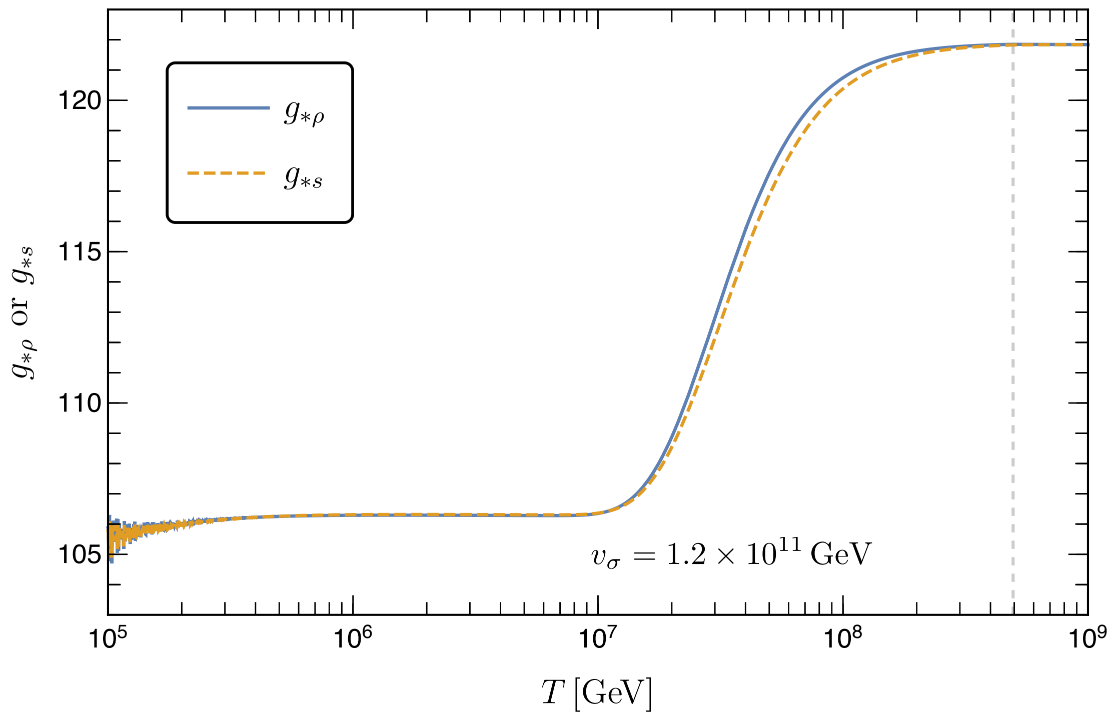
Ultimate DECIGO sensitive to step in SGWB spectrum due to step in EOS at PQ phase transition

Axion 100% DM: $1.1 \times 10^{10}\,\text{GeV} \lesssim v_\sigma < 2.2 \times 10^{11}\,\text{GeV}$

Viable inflation: $10^{-12} \lesssim \lambda_\sigma \lesssim 10^{-9}$

$$10^7\,\text{GeV} \lesssim T_c \simeq \frac{2\sqrt{6\lambda_\sigma}v_\sigma}{\sqrt{8(\lambda_\sigma+\lambda_{H\sigma})+\sum_i Y_{ii}^2+6y^2}} \sim \lambda_\sigma^{1/4}\, v_\sigma \lesssim 10^9\,\text{GeV}$$



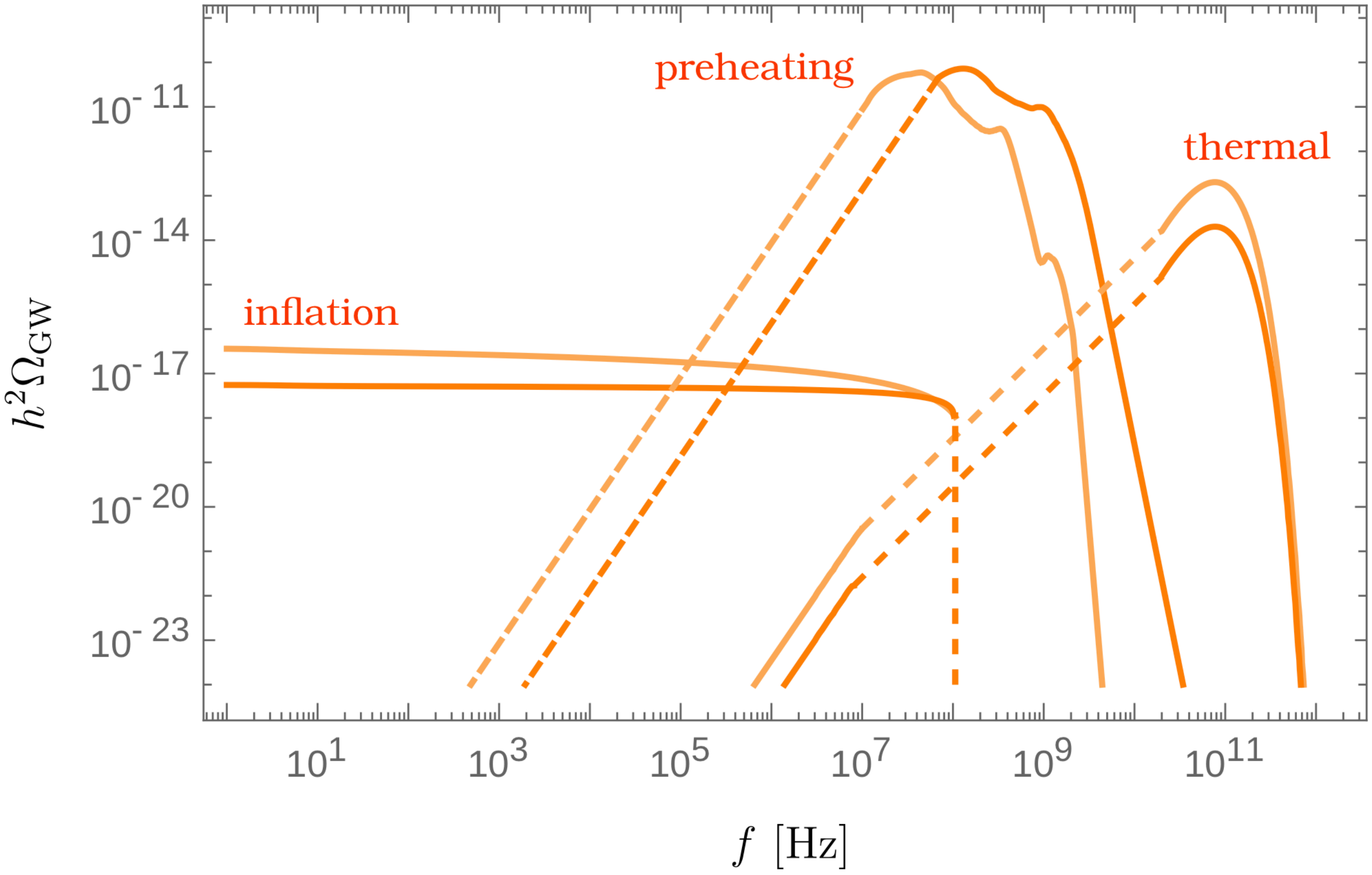


[AR, Saikawa, Tamarit, arXiv:2009.02050]

Stochastic Gravitational Wave Background from SM*A*S*H

Complete SGWB spectrum

[AR, Carlos Tamarit, arXiv:2203.00621]

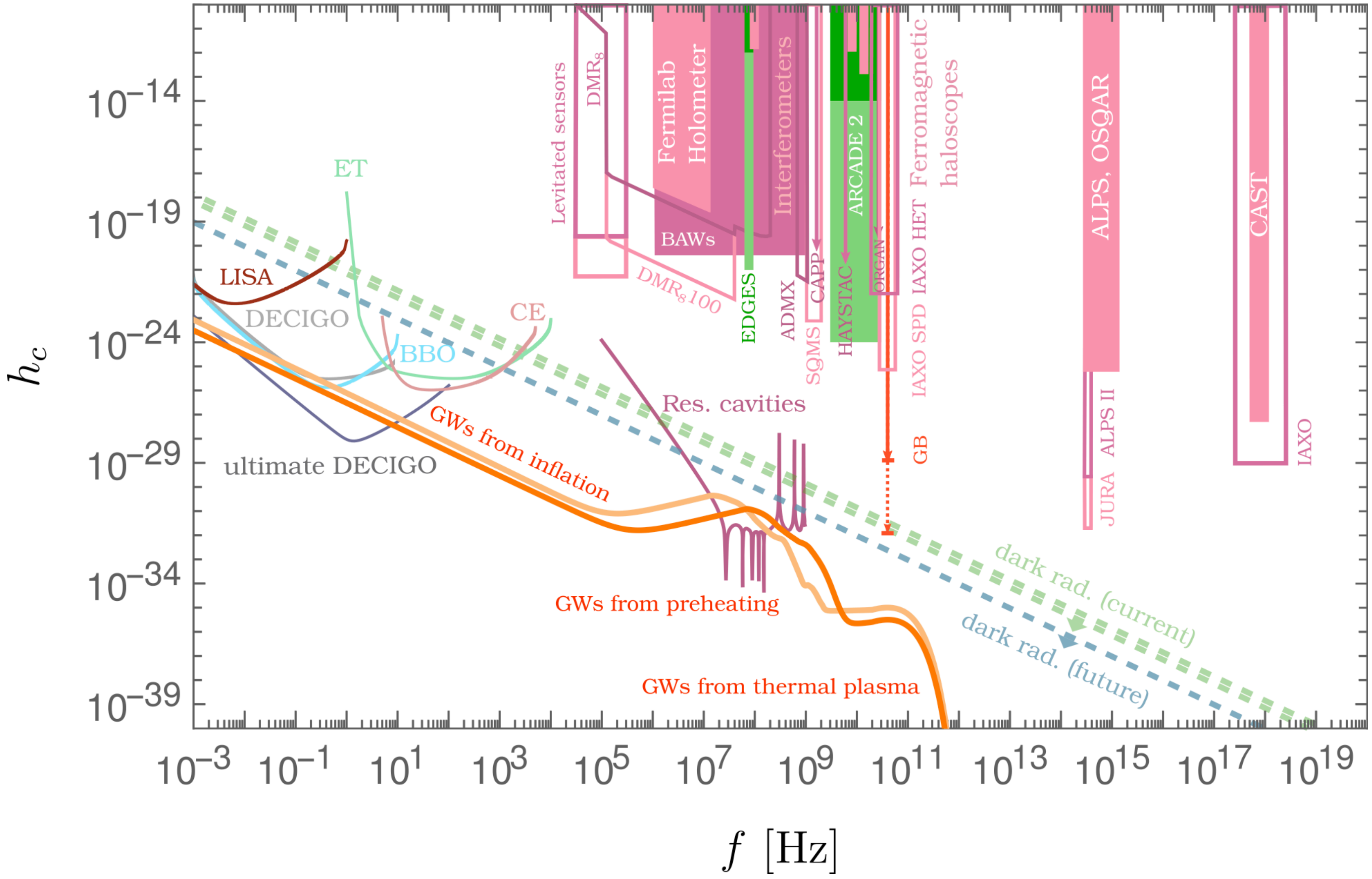


cf. Gonzalo Villa, WG1 (parallel)

Stochastic Gravitational Wave Background from SM*A*S*H

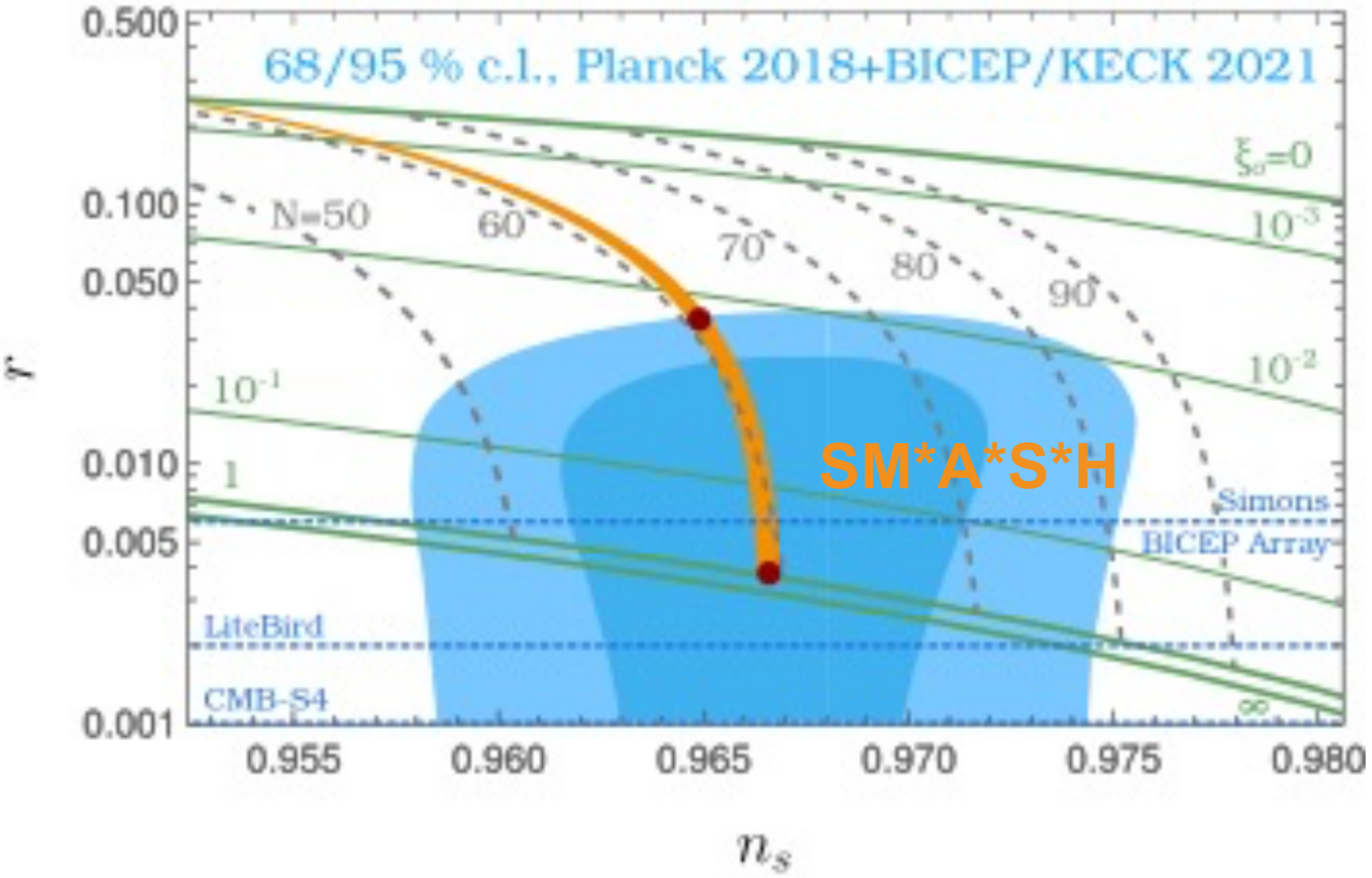
Sensitivity of current and proposed GW experiments

[AR, Carlos Tamarit, arXiv:2203.00621]



Summary

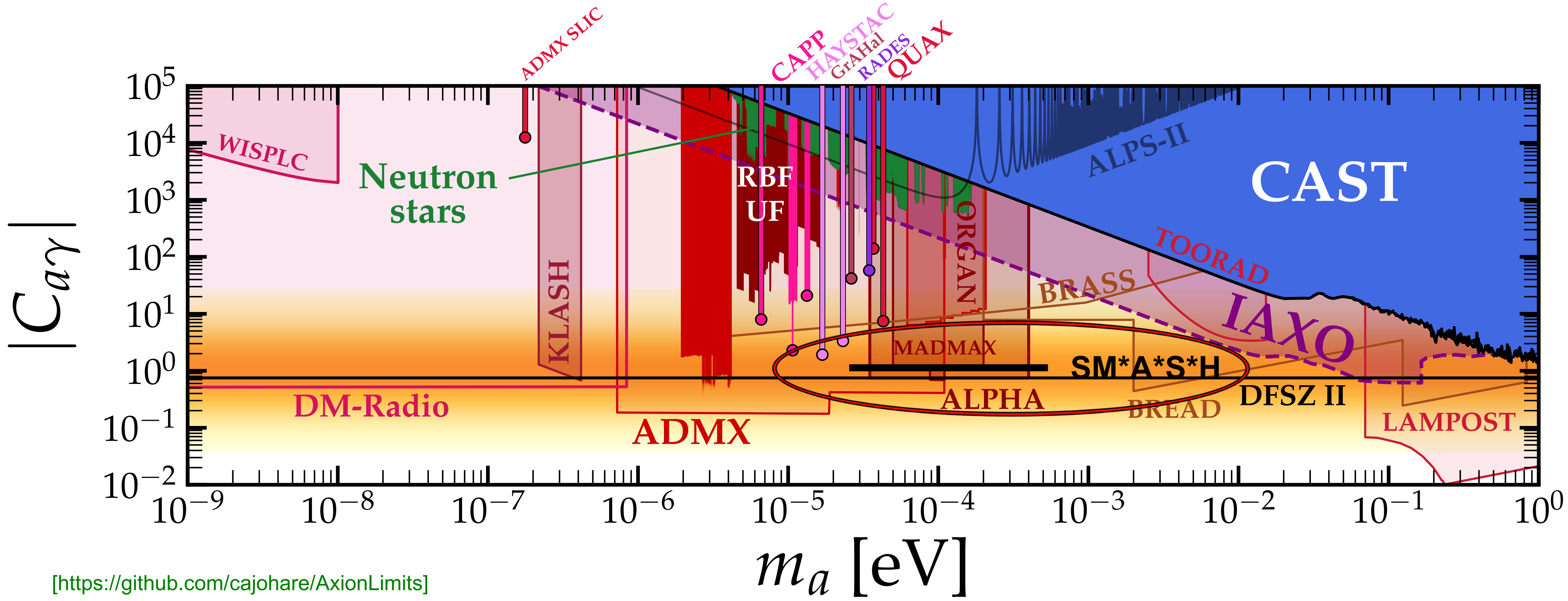
- **SM*A*S*H** can be smashed by upcoming CMB polarisation experiments



[AR,Tamarit, arXiv:2203.00621]

Summary

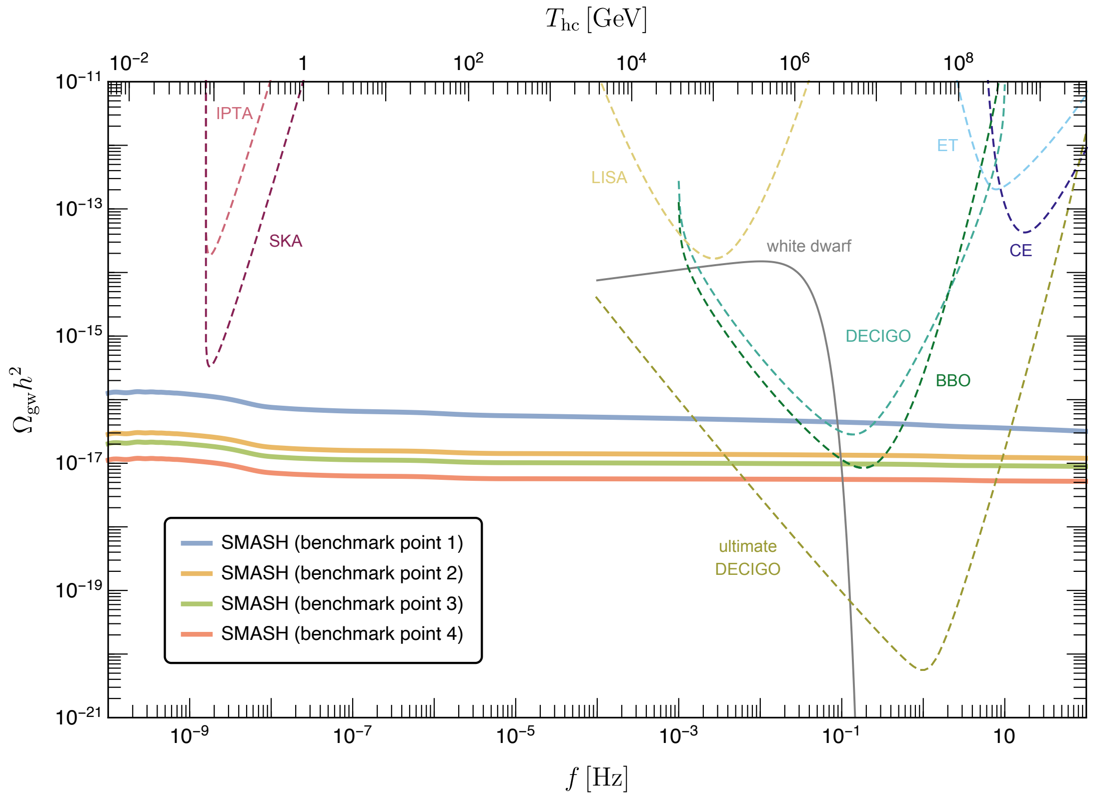
- **SM*A*S*H** can be smashed by upcoming CMB polarisation experiments and haloscopes

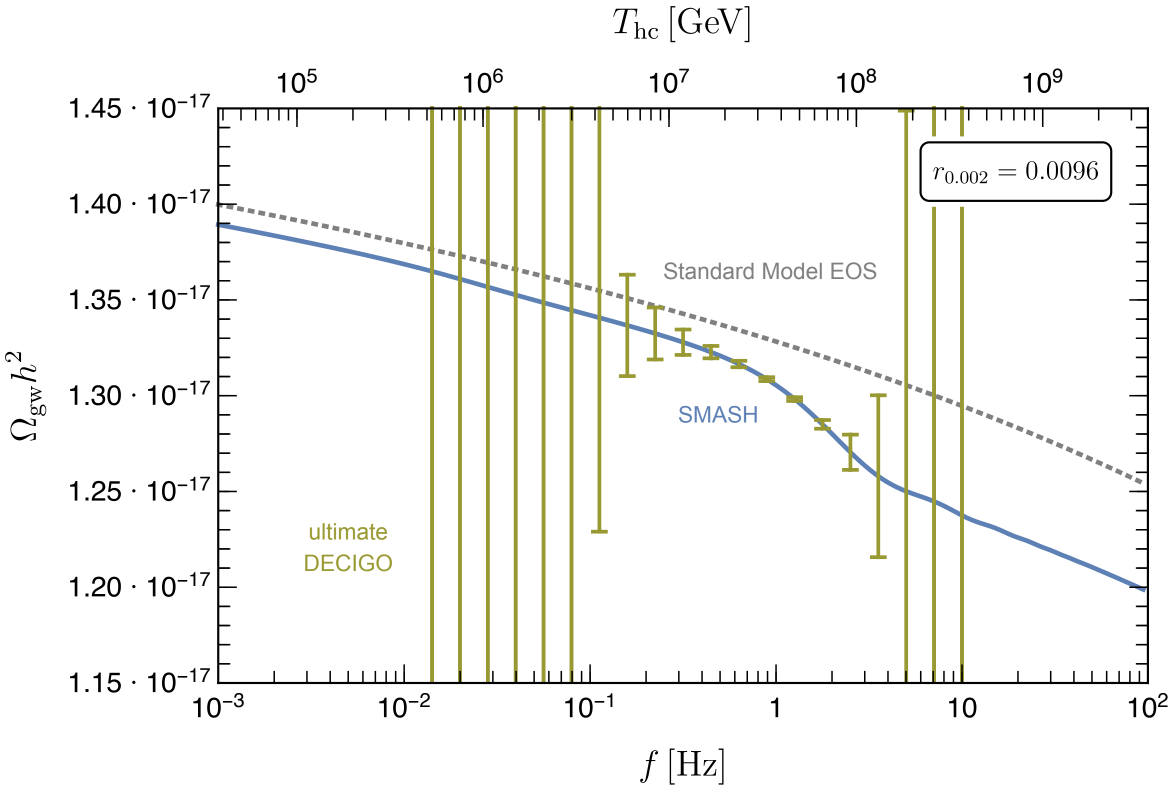


[https://github.com/cajohare/AxionLimits]

Summary

- **SM*A*S*H** can be smashed by upcoming CMB polarisation experiments and haloscopes
- If it survives these tests, it can be further scrutinised with proposed space-born GW interferometer

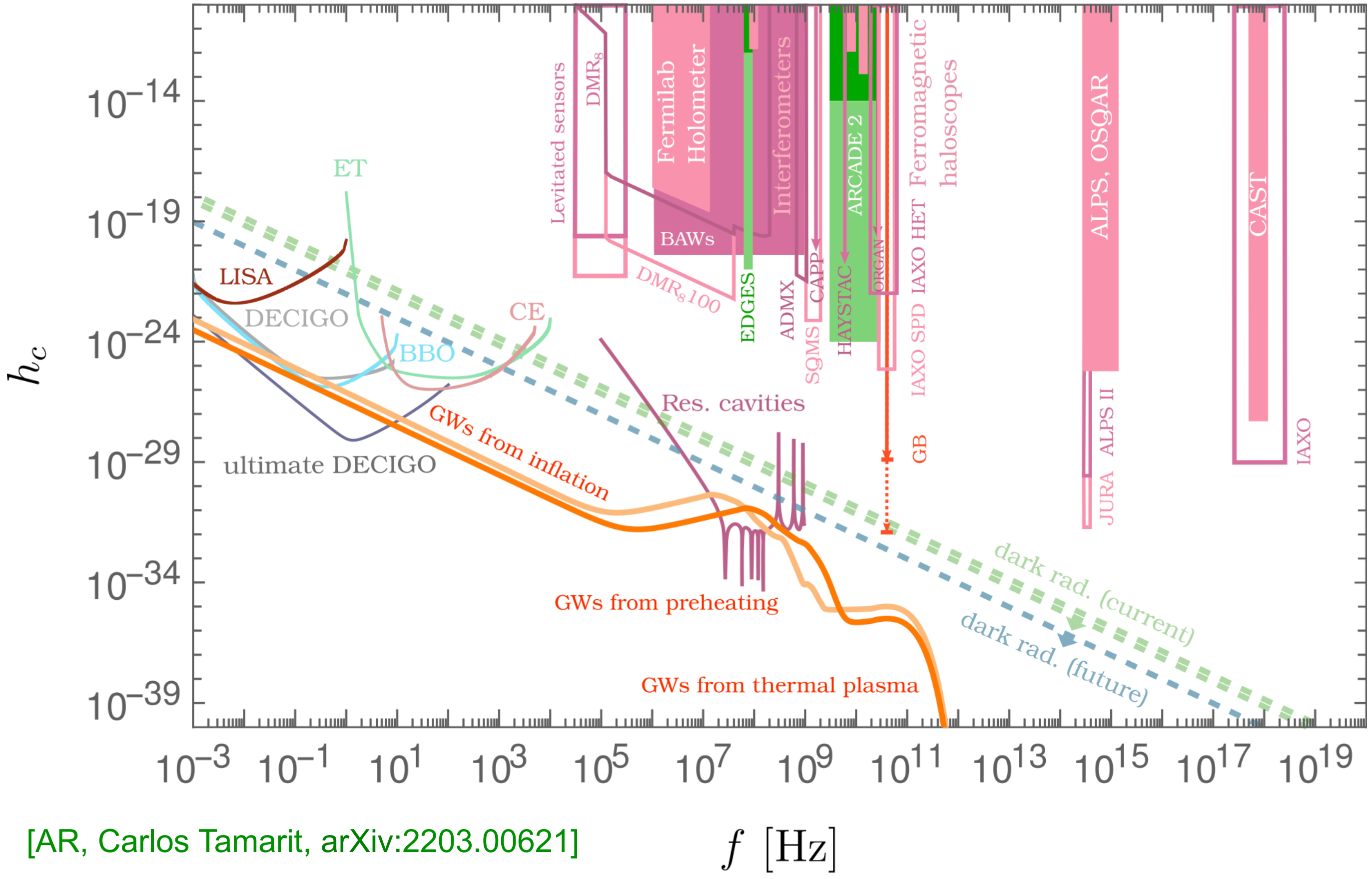




[AR, Saikawa, Tamarit, arXiv:2009.02050]

Summary

- **SM*A*S*H** can be smashed in the upcoming decade by CMB polarisation measurements and haloscopes
- If it survives these tests, it can be further scrutinised (in 30 years?) with space-born GW interferometer
- It motivates also the development of high frequency GW detectors, beyond the reach of interferometers:



[AR, Carlos Tamarit, arXiv:2203.00621]

Is SM*A*S*H smashed by swampland conjectures?

- This is not expected, since ordinary Higgs inflation can be in landscape:

[Cheong et al., arXiv:1811.03622; Liu, arXiv:2112.14571]

Physics Letters B 789 (2019) 336–340

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Higgs inflation and the refined dS conjecture

Dhong Yeon Cheong, Sung Mook Lee, Seong Chan Park *

Department of Physics, IPAP & Lab for Dark Universe, Yonsei University, Seoul 03722, Republic of Korea

A R T I C L E   I N F O

Article history:
Received 18 November 2018
Received in revised form 19 December 2018
Accepted 20 December 2018
Available online 21 December 2018
Editor: J. Hisano

Keywords:
Swampland conjecture
Higgs inflation

A B S T R A C T

The refined de Sitter derivative conjecture provides constraints to potentials that are low energy effective theories of quantum gravity. It can give direct bounds on inflationary scenarios and determine whether the theory is in the Landscape or the Swampland. We consider the 'Higgs inflation' scenario taking the refined de Sitter derivative conjecture into account. Obtaining the critical lines for the potential, we find a conjecture parameter space in which the 'Higgs inflation' is to be in the Landscape. Comparing with the model independent observational bounds from recent data we find that the observational bounds represent the Higgs inflation can be in the Landscape.

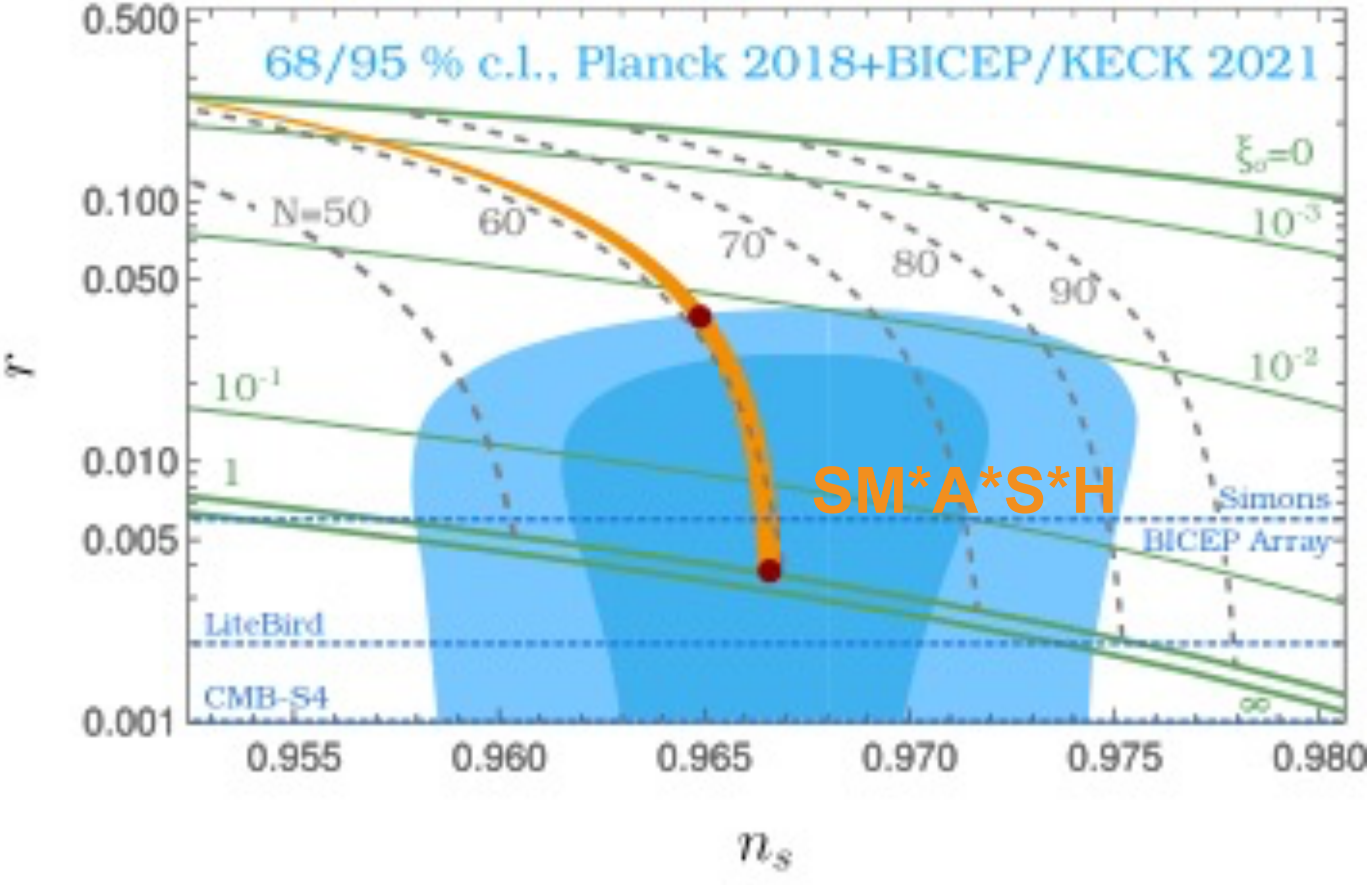
- Could be an interesting prospect to investigate whether the requirement of being in the landscape gives further restrictions to the allowed parameter space in SM*A*S*H

Is SM*A*S*H smashed by swampland conjectures?

- In observationally constrained SM*A*S*H inflation, inflaton field travels a distance of O(10) M_P:

Benchmark for $r(k_*) = 0.0037$:

$$\phi_* = 8.4 M_P$$
$$\xi_\sigma(\phi_*) = 1.0$$
$$\tilde{\lambda}_\sigma(\phi_*) = 5.3 \times 10^{-10}$$
$$\hat{\kappa} = 0.08$$
$$\phi_{\rm end} = 0.76\, M_P$$
$$N_{\rm post} = 64.0$$
$$\alpha = 3 \times 10^{-4}$$
$$\mathcal{H}_{\rm end} = 2.4 \times 10^{-6} M_P$$



[AR,Tamarit, arXiv:2203.00621]

Benchmark for $r(k_*) = 0.036$:

$$\phi_* = 21.4 M_P$$
$$\xi_\sigma(\phi_*) = 0.014$$
$$\tilde{\lambda}_\sigma(\phi_*) = 1.25 \times 10^{-12}$$
$$\hat{\kappa} = 0.05$$
$$\phi_{\rm end} = 2.2\, M_P$$
$$N_{\rm post} = 64.3$$
$$\alpha = 1 \times 10^{-5}$$
$$\mathcal{H}_{\rm end} = 1.8 \times 10^{-6} M_P$$

GWs from Stochastic Scalar Fluctuations during Reheating

Lattice simulations

- Simulated 3 real scalars, $\phi_1 = \sqrt{2}\mathrm{Re}\sigma(\mathrm{t},\mathbf{x}), \phi_2 = \sqrt{2}\mathrm{Im}\sigma(\mathrm{t},\mathbf{x}), \mathrm{h}(\mathrm{t},\mathbf{x})$, with h decaying into a relativistic bath of SM particles with energy density $\rho_{\mathrm{SM}}(t)$, in an expanding FRW universe:

$$\ddot{\phi}_n + 3\frac{\dot{a}}{a}\dot{\phi}_n - \frac{1}{a^2}\vec{\nabla}^2\phi_n + \frac{\partial V}{\partial \phi_n}, \; n = 1, 2,$$

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

$$\dot{\rho}_{\mathrm{SM}} + 4\frac{\dot{a}}{a}\rho_{\mathrm{SM}} - \Gamma_h \dot{h}^2 = 0,$$

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

- Used modified version of “CLUSTEREASY” [Felder, Tkachev 08] . Changes account for Higgs decay, SM radiation and impact on scale factor evolution, modified initial conditions for super-horizon modes

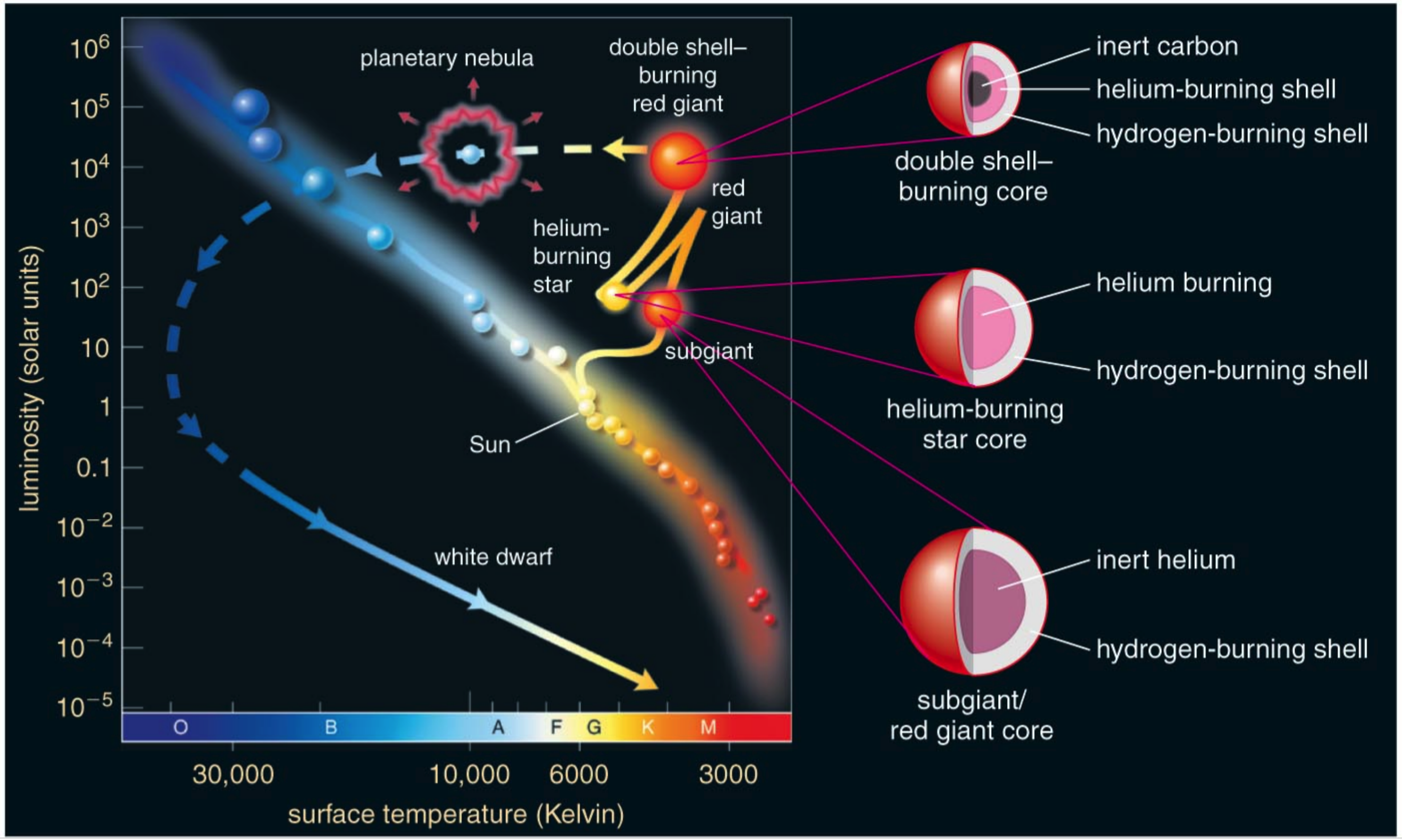
[Ballesteros,AR,Tamarit,Welling, arXiv:2104.13847; AR,Tamarit, arXiv: 2203.00621]

- Used lattices with 256^3 points
- Used 8 powerful CPU cores running for ~7 days,
- Computed up to tau = 2000 (rescaled conformal time in program units)

Astrophysical Hints for Axions/ALPs

Excessive stellar energy losses

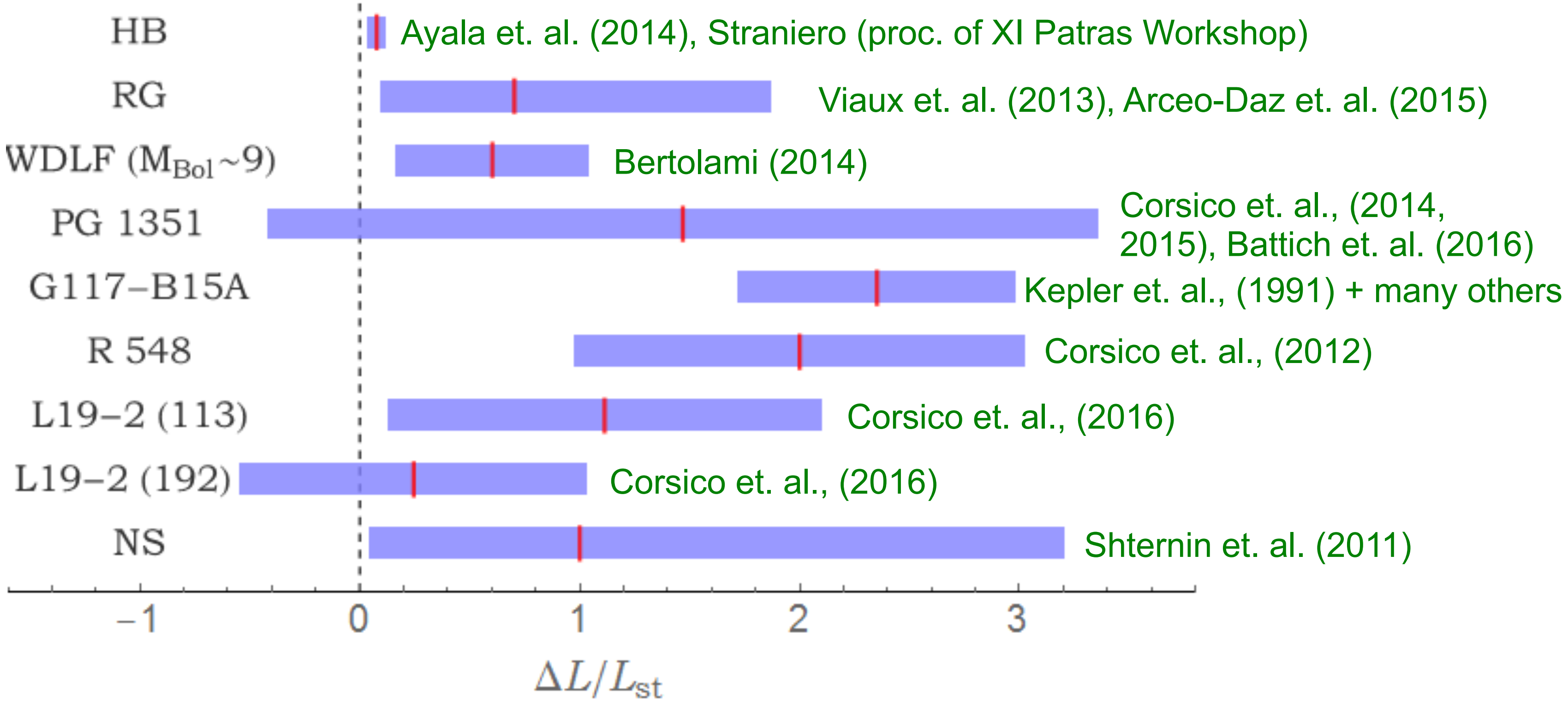
- Evolution of stars (Main Sequence – Red-Giant (RG) – Helium Burning (HB) – White Dwarf (WD)) sensitive to non-SM energy losses



Astrophysical Hints for Axions/ALPs

Excessive stellar energy losses

- Practically every stellar systems seems to be cooling faster than predicted by models:

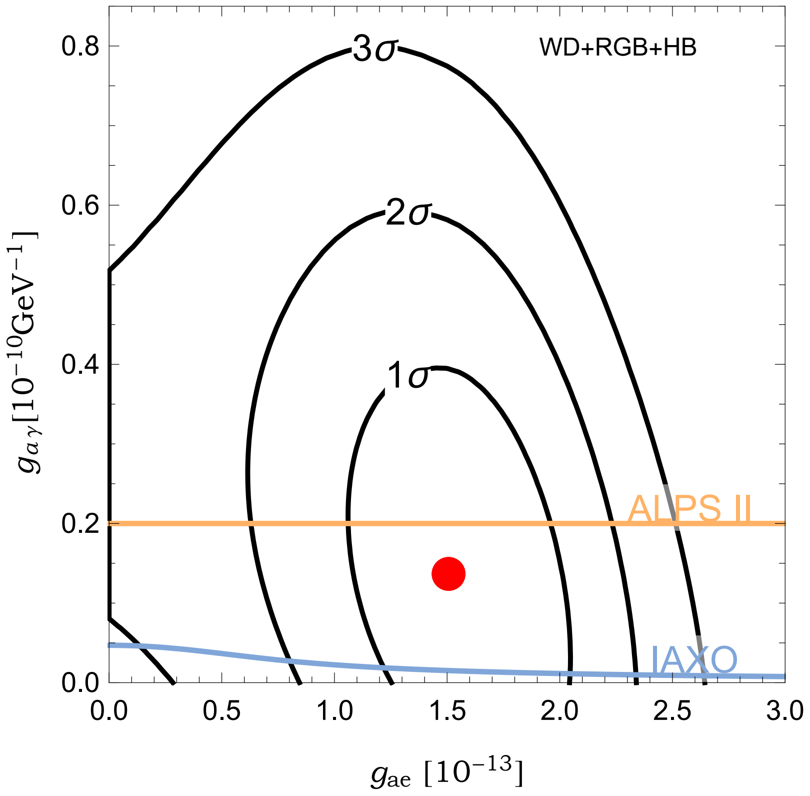


[Giannotti, Irastorza, Redondo, AR ‘15; Giannotti, Irastorza, Redondo, AR, Saikawa ‘17]

Astrophysical Hints for Axions/ALPs

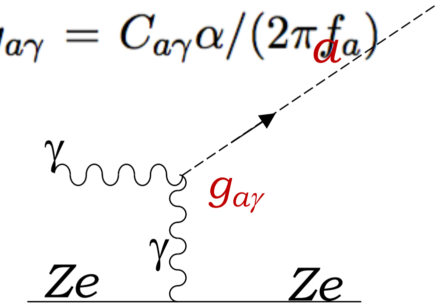
Excessive stellar energy losses

- Excessive energy losses of HBs, RG, WDs can be explained at one stroke by production of axion/ALP with coupling to photons and electrons:

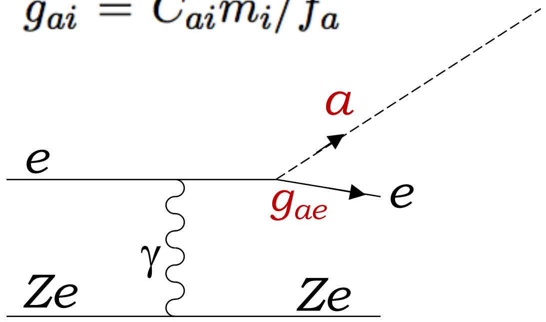


[Giannotti,Irastorza,Redondo,AR,Saikawa 17]

$$g_{a\gamma} = C_{a\gamma}\alpha/(2\pi f_a)$$



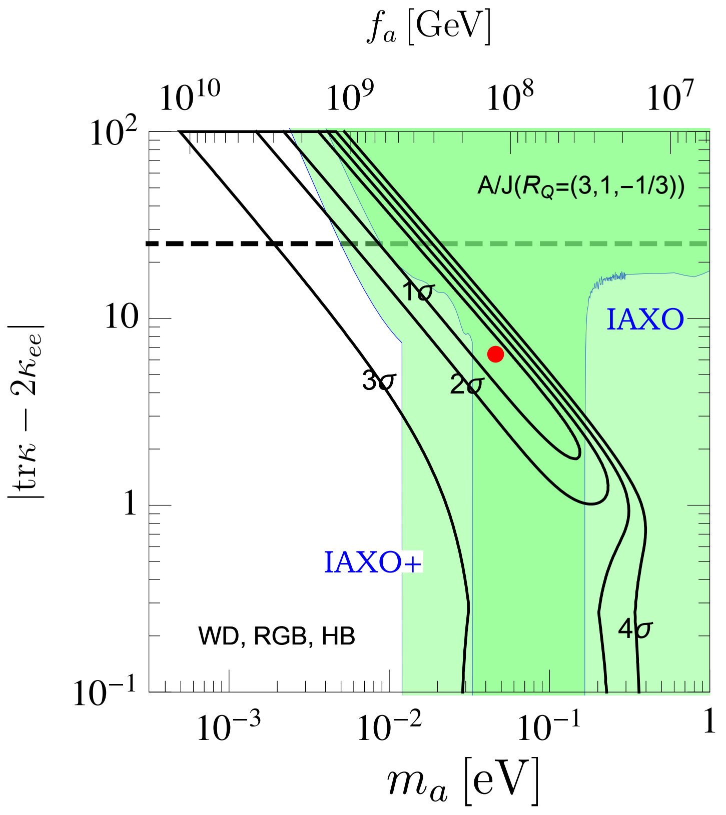
$$g_{ai} = C_{ai} m_i / f_a$$



Astrophysical Hints for Axions/ALPs

Excessive stellar energy losses

- Excessive energy losses of HBs, RG, WDs can be explained at one stroke by production of axion/ALP with coupling to photons and electrons, e.g. KSVZ axion/majoron model [Shin `88]



[Giannotti,Irastorza,Redondo,AR,Saikawa 17]

$$C_{a\gamma} = \frac{2}{3} - 1.92(4)$$

$$C_{ae}^{A/J} \simeq -\frac{1}{16\pi^2 N}\left(\mathrm{tr}\kappa - 2\kappa_{ee}\right)$$

$$\kappa \equiv \frac{m_D m_D^\dagger}{v^2}$$