Unifying inflation with the axion, dark matter, baryogenesis and the seesaw mechanism

Carlos Tamarit, Durham IP[3]

Phys.Rev.Lett. 118 (2017) [arXiv:1608.05414]
arXiv:1610.01639

In collaboration with

Guillermo Ballesteros
SACLAY

Javier Redondo
Universidad de Zaragoza,
Max Planck München

Andreas Ringwald
DESY

The aim:

Introduce a theory, “SMASH”, that builds upon the νMSM and addresses several problems in particle physics and cosmology, providing a consistent picture of the evolution of the universe, while remaining falsifiable.

The plan:

Discussion of the problems

Definition of the model

Overview of the cosmological evolution and the way problems are addressed.

The particle physics and cosmology paradigm

The Standard Model plus neutrino masses plus dark matter, together with a cosmological constant and an early period of inflation, is able to explain the overwhelming majority of experiments in Earth and in space.

Open questions relevant for this talk:

Mechanism of inflation

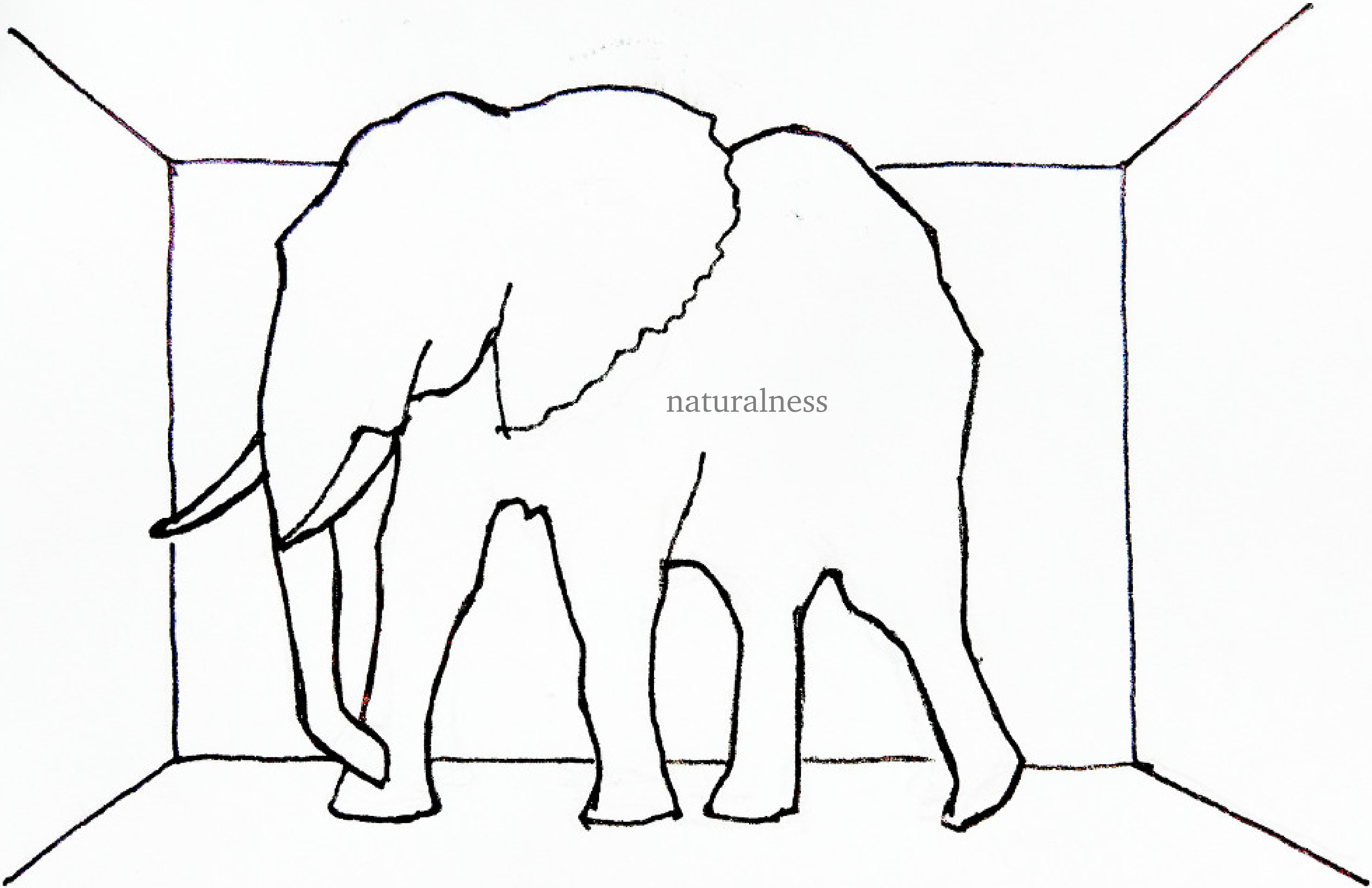
BEH stability

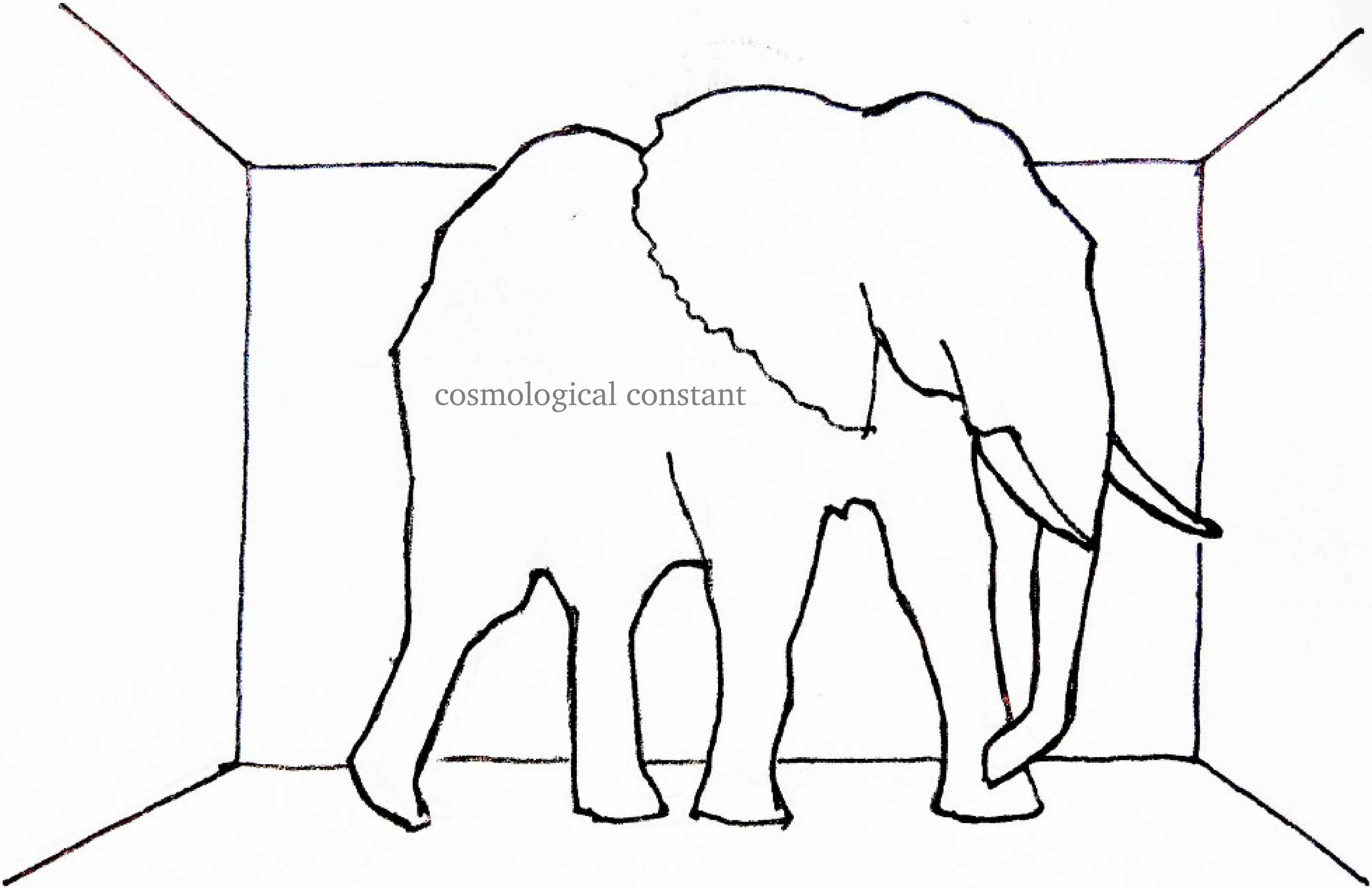
Origin of neutrino masses

Strong CP problem

Origin of dark matter

Origin of the baryon asymmetry


naturalness


cosmological constant

Abridged problem dictionary

Inflation. Period of accelerated expansion needed to explain the isotropy and homogeneity of the Universe.

A slowly-rolling scalar field with positive potential energy can drive accelerated expansion. Could it be the BEH boson [Bezrukov,Shaposhnikov]??

H inflation problem: Lack of predictivity! [Barbon, Espinosa, Burgess, Lee, Trott]

$$S_{HI} = \int d^4x\sqrt{-g}\left[\mathcal{L}_{SM} - \frac{M^2}{2}R - \xi H^\dagger H R\right]$$

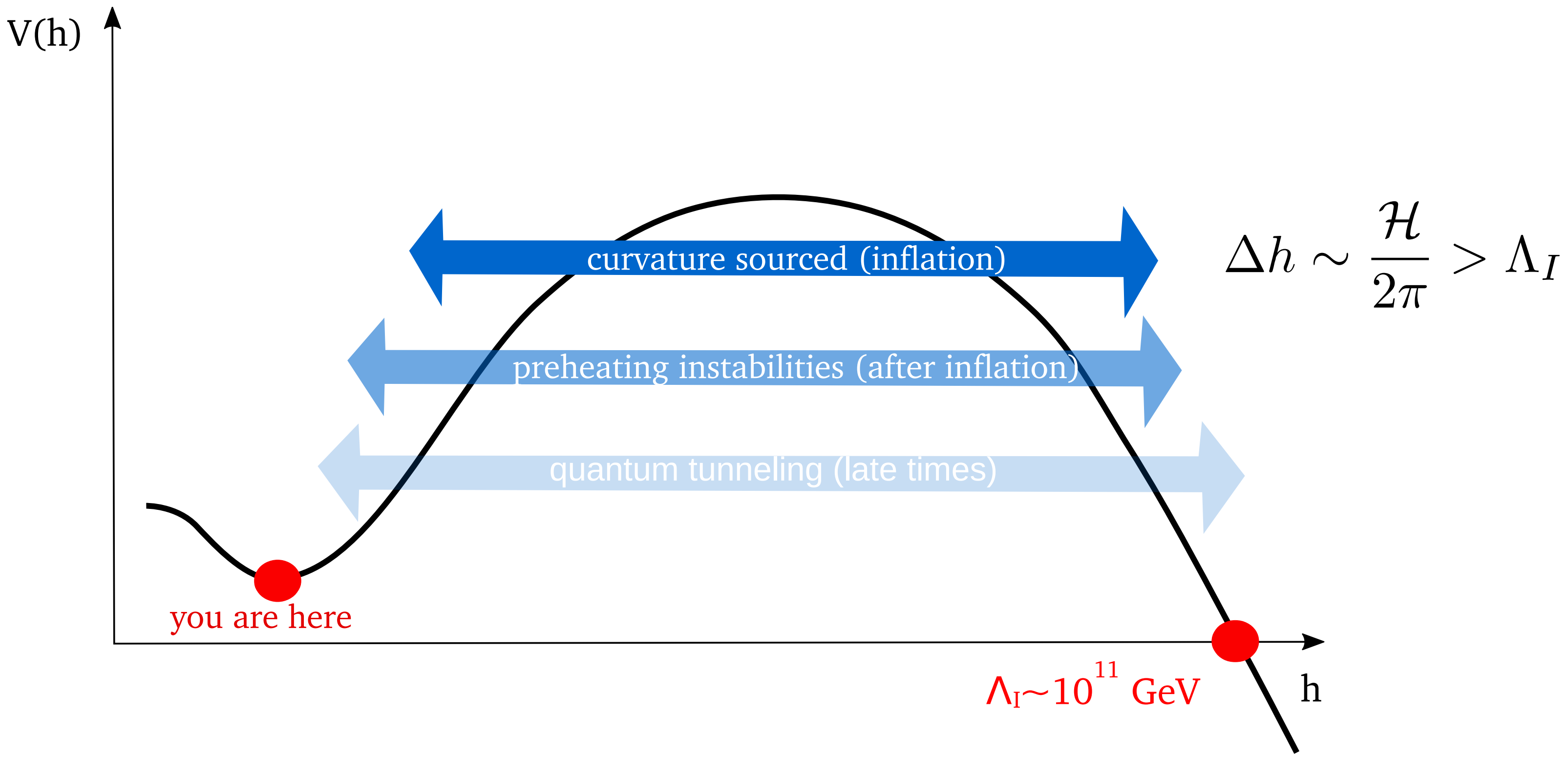
CMB fluctuations require $\xi \sim 10^5\sqrt{\lambda_H} \sim 10^4$

Theory has cutoff below field scales probed during inflation!

$$\Lambda = \frac{M}{\xi} \sim \frac{M_P}{\xi} > h_{\rm inf} \sim \frac{M_P}{\sqrt{\xi}}$$

Abridged problem dictionary

H stability problem



Neutrino mass problem. Neutrino oscillation data imply that neutrinos are massive, while in the SM they remain massless.

$$\sum_i m_{\nu,i} < 0.23\,\mathrm{eV} \quad \text{[PLANCK 2015]}, \quad |\Delta m^2_{ij}| < 3 \times 10^{-3}\,\mathrm{eV}^2 \quad \text{[NuFIT 2016]}$$

Abridged problem dictionary

CP problem. Absence of CP violation in strong interactions

$$\mathcal{L}_{QCD} \supset \frac{g^2\theta}{16\pi^2} \mathrm{Tr}\, \tilde{G}_{\mu\nu} G^{\mu\nu}, \quad \theta_{\mathrm{phys}} = \theta - \arg\det M_q, \quad |\theta_{\mathrm{phys}}| < 10^{-11} \quad \text{[Kim 09]}$$

Dark matter. Galactic rotation curves and the CMB power spectrum imply the existence of non-baryonic matter in the Universe, which SM particles cannot account for.

$$\Omega_B = 0.05, \quad \Omega_{DM} = 0.26 \quad \text{[Planck 2015]}$$

Baryogenesis. The known Universe is overwhelmingly made of matter rather than antimatter, although physical laws don't establish a fundamental distinction.

$$\eta = \frac{n_B}{n_\gamma} = \frac{n_b - \overline{n}_b}{n_\gamma} = 6.1 \times 10^{-10} \quad \text{[Cyburt et al, 2015 Planck data]}$$

All those problems… all those solutions

Zero T	Inflation	Scalar inflaton
	Higgs stability	Scalar interactions
	Neutrino masses	Seesaw models, radiative mass generation
	CP problem	Axion, Nelson-Barr
Finite T	Dark matter	WIMP, sterile neutrinos, axion
	Baryogenesis	Electroweak baryogenesis, leptogenesis, Affleck-Dine…

Relating solutions

CP problem plus dark matter	Abbot et al, Dine et al, Preskill et al,…
Neutrino masses plus axion	Dias et al, Kim, Mohapatra et al, Berezhiani, Shafi et al, Langacker et al, Shin, He et al, Celis et al, Bertolini et al, Ng et al, Carvajal et al, Clarke et al, Ahn et al,...
Neutrino masses plus inflation	Boucenna et al, Budhi et al ,...
Inflation plus dark matter	Lerner, McDonald, Kahlhofer,...
Inflation plus dark matter plus CP problem	Fairbairn & Marsh,...

Non-minimal list of minimal models of the Universe

νMSM [Asaka, Blanchet, Shaposhnikov]

SM+ RH neutrinos

(Inflaton=Higgs, DM=RH neut, baryogenesis: RH neut. oscillations)

---

nMSM [Davoudiasl, Kitano, Li, Murayama]

SM+two real scalars+RH neutrinos

(Inflaton, DM: scalars, baryogenesis: Decays of RH neut)

Salvio [Salvio]

SM+KSVZ axion+ RH neutrinos

(Inflaton=Higgs, DM=axion, baryogenesis: Decays of RH neut)

Non-minimal list of minimal models of the Universe

		νMSM	nMSM	Salvio	SMASH
Zero T	Inflation	?	✓	?	✓
	Stability	✗	⚠	✓	✓
	ν masses	✓	✓	✓	✓
	CP	✗	✗	✓	✓
Finite T	DM	✓	✓	✓	✓
	Baryogenesis	✓	✓	✓	✓
	New scales	M_a	M_a, m^2_S,m^2_ϕ	M_a, f_A	f_A

S.M.A.S.H

A minimal model providing a consistent, predictive picture of:

Particle physics from the electroweak to the Planck scale

Cosmology from inflation to today

Highlights:

A single new scale, playing a role in dark matter, the CP problem and baryogenesis

Predictive inflation free from unitarity concerns

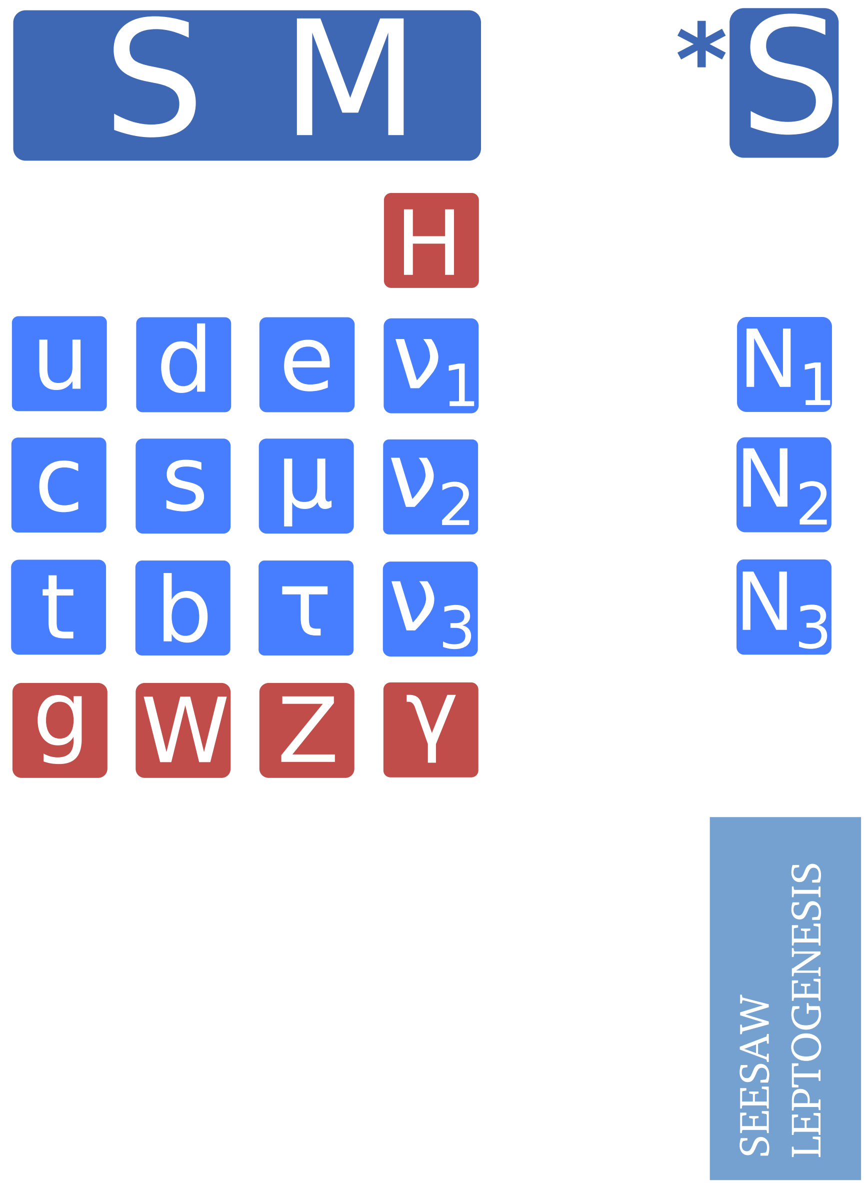
Detailed understanding of parameter space yielding stability

Detailed understanding of reheating

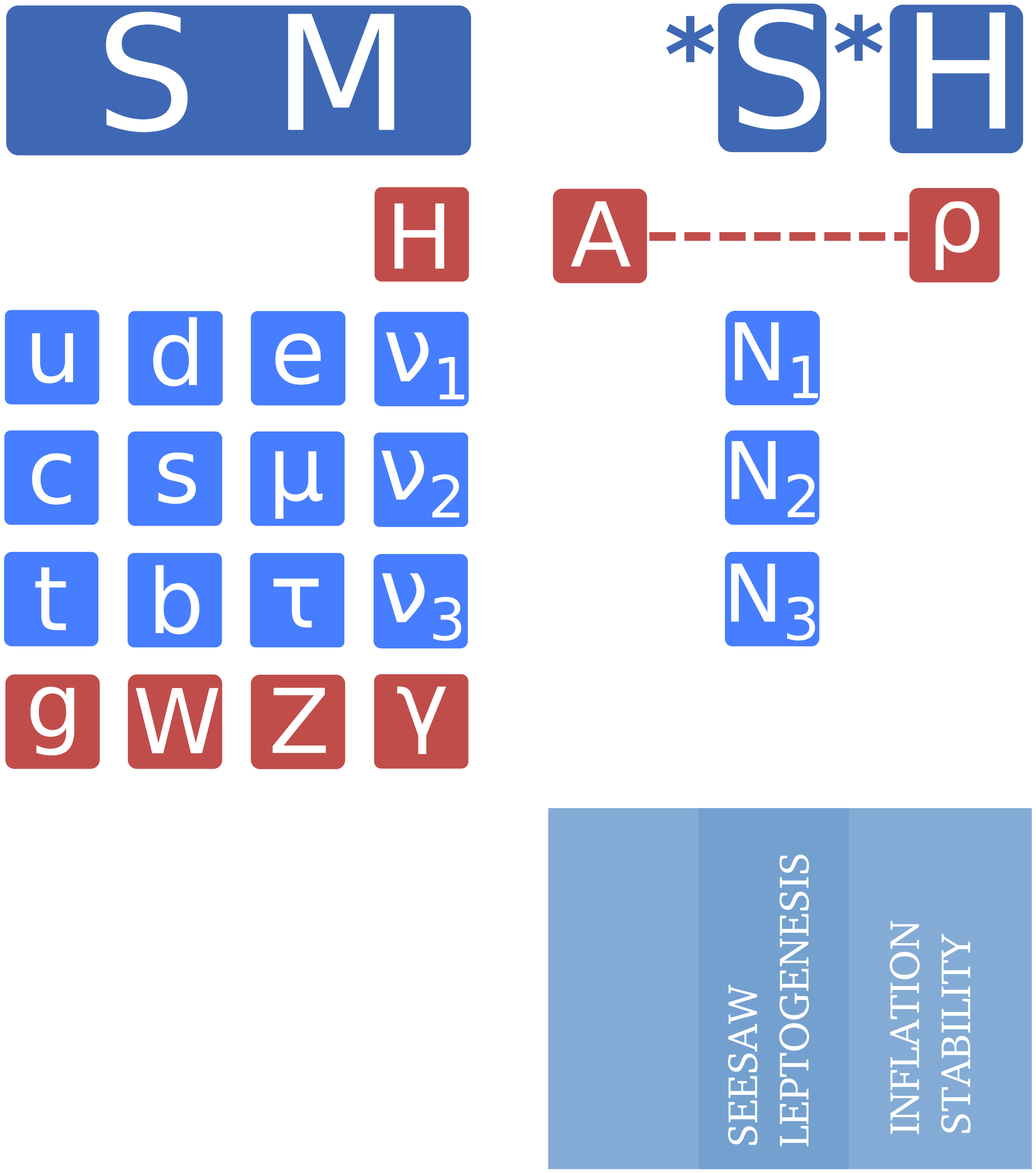
Accurate predictions for ns, r, axion mass, N_{eff} in the reach of future experiments

Building up SMASH

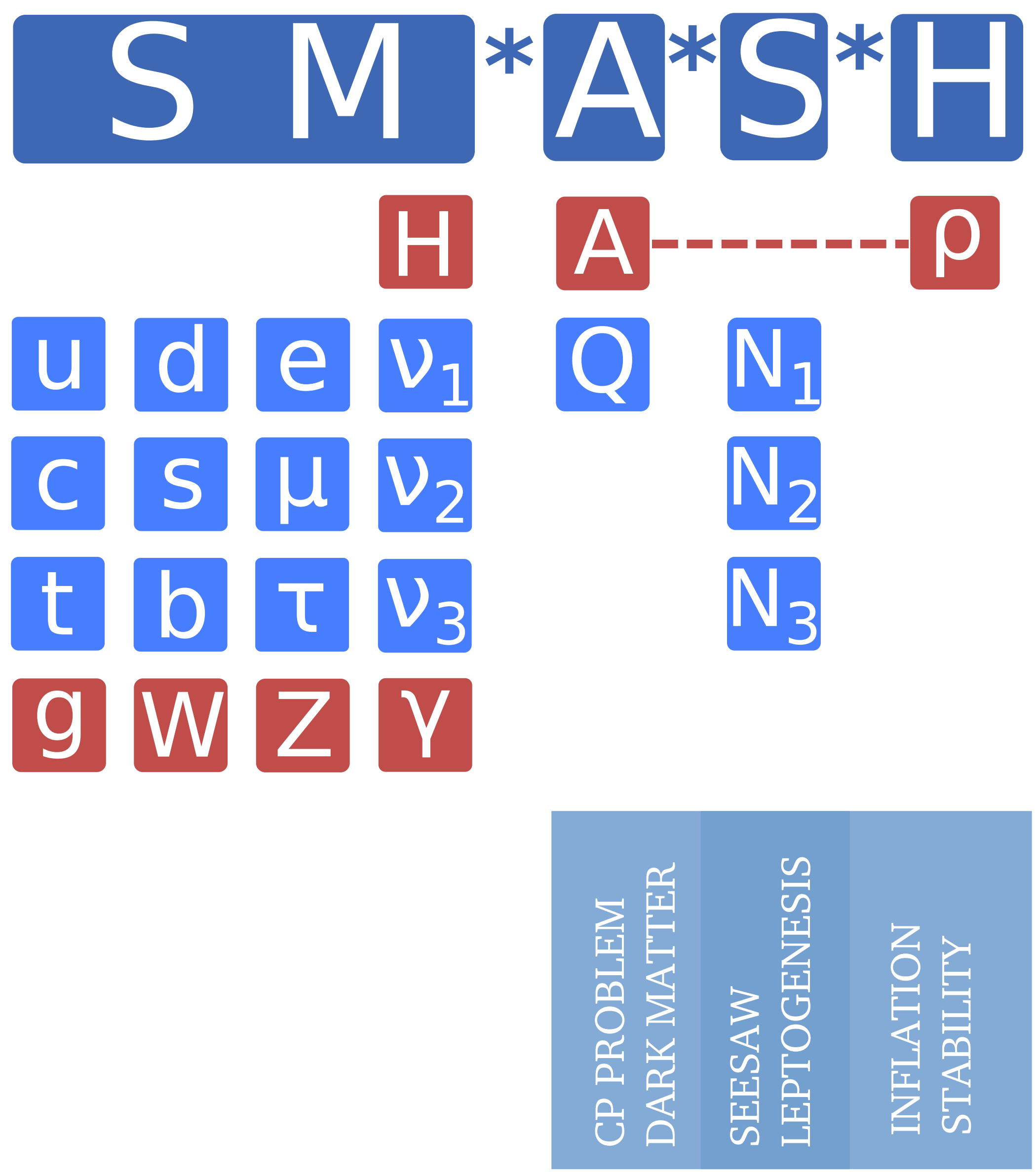
Building up SMASH



Building up SMASH



Building up SMASH



SMASH recap

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

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

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

STABILITY

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

CP PROBLEM
DARK MATTER

INFLATION

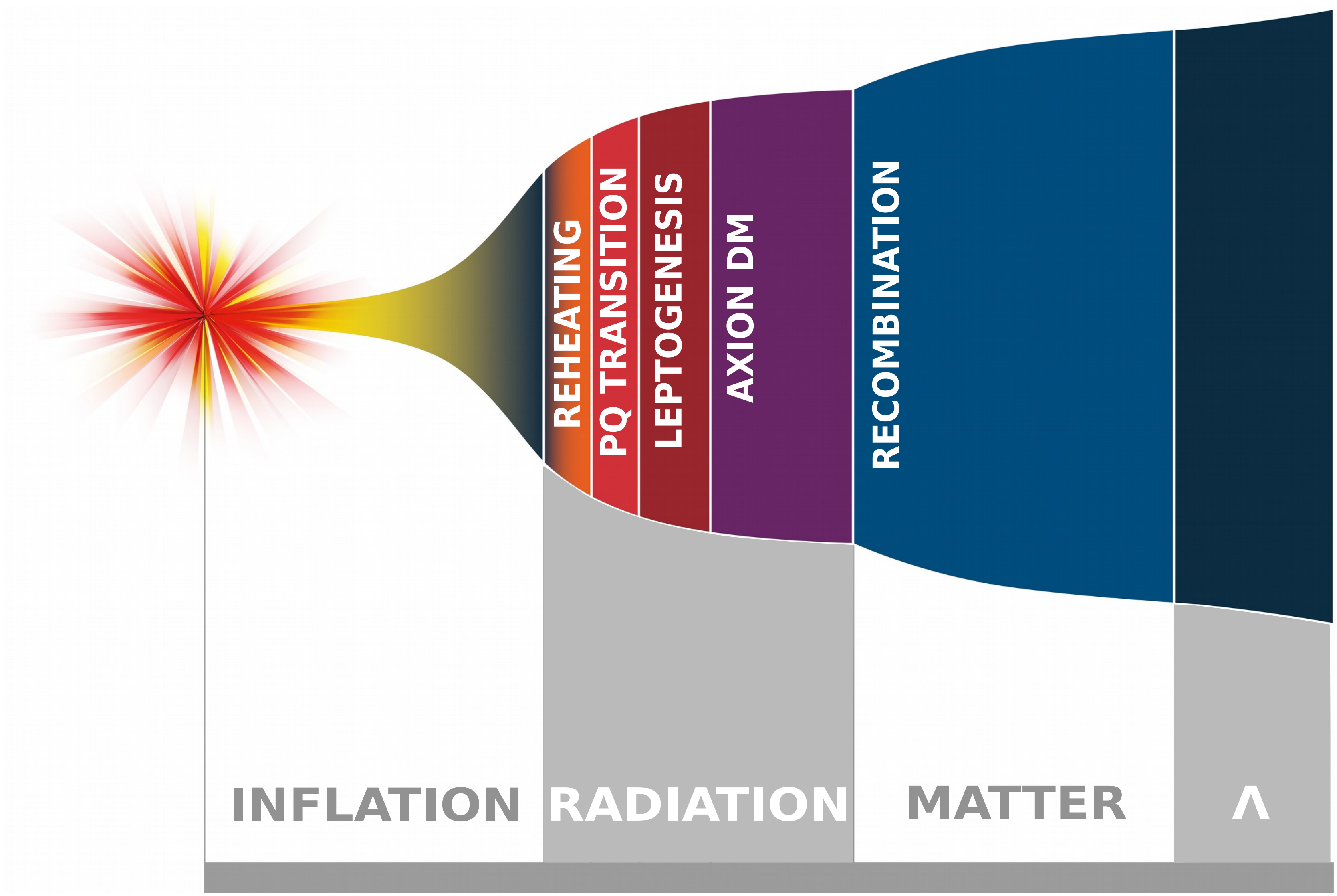
$$-[F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j + c.c.]$$

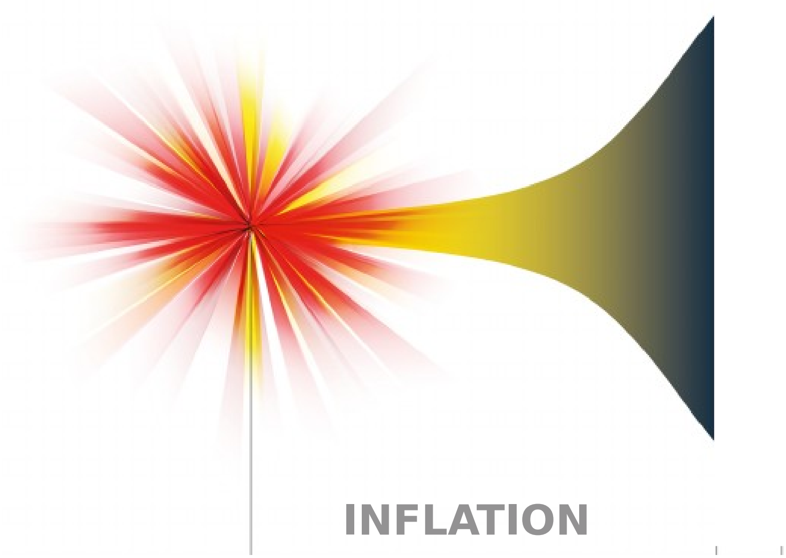
SEESAW AND LEPTOGENESIS

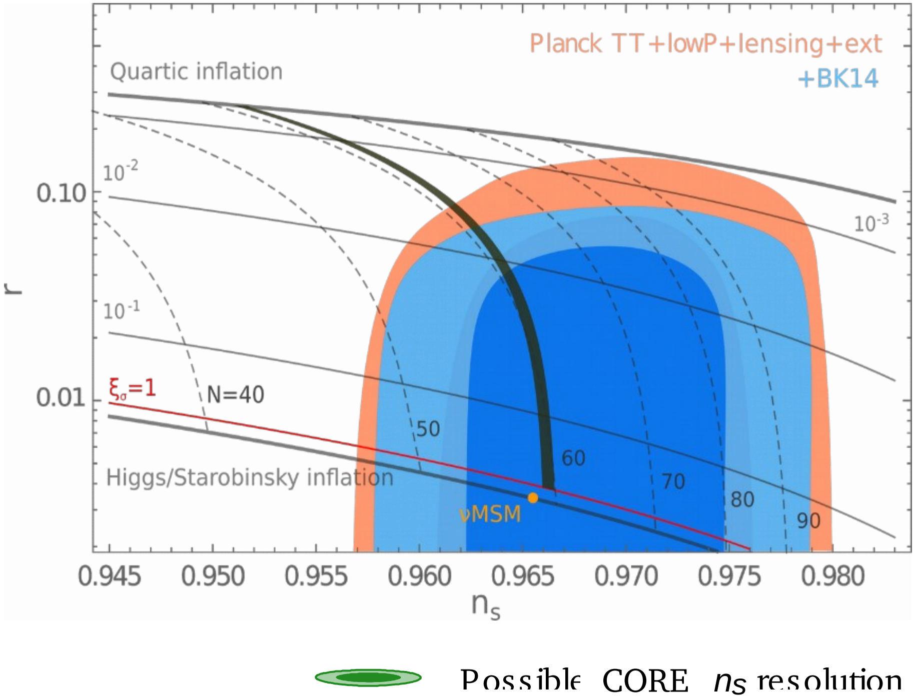
Most general, renormalizable Lagrangian compatible with the following global Peccei-Quinn (PQ) symmetry:

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

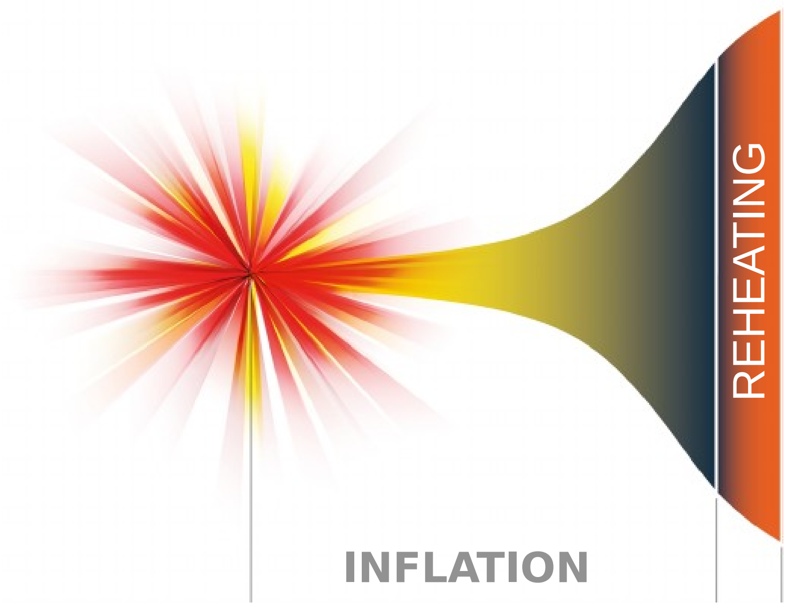
SMASHY history of the Universe

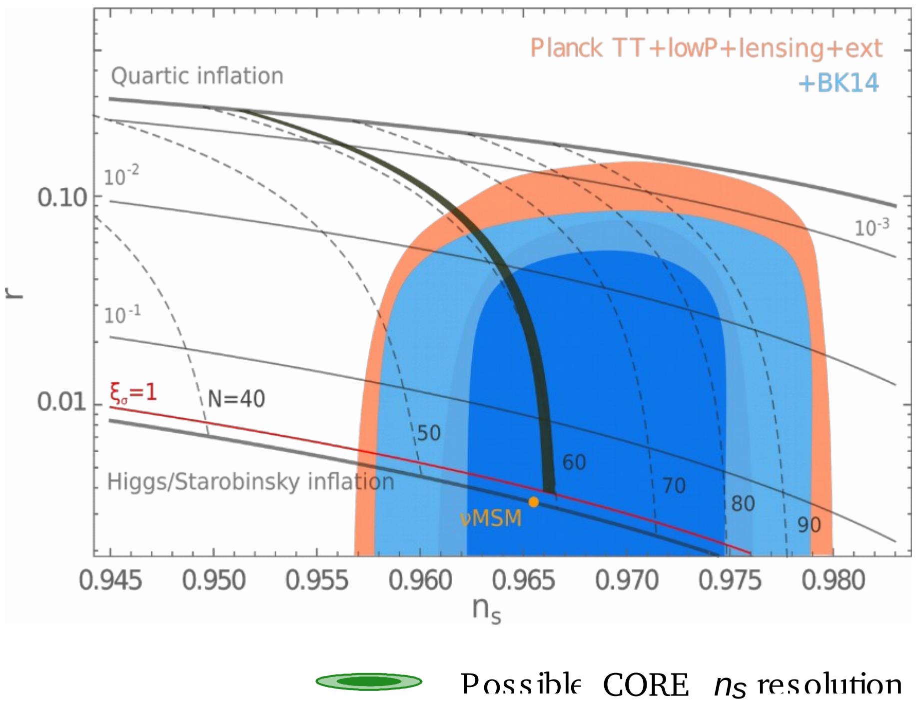






H stabilized by portal coupling

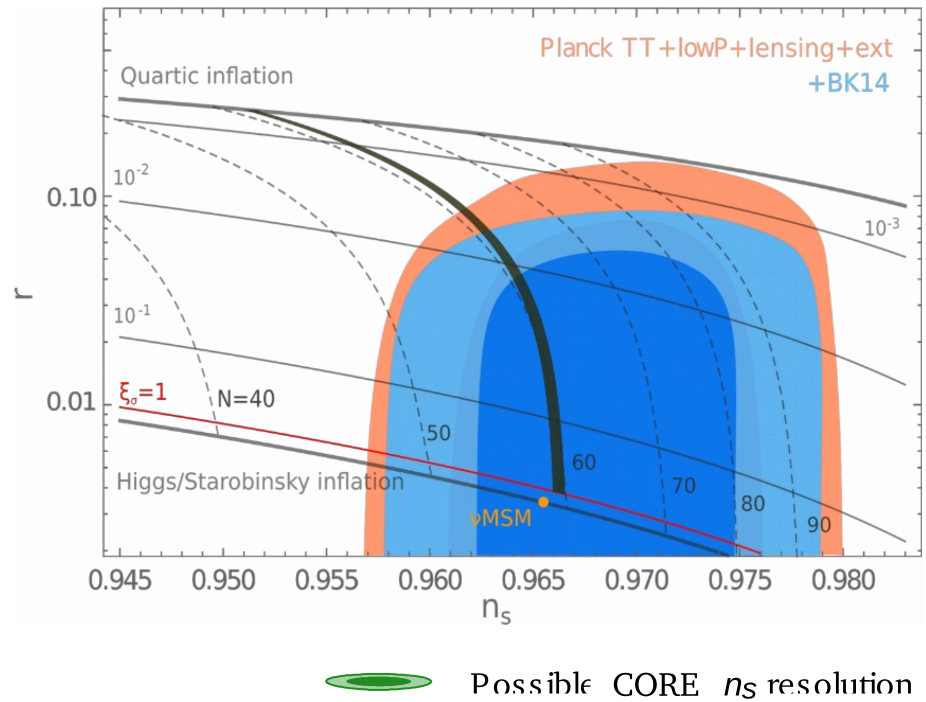




H stabilized by portal coupling

Radiation domination after inflation

σ fluctuations take over



H stabilized by portal coupling

Radiation domination after inflation

σ fluctuations take over

PQ symmetry restored

Pure σ inflation ruled out by $\Delta N_{\rm eff} \sim 1$

Mixed σ-H inflation $T_R \sim 10^{10}$ GeV

PQ TRANSITION

LEPTOGENESIS

SM plasma dominates energy from T~10^{10} GeV but reaches higher T.

At T=T_c~10^8 GeV the PQ symmetry breaks in second order phase transition.

$$\langle\sigma\rangle = \frac{f_A}{\sqrt{2}}$$

RH neutrinos acquire masses $M_i = Y_{ii}\langle\sigma\rangle$

Stability in σ direction requires $M_i \lesssim 10^7\,\mathrm{GeV} < T_c$ so RH neutrinos can keep a thermal abundance: thermal leptogenesis from decays of Ni at $T \lesssim 10^7$ GeV.

At the EW phase transition, SM neutrinos acquire see-saw masses

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

AXION DM

Relativistic axions:

Sourced early on by SM-axion interactions in equilibrium for $T \gtrsim 10^9$ GeV. After freezout they end up giving

$$\Delta N_{\rm eff} \sim 0.02 - 0.03$$

Non-relativistic axions:

Axions couple to the SU(3) anomaly like the ∂ term: dynamical $\partial_{\rm eff}$

After the QCD phase transition, $\partial_{\rm eff}$ acquires a mass, solving the CP problem.

Axion field starts oscillating, behaving as dark matter. Additional nonrelativistic axions are radiated by decaying strings.

Relic abundance and lattice results for m_A [Borsanyi et al] enforce

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

Summary: predictions of the model

Axion mass and coupling to photons in reach of upcoming experiments (MADMAX, CULTASK)

$$50\,\mu\text{eV} \lesssim m_A \lesssim 200\,\mu\text{eV}, |C_{A\gamma}| = 1.25(4)$$

Precise predictions for cosmological observables n_s, r, $\alpha \lesssim 10^{-3}$, ΔN_{eff}=0.02-0.03 can be probed by experiments (LiteBird, CORE, 21cm measurements)

QCD axion window could be probed by microlensing data (EROS, Subaru)

[Fairbain et al]