MSSM-inflation

MSSM = Minimal Supersymmetric Standard Model

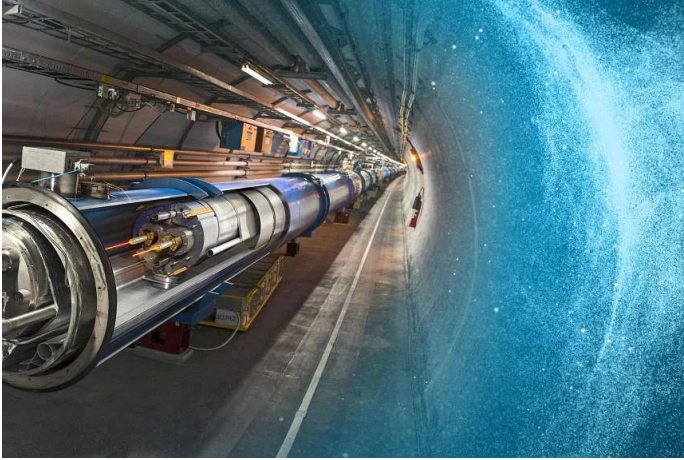## Linking cosmic inflation to high energy physics

Gilles Weymann-Despres

in collaboration with

Gilbert Moultaka, Sophie Henrot-Versillé, Vincent Vennin,
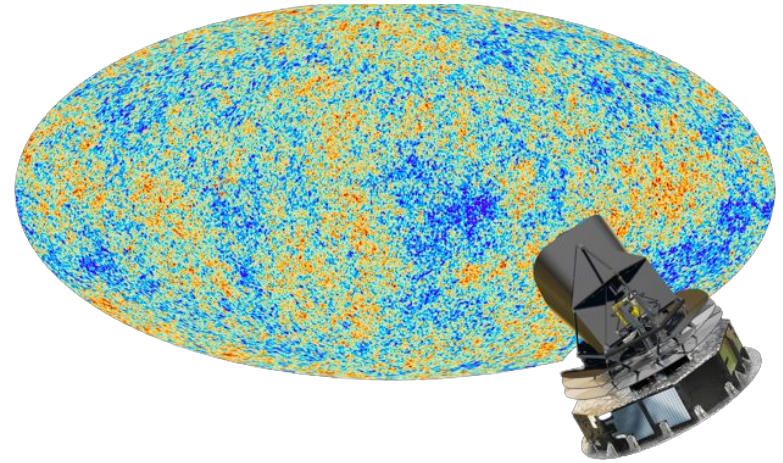Laurent Duflot, Richard Freiherr von Eckardstein

Based on arXiv:2304.04534 (PhysRevD.108.023511)

AstroParticle Symposium 2023
25/10/2023

université
PARIS-SACLAY

IJCLab
Irène Joliot-Curie
Laboratoire de Physique
des 2 Infinis

Outline

HEP (eg: at LHC)

Bridge: MSSM

Cosmology and CMB (eg: Planck satellite, …)

1) The **paradigm**: **slow-roll inflation**
2) The **model**: **MSSM-inflation**
3) The **main results**:
   i. Importance of **radiative corrections**
   ii. **HEP x Planck** constraints

Scalar field rolling on its potential

Action of a **single scalar field** minimally coupled to gravity:

$$S_\phi = -\int \mathrm{d}^4 x \sqrt{-g} \left[\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + V(\phi) \right]$$

Energy-momentum tensor:

$$T_{\mu\nu}^{(\phi)} = \partial_\mu \phi \partial_\nu \phi + g_{\mu\nu} \left[-\frac{1}{2} g^{\rho\sigma} \partial_\rho \phi \partial_\sigma \phi + V(\phi) \right]$$

$$T_{\mu\nu} \equiv -\frac{2}{\sqrt{-g}} \frac{\partial \mathcal{S}_{\mathrm{matter}}}{\partial g_{\mu\nu}}$$

*T00 is the density
Tii the pressure*
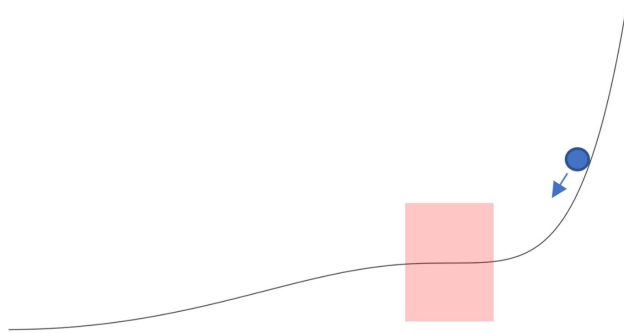
*In the Friedmann
equations:*

Density and pressure:

$$\rho = \frac{\dot{\phi}^2}{2} + V,$$

$$p = \frac{\dot{\phi}^2}{2} - V.$$

Klein-gordon equation:

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

Same equation: **ball rolling down** a **slope**!

Slow-rolling of a scalar field

If the potential has a **flat region**, the scalar field **velocity** will become small
and its kinetic energy **negligible** with respect to its **potential energy**.

$$\rho = \frac{\dot{\phi}^2}{2} + V,$$

$$p = \frac{\dot{\phi}^2}{2} - V.$$

=> $\rho = -P$

The **slow-roll approximation** consists of that alongside with

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

Equivalent to conditions on the potential,
that quantify the **deviation from de-Sitter**
and the **flatness of the potential**

$$\epsilon_0 \equiv \frac{H_{in}}{H} = H_{in}\sqrt{\frac{3M_{PL}^2}{V}},$$

$$\epsilon_1 \equiv \frac{\mathrm{d}\ln|\epsilon_0|}{\mathrm{d}N} = \frac{M_{PL}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1,$$

$$\epsilon_{n+1} \equiv \frac{\mathrm{d}\ln|\epsilon_n|}{\mathrm{d}N} \ll 1.$$

Linking slow-roll to observables

Now we have a **quasi de-Sitter** universe that can **solve** the ΛCDM **opened questions**, and in particular which **predicts** the origin of the **perturbations**, and their primordial power spectra, **scalar** $\mathscr{P}_\zeta$ and **tensor** $\mathscr{P}_h$.

How? Add a perturbation to the scalar action, derive the new equation of motions for the perturbation, quantize it, and after some calculus…

Result:

Amplitude	**Tilt**	**Running**
$A_{\mathrm{S}} \equiv \left.\mathscr{P}_\zeta\right|_{k_*} \overset{\mathrm{SRLO}}{\simeq} \dfrac{V_*}{24\pi^2 M_{\mathrm{Pl}}^4 \varepsilon_{1*}}$,	$n_{\mathrm{S}} \equiv 1 + \left.\dfrac{\mathrm{d}\ln\mathscr{P}_\zeta}{\mathrm{d}\ln k}\right|_{k_*} \overset{\mathrm{SRLO}}{\simeq} 1 - 2\varepsilon_{1*} - \varepsilon_{2*}$	$n_{\mathrm{S,run}} \equiv \left.\dfrac{\mathrm{d}^2\ln\mathscr{P}_\zeta}{(\mathrm{d}\ln k)^2}\right|_{k_*} \overset{\mathrm{SRLO}}{\simeq} -2\varepsilon_{1*}\varepsilon_{2*} - \varepsilon_{2*}\varepsilon_{3*}$
$r \equiv \left.\dfrac{\mathscr{P}_h}{\mathscr{P}_\zeta}\right|_{k_*} \overset{\mathrm{SRLO}}{\simeq} 16\varepsilon_{1*}$,	$n_{\mathrm{T}} \equiv \left.\dfrac{\mathrm{d}\ln\mathscr{P}_h}{\mathrm{d}\ln k}\right|_{k_*} \overset{\mathrm{SRLO}}{\simeq} -2\varepsilon_{1*}$	$n_{\mathrm{T,run}} \equiv \left.\dfrac{\mathrm{d}^2\ln\mathscr{P}_h}{(\mathrm{d}\ln k)^2}\right|_{k_*} \overset{\mathrm{SRLO}}{\simeq} -2\varepsilon_{1*}\varepsilon_{2*}$

Inferring the potential from the measures

$$\phi \rightarrow V(\phi, p), \quad \ln R_{\text{rad}} \implies \phi_* \implies \{\varepsilon_i *\} \implies \{A_{\text{S}}, \; n_{\text{S}}, \; n_{\text{S,run}}, \; r, \; n_{\text{T}}, \; n_{\text{T,run}}, \; N_{\text{e-folds}} \ldots\}$$

(Motivated) choice. Eg:
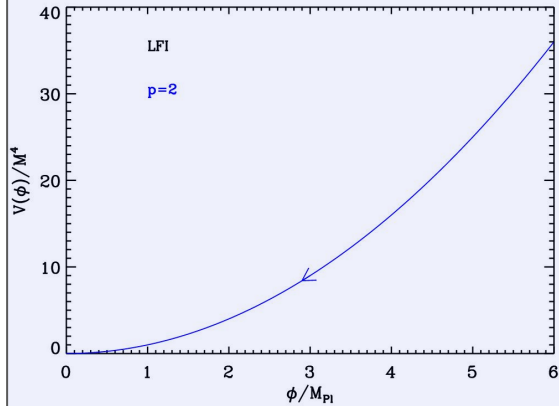
(Motivated) choice

$$V(\phi) = M^4 \left[1 - \left(\frac{\phi}{\mu} \right)^p \right]$$

LFI

p=2

Inferring the potential from the measures

$$\phi \to V(\phi, p), \ \ln R_{\mathrm{rad}} \implies \phi_* \implies \{\varepsilon_{i*}\} \implies \{A_{\mathrm{S}}, \ n_{\mathrm{S}}, \ n_{\mathrm{S,run}}, \ r, \ n_{\mathrm{T}}, \ n_{\mathrm{T,run}}, \ N_{\mathrm{e-folds}} \ ... \}$$

$$\Delta N_*^{\mathrm{SRLO}} \simeq \ln R_{\mathrm{rad}} - \ln\left(\frac{k_*}{a_0 \tilde{\rho}_\gamma^{1/4}}\right) - \frac{1}{4}\ln\left[\frac{9 V_{\mathrm{end}}}{\varepsilon_{1*}(3 - \varepsilon_{\mathrm{1end}}) V_*}\right] + \frac{1}{4}\ln(8\pi^2 A_{\mathrm{S}})$$

CF APPENDIX

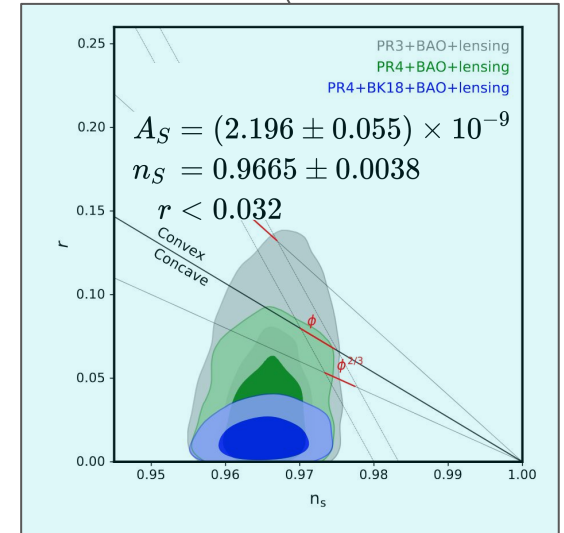$$\Delta N_*^{\mathrm{SRLO}} \simeq \int_{\phi_{\mathrm{end}}}^{\phi_*} \frac{V(\phi)}{V_\phi(\phi)} \mathrm{d}\phi$$

Inferring the potential from the measures

$$\phi \to V(\phi, p), \; \ln R_{\mathrm{rad}} \implies \phi_* \implies \{\varepsilon_i*\} \implies \{A_{\mathrm{S}}, \; n_{\mathrm{S}}, \; n_{\mathrm{S,run}}, \; r, \; n_{\mathrm{T}}, \; n_{\mathrm{T,run}}, \; N_{\mathrm{e-folds}} \ldots\}$$

$$\varepsilon_1 \overset{\mathrm{SRLO}}{\simeq} \frac{M_{\mathrm{Pl}}^2}{2}\left(\frac{V_\phi}{V}\right)^2,$$

$$\varepsilon_2 \overset{\mathrm{SRLO}}{\simeq} 2M_{\mathrm{Pl}}^2\left[\left(\frac{V_\phi}{V}\right)^2 - \frac{V_{\phi\phi}}{V}\right],$$

$$\varepsilon_3 \overset{\mathrm{SRLO}}{\simeq} \frac{2}{\varepsilon_2}M_{\mathrm{Pl}}^4\left[\frac{V_{\phi\phi\phi}V_\phi}{V^2} - 3\frac{V_{\phi\phi}}{V}\left(\frac{V_\phi}{V}\right)^2 + 2\left(\frac{V_\phi}{V}\right)^4\right]$$

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Inferring the potential from the measures

$$\phi \to V(\phi, p), \ln R_{\rm rad} \implies \phi_* \implies \{\varepsilon_i *\} \implies \{A_{\rm S}, \, n_{\rm S}, \, n_{\rm S,run}, \, r, \, n_{\rm T}, \, n_{\rm T,run}, \, N_{\rm e-folds} \, ...\}$$

Amplitude

$$A_{\rm S} \equiv \mathcal{P}_\zeta \big|_{k_*} \overset{\rm SRLO}{\simeq} \frac{V_*}{24\pi^2 M_{\rm Pl}^4 \varepsilon_{1*}},$$

$$r \equiv \frac{\mathcal{P}_h}{\mathcal{P}_\zeta} \bigg|_{k_*} \overset{\rm SRLO}{\simeq} 16\varepsilon_{1*},$$

Tilt

$$n_{\rm S} \equiv 1 + \frac{{\rm d}\ln \mathcal{P}_\zeta}{{\rm d}\ln k} \bigg|_{k_*} \overset{\rm SRLO}{\simeq} 1 - 2\varepsilon_{1*} - \varepsilon_{2*}$$

$$n_{\rm T} \equiv \frac{{\rm d}\ln \mathcal{P}_h}{{\rm d}\ln k} \bigg|_{k_*} \overset{\rm SRLO}{\simeq} -2\varepsilon_{1*}$$

Running

$$n_{\rm S,run} \equiv \frac{{\rm d}^2 \ln \mathcal{P}_\zeta}{({\rm d}\ln k)^2} \bigg|_{k_*} \overset{\rm SRLO}{\simeq} -2\varepsilon_{1*}\varepsilon_{2*} - \varepsilon_{2*}\varepsilon_{3*}$$

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Inferring the potential from the measures

$$\phi \to V(\phi, p), \ln R_{\text{rad}} \implies \phi_* \implies \{\varepsilon_i*\} \implies \{A_{\text{S}}, n_{\text{S}}, n_{\text{S,run}}, r, n_{\text{T}}, n_{\text{T,run}}, N_{\text{e-folds}} \ldots\}$$

PR3+BAO+lensing
PR4+BAO+lensing
PR4+BK18+BAO+lensing

$A_S = (2.196 \pm 0.055) \times 10^{-9}$

$n_S = 0.9665 \pm 0.0038$

$r < 0.032$

Convex
Concave

ϕ

$\phi^{2/3}$

*M. Tristram et al. (2022), **2112.07961***

Inferring the potential from the measures

$$\phi \rightarrow V(\phi, p), \ln R_{\rm rad} \implies \phi_* \implies \{\varepsilon_i *\} \implies \{A_{\rm S}, \, n_{\rm S}, \, n_{\rm S,run}, \, r, \, n_{\rm T}, \, n_{\rm T,run}, \, N_{\rm e-folds} \, ...\}$$

for a given potential shape

PR3+BAO+lensing
PR4+BAO+lensing
PR4+BK18+BAO+lensing

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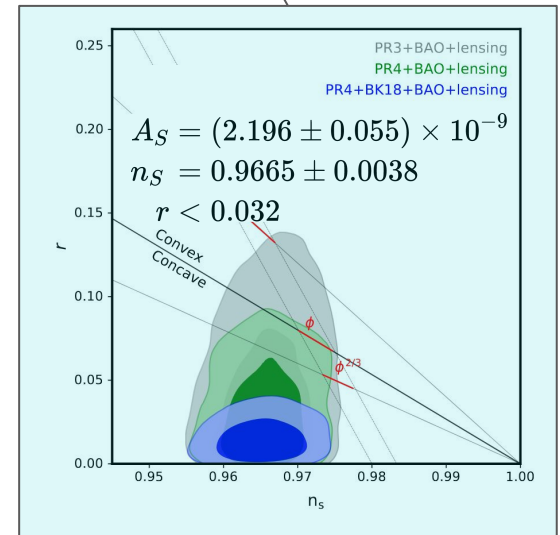
Given an observation, we can deduce the allowed potential params as done in

J. Martin, C. Ringeval, and V. Vennin, Phys. Dark Univ. 5-6, 75 (2014), **1303.3787**
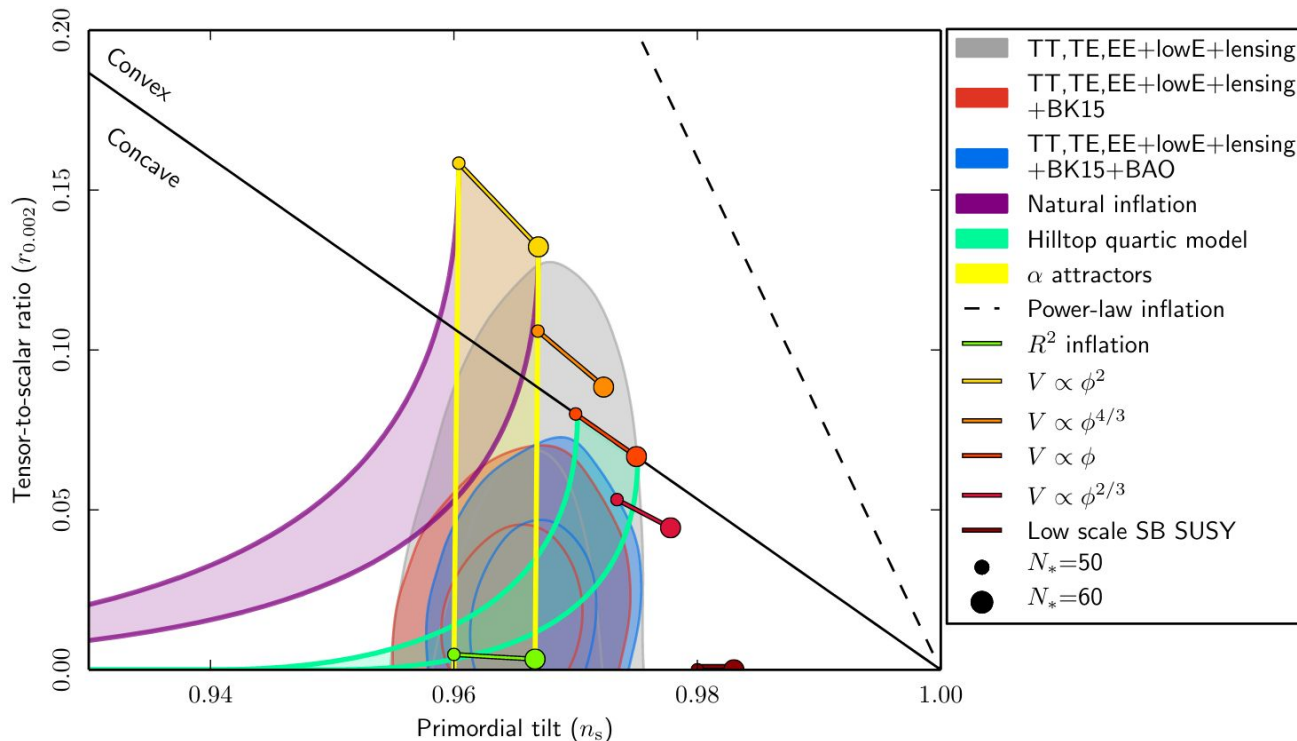
Planck collaboration X, Astron. Astrophys. 641, A10 (2020).

Legend for the figure:
- TT,TE,EE+lowE+lensing
- TT,TE,EE+lowE+lensing +BK15
- TT,TE,EE+lowE+lensing +BK15+BAO
- Natural inflation
- Hilltop quartic model
- α attractors
- Power-law inflation
- R^2 inflation
- $V \propto \phi^2$
- $V \propto \phi^{4/3}$
- $V \propto \phi$
- $V \propto \phi^{2/3}$
- Low scale SB SUSY
- $N_* = 50$
- $N_* = 60$

Axis labels: Tensor-to-scalar ratio ($r_{0.002}$) vs Primordial tilt (n_s); lines labeled "Convex" and "Concave".

- In this work:

Measurement	Value and error
A_S	3.047 ± 0.014
n_S	0.9665 ± 0.0038

Planck Collaboration VI, Astron. Astrophys. 641, A6 (2020).

- The shape of these **potentials** are theoretically well-**motivated** but still quite **effective**
- **Few** of them come with a **complete study of their embedding** within a **model** of particle physics
- In the following, a **case study: MSSM-inflation**

6
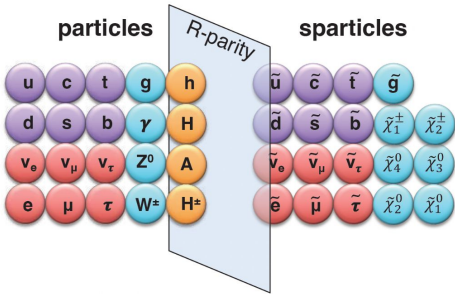
MSSM-inflation

- **MSSM** = **SUperSYmmetric** extension of the HEP SM.
  - Naturally provides a **WIMP** that can explain the measured $\Omega_{\mathrm{cdm}} h^2$.
  - Only a **small fraction** of its parameter space is **excluded** by LHC data.

- **Inflaton** = **scalar field**, evolves with the Klein-Gordon equation in the **MSSM scalar potential** along its **valleys ("flat directions")**.

- We focus on two of its **flat-directions** combinations of **scalar fields:**
  - "*LLe*"
  - "*udd*"

Studied previously in (not exhaustive):
K. Enqvist and A. Mazumdar, Physics Reports 380, 99 (2003), ISSN
R. Allahverdi, K. Enqvist, J. Garcia-Bellido, and A. Mazumdar, Phys. Rev. Lett. 97, (2006)
C. Boehm, J. Da Silva, A. Mazumdar, and E. Pukartas, Phys. Rev. D 87, 023529 (2013)
....
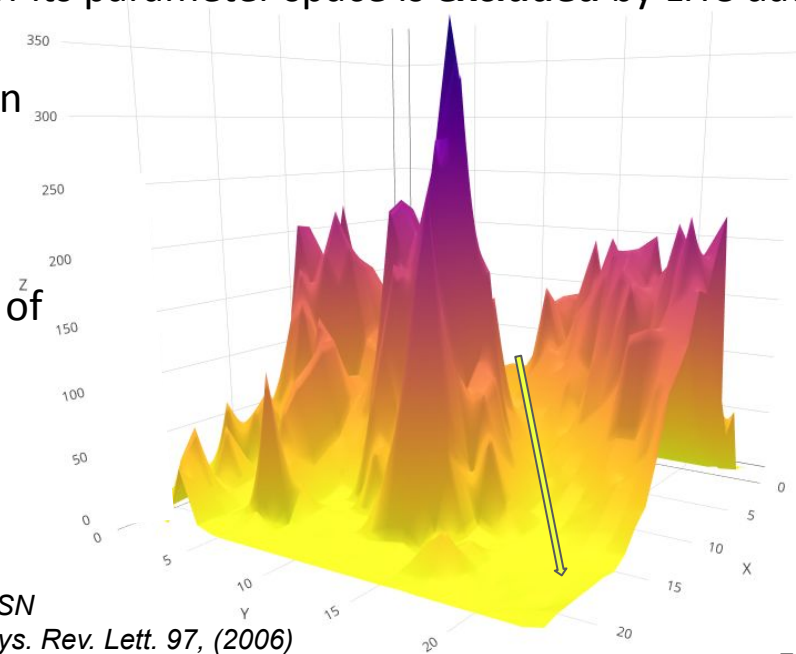
MSSM-inflation potential

The **potential** for *LLe* and *udd:*
$$V_{\text{tree}}(\phi) = \frac{1}{2} m_\phi^2 \phi^2 - \sqrt{2} A_6 \frac{\lambda_6 \phi^6}{6 M_{\text{Pl}}^3} + \lambda_6^2 \frac{\phi^{10}}{M_{\text{Pl}}^6}$$

where ϕ is the real **field value** associated to the inflaton, m_ϕ its **mass**. m_ϕ and A_6 are **linked** to the underlying **supersymmetric parameters**.

MSSM-inflation potential

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Recipe =>
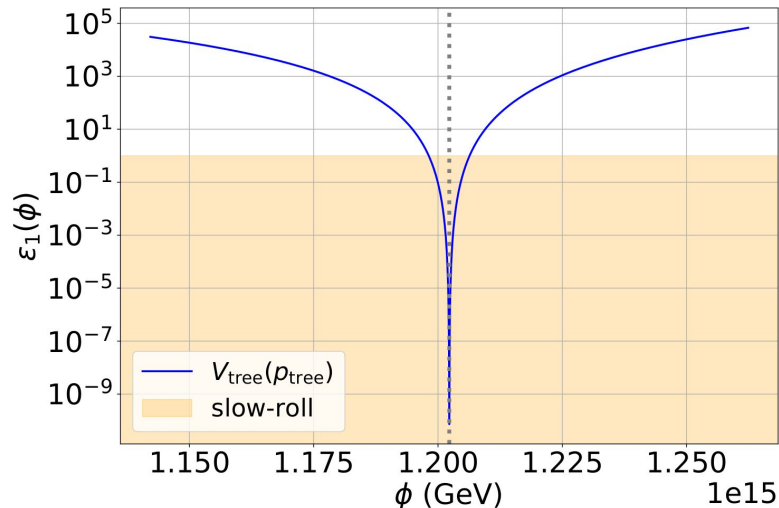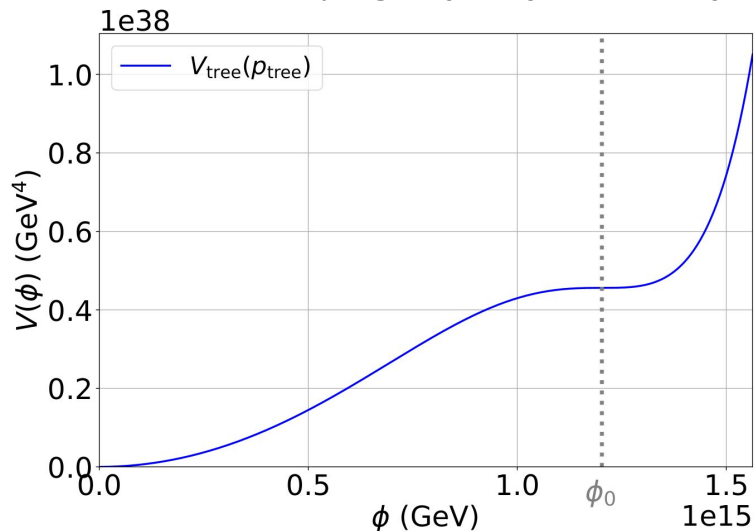
- **Narrow slow-roll** region ($|\phi - \phi_0| \sim \frac{\phi_0^3}{60 M_{\text{P}}^2}$) & **very-close-from-flat inflection point** ϕ_0.

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Radiative corrections impact on the potential

NEW • V_{RGE} whose parameters depend on ϕ.

$m_\phi^2 = m_\phi^2(\phi)$

$A_6 = A_6(\phi)$

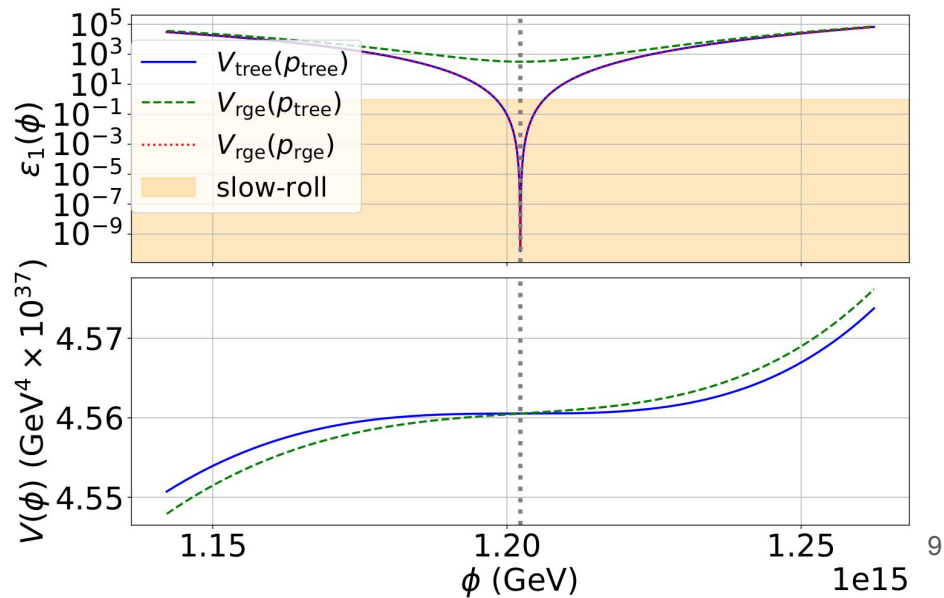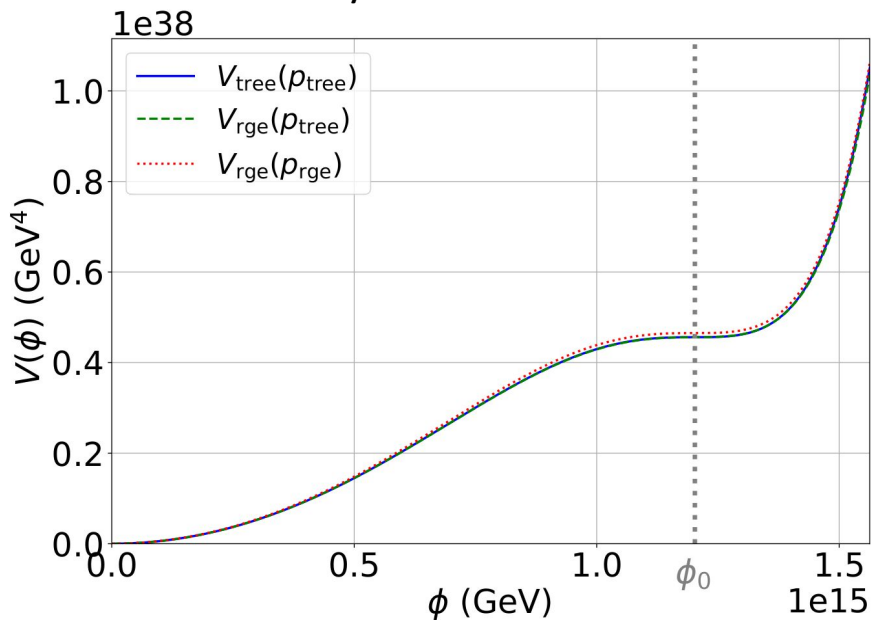$\lambda_6 = \lambda_6(\phi)$

- **Radiative corrections**
  - fully computable with the **Renormalization Group Equations**
  - functions of the **gaugino masses** and the **gauge couplings** at **GUT**.
  - vary whether the inflaton is along *udd or LLe*

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Radiative corrections impact on the parameters

- **Regions allowed by cosmology** in (illustrative) plans of the **tree-level** parameter space:
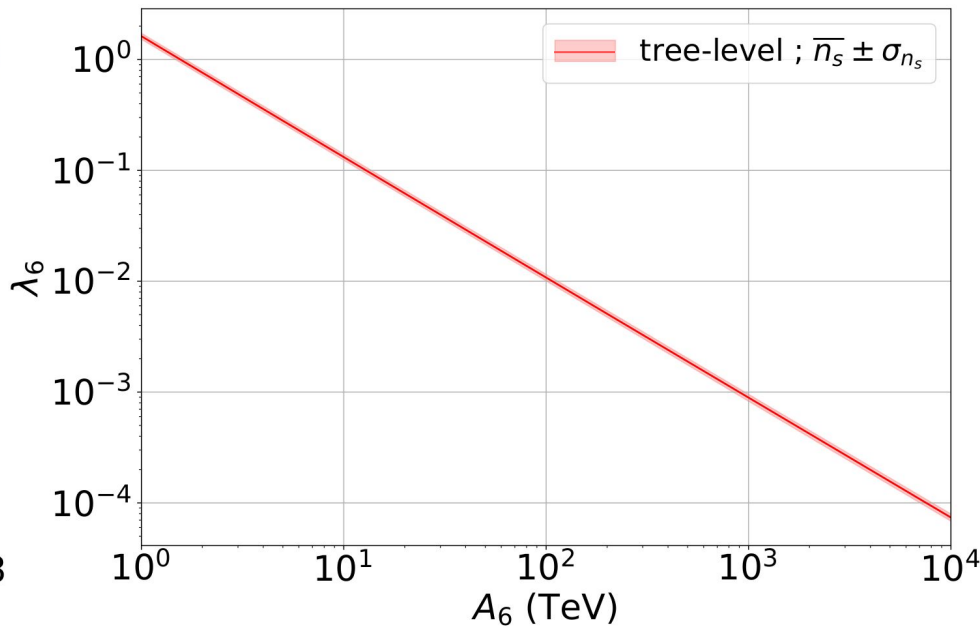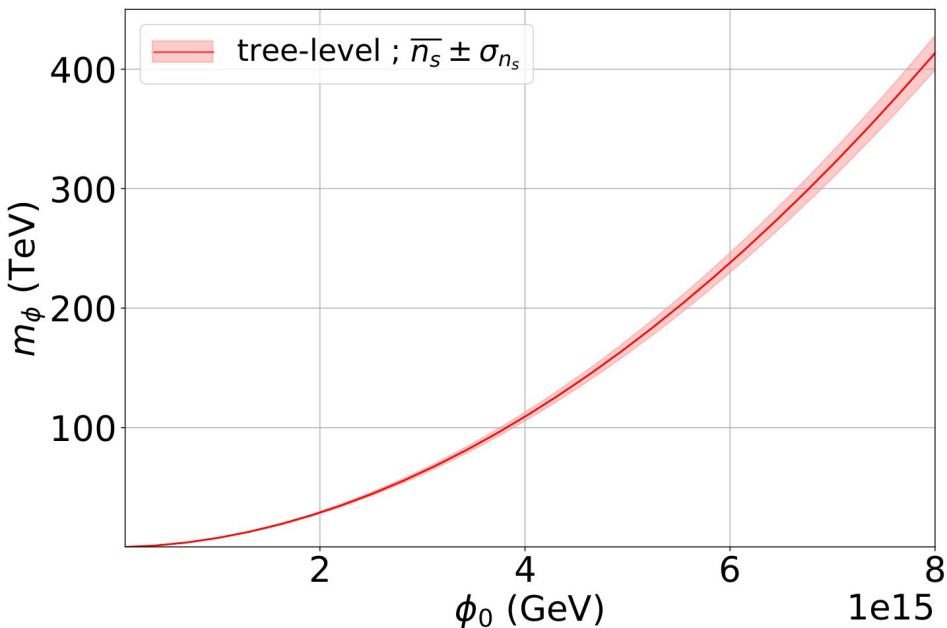
- How do these contours **change** beyond tree-level?

Radiative corrections impact on the parameters
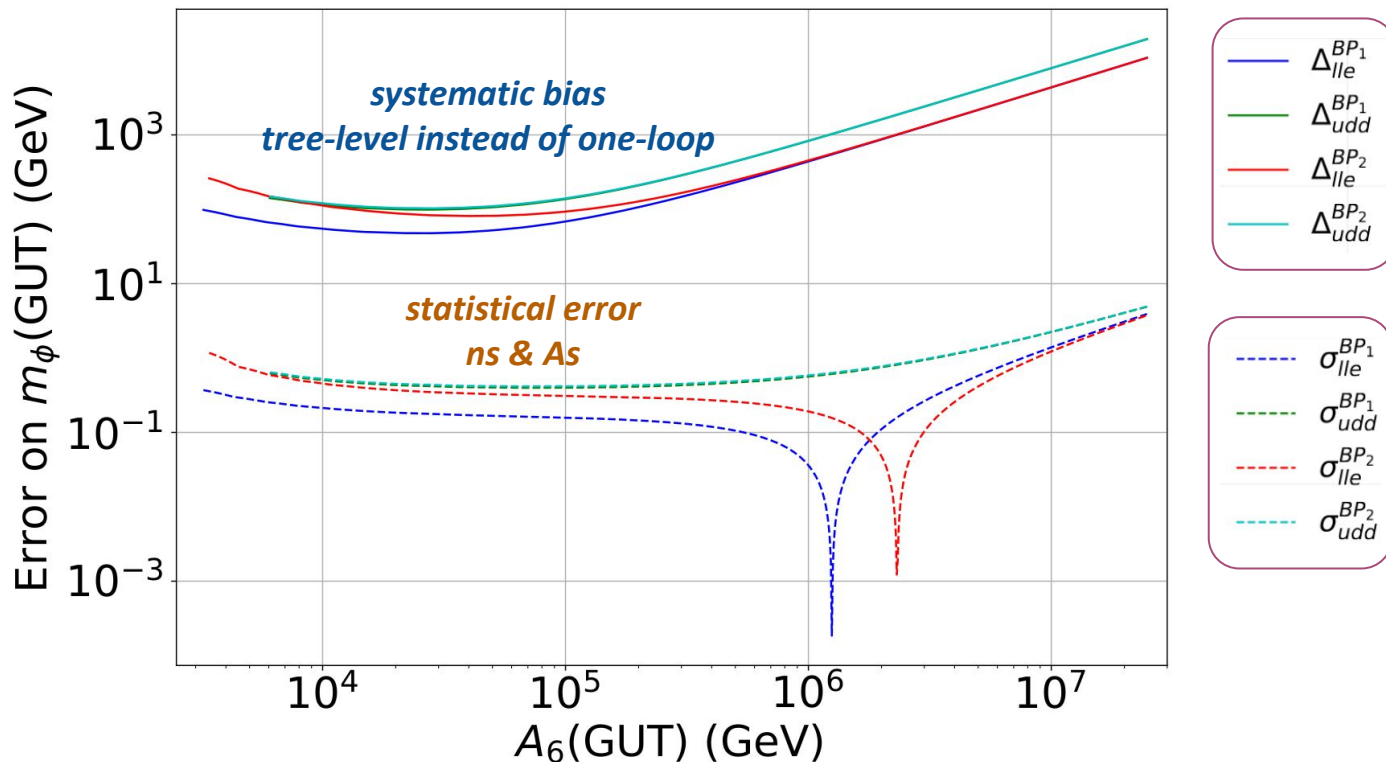
- **Not** taking properly **into account** the **RGE corrections** induces a *systematic bias*:
  - of order **100-1000 GeV** depending on the inflation scale!
  - **well above the *ns & As statistical error*!**

Crucial RGE impact!

Toward a global fit

We have identified **some points** for **various dark matter annihilation processes** satisfying:

HEP Constraints (~ 80):
- Higgs mass (and BR)
- LHC SUSY searches
… not exhaustive

Cosmo constraints:
- $\Omega_{cdm}h^2$

NEW **As, ns**

Toward a global fit

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- … not exhaustive

Cosmo constraints:
- $\Omega_{cdm}h^2$
- **NEW** **As, ns**

ϕ_0 $1.57 \; 10^{15}$ GeV
$m_\phi(\phi_0)$ 16954   GeV

ϕ_0 $9.58 \; 10^{14}$ GeV
$m_\phi(\phi_0)$ 6601.5   GeV
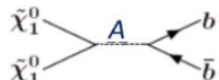
EXCLUDED

HEP measurements give constraints on inflation

ϕ_0 $1.41 \; 10^{15}$ GeV
$m_\phi(\phi_0)$ 13933   GeV

Cosmology restricts the MSSM parameter space

Interplay of the **constraints** in the **same region** of the **parameter space!**
=> HEP-cosmology bridge.

13
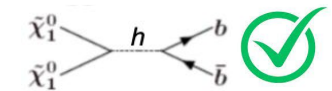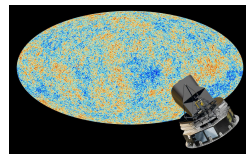
Conclusions & Outlooks

We have revisited the **MSSM-inflation,** a **rigorous** and **computable** framework which builds a bridge between two worlds, **HEP** and **inflation,** thanks to a **slow-roll flat-inflection potential**.

In this study-case, **RGE corrections cannot be neglected**, and should be accounted for precisely

=> We have shown that **cosmology** can be very **sensitive** to them.

This will be even more true in the coming years (with the expected **improvement** of the cosmological measures and the **new LHC runs**).

This **work** + **additional results** (initial conditions of the field, fine-tuning, …):
arXiv:2304.04534

Future:
More systematic **exploration** of the **parameter space**
Inclusion of the **reheating duration** computation

Slow-roll attractor

Analogy: $\{\phi,\ V\}$ $\longleftrightarrow$ {**skier, slope**}

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0 \qquad ma + fv + mg = 0$$

Slow-roll attractor

SAME SPEED
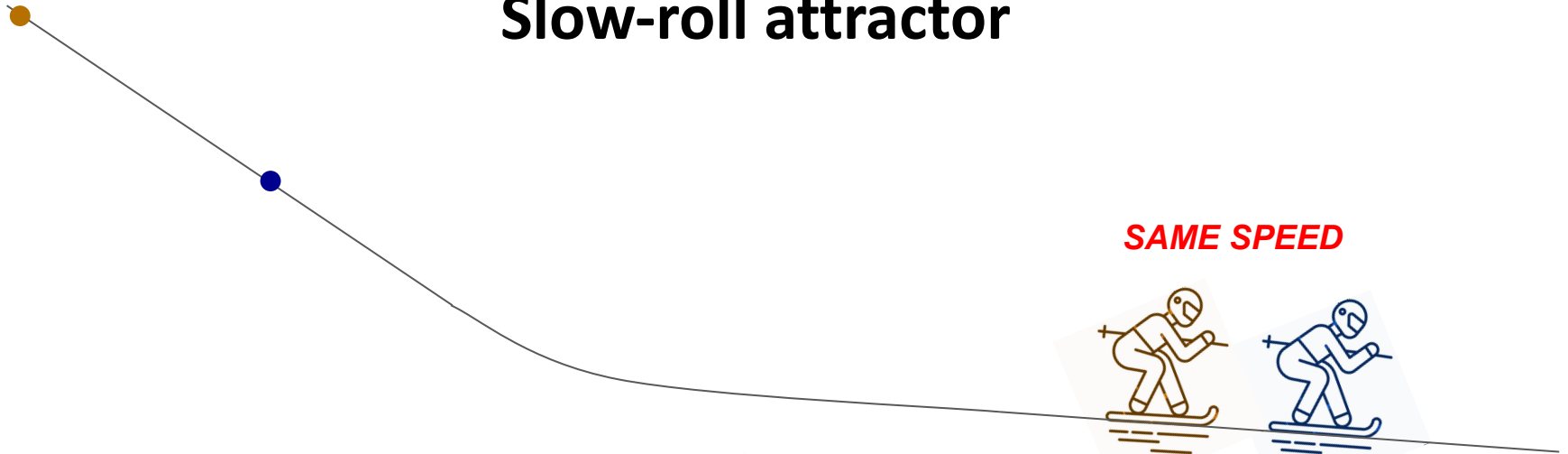
Analogy: $\{\phi,\ V\}$ $\longleftrightarrow$ {skier, slope}

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0 \qquad ma + fv + mg = 0$$

Convenient for inflation:
If the slow-roll region (where the potential is quasi-flat) is sufficiently long,
then all the **trajectories** end being attracted into the low-velocity **slow-roll regime**.
No need to **worry** about the initial conditions $\left(\phi,\ \dot{\phi}\right)_{t_0}$.

Phase space of the inflaton

To study that, go to phase space

Already one sees that the **trajectories** beginning **too far from flat inflection point do not follow the SR** trajectory (black-dashed line)

Robustness of slow-roll attractor

- **Very narrow slow-roll** region implies for various **trajectories**:
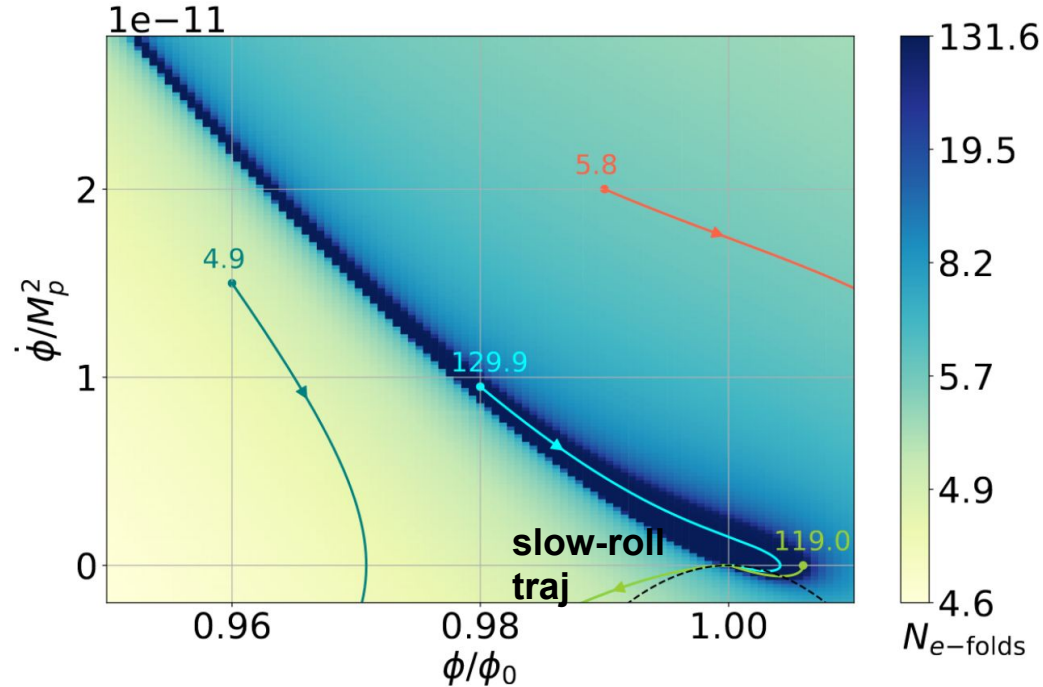
- Only few **trajectories are attracted into the slow-roll** regime

Slow-roll NOT independent of the initial conditions ... *not usual for a single field slow-roll*

How to get ϕ_*?

From *(P)reheating Effects of the Kähler Moduli Inflation I Model*, Islam Khan, Aaron C. Vincent and Guy Worthey, **2111.11050**

How to get ϕ_*?

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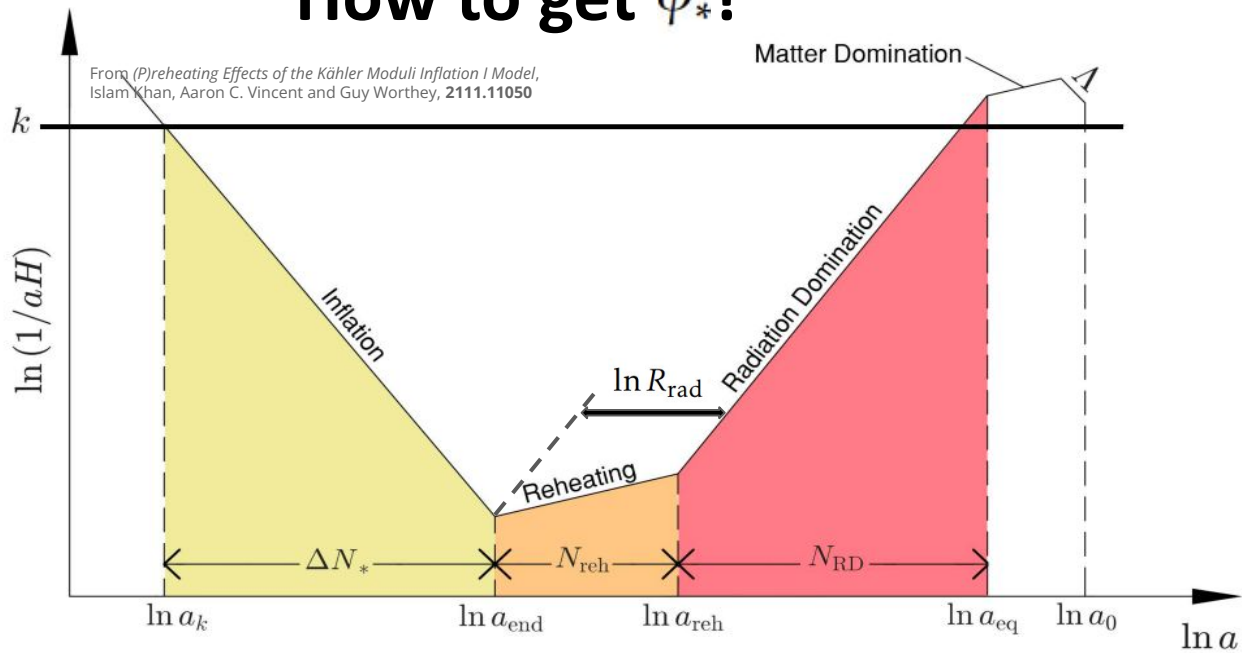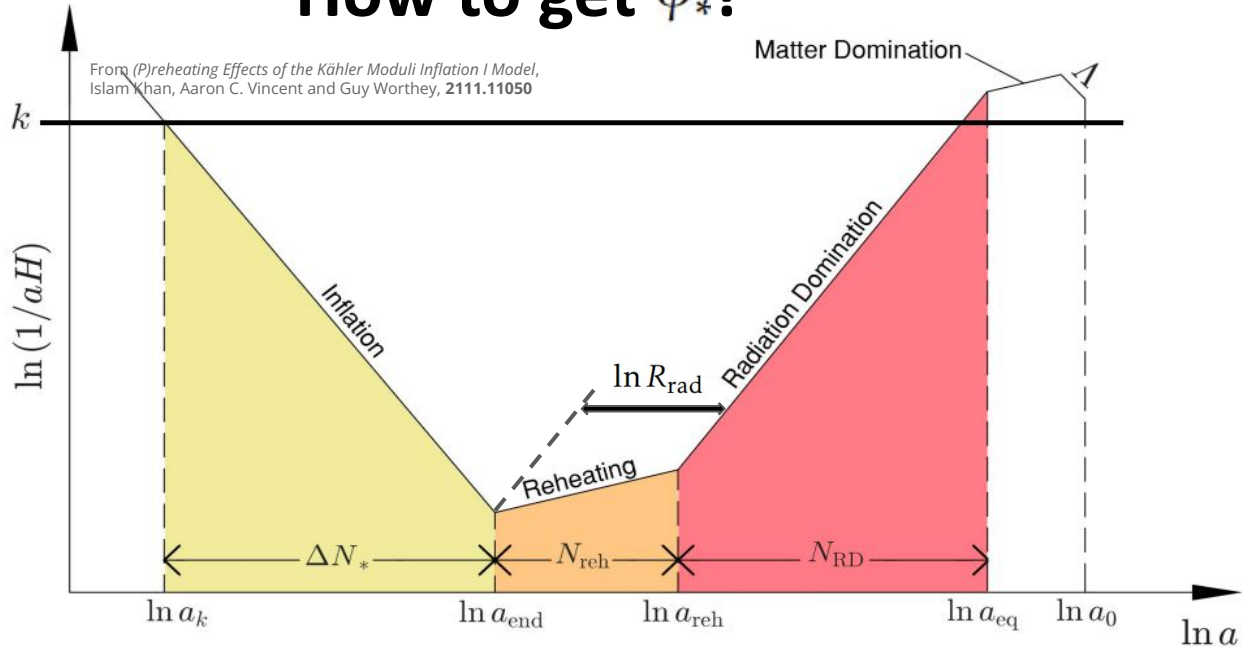
$$\Delta N_* \overset{\text{SRLO}}{\simeq} \int_{\phi_{\text{end}}}^{\phi_*} \frac{V(\phi)}{V_\phi(\phi)} d\phi$$

How to get $\Delta N_*^`$ then?

How to get ϕ_*?

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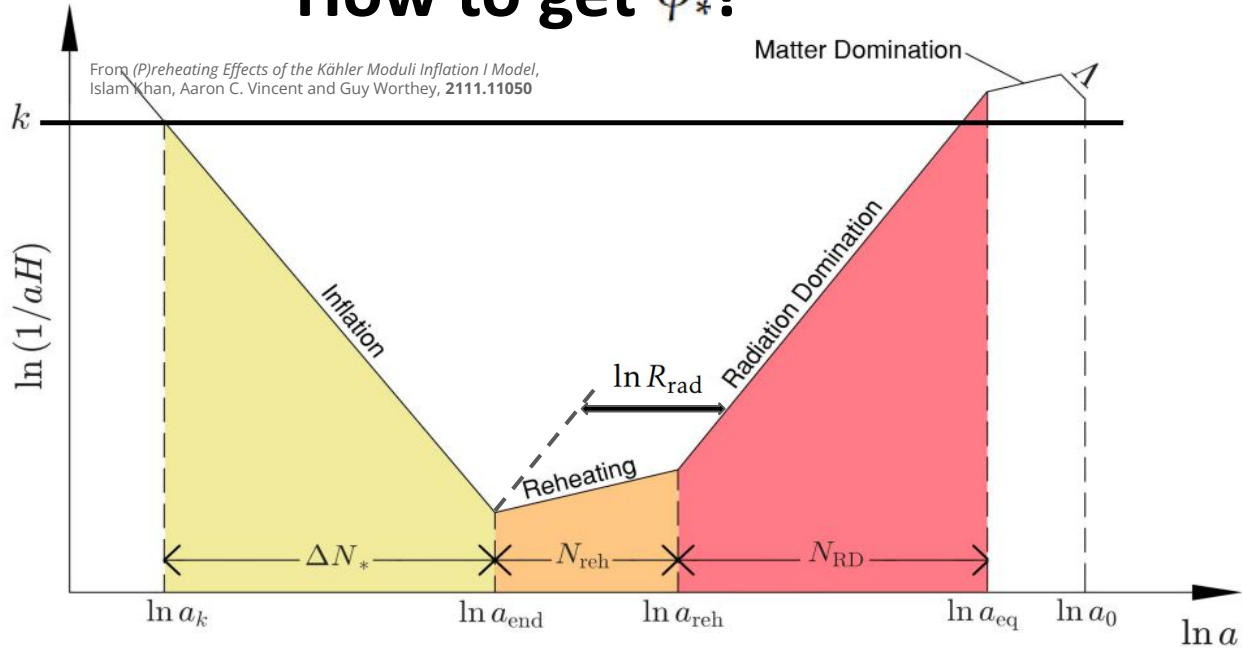
$$\Delta N_* \stackrel{\text{SRLO}}{\simeq} \int_{\phi_{\text{end}}}^{\phi_*} \frac{V(\phi)}{V_\phi(\phi)} d\phi$$

$$\Delta N_* \stackrel{\text{SRLO}}{\simeq} \ln R_{\text{rad}} - \ln\left(\frac{k_*}{a_0 \tilde{\rho}_\gamma^{1/4}}\right) - \frac{1}{4} \ln\left[\frac{9 V_{\text{end}}}{\varepsilon_{1*}(3 - \varepsilon_{1\text{end}}) V_*}\right] + \frac{1}{4} \ln(8\pi^2 A_{\text{S}})$$

Cosmology: observables (1)

- **Hubble's law** & **cosmic expansion** (1929):
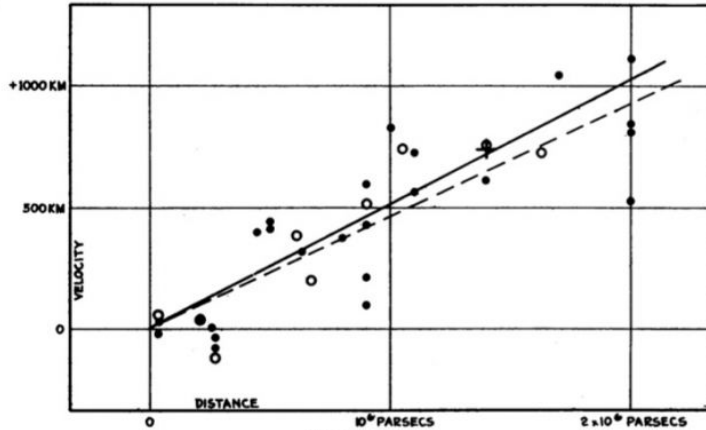
FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

=> **High energy** in the **past**.
=> **prediction** of

- Primordial **nucleosynthesis**

- **Cosmic microwave background** emission

a   Before recombination   b   After recombination
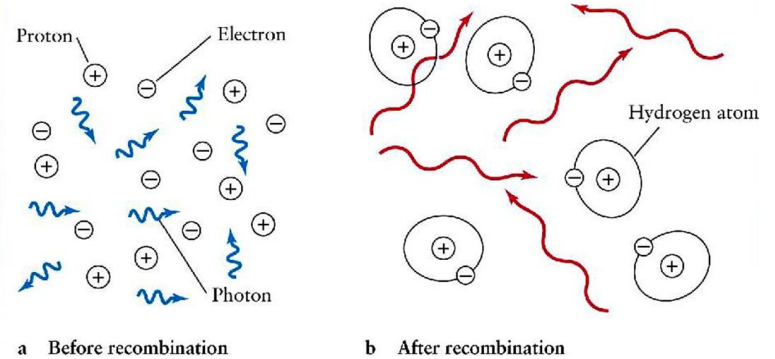
Cosmology: observables (2)

- **Primordial nucleosynthesis**
- **Cosmic microwave background**

TT:
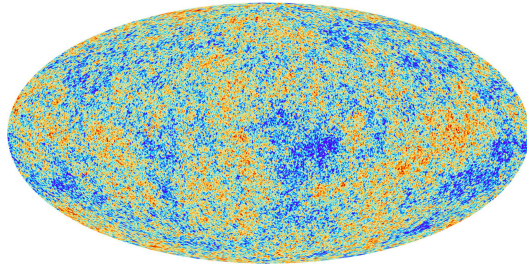
TE:
EE:
BB:

decomposition in spherical harmonics
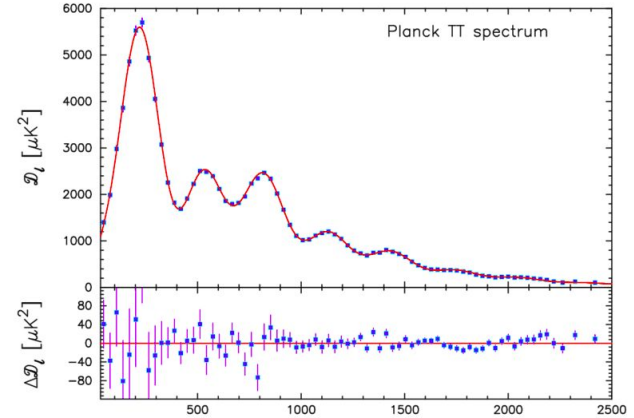
- **Large sky surveys**

3D Fourier transform

- **BAO**
- **...**

other stuff
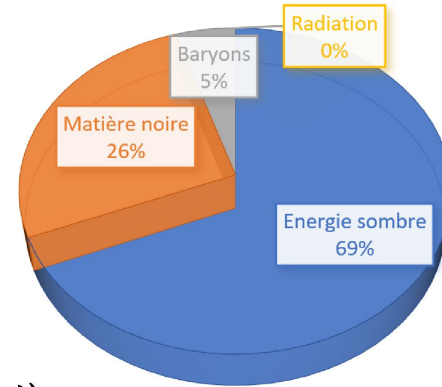
ΛCDM: 1) ingredients

Einstein equations for the whole universe
=> **Friedman** equations

$$H^2 = \frac{8\pi G}{3}\rho - \frac{\mathcal{K}}{a^2} + \frac{\Lambda}{3},$$

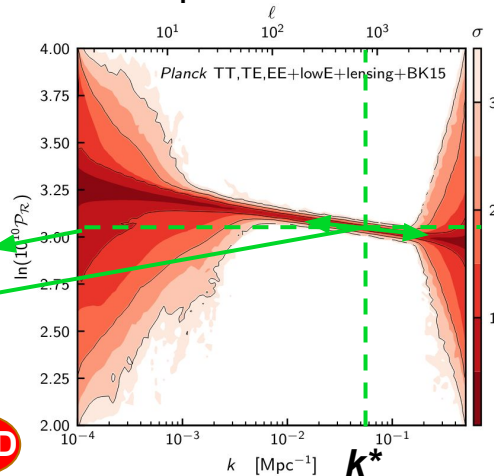$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3},$$

ΛCDM: 1) ingredients

Einstein equations for the whole universe
=> **Friedman** equations

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+   **Initial conditions** for the densities (today)

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+   Initial conditions for the perturbations
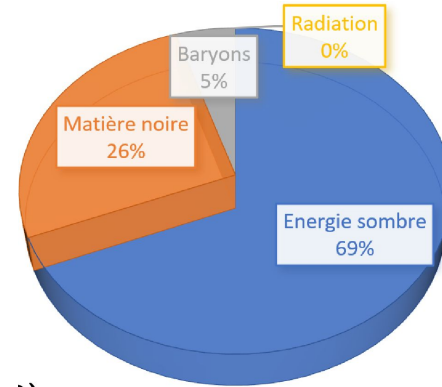
● **scalar** ones:

at **k***:
-    amplitude: **As**
-    slope: **ns**
-    running: **nsrun**

TBD

+   Initial conditions for the densities (today)

Radiation
0%

Baryons
5%

Matière noire
26%

Energie sombre
69%

● **tensor** ones:

at **k***:
-    amplitude: **r**   **TBD**
-    slope: **nt**   **TBD**

Planck TT,TE,EE+lowE+lensing+BK15

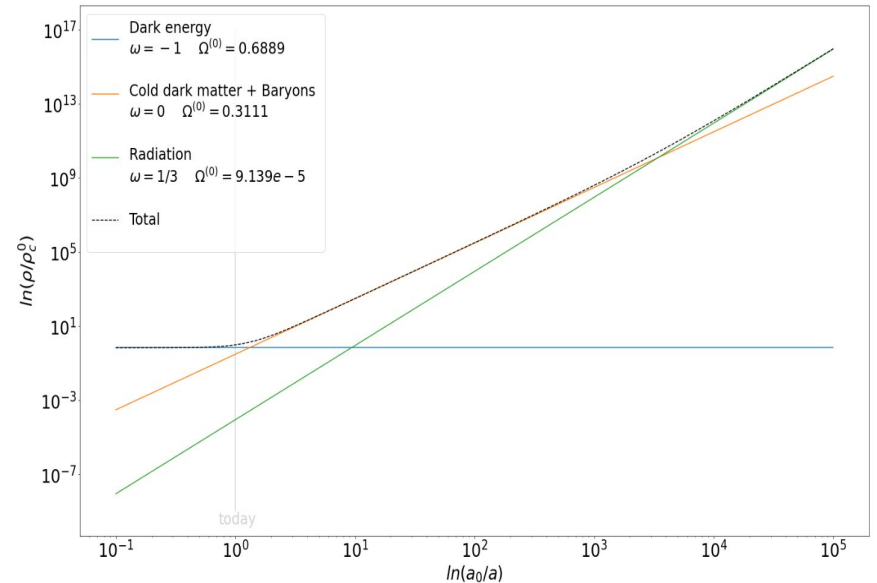$\ln(10^{10}\mathcal{P}_\mathcal{R})$

k [Mpc^{-1}]   **k***

ΛCDM: 2) results

only **6 dof's**
- **3 density** params
- **2** params linked to **IC for perturbations**
- **1 late-time** param
  - that **fits** very well **the data**
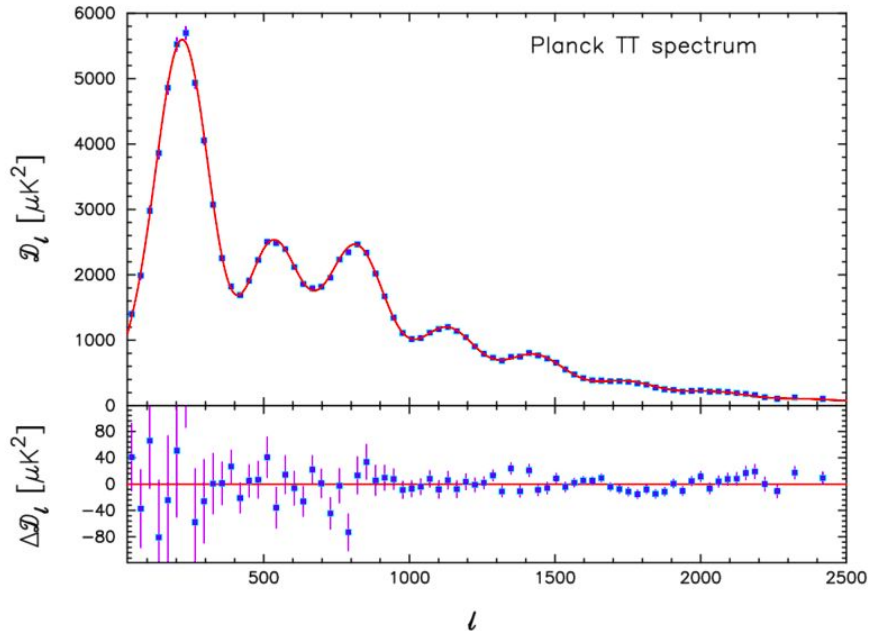
- **predicts** unambiguously an **universe history**

ΛCDM: 3) conceptual problems

The **universe today** looks so far **very flat**.
… lambda CDM predicts that in the past this **curvature** was even much low. Is it **natural**?

At **large scales**, we see an **uniform-temperature** CMB.
… lambda CDM do not suggest that. **Conflict**?

The **primordial fluctuations:**
- Why their **power spectrum** looks like a **power law**?
- What is the **mechanism** that generated them?

one **mechanism** to solve them all:
Inflation: A phase of **accelerated expansion** with **ä > 0** in the **very young universe,**
which needs to be sufficiently **long** $N = \ln \frac{a_{end}}{a_{in}} > 50$.

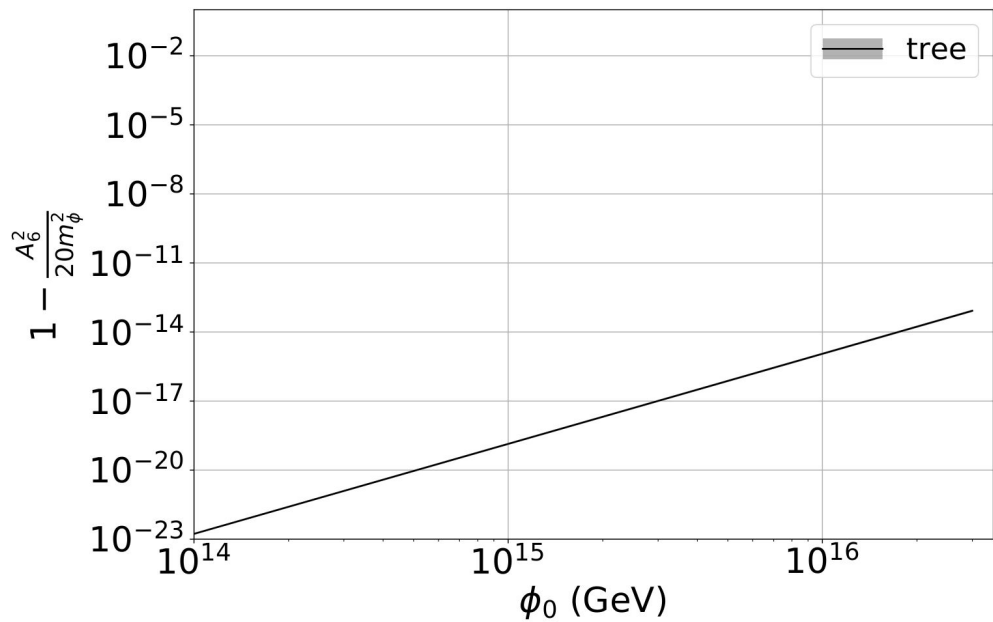**Λ** gives an example of **ä > 0** universe: **the quasi-de-Sitter universe**.
- The **galaxies get diluted exponentially**
- But the **dark energy density** remains **constant** with the expansion
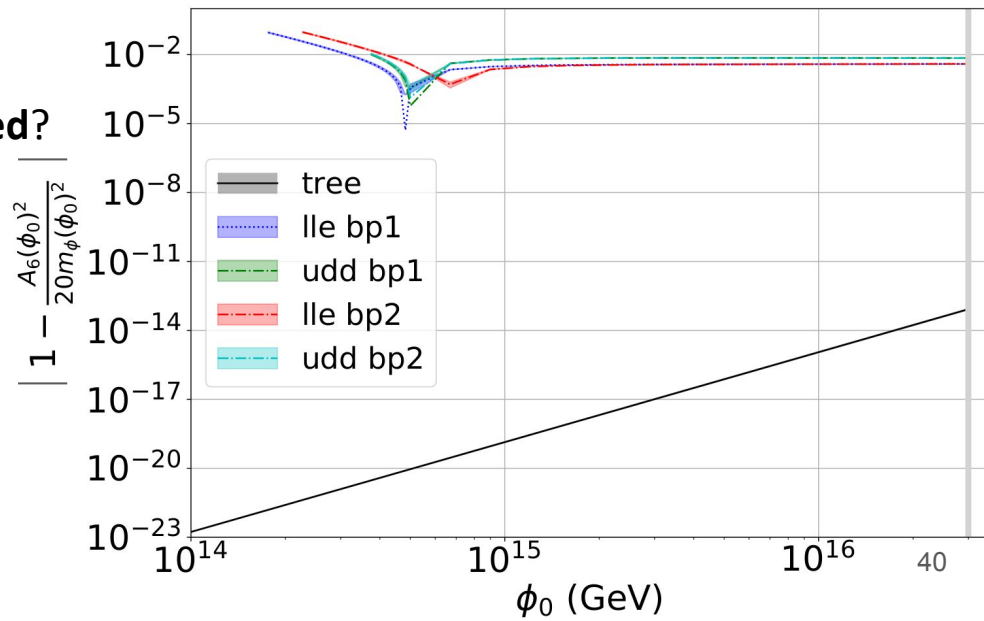- Friedmann equations => it is like a **fluid** with $\rho = -P$

Radiative corrections impact on the fine-tuning

- The potential at **inflection point** ϕ_0 has to be very close to flat.
$$\begin{cases} V_{\phi\phi}(\phi_0) = 0 \\ V_\phi(\phi_0) = v \simeq 0 \end{cases}$$

- At **tree level**:
$$0 < \ 1 - \frac{A_6^2}{20m_\phi{}^2} \ll 1 \ \ .$$

Radiative corrections impact on the fine-tuning

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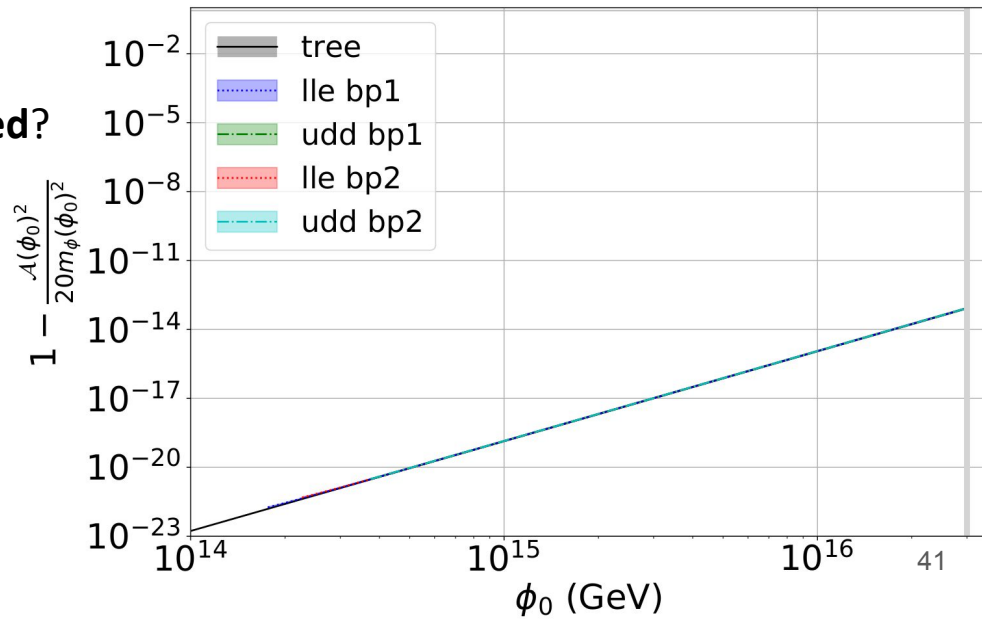
- At **tree level**:

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- **RGE**: Does it mean the fine tuning is **relaxed**?
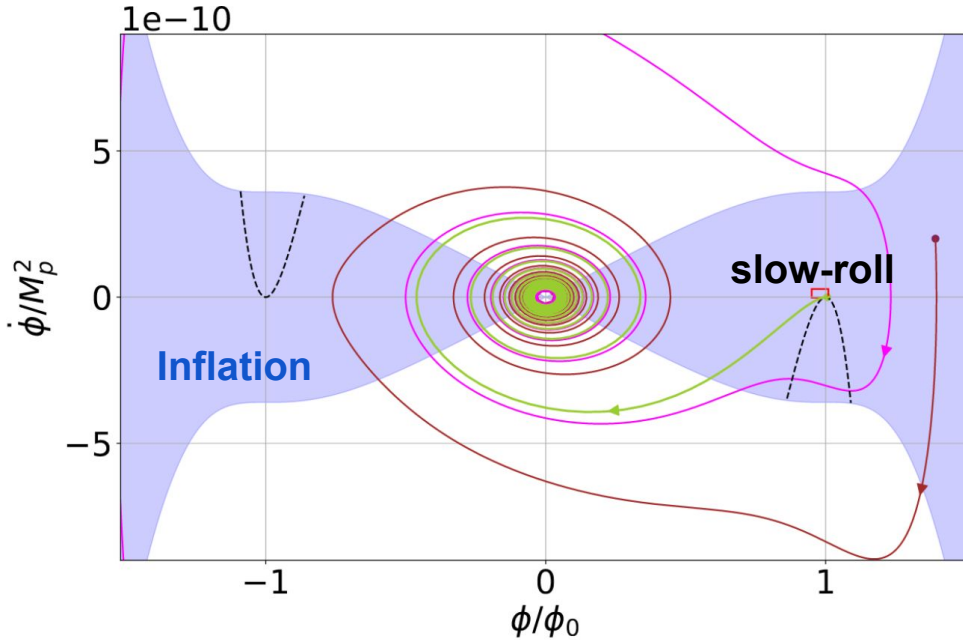
Radiative corrections impact on the fine-tuning

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- At **tree level**:

$$0 < 1 - \frac{A_6^2}{20m_\phi^2} \ll 1 \;.$$

- **RGE**: Does it mean the fine tuning is **relaxed**?

We showed that

NEW ▸ $\quad 0 < 1 - \frac{\mathscr{A}^2(\phi_0)}{20m_\phi^2(\phi_0)} \ll 1$
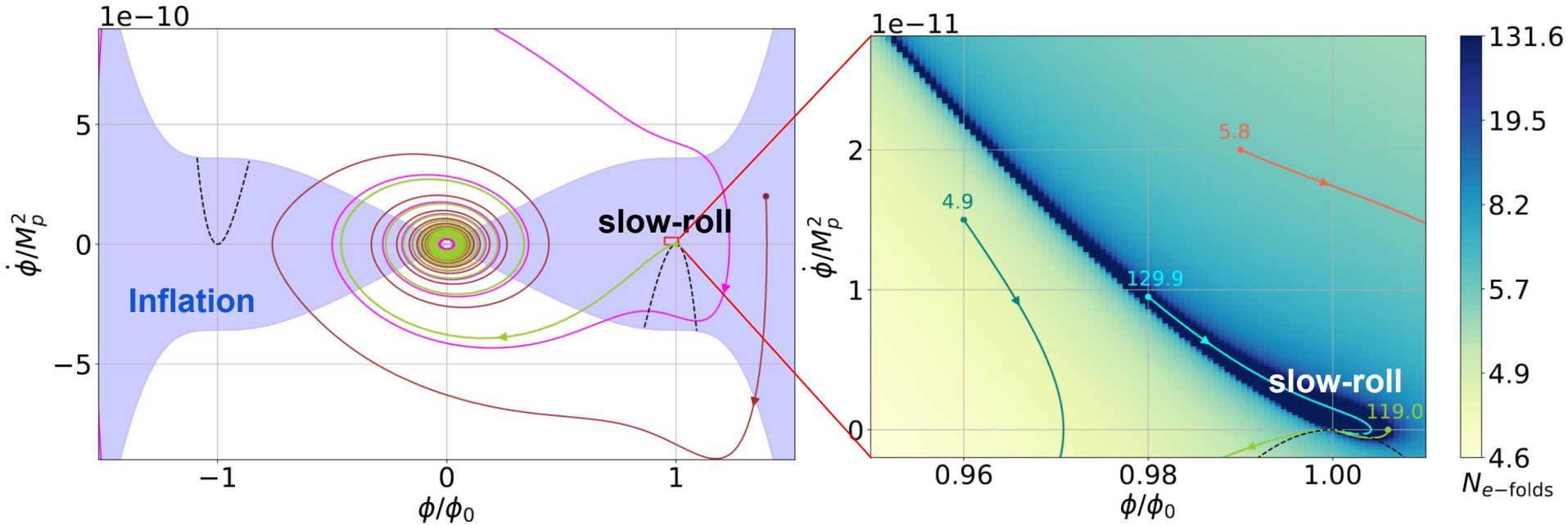
- No! Actually, **same fine-tuning**

Robustness of slow-roll attractor

- **Very narrow slow-roll** region implies for various **trajectories**:

Robustness of slow-roll attractor

- **Very narrow slow-roll** region implies for various **trajectories**:

- The **trajectories attracted into the slow-roll** regime are rare

… **Not a very good attractor!**   … *not usual* for a single field slow-roll

RGE impact on the parameter space

- Two types of error, either versus ϕ_0 or $A_6(\text{GUT})$.
  - A **statistical** error on ns/As: $\sigma_{n_S,i}^{\text{BP}_j}[p] = \frac{1}{2}\left| p^{\text{RGE}}(n_S = \overline{n_S} + \sigma_{n_S}) - p^{\text{RGE}}(n_S = \overline{n_S} - \sigma_{n_S}) \right|$
  - Impact of corrections $\Delta_i^{\text{BP}_j}[p] = p^{\text{RGE}}(n_S = \overline{n_S}) - p^{\text{tree}}(n_S = \overline{n_S})$
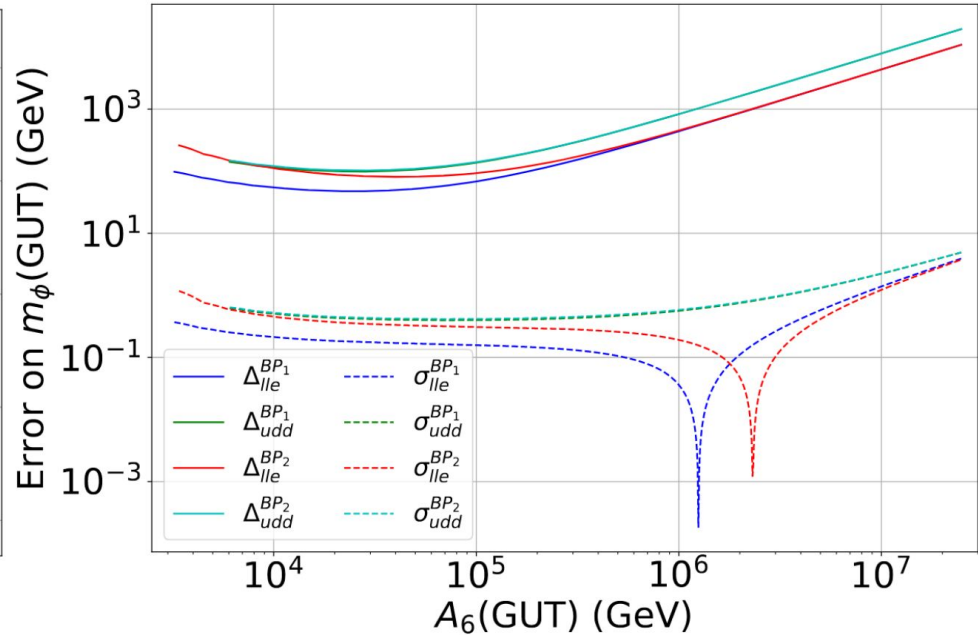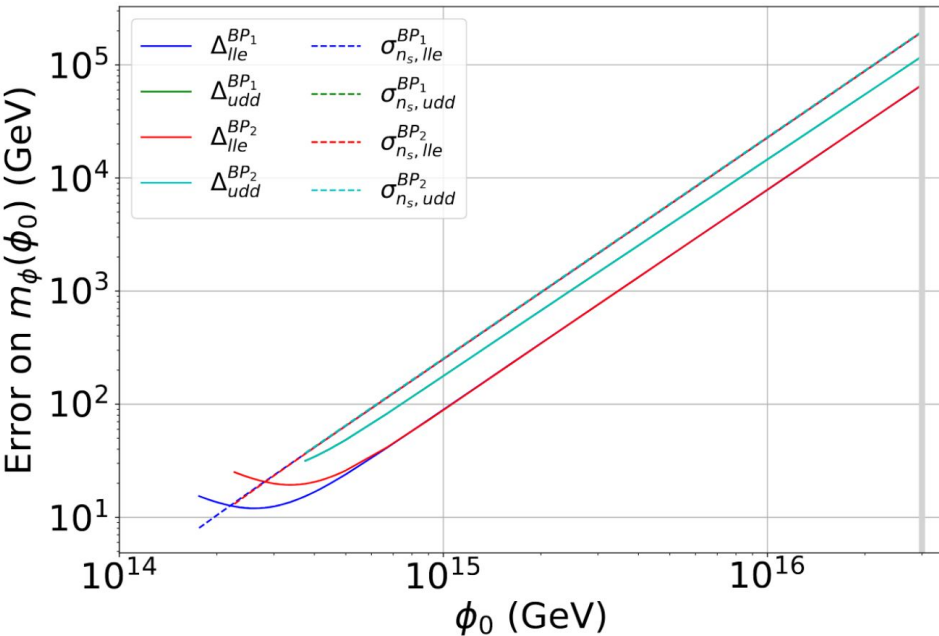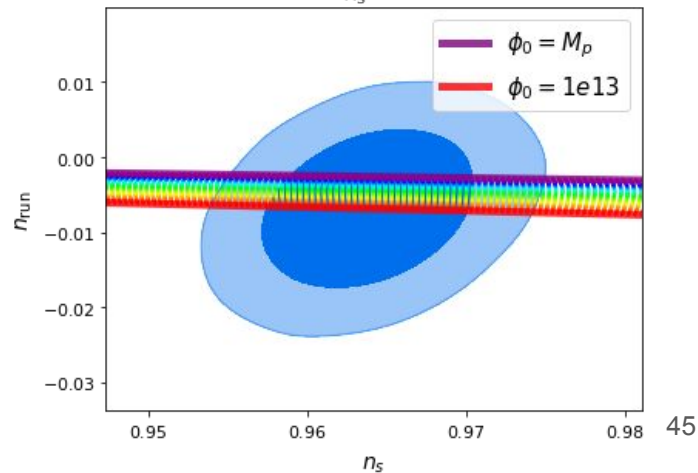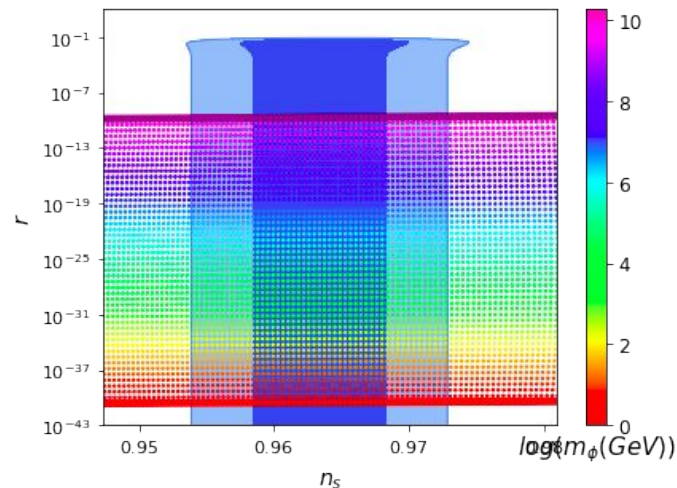

- The **systematic error** is not **negligible!**

Cosmology beyond As and ns

- r

- ns_run: potential constraining power in a near future

for phi0 = 1e15 (<= mphi at lhc), ns_run = **4.4e-3**

- nt and nt_run: beyond experimental reach
- No induced gravitational waves
- No non gaussianities

Robust forecasts on fundamental physics from the foreground-obscured, gravitationally-lensed CMB polarization

Josquin Errard,[*,a,b,c,d] Stephen M. Feeney,[*,e] Hiranya V. Peiris,[f] and Andrew H. Jaffe[e]

We show that in the case of CMB, synchrotron and dust, and after delensing and marginalization over foreground residuals, the best pre-2020 instruments in combination with Planck can reach $\sigma(r) \sim 3 \times 10^{-3}$, $\sigma(n_t) \sim 0.2$, $\sigma(n_s) \sim 2.2 \times 10^{-3}$, $\sigma(\alpha_s) \sim 3 \times 10^{-3}$, $\sigma(M_v) \sim 55$ meV, $\sigma(w) \sim 0.16$, $\sigma(w_0) \sim 0.36$, $\sigma(w_a) \sim 0.71$, $\sigma(N_{eff}) \sim 0.05 - 0.06$ and $\sigma(\Omega_k) \sim 2.5 \times 10^{-3}$ when delensing using the CMB×CIB method. Post-2020 instruments, in particular the combination of the ground-based Stage-IV and a space mission, could reach constraints $\sigma(r) \sim \mathbf{1.3 \times 10^{-4}}$, $\sigma(n_t) \sim 0.03$, $\boldsymbol{\sigma(n_s) \sim 1.8 \times 10^{-3}}$, $\boldsymbol{\sigma(\alpha_s) \sim 1.7 \times 10^{-3}}$, $\sigma(M_v) \sim 31$ meV, $\sigma(w) \sim 0.09$, $\sigma(w_0) \sim 0.25$, $\sigma(w_a) \sim 0.50$, $\sigma(N_{eff}) \sim 0.024$ and $\sigma(\Omega_k) \sim 1.5 \times 10^{-3}$

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Slow-roll inflation

Previous inflation talk(s):

"- **Inflation**: solution the

Slow-roll:
$$V \gg \dot{\phi}^2$$

- On its simplest versions, only needs to introduce a **single scalar field *slow-rolling* on a quasi-flat potential** *V*.

Deviation from **de-Sitter**:

$$\left. \begin{array}{l} \varepsilon_1 \overset{\text{SRLO}}{\simeq} \dfrac{M_{\text{Pl}}^2}{2} \left(\dfrac{V_\phi}{V}\right)^2 \\[2mm] \varepsilon_i \overset{\text{SRLO}}{\simeq} \varepsilon_i\left(V(\phi), V_\phi(\phi), ...\right) \end{array} \right\} \ll 1$$

- On top of that, allows one to explain the density **fluctuations** origin and to predict their primordial power spectra, **scalar** $\mathscr{P}_\zeta$ and **tensor** $\mathscr{P}_h$, around the **CMB scale k*"**

$$\mathscr{P}_\zeta(k \simeq k_*) \overset{\text{SRLO}}{\simeq} \mathscr{P}_\zeta(V_*, \{\varepsilon_{i*}\})$$

$$\mathscr{P}_h(k \simeq k_*) \overset{\text{SRLO}}{\simeq} \mathscr{P}_h(V_*, \{\varepsilon_{i*}\})$$

$$\phi_* \overset{\text{SRLO}}{\simeq} \phi_*(V, k_*)$$

Potential <-> Power spectra

- **Ingredients**:
  - The **potential** $\phi \rightarrow V(\phi, p)$
  - Two necessary conditions so **slow-roll takes place**
    - $\varepsilon_1 < 1$
    - **Trajectories reach** and **stay** in the SR region ▲

- **Recipe**:
  - **Potential parameters --> power spectra parameters**

$$\phi \rightarrow V(\phi, p), \Longrightarrow \phi_* \Longrightarrow \{\varepsilon_i*\} \Longrightarrow \{A_\mathrm{S}, \, n_\mathrm{S}, \, n_\mathrm{S,run}, \, r, \, n_\mathrm{T}, \, n_\mathrm{T,run}, \, N_\mathrm{e-folds} \ldots\}$$

MSSM-inflation potential

- The **potential** for *LLe* and *udd* reduces to

$$V(\phi) = \frac{1}{2} m_\phi^2(\phi)\phi^2 - \sqrt{2}A_6(\phi)\frac{\lambda_6(\phi)\phi^6}{6M_{\text{Pl}}^3} + \lambda_6(\phi)^2 \frac{\phi^{10}}{M_{\text{Pl}}^6}$$

where ϕ is the real **field value** associated to the inflaton, m_ϕ its **mass**, A_6 its trilinear **coupling** and another λ_6 **coupling** of order **1**. They are linked to the MSSM spectrum.

- Approximation usually done
    - ***Tree-level*** approximation V_{tree} =>

$$m_\phi^2(\phi) = m_\phi^2$$
$$A_6(\phi) = A_6$$
$$\lambda_6(\phi) = \lambda_6$$

- **<u>NEW</u>** **RGE** potential: V_{RGE} whose parameters depend on ϕ, on the gaugino masses and gauge couplings (well defined through the **Renormalization Group Equations (RGE))**. Varies whether the inflaton is along *udd* or *LLe*.

BP1 resp BP2:
given gaugino masses
& gauge couplings

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Come-back to our hypothesis
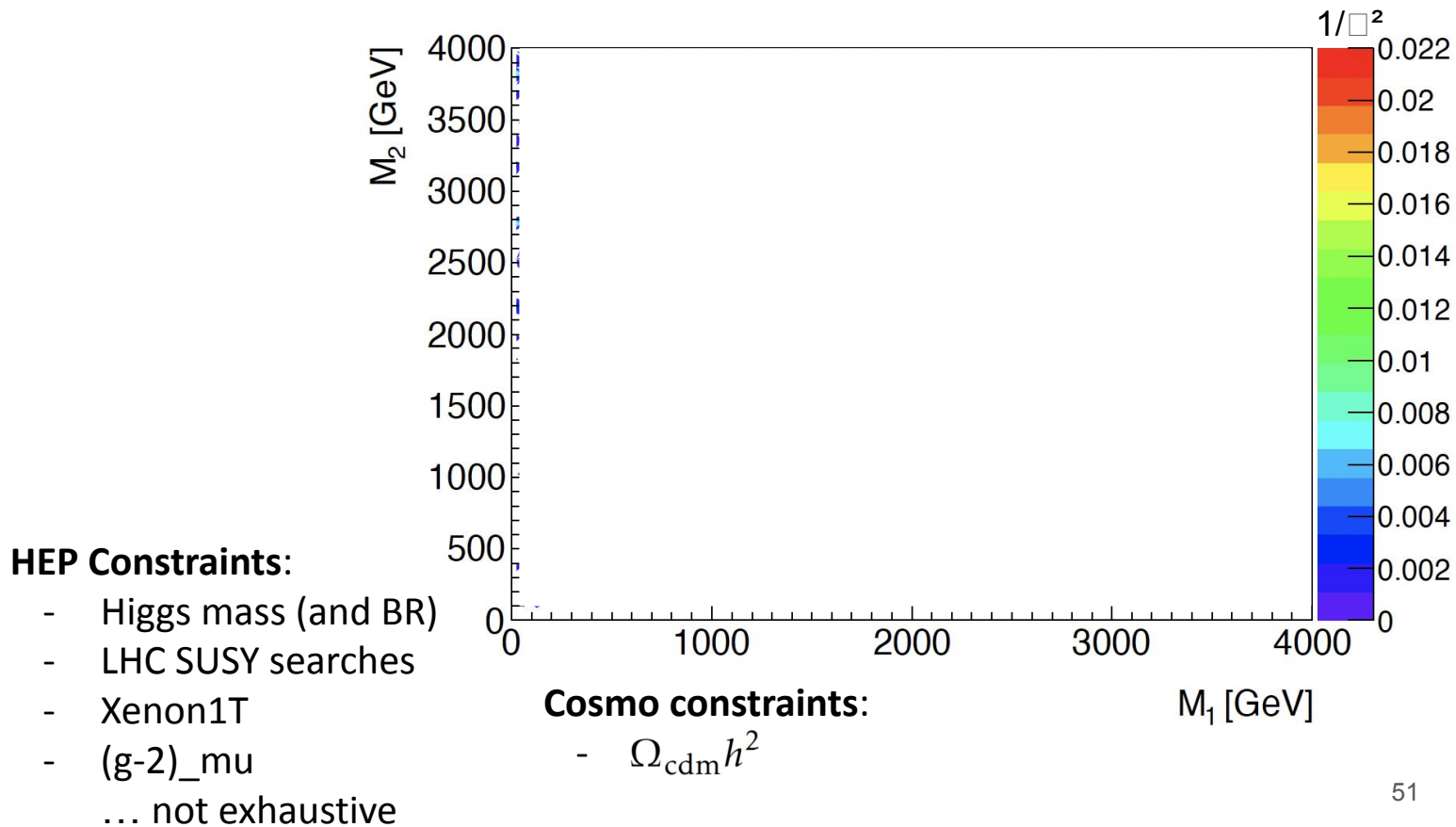
- *Remember slide 3…*

    - Two necessary conditions so **slow-roll takes place**

        - $\varepsilon_1 < 1$

        - **Trajectories get to** and **stay** in the SR region 🔺
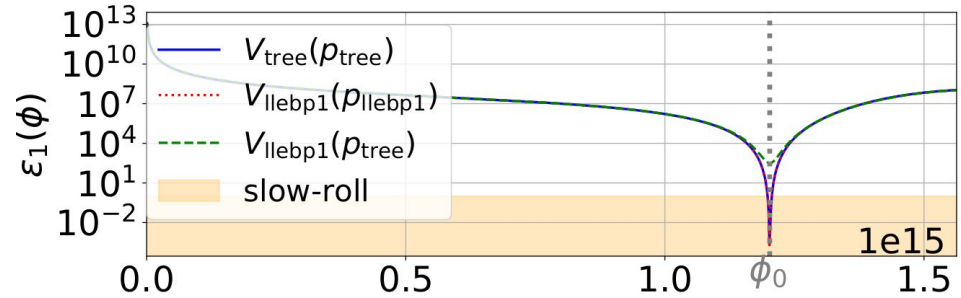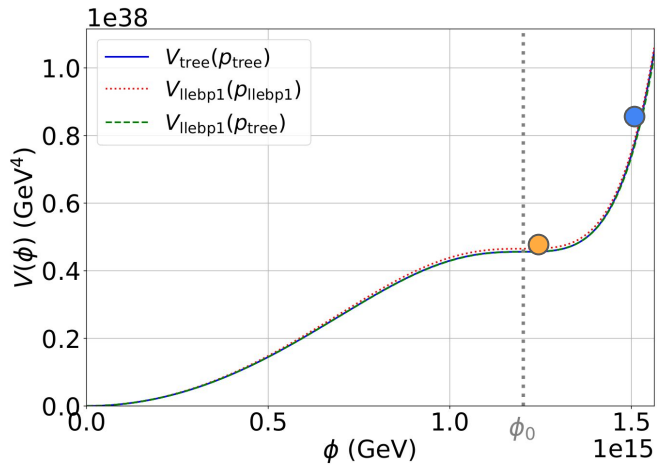
- Initial condition 🟠 should be ok but what about 🔵 ?
- Is the **slow-roll** region to **thin Deltaphi/phi ~ phi0^2/Mp^2** to act like an attractor?

Constrained MSSM parameters space
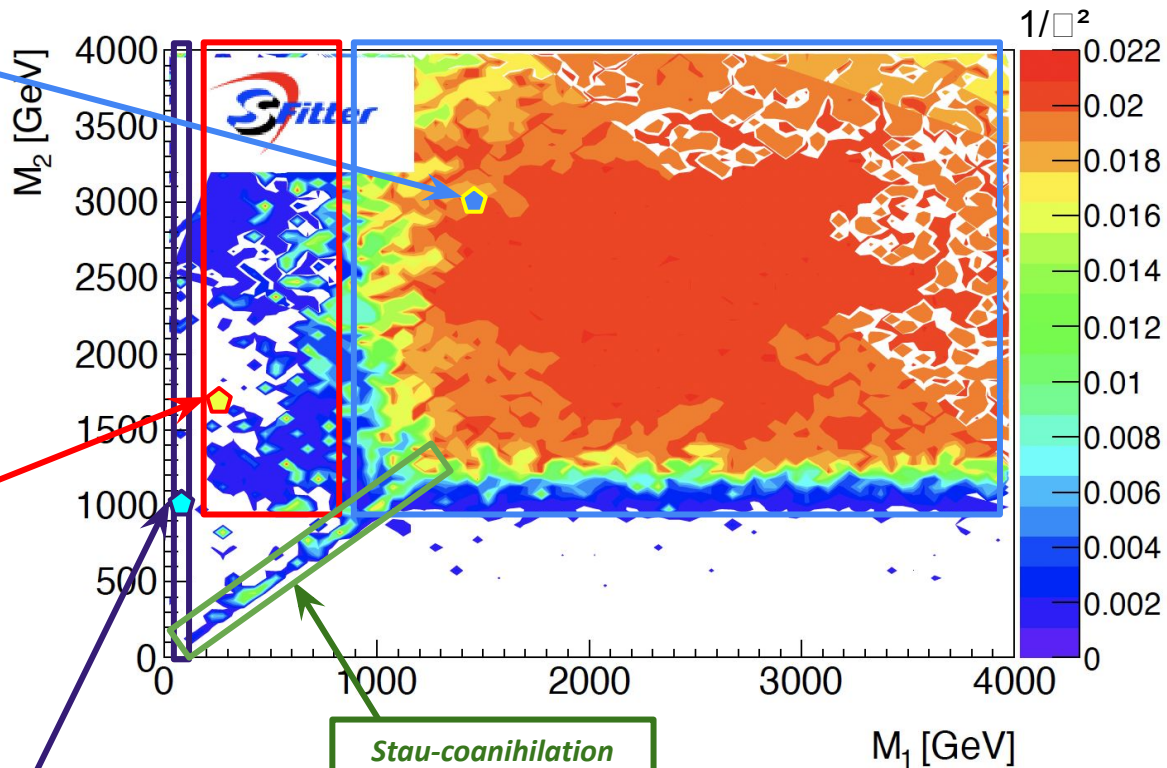
Dark matter:
neutralino $\tilde{\chi}_1^0$

HEP Constraints:
- Higgs mass (and BR)
- LHC SUSY searches
- Xenon1T
- (g-2)_mu

    … not exhaustive

Cosmo constraints:
- $\Omega_{\text{cdm}} h^2$

Constrained MSSM parameters space

Dark matter:
neutralino $\tilde{\chi}_1^0$

Higgs funnel	HEP Spectrum	udd inflaton
$\tilde{\chi}_1^0$ — h — b, $\bar{b}$	$\tilde{g}$ 2422 $\tilde{\chi}_1^0$ 60.0	ϕ_0 1.41 10^{15} $m_\phi(\phi_0)$ 13933 $A_6(\phi_0)$ 44204 $\lambda_6(\phi_0)$ 0.0159
satisfies $\Omega_{\text{cdm}}h^2$, Xenon1T	m_h, LHC, ...	A_S, n_S, $n_{S,\text{run}}$, r

A funnel	HEP Spectrum	lle inflaton
$\tilde{\chi}_1^0$ — A — b, $\bar{b}$	$\tilde{g}$ 1464 $\tilde{\chi}_1^0$ 359	ϕ_0 9.64 10^{14} $m_\phi(\phi_0)$ 6590 $A_6(\phi_0)$ 20857 $\lambda_6(\phi_0)$ 0.0347
satisfies $\Omega_{\text{cdm}}h^2$, Xenon1T	m_h	A_S, n_S, $n_{S,\text{run}}$, r
excluded	LHC (gluinos)	

Higgsino	HEP Spectrum	udd inflaton
$\tilde{\chi}_1^0$ — $\tilde{\chi}_1^+$ — W^-, $\tilde{\chi}_1^0$ — W^+	$\tilde{g}$ 2444 $\tilde{\chi}_1^0$ 1110	ϕ_0 1.57 10^{15} $m_\phi(\phi_0)$ 16954 $A_6(\phi_0)$ 53787 $\lambda_6(\phi_0)$ 0.0128
satisfies $\Omega_{\text{cdm}}h^2$, Xenon1T	m_h, LHC, ...	A_S, n_S, $n_{S,\text{run}}$, r

Stau-coanihilation
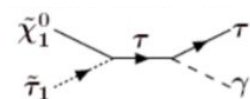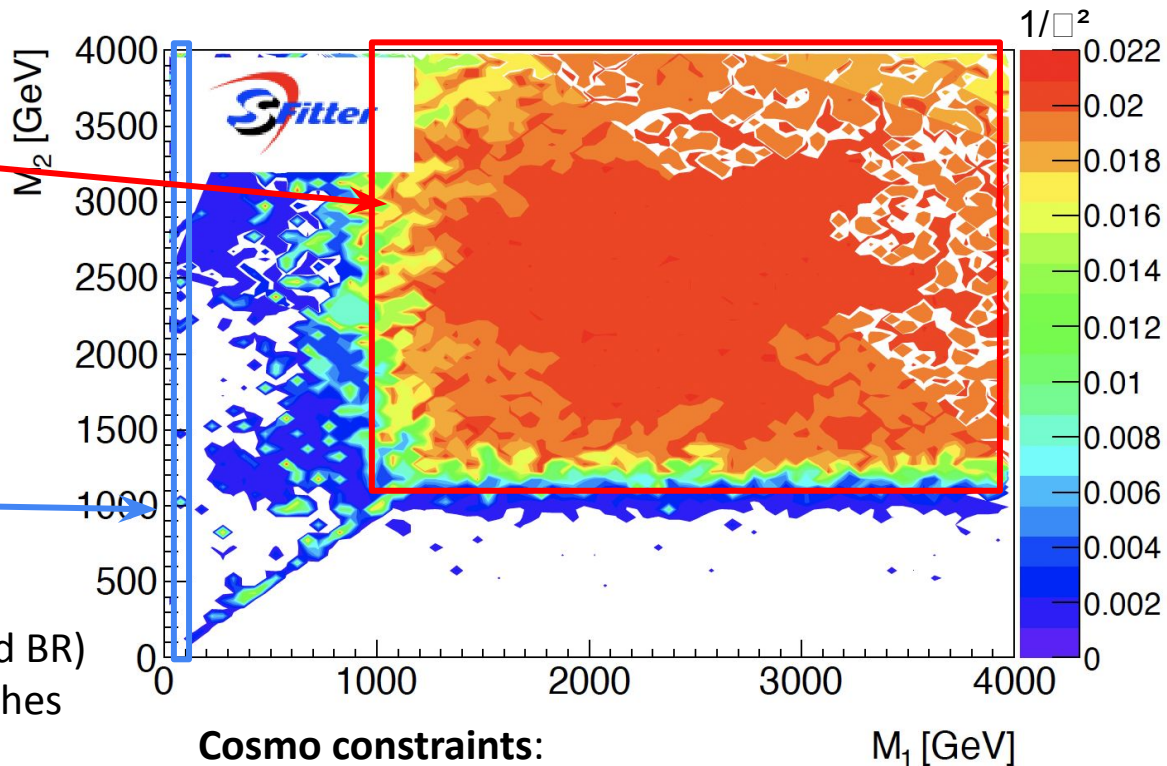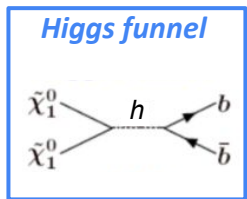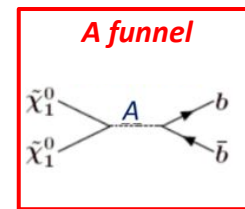
$\tilde{\chi}_1^0$ — τ — τ, $\tilde{\tau}_1$ — γ

Constrained MSSM parameters space

Dark matter:
neutralino $\tilde{\chi}_1^0$

*S. Henrot-Versillé, R. Lafaye, T. Plehn, M. Rauch, D. Zerwas, S. Plaszczynski, B. Rouillé d'Orfeuil, and M. Spinelli, Phys. Rev. D 89, 055017 (2014), **1309.6958***

HEP Constraints:
- Higgs mass (and BR)
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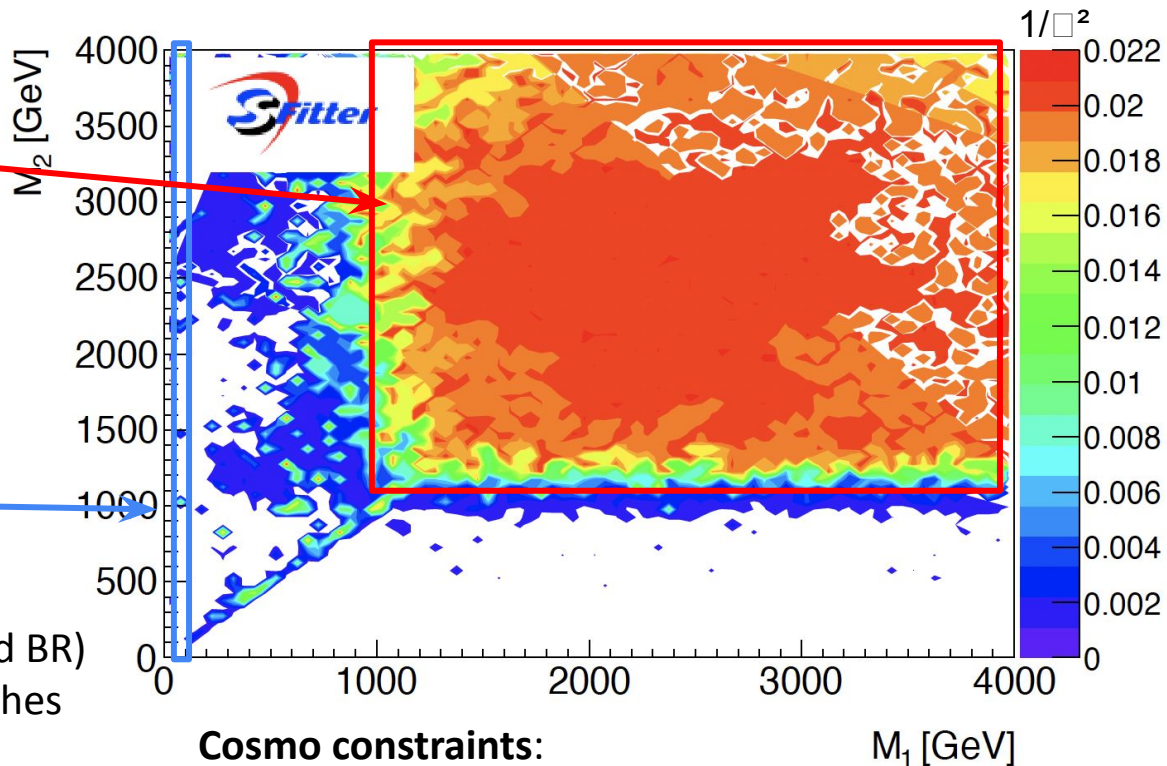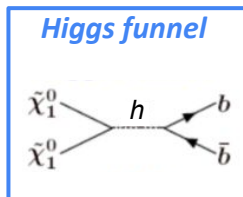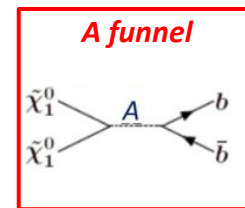- Xenon1T
- (g-2)_mu
  … not exhaustive

Cosmo constraints:
- $\Omega_{\mathrm{cdm}} h^2$

Constrained MSSM parameters space

Dark matter:
neutralino $\tilde{\chi}_1^0$

*S. Henrot-Versillé, R. Lafaye, T. Plehn, M. Rauch, D. Zerwas, S. Plaszczynski, B. Rouillé d'Orfeuil, and M. Spinelli, Phys. Rev. D 89, 055017 (2014), **1309.6958***

A funnel
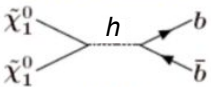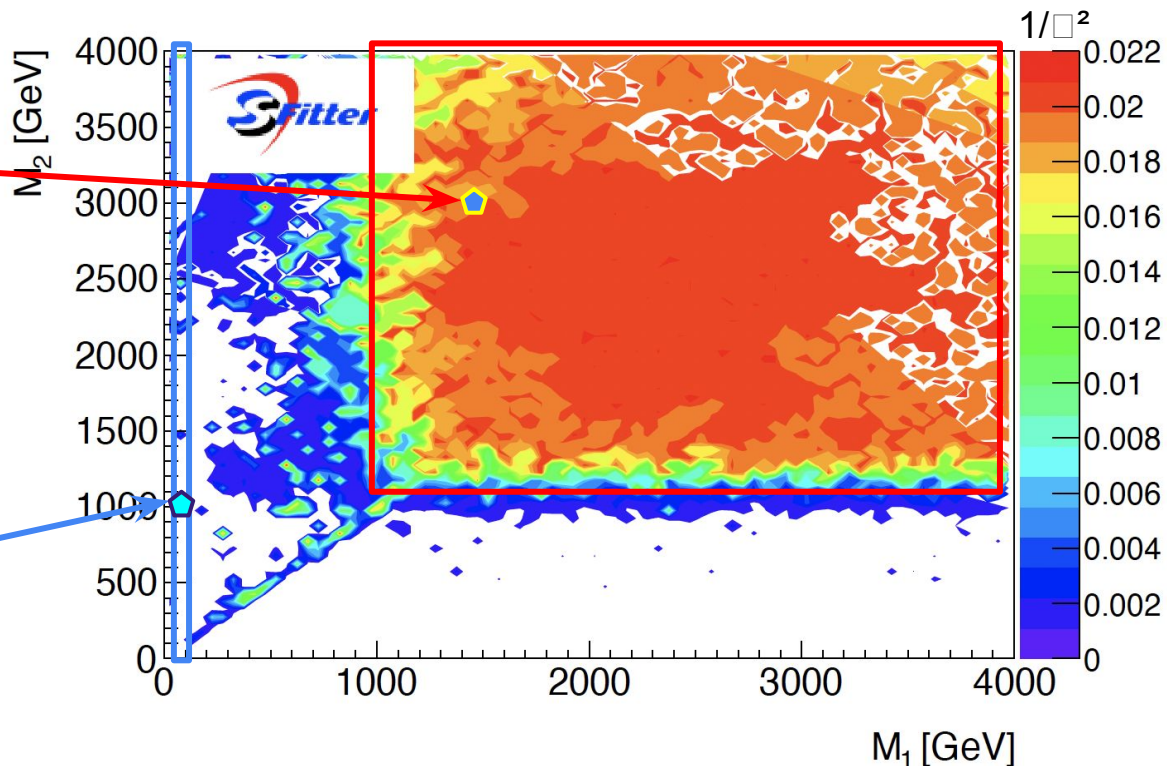
$\tilde{\chi}_1^0$ A b
$\tilde{\chi}_1^0$ $\bar{b}$

Higgs funnel

$\tilde{\chi}_1^0$ h b
$\tilde{\chi}_1^0$ $\bar{b}$

HEP Constraints:
- Higgs mass (and BR)
- LHC SUSY searches
- Xenon1T
- (g-2)_mu
- … not exhaustive

Cosmo constraints:
- $\Omega_{\mathrm{cdm}} h^2$

NEW ▸ **ns, As**


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Constrained MSSM parameters space

Dark matter:
neutralino $\tilde{\chi}_1^0$

A funnel	HEP Spectrum	Ile inflaton		
$\tilde{g}$ 1464 $\tilde{\chi}_1^0$ 359		ϕ_0 $9.64\,10^{14}$ $m_\phi(\phi_0)$ 6590 $A_6(\phi_0)$ 20857 $\lambda_6(\phi_0)$ 0.0347		
satisfies	$\Omega_{cdm}h^2$, Xenon1T	m_h	$A_s,\ n_s,\ n_{s,run},\ r$
excluded		LHC (gluinos)	

Higgs funnel	HEP Spectrum	udd inflaton		
$\tilde{g}$ 2422 $\tilde{\chi}_1^0$ 60.0		ϕ_0 $1.41\,10^{15}$ $m_\phi(\phi_0)$ 13933 $A_6(\phi_0)$ 44204 $\lambda_6(\phi_0)$ 0.0159		
satisfies	$\Omega_{cdm}h^2$, Xenon1T	m_h, LHC, ...	$A_s,\ n_s,\ n_{s,run},\ r$

- This specific **A-funnel configuration** is excluded by LHC searches
    => constraints on inflation from HEP
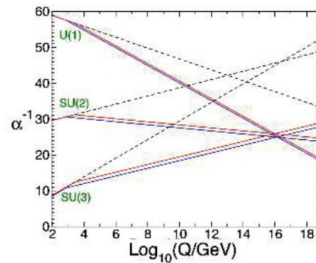
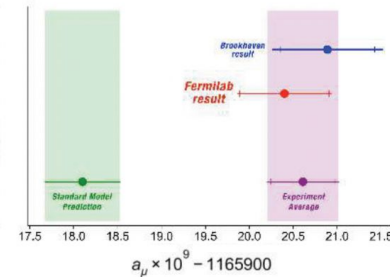particles — R-parity — sparticles
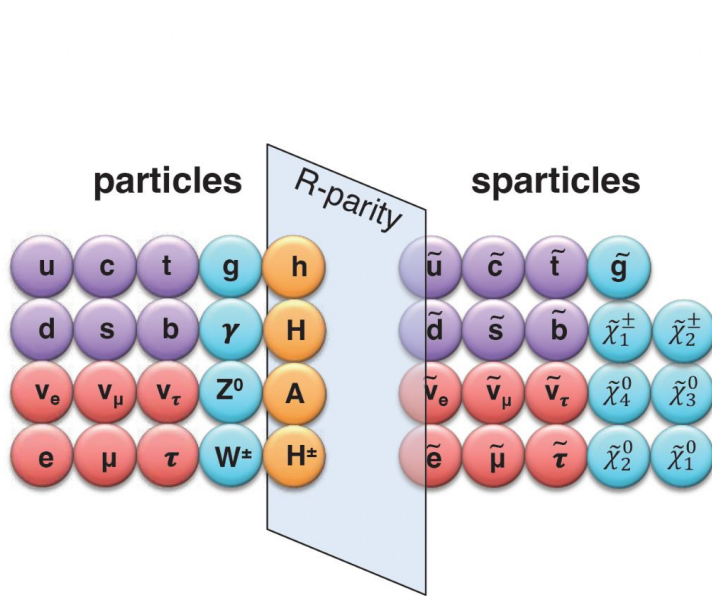
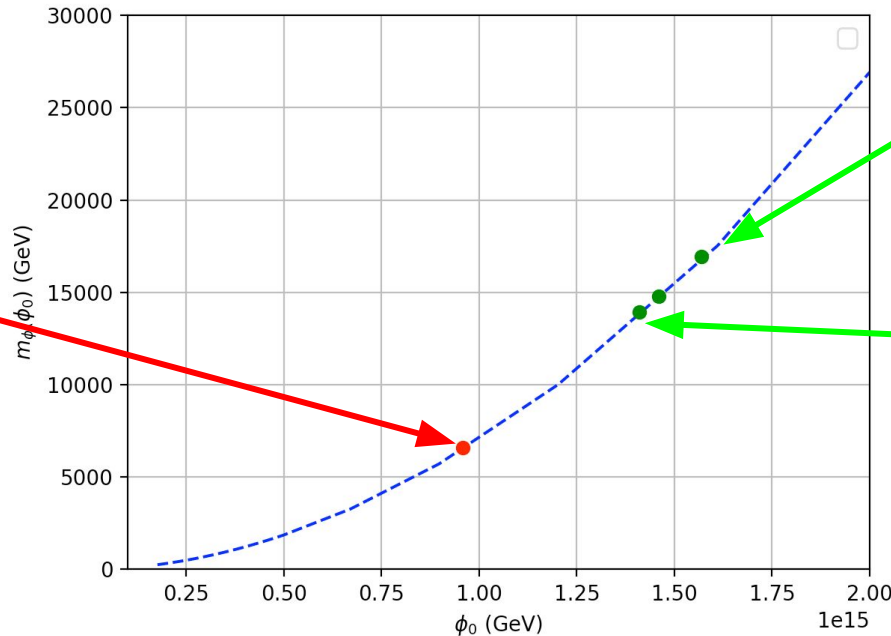hierarchy problem
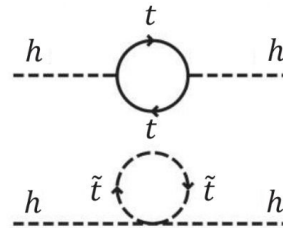
dark matter

gauge coupling unification

g-2

- SUSY can explain disparate phenomena and SM theoretical shortcomings

Global fit: first results

We have identified some points (motivated by [*]) compatible with m(Higgs), $\Omega_{\mathrm{cdm}}h^2$ and (As,ns) for various dark matter annihilation channels

[*] *S. Henrot-Versillé, et al. Phys. Rev. D 89, 055017 (2014), **1309.6958***

$$\phi_0 \quad \overline{1.57\ 10^{15}}\ \text{GeV}$$
$$m_\phi(\phi_0) \quad 16954 \quad \text{GeV}$$

$$\phi_0 \quad \overline{1.41\ 10^{15}}\ \text{GeV}$$
$$m_\phi(\phi_0) \quad 13933 \quad \text{GeV}$$

$$\phi_0 \quad 9.58\ 10^{14}\ \text{GeV}$$
$$m_\phi(\phi_0) \quad 6601.5 \quad \text{GeV}$$

EXCLUDED by LHC searches

=> LHC searches give constraints on inflation

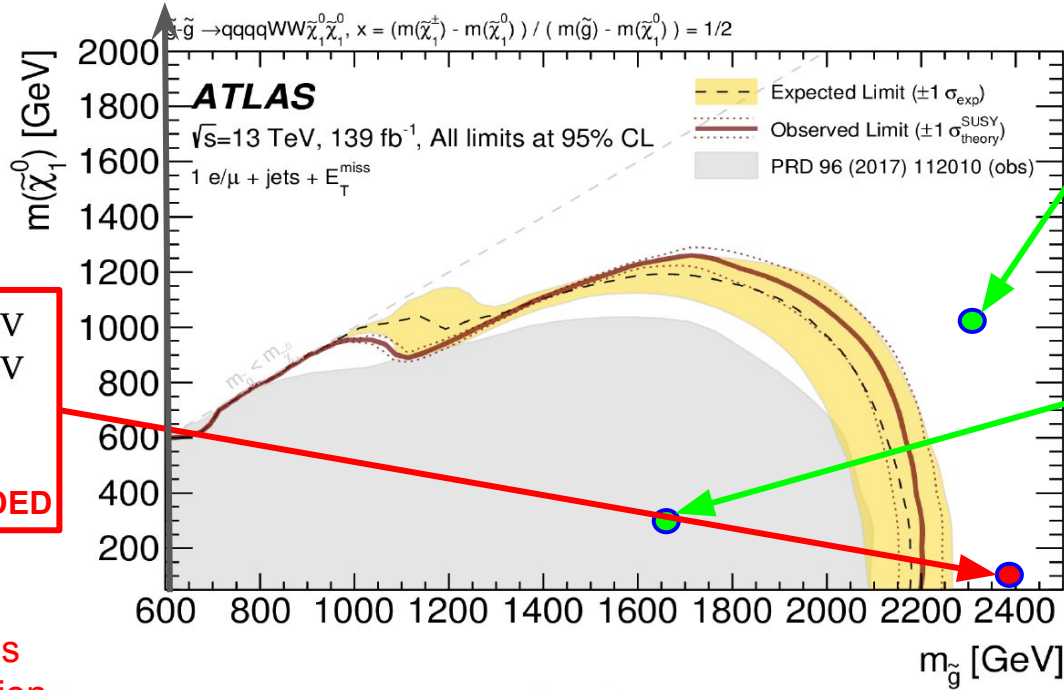=> (As,ns) restrict the MSSM parameter space
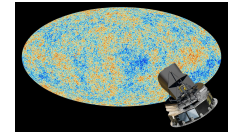
=> First steps toward a full exploration of the parameter space including all constraints

Global fit: first results

We have identified some points (motivated by [*]) for various dark matter annihilation processes

[*] *S. Henrot-Versillé, et al. Phys. Rev. D 89, 055017 (2014), **1309.6958***

$\phi_0 \qquad \overline{1.57\ 10^{15}}\ $ GeV
$m_\phi(\phi_0) \quad 16954 \quad$ GeV

$\phi_0 \qquad 9.58\ 10^{14}\ |$ GeV
$m_\phi(\phi_0) \quad 6601.5 \quad |$ GeV

$\phi_0 \qquad \overline{1.41\ 10^{15}}\ |$ GeV
$m_\phi(\phi_0) \quad 13933 \quad |$ GeV

EXCLUDED

=> here HEP measurements gives constraints on inflation

=> here cosmology restricts the MSSM parameter space

=> First steps toward a full exploration of the parameter space including all constraints

How to get phi*?...

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$$\Delta N_* \overset{\text{SRLO}}{\simeq} \int_{\phi_{\text{end}}}^{\phi_*} \frac{V(\phi)}{V_\phi(\phi)} d\phi$$

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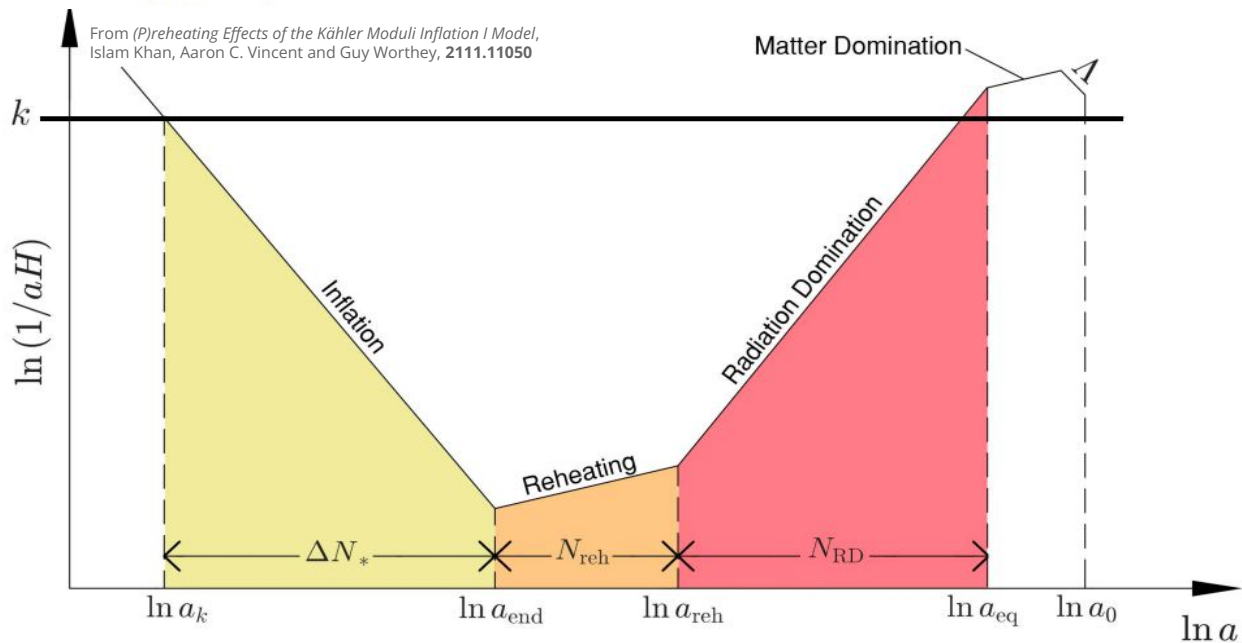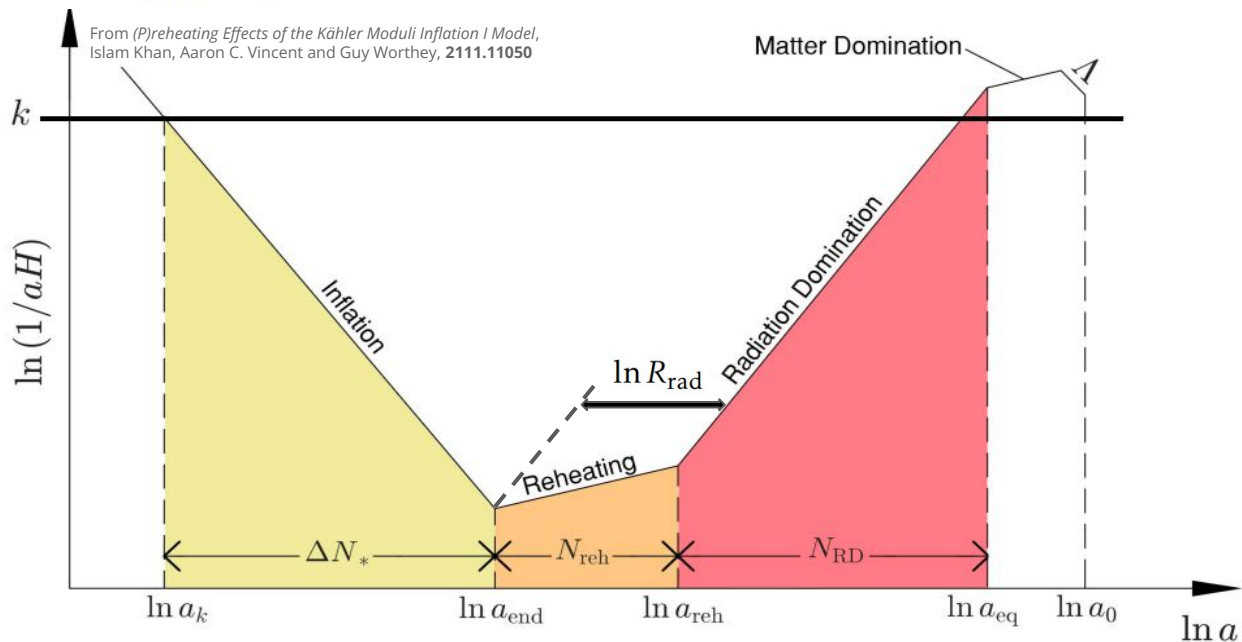
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$$\Delta N_*^{\text{SRLO}} \simeq \ln R_{\text{rad}} - \ln\left(\frac{k_*}{a_0 \tilde{\rho}_\gamma^{1/4}}\right) - \frac{1}{4}\ln\left[\frac{9 V_{\text{end}}}{\varepsilon_{1*}(3 - \varepsilon_{1\text{end}}) V_*}\right] + \frac{1}{4}\ln(8\pi^2 A_{\text{S}})$$

Now, we have all the ingredients to predict the cosmological observables of any potential:

$$\phi \to V(\phi, p), \ \ln R_{\mathrm{rad}} \implies \phi_* \implies \{\varepsilon_{i^*}\} \implies \{A_{\mathrm{S}}, \ n_{\mathrm{S}}, \ n_{\mathrm{S,run}}, \ r, \ n_{\mathrm{T}}, \ n_{\mathrm{T,run}}, \ N_{\mathrm{e-folds}} \ \ldots\}$$

Conversely, given an observation, we can deduce the allowed potentials as done

J. Martin, C. Ringeval, and V. Vennin, Phys. Dark Univ. 5-6, 75 (2014), **1303.3787**

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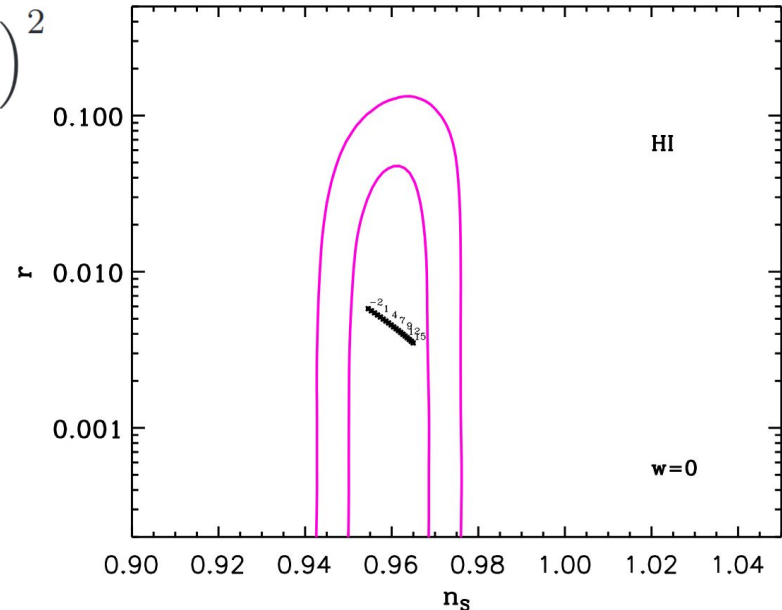
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Examples of potentials

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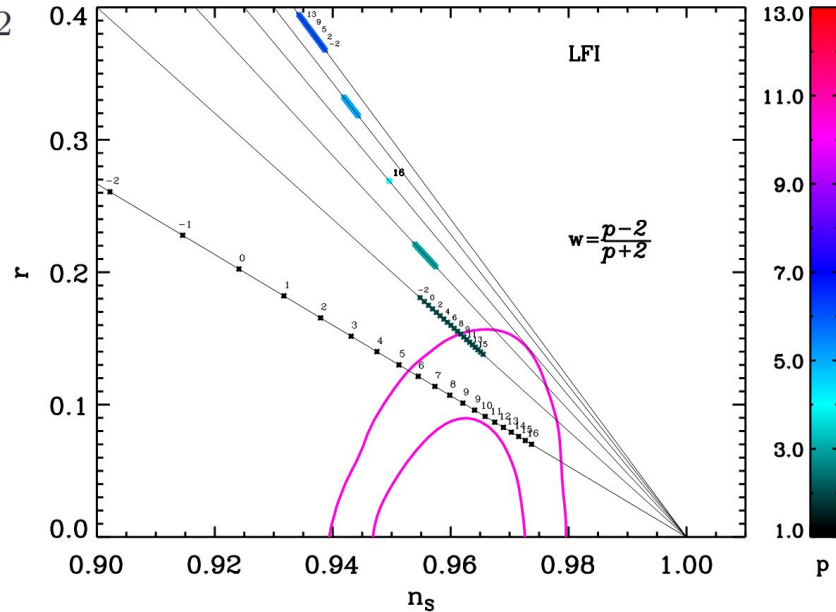
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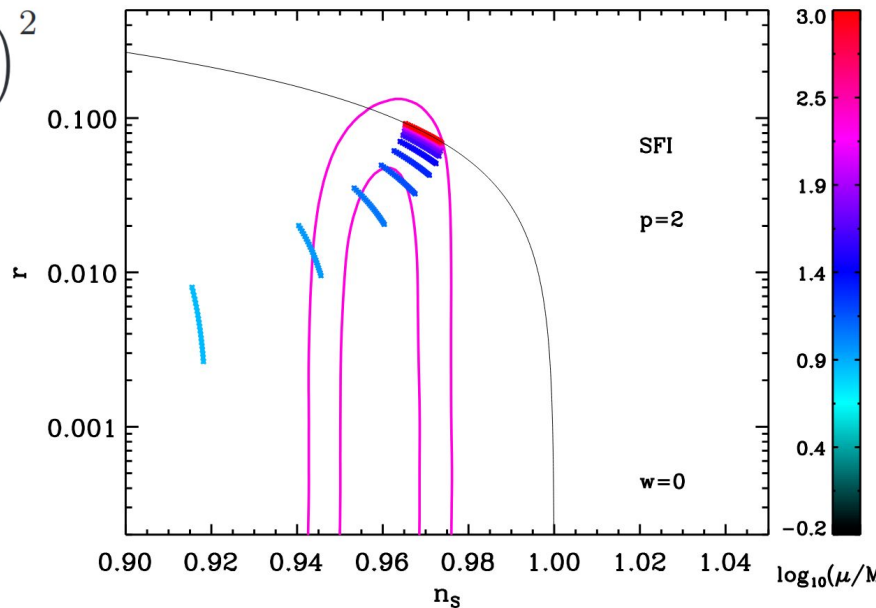
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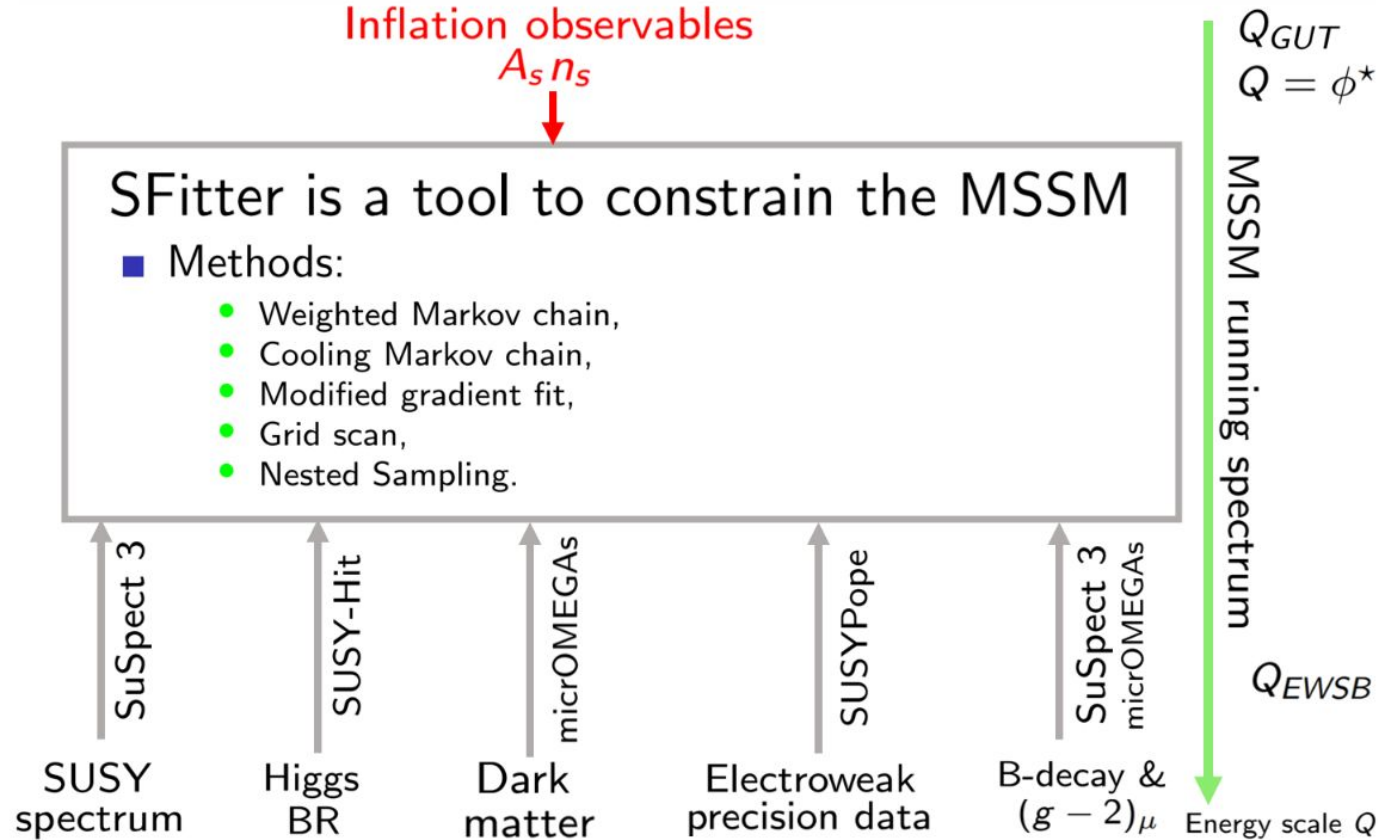
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- Small field inflation: $V(\phi) = M^4 \left[1 - \left(\dfrac{\phi}{\mu}\right)^p\right]$

Join the constraint from CMB to the other observables

Conclusions

is **finely-tuned flat** (which propagates to the parameters)
- **does not attract** all the pre-inflation trajectories

is able to generate a **CMB-like power spectrum**

needs to account for radiative **RGE corrections** at the level **of the potential**

MSSM-inflation

- **ns** improvements => propagated **experimental errors** will fall **below** the **systematic errors**
- **ns_run** improvement => will begin to constrain the **inflation scale of the model**
- **r** detection would **exclude** the model

ns, As and **HEP observables constrain jointly** the same region of the parameter space.

bridge between two worlds, **HEP** and **inflation**

will be more constrained with **next LHC runs**

This work: soon on arXiv

Future:
- More systematic **exploration** of the **parameter space**
- Inclusion of the **reheating duration** computation
- Beyond MSSM : **eNMSSM**, **Multi-field** inflation…