STRING THEORY AND THE DARKNESS

MICHELE CICOLI

BOLOGNA UNIV. & INFN

29/7/2022

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

OUTLINE

- DARK ENERGY
- DARK MATTER
- GWs
- DARK RADIATION

dS from STRING THEORY ?

NO: • DIFFICULTY to get dS with EFT under CONTROL

⇒ dS might be INCOMPATIBLE with QG

⇒ NO dS CONJECTURES

$$V' \geq \frac{c}{M_P} V \quad \text{or} \quad V'' \leq -\frac{\tilde{c}}{M_P^2} V$$ [Ooguri,Palti,Shiu,Vafa]

YES: • NO dS with PARAMETRIC CONTROL BUT can have dS with NUMERICAL CONTROL due to SMALL parameters [MC,de Alwis,Maharana,Muia,Quevedo]

$$\begin{cases} W_0 \ll 1 & \text{in KKLT} \\ 1/\mathcal{V} \simeq e^{-1/g_s} \ll 1 \text{ for } g_s \lesssim 0.1 & \text{in LVS} \end{cases}$$

- SEVERAL UPLIFTING MECHANISMS:
  $\overline{D3}$, D-TERMS, T-BRANES, α' CORR., $F^u \neq 0$, NON-PERT. EFFECTS at SING.
- PROGRESS in CLASSIFYING α' AND g_s CORR. using 10D SYMMETRIES
  [Burgess,MC,Ciupke,Krippendorf,Quevedo]
- GLOBAL CY MODELS with SM on D3's and dS from T-BRANES
  [MC,Garcia Etxebarria,Quevedo,Schachner,Shukla,Valandro]

QUINTESSENCE from STRING THEORY?

- TAKE NO dS POINT of VIEW

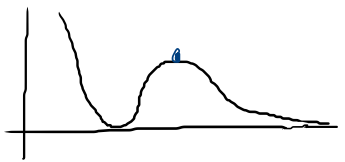
  $\Rightarrow$ IMPLICATIONS for QUINTESSENCE?

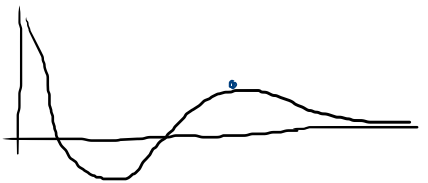
- MODELS that would be RULED OUT:

1) SAXION QUINT. slow-roll down a SHALLOW POTENTIAL
2) AXION QUINT. with $f_a \gtrsim M_P$ (due to WGC)

- MODELS that would be OK:

1) SAXION HILLTOP for MINKOWSKI/AdS VACUUM





2) AXION HILLTOP for MINK. VACUUM

3) SAXION RUNAWAY

NO QUINTESSENCE at BOUNDARY of MODULI SPACE

- SIMILAR to dS. FOCUS on TYPE IIB (VALID also for IIA and HETEROTIC)

VOLUME MODE

[MC,Cunillera,Padilla,Pedro]

$K = -3 \ln(T+\bar{T}) \qquad T = \tau + i\vartheta$

$\Rightarrow \mathcal{L}_{kin} \supset \frac{3}{4\tau^2}\partial_\mu \tau \partial^\mu \tau = \frac{1}{2}\partial_\mu \varphi \partial^\mu \varphi$ for $\tau = e^{\sqrt{\frac{2}{3}}\varphi}$

SCALAR POTENTIAL for $\partial_T W = 0$ and $\tau \to \infty$ (α' EXPANSION under CONTROL)

NO-SCALE CANCELLATION at TREE-LEVEL

$V = e^K \left(|D_U W|^2 + |D_S W|^2 \right) = \frac{V_0}{\tau^3} \geq 0$

QUANTUM CORRECTIONS give a LARGER τ-SUPPRESSION for $\tau \gg 1$

$\Rightarrow V = \frac{V_0}{\tau^{3+\mu}} = V_0 e^{-\lambda\varphi} \qquad \lambda = \sqrt{6}(1+\mu) \qquad \mu \geq 0$

$\Rightarrow \varepsilon = \frac{1}{2}\left(\frac{V_\varphi}{V}\right)^2 = \frac{\lambda^2}{2} = 3(1+\mu)^2 > 1$ NO ACCELERATION

SIMILAR RESULT for DILATON $\to \infty$ (g_s EXPANSION under CONTROL)

MULTIFIELD QUINTESSENCE ?

QUINT. could still WORK due to KINETIC COUPLING with AXION

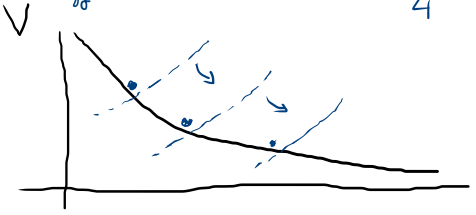
⇒ NON-GEODESIC MOTION in CURVED FIELD SPACE gives ACCELERATION

IDEA: $\frac{3}{4\tau^2}\partial_\mu\vartheta\partial^\mu\vartheta = \frac{3}{4}e^{-2\sqrt{\frac{2}{3}}\varphi}\dot{\vartheta}^2$

gives EFFECTIVE TIME-DEPENDENT CONTRIBUTION to $V(\varphi)$ if $\dot{\vartheta}\neq 0$

[MC,Dibitetto,Pedro]

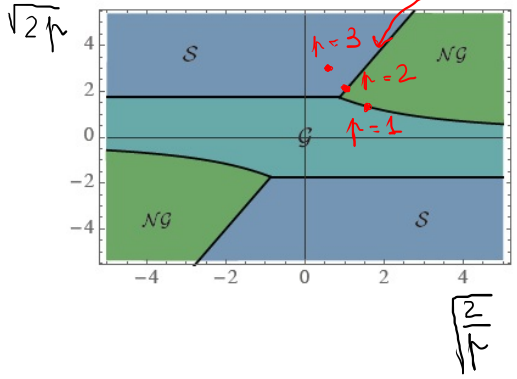
⇒ $V_{\text{eff}}(\varphi) = V_0 e^{-\lambda\varphi} - \frac{3}{4}e^{-2\sqrt{\frac{2}{3}}\varphi}\dot{\vartheta}^2$

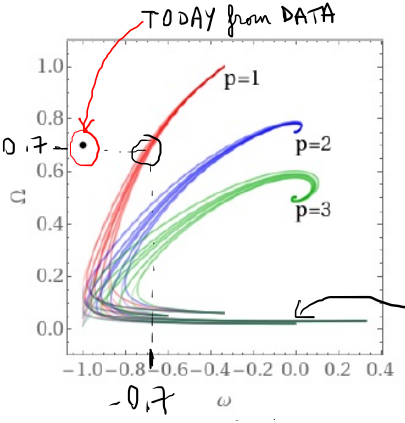


$\dot{\vartheta}^2 \propto \frac{1}{a^6}$ for $m_\vartheta \simeq 0$

HOWEVER it does NOT WORK in STRINGS: $K = -p\ln(X+\bar{X}) \Rightarrow V = V_0 e^{-\sqrt{2p}\varphi} - \frac{p}{4}e^{-2\sqrt{\frac{2}{p}}}\dot{\vartheta}^2$

FIXED POINTS of DYNAMICAL SYSTEM





[Brinkmann,MC,Dibitetto,Pedro]

MATTER DOMINATION INIT. COND.

CHALLENGES for QUINTESSENCE

$\Rightarrow$ QUINTESSENCE, as dS, has to be in BULK of MODULI SPACE

$\Rightarrow$ SAME CONTROL ISSUES of dS + EXTRA CHALLENGES:

1) ULTRA-LIGHT QUINTESSENCE FIELD

$$m_\varphi \lesssim H_0 \sim 10^{-60} M_P \quad \text{from} \quad \eta \sim \frac{V_{\varphi\varphi}}{V} \lesssim 1$$

RADIATIVELY STABLE?
FIFTH-FORCES?

2) STRING SCALE ABOVE 1 TeV

$$M_s \simeq \frac{M_P}{\sqrt{\mathcal{V}}} \gtrsim 1\ \text{TeV} \quad \Leftrightarrow \quad \mathcal{V} \lesssim 10^{30}$$

3) HEAVY VOLUME MODE

$$m_\mathcal{V} \gtrsim 1\ \text{meV} \simeq 10^{-30} M_P \quad \text{from FIFTH-FORCES} \quad \Rightarrow \quad m_\mathcal{V} \gg m_\varphi$$

$\Rightarrow$ LEADING ORDER: $\mathcal{V}$ is LIFTED while φ is FLAT

$$V = V_{lead}(\mathcal{V}) + V_{sub}(\varphi, \mathcal{V})$$

$$\frac{V_{sub}}{V_{lead}} \sim \left(\frac{m_\varphi}{m_\mathcal{V}}\right)^2 \lesssim 10^{-60}$$ CANNOT be OBTAINED with PERT. CORR.

SINCE $$\frac{V_{\alpha'^4 g_s^2}}{V_{\alpha'^3}} \simeq \frac{1}{\mathcal{V}^{1/3}} \lesssim 10^{-60} \quad \Leftrightarrow \quad \mathcal{V} \gtrsim 10^{180} \quad \Rightarrow \quad M_s \ll 1\ \text{TeV}$$

LIGHT VOLUME PROBLEM

$\Rightarrow$ for SAXION QUINT with $m_\varphi \sim 10^{-32}$ eV

$\Rightarrow$ $m_\nu \ll 1$ meV + RADIATIVE INSTABILITY

WAY-OUT: Consider AXION QUINTESSENCE where

$$V_{sub} \sim e^{-aT} \sim e^{-a\nu^{2/3}} \sim V_{non-pert}$$

$$\Rightarrow \frac{V_{lead}}{V_{sub}} \sim \frac{e^{a\nu^{2/3}}}{\nu^3} \gtrsim 10^{60} \quad \text{for} \quad \nu \lesssim 10^{30} \quad \text{and} \quad M_s \gtrsim 1 \text{ TeV}$$

+ AXIONIC PERTURBATIVE SHIFT SYMM. gives RADIATIVE STABILITY

BUT QUINTESSENCE has another CHALLENGE:

KALLOSH-LINDE PROBLEM for QUINTESSENCE

KL PROBLEM for QUINTESSENCE

$V(\nu)$ FIXES ν which couples to INFLATON σ and QUINT. FIELD φ

$$\Rightarrow \quad V_{tot} = V(\nu) + \underbrace{V(\sigma,\nu)}_{\gtrsim H_{inf}^2} + \underbrace{V(\varphi,\nu)}_{\gtrsim H_0^2}$$

$$H_{inf}^2 \gg H_0^2$$

NO KL PROBLEM for INFLATON: $\quad V(\sigma,\nu) \lesssim V(\nu) \quad \Leftrightarrow \quad H_{inf} \lesssim m_{3/2}$

[Kallosh, Linde]

$$\Rightarrow \quad V(\varphi,\nu) \ll V(\sigma,\nu) \lesssim V(\nu)$$

$\downarrow$ at the END of INFLATION

0

$$\Rightarrow \quad \boxed{V(\varphi,\nu) \ll V(\nu)}$$

MORE PRECISELY: $\quad V(\varphi,\nu) \sim \left(\frac{H_0}{H_{inf}}\right)^2 V(\sigma,\nu) \lesssim \left(\frac{H_0}{H_{inf}}\right)^2 V(\nu)$

$H_0 \sim 10^{-60} M_p$ $\qquad 10^{-42} M_p \lesssim H_{inf} \lesssim 10^{-4} M_p$

↑ from $T_{rh} \sim \sqrt{H_{inf} M_p} \gtrsim 1\,MeV$ for BBN $\qquad$ ↖ from $r \lesssim 0.01$

$$\Rightarrow \quad 10^{-108} \lesssim \frac{V(\varphi,\nu)}{V(\nu)} \lesssim 10^{-36}$$

QUINTESSENCE MODEL BUILDING

$V(\nu)$ has a SUSY MINK. VACUUM and φ is a FLAT AXION

$V(\varphi,\nu)$ generated by TINY NON-PERT EFFECTS

- RIGHT HIERARCHY: $V(\varphi,\nu) \ll V(\nu)$
  $\Rightarrow$ NO KL PROBLEM + NO ν DESTABILISATION by QUINT
- NO RADIATIVE INSTABILITY due to PERT. SHIFT SYMM
- NO 5-th FORCE PROBLEM

HOWEVER $V(\varphi,\nu) = \Lambda(\nu)\left(1 - \cos\left(\frac{\varphi}{f}\right)\right)$ gives ACCELERATION

ONLY for $f > M_P$

↖ NEVER OBTAINED in EFT + FORBIDDEN by WGC

$\Rightarrow$ FOCUS on
- ALIGNMENT ← requires TUNING + CONTROL ISSUES
- AXION HILLTOP ← requires TUNING of INIT. COND. + LOW H_{inf} in TENSION with NO dS CONJ.

AXION HILLTOP

FOCUS on AXIONS in LVS

$$\mathcal{V} = \tau_B^{3/2} - \tau_S^{3/2} \qquad T_B = \tau_B + i\theta_B \qquad T_S = \tau_S + i\theta_S$$

$$K = -2\ln\left(\mathcal{V} + \frac{\xi}{2 g_s^{3/2}}\right) \qquad W = W_0 + A_S e^{-a_S T_S} + A_B e^{-a_B T_B}$$

LEADING ORDER V DEPENDS on $\mathcal{V}$, τ_S and θ_S

$$V \simeq \frac{C_{up}}{\mathcal{V}^{8/3}} + \frac{C_1}{\mathcal{V}} \sqrt{\tau_S}\, e^{-2a_S\tau_S} + \frac{C_2}{\mathcal{V}^2} \cos(a_S\theta_S)\, e^{-a_S\tau_S} + \frac{C_3}{\mathcal{V}^3}$$

T-BRANE UPLIFTING ($F^{matter} \neq 0$ due to $D \neq 0$)

GENERIC in FLUX COMPACTIFICATIONS

- D7's from TADPOLE CANC. with $\mathcal{F}_2 \neq 0$ due to FREED-WITTEN ANOMALY CANC.

$$\Rightarrow \xi_{FI} \sim \frac{1}{\mathcal{V}} \int_D J \wedge \mathcal{F}_2 \sim \frac{\lambda}{\mathcal{V}^{2/3}} \Rightarrow V_D \sim g^2 \left(|\chi|^2 - \xi_{FI}\right)^2 = 0 \Leftrightarrow |\chi|^2 = \xi_{FI}$$

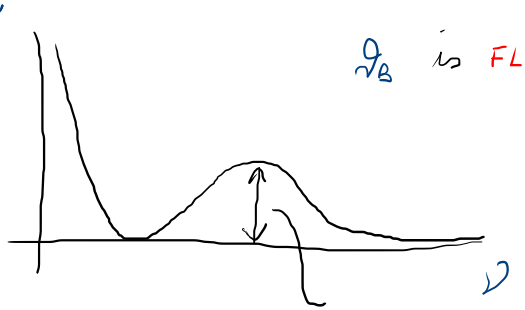
- $H_3, F_3 \Rightarrow V_{up} \sim m_{3/2}^2 |\chi|^2 \sim \frac{W_0^2}{\mathcal{V}^2} \xi_{FI} \sim \frac{C_{up}}{\mathcal{V}^{8/3}}$

[MC,Quevedo,Valandro]

AXION HILLTOP

- LEADING ORDER STABILISATION:

SUSY MINK at $\vartheta_S = 0$, $\tau_S \sim \frac{1}{g_s}$, $\mathcal{V} \sim e^{a_S \tau_S} \gg 1$ $\quad g_s \lesssim 0.1$



$$V_{lead}(\mathcal{V}_{max}) \sim \frac{W_0^2}{\mathcal{V}^3} \sim m_{\mathcal{V}}^2$$

- SUBLEADING ORDER

$$V_{sub}(\vartheta_B, \mathcal{V}) \sim \Lambda(\mathcal{V}) \left(1 - \cos(a_B \vartheta_B)\right) \ll V_{lead} \quad \text{since } \Lambda(\mathcal{V}) \sim W_0 e^{-a_B \tau_B} \ll 1$$

KINETIC TERMS

$$\mathcal{L}_{kin} = \frac{3}{4\tau_B^2} \partial_\mu \vartheta_B \partial^\mu \vartheta_B = \frac{1}{2} \partial_\mu \varphi \partial^\mu \varphi \qquad \varphi = \sqrt{\frac{3}{2}} \frac{\vartheta_B}{\tau_B} \Rightarrow a_B \vartheta_B = \sqrt{\frac{2}{3}} a_B \tau_B \varphi = \frac{\varphi}{f}$$

$$\Leftrightarrow \quad f = \sqrt{\frac{3}{2}} \frac{M_P}{a_B \tau_B} \Rightarrow V_{sub} = C \underbrace{e^{-\sqrt{\frac{3}{2}} \frac{M_P}{f}}}_{10^{-120} \text{ for } \frac{M_P}{f} \sim 300} M_P^4 \left(1 - \cos\left(\frac{\varphi}{f}\right)\right)$$

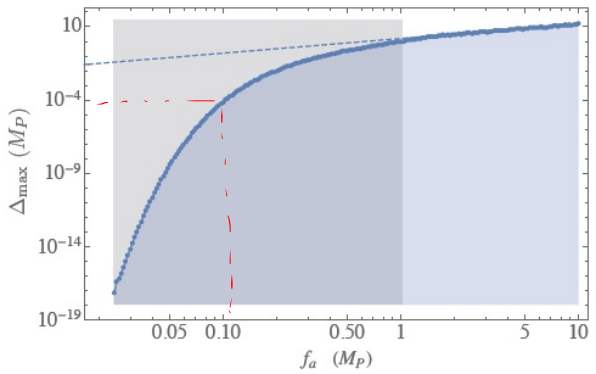
$\Rightarrow m_{\mathcal{V}} \sim 10^{13}$ GeV OK!

$\Leftrightarrow \mathcal{V} \sim \tau_B^{3/2} \sim 10^3$ NATURAL!

$\Rightarrow$ EFT under CONTROL!

HILLTOP and INITIAL CONDITIONS

HOW CLOSE should φ be to the MAXIMUM to get ACCELERATION with $\omega_\varphi \simeq -1$ and $\Omega_\varphi \simeq 0.7$?



EFT under CONTROL?

$f_a = 0.1\ M_P \Rightarrow \Delta_{max} \lesssim 10^{-4} M_P$

$f_a = 0.02\ M_P \Rightarrow \Delta_{max} \lesssim 10^{-18} M_P$

EFT under CONTROL

$f_a \sim \frac{M_P}{V^{2/3}} \lesssim 10^{-2} M_P$ for $V \gtrsim 10^3$

as α'-EXPANSION $\frac{\alpha'}{Vol^{1/3}} = \frac{1}{V^{1/3}} \lesssim 0.1$

QUANTUM DIFFUSION during INFLATION causes FLUCTUATIONS $\Delta\varphi \sim H_{inf}$

$\Rightarrow$ need to REQUIRE $H_{inf} \lesssim \Delta_{max}$

$\Rightarrow$ for $f_a = 0.02\ M_P$

$H_{inf} \lesssim 10^{-18} M_P \sim 1\ GeV$ VERY STRONG BOUND!

CONCLUSIONS on DARK ENERGY

BUT $\left(\frac{\delta\rho}{\rho}\right)^2 \sim \frac{H_{inf}^2}{\epsilon} \sim 10^{-10} \Rightarrow \epsilon \sim 10^{+10} H_{inf}^2 \lesssim 10^{-26}$ for $f = 0.02\, M_p$

$\Rightarrow$ SUPER SHALLOW V in TENSION with NO dS CONJ.

NO dS CONJ. + THEORETICAL and PHENO CONSIDERATIONS

$\Rightarrow$ QUINTESSENCE is in the SWAMPLAND

OR QUINTESSENCE is as CHALLENGING as dS + EXTRA CONSTRAINTS
(FIFTH FORCES, KL PROBLEM, RADIATIVE STABILITY)

BUT OBSERVATIONS TODAY REQUIRE ACCELERATED EXPANSION

$\Rightarrow$ WORK HARD and SEARCH for dS in BULK of MODULI SPACE
with NUMERICAL, even if NOT PARAMETRIC, CONTROL

- KNOWN EXAMPLES in PHYSICS:
  - QED $\alpha = 1/137$
  - COSMOLOGICAL PERT. THEORY $\delta\rho/\rho \sim 10^{-5}$

DARK MATTER from STRING THEORY?

- INTENSIVE EXPERIMENTAL SEARCHES for DM

  ⇒ what is the MOST NATURAL DM CANDIDATE from STRING THEORY?

SEVERAL CANDIDATES:

- THERMAL WIMP
- NON-THERMAL WIMP
- QCD AXION (CLOSED or OPEN STRING)
- ULTRALIGHT ALP (FUZZY DM)
- PBHs
- HIDDEN SECTOR PHYSICS (GLUEBALLS, U(1)s, BARYONS, ...)

CONSTRAIN THEM USING UV CORRELATIONS WITH INFLATION, DARK RADIATION, GWs, SUSY, REHEATING, ...

DM and HIGH SCALE INFLATION

- FOCUS on FIBRE INFLATION [MC,Burgess,Quevedo]

$$H_{inf} \simeq \frac{M_P}{\mathcal{V}^{2/3}} \simeq 10^{13}\ GeV \quad \Leftrightarrow \quad r \simeq 0.007$$

$\mathcal{V} \simeq 10^3$

1) SM on D7: $\mathcal{V} = \sqrt{\tau_f}\,\tau_b - \tau_s^{3/2}$ $\quad T_f = \tau_f + i c_f$ $\quad T_b = \tau_b + i c_b$

- $M_{SOFT} \simeq m_{3/2} \simeq \frac{M_P}{\mathcal{V}} \simeq 10^{15}\ GeV \Rightarrow$ WIMP DM ✗
- QCD AXION in c_f: $f_{QCD} \simeq \frac{M_P}{\mathcal{V}^{2/3}} \simeq 10^{16}\ GeV > H_{inf}$

$\Rightarrow$ ISOCURVATURE BOUND

$$H_{inf} \lesssim 10^{-5} \left(\frac{\Omega_{DM}}{\Omega_{QCD}}\right) \vartheta_{in}\, f_{QCD}$$

$$\frac{\Omega_{QCD}}{\Omega_{DM}} \simeq \left(\frac{f_{QCD}}{10^{12}\ GeV}\right)^{7/6} \vartheta_{in}^2 \simeq 1 \quad \text{if} \quad \vartheta_{in} \simeq 0.01$$

$\Rightarrow H_{inf} \lesssim 10^{-7} f_{QCD} \simeq 10^9\ GeV$ TOO LOW!

$\Rightarrow$ QCD AXION DM ✗

FUZZY DM

- ALP as CDM: $f_{ALP} \simeq \frac{M_P}{V^{2/3}} \simeq 10^{16}\ GeV > H_{inf}$ ⇒ ISOCURVATURE BOUND

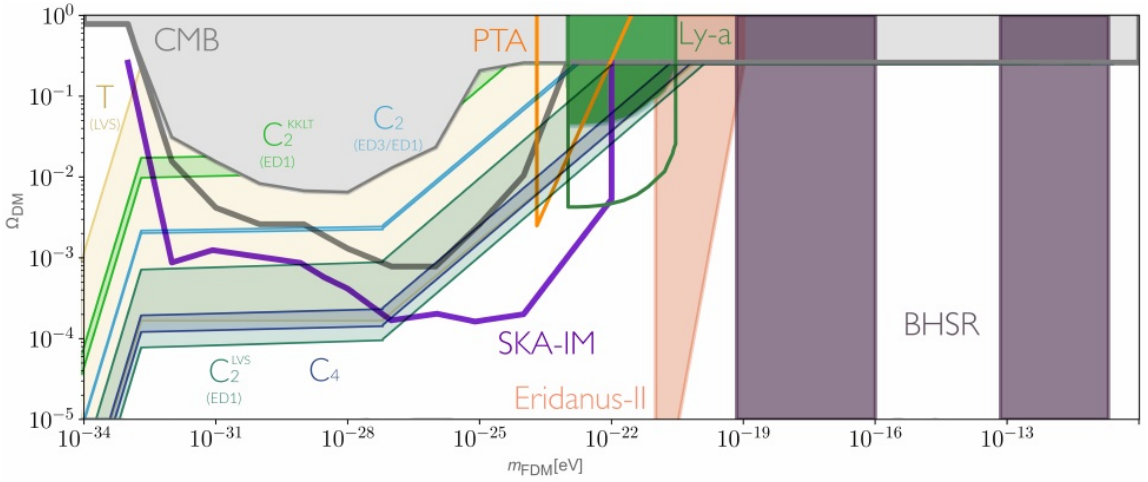
$$\frac{\Omega_{ALP}}{\Omega_{DM}} \simeq \sqrt{\frac{m_{ALP}}{10^{-22}\,eV}} \left(\frac{f_{ALP}}{10^{17}\,GeV}\right)^2 \vartheta_i^2 \simeq 1 \quad \text{for } \vartheta_i \simeq 1$$

$$\Rightarrow \quad H_{inf} \lesssim 10^{-5} f_{ALP} \simeq 10^{11}\ GeV \quad \text{STILL TOO LOW!}$$

CAN HAVE $H_{inf} \lesssim 10^{13}\ GeV$ for $\Omega_{ALP} \simeq 0.01\,\Omega_{DM}$ ⇒ FUZZY DM ✗

HOWEVER HARD to get $\Omega_{ALP} \simeq \Omega_{DM}$ since NEED to VIOLATE WGC

$$\mathcal{L} = \frac{1}{2} f_{ALP}^2 (\partial\vartheta)^2 - A e^{-S} \cos(\vartheta) M_P^4 \quad \Rightarrow \quad S \cdot f_{ALP} = f_{ALP} \ln\left(\frac{A M_P^4}{m_{ALP}^2 f_{ALP}^2}\right) \simeq O(5\text{-}10)\, M_P$$



[MC,Guidetti,Righi,Westphal]

PBH DM

- DM can be PBH if DENSITY PERT. are ENHANCED at LARGE k SCALES VIA ULTRA SLOW-ROLL due to a NEAR INFLECTION POINT

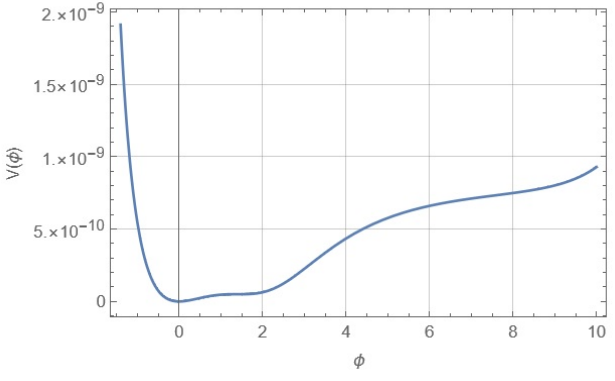
$$P_{CMB} \simeq \frac{H^2}{\varepsilon} \sim 10^{-9} \quad \text{while} \quad P_{PBH} \simeq \frac{H^2}{\varepsilon} \sim 10^{-2} \quad \text{for } \varepsilon \ll 1 \text{ in USR}$$

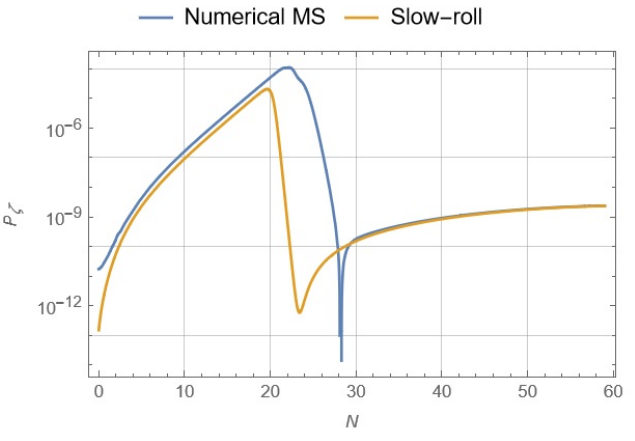
SINCE

$$\sqrt{\frac{P_{PBH}}{2\pi}}\, e^{-\frac{1}{2P_{PBH}}} \simeq 10^{-8} \sqrt{\frac{M_{PBH}}{M_\odot}}\, f_{PBH}(M_{PBH})$$ [MC,Diaz,Pedro]

$$\Rightarrow f_{PBH} \simeq 1 \text{ at } M_{PBH} \simeq 10^{-12} M_\odot \text{ for } P_{PBH} \simeq 10^{-2} \Rightarrow \text{PBH DM} \checkmark$$

$$\Delta N^{PBH}_{CMB} \simeq 20 - \frac{1}{2} \ln\left(\frac{M_{PBH}}{M_\odot}\right) \simeq 32 \text{ for } M_{PBH} \simeq 10^{-12} M_\odot$$

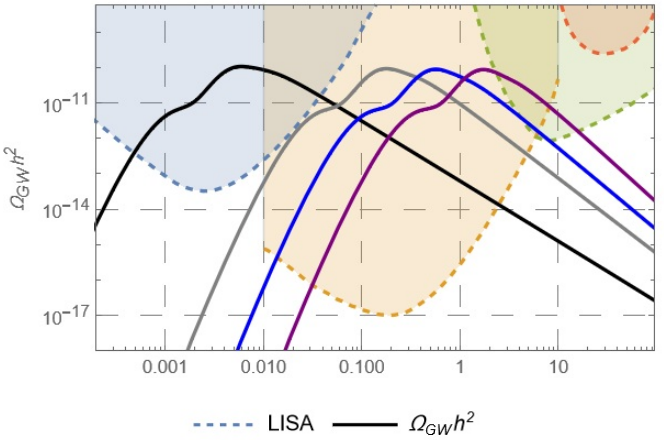




PBHs and GWs

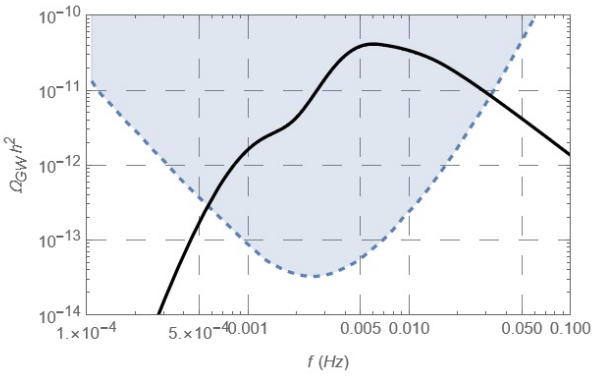
- PBHs SOURCE SECONDARY GWs [MC,Pedro,Pedron]

$$\Omega_{GW}(k) \simeq 10^{-6}\, P_\zeta^2(k)$$



$\rightarrow f_{PBH} \simeq 1$

$\rightarrow f_{PBH} \simeq 10^{-3}$



$\rightarrow M_{PBH} \simeq 10^{-12} M_\odot$ and $f_{PBH} \simeq 10^{-3}$

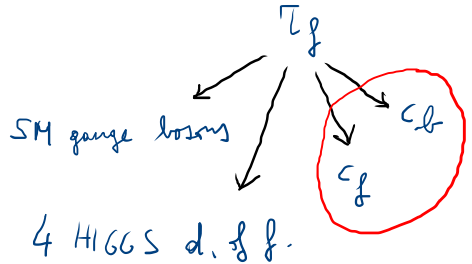
$\Rightarrow$ DETECTABLE GWs even with NO PBH DM

↓

JUST due to USR

REHEATING and DR

- REHEATING from INFLATON PERTURBATIVE DECAY [MC,Piovano] [MC,Licheri,Piantadosi,Quevedo,Shukla] in progress



$\rightarrow \Delta N_{eff} \neq 0$ where $\Delta N_{eff} \lesssim 0.3$ at 95% CL from PLANCK2018

- ENHANCED HIGGS COUPLING from [MC,Hebecker,Jaeckel,Wittner]

$$m_h^2 h^2 = m_{3/2}^2 \left[c_{tree} - c_{loop} \ln\left(\frac{M_{KK}}{m_{3/2}}\right) \right] h^2$$

where $$\ln\left(\frac{M_{KK}}{m_{3/2}}\right) = c \ln V \simeq c \ln \langle V \rangle + c \frac{\hat{V}}{\langle V \rangle}$$

$$\frac{\hat{V}}{\langle V \rangle} = O(1)\, \varphi_V + O\left(\frac{1}{\langle V \rangle^{1/3}}\right) \varphi_f$$ from [MC,Tasinato,Zavala,Burgess,Quevedo]

$$\Rightarrow c_{loop} \frac{m_{3/2}^2}{V^{1/3}} \varphi_f h^2 \Rightarrow \Gamma_{\tau_f \to h+h} \simeq \frac{c_{loop}^2}{V^3} \gg \Gamma_{\tau_f \to \gamma+\gamma} \simeq \Gamma_{\tau_f \to DR} \simeq \frac{1}{V^5}$$

$$\Rightarrow \Delta N_{eff} \simeq 0 \Rightarrow T_{RH} \simeq \sqrt{\Gamma_{\tau_f \to h+h} M_p} \simeq 10^{12}\ GeV \Rightarrow N_e \simeq 53$$

DM and HIGH SCALE INFLATION

2) SM on D3: $V = \sqrt{\tau_f}\,\tau_f - \tau_s^{3/2}$ ($\tau_s \to 0$)

[MC,Deal,Sinha] in preparation

- $M_{SOFT} \simeq \frac{m_{3/2}^2}{M_P} \simeq \frac{M_P}{V^2} \simeq 10^{11}$ GeV $\Rightarrow$ WIMP DM ✗
- ALPs are c_f and c_b: $f_{ALP} \simeq \frac{M_P}{V^{2/3}} \simeq 10^{16}$ GeV $> H_{inf}$

  $\Rightarrow$ ISOCURVATURE BOUND $\Rightarrow$ FUZZY DM ✗
- QCD AXION from OPEN STRINGS: $\varphi = \rho\, e^{i\vartheta}$

  $V_D \simeq g^2 (\rho^2 - \xi)^2 \Rightarrow \rho = \sqrt{\xi} = \sqrt{\frac{\tau_s}{V}}$ FIXES τ_s

  c_s is EATEN by ANOMALOUS $U(1)$

  ρ FIXED by SUSY CONTRIBUTIONS

  $V = -M_0^2 \rho^2 + A\rho^3 \Rightarrow \rho = f_{QCD} \simeq \frac{m_0^2}{A} \simeq M_{SOFT} \simeq 10^{11}$ GeV

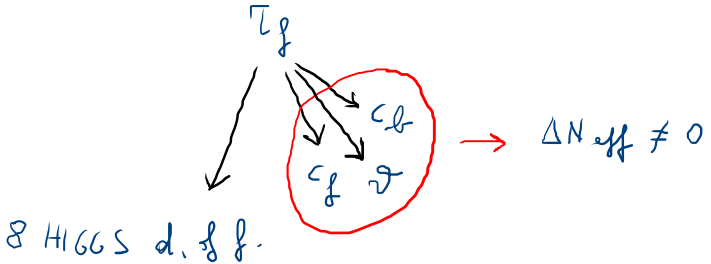
  $\Rightarrow \Omega_{QCD} \simeq \Omega_{DM}$ for $\vartheta_{in} \simeq 1$ NATURAL

  $\Rightarrow f_{QCD} < H_{inf} \simeq 10^{13}$ GeV NO ISOCURVATURE BOUNDS

  $\Rightarrow$ QCD AXION DM ✓

REHEATING and DR

- REHEATING from INFLATON PERTURBATIVE DECAY



- HIGGS COUPLING from [MC,Hebecker,Jaeckel,Wittner] is NOT ENHANCED ANYMORE since

$$c_{loop}\frac{M_{SOFT}^2}{v^{11/3}}\varphi_f h^2 \Rightarrow \Gamma_{\tau_f \to h+h} \simeq \frac{c_{loop}^2}{v^7} << \Gamma_{\tau_f \to DR} \simeq \frac{1}{v^5}$$

- NEED GIUDICE-MASIERO COUPLING [MC,Conlon,Quevedo]

$$K \supset Z \frac{H_u H_d}{\tau_f^{\lambda}\,\tau_b^{\mu}} \quad \text{with} \quad \lambda+\mu=1 \quad \text{and} \quad \lambda \neq 1/3 \quad \text{OTHERWISE} \quad \tau_f^{1/3}\tau_b^{2/3} = v^{2/3}$$

$$\Rightarrow \tau_f\text{-HIGGS DECOUPLING [Angus]}$$

$$\Rightarrow \Gamma^{GM.}_{\tau_f \to HIGGS} \simeq \Gamma_{\tau_f \to DR} \quad \text{and} \quad \Delta N_{eff} \simeq \frac{1.5}{Z^2} \Rightarrow Z \gtrsim 3$$

$$\Rightarrow T_{RH} \simeq 10^{10}\,GeV \quad \text{and} \quad N_e \simeq 52$$

CONCLUSIONS on DARK MATTER

- HIGH SCALE INFLATION and SM on D7 :
  1) WIMP DM is OVERPRODUCED and QCD AXION DM OVERPRODUCES ISOCURVATURE MODES
  2) ULTRALIGHT ALP can be at most $\Omega_{ALP} \simeq 0.01\, \Omega_{DM}$
  3) PBH DM OK with DETECTABLE GWs
  4) $\Delta N_{eff} \simeq 0$ due to ENHANCED INFLATON-HIGGS COUPLING
- HIGH SCALE INFLATION and SM on D3 :
  1) WIMP DM is OVERPRODUCED and FUZZY DM can be at most O(1%) of DM
  2) QCD AXION DM from OPEN STRINGS with $f_{QCD} \simeq 10^{11}$ GeV OK
  3) TENSION with DR since NEED GIUDICE-MASIERO TERM with $Z \gtrsim 3$
- FOR LOW SCALE INFLATION: BLOW-UP INFL. with $H_{inf} \simeq 10^{9}$ GeV $\Leftrightarrow$ $n \simeq 10^{-10}$ [Conlon,Quevedo]
  1) SM on D7 : CLOSED STRING QCD AXION DM with $f_{QCD} \simeq 10^{15}$ GeV [MC,Hebecker,Jaeckel,Wittner]
     REHEATING from INFLATON DECAY with $\Delta N_{eff} \simeq 0.13$
  2) SM on D7 and HIDDEN D7 on INFLATON: SUPERHEAVY WIMP DM with $m_{DM} \simeq 10^{10}$ GeV
     DILUTED by DECAY of LIGHTEST MODULUS with $\Delta N_{eff} \simeq 0$ [Allahverdi,Broeckel,MC,Osinski]
  3) SM on D3 : HIGGSINO DM with $m_{DM} \sim O(5)$ TeV from DECAY of LIGHTEST MODULUS
     TENSION with DR since NEED G.M. TERM with $Z \gtrsim 3$ [Allahverdi,MC,Dutta,Sinha]