Ultra-light axions in string cosmology

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Ultra-light axions: a way to test string theory?

- String theory yields a landscape of 4D vacua

  → stringy signatures?

- From both explicit computations for small $h^{1,1}$ and statistics

  → ultra-light axions: generic feature of controlled 4D EFTs from strings
  which is not really motived from QFT point of view

  → ultra-light axion model building is a promising arena to test string theory

  → applications to cosmology:
  i) dark radiation
  ii) fuzzy dark matter
  iii) quintessence
  iv) early dark energy

Axions from closed strings

- Type II strings: U(N) realised on N Dp-branes wrapping internal (p-3) cycles $\Sigma_{p\text{-}3}$
- Closed string spectrum contains p-forms C_p with gauge symmetry

$$C_p \to C_p + d\Lambda_{p-1}$$

- Dp-brane action

$$S_{Dp} = \underbrace{\int_{M^4\times\Sigma_{p-3}} \sqrt{g+F}}_{\text{DBI}} + i \underbrace{\int_{M^4\times\Sigma_{p-3}} \sum_q C_q \wedge e^F}_{\text{Chern–Simons}}$$

- From DBI:

$$S_{\text{DBI}} = \ldots + \int_{M^4} \sqrt{g_{4D}} F_{\mu\nu} F^{\mu\nu} \quad \underbrace{\int_{\Sigma_{p-3}} \sqrt{g_{6D}}}_{g^{-2} = \text{Vol}(\Sigma_{p-3}) \equiv \tau}$$

- From Chern-Simons:

$$S_{\text{CS}} = \ldots + \int_{M^4} F \wedge F \; \underbrace{\int_{\Sigma_{p-3}} C_{p-3}}_{\vartheta}$$

→ Gauge kinetic function: $f = T$ with $T = \tau + i\vartheta$ String modulus

→ Axion shift symmetry: $C_p(x,y) = \vartheta(x)\omega_p(y) \xrightarrow[\vartheta(x)\to\vartheta(x)+c]{} C_p + c\omega_p = C_p + d\Lambda_{p-1}$

locally in the extra dimensions

Axions from closed strings

- Shift symmetry breaking:

  i) Perturbative level: complete breaking by fluxes which break SUSY

  $m_{\vartheta,flux} \simeq m_{3/2} \simeq M_p/V$ e.g. type IIB dilaton and complex structure moduli

  ii) Non-perturbative level: breaking to discrete shift symmetry by stringy instantons

  $m_{\vartheta,inst} \simeq m_\tau \simeq m_{3/2} > 50\,TeV$ if τ fixed non-perturbatively as in KKLT models

  $m_{\vartheta,inst} \simeq m_\tau e^{-c\tau} \ll m_\tau \simeq m_{3/2}$ if τ fixed perturbatively as in LVS models → ultra-light axions

- Too get viable QCD axion need to check $m_{\vartheta,inst} \ll m_{\vartheta,QCD} \simeq \Lambda_{QCD}^2/f_a$

- f_a from kinetic terms determined by Kaehler potential K

$$L_{kin} = \frac{1}{4}\frac{\partial^2 K}{\partial\tau_i\partial\tau_j}\left(\partial_\mu\tau_i\partial^\mu\tau_j + \partial_\mu\vartheta_i\partial^\mu\vartheta_j\right)$$

i) bulk cycles: $K = -3\ln\tau_{bulk}$ $\longrightarrow$ $f_a^2 \simeq M_p^2/\tau_{bulk}^2 \simeq M_{KK}^2$

ii) local cycles (blow-ups): $K = \tau_{loc}^2/V$ $\longrightarrow$ $f_a^2 \simeq M_p^2/V \simeq M_s^2$

→ $U(1)_{PQ}$ always broken in EFT → $f_a > H_{\inf}$

→ $f_a \sim 10^{16}$ GeV unless $M_s \sim 10^{11}$ GeV with $m_{3/2} \sim 1$ TeV for $V \sim 10^{15}$ but CMP problems

Axion statistics

- LVS moduli stabilisation at large $h^{1,1}$: [MC,Ciupke,deAlwis,Muia]

  $Vol \sim e^{\frac{c}{g_s}} \gg 1$ consistent with $Vol \geq (h^{1,1})^7 \simeq O(10^{14})$ for $h^{1,1} \sim O(100)$ [Demirtas et al]

  $\frac{\tau_i}{\tau_j} = \frac{\Pi_i}{\Pi_j}$ $\forall i \neq j = 1, \ldots, h^{1,1}$ due to higher α' effects $\Pi_i = \int_{CY} c_2 \wedge \widehat{D}_i$

- Axion decay constants and masses:

  $$f_{a,i} \simeq \frac{M_p}{\tau_i} \simeq \lambda_i \, M_p \, e^{-2c/(3g_s)} \qquad \text{and} \qquad m_{a_i} \simeq M_p \, e^{-k_i M_p / f_{a,i}}$$

  Axiverse
  [Arvanitaki et al]

- Statistical log-distribution in the string flux landscape for uniform dilaton distribution

  $$df_a = \frac{df_a}{dg_s} dg_s \simeq f_a \, dg_s \simeq f_a dN$$

  [Broeckel,MC,Maharana,Singh,Sinha]

  $$N(f_a) \simeq \ln\left(\frac{f_a}{M_p}\right) \qquad \text{and} \qquad N(m_a) \simeq \ln\left(\frac{m_a}{M_p}\right)$$

- Valid at fixed $h^{1,1}$ when moving in Kaehler moduli space along stable vacua by varying g_s

- Complementary to results of [Mehta et al] at tip of stretched Kaehler cone varying $h^{1,1}$ mean value of f_a decreases when $h^{1,1}$ increases since $\tau_i^{max} \simeq (h^{1,1})^3$

→ upper bound on validity of log-distribution

$$f_a \leq f_{a,max}(h^{1,1}) \simeq \frac{M_p}{(h^{1,1})^3}$$

→ massless axions

$$m_a \leq M_p \, e^{-k\left(h^{1,1}\right)^3} \sim 0$$

Axions from open strings

- SM on D-branes at singularities

  → anomalous U(1)

- Local T-modulus gets a U(1) charge
- Axion ϑ eaten up by U(1) while τ yields a field-dependent FI-term

$$\xi \simeq \frac{\partial K}{\partial \tau_{loc}} M_p^2 \simeq \frac{\tau_{loc}}{V} M_p^2$$

- $M_{U(1)} \sim M_s$ → global $U(1)_{PQ}$ in EFT
- D-term potential for charged open string $\Phi = \rho\, e^{i\zeta}$

$$V_D \simeq g^2(\rho^2 - \xi)^2$$

- D = 0 gives $\langle \rho \rangle = \sqrt{\xi} = f_a^{open}$ → spontaneous breaking of $U(1)_{PQ}$

$$\left(f_a^{open}\right)^2 \simeq \tau_{loc} M_s^2 \ll \left(f_a^{closed}\right)^2 \simeq M_s^2 \qquad for \qquad \tau_{loc} \ll 1$$

→ $U(1)_{PQ}$ spontaneously broken at low energy → $f_a < H_{\inf}$

→ $f_a \sim 10^{11}$ GeV << $M_s \sim 10^{15}$ GeV with $m_{3/2} \sim 10^{11}$ GeV for $\mathcal{V} \sim 10^6$
and $M_{soft} \sim 1$ TeV from sequestered SUSY breaking and no cosmo problems

Stringy axion summary

- 4D string axions:
  i) closed string ϑ ($T = \tau + i\,\vartheta$)
  $f_a \approx 10^{16\text{-}17}$ GeV → "stringy" QCD axion, inflation, quintessence, fuzzy DM, dark radiation…
  ii) open string ζ ($\phi = \rho\, e^{i\zeta}$)
  $f_a \approx 10^{10\text{-}11}$ GeV → "field-theory" QCD axion, astrophysical hints,….

- But axions can be:
  i) removed by orientifold projection
  ii) eaten up by anomalous U(1)s
    a) ζ eaten up for branes on bulk cycles
    b) ϑ eaten up for branes at singularities

- Axion masses:
  i) axions are heavy ($m_\vartheta \approx m_\tau > 50$ TeV) if saxions are fixed non-perturbatively
  ii) axions are light ($m_\vartheta \ll m_\tau$) if saxions are fixed perturbatively

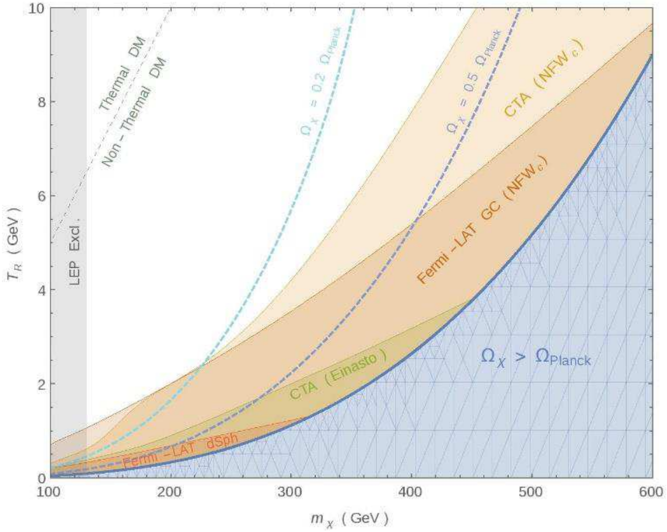
- Generic prediction: ultra-light axions unavoidable in controlled EFT with $\mathcal{V} \gg 1$

- Generic implications:
  i) early matter domination from saxion oscillations → dilution and non-standard DM
  ii) relativistic axions from saxion decay → extra dark radiation $\Delta N_{eff} \neq 0$
  iii) Ultra-light axions suitable for quintessence

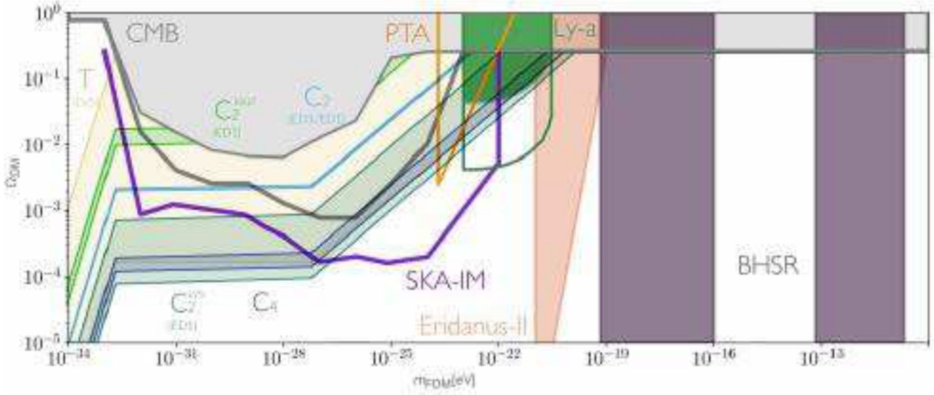
- Need to develop explicit models + statistical analysis + UV correlations among observables

Non-standard dark matter

Non-thermal WIMPs



Fuzzy DM



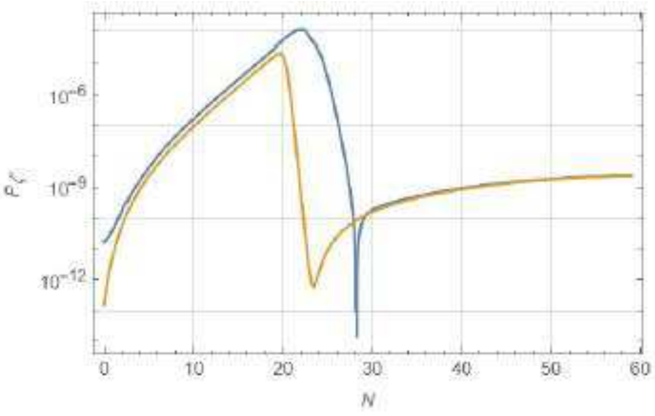
Fuzzy DM from ultra-light ALPs with m $\sim 10^{-22}$ eV

[MC,Guidetti,Righi,Westphal]

Higgsino DM with m~300 GeV or WIMPs with m$\sim 10^{10}$ GeV

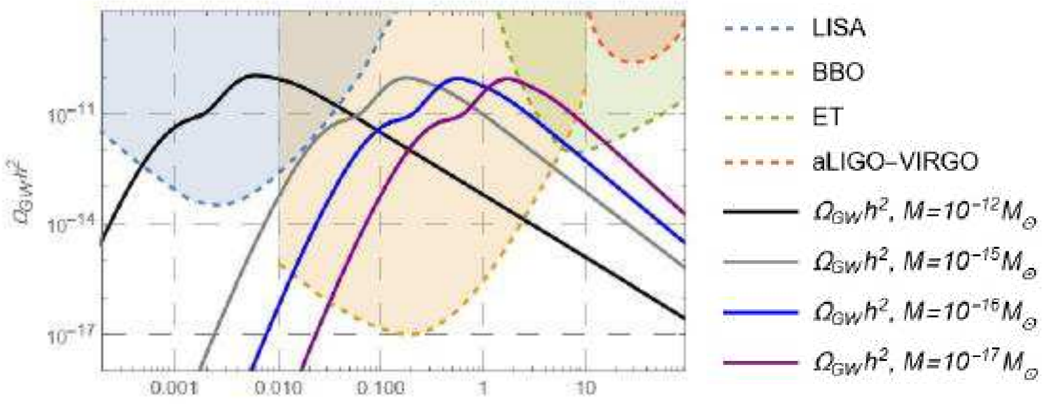
[Aparicio et al] [Allahverdi et al]

PBH DM



Detectable secondary GWs

[MC,Pedro,Pedron]



Constrain DM origin from UV correlations between inflation, DM, DR, reheating, SUSY breaking, GWs….

DM and HIGH SCALE INFLATION

- FOCUS on FIBRE INFLATION $V \simeq V_0\left(1-\frac{4}{3}e^{-\varphi/\sqrt{3}}\right)$ [MC,Burgess,Quevedo]

$$H_{inf} \simeq \frac{M_P}{\mathcal{V}^{5/3}} \underset{\mathcal{V}\sim 10^3}{\simeq} 10^{13}\,\mathrm{GeV} \iff r \simeq 0.007$$

1) SM on D7s: $\mathcal{V} = \sqrt{\tau_f}\,\tau_b - \tau_s^{3/2}$ $\quad T_f = \tau_f + i\vartheta_f \quad T_b = \tau_b + i\vartheta_b$

- $M_{SOFT} \simeq m_{3/2} \simeq \frac{M_P}{\mathcal{V}} \simeq 10^{15}\,\mathrm{GeV}$ ⇒ WIMP DM ✗
- QCD AXION is ϑ_f: $f_{QCD} \simeq \frac{M_P}{\mathcal{V}^{2/3}} \simeq 10^{16}\,\mathrm{GeV} > H_{inf}$

⇒ ISOCURVATURE BOUND

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

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

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

⇒ QCD AXION DM ✗

DM and HIGH SCALE INFLATION

- ALP is ϑ_b : $f_{ALP} \simeq \frac{M_P}{\mathcal{V}^{2/3}} = 10^{16}\,\text{GeV} > H_{inf}$ ⇒ ISOCURVATURE BOUND with

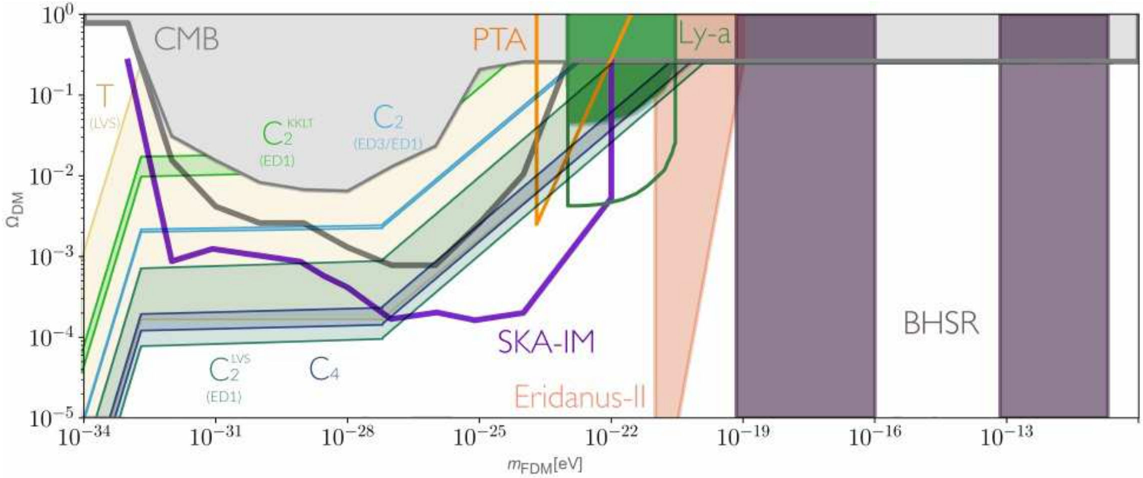
$$\frac{\Omega_{ALP}}{\Omega_{DM}} \simeq \sqrt{\frac{m_{ALP}}{10^{-22}\,\text{eV}}} \left(\frac{f_{ALP}}{10^{17}\,\text{GeV}}\right)^2 \vartheta_{in}^2 \simeq 1 \qquad \text{for } \vartheta_{in} \simeq 1$$

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

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

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

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



[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

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

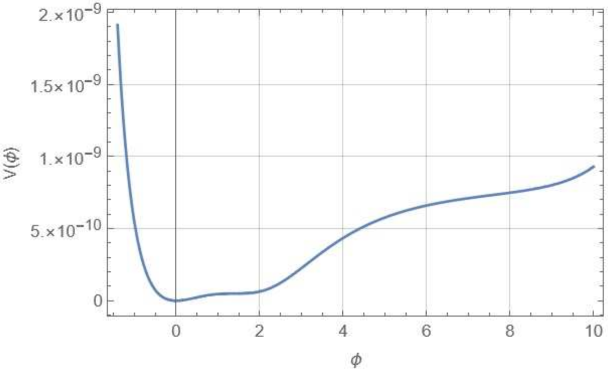
SINCE

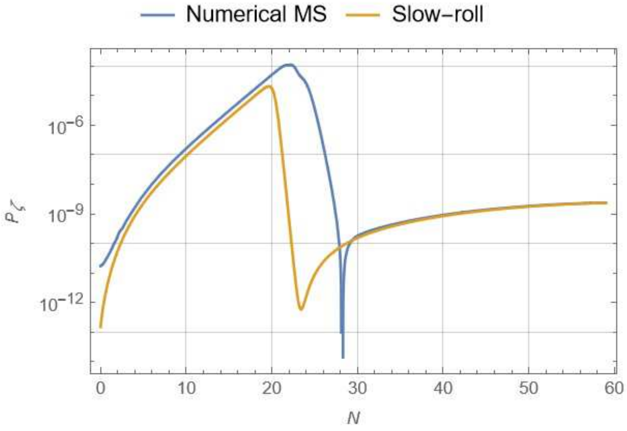
$$\sqrt{\frac{P_{PBH}}{2\pi}}\, e^{-\frac{1}{2P_{PBH}}} \simeq 10^{-8}\sqrt{\frac{M_{PBH}}{M_\odot}}\, f_{PBH}(M_{PBH})$$

[MC,Diaz,Pedro]

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

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

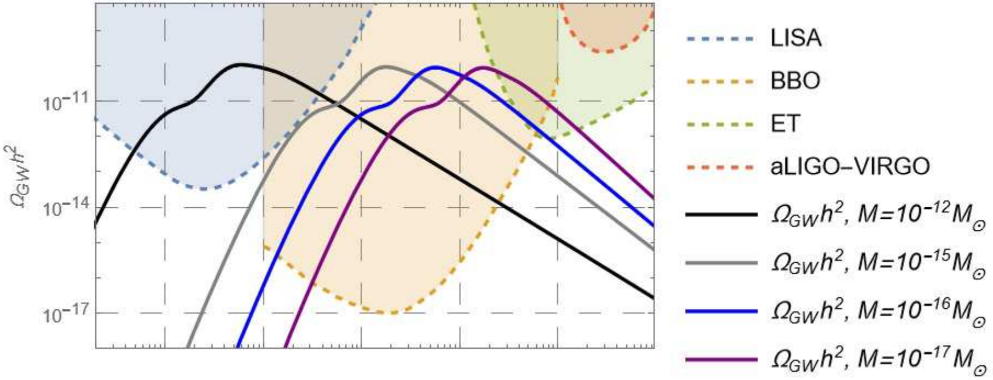




PBHs and GWs

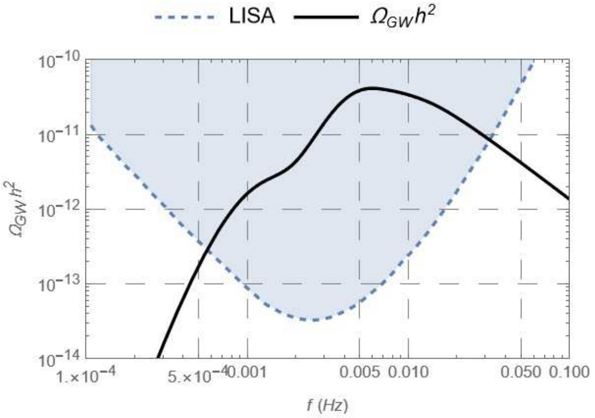
- PBHs SOURCE SECONDARY GWs [MC,Pedro,Pedron]

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



$f_{PBH} \simeq 1$

→ $f_{PBH} \simeq 10^{-3}$



→ $M_{PBH} \simeq 10^{-12} M_{\odot}$ and $f_{PBH} \simeq 10^{-8}$

⇒ DETECTABLE GWs even with NO PBH DM

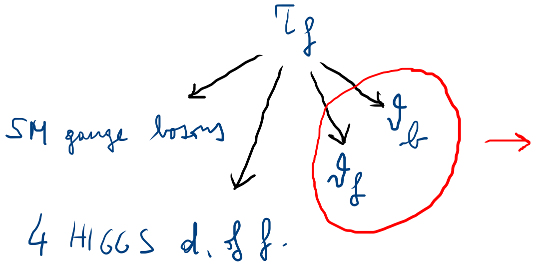
↓

JUST due to USR

REHEATING and DR

- REHEATING from INFLATON PERTURBATIVE DECAY

[MC, Piovano]
[MC,Licheri,Piantadosi,Quevedo,Shukla]
in progress



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

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

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

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

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

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

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

DM and HIGH SCALE INFLATION

2) SM on D3s: $\mathcal{V} = \sqrt{\tau_f}\,\tau_b - \underset{\substack{\downarrow \\ 0}}{\tau_s}^{3/2}$ [MC,Deal,Sinha]

- $M_{SOFT} \simeq \frac{m_{3/2}^2}{M_P} \simeq \frac{M_P}{\mathcal{V}^2} \simeq 10^{12}$ GeV $\Rightarrow$ WIMP DM ✗
- ALPs are ϑ_f and ϑ_b: $f_{ALP} \simeq \frac{M_P}{\mathcal{V}^{2/3}} \simeq 10^{16}$ GeV $> H_{inf}$

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

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

  ϑ_s is EATEN by ANOMALOUS $U(1)$

  ρ FIXED by SUSY CONTRIBUTIONS

  $V = -m_0^2\rho^2 + A\rho^3 \Rightarrow \rho = f_{QCD} \simeq \frac{m_0^2}{A} \simeq M_{SOFT} \simeq 10^{12}$ GeV

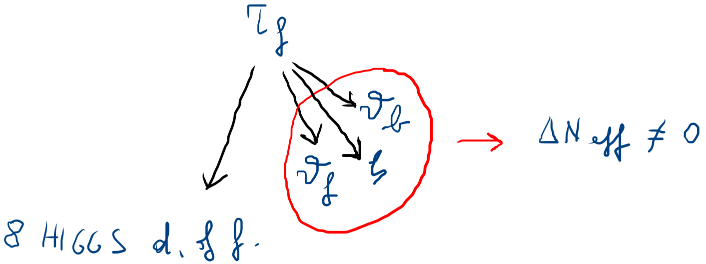
  $\Rightarrow \Omega_{QCD} \simeq \Omega_{DM}$ for $\vartheta_{in} \simeq 1$ NATURAL

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

  $\Rightarrow$ QCD AXION DM ✓

REHEATING and DR

- REHEATING from INFLATON PERTURBATIVE DECAY [MC,Deal,Sinha]



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

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

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

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

$\Rightarrow$ τ_f - HIGGS DECOUPLING [Angus]

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

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

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 CONTRIBUTE 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 be at most $O(1\%)$ of DM
  2) QCD AXION DM from OPEN STRINGS with $f_{QCD} \simeq 10^{12}$ 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 $\Leftrightarrow$ $r \simeq 10^{-10}$ [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]

CHALLENGES for QUINTESSENCE

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

⇒ 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

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

⇒ 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

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

⇒ $m_{\mathcal{V}} \ll 1$ meV + RADIATIVE INSTABILITY

WAY-OUT: consider AXION QUINTESSENCE where

$$V_{sub} \sim e^{-a\tau} \sim e^{-a\mathcal{V}^{2/3}} \sim V_{non-pert}$$

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

+ AXIONIC PERTURBATIVE SHIFT SYMM. gives RADIATIVE STABILITY

⇒ φ has to be an AXIONIC FLAT DIRECTION LIFTED BY NON-PERT. EFFECTS

QUINTESSENCE MODEL BUILDING

[MC,Cunillera,Padilla,Pedro]

$V(\nu)$ has a $\cancel{\text{SUSY}}$ MINK. VACUUM and φ is FLAT

$V(\varphi,\nu)$ generated by TINY NON-PERT EFFECTS for φ = AXION :

- 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 $H_{inf} \lesssim 1$ GeV.

AXION HILLTOP

FOCUS on AXIONS in LVS

$\mathcal{V} = \tau_B^{3/2} - \tau_S^{3/2}$ $\quad T_B = \tau_B + i\vartheta_B \quad T_S = \tau_S + i\vartheta_S$

$K = -2\ln\left(\mathcal{V} + \frac{\xi}{2 g_s^{3/2}}\right) \quad W = W_0 + A_s e^{-a_s T_s} + A_B e^{-a_B T_B}$

LEADING ORDER V DEPENDS on $\tau_B \simeq \mathcal{V}^{2/3}$, τ_s and ϑ_s

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

$\uparrow$

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

GENERIC in FLUX COMPACTIFICATIONS because of CONSISTENCY

- 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]

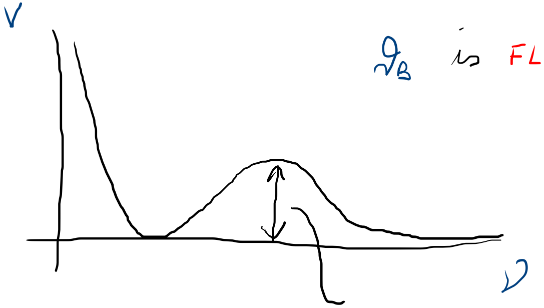
AXION HILLTOP

[MC,Cunillera,Padilla,Pedro]

- LEADING ORDER STABILISATION:

SUSY MINK at $\vartheta_s = 0$, $\tau_s \sim \frac{1}{g_s}$, $\mathcal{V} \sim e^{a_s \tau_s} \sim e^{a_s/g_s} \gg 1$

for $g_s \lesssim 0.1$



ϑ_B is FLAT

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

- SUBLEADING ORDER

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

KINETIC TERMS

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

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

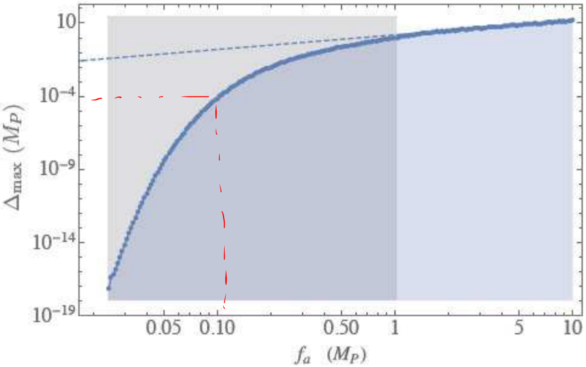
$\Rightarrow$ $m_{\mathcal{V}} \sim 10^{13}$ GeV OK!

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

$\Rightarrow$ EFT under CONTROL!

HILLTOP and INITIAL CONDITIONS

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



EFT under CONTROL?

$$\begin{cases} f_a = 0.1\, M_p \Rightarrow \Delta_{max} \lesssim 10^{-4}\, M_p \\ f_a = 0.02\, M_p \Rightarrow \Delta_{max} \lesssim 10^{-18}\, M_p \end{cases}$$

EFT under CONTROL

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

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

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

⇒ need to REQUIRE $H_{inf} \leq \Delta_{max}$

⇒ for $f_a = 0.02\, M_p$ where EFT is under CONTROL

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

⇒ TRY ALIGNMENT

Quintessence from axion alignment

[Angus,Choi,Shin]
[MC,Padilla,Pedro]
In progress

- Focus again on fibred CYs: $Vol = \sqrt{\tau_f}\tau_b - \tau_s^{3/2}$
- Structure of the scalar potential:

$$V = V_{lead}(Vol,\tau_s,\vartheta_s) + V_{inf}(\tau_f) + V_{sub}(\vartheta_b,\vartheta_f)$$

with

$$V_{inf} \simeq V_0\left(1-\tfrac{4}{3}e^{-\phi/\sqrt{3}}\right) \qquad \text{and} \qquad H_{inf} \simeq 10^{-5}M_p$$

- 3 ultra-light axions: ζ = QCD axion DM, ϑ_b and ϑ_s = DM (up to 0.1%) and DE via alignment
- Alignment mechanism [Kim,Nilles,Peloso]

$$W = W_{LVS} + A_1 e^{-\frac{2\pi}{N_1}(q_{1f}T_f+q_{1b}T_b)} + A_2 e^{-\frac{2\pi}{N_2}(q_{2f}T_f+q_{2b}T_b)}$$

- After canonical normalisation: $\phi_H \propto q_{1f}\vartheta_f + q_{1b}\vartheta_b$ and $\phi_L \propto (q_{1b}/\tau_f^2)\vartheta_f - (2q_{1f}/\tau_b^2)\vartheta_b$

$$\longrightarrow \quad V_{sub} = \Lambda_1^4\left[1-\cos\left(\frac{\phi_H}{f_H}\right)\right] + \Lambda_2^4\left[1-\cos\left(\frac{\phi_H}{\tilde f_H}+\frac{\phi_L}{f_L}\right)\right]$$

$$f_H \sim \tilde f_H \sim O\left(\tau_f^{-1},\tau_b^{-1}\right) \ll 1 \quad \text{while} \quad f_L \sim \frac{\sqrt{q_{1b}^2/\tau_f^2+2q_{1f}^2/\tau_b^2}}{|q_{1f}q_{2b}-q_{2f}q_{1b}|} \to \infty \quad \text{for} \quad q_{1f}q_{2b} \simeq q_{2f}q_{1b}$$

$$m_H^2 \simeq \frac{\Lambda_1^4}{f_H^2} \quad \text{and} \quad m_L^2 \simeq \frac{\Lambda_2^4}{f_L^2} \to 0$$

$$V_{DE} = \Lambda_2^4\left[1-\cos\left(\frac{\phi_L}{f_L}\right)\right] \quad \text{after fixing } \phi_H = 0$$

- Numerical results:

$\tau_f \sim \tau_b \sim O(100)$ $N_1 \sim N_2 \sim O(20)$ $q_{ij} \sim O(10)$ $\longrightarrow$ $f_H \sim 10^{-3}$ $m_H \sim 10^{-25}\,eV$

$f_L \sim 10^{-1}$ $m_L \sim 10^{-32}\,eV$

Early dark energy

- EDE proposed to solve Hubble tension: [Poulin et al]
  10% of energy density briefly before recombination and then decays faster than radiation
  ⟶ late-time evolution is unchanged
  ⟶ expansion rate is increased shortly before CMB formation raising H_0 from CMB

$$V_{EDE} = V_0\left[1-\cos\left(\frac{\phi}{f}\right)\right]^n \quad \text{with} \quad V_0 \sim eV^4 \quad n \simeq 3 \quad f \simeq 0.2\, M_p$$

- Embedding in string theory: Swiss-cheese LVS with 1 orientifold odd axion

$$G = \int_{\Sigma_2} B_2 + \int_{\Sigma_2} C_2 = b + ic$$

[MC,Licheri,Mahanta, McDonough,Pedro,Scalisi]

- Superpotential from 3 gaugino condensates on D7s with gauge fluxes k, 2k and 3k

$$W = W_{LVS} + A_1 e^{-a(T_b+k\,G)} + A_2 e^{-a(T_b+2k\,G)} + A_3 e^{-a(T_b+3k\,G)} \qquad a = 2\pi/M$$

⟶ $V_{EDE} = V_0[A + A_1\cos(akc) + A_2\cos(2akc) + A_3\cos(3akc)] = V_0\left[1-\cos\left(\frac{\phi}{f}\right)\right]^3$

if $A = \frac{5}{2}, A_1 = -\frac{15}{4}, A_2 = \frac{3}{2}, A_3 = -\frac{1}{4}$ $\qquad f \simeq 0.2\sqrt{g_s}\,M\,Vol^{-1/3}$

- Need to violate WGC to get right V_0 without tuning prefactors since

$$V_0 \simeq A\,e^{-S} M_p^4 = A\,e^{-\frac{\lambda M_p}{f}} M_p^4 = A\,e^{-5\lambda} M_p^4 \sim 10^{-110} M_p^4 \quad \text{for} \quad A \sim O(1) \quad \text{only if} \quad \lambda \gg 1$$

⟶ C_2 axions with fluxed D7s have $\lambda \simeq \sqrt{g_s}\,Vol^{1/3} \gg 1$

- Can get right EDE scale and decay constant for $g_s \sim 0.1$, $Vol \sim 10^5$ and $M \sim O(100)$

COSMIC WISPers in the Dark Universe

- Relatively new COST action:
  Start: Oct 2022
  End: Sep 2026
- Website: https://www.cost.eu/actions/CA21106/
- Chair: Alessandro Mirizzi (Bari)
- Vice-chair: Francesca Calore (Annecy)
- Keywords: axion and hidden photon theory - axion dark matters searches
  axion and hidden photon astrophysics - axion and hidden photon experiments
- 5 Working Groups:
  WG1: WISPs Model Building – Michele Cicoli and Ilaria Brivio
  WG2: WISPs Dark Matter and Cosmology – Vitagliano and Redondo
  WG3: WISPs in Astrophysics – Caputo and Straniero
  WG4: Direct WISPs Searches – Gatti and Karuza
  WG5: Dissemination and Outreach – Mena and Gastaldo
- Activities:
  i) Kick-off Meeting, 23-24 Feb 2023, Frascati
  ii) 1st General Meeting, 5-8 Sep 2023, Bari
  iii) 1st Training School, 11-14 Sep 2023, Lecce
  iv) Monthly WG online meetings
- Funding for:
  Short term scientific missions, Workshops, PhD Schools, ……

→ Apply online to join WG1 + another WG (if interested)!

COSMIC WISPERS
CA21106

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