Axiverse Project Overview

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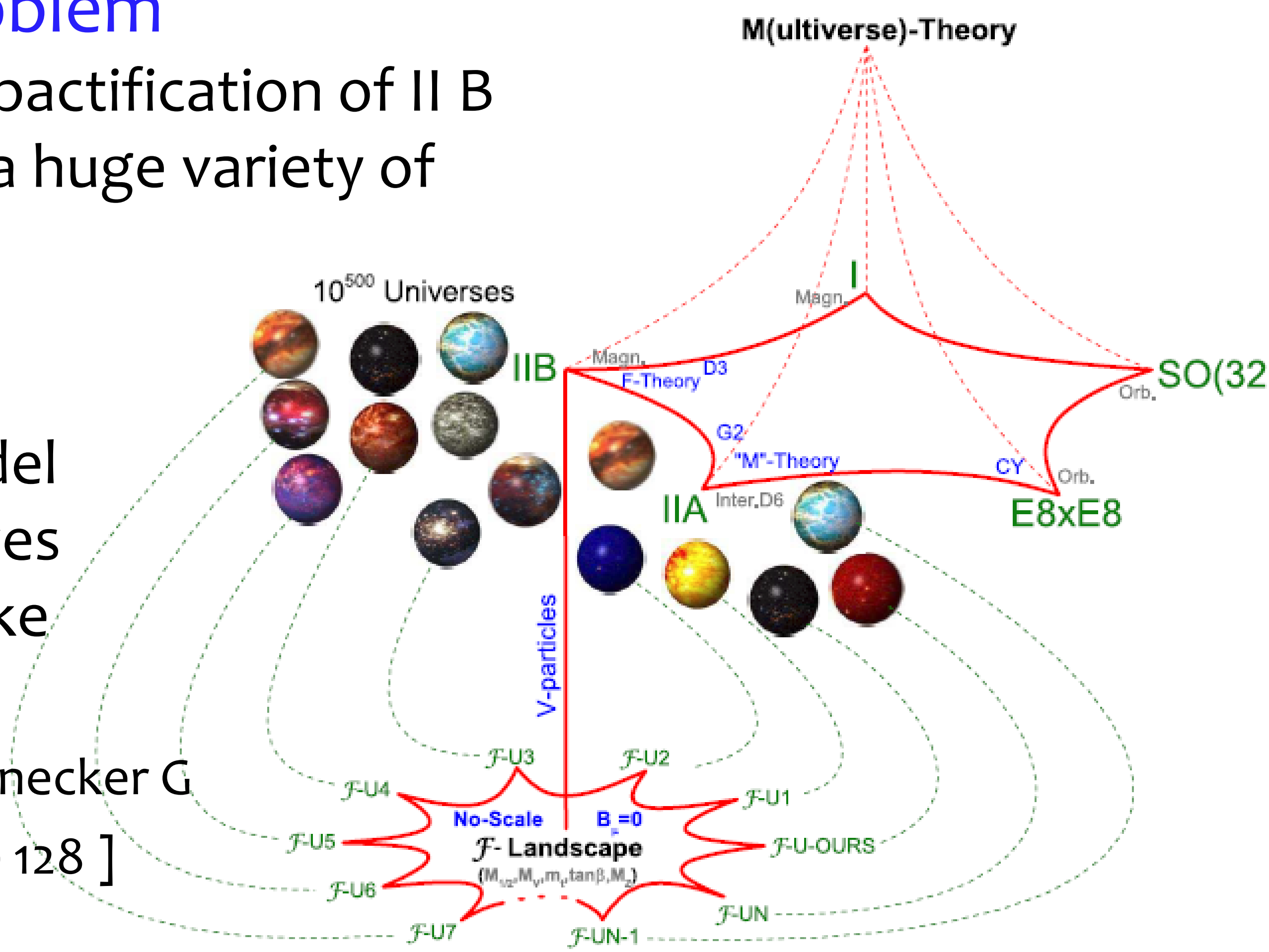
Contents

BASIC IDEA

Does SST actually describe our Universe?

- Landscape Problem
  - The flux compactification of II B SST predicts a huge variety of universes.
  - Intersecting D-brane model in IIA SST gives 10^{15} MSSM-like models.

    [Gmeiner F, Honecker G JHEP 09 (2007) 128]



Li T, Maxin JA, Nanopoulos DV, Walker JW: arXiv: 1111.0236

- Our Universe not in this landscape?

  - On the particle physics side:

    "Not a single string based model has yet been found which satisfies all known constraints."

    [Heckman JJ: arXiv:1001.0577]

  - On the cosmology side:

    "A typical analysis collects 'ingredients' that are understood to varying degrees in isolation, and assembles them in a single compactification with suitable cosmological properties … in which the mutual interactions are neglected."

    [Burgess CP, McAllister L: CQG28(2011)204002]

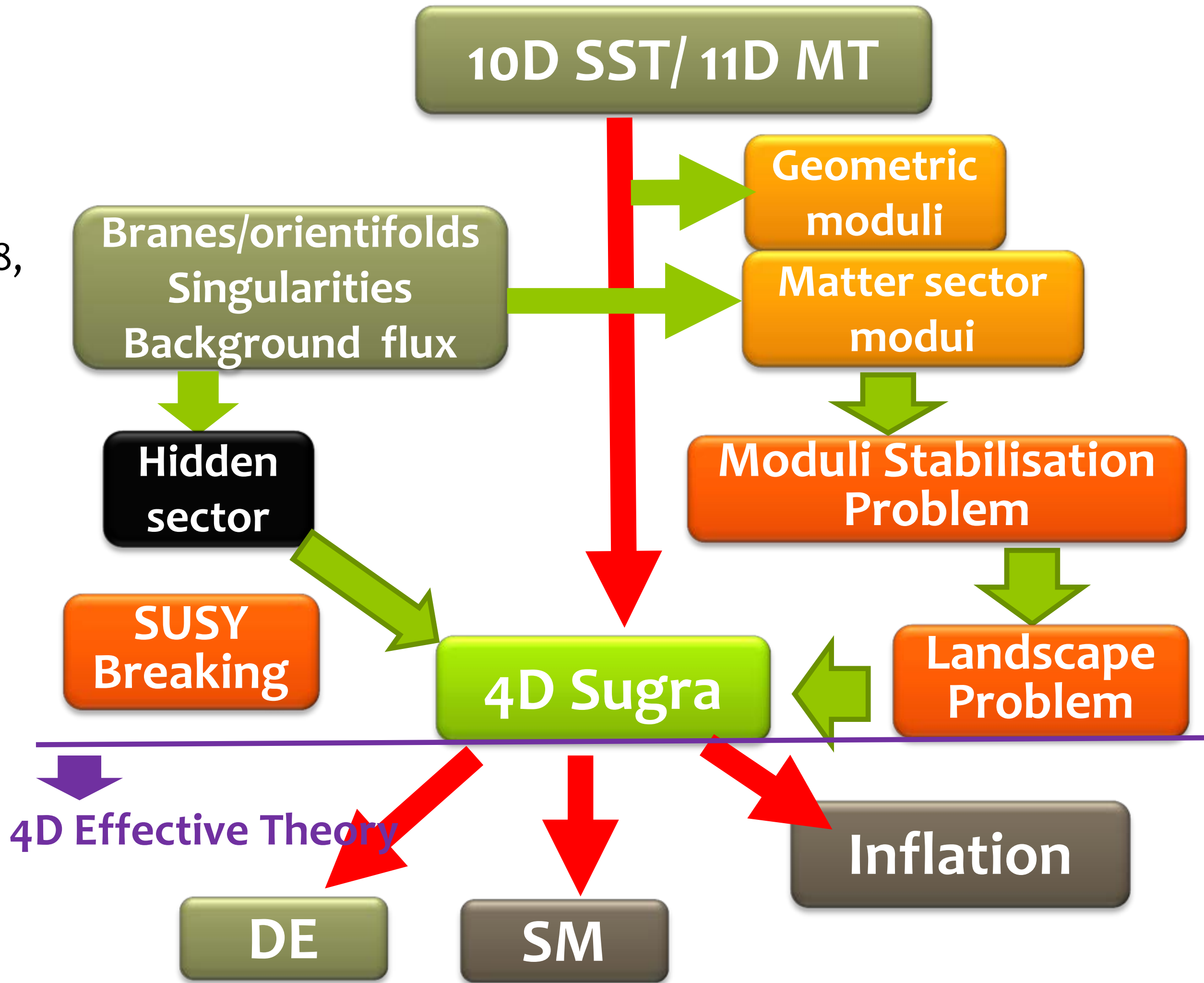
We need more info !!

How is Our Universe related to SST?

Basic features of superstring/M theories

- Consistent only in 10/11-D spacetime.
- Perturbative:

  Lots of facets: HET-E8xE8, HET-SO(32), I-SO(32), IIA/M, IIB/F
- Only gravity sector in type II/M. Too large gauge group in HET/I.
- A single parameter: almost everything is dynamical !
- Supersymmetric.



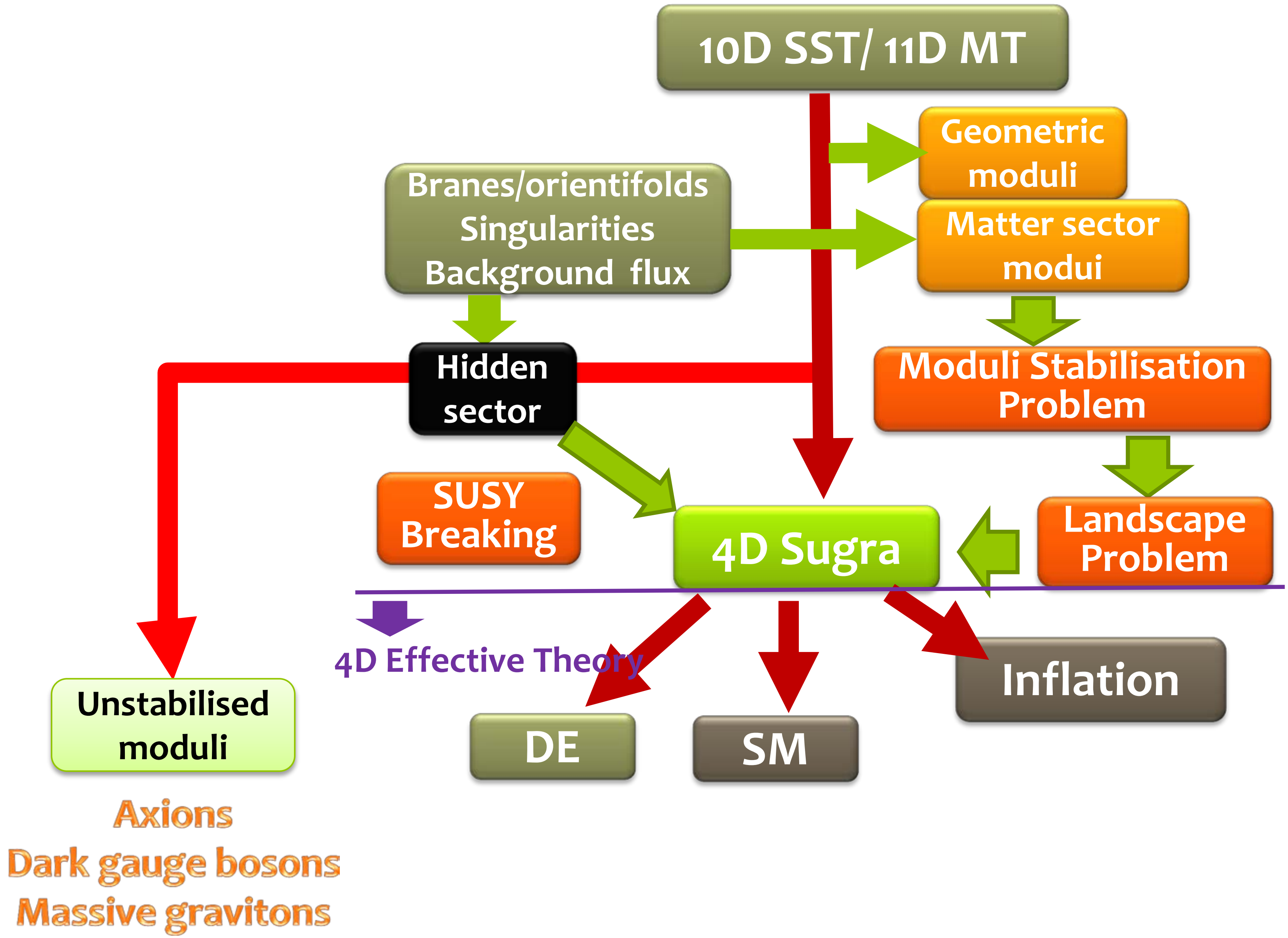
How to probe/test it?

- Observing inflation is not so illuminating.

“Although any such a detection would transform our picture of how inflation works—telling us much about the energy scales responsible for inflation and the mechanism responsible for generating primordial perturbations—unfortunately, with the present state of the art, we learn very little about string theory itself.”

[Burgess CP, McAllister L: CQG28(2011)204002]

Find phenomena characteristic to string theory!!

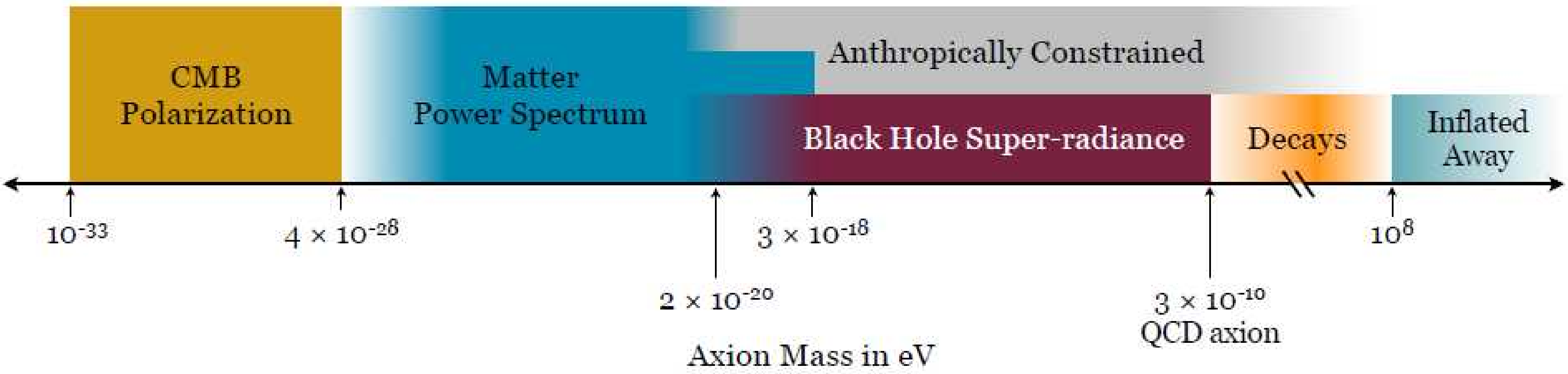


Characteristic Mass Scales

- Compton wavelength= Horizon size $(m=3H)$
  - Present $t=t_0$: $m_0=4.5\times 10^{-33}$ eV $c/H_0=4.3$ Gpc
  - CMB last scattering $t=t_{ls}$: $m_{ls}=0.7\times 10^{-28}$ eV $c/H_0=300$kpc
  - Equidensity time $t=t_{eq}$: $m_{eq}=0.9\times 10^{-27}$ eV $c/H_0=20$kpc
- Compton wavelength= BH size $(1/m=M_{pl}^2/M)$
  - Supermassive BH $M=10^{10}\,M_\odot$: $m_{bh,max}=1.3\times 10^{-20}$ eV $1/m=10^{-3}$ pc
  - Solar mass BH $M=1\,M_\odot$: $m_{bh,min}=1.3\times 10^{-10}$ eV $1/m=3$ km
- QCD axion $m \approx \Lambda_{QCD}^2/f_a$
  - $f_a=10^{16}$ GeV: $m \sim 10^{-9}$ eV
  - $f_a=10^{12}$ GeV: $m \sim 10^{-5}$ eV

Cf. $m_a = 1\text{eV} \times \left(\frac{6\times 10^6\,\text{GeV}}{f_a}\right)$

Probing the Ultimate Theory by Axion Cosmophysics

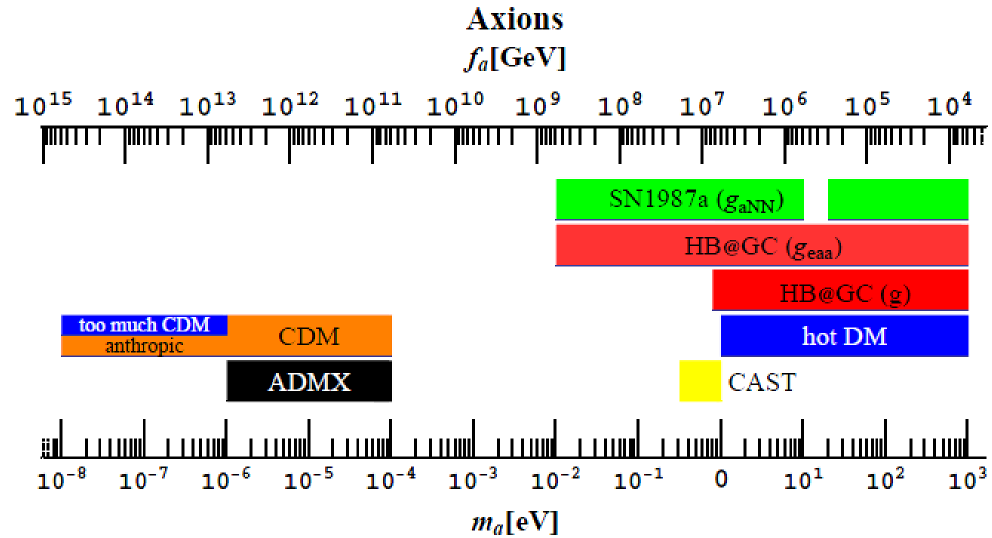


String theories $\Rightarrow$ superlight axionic fields + QCD axion

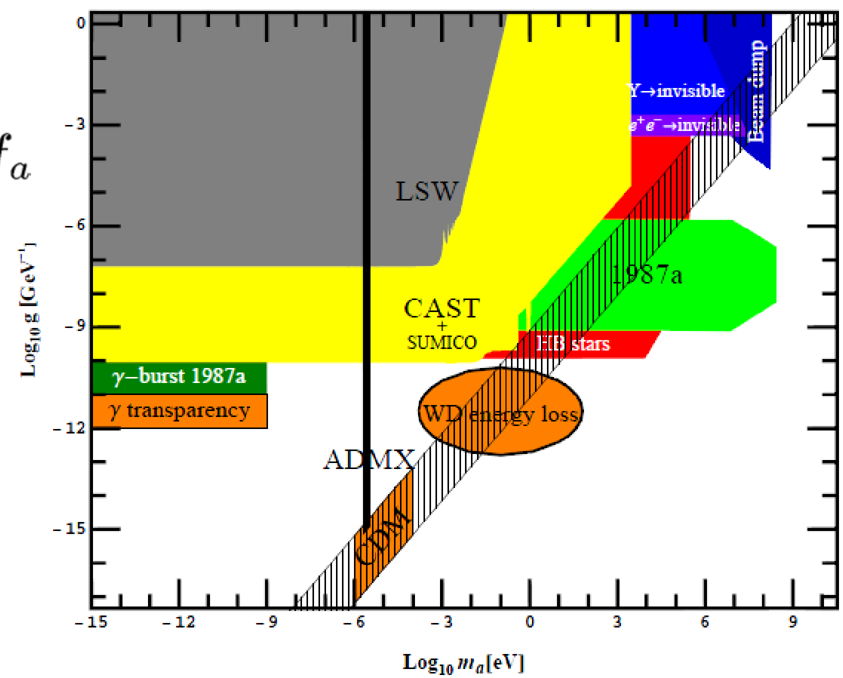
$\Rightarrow$ String axiverse $\Rightarrow$ new cosmophysical phenomena.

[Arvanitaki A, Dimopoulos S,Dubovsky S, Kaloper N, March-Russell, J: "String Axiverse" Phys.Rev. D81 (2010) 123530[arXiv: 0905.4720]]

Various Experimental Bounds



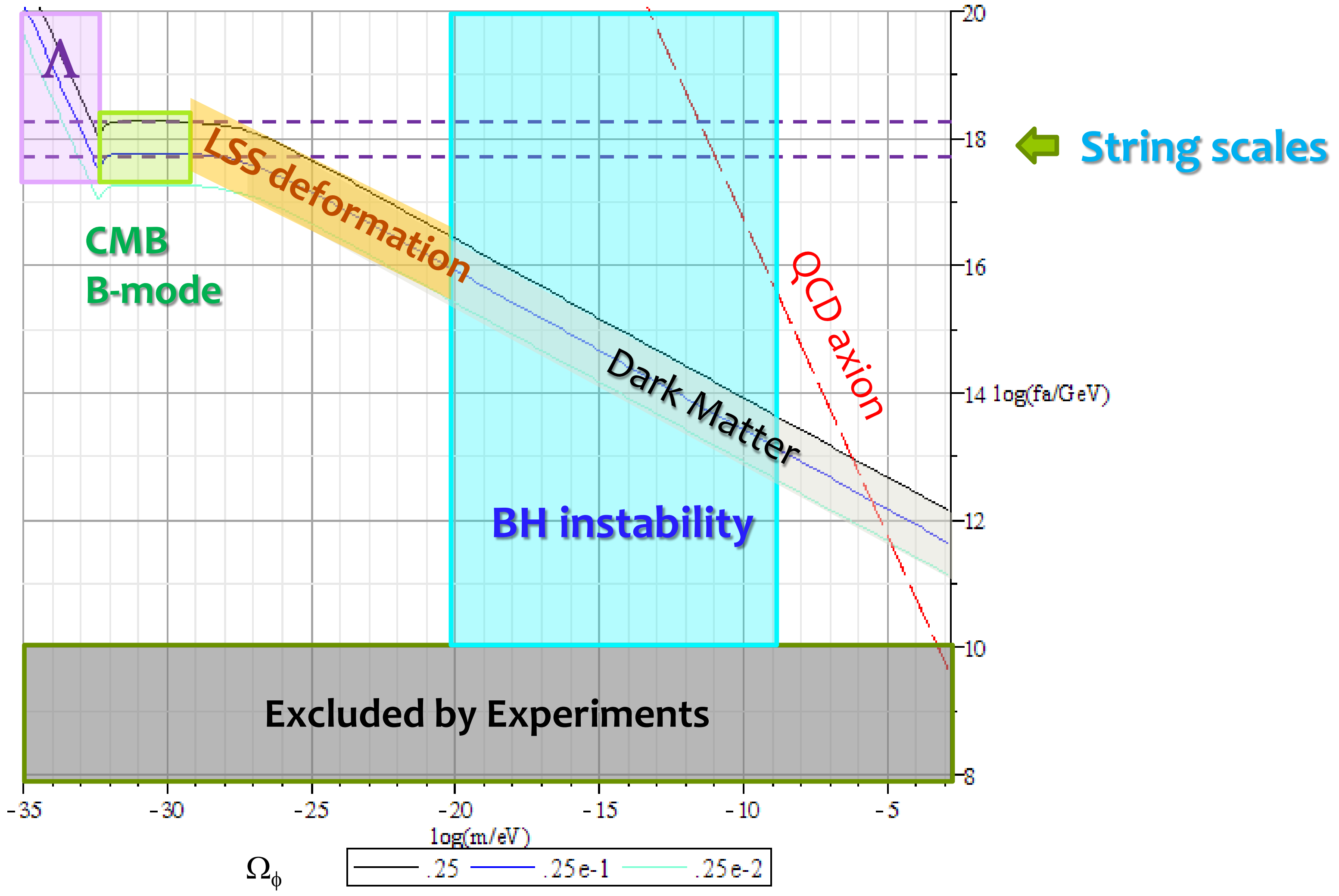
$1/f_a$



J. Jaeckel, A. Ringwald:
arXiv:1002.0329
The Low-Energy Frontier of Particle Physics

$$\text{Cf.}\ \ m_a = 1\text{eV} \times \left(\frac{6\times 10^6\,\text{GeV}}{f_a}\right)$$

Present Abundance



Possible Topics

- **Cosmology**
  - Dark energy: quintessence, quantum vacuum energy
  - Variation of fundamental constants
  - CMB polarisation : Birefringence
  - Cosmic strings/DW: axion emissions
  - Bosonic/hybrid dark matter: particle vs field
  - Large scale structure : Power spectrum modification
  - Inflation: anisotropic inflation, magnetic field generation, gravitational CP/P violation

- Black hole
  - Black hole instability : axion siren/bose nova/…
  - Modification of the horizon structure by moduli fields
- High energy astrophysics
  - Anomaly of CIRB vs UHE gamma
  - UHE CR vs gamma astronomy
- Superstring
  - First principle cosmology
  - Axion spectroscopy: requires explicit models realising inflation, dark energy and MSSM.

Axiverse Project Members

- PI: Hideo Kodama (KEK)
- Gravity/BH Physics

  Hirotaka Yoshino (KEK), Akihiro Ishibashi (Kinki U) , Jiro Soda (Kyoto U.), Masaru Shibata (YITP), Hideki Maeda (CECS)
- High Energy Astrophysics

  Kunihito Ioka (KEK), Kazunori Kohri (KEK)
- Cosmology

  Jiro Soda, Kazunori Nakayama (U Tokyo), Fuminobu Takahashi (Tohoku U)
- String Theory

  Tatsuo Kobayashi (Kyoto U), Nobuyoshi Ohta (Kinki U), Shyunya Mizoguchi (KEK)

STRING AXIONS

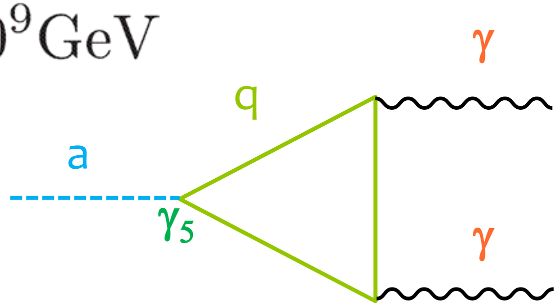
QCD Axion

A psued-Goldstone boson for the Peccei-Quinn chiral symmetry to resolve the strong CP problem.

- **Basic features of the invisible QCD axion**
  - **CP violating very weak coupling to matter**

$$g_{aq}\, a\,(\bar{q}\gamma_5 q): \quad g_{aq} \approx m_q/f_a;\;\; f_a \gtrsim 10^9\mathrm{GeV}$$

$$g_{a\gamma}\, a\, F \wedge F: \quad g_{a\gamma} \approx 1/f_a$$



  - **Small mass by the QCD instanton effect:**

$$m_a \approx 10^{-3}\ \mathrm{eV}\ (10^{10}\mathrm{GeV}/f_a)$$

  - **Dark matter candidate:** $\Omega_a \lesssim 0.01\,(f_a/10^{10}\mathrm{GeV})^{1.175}$

Axion Like Particles (ALP)

- ***General Definition***

  A pseudo scalar with tree-level shift symmetry and P/CP odd interactions.

- **Basic features**

  - **Shift symmetry => massless, derivative coupling**

  The shift symmetry of axions is protected from perturbative quantum corrections.

  - **Chiral feature of the shift symmetry**

    => anomaly

    => a periodic potential by instanton effets => a tiny mass

General Form of the Axion Potential

- Chiral Anomaly

$$\nabla \cdot J_{\rm ss} = -\frac{1}{4\pi^2}{\rm Tr}(QF \cdot \ *F)$$

$$\Rightarrow \quad S = \cdots - \frac{1}{4\pi^2 f_a} a{\rm Tr}(QF \wedge F)$$

- Effective potential by instantons

$$\left\langle e^{-S_a^E} \right\rangle = \sum_{n,m} \frac{1}{n!m!} \left(M_i^4 e^{-S_i^E} \right)^{n+m} e^{i(n-m)ka/f_a} = e^{-V_a}$$

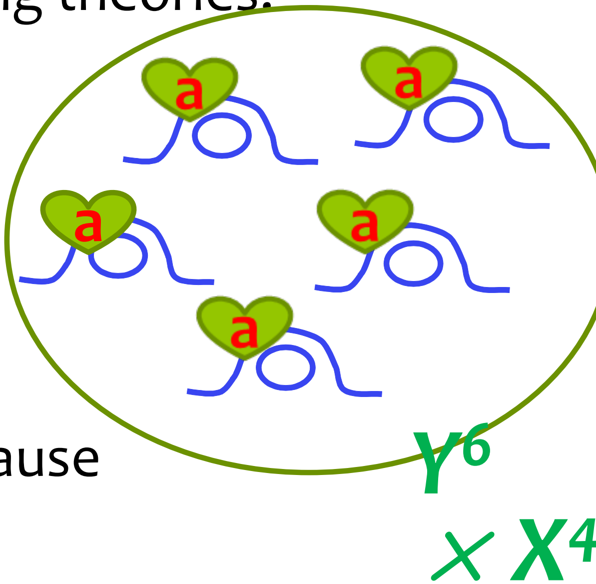
$$\Rightarrow \quad V_a = \sum_i 2\Lambda_i^4 \cos\left(k_i a / f_a\right), \quad \Lambda_i = M_i^4 e^{-S_i^E}$$

String axions

- A plethora of string axions are expected to arise from various form fields with Chern-Simons coupling that are characteristic to higher-dimensional supergravity / superstring theories.

$$C = \sum_i a_i(x)\omega_i(y) \Rightarrow \quad a_i(x)$$

$$C \wedge \mathrm{ch}(F) \cdot \frac{\sqrt{\hat{A}(\mathrm{TB})}}{\sqrt{\hat{A}(\mathrm{NB})}} \Rightarrow \quad \frac{1}{f_a} a\, F \wedge F, \quad \frac{1}{f_a} a\, \mathscr{R} \wedge \mathscr{R}$$



- The shift symmetry is naturally realised because

$$\omega_i \wedge \mathrm{ch}(F) \cdot \sqrt{\hat{A}(\mathrm{TB})}/\sqrt{\hat{A}(\mathrm{NB})}$$

is a closed form.

- In supersymmetric theories, scalar fields always appear in a pair to form a complex field.

  e.g.: axion => axion + saxion, dilaton => axidilaton

- In general, one of such pair is a pseud scalar.
- Hence, axion-type moduli fields are ubiquitous and quite abundant.

Estimation of mass and f_a

- Lagrangian of an axion

$$\mathscr{L} = -\frac{1}{2} f_a^2 (\partial\theta)^2 - \Lambda^4 U(\theta); \quad \Lambda^4 \approx M^4 e^{-S}$$

where S is the instanton action.

- From the relations

$$m_{\rm pl}^2 \sim g_s^{-2} L^6 l_s^{-8}, \quad f_a^2 \sim g_s^{-2} L^6 l_s^{-4} (L^2)^{-2} = g_s^{-2} L^2 l_s^{-4}, \quad S \sim l_s^{-2} L^2$$

we have $f_a \sim m_{\rm pl}/S$. Hence,

$$m_a \approx \Lambda^2 / f_a \sim (M^2/m_{\rm pl}) S e^{-S/2}$$

- The total potential for the axion is the sum of the QCD contribution and the stringy contribution:

$$V = V_{\rm QCD} + V_{\rm s}: \quad V_{\rm QCD} = \frac{a^2}{8f_a^2} r^2 F_\pi^2 m_\pi^2 \frac{m_u m_d}{(m_u + m_d)^2}; \quad V_{\rm s} = \Lambda^4 \cos\left(\frac{a}{f_a} + \psi\right).$$

- If we require that this stringy effect is less than the QCD instanton effect for the QCD axion, we have

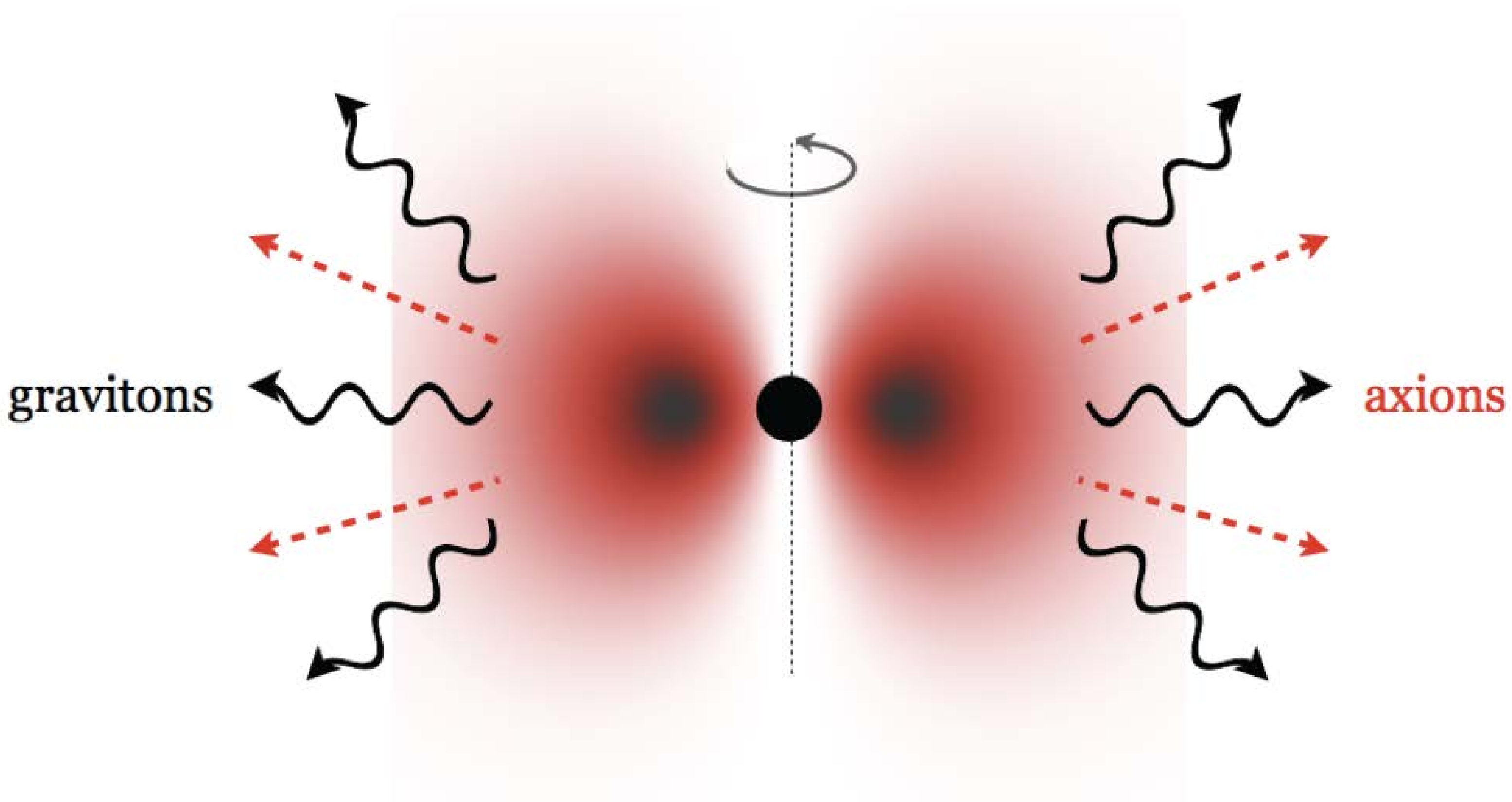
$$a \approx \frac{M^4 e^{-S}}{m_\pi^2 F_\pi^2} < 10^{-10} \quad \Rightarrow \quad S \approx 200 \Rightarrow \begin{array}{l} f_a \approx 10^{16}\,\text{GeV} \\ m_a \lesssim 10^{-15}\,\text{eV} \end{array}$$

BH PHYSICS

With Hirotaka Yoshino

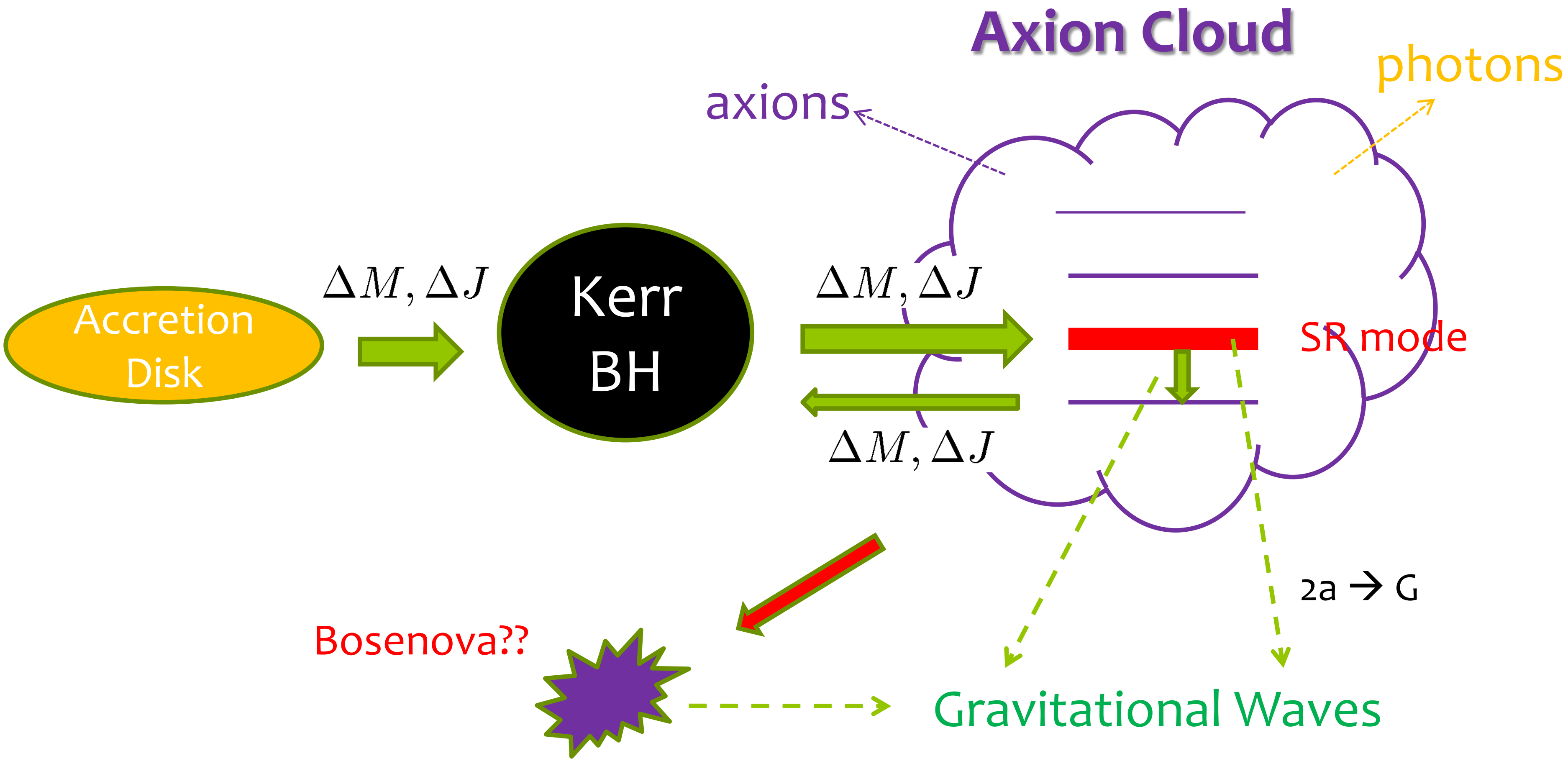
New Activities in Astrophysical Black Hole Systems

Any axion: $m_a = 10^{-10} \sim 10^{-20}$ eV



Arvanitaki A, Dubovsky S: arXiv:1004.3558

Fate of G-Atom?



Non-linear Effects

- Axion Action

$$S = \int d^4x \sqrt{-g} \left[-\frac{1}{2} (\nabla \phi)^2 - \frac{\mu^2 f_a^2}{2} \sin^2 (\phi / f_a) \right]$$

- Non-relativisitc effective action

$$\phi \simeq \frac{1}{\sqrt{2\mu}} \left(e^{-i\mu t} \psi + e^{i\mu t} \psi^* \right)$$

Averaging S over a time scale >> 1/μ

$$S_{\rm NR} = \int d^4x \left[i\psi^* \partial_t \psi - \frac{1}{2\mu} \partial_i \psi \partial_i \psi^* - \mu \Phi_g \psi^* \psi + \frac{1}{16 f_a^2} (\psi^* \psi)^2 \right]$$

Attractive interaction

Effective Theory

- Wavepacket approximation

$$\psi = A(t,r,\nu)e^{iS(t,r,\nu)+im\phi}, \quad \nu = \cos\theta$$

- Collective coordinates

$$A(t,r,\nu) \approx A_0 \exp\left[-\frac{(r-r_p)^2}{4\delta_r r_p^2} - \frac{\nu^2}{4\delta_\nu}\right]$$

$$S(t,r,\nu) \approx S_0(t) + p(t)(r - r_p(t)) + P(t)(r - r_p(t))^2 + \pi_\nu \nu^2$$

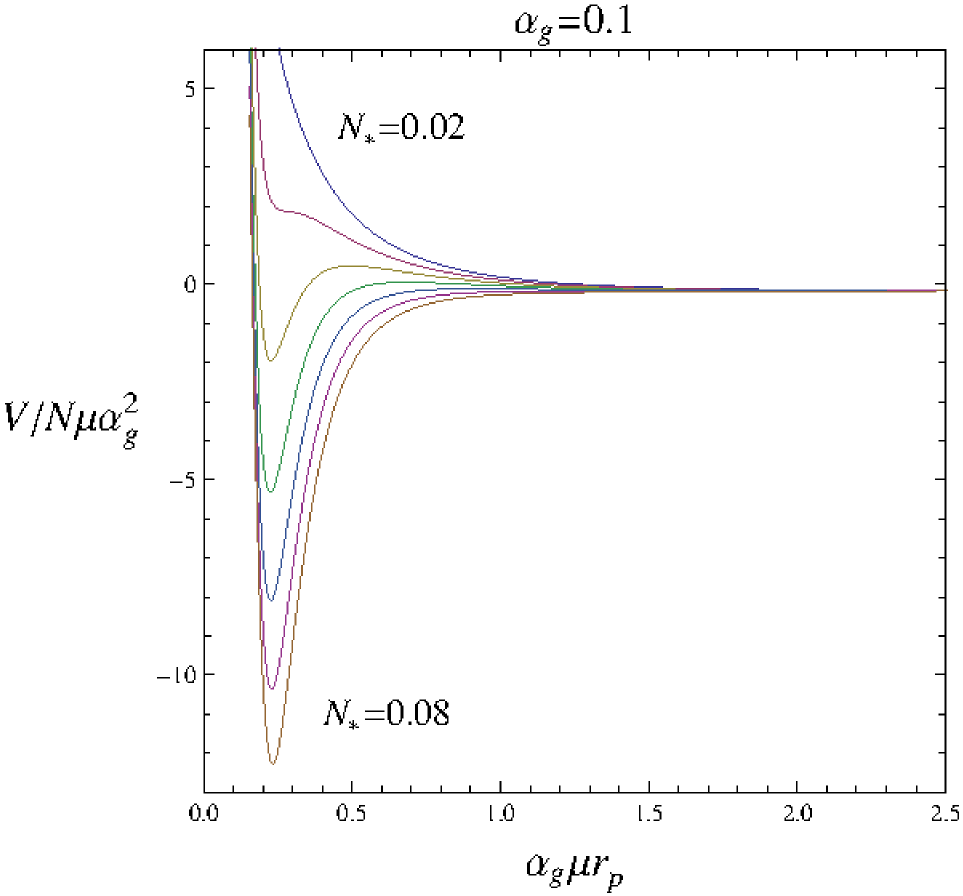
- Hamiltonian $\quad \delta_r = we^u, \delta_\nu = we^{-u}$

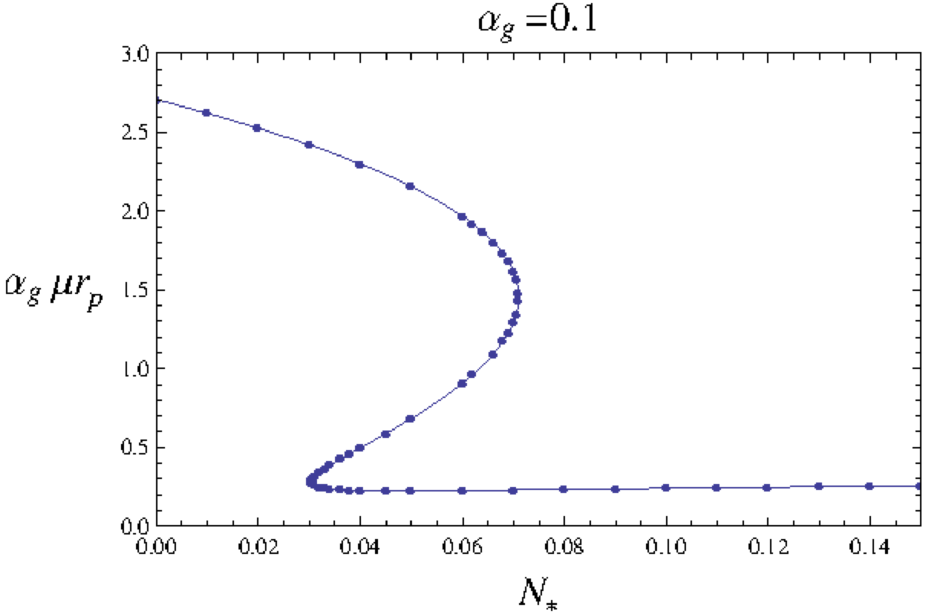
$$L = \mu N(p_r \dot{r}_p + p_w \dot{w} + p_u \dot{u}) - \left(K^{ij}(r_c, w, u)p_i p_j + V\right)$$

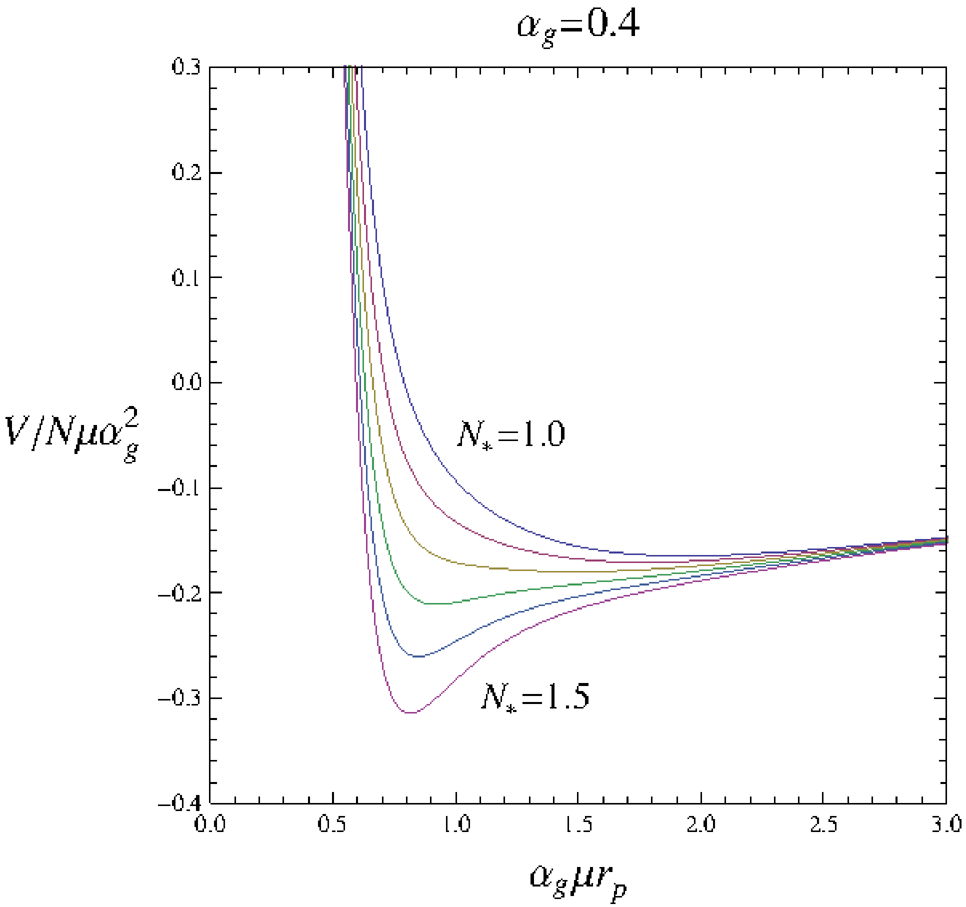
$$V = -\frac{\alpha_g}{\mu r_p} + \frac{1}{2(\mu r_p)^2}\left\{m^2 + \left(2m^2 w + \frac{1}{2w}\right)\cosh u\right\} + V_{\rm NL}\left(\frac{\beta}{w(\alpha_g \mu r_p)^3}\right)$$

$$\beta = \frac{N}{N_*}, \quad N_* = 2(2\pi)^2 \alpha_g^{-3}(f_a/\mu)^2, \quad \frac{\mu N_*}{M} = \frac{\pi}{\alpha_g^4}\left(\frac{f_a}{m_{\rm pl}}\right)^2$$

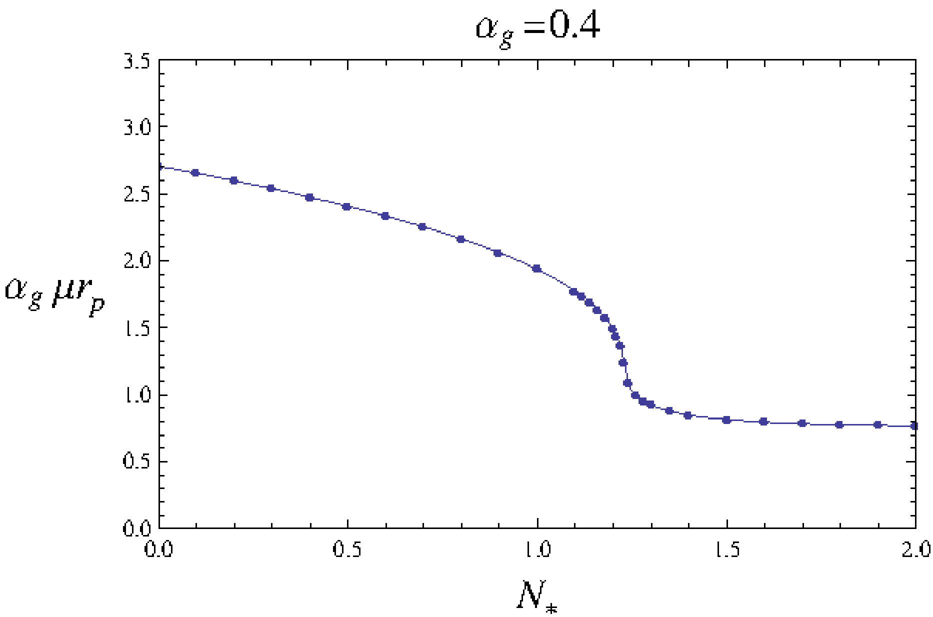
Effective Potential







α_g=0.4
$V/N\mu\alpha_g^2$
N_*=1.0
N_*=1.5
$\alpha_g \mu r_p$



α_g =0.4
$\alpha_g \mu r_p$
N_*

Our results

arXiv: 1203.5070
=> Yoshino's talk on 4/2

- Bose nova really happens for a G-atom of sine-Gordon axion formed by SR instability around a Kerr BH.
  - The occurrence of this phenomenon is controlled by the parameter $\alpha_g = GM\mu$.
  - Characteristics of that dynamics can be semi-quantitatively understood in terms of an effective theory for collective coordinates.
- Bosenova of a G-atom is expected to produce bust-like GW emissions, but details are yet to be studied.
- Interactions of the axionic cloud with magnetic fields of a black hole-accretion disk system are expected to provoke other interesting phenomena.

CONCLUSION

- Superstring theory predicts the existence of a plethora of super-light axionic fields in the present universe.
- Such superlight axions/moduli can produce a variety of new observable phenomena in the universe, and also may explain the fundamental mysteries of the universe such as dark matter, dark energy and inflation.
- Observational discoveries of such cosmophysical phenomena give a very distinctive evidence for the superstring theory to be behind the nature and provide a valuable probe for the structure of string compactification.

Let's explore the hidden sector !!