Quest for the Ultimate Theory by Cosmophysics

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Contents

- String theory as the Ultimate Theory
- Axiverse
- Axionic bose nova ?
- Conclusion

STRING THEORY
AS THE ULTIMATE THEORY

Motivations and Candidates of the Ultimate Theory

- Mysteries of SM
- Inflation in the early Universe
- Dark Energy

	SST	Riem² Gravity	Horava Gravity	Loop QG
UV completion of Einstein gravity	Perturtatively finite	Renomalisable with ghosts	Renomalisable? Einstein at IR?	Not a sensible theory yet
Any info on physics beyond SM?	Unified theory of all interactions	NA	Violation of Lorentz inv. No other info on the matter sector	NA

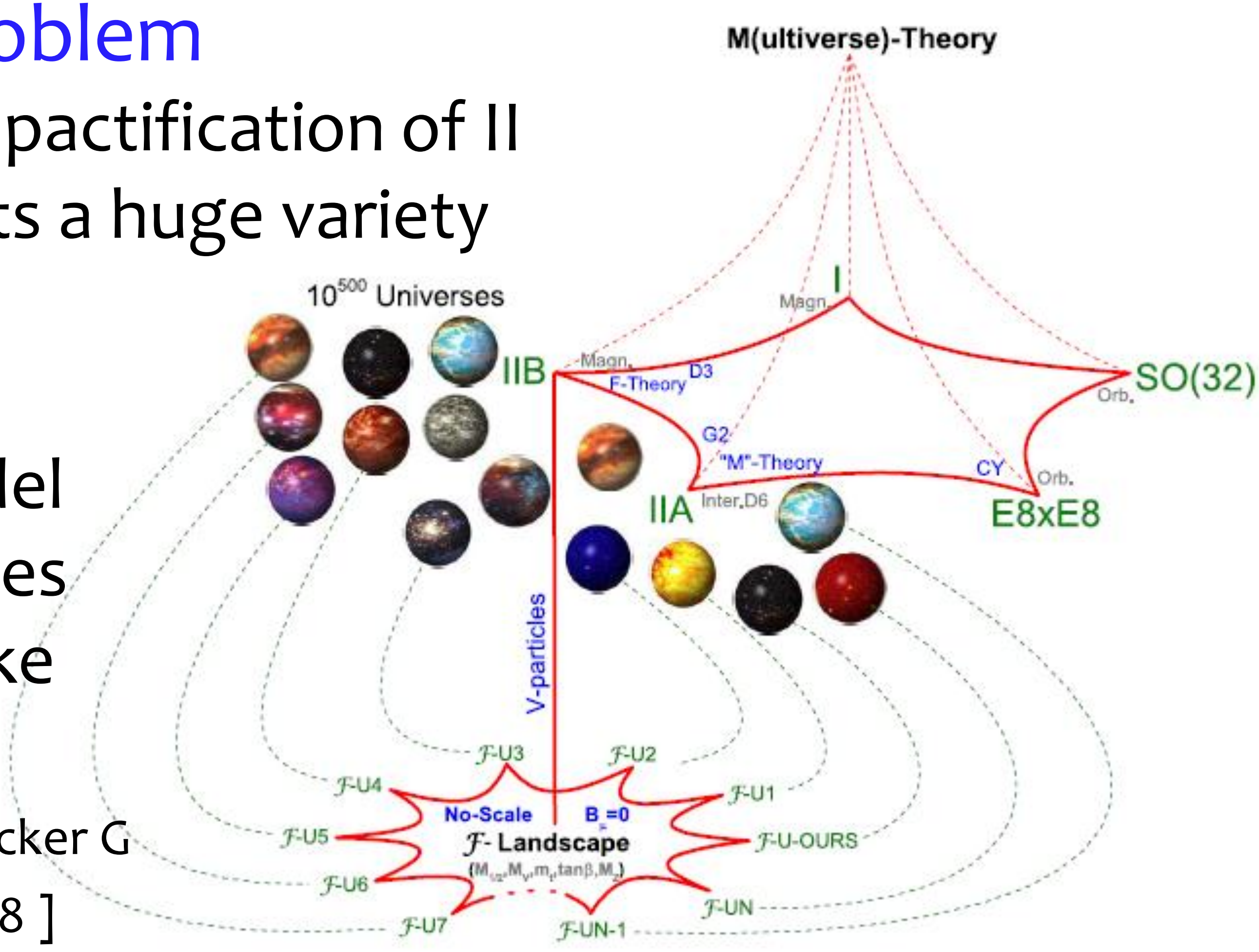
At present, superstring theory and its extension is the only viable candidate of the ultimate theory.

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."

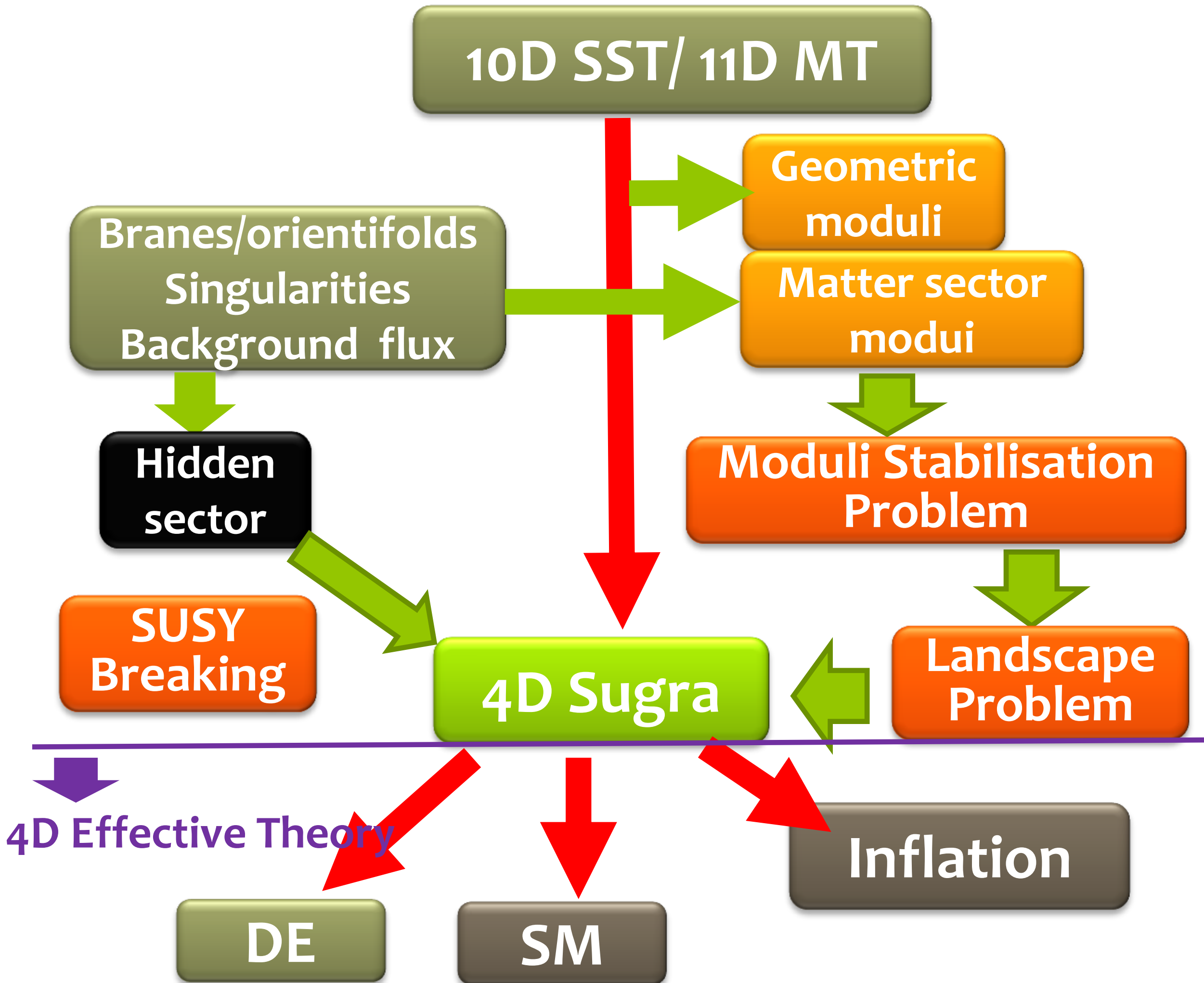
  [Burgess CP, McAllister L: CQG28(2011)204002]

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.



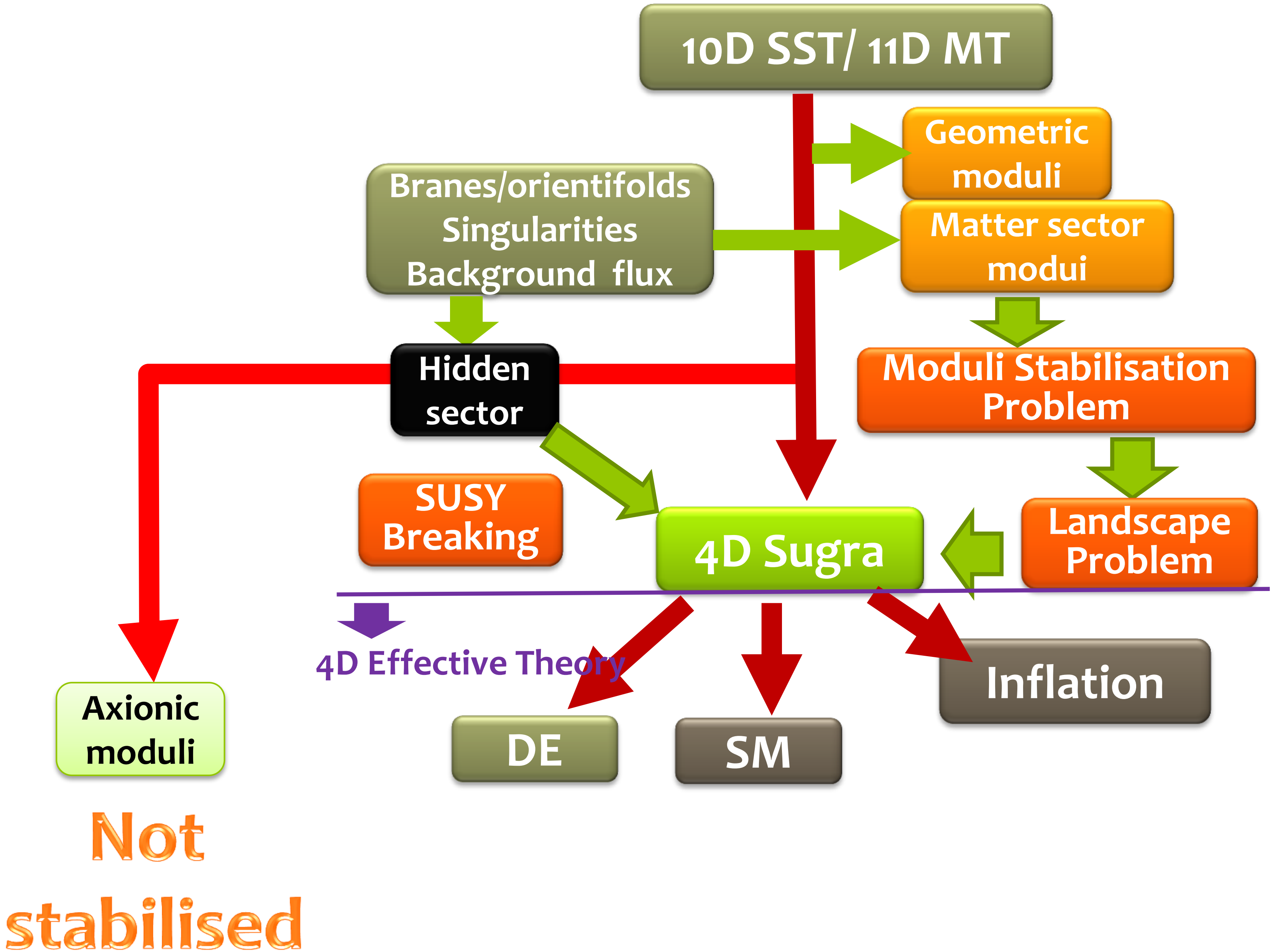
How to probe/test it?

- 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!!

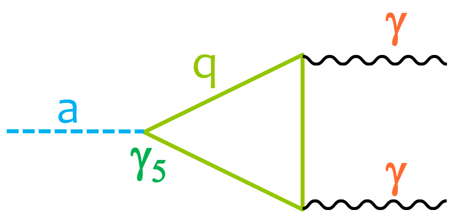


AXIVERSE

What Is Axion?

Originally,

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:**

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

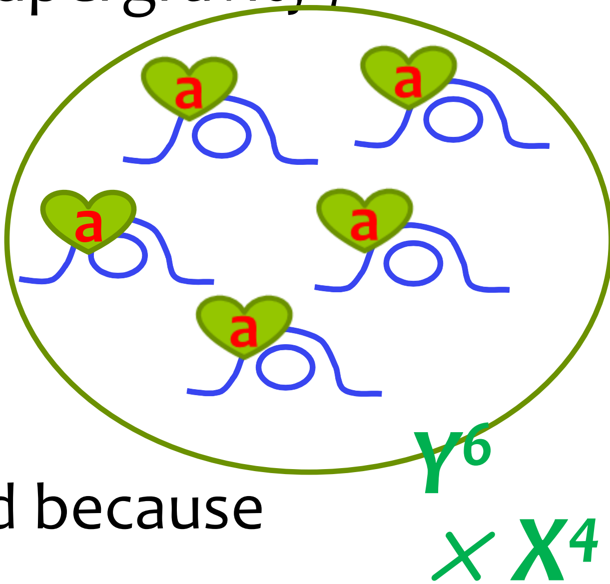
- **Dark matter candidate:** $\Omega_a \lesssim 0.01\,(f_a/10^{10}\mathrm{GeV})^{1.175}$

General Definition (ALP)

- **A pseudo scalar with tree-level shift symmetry and P/CP violation**

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.

String axions

- The shift symmetry of axions is protected from perturbative quantum corrections. Therefore, their masses m_a can be produced only non-perturbatively,

$$m_a \approx (M^2/m_{\rm pl}) \times S_E e^{-S_E/2}$$

and become very tiny naturally. Further, $\log(m_a)$ is expected to be distributed uniformly.

- If we require that stringy instanton effects are less than the QCD instanton effect on the QCD axion, we obtain

$$S_E \approx 200 \Rightarrow \quad f_a \sim S_E/m_{\rm pl} \sim 10^{16}{\rm GeV}, \quad m_a \lesssim 10^{-15}{\rm eV}$$

Characteristic Mass Scales

Compton wavelength= Horizon size (m=3H)

- Present $t=t_0$: $m_0=4.5\times 10^{-33}$ eV $c/H_o=4.3$ Gpc
- CMB last scattering $t=t_{ls}$: $m_{ls}=0.7\times 10^{-28}$ eV $c/H_o=300$kpc
- Equidensity time $t=t_{eq}$: $m_{eq}=0.9\times 10^{-27}$ eV $c/H_o=$ 20kpc

Compton wavelength= BH size ($1/m=M_{pl}^2/M$)

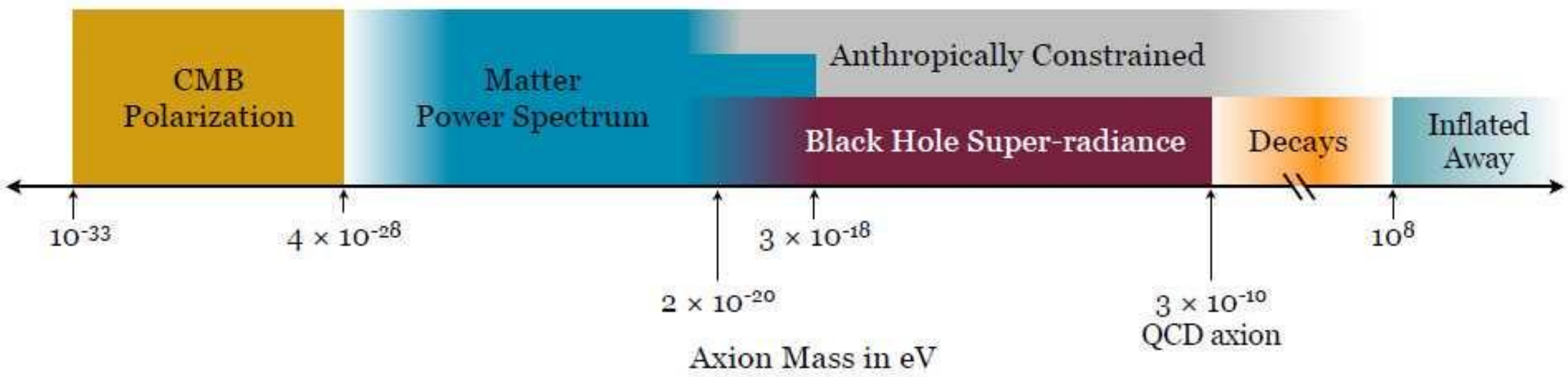
- Supermassive BH $M=10^{10}\ M_\odot$: $m_{bh,max}=1.3\times 10^{-20}$ eV $1/m=10^{-3}$ pc
- Solar mass BH $M=1\ M_\odot$: $m_{bh,min}=1.3\times 10^{-10}$ eV $1/m=3$ km

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

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

Probing the Ultimate Theory by Axion Cosmophysics



String theories ⇒ superlight axionic fields + QCD axion

⇒ String axiverse ⇒ new cosmophysical phenomena.

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

AXIONIC BOSENOVA

Superradiance

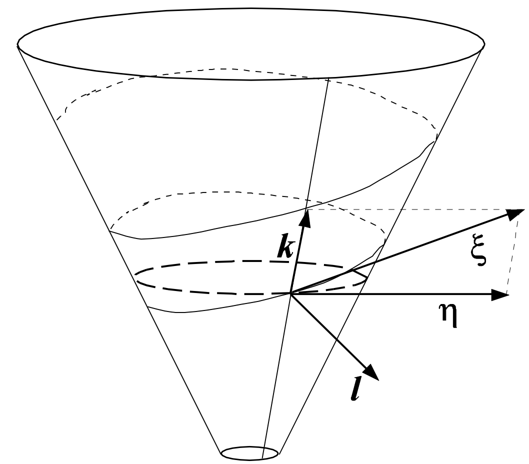
On the horizon of a rotating black hole

$\xi = \partial_t$: spacelike

$\Rightarrow$ The null generator: $k = \xi + \Omega_h \eta$

For an infalling bosonic wave $\Phi \propto \exp(-i\omega t + im\varphi)$

$$I_{\mathscr{H}^+} \propto i\bar{\Phi}\overleftrightarrow{\partial}_k\Phi = 2(\omega - m\Omega_h)|\Phi|^2$$



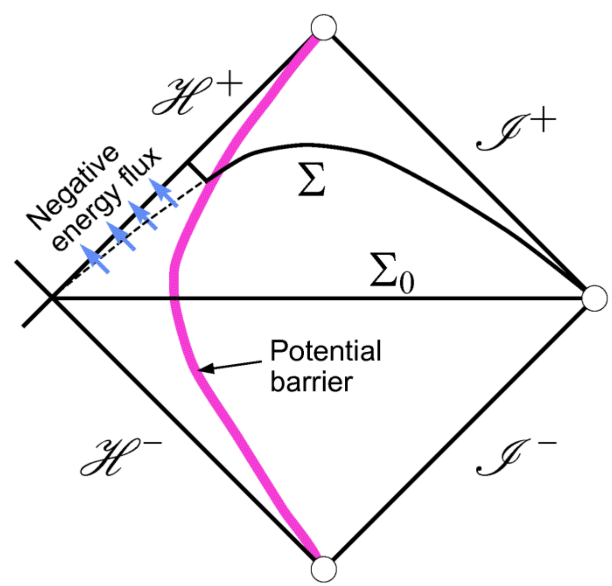
Flux conservation

$$I_{\mathscr{I}^-} = I_{\mathscr{I}^+} + I_{\mathscr{H}^+}$$

$$\omega\langle|A^-_{\omega,m}|^2\rangle = \omega\langle|A^+_{\omega,m}|^2\rangle + (\omega - m\Omega_h)\langle|C_{\omega,m}|^2\rangle$$

Superradiance condition

$0 < \omega < m\Omega_h$ ⇨ $I_{\mathscr{I}^+} > I_{\mathscr{I}^-}$



Black Hole Bombs

Black hole in a mirror box

[Zel'dovich 1971; Press, Teukolsky 1972; Cardoso, Dias, Lemos, Yoshida 2004]

If a rotating black hole is put inside a box with reflective boundary, superradiance provokes infinite growth of massless bosonic field inside the box.

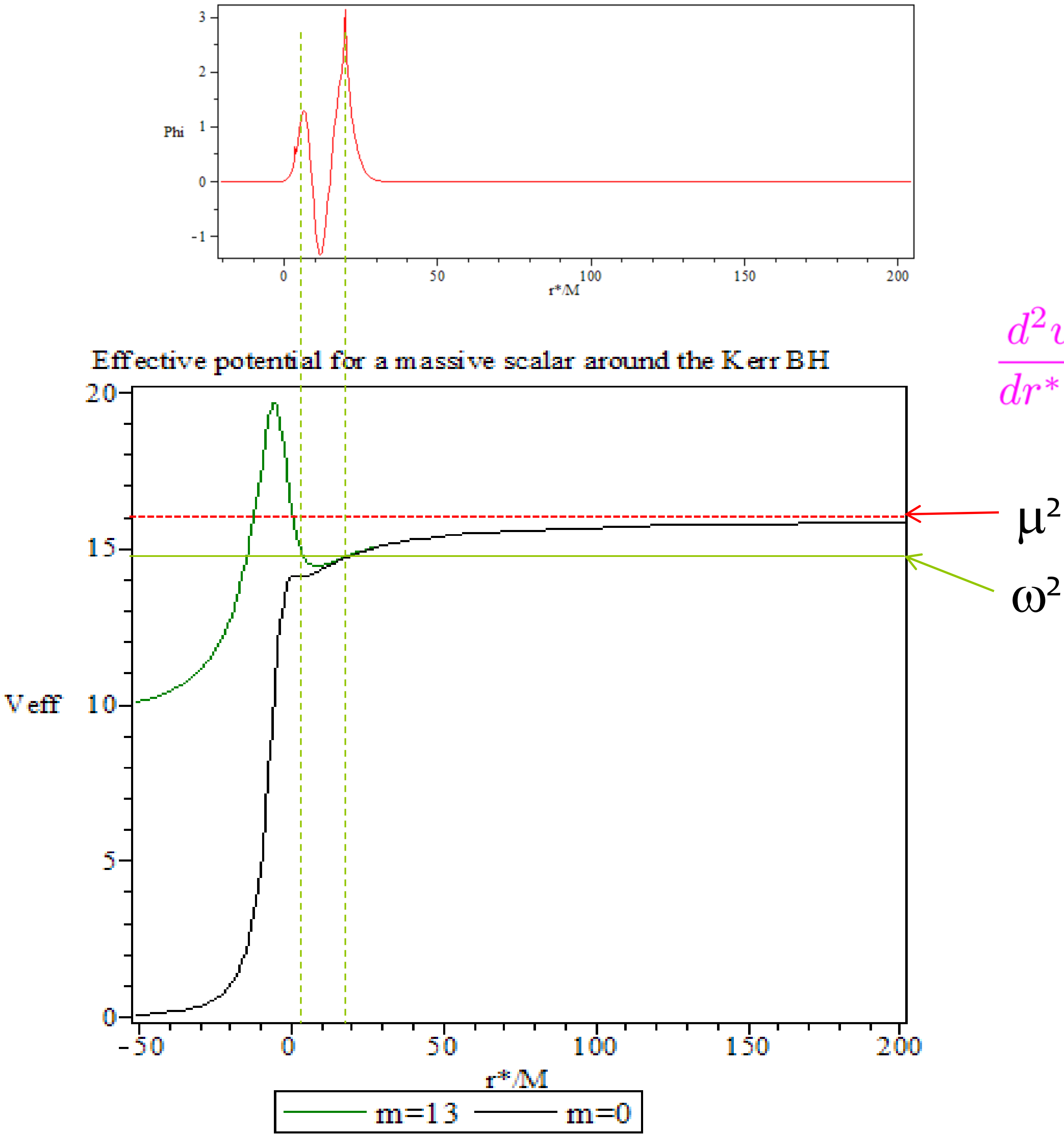
Cf. No instability for fermions.

Massive bosonic fields around a black hole

[Damour, Deruelle, Ruffini 1976;]

A similar instability occurs for massive bosonic fields!

WKB wavefunction for a bound state



$$\frac{d^2u}{dr^{*2}} + \left[\omega^2 - V(r,\omega)\right] u = 0$$

$a/M = 0.998$

$\mu M = 4$

$\omega/M = 3.85$

$\ell = 13$

Superradiance Instability

The growth timescale of the SR instability

$$\frac{\tau}{GM} \approx \begin{cases} 10^7 e^{1.84\alpha_g} & ; \alpha_g \gg 1,\ a/M = 1 \\ 24\left(\frac{a}{M}\right)^{-1} (\alpha_g)^{-9} & ; \alpha_g \ll 1, \end{cases}$$

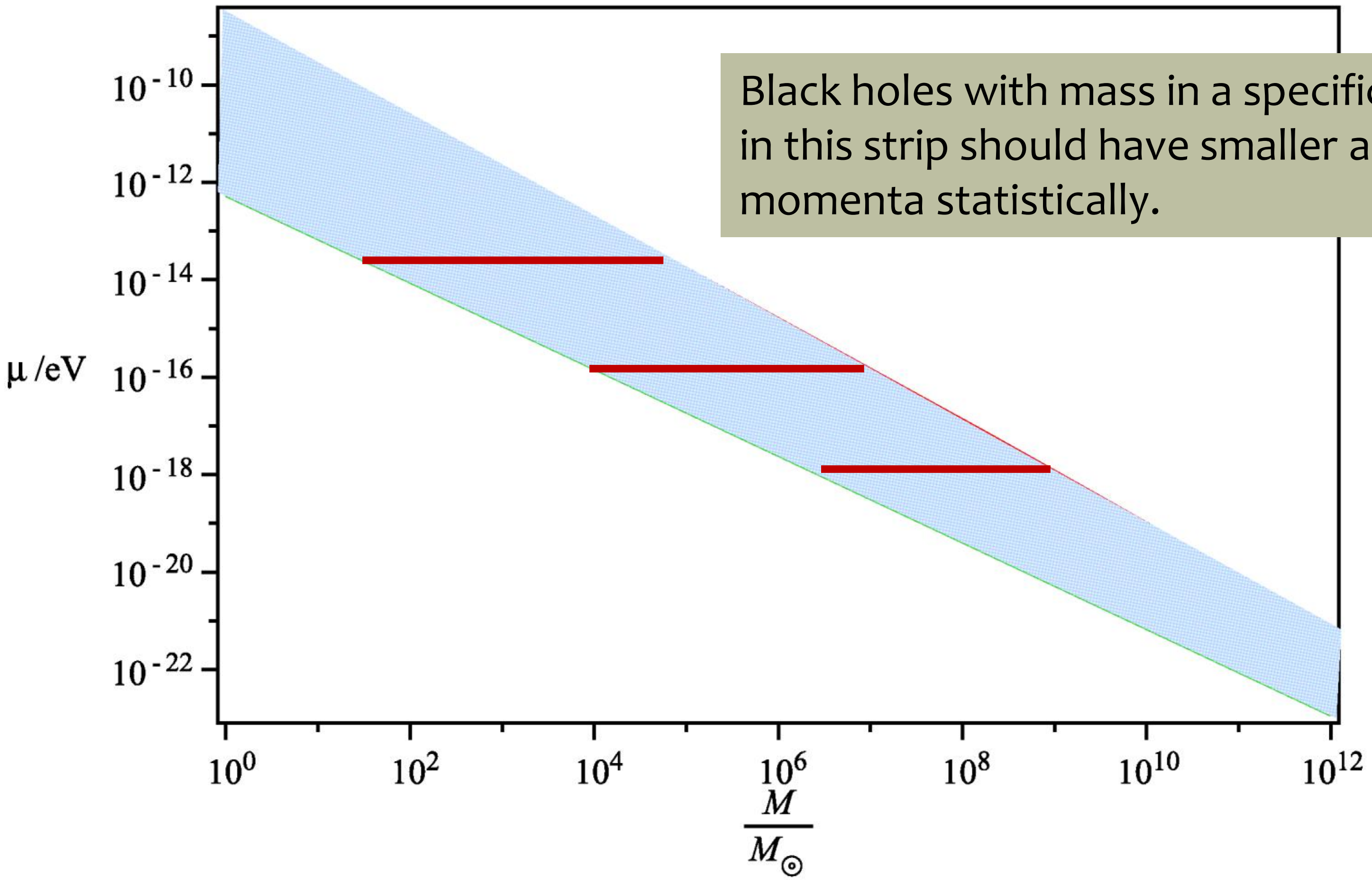
where

$$\alpha_g := GM\mu = \frac{\mu}{1.34 \cdot 10^{-10}\mathrm{eV}} \cdot \frac{M}{M_\odot}.$$

It becomes maximum at $\alpha_g \sim 1$:

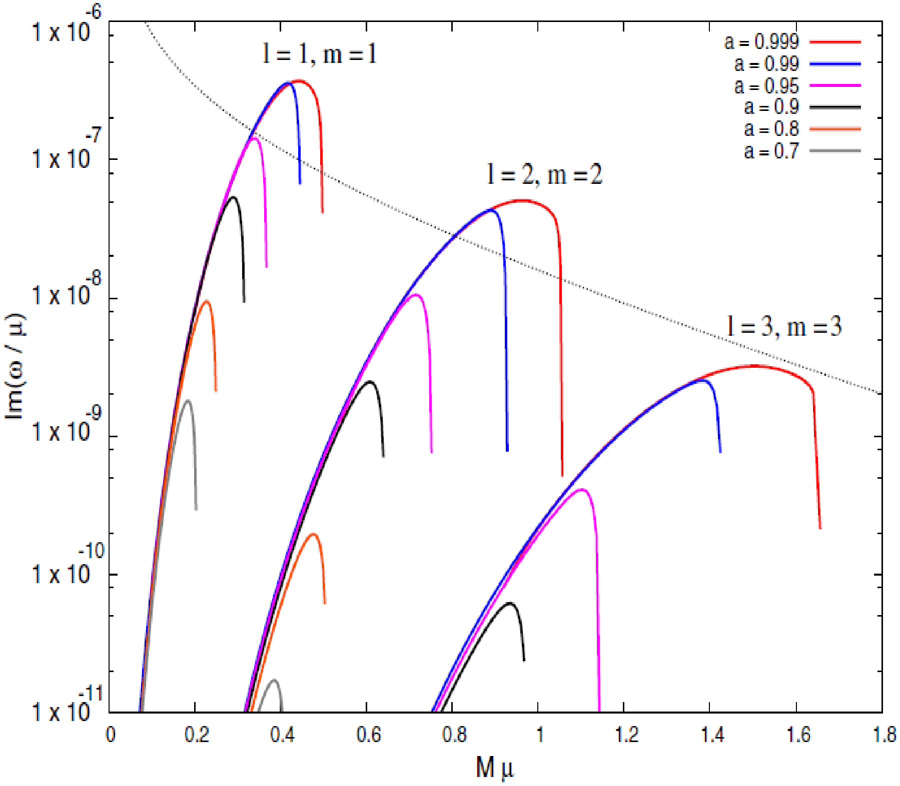
$$\tau_{\mathrm{sr}} \approx 0.2 \cdot 10^7 GM; \quad \alpha_g \simeq 0.44,\ a/M \simeq 0.999.$$

SR instability strip in the M-μ plane

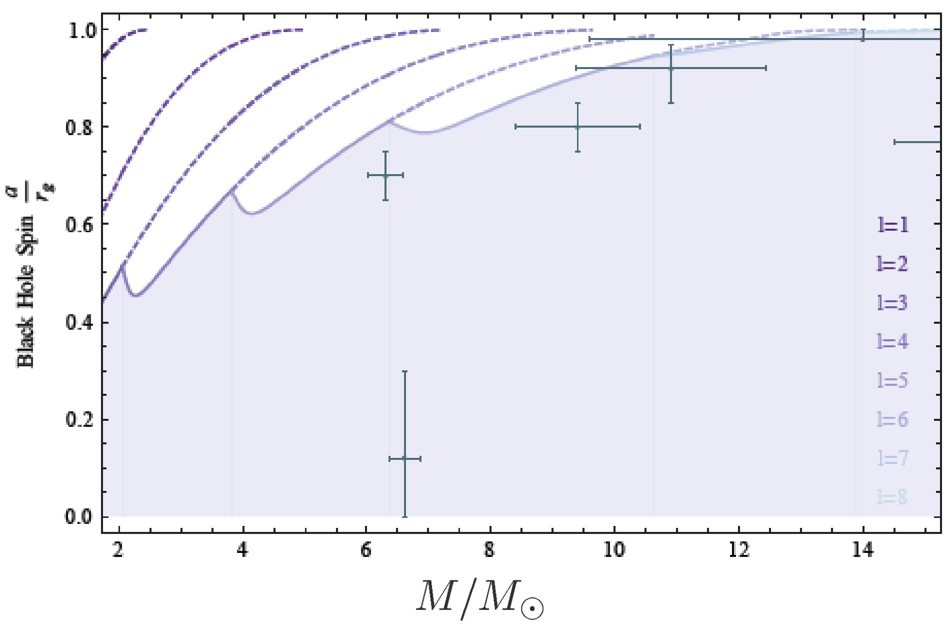


Black holes with mass in a specific range in this strip should have smaller angular momenta statistically.

Black Hole Spin



$\mu = 3 \times 10^{-11}\mathrm{eV}$

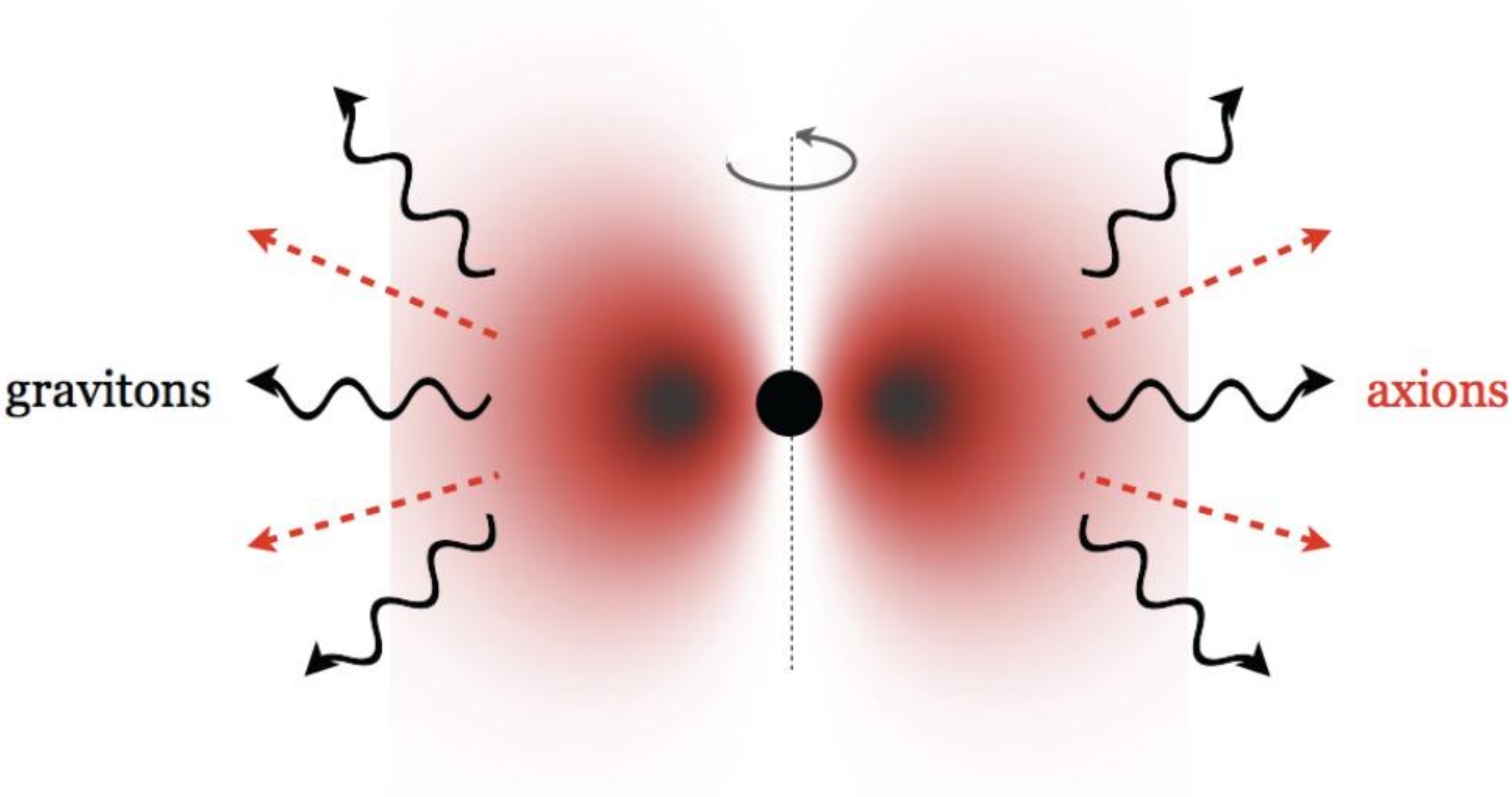


Arvanitaki A, Dubovsky S: arXiv:1004.3558

G-Atom

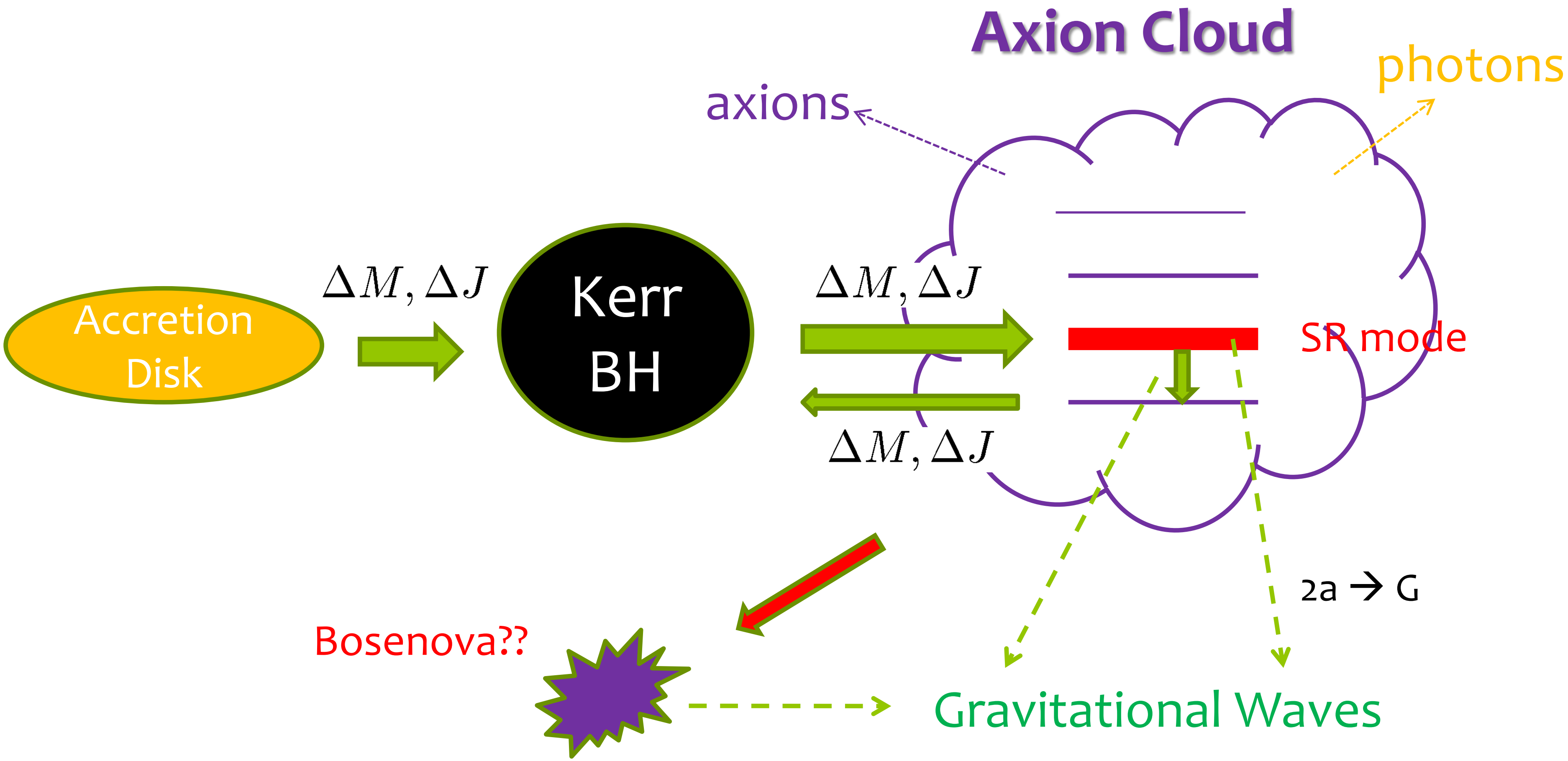
SR unstable states are quantum for near extremal cases !!

$$\mu r \sim 4\alpha_g \left(\frac{r_h}{a}\right)^2 \sim 1$$



Arvanitaki A, Dubovsky S: arXiv:1004.3558

Fate of G-Atom?



GW estimation: 2*a* (2p) → G

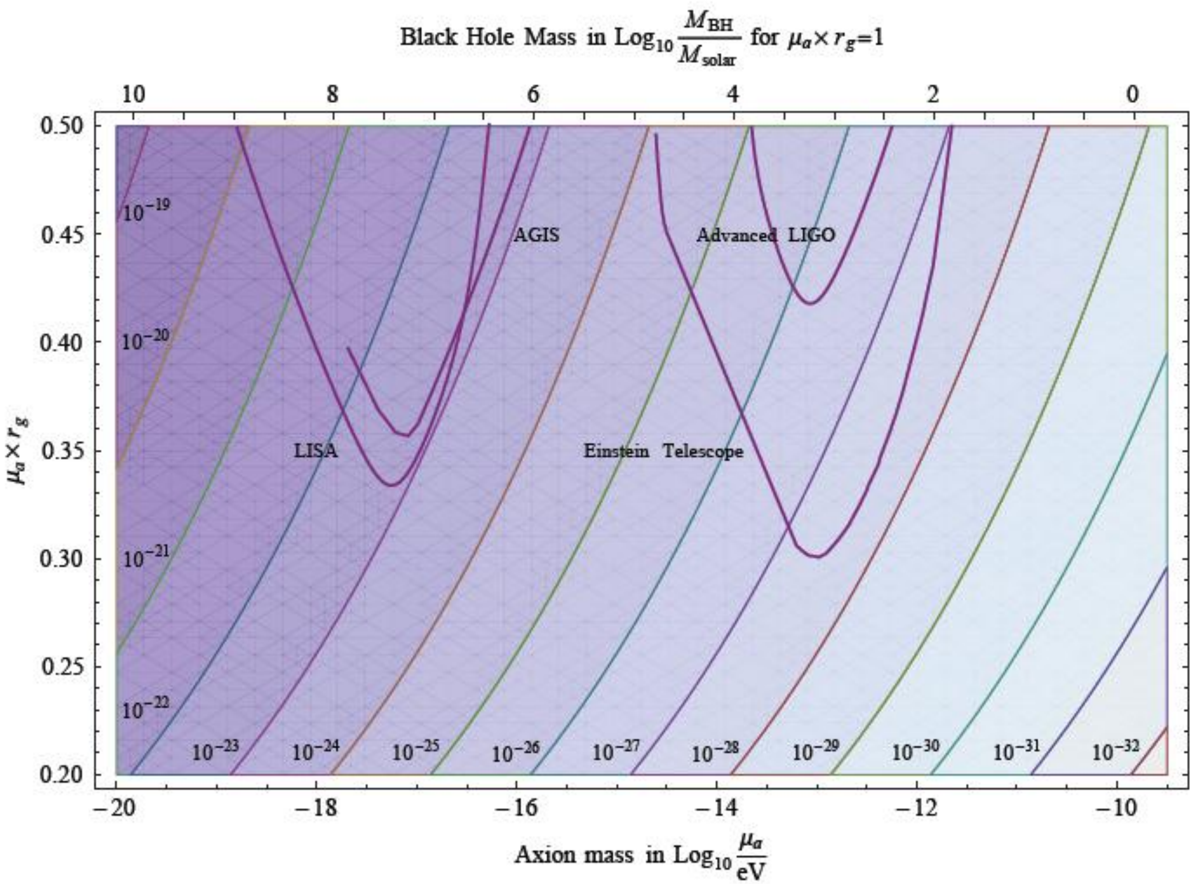


Figure 11: The contour plot of constant gravitational wave signal from axion annihilations in the 2p level for a black hole located at 20 Mpc away from the Earth. The projected sensitivity curves assume 10^6 seconds of a coherent integration time for LISA [41], AGIS, Advanced LIGO and Einstein Telescope.

$$h \sim 10^{-22}\alpha_g^7\epsilon\left(\frac{10\text{Mpc}}{d}\right)\left(\frac{M_{\text{BH}}}{M_\odot}\right)$$

$$\nu \approx 30\text{kHz} \times \alpha_g\left(\frac{2M_\odot}{M_{\text{BH}}}\right)$$

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

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

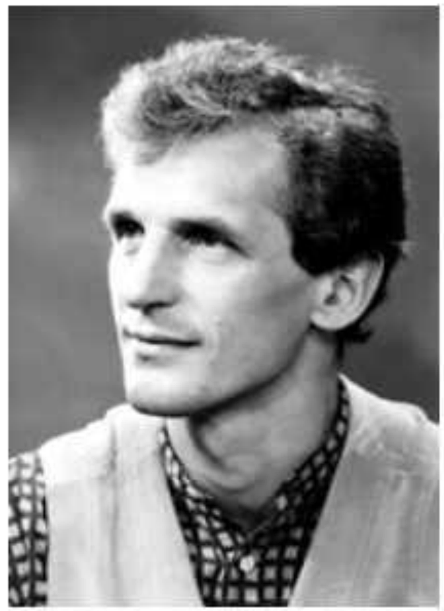
Averaging S over a time scale >> 1/μ

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

Attractive interaction

The Nobel Prize in Physics 2001
Eric A. Cornell, Wolfgang Ketterle, Carl E. Wieman


Eric A. Cornell

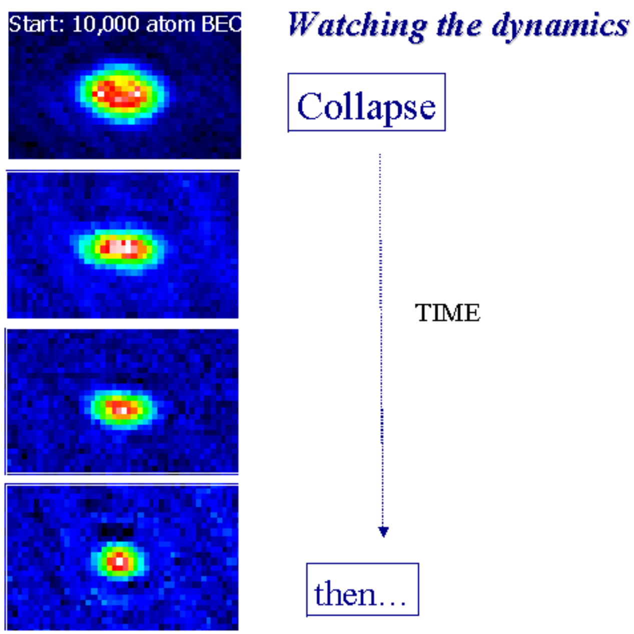

Wolfgang Ketterle

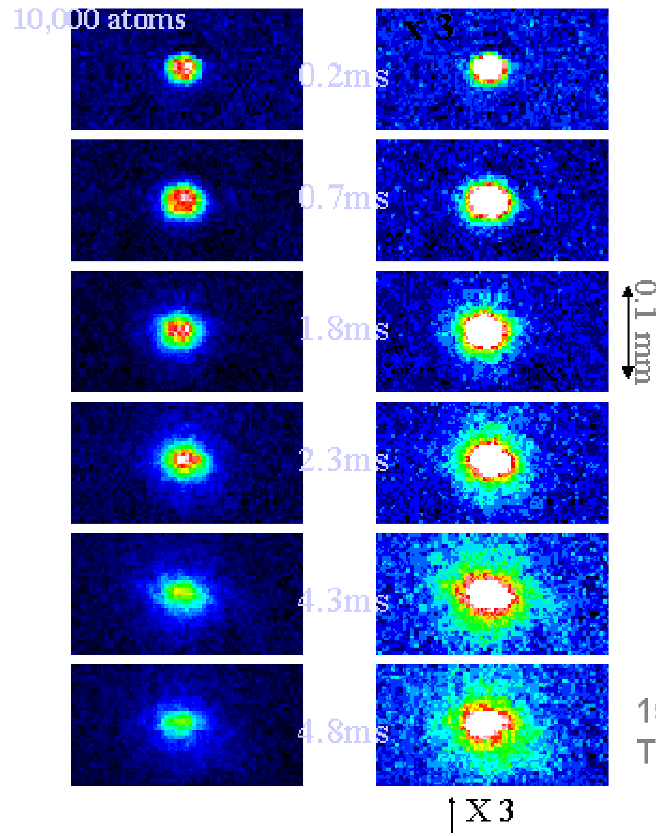

Carl E. Wieman

The Nobel Prize in Physics 2001 was awarded jointly to Eric A. Cornell, Wolfgang Ketterle and Carl E. Wieman *"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"*.

Bosenova in condensed matter physics

http://spot.colorado.edu/~cwieman/Bosenova.html





"Bosenova"

like tiny supernova:

- collapse
- explosion
- small cold remnant

1500 atom burst
T ~ 200 nK

BEC state of Rb85（interaction can be controlled）

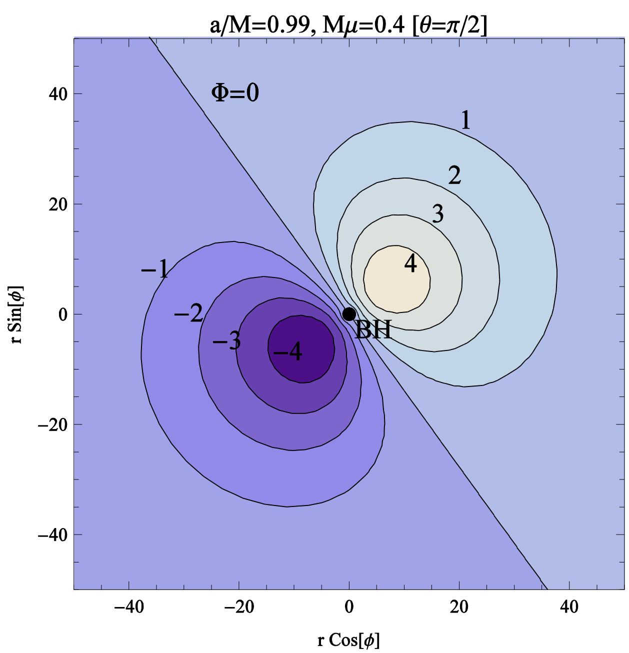
Switch from repulsive interaction to attractive interaction

Wieman et al., Nature 412 (2001), 295

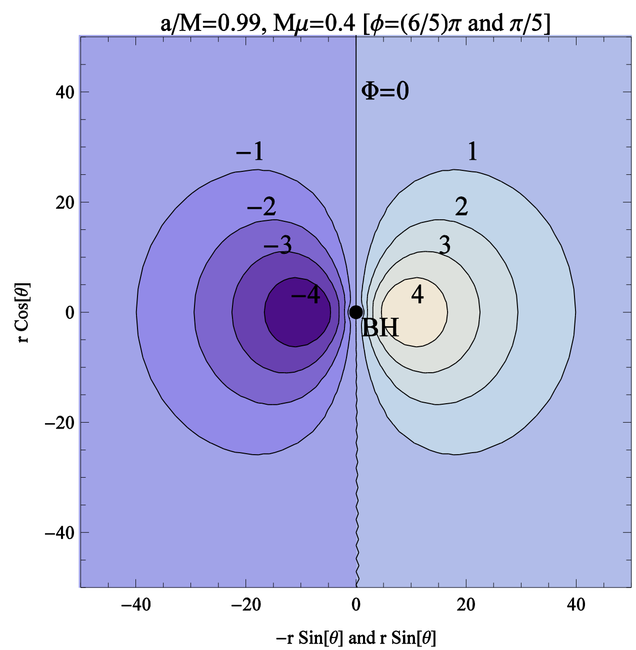
Numerical Simulation

Simulations	Initial condition	β	Nonlinearlity
(A)	KG bound state, ϕ(A)peak(0) = 0.60	0.46	weak
(B)	KG bound state, ϕ(B)peak(0) = 0.65	0.52	moderate
(C)	KG bound state, ϕ(C)peak(0) = 0.70	0.6	strong

Wavefunction for the SR unstable bound state: l=m=1

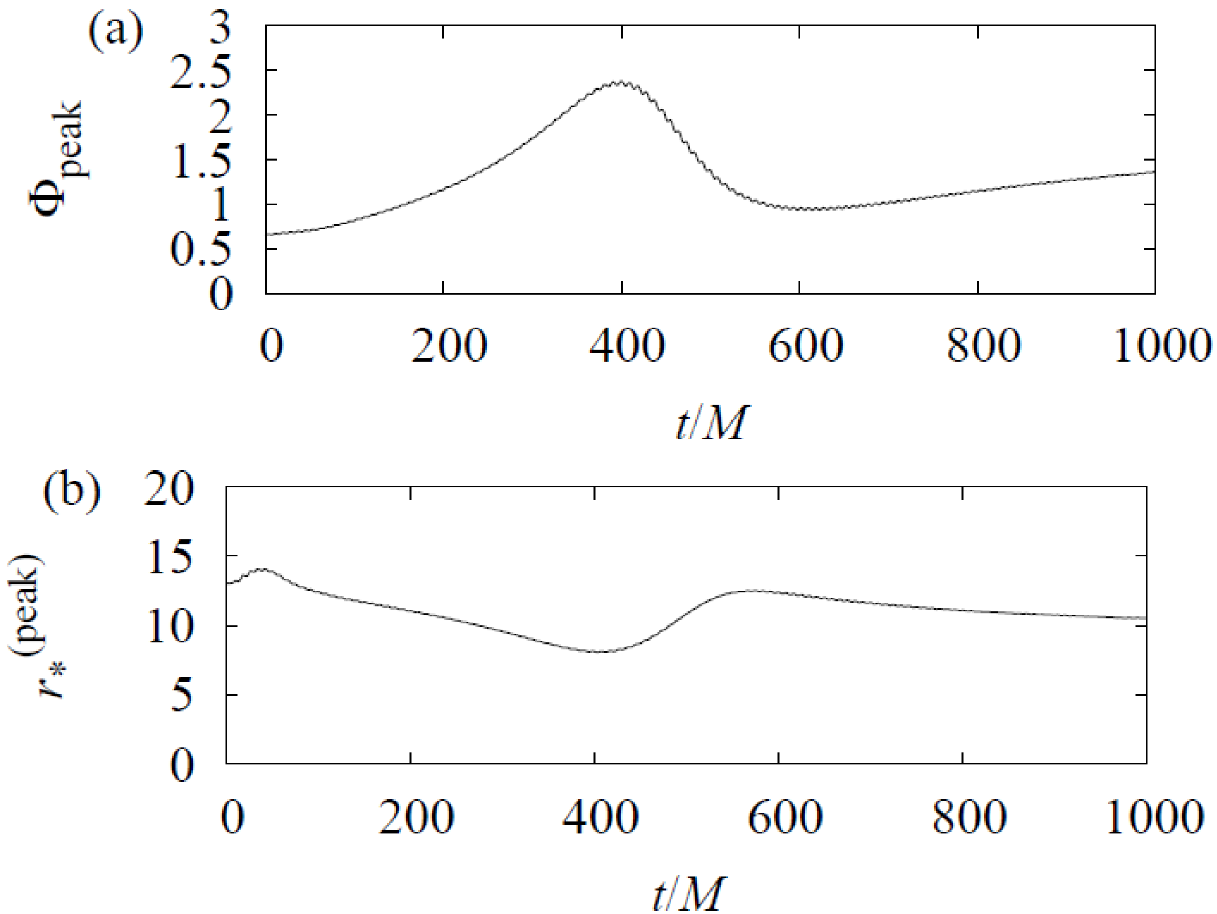


Equatorial plane

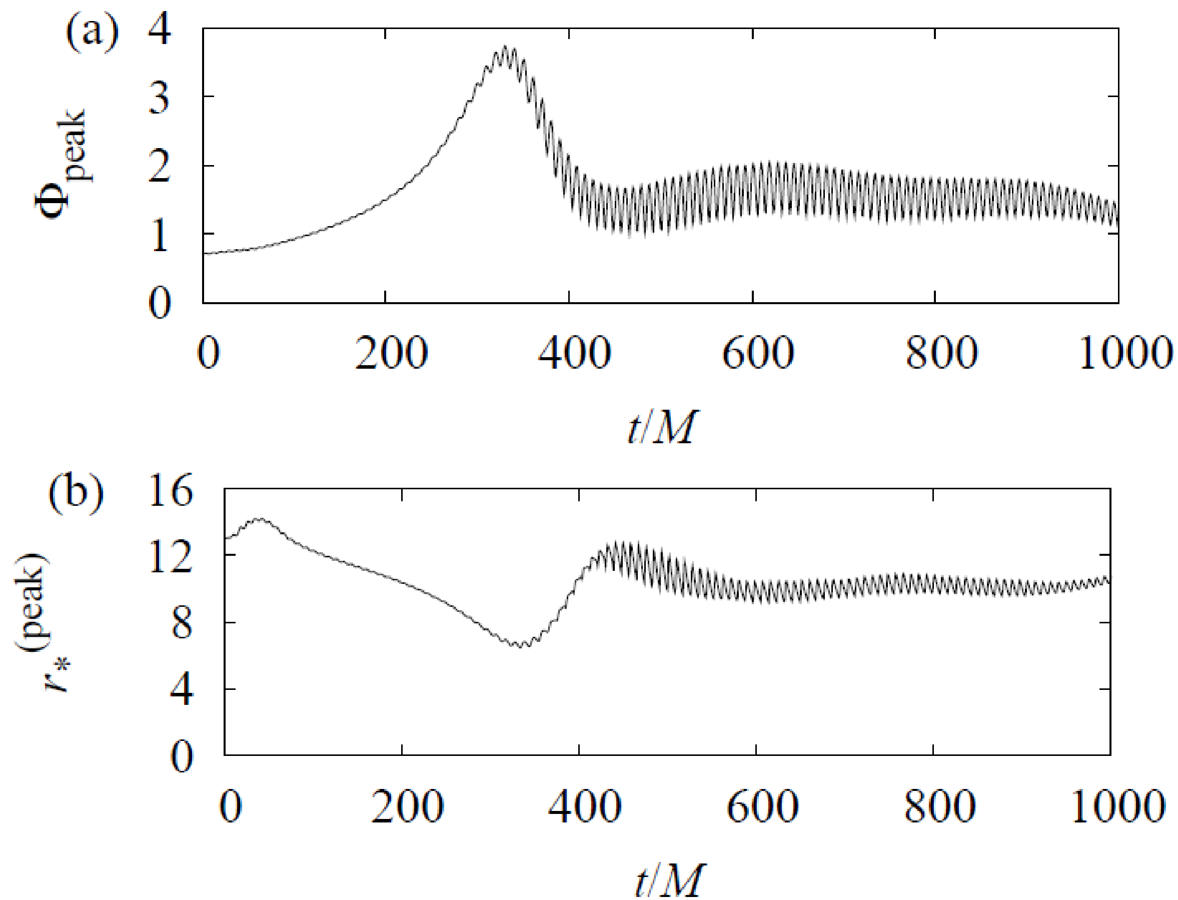


r-z plane

Model (B)


(a)
Φ_{peak}
3
2.5
2
1.5
1
0.5
0
0
200
400
600
800
1000
t/M
(b)
$r_*^{(peak)}$
20
15
10
5
0
0
200
400
600
800
1000
t/M

Model (C)



Kodama H, Yoshino H: in preparation

Results and Implications

- 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 !!