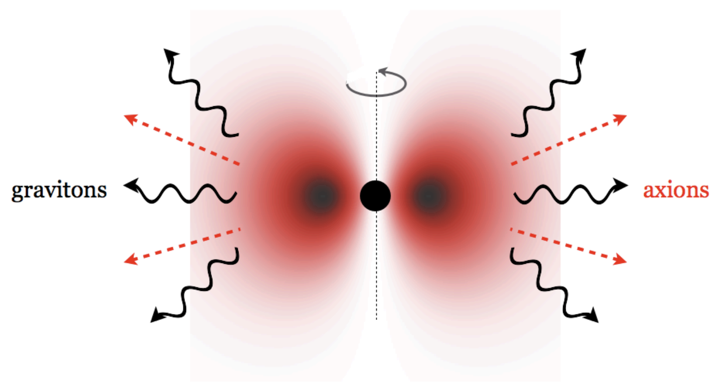
Axion Bosenova
and
Gravitational Waves

Hirotaka Yoshino
Hideo Kodama
(KEK)



PTP128, 153 (2012)
PTEP2014, 043E02 (2014)
arXiv:1406.xxxx (in progress)

3-day workshop (holographic vistas) @ YITP at Kyoto U.
(May 26th, 2014)

CONTENTS

- Introduction

PTP128, 153 (2012)
PTEP2014, 043E02 (2014)

- Constraining string axion models from GW observations

in Progress

- Summary

Introduction

Very interesting era of GR

Advanced VIRGO

Advanced LIGO

KAGRA

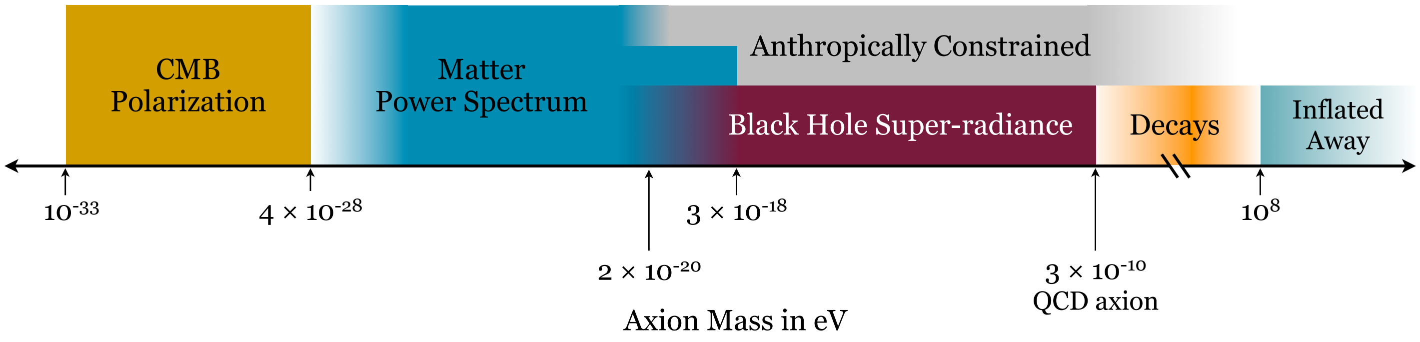
- One of the interesting possibilities is to find new physics beyond GR!

Can we find a signal of string theory?

Arvanitaki, Dimopoulos, Dubvosky, Kaloper, March-Russel,
PRD81 (2010), 123530.

⇨ *Maybe Yes,* if there are String Axions with very tiny mass

- In string theory, many moduli appear when the extra dimensions get compactified.
- Some of them (10-100) are expected to behave like scalar fields with very tiny mass, which are called string axions.

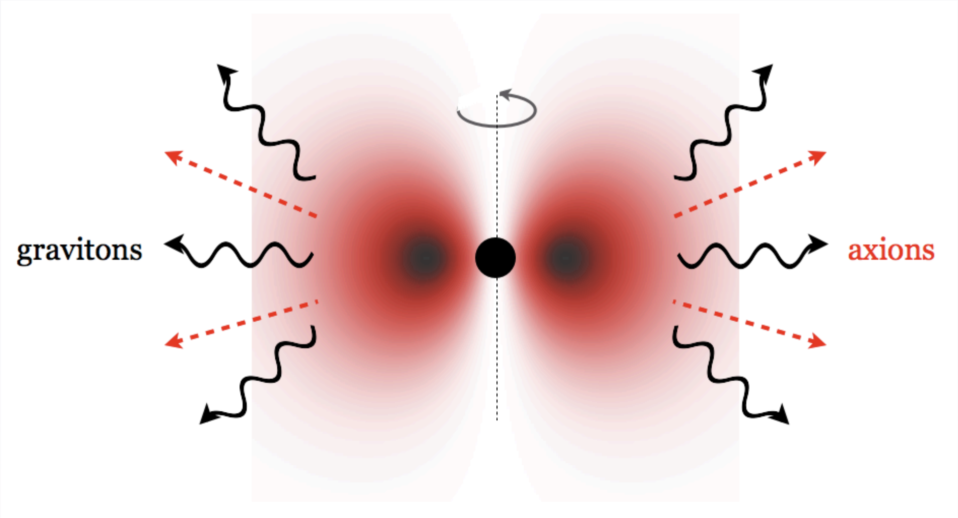


AXIVERSE SCENARIO

Axion field around a rotating BH

- Axion field extracts BH rotational energy and forms an “axion cloud”

⇨ Gravitational atom



Detweiler, PRD22 (1980), 2323.

Zouros and Eardley, Ann. Phys. 118 (1979), 139.

Kerr BH

- Metric

$$ds^2 = -\left(\frac{\Delta - a^2\sin^2\theta}{\Sigma}\right)dt^2 - \frac{2a\sin^2\theta(r^2+a^2-\Delta)}{\Sigma}dt\,d\phi$$
$$+\left[\frac{(r^2+a^2)^2 - \Delta a^2\sin^2\theta}{\Sigma}\right]\sin^2\theta\, d\phi^2 + \frac{\Sigma}{\Delta}dr^2 + \Sigma d\theta^2$$

$$\Sigma = r^2 + a^2\cos^2\theta,$$
$$\Delta = r^2 + a^2 - 2Mr.$$

$$J = Ma$$

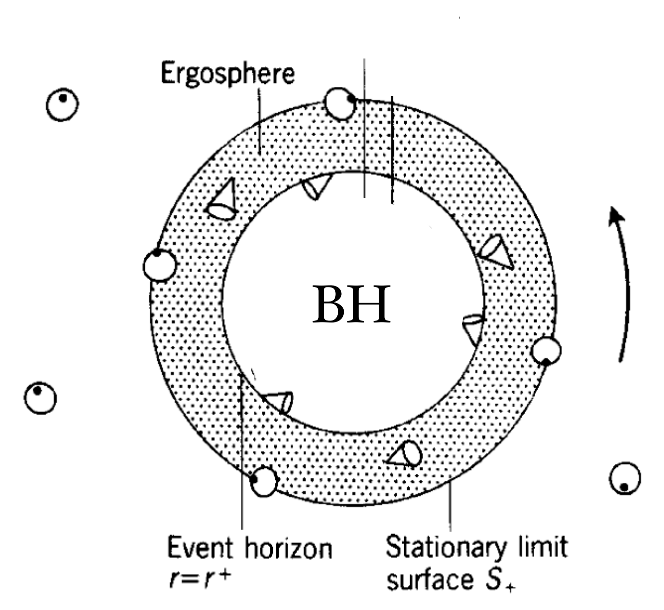
- Ergoregion

ξ^μ becomes spacelike

⇓

Energy density can be $-T_{\mu\nu}\xi^\mu n^\nu < 0$

Superradiant condition: $\omega < m\Omega_H$



Gravitational Atom

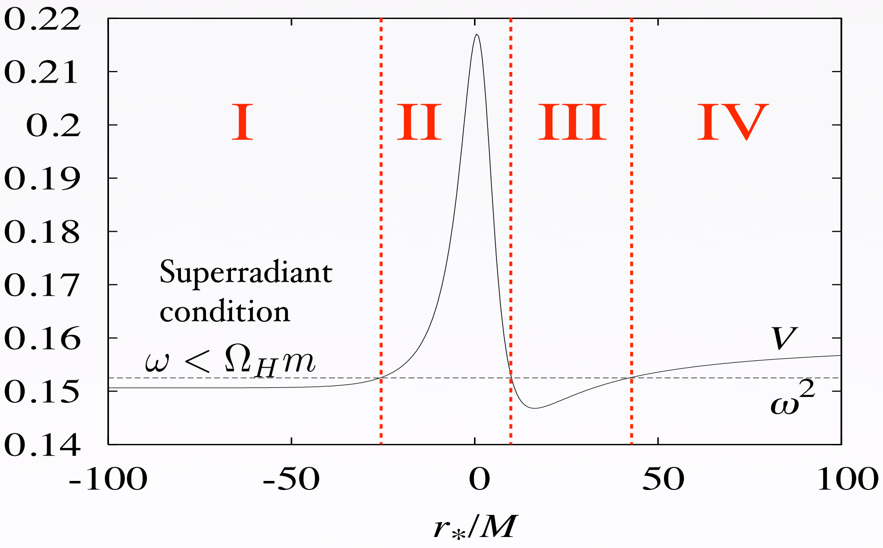
- Massive Klein-Gordon field $\nabla^2\Phi - \mu^2\Phi = 0$

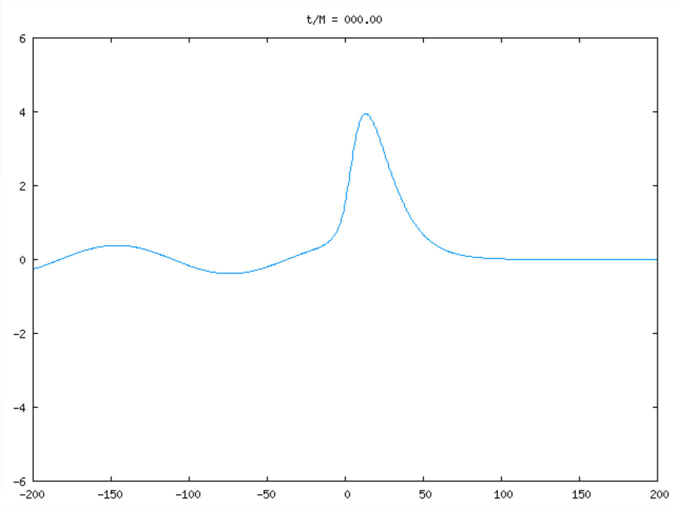
$$\Phi = \mathrm{Re}[e^{-i\omega t}R(r)S(\theta)e^{im\phi}]$$

$$R = \frac{u}{\sqrt{r^2+a^2}}$$

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

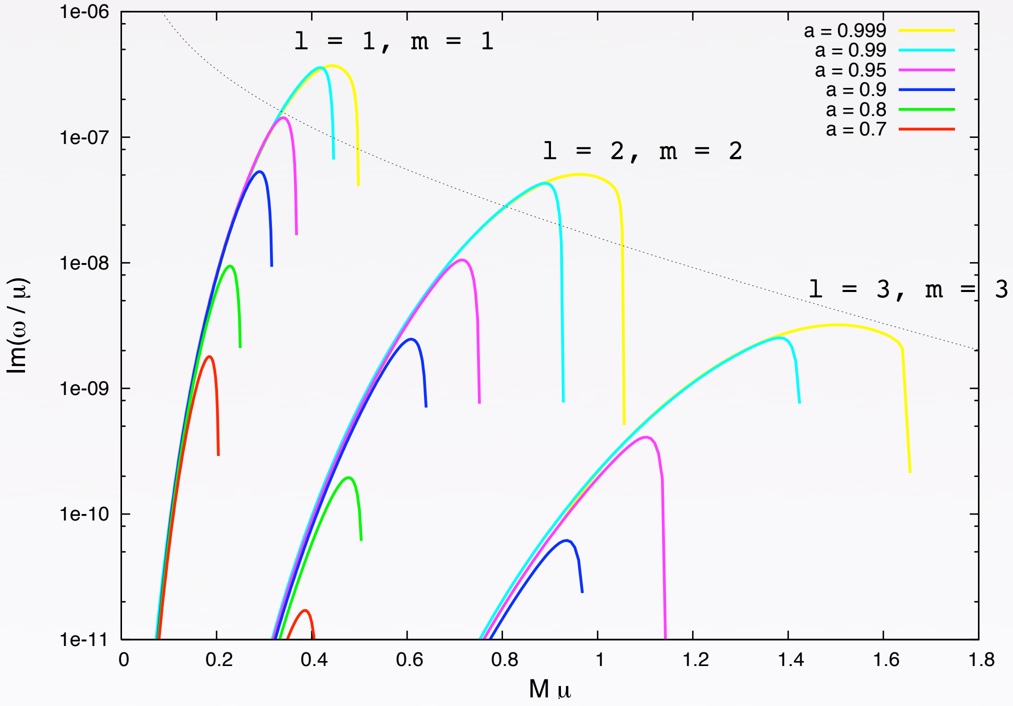
$$\omega = \omega_R + i\,\boxed{\omega_I} \leftarrow$$ Unstable if positive





Growth rate

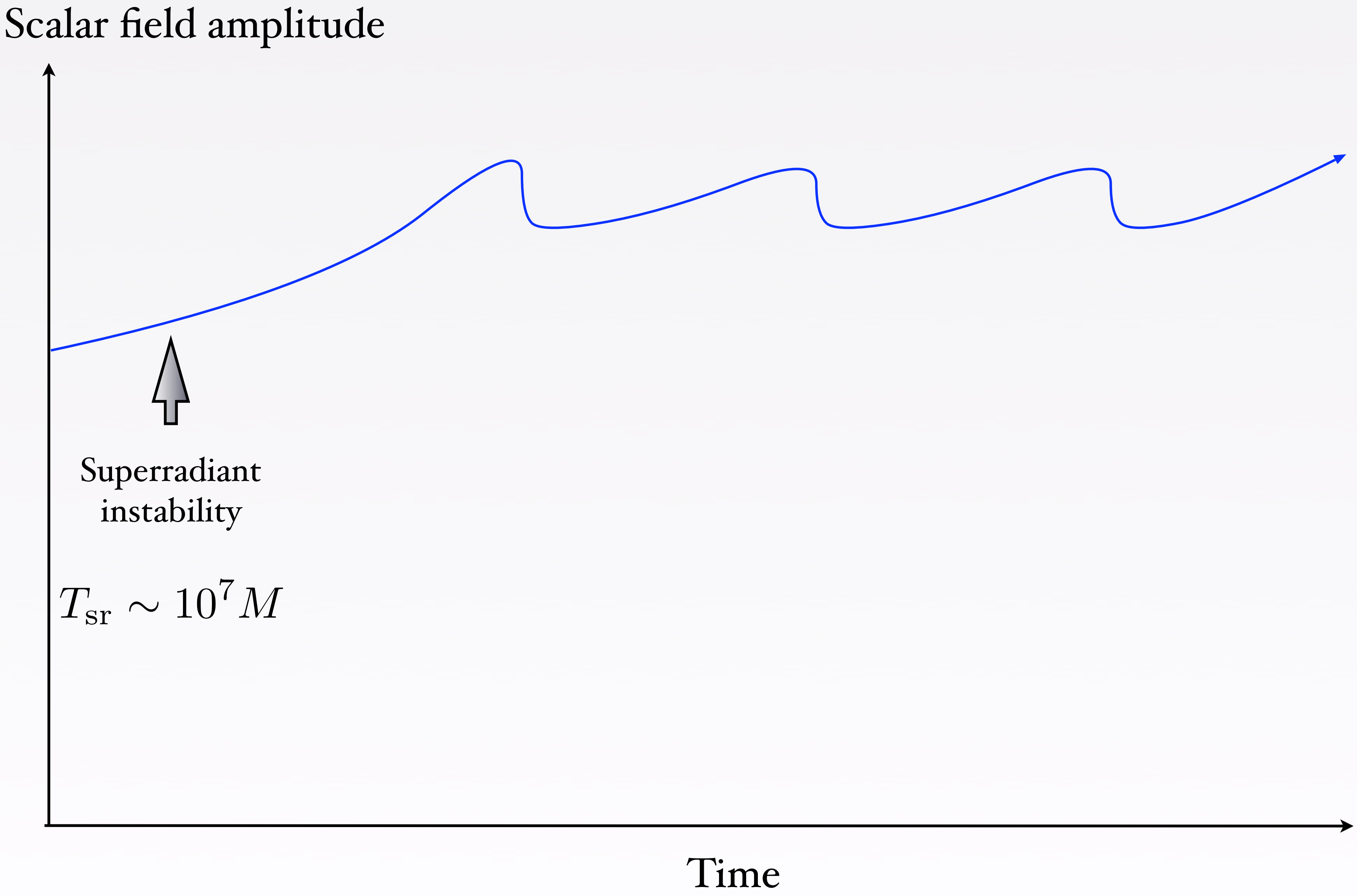
- Growth rate (continued fraction method) Dolan, PRD76 (2007), 084001.



- Typical time scale:

$$M = M_\odot \qquad \begin{array}{lll} \omega_I M \sim 10^{-7} & \Rightarrow & \sim 1 \text{ min.} \\ \omega_I M \sim 10^{-12} & \Rightarrow & \sim 1 \text{ day} \end{array}$$

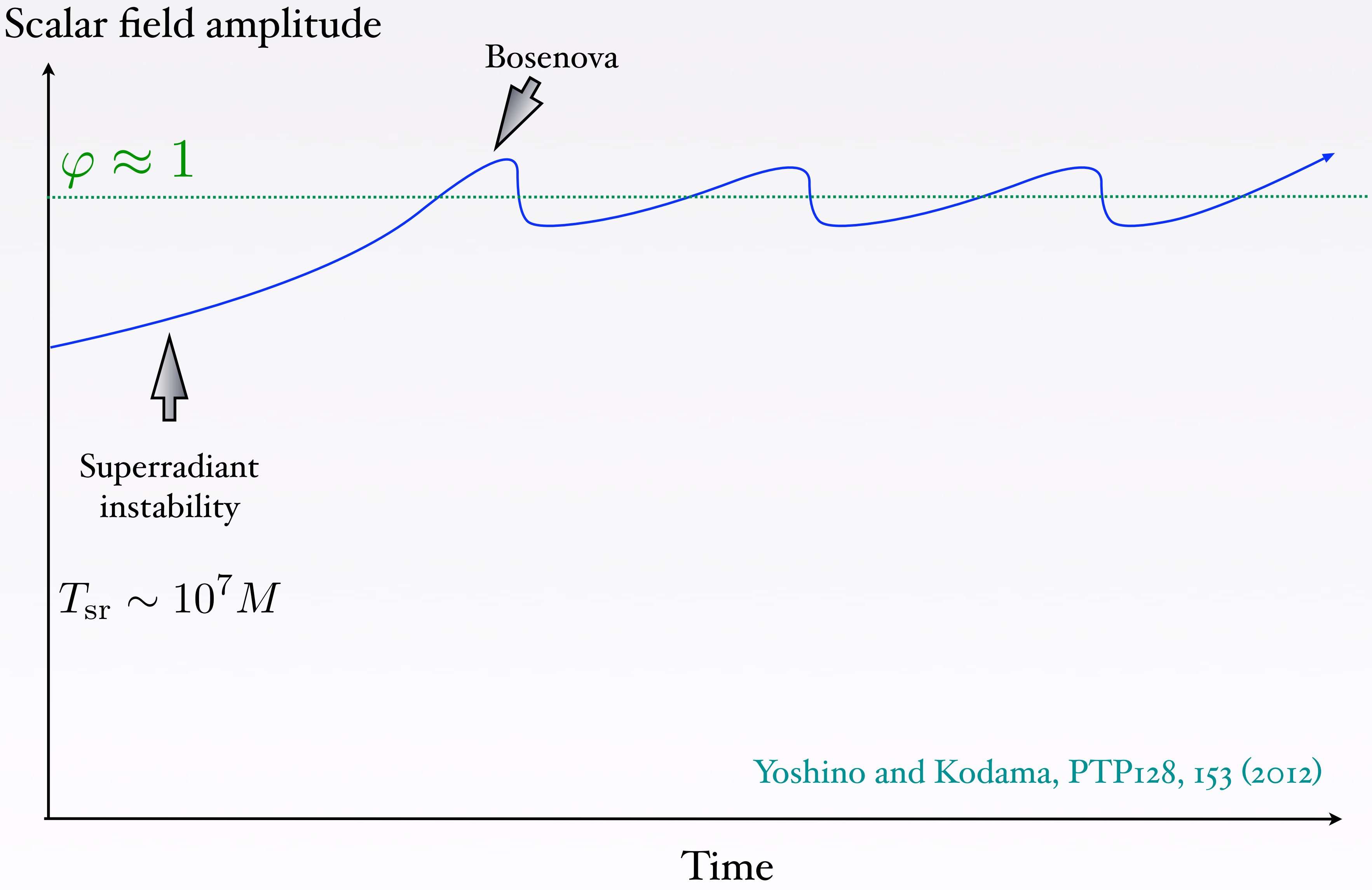
Gross phenomena of the BH-axion system



Superradiant instability

$T_{\mathrm{sr}} \sim 10^7 M$

Gross phenomena of the axion-BH system



Scalar field amplitude

Bosenova

$\varphi \approx 1$

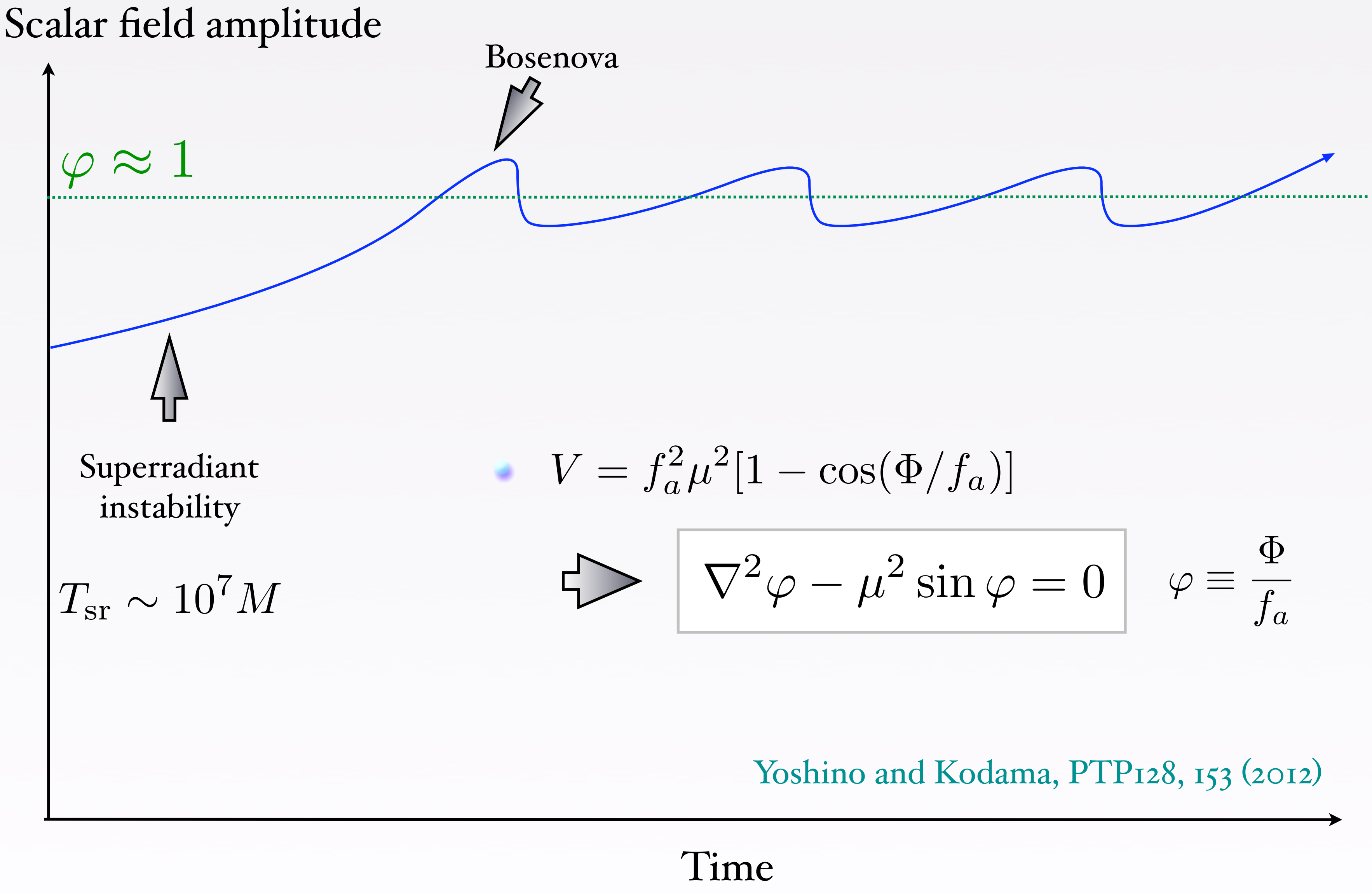
Superradiant instability

$T_{\mathrm{sr}} \sim 10^7 M$

Time

Yoshino and Kodama, PTP128, 153 (2012)

Gross phenomena of the axion-BH system



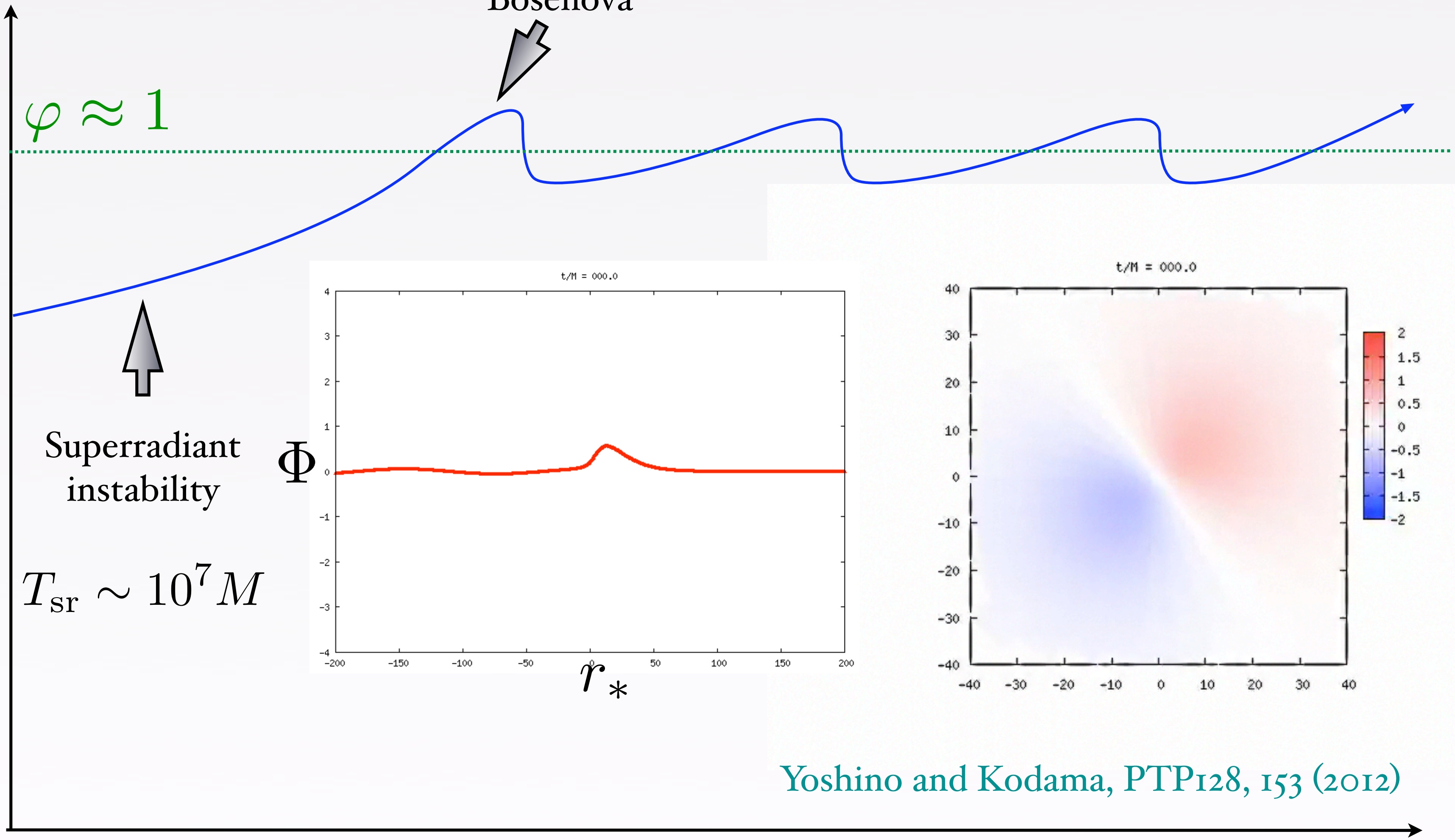
$T_{\rm sr} \sim 10^7 M$

- $V = f_a^2 \mu^2 [1 - \cos(\Phi/f_a)]$

$$\boxed{\nabla^2 \varphi - \mu^2 \sin\varphi = 0} \qquad \varphi \equiv \frac{\Phi}{f_a}$$

Yoshino and Kodama, PTP128, 153 (2012)

Gross phenomena of the axion-BH system



Scalar field amplitude

Bosenova

$\varphi \approx 1$

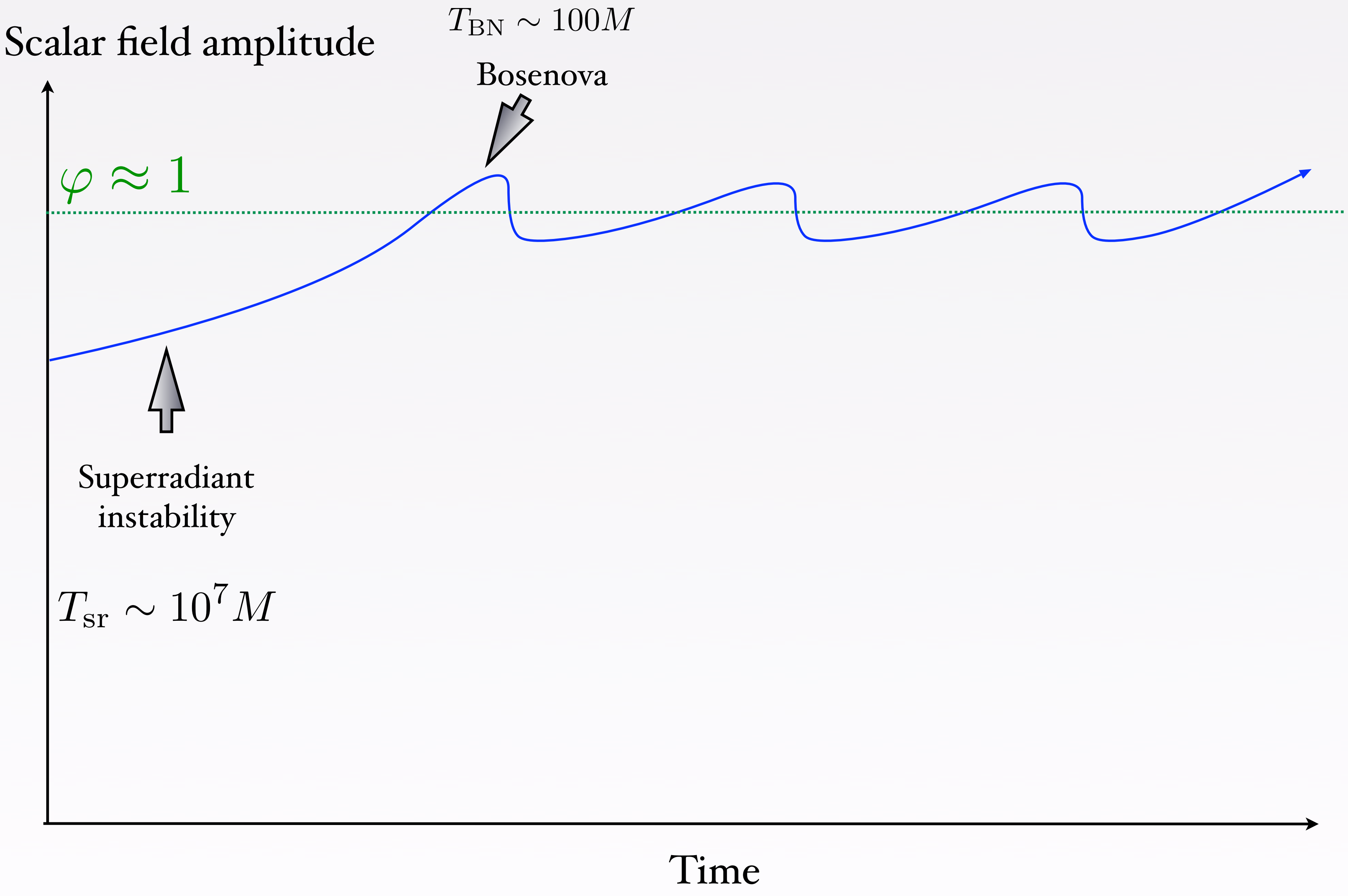
Superradiant instability

$T_{\rm sr} \sim 10^7 M$

Time

Yoshino and Kodama, PTP128, 153 (2012)

Gross phenomena of the axion-BH system



Scalar field amplitude

$T_{\mathrm{BN}} \sim 100M$

Bosenova

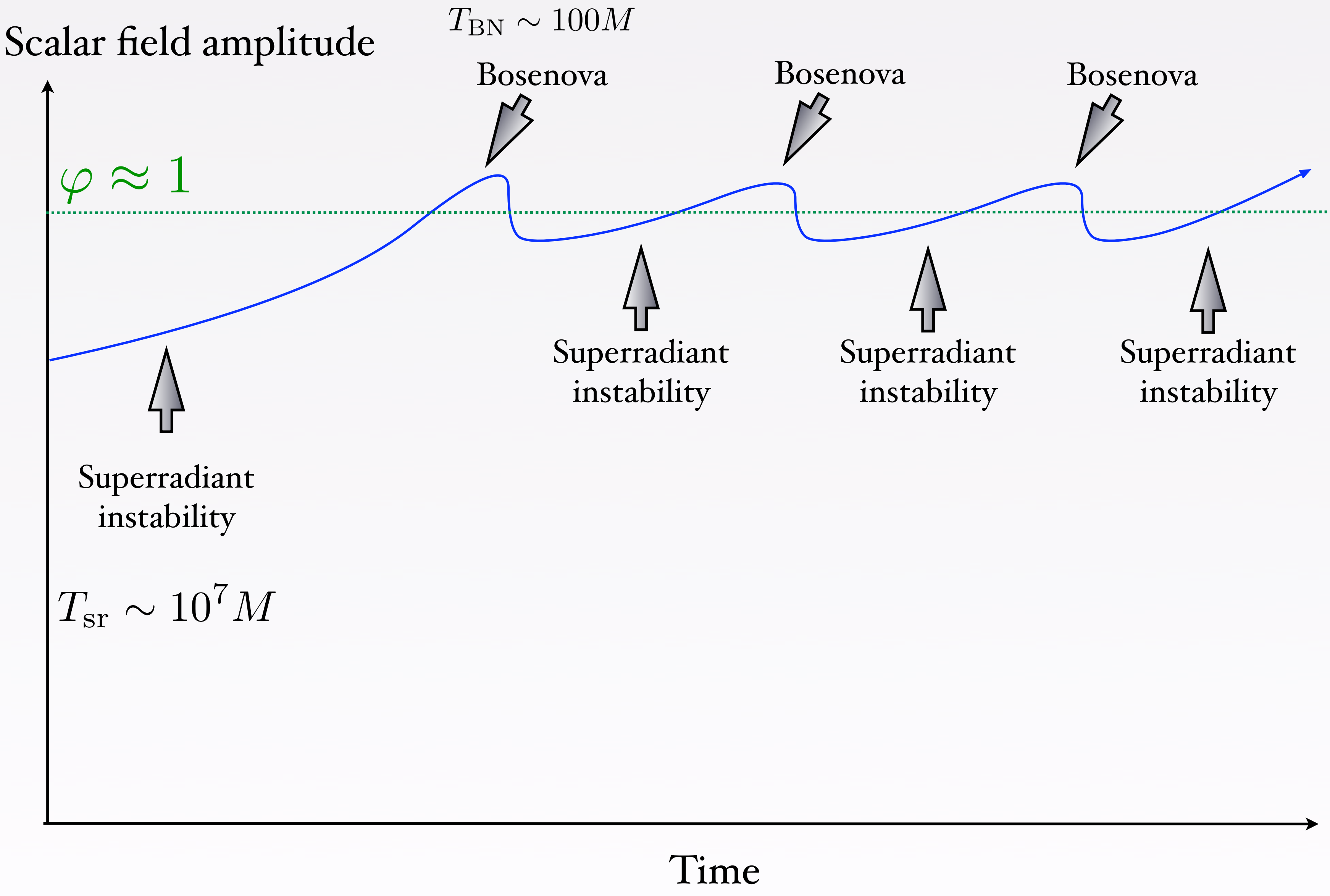
$\varphi \approx 1$

Superradiant
instability

$T_{\mathrm{sr}} \sim 10^7 M$

Time

Gross phenomena of the axion-BH system



Scalar field amplitude

$T_{\mathrm{BN}} \sim 100M$

Bosenova

Bosenova

Bosenova

$\varphi \approx 1$

Superradiant instability

Superradiant instability

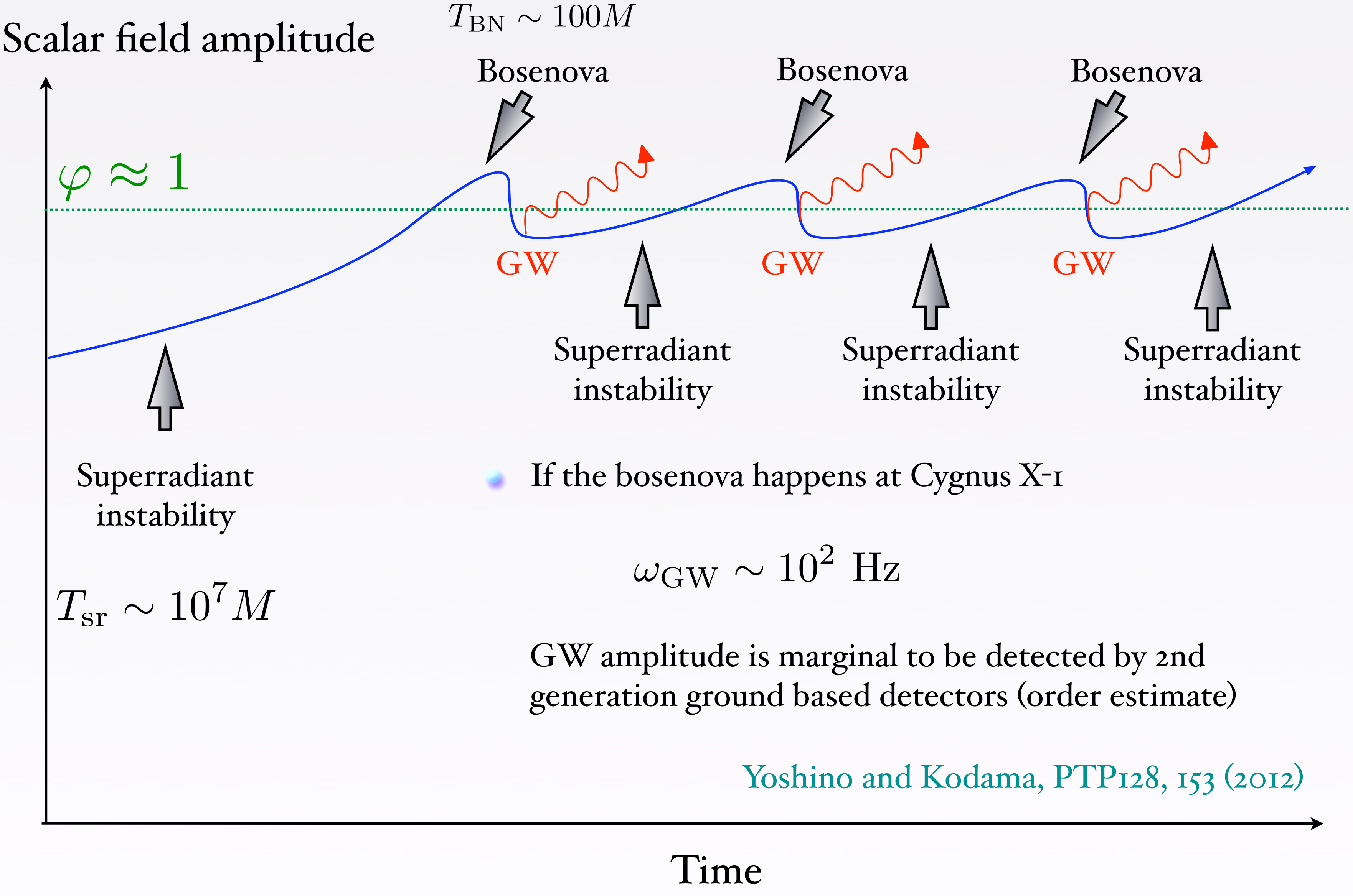
Superradiant instability

Superradiant instability

$T_{\mathrm{sr}} \sim 10^7 M$

Time

Gross phenomena of the axion-BH system



Scalar field amplitude

$T_{\rm BN} \sim 100M$

Bosenova

Bosenova

Bosenova

$\varphi \approx 1$

GW

GW

GW

Superradiant instability

Superradiant instability

Superradiant instability

Superradiant instability

$T_{\rm sr} \sim 10^7 M$

- If the bosenova happens at Cygnus X-1

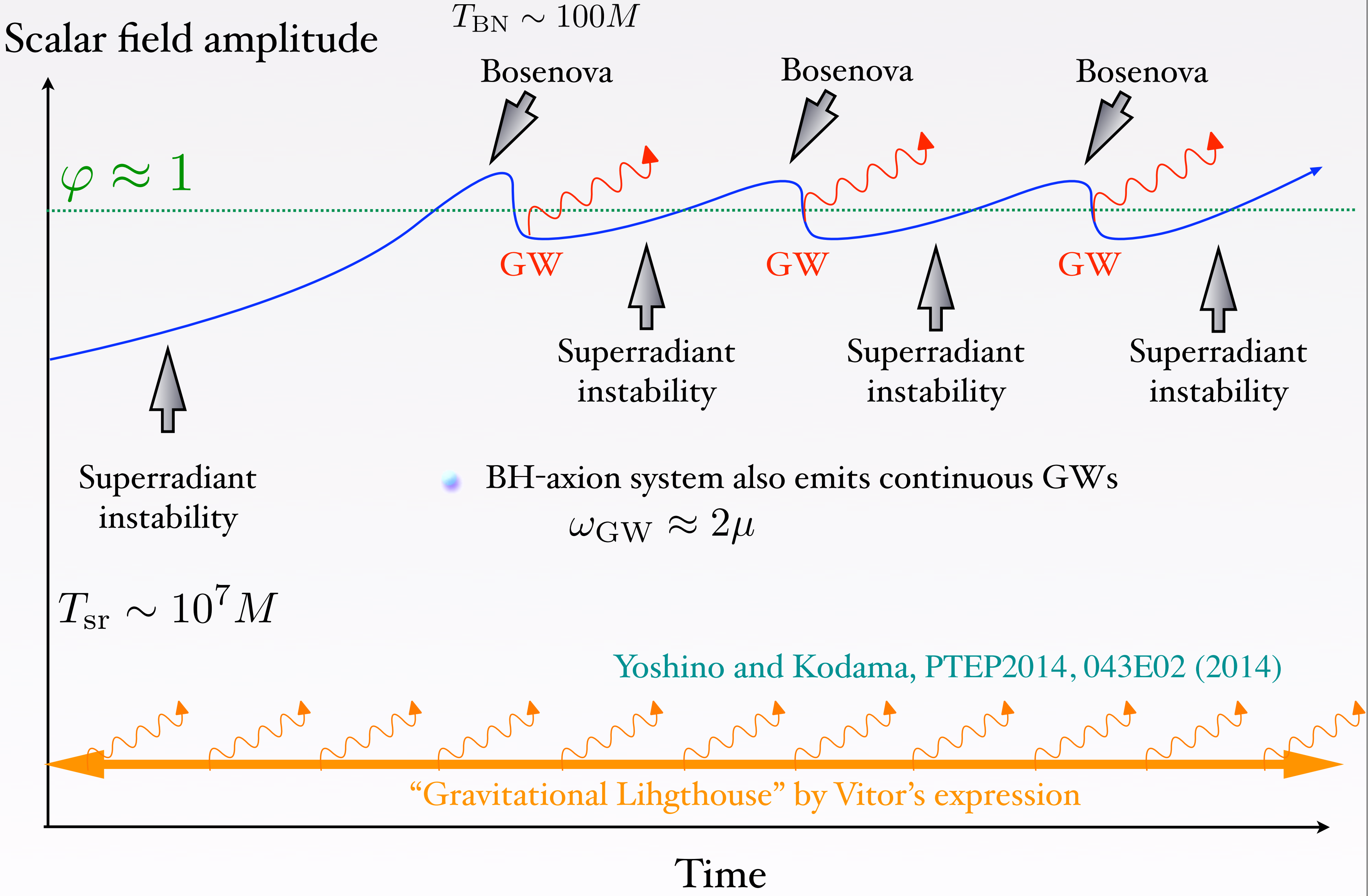
$$\omega_{\rm GW} \sim 10^2 \ \text{Hz}$$

GW amplitude is marginal to be detected by 2nd generation ground based detectors (order estimate)

Yoshino and Kodama, PTP128, 153 (2012)

Time

Gross phenomena of the axion-BH system



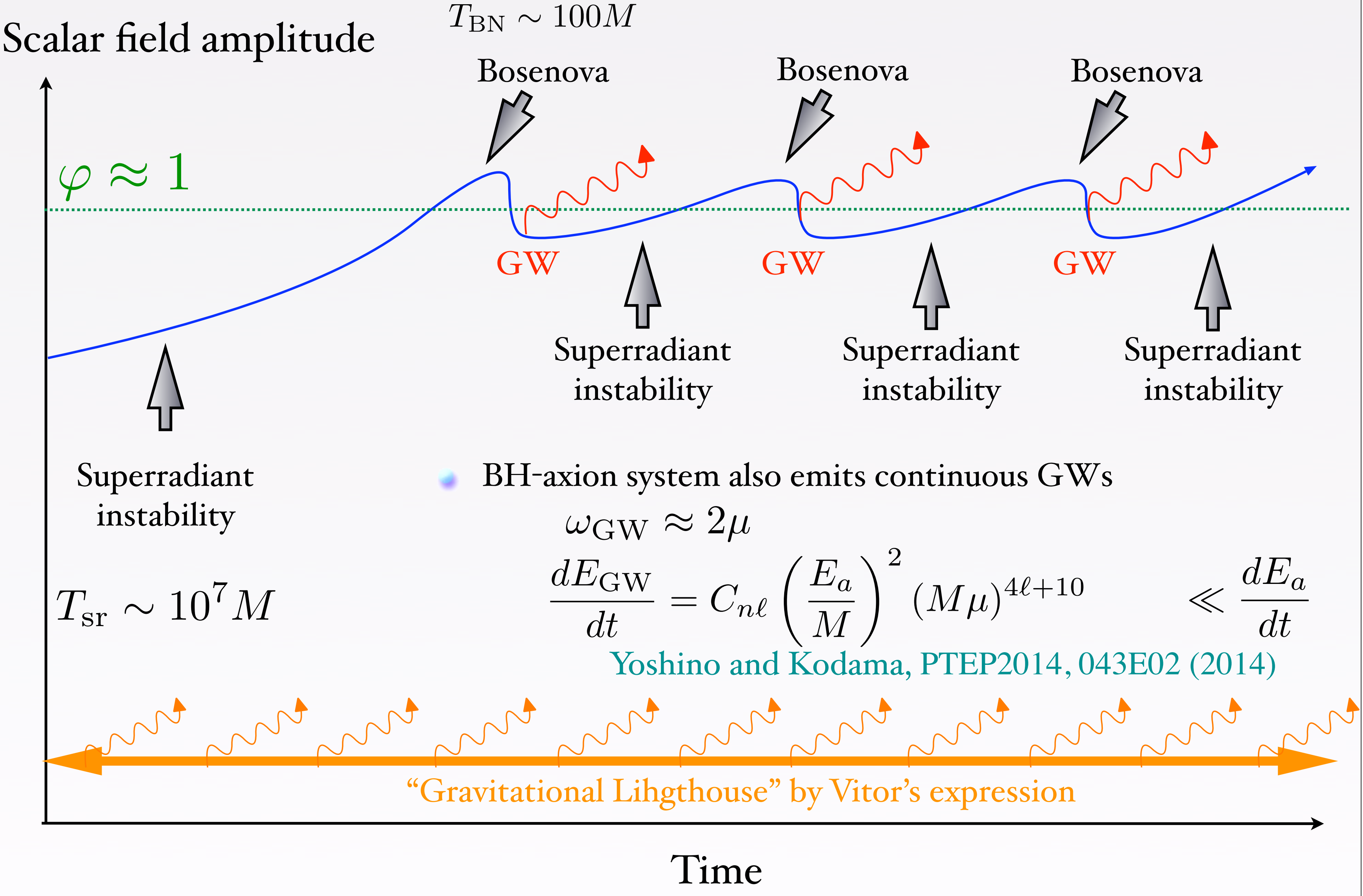
- BH-axion system also emits continuous GWs

$$\omega_{\rm GW} \approx 2\mu$$

Yoshino and Kodama, PTEP2014, 043E02 (2014)

“Gravitational Lihgthouse” by Vitor’s expression

Gross phenomena of the axion-BH system



Scalar field amplitude

$T_{\rm BN} \sim 100M$

Bosenova

Bosenova

Bosenova

$\varphi \approx 1$

GW

GW

GW

Superradiant instability

Superradiant instability

Superradiant instability

Superradiant instability

$T_{\rm sr} \sim 10^7 M$

- BH-axion system also emits continuous GWs

$$\omega_{\rm GW} \approx 2\mu$$

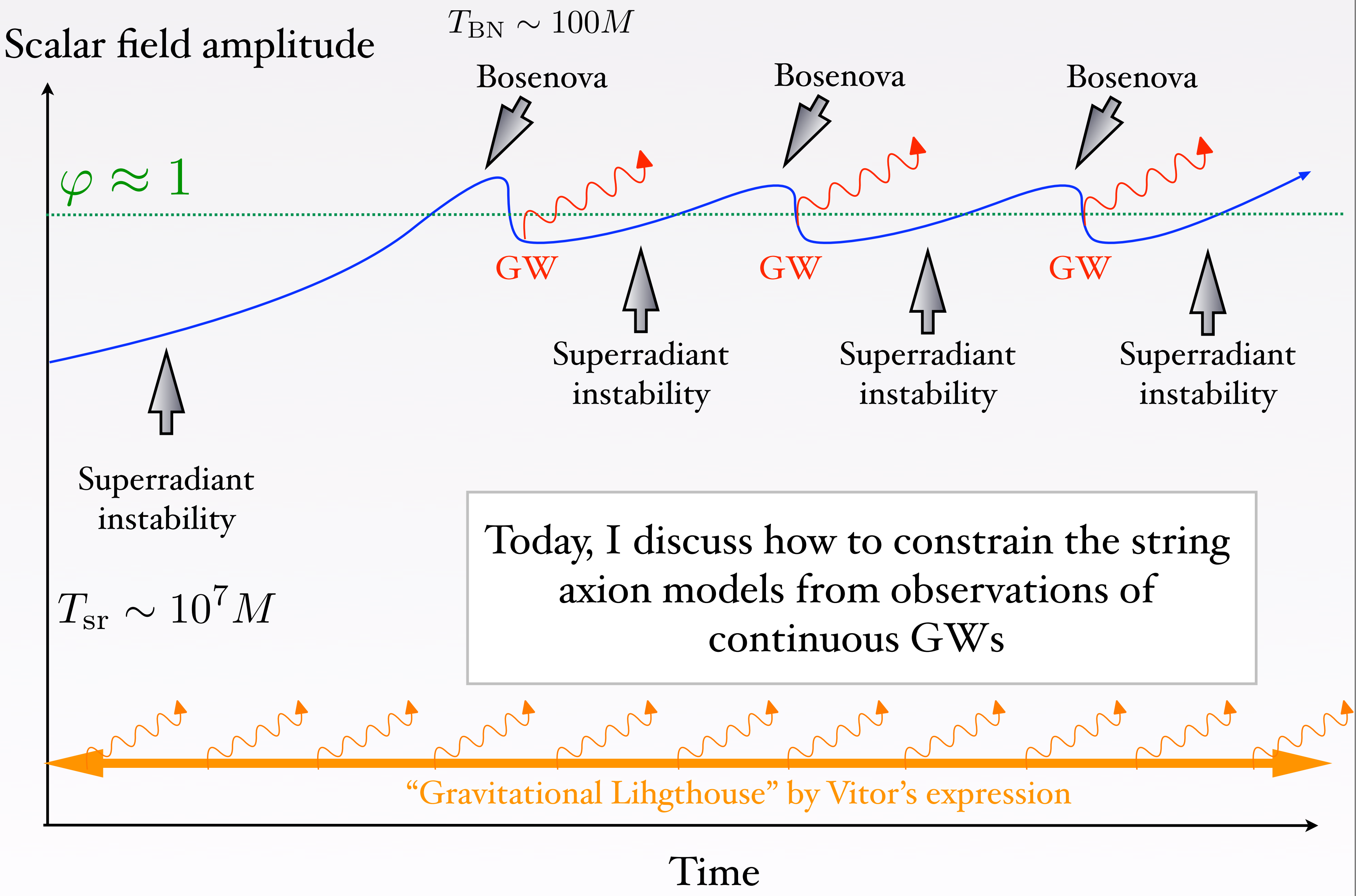
$$\frac{dE_{\rm GW}}{dt} = C_{n\ell}\left(\frac{E_a}{M}\right)^2 (M\mu)^{4\ell+10} \qquad \ll \frac{dE_a}{dt}$$

Yoshino and Kodama, PTEP2014, 043E02 (2014)

“Gravitational Lihghthouse” by Vitor’s expression

Time

Gross phenomena of the axion-BH system



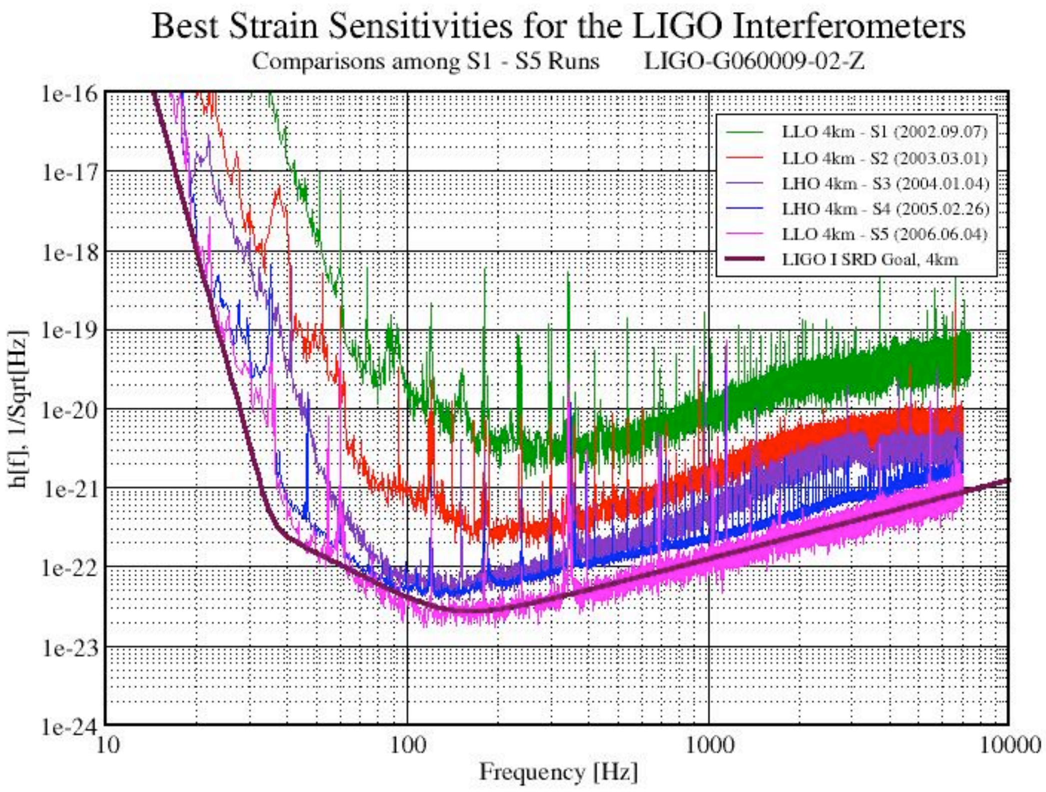
Today, I discuss how to constrain the string axion models from observations of continuous GWs

Constraining string axion models from GW observation

Preliminary

LIGO's science runs (1)

PRD69, 082004 (2004); …; arXiv:1311.2409 [gr-qc]

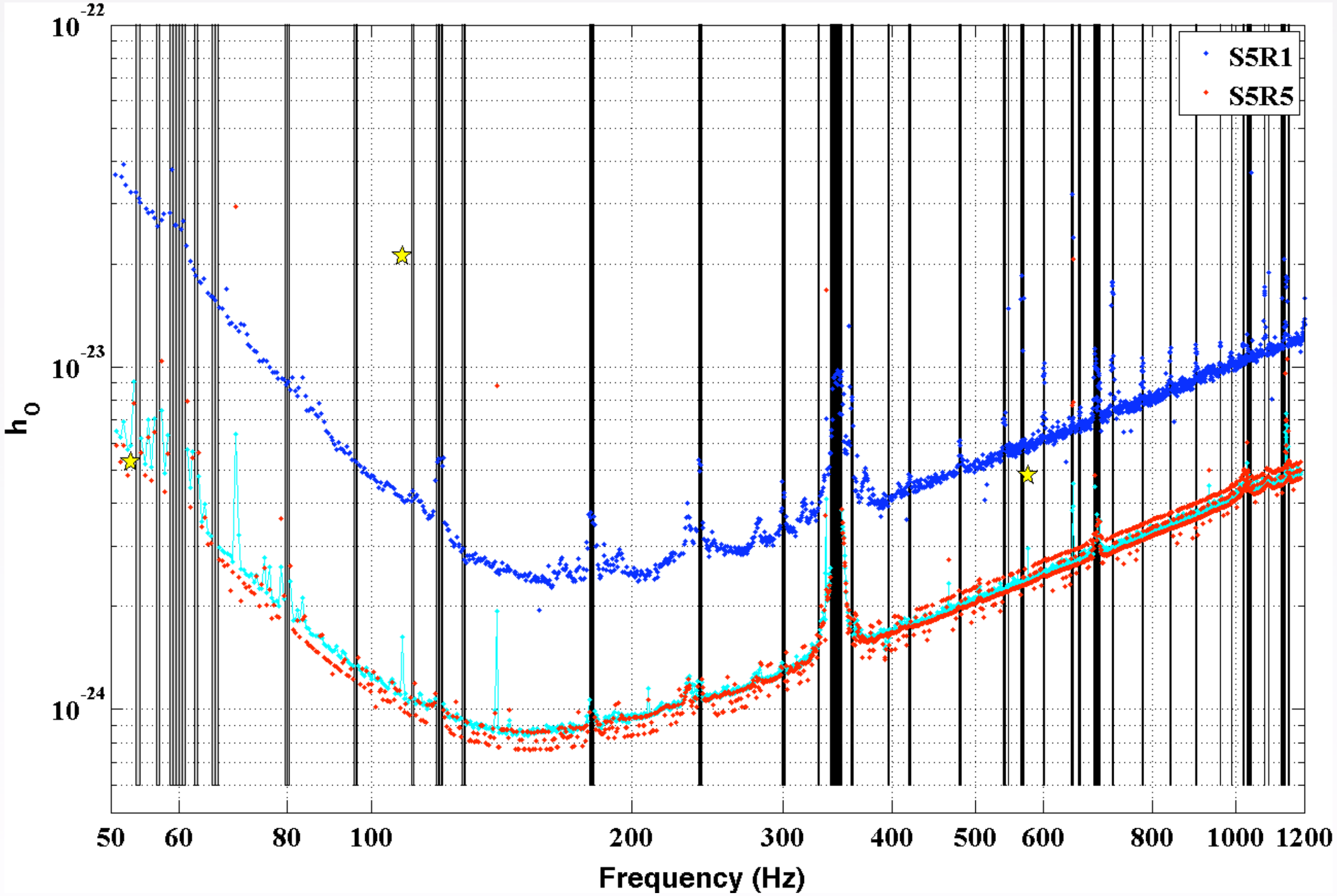


- They looked for continuous waves from distorted pulsars
- Detectable amplitude can be made smaller by increasing observation time

$$h_{\rm rss} \sim h\sqrt{T_{\rm obs}}$$

LIGO's continuous wave search

No GWs have been detected,
upper limit on the amplitude is given.



Our idea (1)

- Consider continuous waves from BH-axion system

$$50 \text{ Hz} \leq f \leq 1200 \text{ Hz}$$

$$\Leftrightarrow \quad 10^{-13} \text{ eV} \leq \mu \leq 2.4 \times 10^{-12} \text{ eV}$$

- If we assume $M \approx 15 M_{\odot}\,,\quad 0.0125 \leq M\mu \leq 0.3$

$\Rightarrow$ We consider axion cloud in the l = m = 1 mode
We use the approximate formula for small $M\mu$

$\Rightarrow$ The wave form is same as the distorted pulsar case

Amplitude: $h_0 \approx \left(\frac{E_a}{M}\right) (\mu M)^6 \left(\frac{M}{d}\right)$

Our idea (2)

- We adopt the axion cloud energy when the nonlinear self-interaction becomes important

$$\frac{\Phi_{\rm max}}{f_a} \approx \frac{1}{\sqrt{8\pi e^2}} \sqrt{\frac{E_a}{M}} \left(\frac{f_a}{M_p}\right)^{-1} (\mu M)^2 \approx 1$$

$$\Rightarrow \boxed{10^{-22} \left(\frac{f_a}{10^{16}{\rm GeV}}\right)^2 \left(\frac{M}{15 M_\odot}\right)^3 \left(\frac{\mu}{10^{-12}{\rm eV}}\right)^2 \left(\frac{d}{1{\rm kpc}}\right)^{-1} < h_{\rm UL}}$$

- In order to exclude the situation where gravitational backreaction is significant, we require

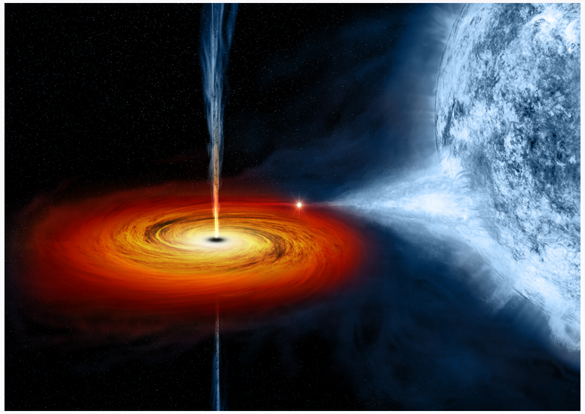
$$\frac{E_a}{M} < 0.05 \quad \Rightarrow \boxed{\frac{f_a}{10^{16}{\rm GeV}} < 0.1 \times \left(\frac{M}{15 M_\odot}\right)^2 \left(\frac{\mu}{10^{-12}{\rm eV}}\right)^2}$$

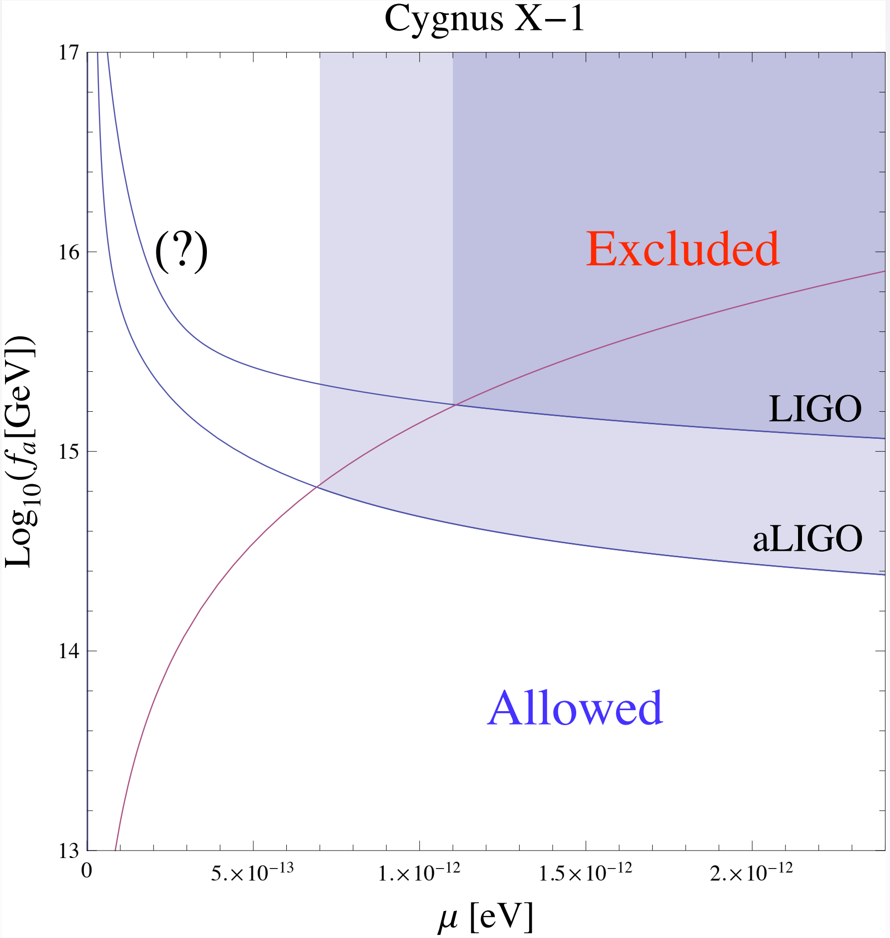
Let us consider Cygnus X-1

$$M \approx 15 M_\odot$$

$$a_* \gtrsim 0.9$$

$$d \approx 1.86 \text{ kpc}$$





McClintock, et al., arXiv:1106.3688-3690{astro-ph}

Remark

- The result of the continuous wave search cannot be used in our case because
    - In the data analysis, isolated pulsar is assumed.
    - Cygnus X-1 is a binary system, and therefore,
      GW frequency fluctuates by the Doppler shift
    - The data analysis strongly depend on the assumed situation
- If the target search of continuous waves from the Cygnus X-1 is carried out, that kind of constraint can be obtained.

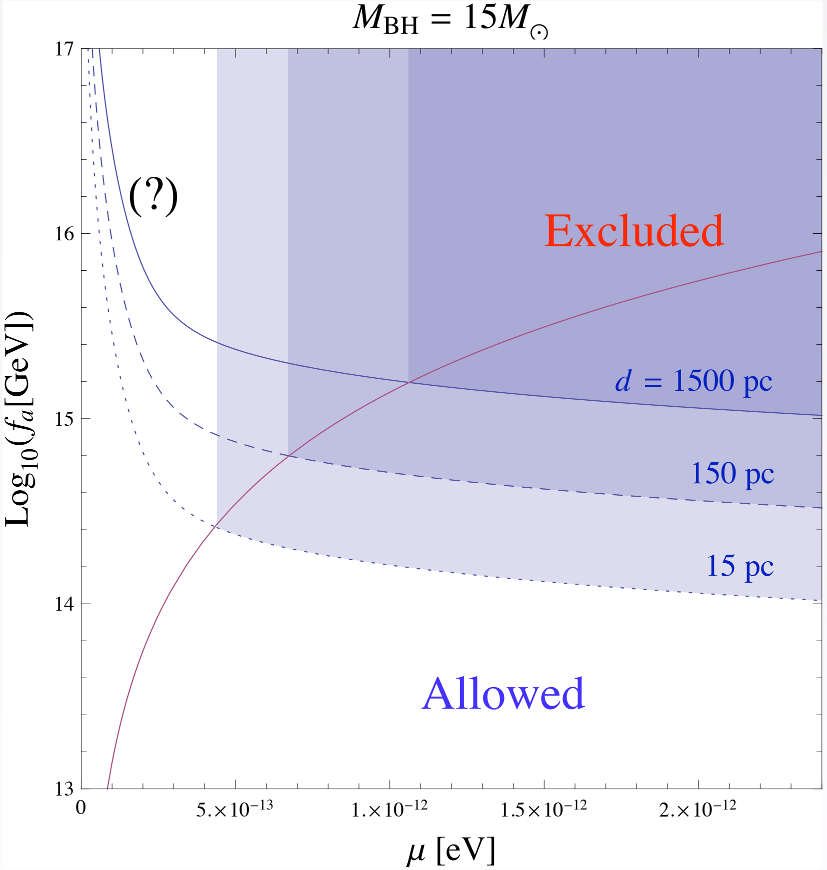
Dependence on the distance

- Some estimates give the BH number in our galaxy as 10^8–10^9

  Timms, Woosley, Weaver, ApJ457, 834 (1996).

- The averaged distance in the neighbouring BHs is expected to be 7–15 pc

$\Rightarrow$ There might exist invisible isolated BH at relatively close position



Summary

Summary

- It is possible to constrain string axion models from existing LIGO observational data.
- Target search from continuous GWs from Cygnus X-1 is required to obtain rigorous constraint.
- Invisible isolated solar mass BHs are likely to exist relatively close to us, and this suggests that string axions may be constrained more strongly.