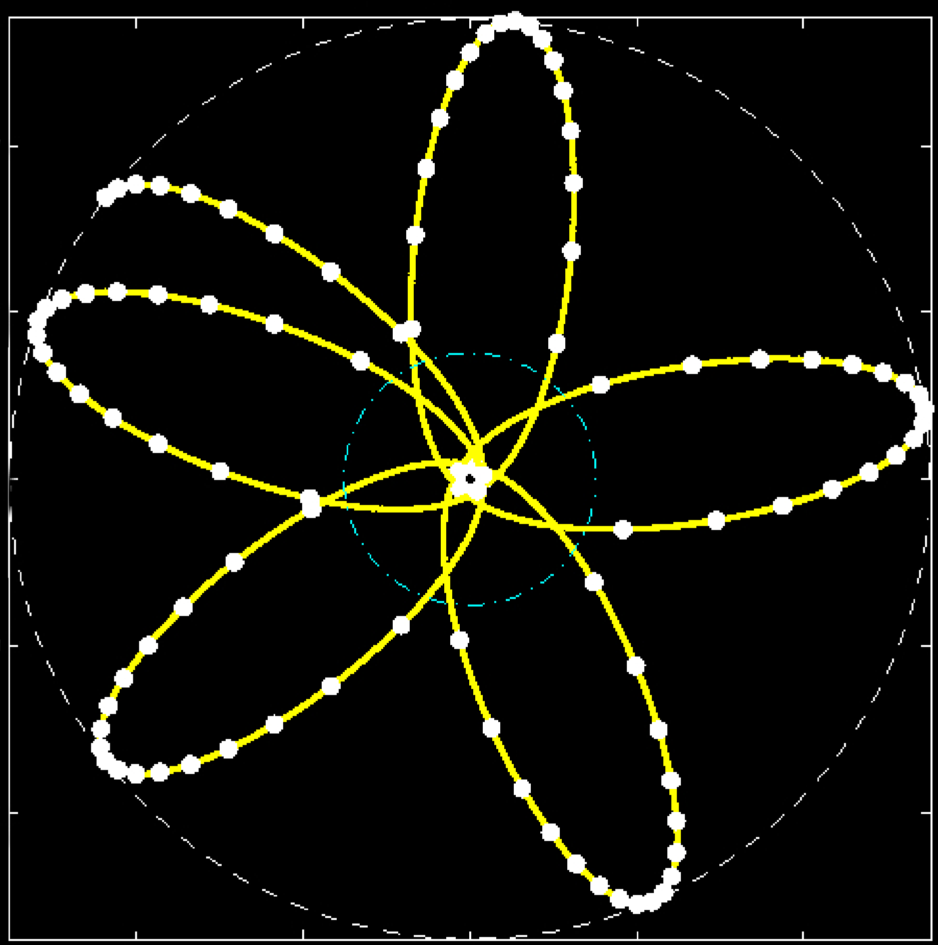
Test particle motion in boson star space-times



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Black Holes VII

Aveiro 19/12/2014

Contents

- Motivation: What are *boson stars*?

  Why study *boson stars*?

- Results: Typical mass and radius of a boson star

  Probing the space-time of a *boson star*

- Conclusions & Outlook

Motivation …

...for studying boson stars

Self-gravitating scalar fields

$$S=\int\sqrt{-g}\,d^4x\left(\frac{R}{16\pi G}+L_{matter}\right)$$

action

Matter Lagrangian

$$L_{matter}=-(\partial_\mu\Phi)(\partial^\mu\Phi)^*-V(|\Phi|)$$

$$V(|\Phi|)=m^2\eta^2\left[1-\exp\left(-|\Phi|^2/\eta^2\right)\right]$$

Scalar potential

Energy scale....

Scalar boson mass

… e.g. SUSY breaking scale:
Copeland, Tsumagari
Phys. Rev. D 80 (2009)

Properties of boson stars

L_{matter} has global U(1) symmetry $\Phi \rightarrow \Phi \exp(i\chi)$

Globally conserved Noether charge Q

$$Q = -i \int \sqrt{-g} \left(\Phi^* \partial^0 \Phi - \Phi \partial^0 \Phi^* \right) d^3 x$$

can be interpreted as number of scalar particles

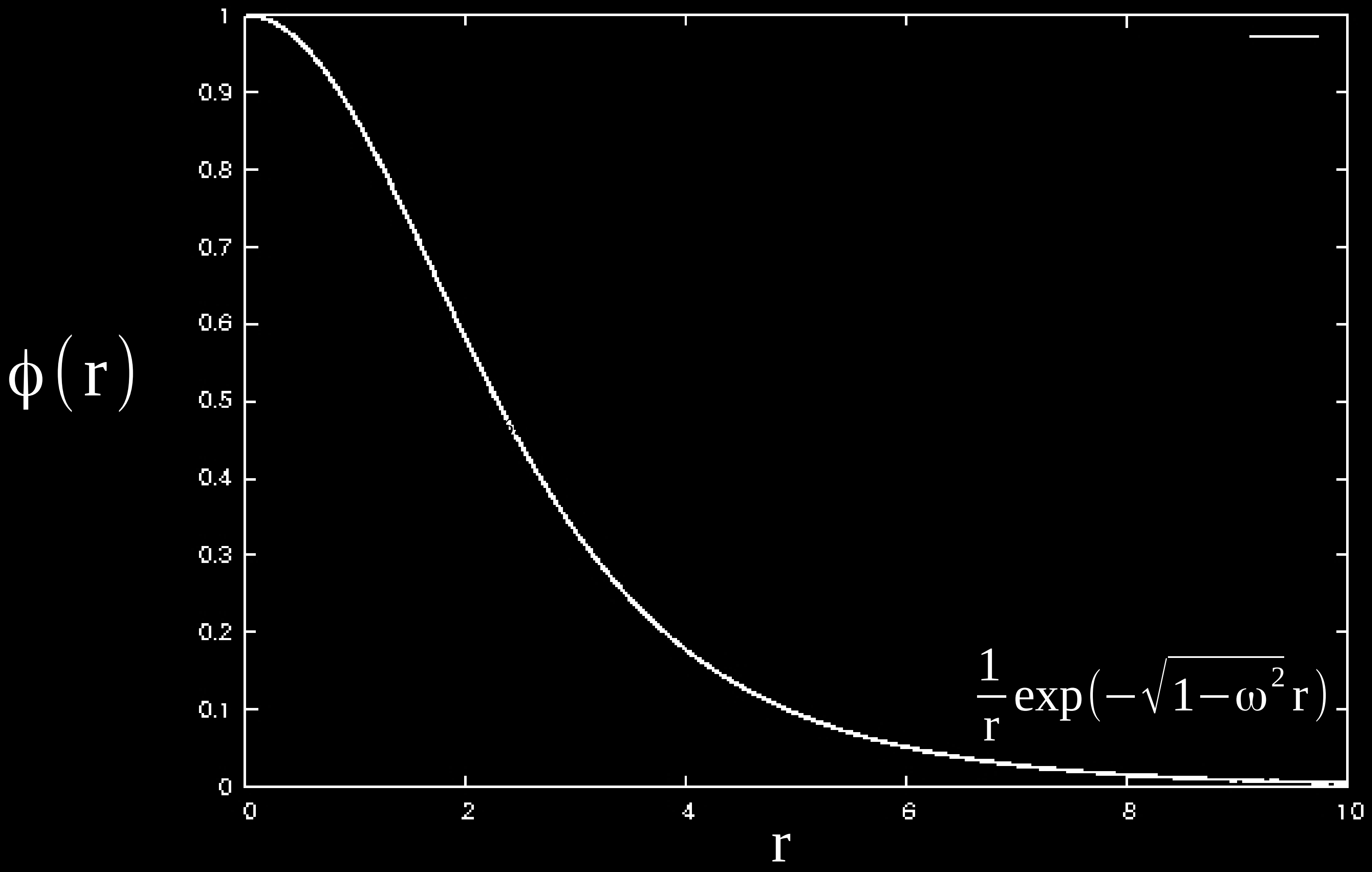
Prevented from collapse by Heisenberg's uncertainty principle

Ansatz for spherically symmetric solutions

$$\Phi = \phi(r) \exp(i \omega t)$$

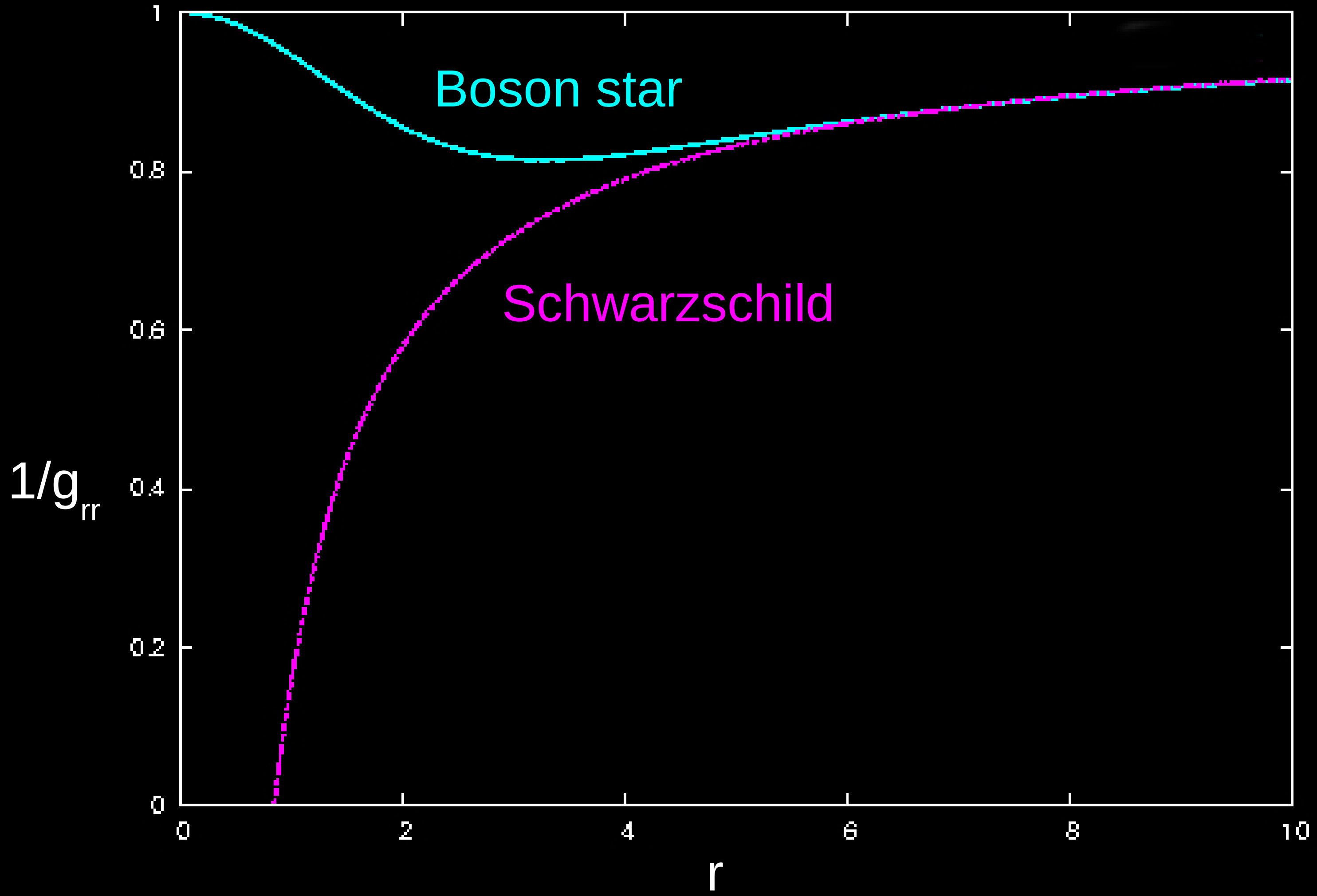
Harmonic time dependence

Boson star vs ordinary star



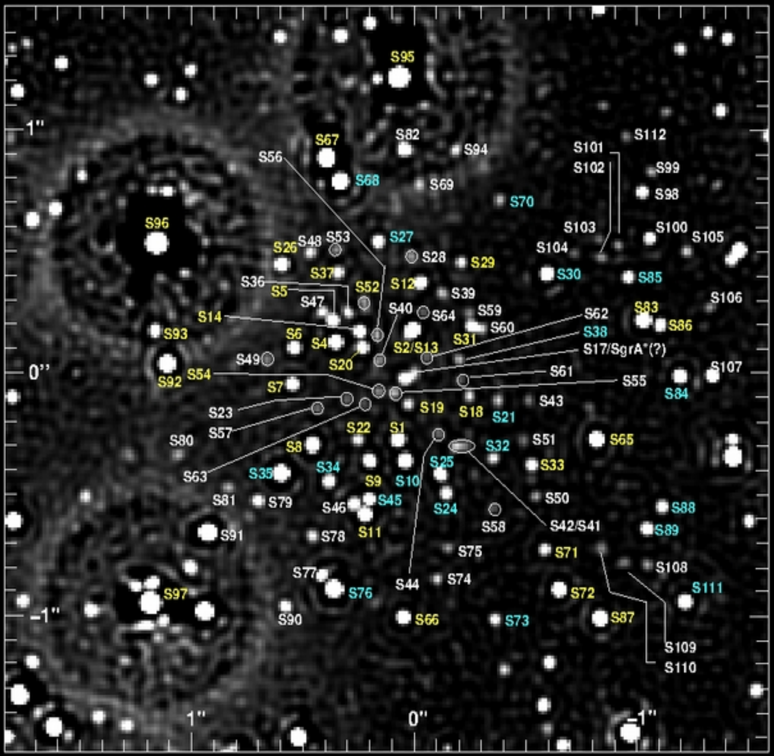
Boson star has no definite surface (no “hard core”)

Boson star vs Black hole

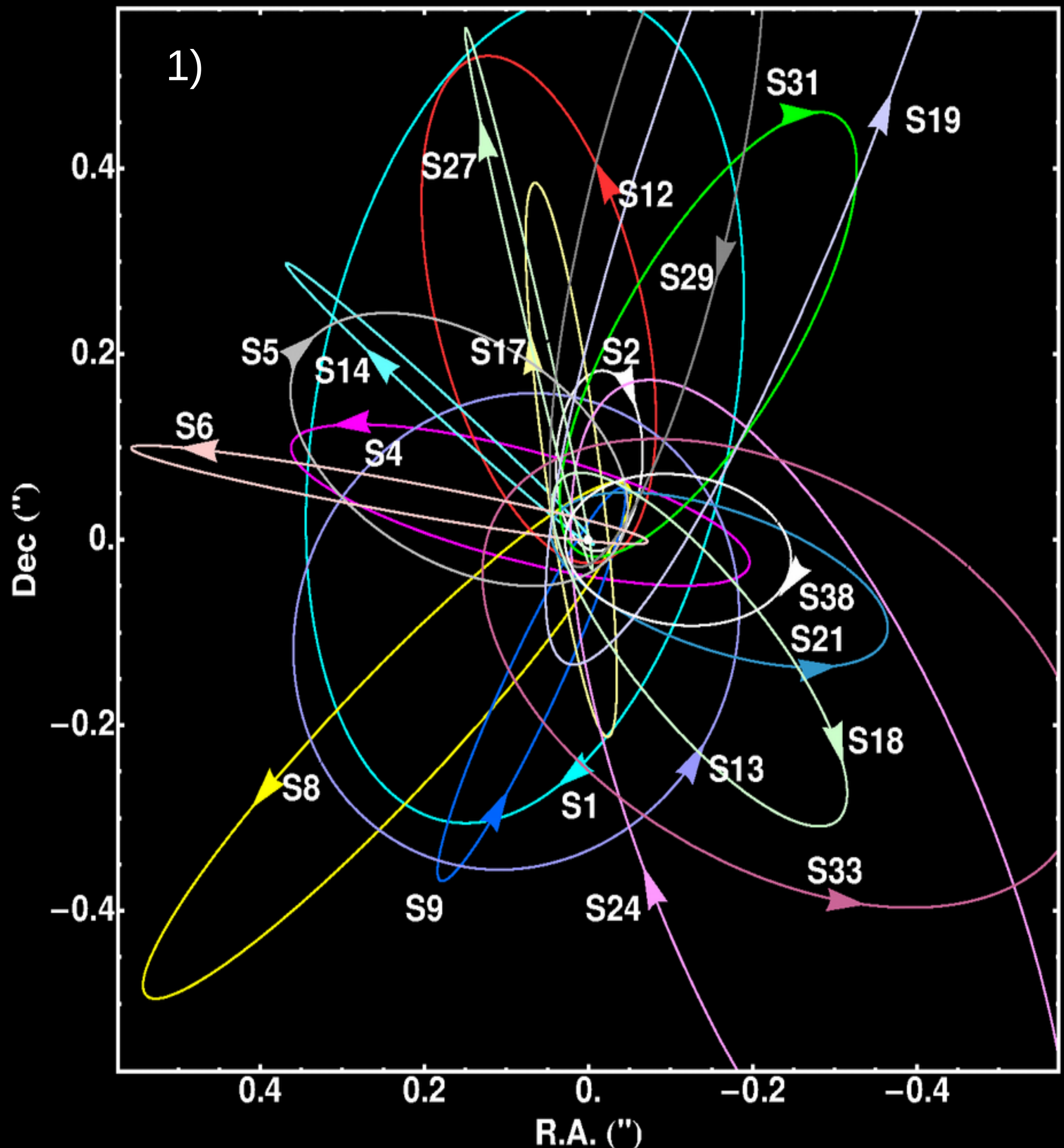


Boson star is globally regular

Supermassive black holes (?!?)

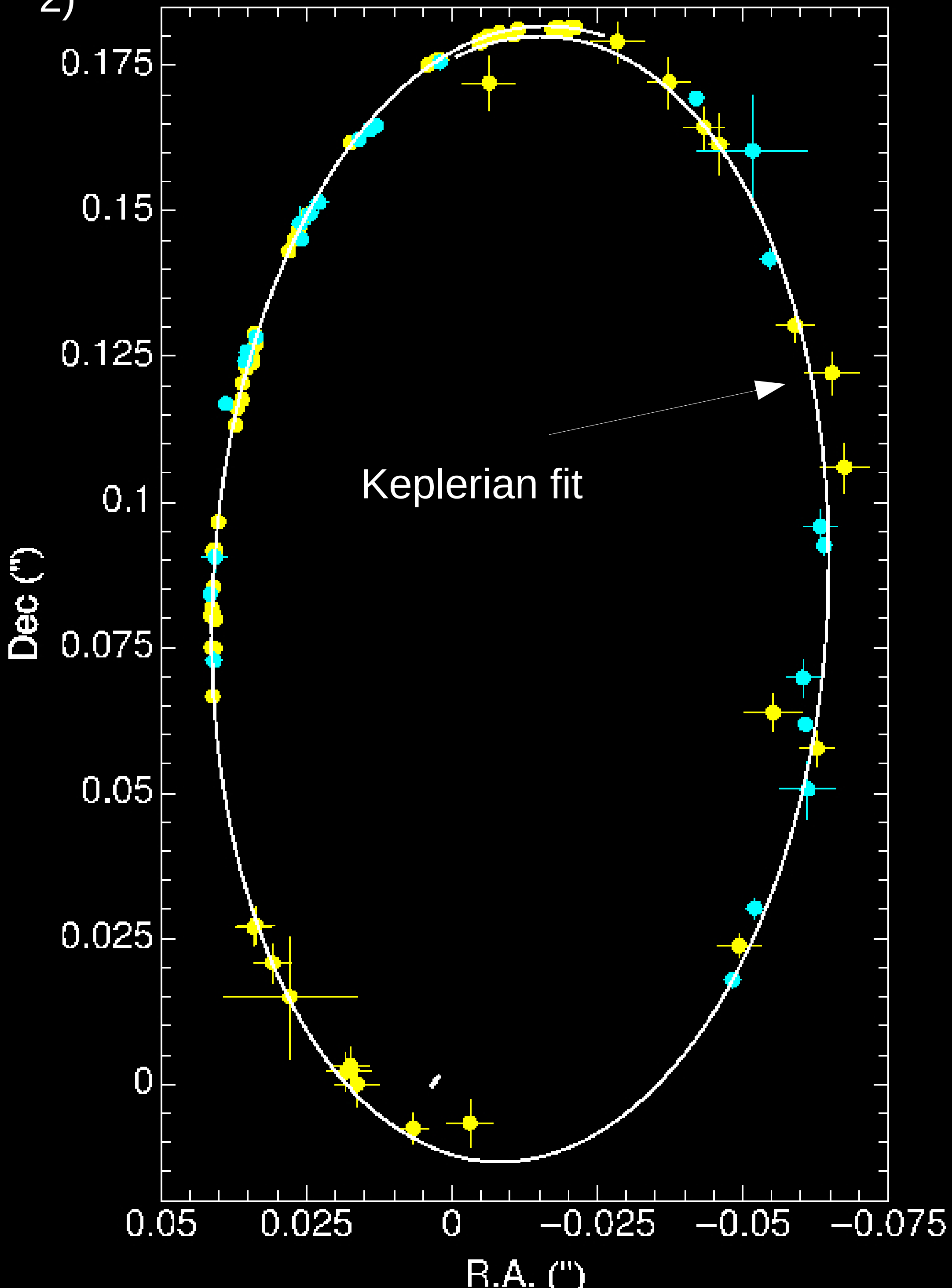
1) 

Monitoring O(100) stars around Sagittarius A* since 1992



1) from:
Gillessen, Eisenhauer, Trippe, Alexander, Genzel, Martins, Ott
Astrophy. J. 692 (2009)

2)



Orbit of S2

Period ≈ 15.2 years

Eccentricity ≈ 0.87

$R_{SgA*} \approx 2.2 \times 10^7$ km

$M_{SgA*} \approx 4.5 \times 10^6 M_{sun}$

SgA*

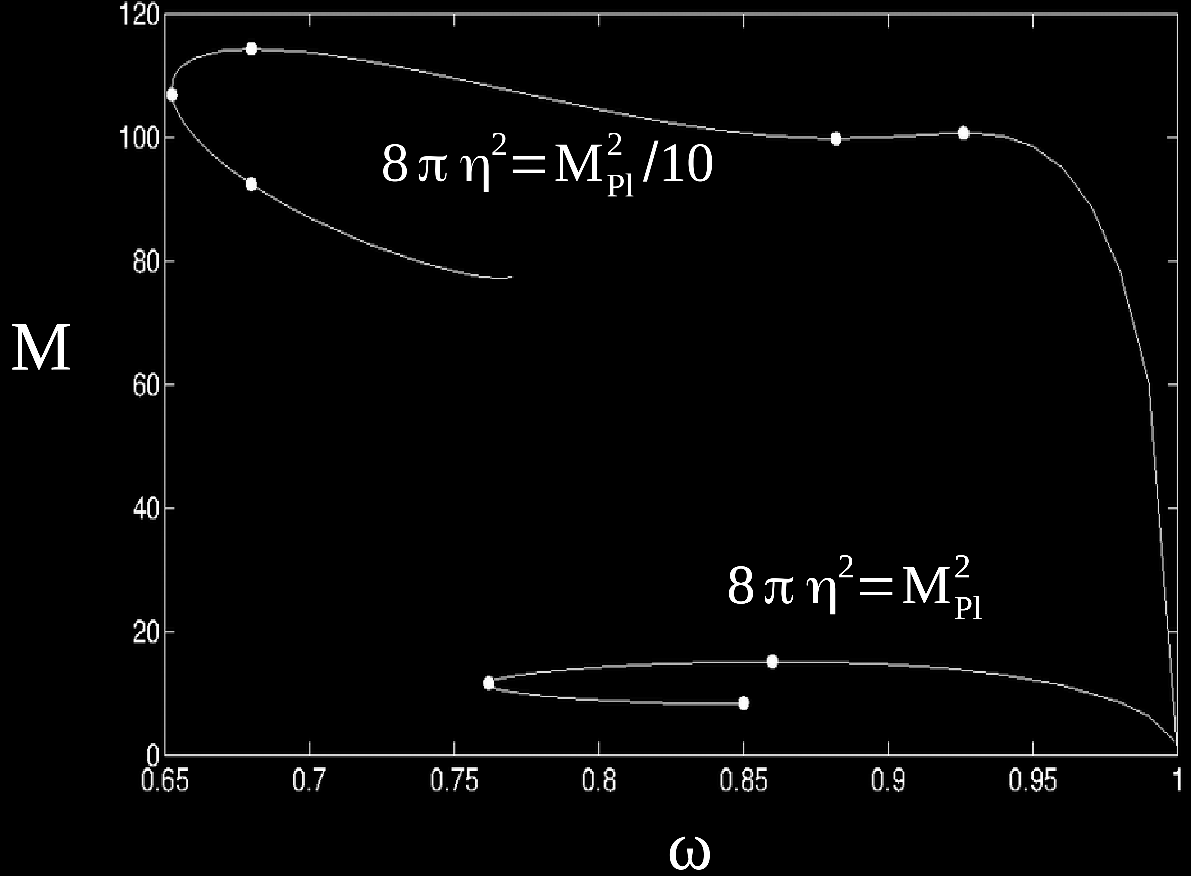
Best "standard" explanation:
Supermassive black hole

2) From:
Gillessen, Eisenhauer, Fritz, Bartko, Dodds-Eden, Pfuhl, Ott, Genzel
Astrophy. J. 707 (2009)

Results

Typical mass of a boson star

Diemer, Eilers, BH, Schaffer, Toma, *Phys. Rev. D88 (2013)*



Physical mass

$$M_{phys} \approx \frac{M \times 10^{20}}{m[eV]}\,\mathrm{kg}$$

Maximal physical mass

$$M_{phys}^{max} \approx \frac{7}{4\pi}\frac{M_{Pl}^4}{\eta^2 m} \approx \frac{10^{76}}{(\eta[eV])^2\, m[eV]}$$

Typical mass & radius of a boson star

Diemer, Eilers, BH, Schaffer, Toma, *Phys. Rev. D88 (2013)*

Example: $8\pi\eta^2 = M_{Pl}^2/10$

Particle	m	M_{phys}	R_{99}
Higgs	125 GeV/c²	10^{11} kg	10^{-15} meters
Pion	140 MeV/c²	10^{14} kg	10^{-13} meters
Axion	10^{-5} eV/c²	10^{27} kg	1 meter
Dilaton	10^{-10} eV/c²	10^{32} kg	100 km

Need very light scalar to model SgA*

R_{99}: radius in which 99% of the mass is contained ← numerics!

Mass SgA* >> mass of S-stars

Test particles

$$\frac{d^2 x^\mu}{d\tau^2} + \Gamma^\mu_{\rho\sigma} \frac{dx^\rho}{d\tau} \frac{dx^\sigma}{d\tau} = 0$$

Geodesic equation

For spherically symmetric, static space-times:

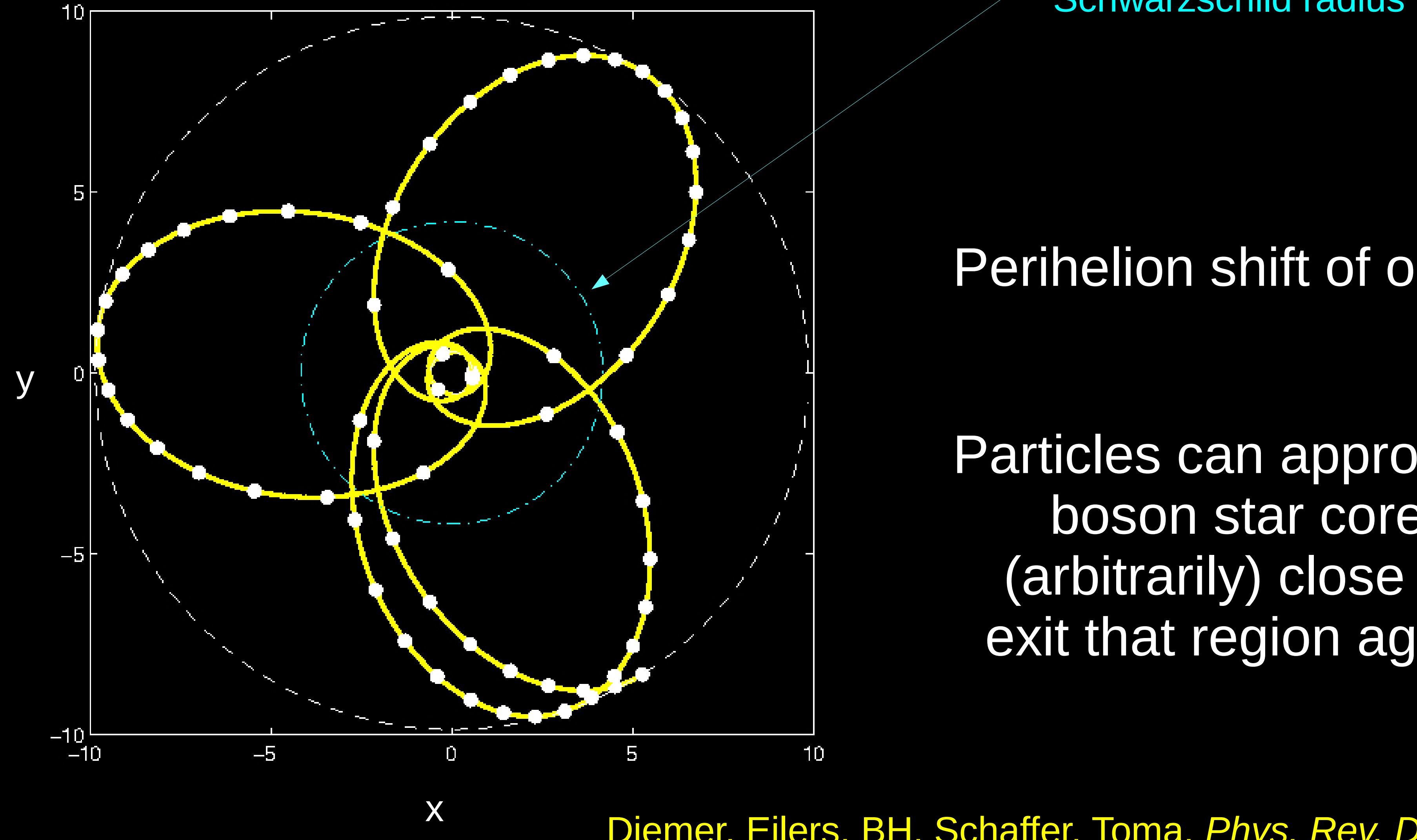
a) test particle motion is planar → restrict to equatorial plane $\theta = \pi/2$

b) constants of motion: energy E and angular momentum L

$$E \sim g_{tt} \frac{dt}{d\tau} \qquad L \sim g_{\varphi\varphi} \frac{d\varphi}{d\tau}$$

Bound orbit of a massive test particle

$L^2 = 1.0$ $E^2 = 0.95$ $8\pi G\eta^2 = 1.0$ $\omega=0.85$



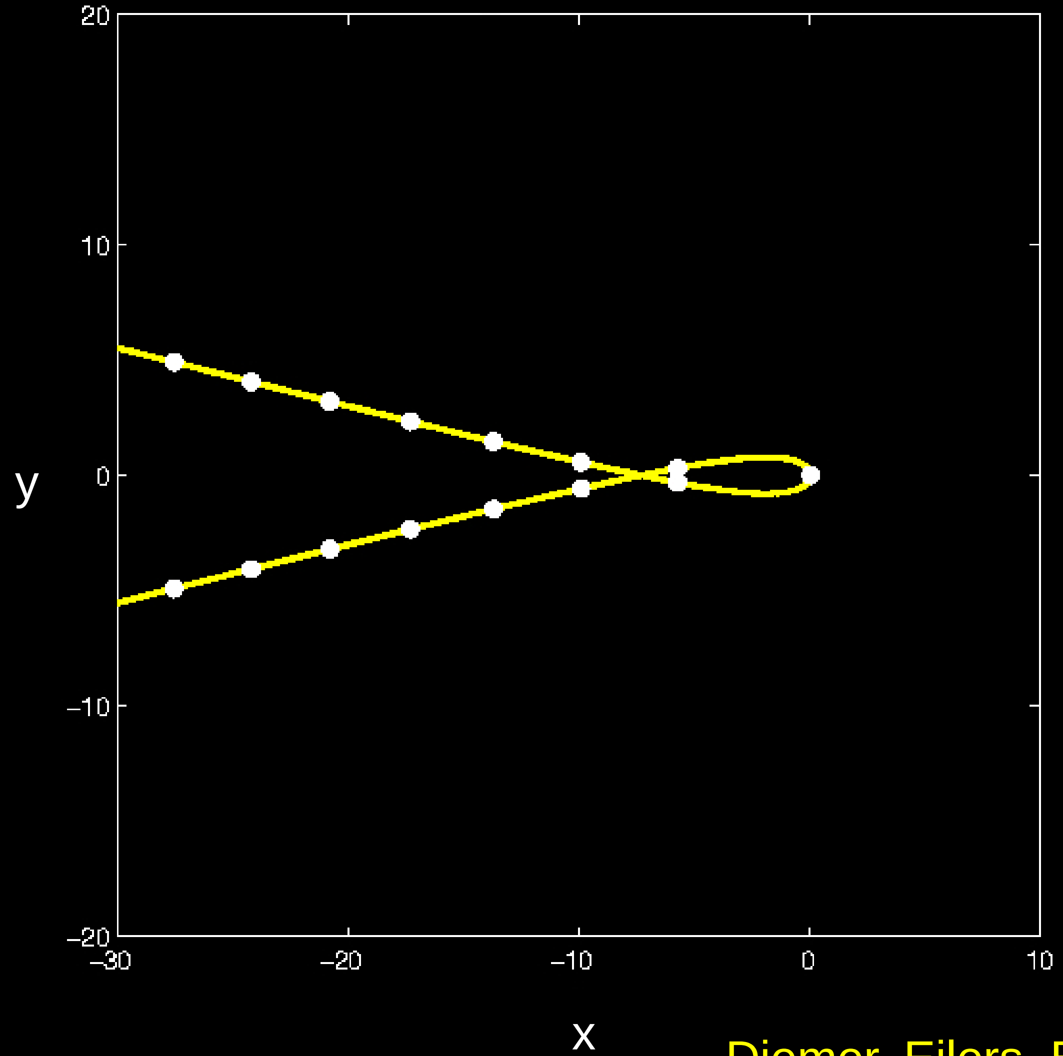
Perihelion shift of orbits

Particles can approach boson star core (arbitrarily) close & exit that region again

Diemer, Eilers, BH, Schaffer, Toma, *Phys. Rev. D88 (2013)*

Escape orbit of a massive test particle

$L^2 = 0.5$ $E^2 = 1.1$ $8\pi G\eta^2 = 0.1$ $\omega=0.68$



New features as compared to Schwarzschild black hole

(e.g. intersecting escape orbits)

Diemer, Eilers, BH, Schaffer, Toma, *Phys. Rev. D88 (2013)*

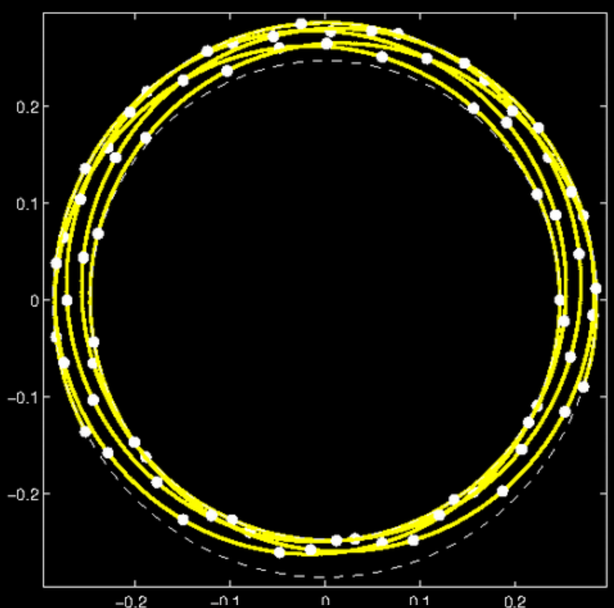
Last stable (nearly) circular orbit

Diemer, Eilers, BH, Schaffer, Toma, *Phys. Rev. D88 (2013)*

M=92.34

E^2 =0.404, L^2=0.5

y

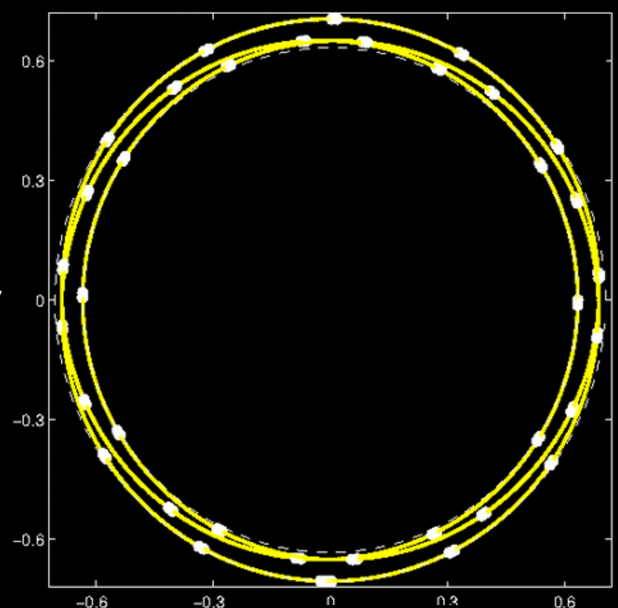


Δx≈0.6

M=106.85

E^2 =0.742, L^2=1.5

y

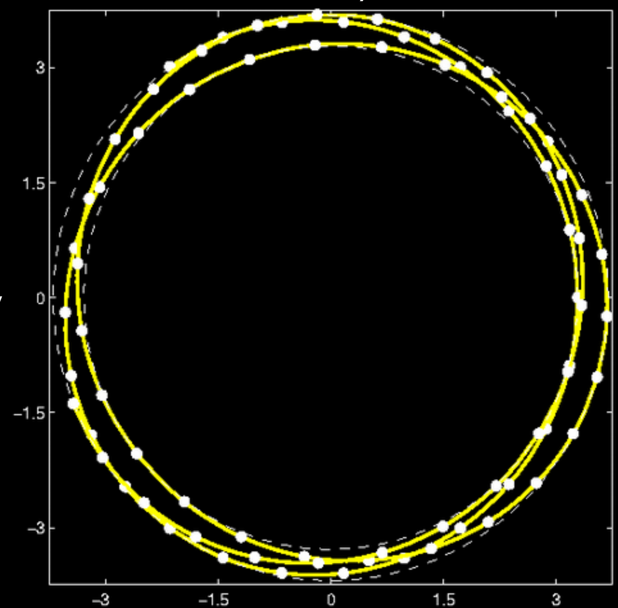


Δx≈1.4

M=100.64

E^2 =0.884, L^2=1.0

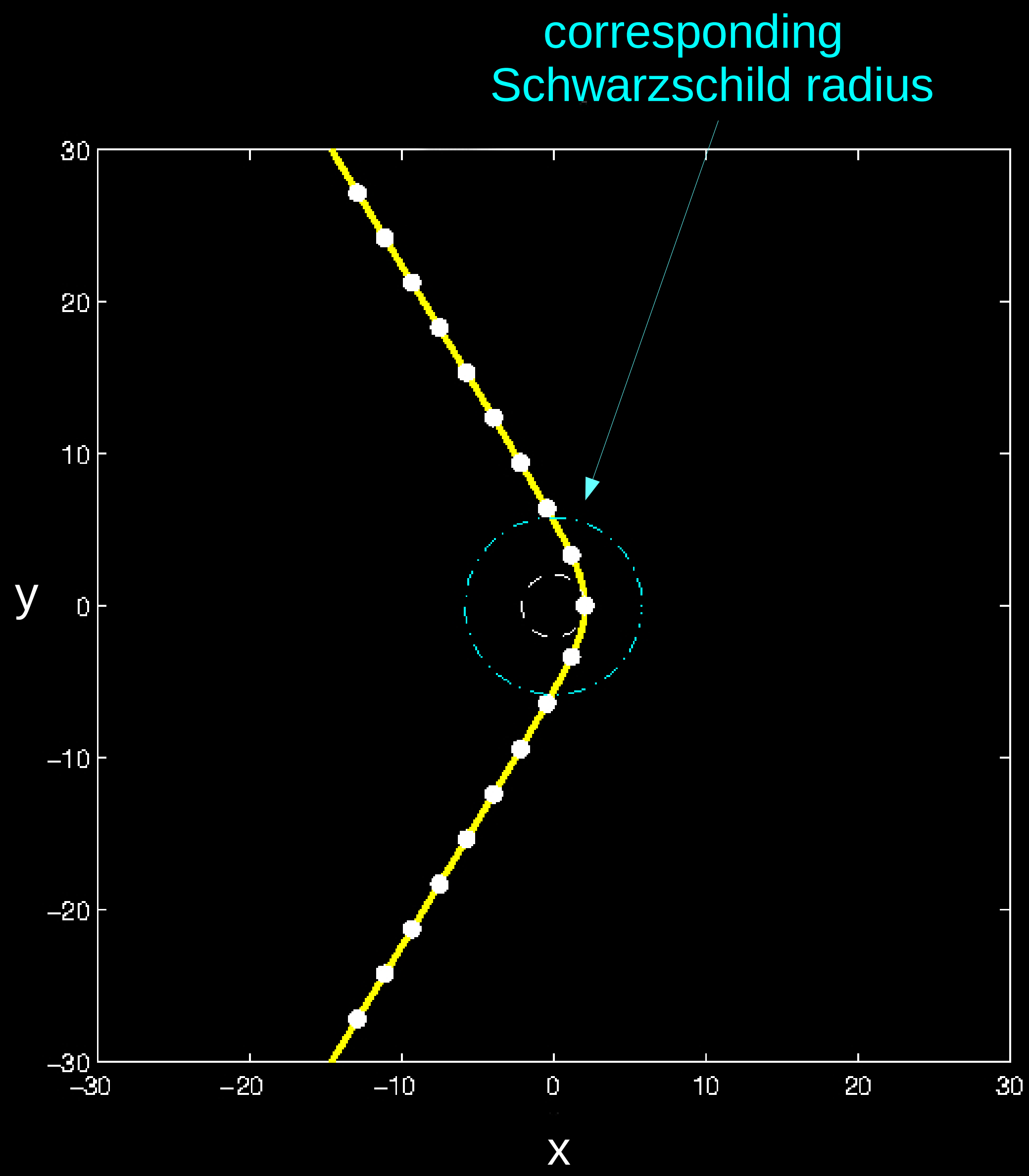
y



Δx≈7.2

length scales measured in units of 1/(boson mass)

Escape orbit of massless test particle



Massless test particle
can enter into &
exist from
region beyond
assumed
Schwarzschild radius

Compare to observation of
emission of **radio waves** (1.3 mm)
from beyond assumed
apparent horizon of SgA*

Doeleman, Weintroub, Rogers,
Plambeck, Freund, Tilanus,
Friberg, Ziurys et al.
Nature 455 (2008)

Diemer, Eilers, BH, Schaffer, Toma,
Phys. Rev. D88 (2013)

Conclusions…

… & Outlook

Boson stars...

… are a (not yet) excluded alternative to supermassive black holes

Objects with “hard core” ruled out (c.f. Broderick, Narayan, Astrophy. J. 638 (2006))

… are well motivated since at least one fundamental scalar field seems to exist in nature (Higgs) – maybe more (Inflation??)

… are highly relativistic and could hence be used as toy models for very compact objects, e.g. neutron stars

We have studied the motion of test particles in the space-time of an uncharged, spherically symmetric boson star

Compatible with observational data

Need data of relativistic signature of gravitational field of SgA*

perihelion shift, light deflection …

… then boson stars can be distinguished from black holes

In the meantime ...

… use test particles to describe formation of accretion discs

(c.f. Tejeda, Taylor, Miller, *Mont. Not. R. Astron. Soc. 419 (2012); ibid 429 (2012)*)

BUT: accretion discs consist of charged particles (plasma)

Charged test particles in charged boson star space-times

Brihaye, Diemer, BH, *Phys. Rev. D 89 (2014)*

U(1) global → U(1) local

Q: charge of boson star

$$\frac{d^2 x^\mu}{d\tau^2} + \Gamma^\mu_{\rho\sigma} \frac{dx^\rho}{d\tau} \frac{dx^\sigma}{d\tau} = q F^{\mu\sigma} \frac{dx^\rho}{d\tau} g_{\rho\sigma}$$

q: charge of test particle

<u>See next talk by J. Riedel</u>

And also: **Boson stars in Anti-de Sitter space-time**...

… are important in the study of non-linear instability of Anti-de Sitter

Thanks to my collaborators

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Valeria Diemer	University of Oldenburg, Germany
Keno Eilers	University of Oldenburg, Germany
Isabell Schaffer	University of Oldenburg, Germany
Catalin Toma	Jacobs University Bremen, Germany

References

V. Diemer, K. Eilers, BH, I. Schaffer, C. Toma, *Phys. Rev. D 88 (2013) 044025*

Y. Brihaye, V. Diemer, BH, *Phys. Rev. D 89 (2014) 084048*


Thank you for your attention!