

# Horizon and exotics

# Main reviews and articles

- gr-qc/0506078 **Black Holes in Astrophysics**
- astro-ph/0207270 **No observational proof of the black-hole event-horizon**
- gr-qc/0507101 **Black holes and fundamental physics**
- astro-ph/0401549 **Constraining Alternate Models of Black Holes:  
Type I X-ray Bursts on Accreting Fermion-Fermion and  
Boson-Fermion Stars**
- arXiv: 0903.1105 **The Event Horizon of Sagittarius A\***
- arXiv: 1312.6698 **Observational evidence (review)**
- arXiv: 1904.05363 **Testing the nature of dark compact objects: a status report**
- arXiv: 1707.03021 **Probing horizons**

# The horizon problem

What can be a 100% proof that we observe a BH?

Of course, only a direct evidence for the horizon existence!

But it is very difficult to prove it!

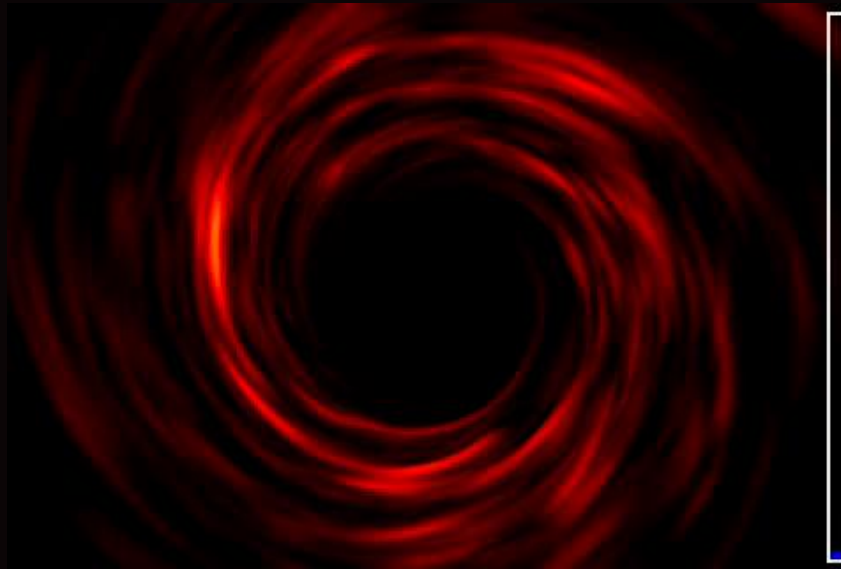
One can try to follow three routes:

1. To look for direct evidence for the horizon.
2. To try to prove the absence of a surface.
3. To falsify the alternative models.

The first approach is not very realistic ([astro-ph/0207270](#) Abramowicz et al.)

We can hope to have direct images from the horizon vicinity (for example, for Sgr A\* the corresponding size is 0.02 milliarcseconds), or to have data from BH coalescence via GW detection. (see Narayan [gr-qc/0506078](#))

# Dreams about direct images



(Narayan 2005)



The MAXIM Project (Cash 2002)  
<http://beyondeinstein.nasa.gov/press/images/maxim/>

Prototype: 100 microarcsecs  
MAXIM: 100 nanoarcsecs  
33 satellites with X-ray optics  
and a detector in 500 km away.

# Absence of surface

Here we mostly discuss close binaries with accretion

- Lack of pulsations
- No burster-like bursts  
Nowhere to collect matter.  
(however, see below about some alternatives)
- Low accretion efficiency (also for Sgr A\*)  
ADAF. Energy is taken under horizon.
- No boundary layer (Sunyaev, Revnivtsev 2000)  
Analysis of power spectra.  
Cut-off in BH candidates above 50 Hz.

# The case of Sgr A\*

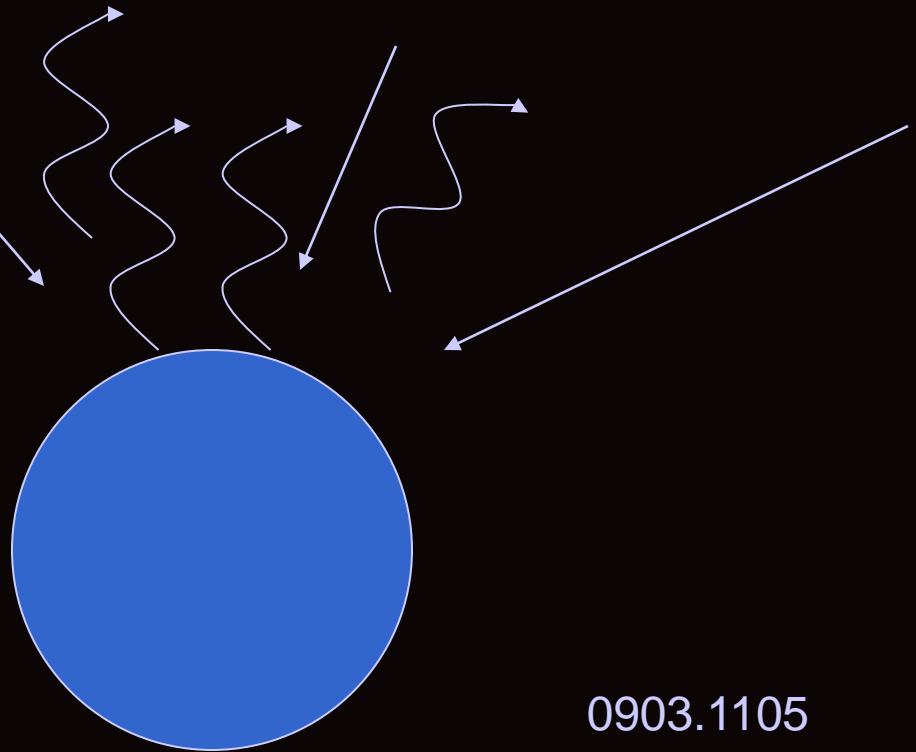
Recent millimeter and infrared observations of Sagittarius A\* (Sgr A\*), the supermassive black hole at the center of the Milky Way, all require the existence of a horizon.

Magnetic field observed around Sgr A\* due to faraday rotation of the radio pulsar emission can explain the energy release in the flow:

1308.3147.

Now fields are observed directly:

1512.01220.



See also 1503.03873 about M87

# Surface emission limits

$$E_{\infty} = \Delta\epsilon_g \dot{m} c^2$$

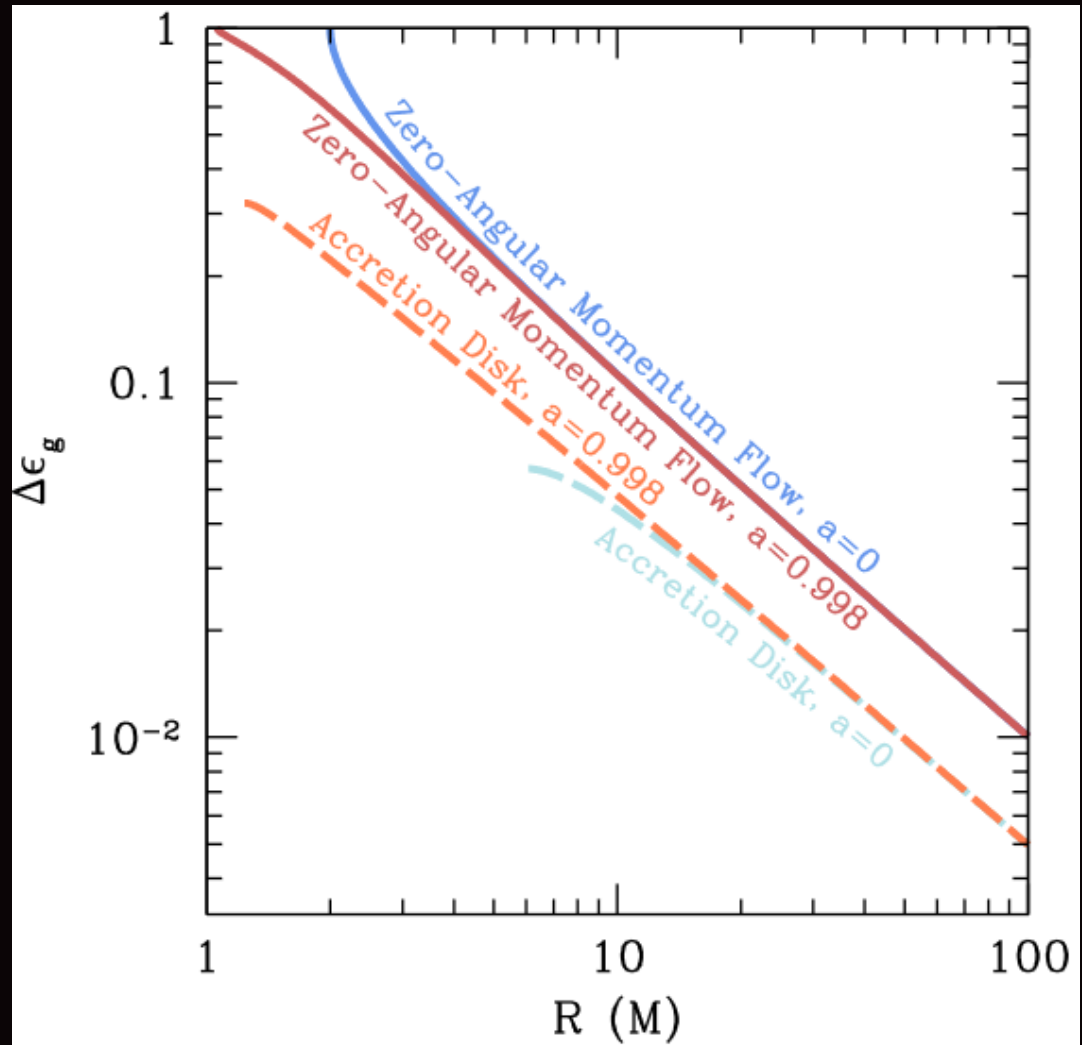
$$L_{\infty} = \Delta\epsilon_g \dot{M} c^2$$

$$L_{\text{obs}} = \eta_r L_{\infty}$$

$$L_{\text{out}} = \eta_k L_{\infty}$$

$$L_{\text{surf}} = L_{\infty} - L_{\text{obs}} - L_{\text{out}}$$

$$= \frac{1 - \eta_r - \eta_k}{\eta_r} L_{\text{obs}}$$



# Limits

$$L_{\text{surf}} = 4\pi\sigma R_a^2 T_\infty^4$$

$$T_\infty = \left( \frac{1 - \eta_r - \eta_k}{\eta_k} \frac{L_{\text{obs}}}{4\pi\sigma R_a^2} \right)^{1/4}$$

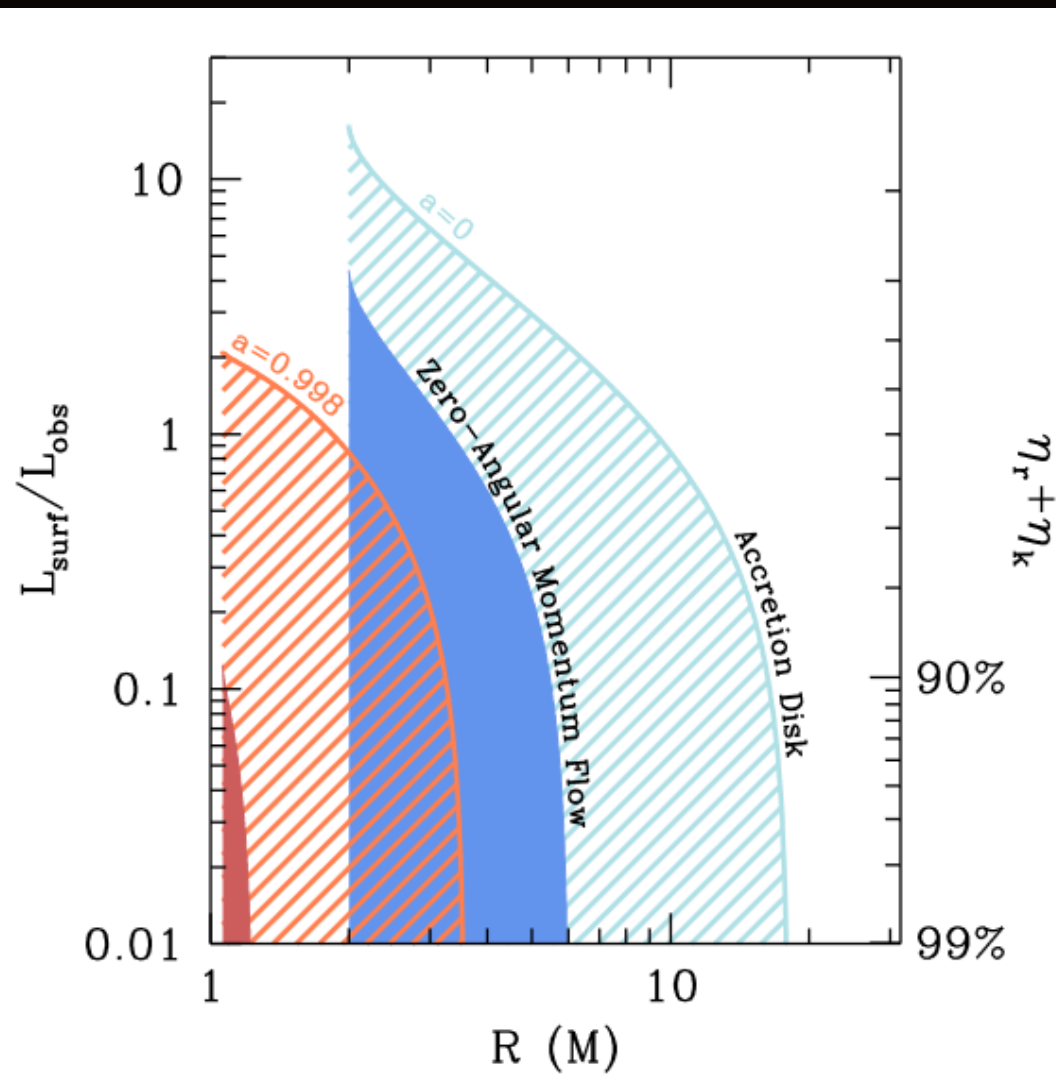
$$F_\nu = \pi \left( \frac{R_a}{D} \right)^2 B_\nu(T_\infty)$$

$$T_{\text{max}} = h\nu / k \ln \left( 1 + \frac{2\pi h\nu^3 R_a^2}{c^2 F_\nu^{\text{obs}} D^2} \right)$$

$$\frac{L_{\text{surf}}}{L_{\text{obs}}} \leq \frac{L_{\text{surf,max}}}{L_{\text{obs}}}$$

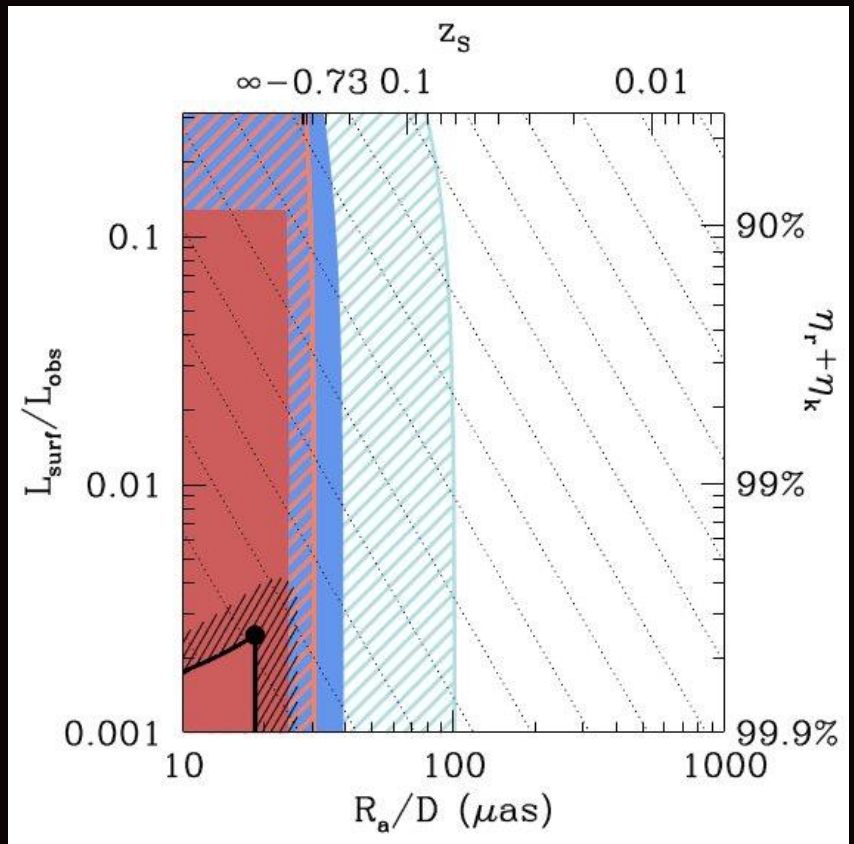
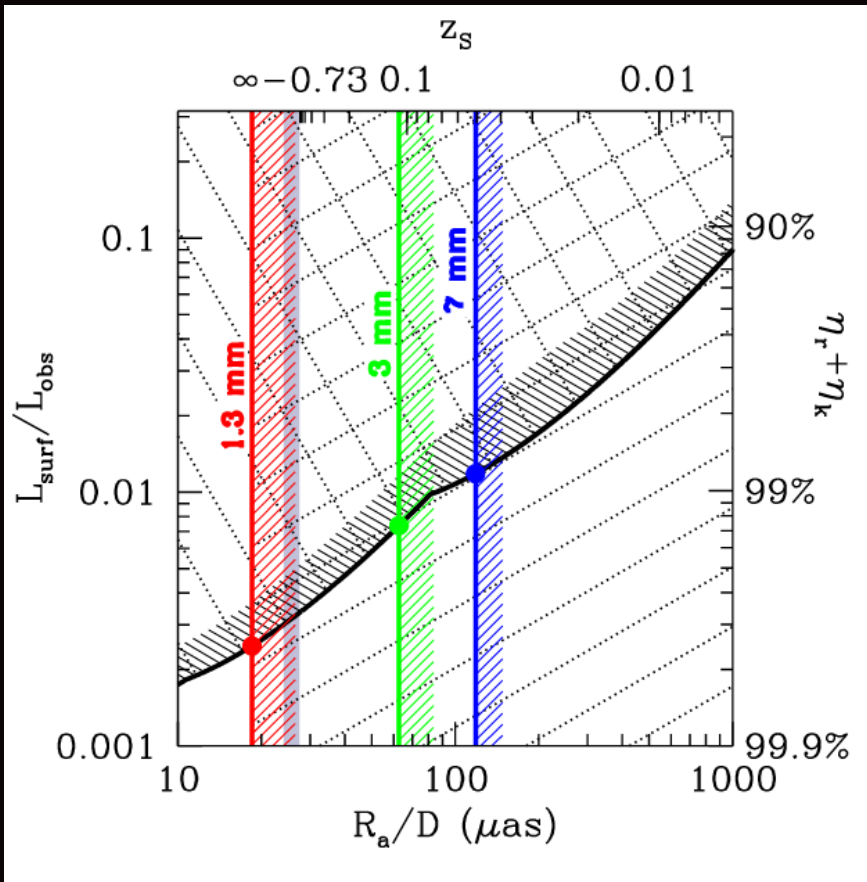
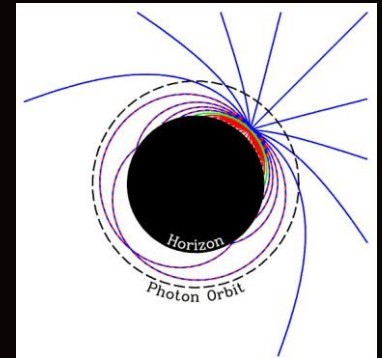
$$\equiv \frac{\sigma R_a^2}{D^2 F_{\text{obs}}} T_{\text{max}}^4 \left( \nu, F_\nu^{\text{obs}}, \frac{R_a}{D} \right)$$

$$\eta_r + \eta_k \geq \frac{1}{1 + L_{\text{surf,max}}/L_{\text{acc}}}$$

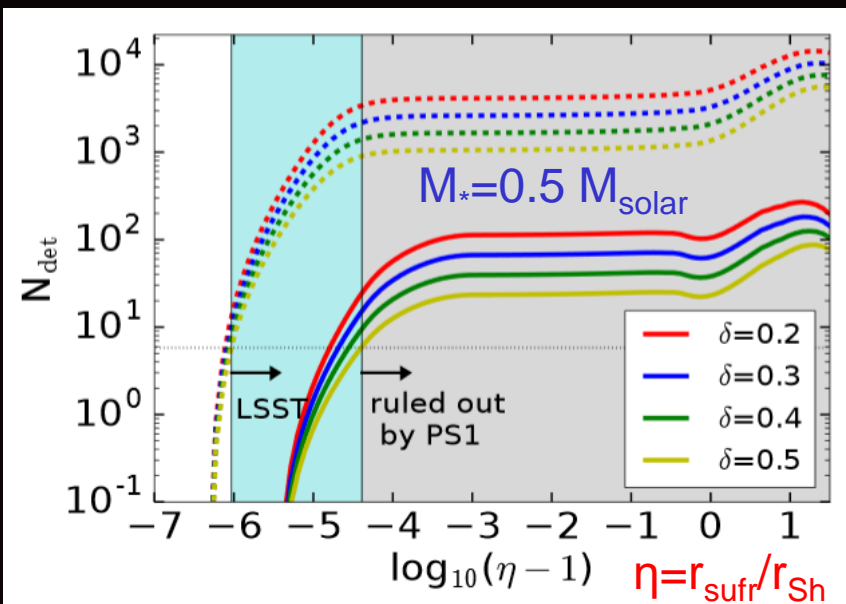
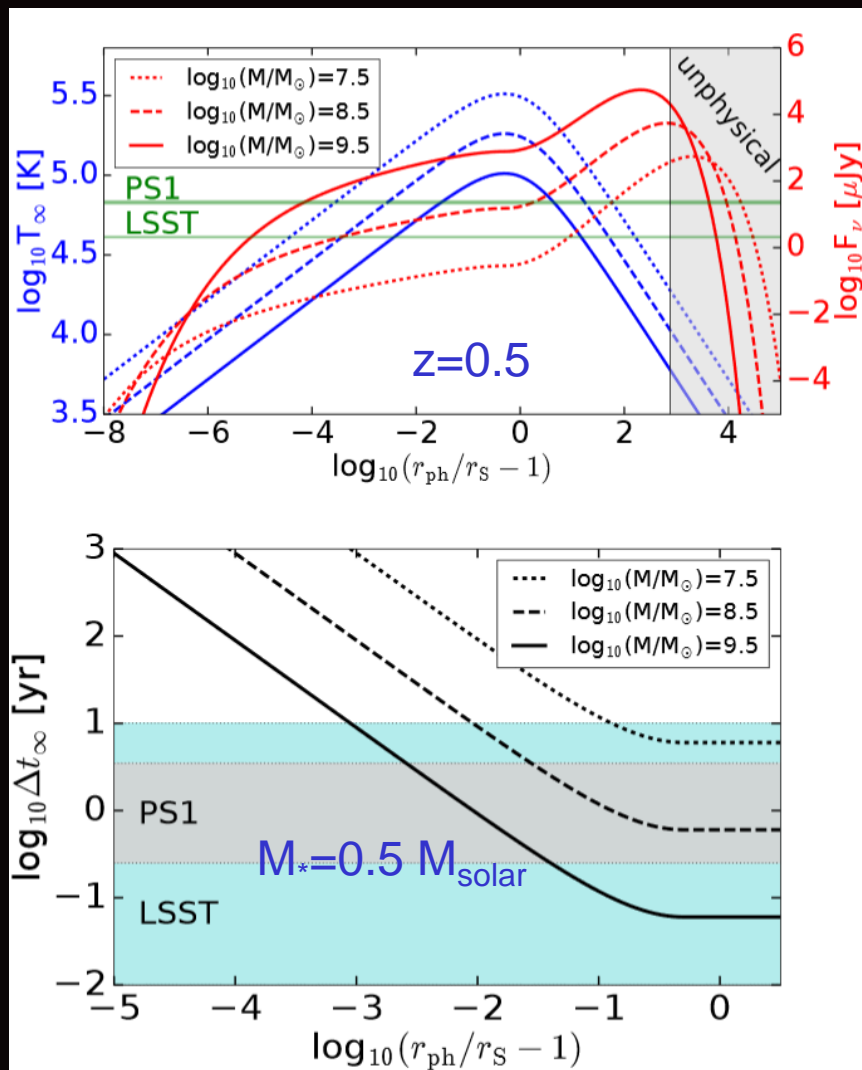




# Sgr A\*



# Tidal disruption and horizons



If there is a hard surface, then a kind of a photosphere might be formed above it.

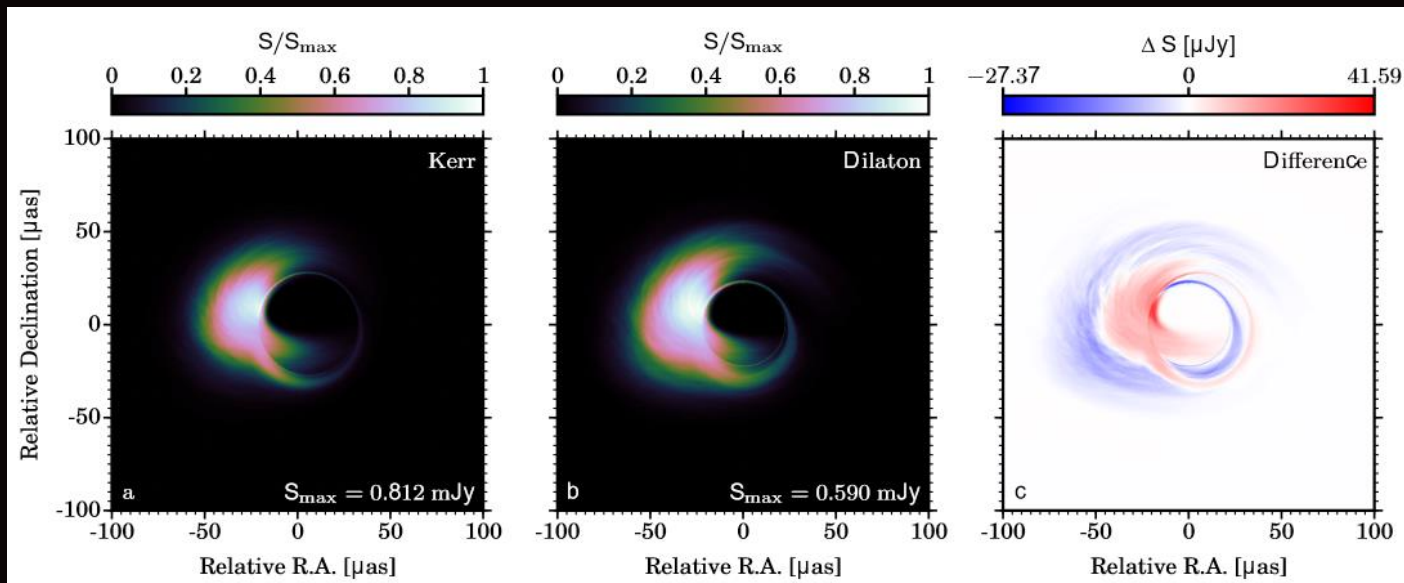
No surface emission after tidal events.  
Limit  $1+10^{-4.4}$  of the Schwarzschild radius.

# BH shadow and alternative theories

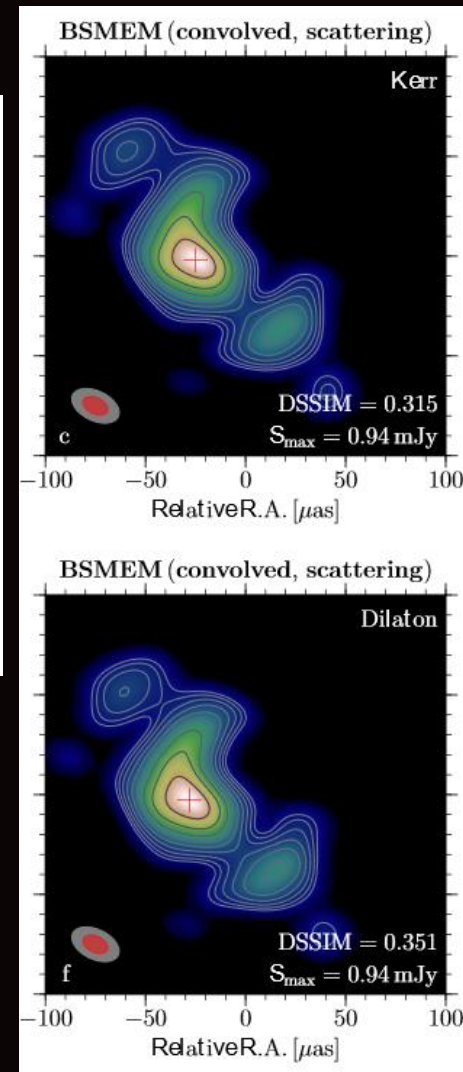
Kerr BH

Dilaton non-rotating

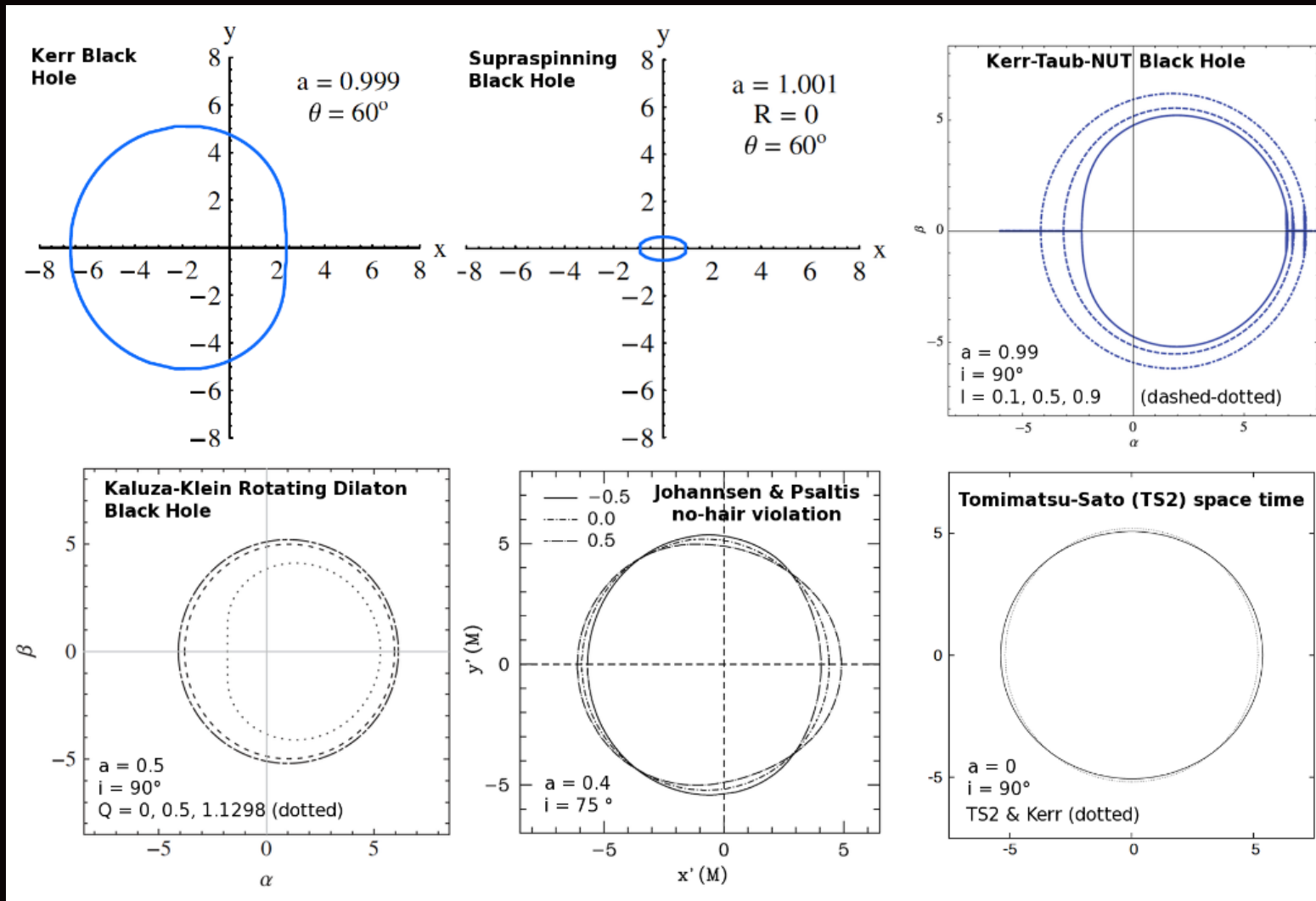
Difference



Impossible to distinguish with present day technique.

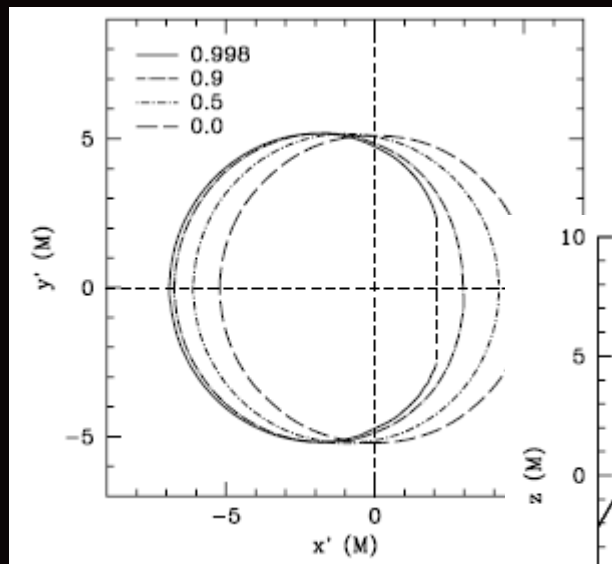


# BH shadow in different models



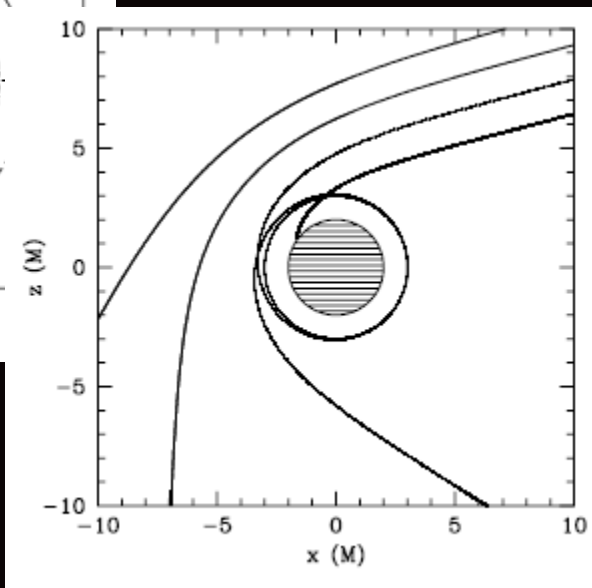
# Testing no-hair theorem

It is possible to study and put limits for the existence of quadrupole moments.

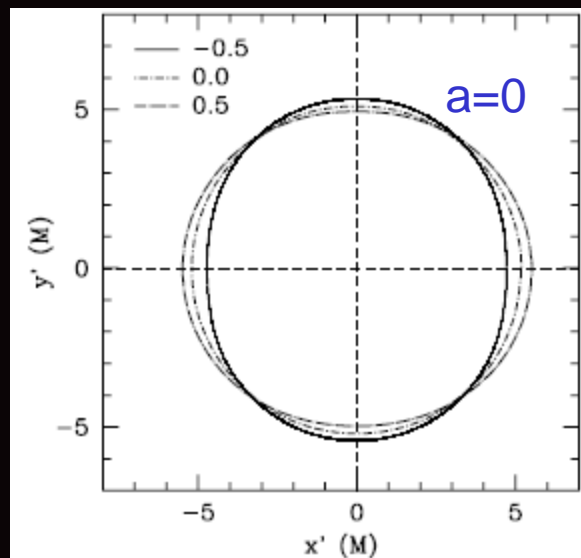


Spinning BHs

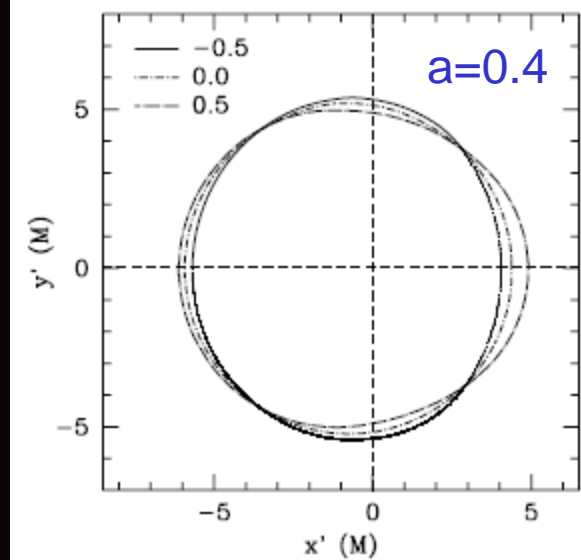
$$Q = -M (a^2 + \epsilon M^2)$$



Photon ring formation



quadrupoles



# Parameters of different models

Fermion stars:

$M_f = 223 \text{ MeV}$  (non-interacting)

$M_{\text{max}} = 12.61 M_0$

$R(M=10M_0) = 252 \text{ km} = 8.6 R_{\text{sh}}$

Collapse after adding  $0.782 M_0$  of gas.

Bozon stars:

$M_b = 2.4 \cdot 10^{-17} \text{ MeV}$ ,  $\lambda = 100$

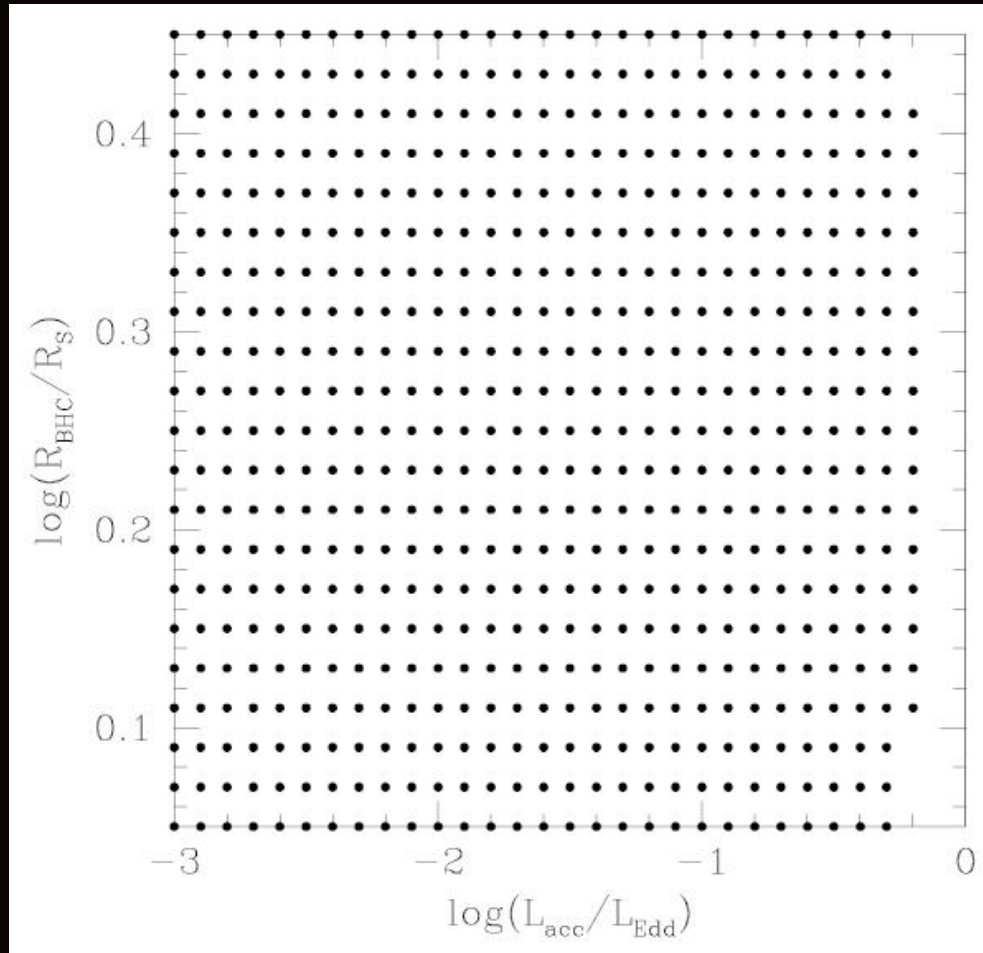
$M_{\text{max}} = 12.57 M_0$

$R(M=10M_0) = 153 \text{ km}$  (99.9% of mass)

Collapse after adding  $0.863 M_0$  of gas.

Model parameters are constrained by limits on the maximum size of an object derived from QPOs at 450 Hz

# Stability respect to flares on a surface



$$R_{\min} = 9/8 R_{\text{sh}}$$

Potentially, smaller radii are possible, but such objects should be unstable in GR.

Still, if they are possible, then one can “hide” bursts due to high redshift.

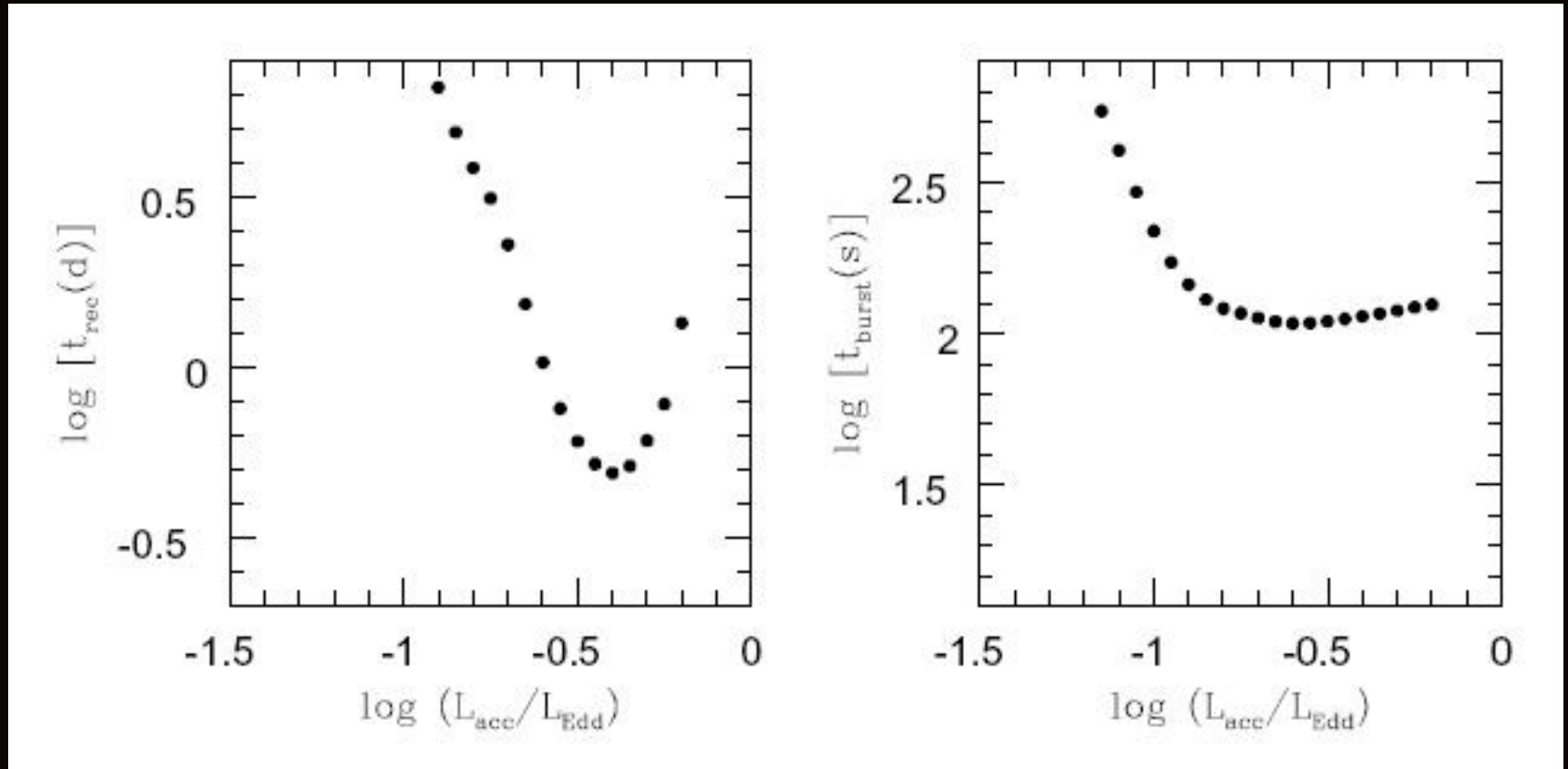
Solid dots – bursts.

Blank field – stable burning.

For a 10 solar mass object with hard surface



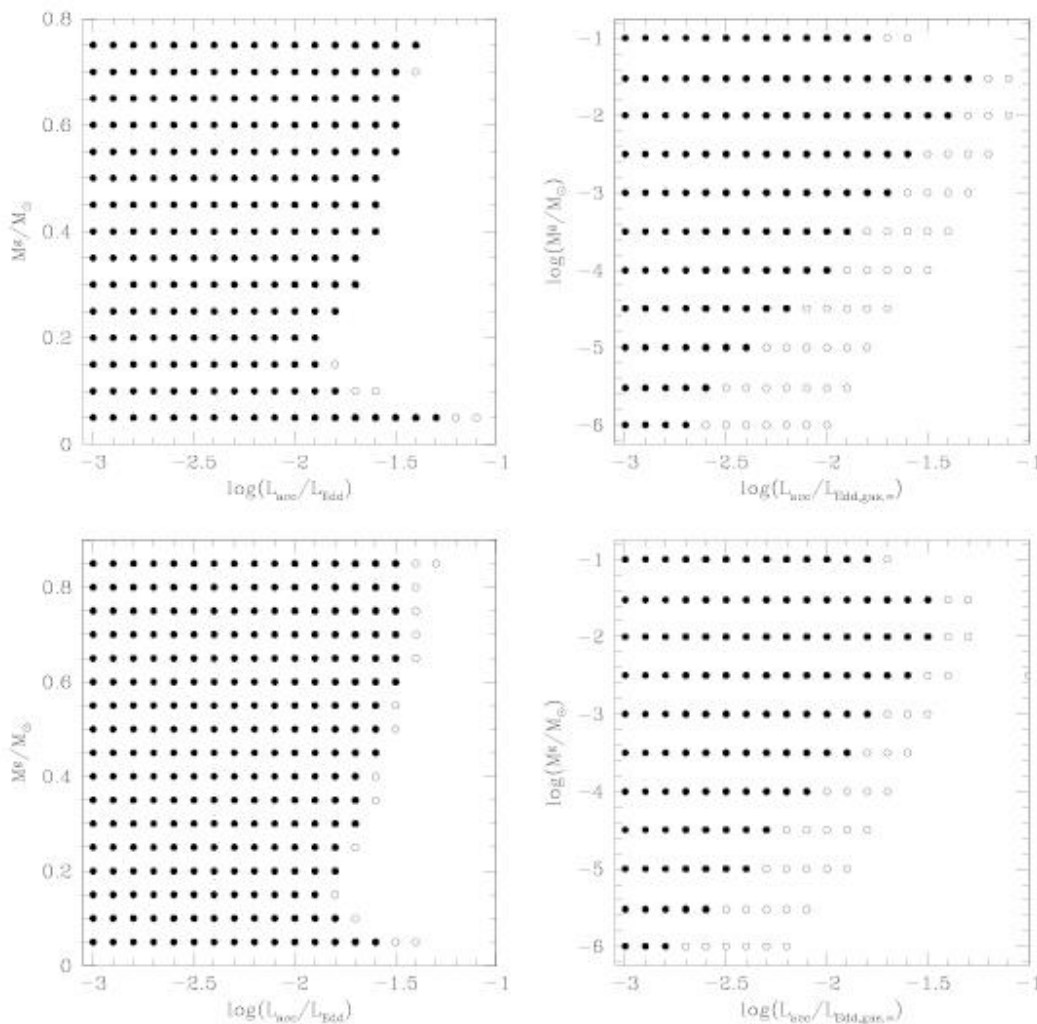
# Timing characteristics of surface bursts



For a 10 solar mass object with hard surface for  $R=2R_{\text{sh}}$



# Stability respect to flares inside an object

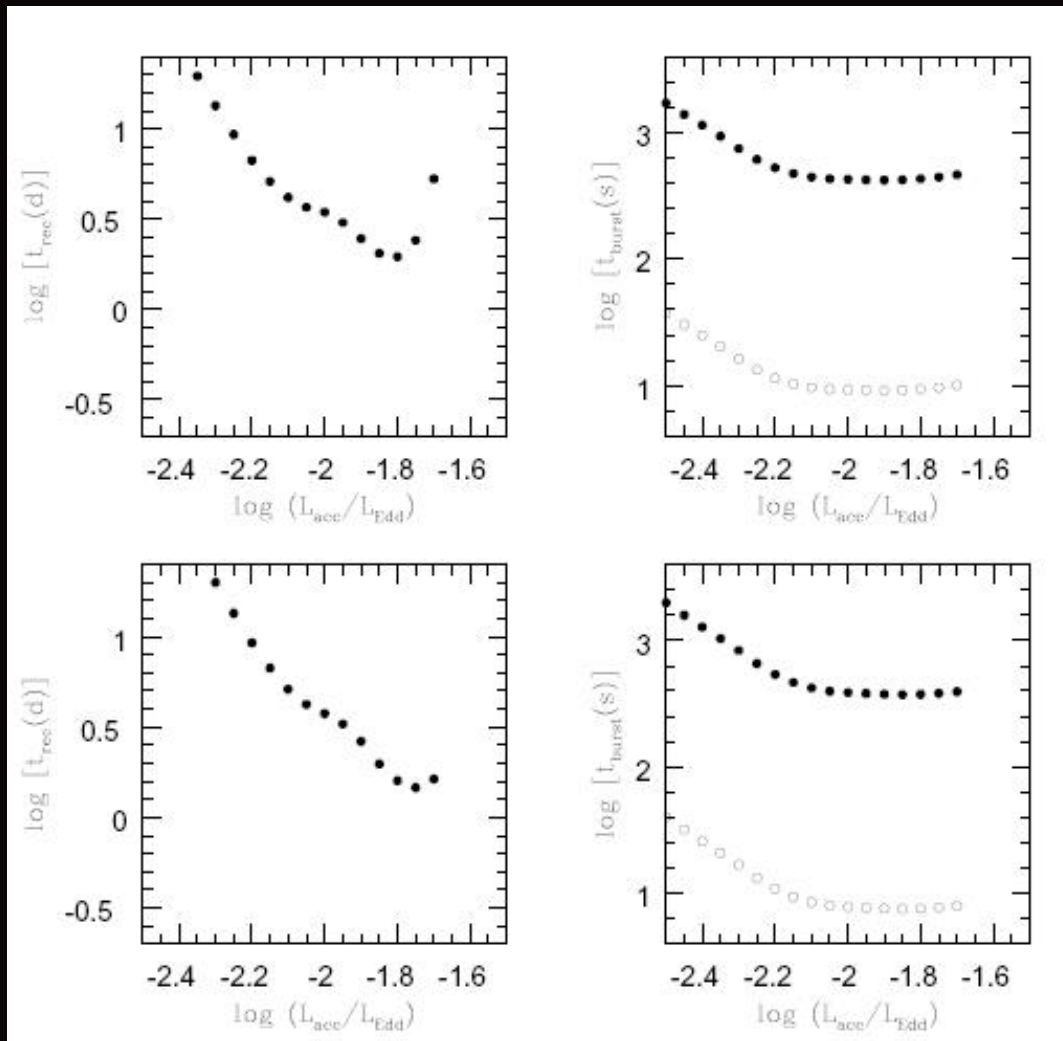


Fermion stars



Bozon stars

# Timing characteristics of internal bursts



Fermion stars



Bozon stars

$M_{\text{gas}} = 0.3$  solar mass

# BHs and fundamental theories

1. Thermodynamics of BHs and Hawking radiation.
2. Testing alternative theories of gravity.
3. Black holes and extra dimensions
4. Accelerator experiments

**Under some reasonable assumptions  
astrophysical data can provide  
strong and important constraints  
on parameters of fundamental theories.**

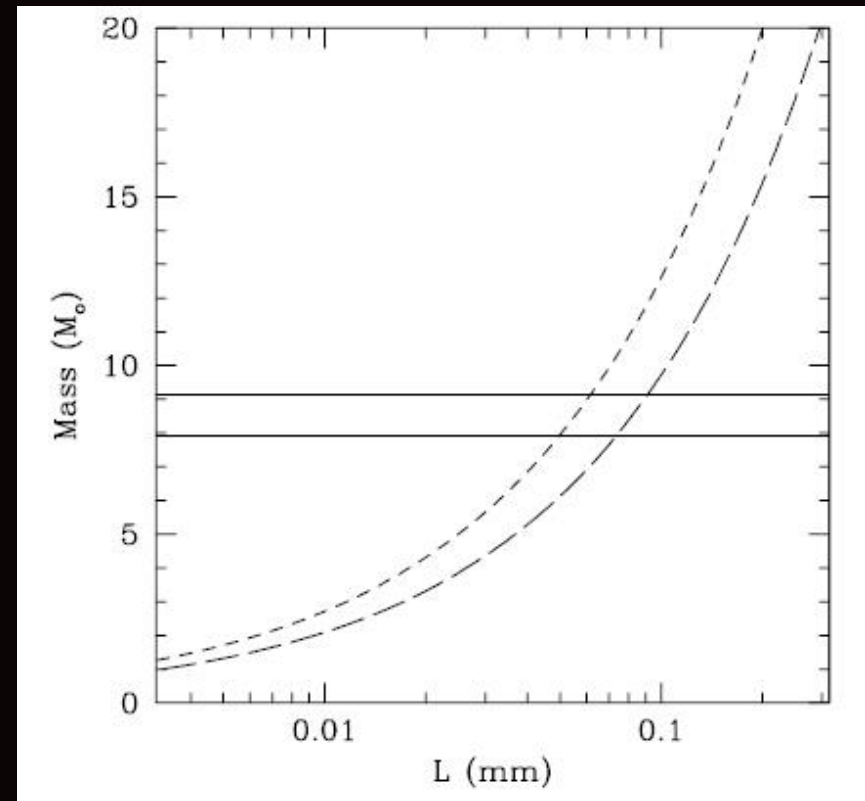
# Brane worlds and black holes

In astro-ph/0612611 the author discuss constraints on parameters of world on brane basing on observations of XTE J1118+408. The idea is the following. In many scenarios of brane world BHs lifetimes are short. An estimated of a lower limit on the age of a BH can provide a stronger limit than laboratory experiments.

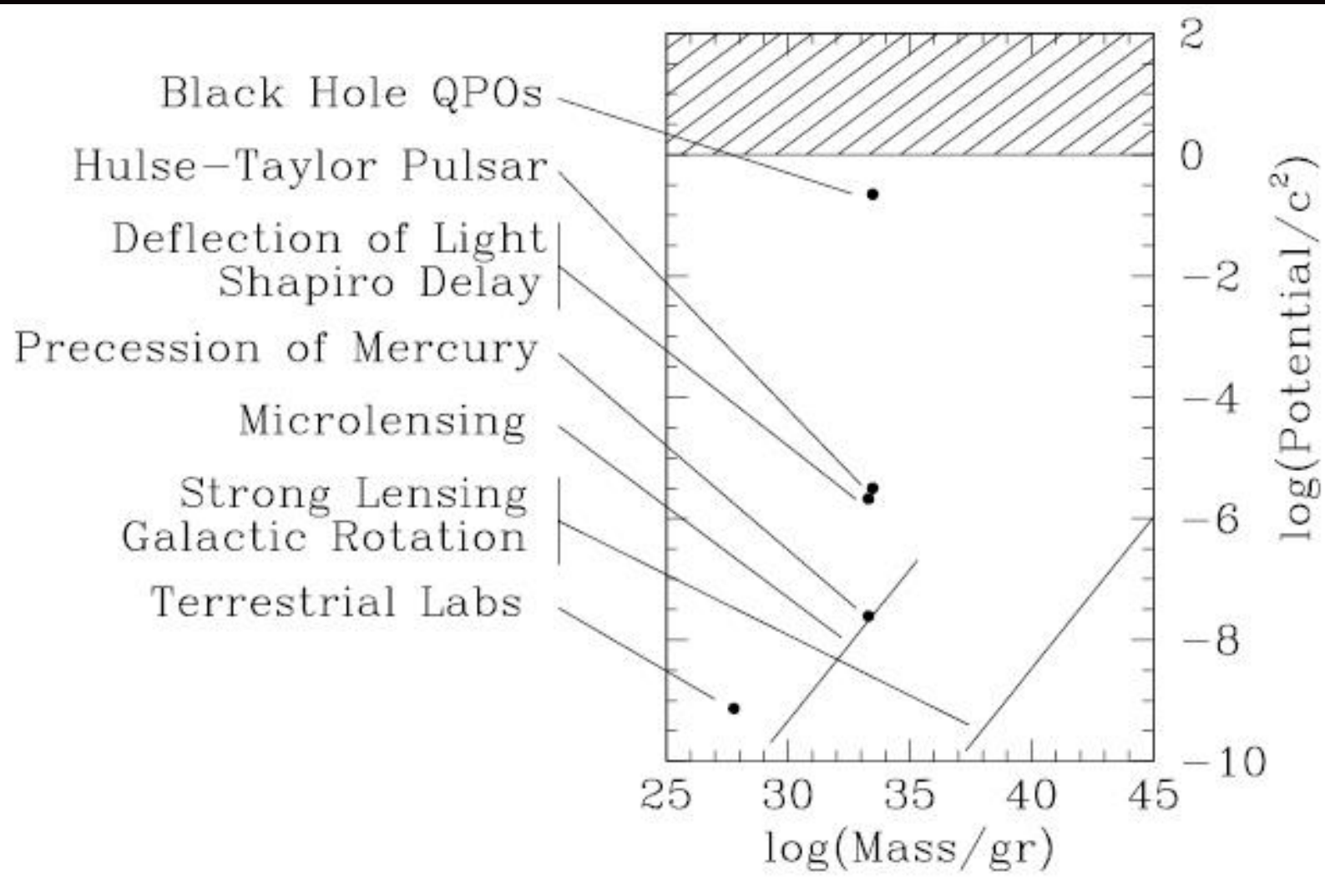
Age estimated by the time of the last galactic crossing.

$$\tau \simeq 1.2 \times 10^2 \left( \frac{M}{M_{\odot}} \right)^3 \left( \frac{L}{1 \text{ mm}} \right)^{-2} \text{ yr}$$

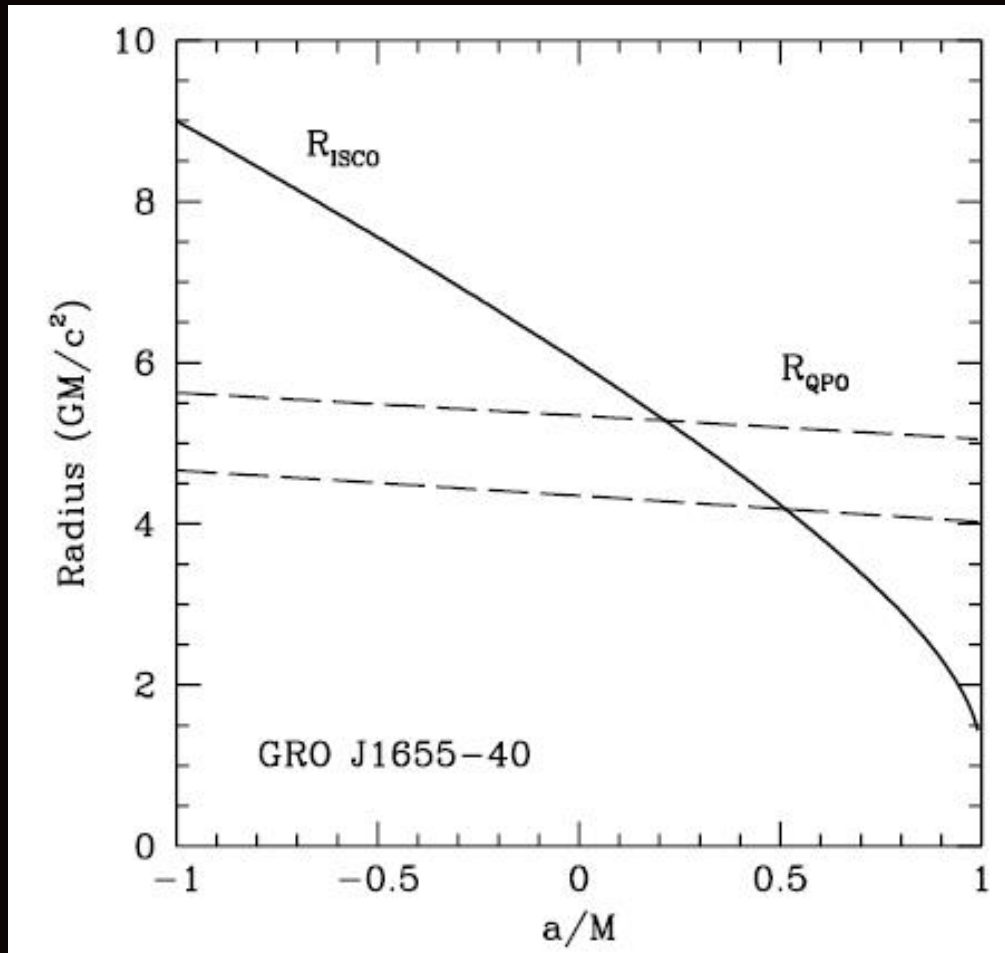
(see also astro-ph/0401466)



# BH spin and testing the GR



# QPO in GRO 1655-40



If the interpretation of QPOs in this source is correct, then we can “look inside”  $3R_g$ .

The observed frequency is 450 Hz. Uncertainties (dashed lines) are due to uncertainty in the mass: 5.8-7.9 solar masses.

However, this conclusion crucially depends on our understanding of the QPO phenomenon.

Here it is assumed that  $f_{\text{QPO}} < f_{\text{AZIM}} = (GM)^{1/2} / 2\pi R^{3/2}$

# Alternatives

1. Gravastar - GRAvitational VAcuum STAR (Mazur, Mottola gr-qc/0109035)
2. Dark energy stars (Chaplin astro-ph/0503200)
3. Boson stars (see, for example, Colpi et al. 1986 Phys. Rev. Lett.)
4. Fermion balls (see discussion in Yuan et al. astro-ph/0401549)
5. Evaporation before horizon formation (Vachaspati et al. gr-qc/0609024 )

Except general theoretical criticism, some models are closed by absence of burster-like flares (Yuan et al. astro-ph/0401549).

This is not the case for models like those proposed by Vachaspati et al. However, they are actively criticized by theorists.

Problems with formation mechanisms and stability.

**Taking all together, black hole – is the most conservative hypothesis!**

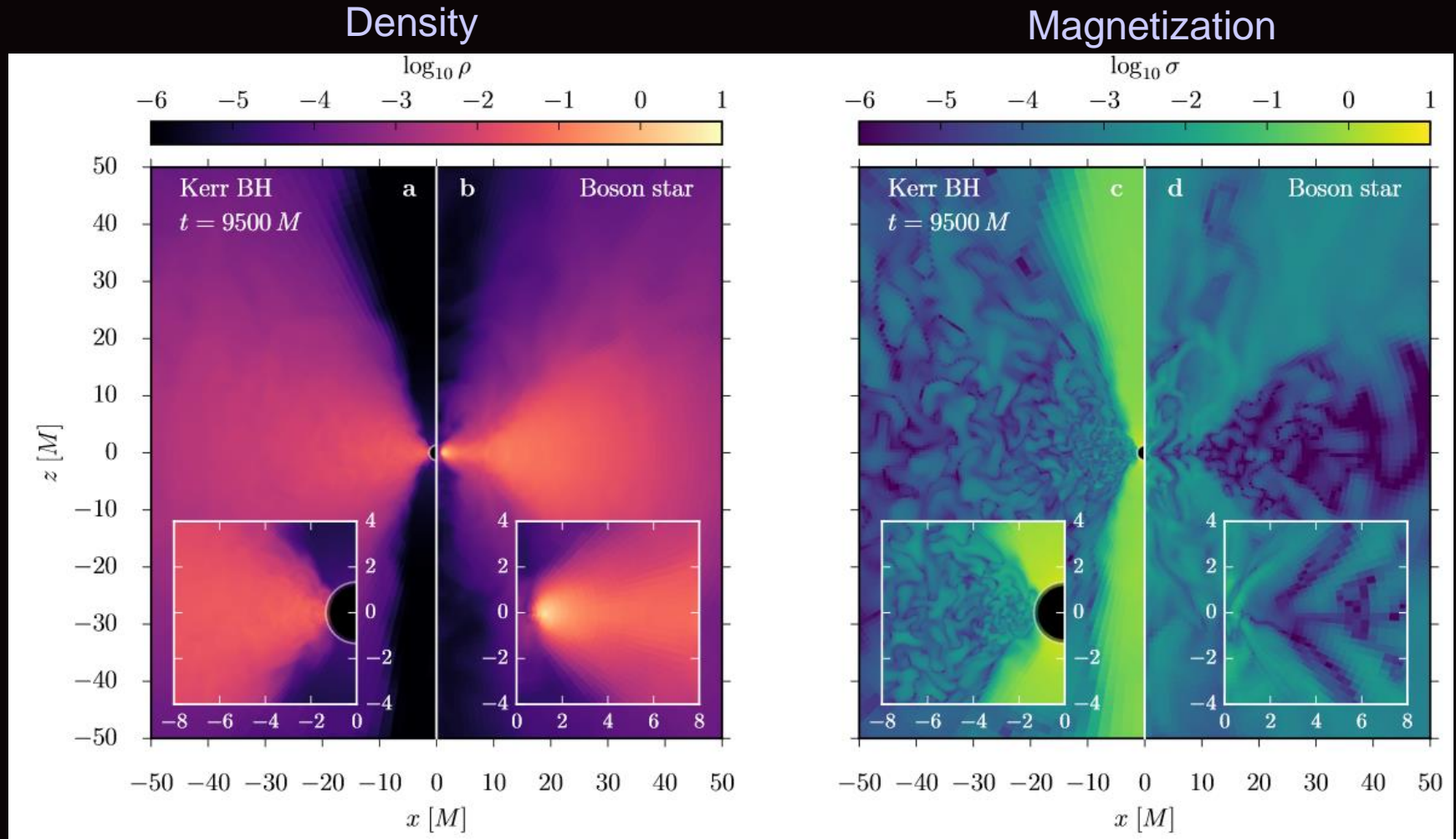
Model	Taxonomy	Formation	Stability	EM signatures	GWs
Fluid stars	UCOs	✗	✓ [18, 25, 33, 56–58]	✓	✓ [18, 25, 30, 56]
Anisotropic stars	ClePhOs [59–61]	✗	✓ [62, 63]	✓ [35, 61, 64]	✓ [35, 64]
Boson stars & oscillatons	UCOs, (ClePhOs?) [65–72]	✓ [68, 71, 73–75]	✓ [70, 76–80]	✓ [81–83]	✓ [24, 50, 55, 84–88]
Gravastars	COs – ClePhOs [4, 89]	✗	✓ [79]	✓ [90–92]	~ [23, 25, 33, 50, 55, 92, 97]
AdS bubbles	UCOs – ClePhOs [98]	✗	✓ [98]	~ [98]	✗
Wormholes	ClePhOs [99–103]	✗	✓ [104, 105]	✓ [106–109]	~ [23, 50, 55]
Fuzzballs	ClePhOs [5, 6]	✗	✗ (but see [110–113])	✗	~ (but see [23, 24, 114])
Superspinars	COs – ClePhOs [115]	✗	✓ [37, 116]	✗ (but see [117])	~ [23, 24]
2 – 2 holes	ClePhOs [118]	✗	✗ (but see [118])	✗ (but see [118])	~ [23, 24]
Collapsed polymers	ClePhOs [119, 120]	✗	✗ (but see [119, 121])	✗	~ [121]
Quantum bounces / black stars	ECO – ClePhOs [7, 8, 122–125]	✗ (but see [123, 126])	✗	✗	~ [125]
Quantum stars*	UCOs – ClePhOs [127, 128]	✗	✗	✗	✗
Fire-walls*	ClePhOs [129–131]	✗	✗	✗	~ [24, 132]

Buchdahl limit in GR:  
 $r > 9/8 R_{\text{sh}}$

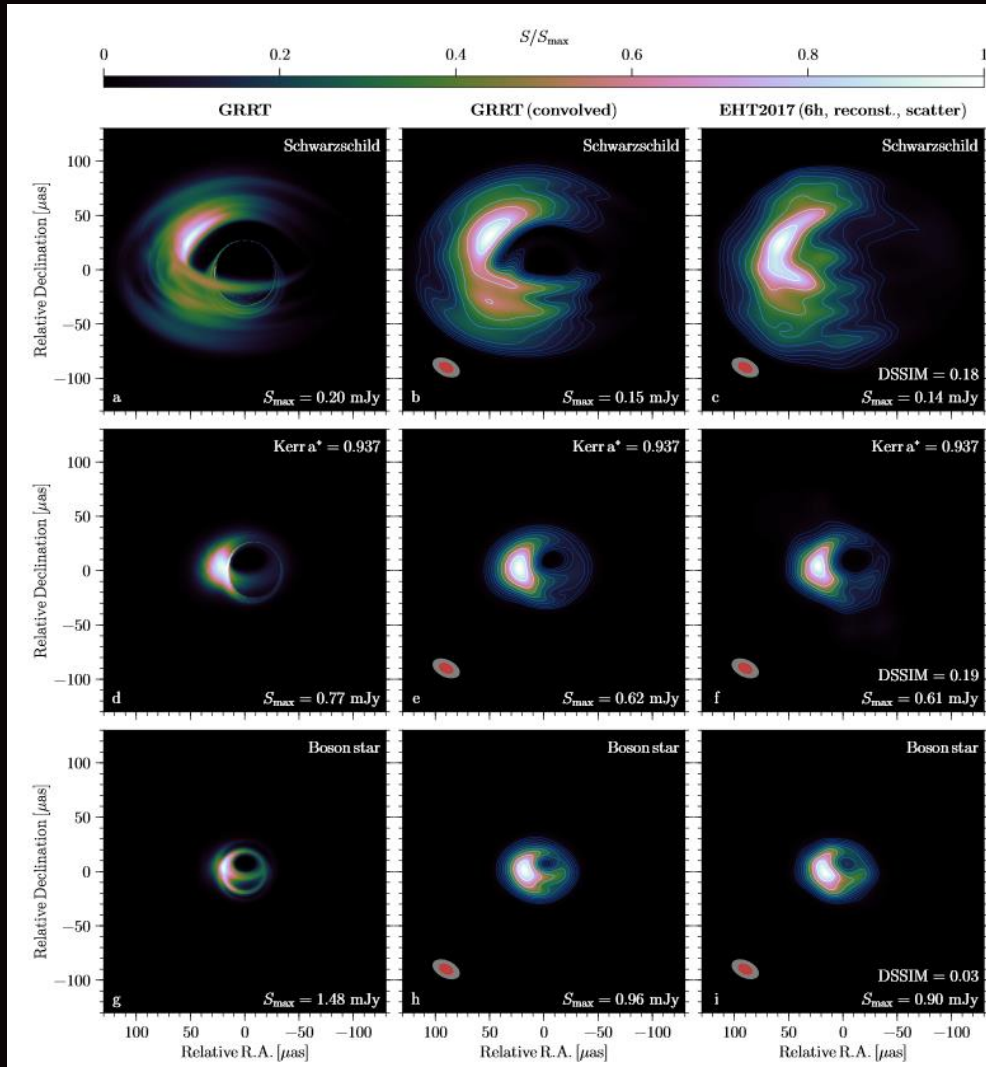
Valid for ordinary fluids.



# BHs vs. boson stars



# 230 GHz images of BHs and boson stars



Potentially, future imaging (most probably with space based millimeter range interferometers) can distinguish between SMBHs and boson stars due to differences in the appearance of the “shadow”.

# GRAvitational VAcuum STAR

- I. Interior :  $0 \leq r < r_1$ ,  $\rho = -p$ ,
- II. Shell :  $r_1 < r < r_2$ ,  $\rho = +p$ ,
- III. Exterior :  $r_2 < r$ ,  $\rho = p = 0$ .

Vacuum outside,  
Vacuum inside

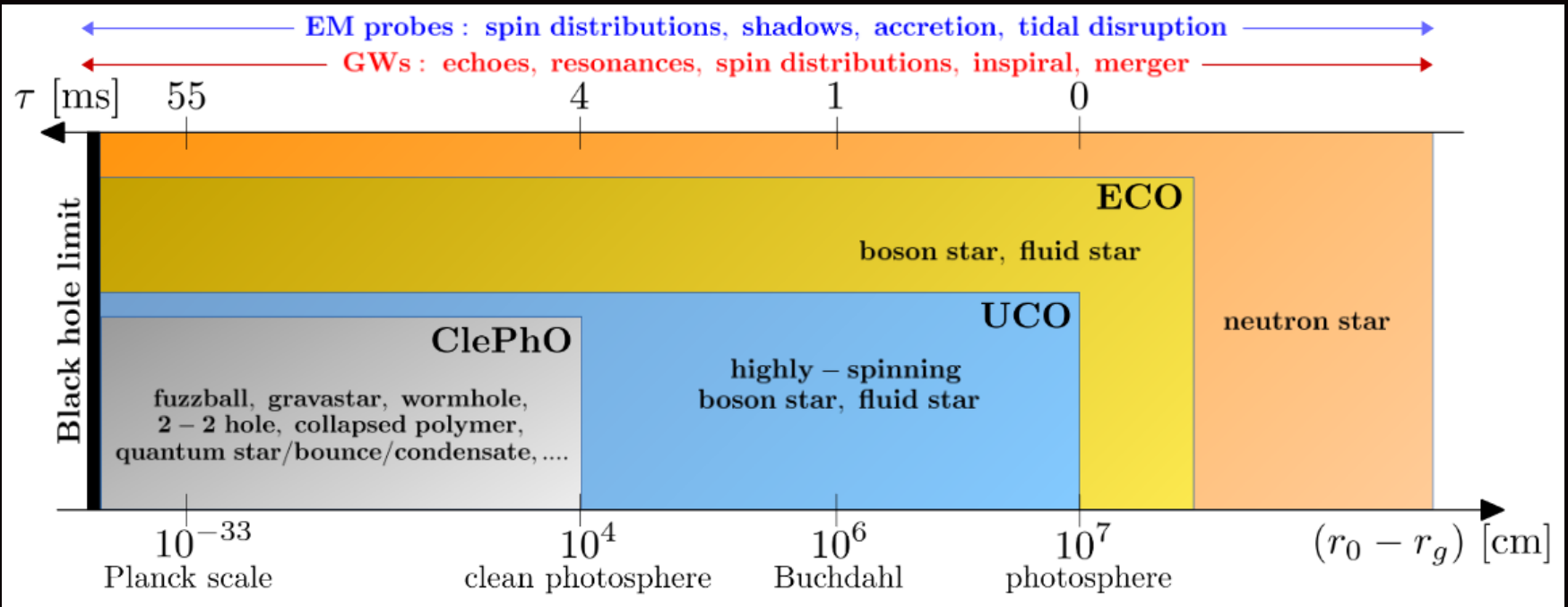
Do not produce  
Hawking radiation.

Can be distinguished  
in coalescence.

See recent developments  
in 1512.07659



# Probing vicinity of a horizon



ECO – more massive than a NS

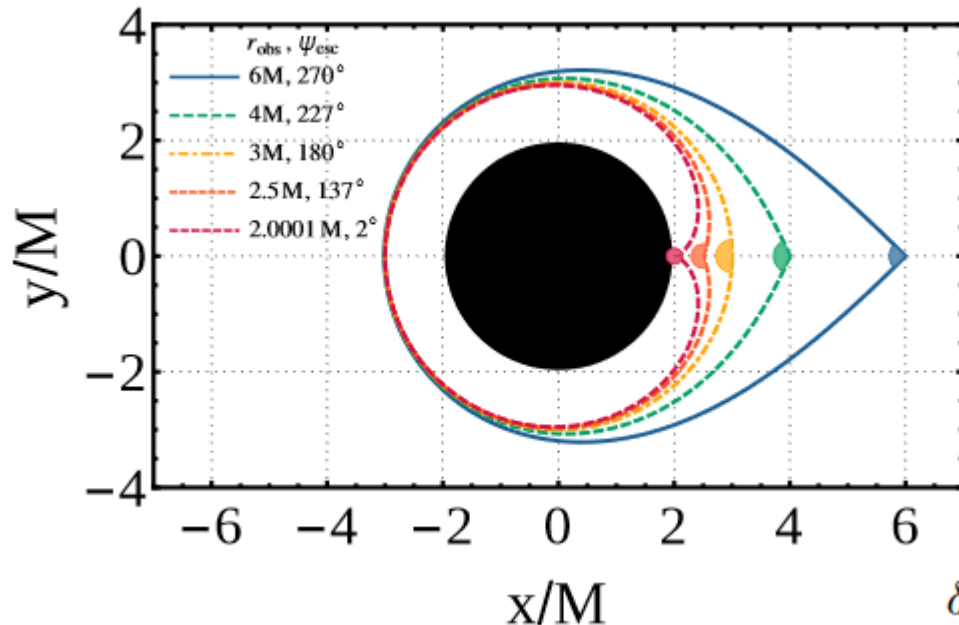
UCO – have a photosphere (radius < photon sphere)

ClePhOs – have surface too close to the horizon

$$r_0 = 2M(1 + \epsilon)$$

$$\epsilon \lesssim \epsilon_{\text{crit}} \sim 0.0165$$

# Emission propagation in the vicinity of a BH horizon



$$f_0 \equiv f(r_0) = 1 - 2M/r_0.$$

$$\sin \psi_{\text{esc}} = 3M\sqrt{3f_0}/r_0$$

$$r_{\text{max}} \sim 2M \left( 1 + \frac{4f_0 M^2}{r_0^2 \sin^2 \psi} \right)$$

$$t_{\text{roundtrip}} \sim 8M \log(\cot(\psi/2))$$

$$\delta(t) \sim \delta_0 e^{\lambda t}, \quad \lambda = \sqrt{\frac{-f^2 V_r''}{2E^2}} = \frac{1}{3\sqrt{3}M}$$

$$\Delta\Omega_{\text{esc}} = 2\pi \left( 1 - \sqrt{1 - \frac{27M^2(r_0 - 2M)}{r_0^3}} \right) \sim 27\pi \left( \frac{r_0 - 2M}{8M} \right)$$

# What can low luminosity rule out?

$$t_{\text{roundtrip}} \sim 8M \log(\cot(\psi/2)) \approx 9.33M$$

$$N = T/t_{\text{roundtrip}}$$

$$\Delta E \sim [1 - (1 - \epsilon)^N] \delta M$$

$$r_0 = 2M(1 + \epsilon)$$

$$\Delta E \sim \epsilon N \delta M \text{ if } \epsilon N \ll 1.$$

$$\epsilon \ll 10^{-16} \left( \frac{M}{10^6 M_\odot} \right) \left( \frac{t_{\text{Hubble}}}{T} \right)$$

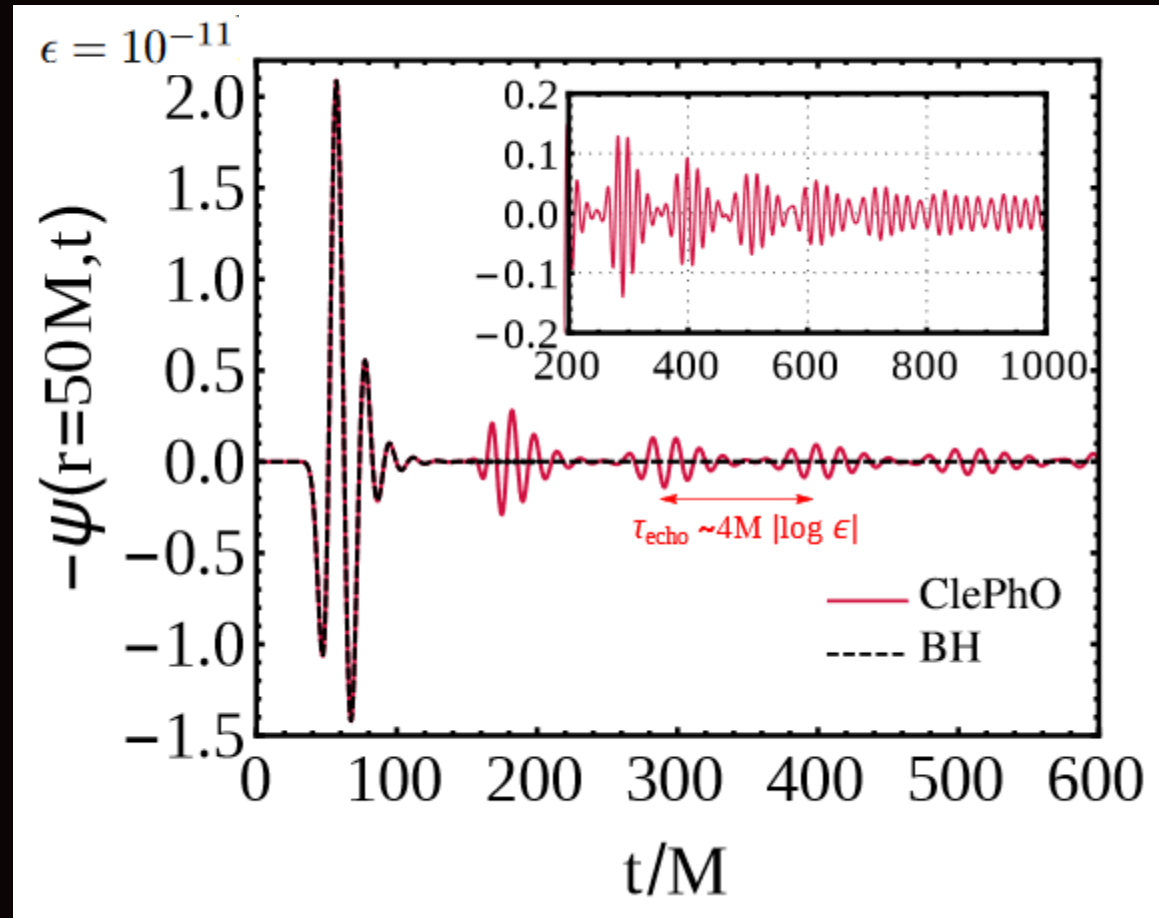
$$\dot{E} \sim 10^{-17} \left( \frac{\epsilon}{10^{-16}} \right) \left( \frac{\delta M}{M} \right)$$

Thus, it is difficult to rule out  $\epsilon \ll 10^{-16}$

with electromagnetic observations.

# Echos in CLePhOs

$$\tau_{\text{echo}} \sim 4M |\log \epsilon|$$



$$\tau_{\text{echo}} \sim 2M [1 + (1 - \chi^2)^{-1/2}] \log \epsilon, \quad \tau_{\text{echo}} \sim (\omega_R - m\Omega)^{-1}$$

# GWs: BHs vs. ECOs

		BH	ECO	ClePhO
ringdown	GW echoes	$\times$	$\checkmark$ (only UCOs)	$\checkmark (\tau_{\text{echo}} \sim M  \log \epsilon )$
	Modified prompt ringdown	$\times$	$\checkmark$	$\times$
	Extra modes	$\times$	$\checkmark$	$\checkmark$
inspiral	Multipolar structure (2PN)	$\delta M_l = \delta S_l = 0$	$\delta M_l \neq 0, \delta S_l \neq 0$	$\delta M_l \simeq 0, \delta S_l \simeq 0$
	Tidal heating (2.5 – 4PN)	$\checkmark$	$\times$	$\times$
	Tidal Love number (5PN)	$k = 0$	$k \lesssim \mathcal{O}(k_{\text{NS}})$	$k \sim [\log \epsilon]^{-1}$
	Resonances	$\times$	$[80, 96]$	$\omega M \sim [\log \epsilon]^{-1}$

$$\tau_{\text{echo}} \sim M |\log \epsilon|$$



# Conclusions

It is very difficult to prove that a given object is a real BH with horizon, or may be even impossible (see 1904.05363).