# 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

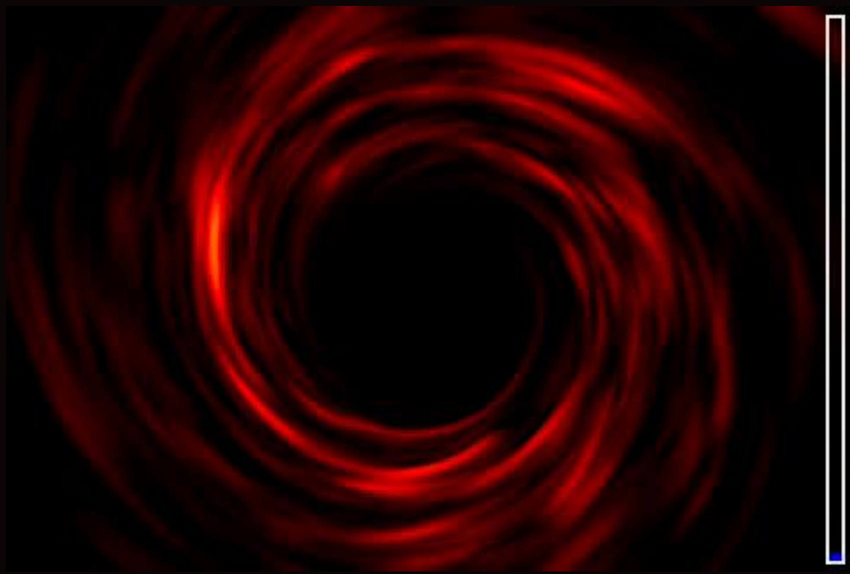
What can be a 100% proof that we observe a BH?
Of course, only a direct evidence for the horizon existence!
But it is very difficult to prove it!
One can try to follow three routes:

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.

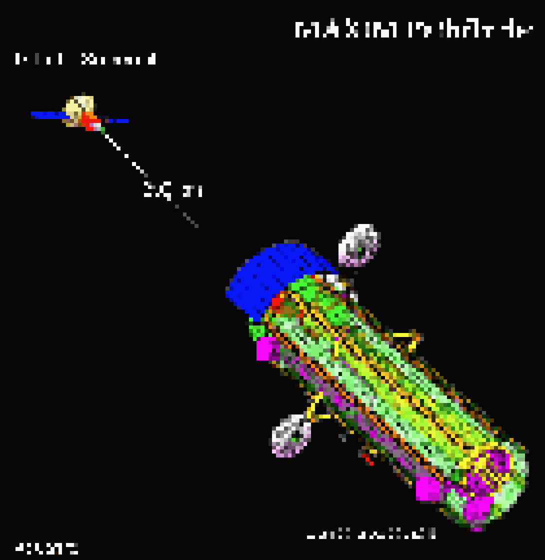
The first approach is not very realistic (astro-ph/0207270 Abramowicz et al.)

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)



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

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

# Absence of surface

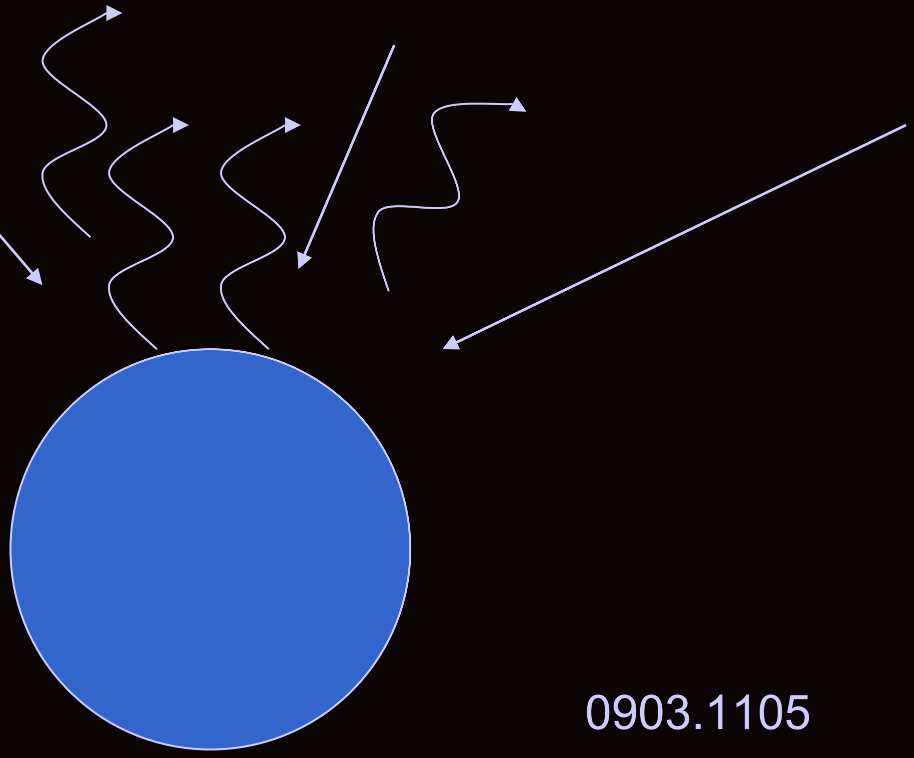
Here we mostly discuss close binaries with accretion

- 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.



0903.1105

See also 1503.03873 about M87

# Surface emission limits

$$E_\infty = \Delta\epsilon_g mc^2$$

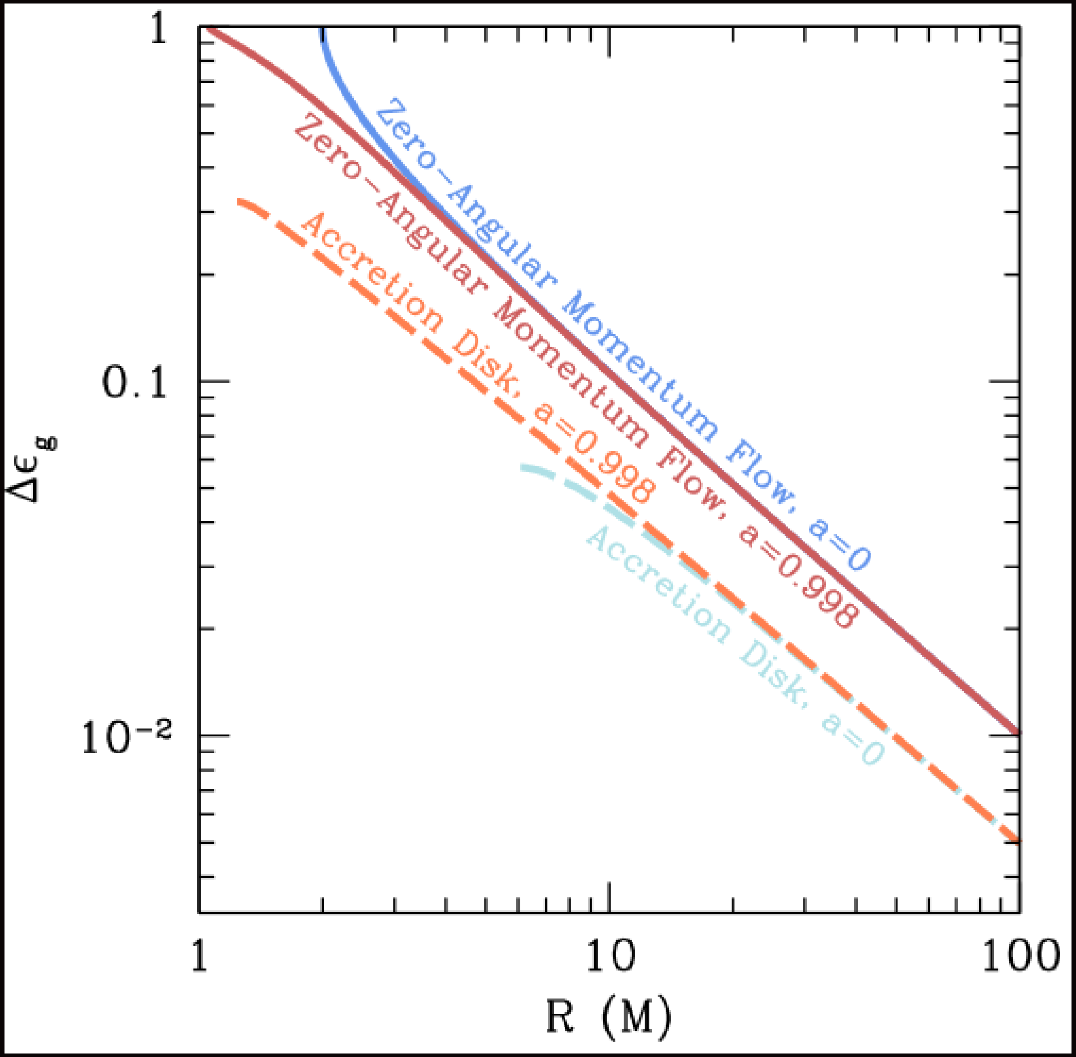
$$L_\infty = \Delta\epsilon_g \dot{M} c^2$$

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

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

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

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




arXiv:0903.1105

# Limits

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

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

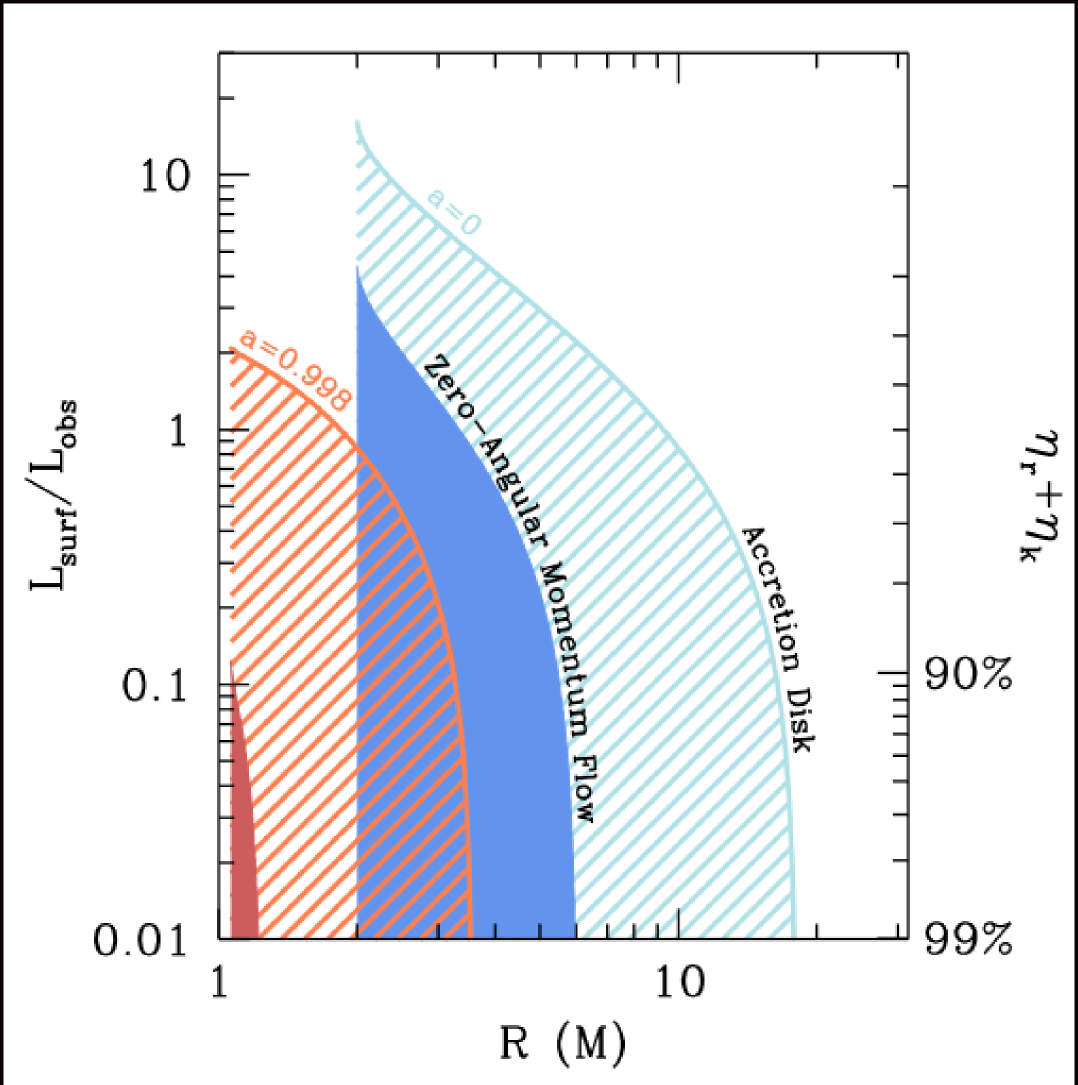
$$F_\nu = \pi\left(\frac{R_a}{D}\right)^2 B_\nu\left(T_\infty\right)$$

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

$$\frac{L_{\rm surf}}{L_{\rm obs}} \le \frac{L_{\rm surf,max}}{L_{\rm obs}}$$

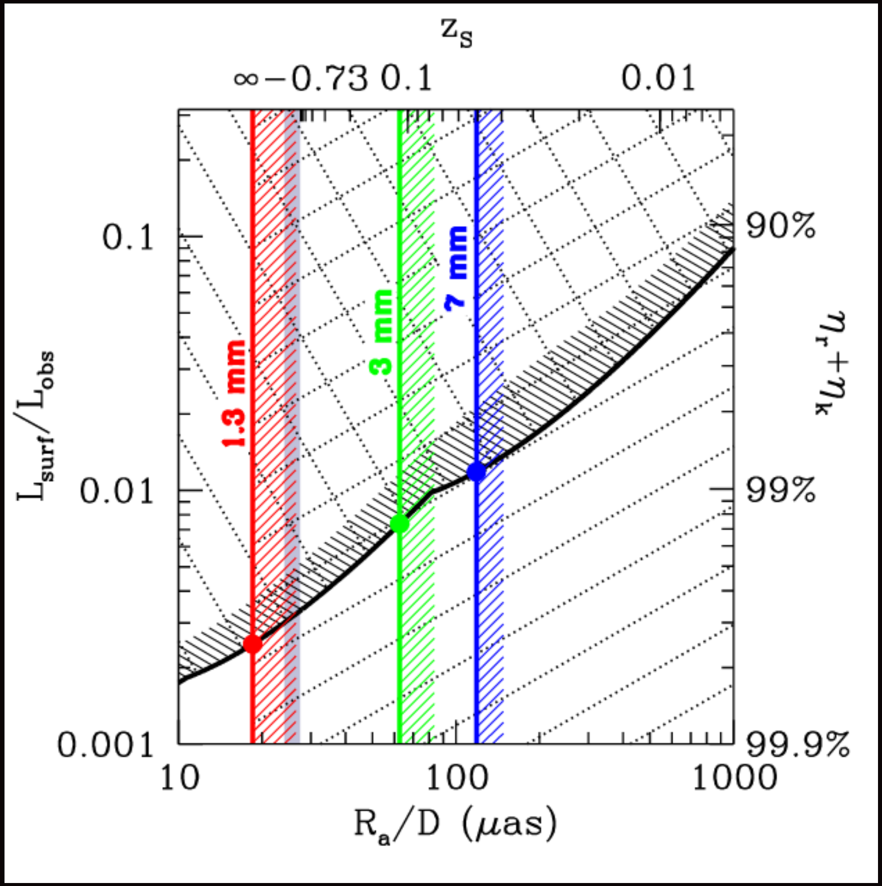
$$\equiv \frac{\sigma R_a^2}{D^2 F_{\rm obs}} T_{\rm max}^4\left(\nu, F_\nu^{\rm obs}; \frac{R_a}{D}\right)$$

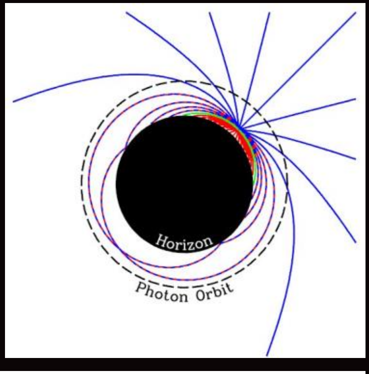
$$\eta_r + \eta_k \ge \frac{1}{1+L_{\rm surf,max}/L_{\rm acc}}$$

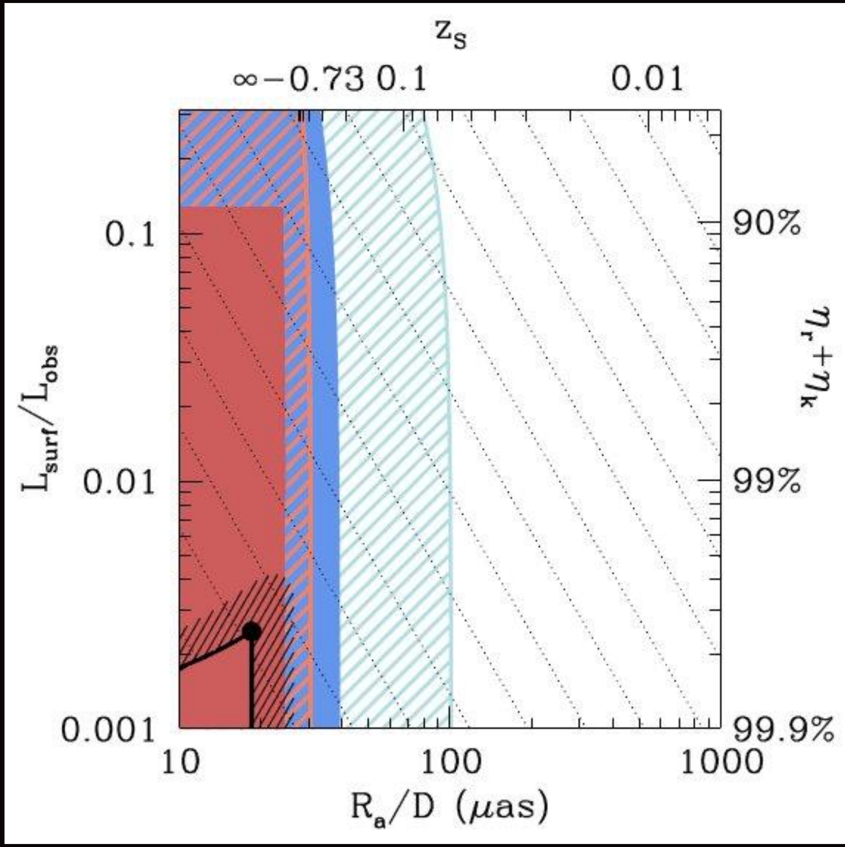



arXiv:0903.1105

# Sgr A*

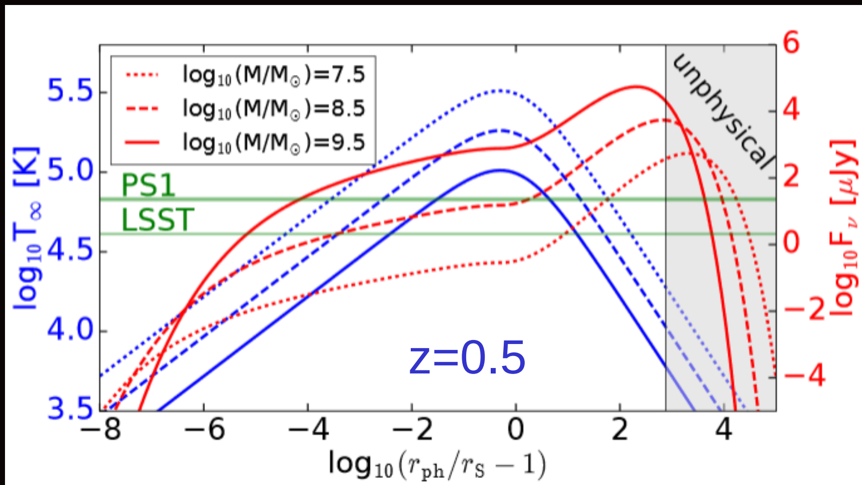


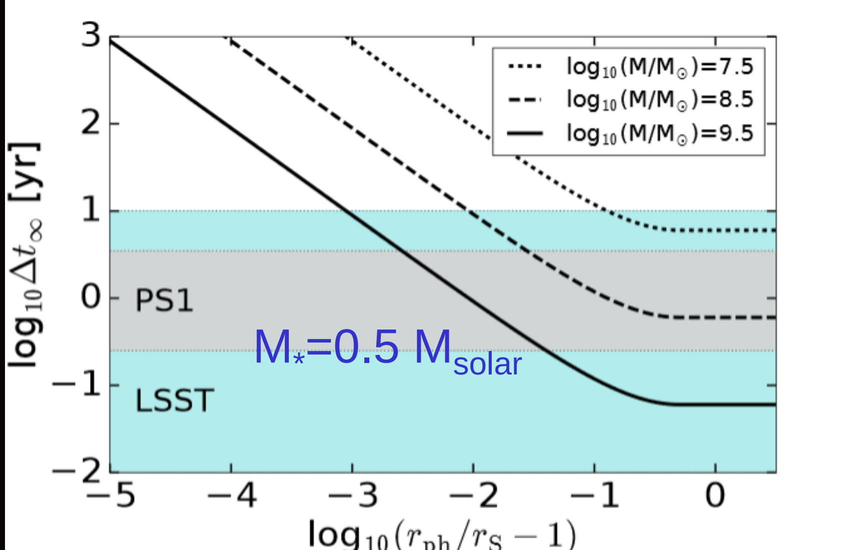



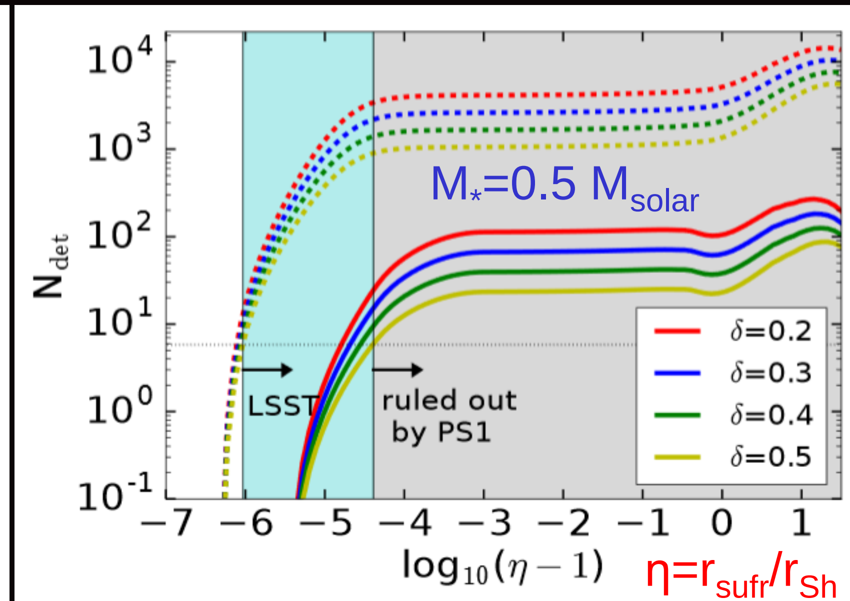




arXiv:0903.1105

# Tidal disruption and horizons



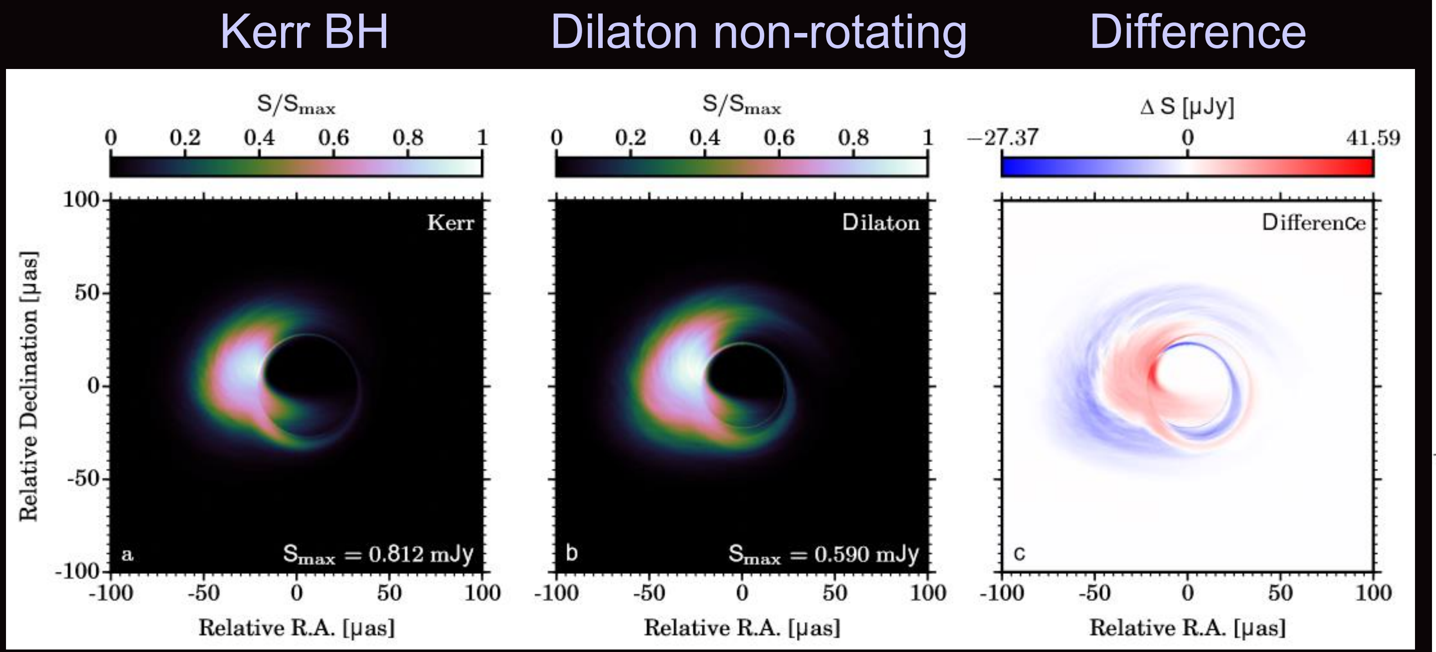



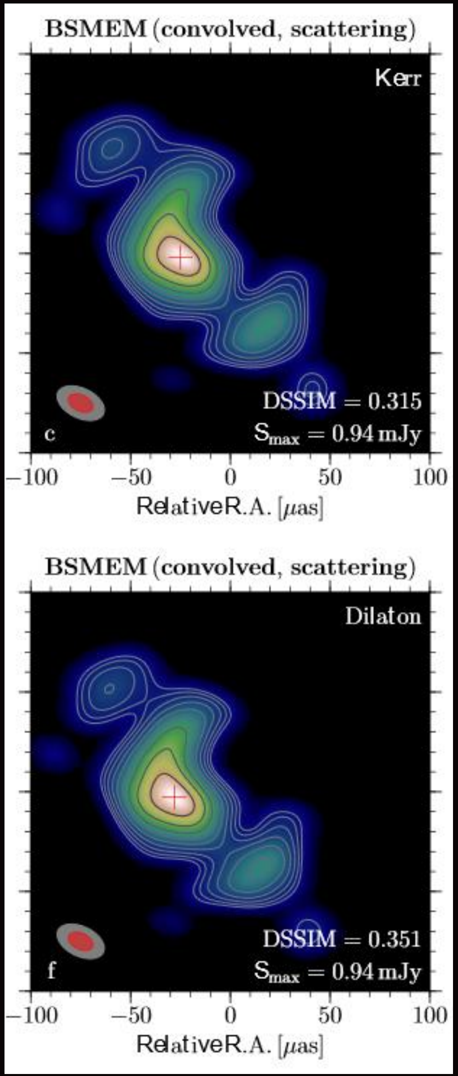

If there is a hard surface, then a kind of a photosphere might be formed above it.

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

1703.00023

# BH shadow and alternative theories

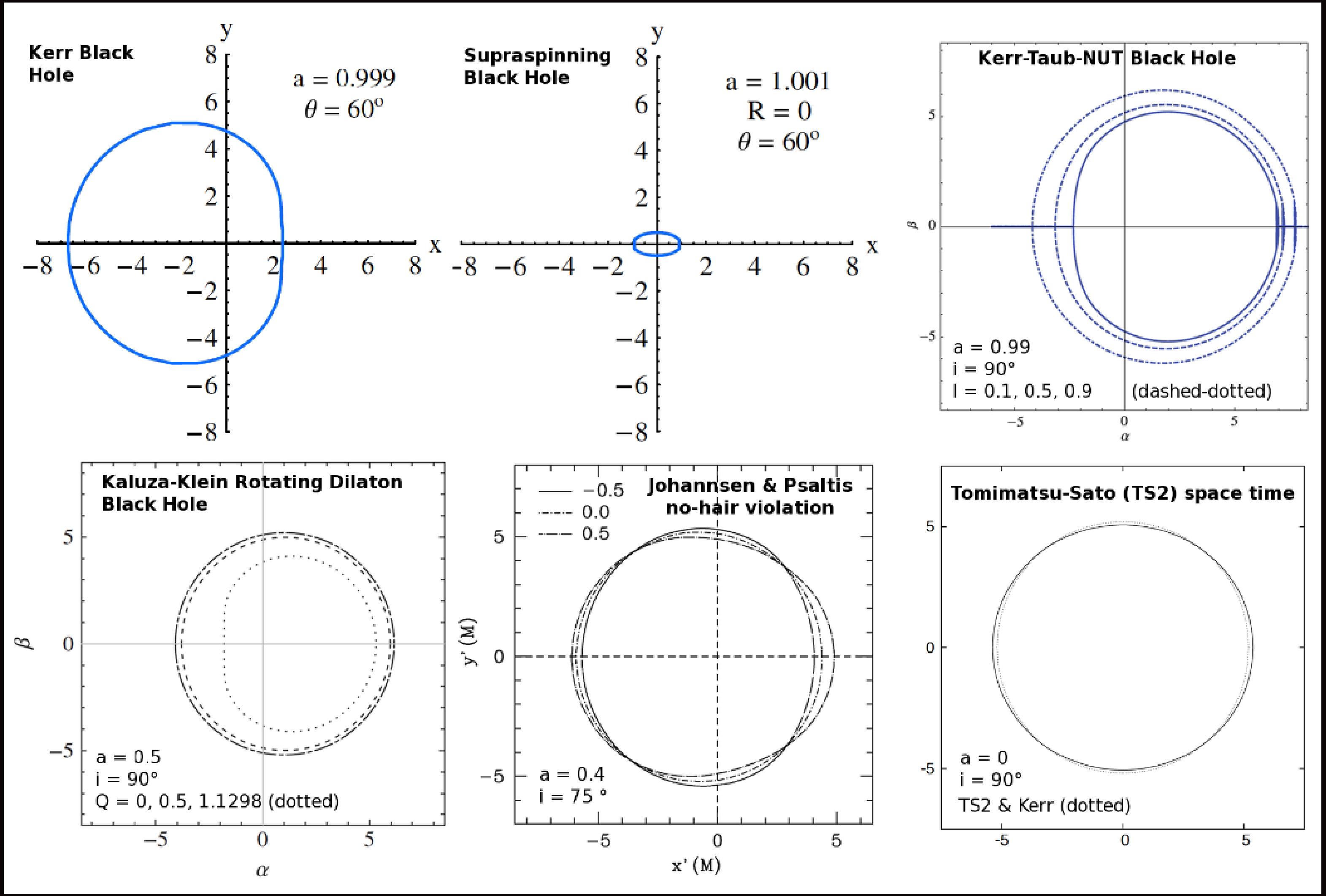



Impossible to distinguish with present day technique.

1804.05812

# BH shadow in different models

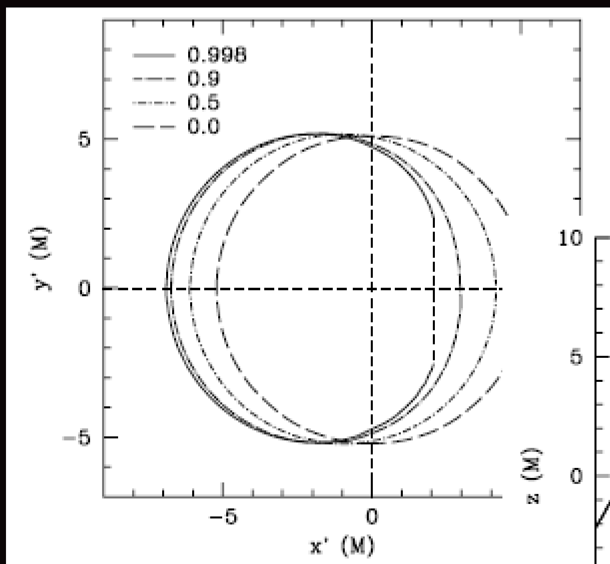



1311.1841

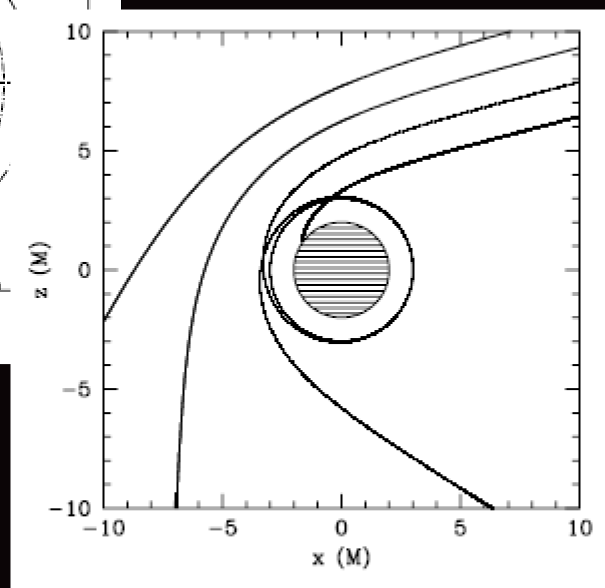
# Testing no-hair theorem

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

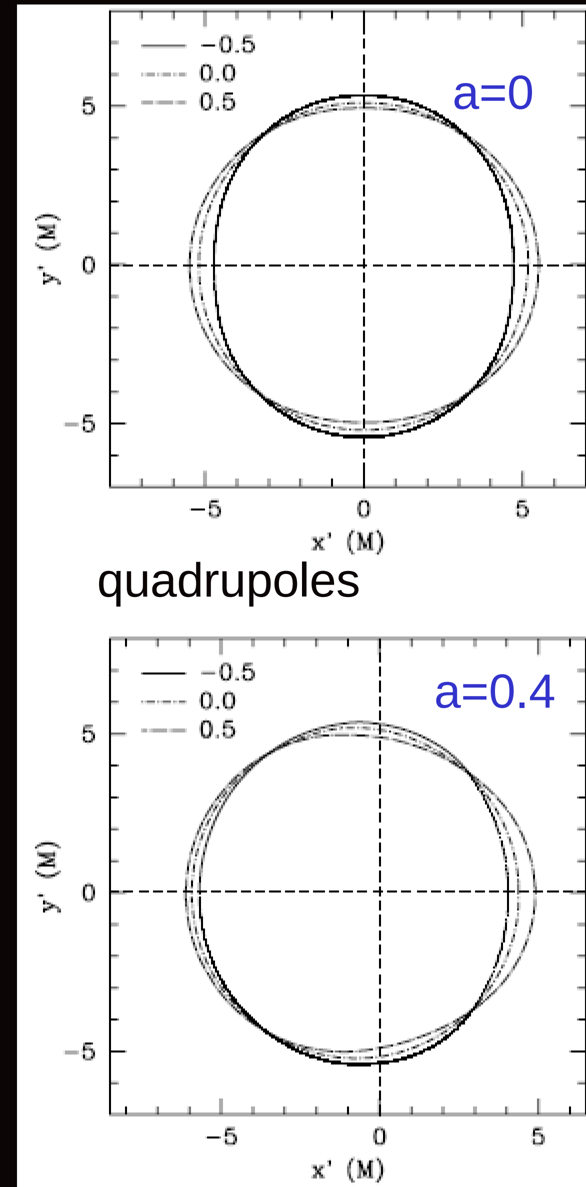
$$Q = -M\left(a^2 + \epsilon M^2\right)$$




Spinning BHs




Photon ring formation




1005.1931

# Parameters of different models

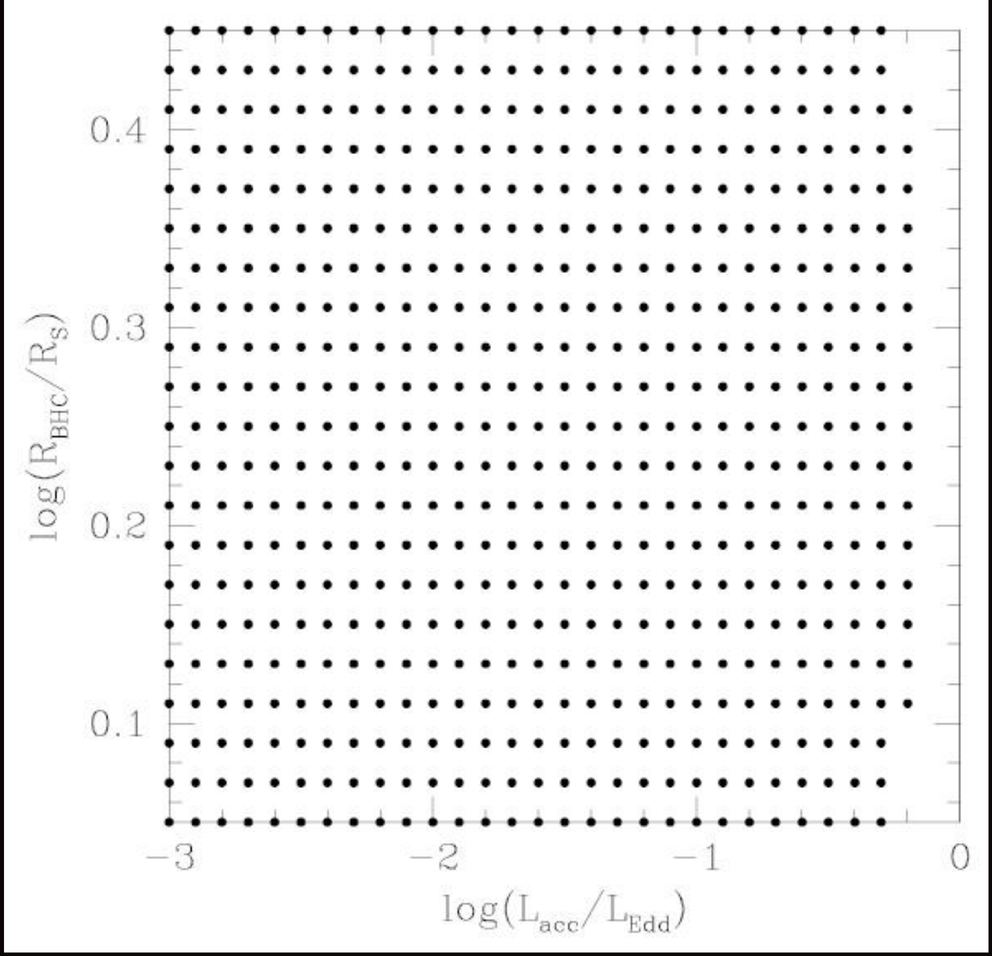
Fermion stars:
$M_f$=223 MeV (non-interacting)
$M_{max}$=12.61 $M_0$
R(M=10$M_0$)= 252 km= 8.6 $R_{sh}$
Collapse after adding 0.782 $M_0$ of gas.

Bozon stars:
$M_b$=2.4 $10^{-17}$MeV, λ=100
$M_{max}$=12.57 $M_0$
R(M=10$M_0$)= 153 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

astro-ph/0401549

# Stability respect to flares on a surface




For a 10 solar mass object with hard surface

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

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

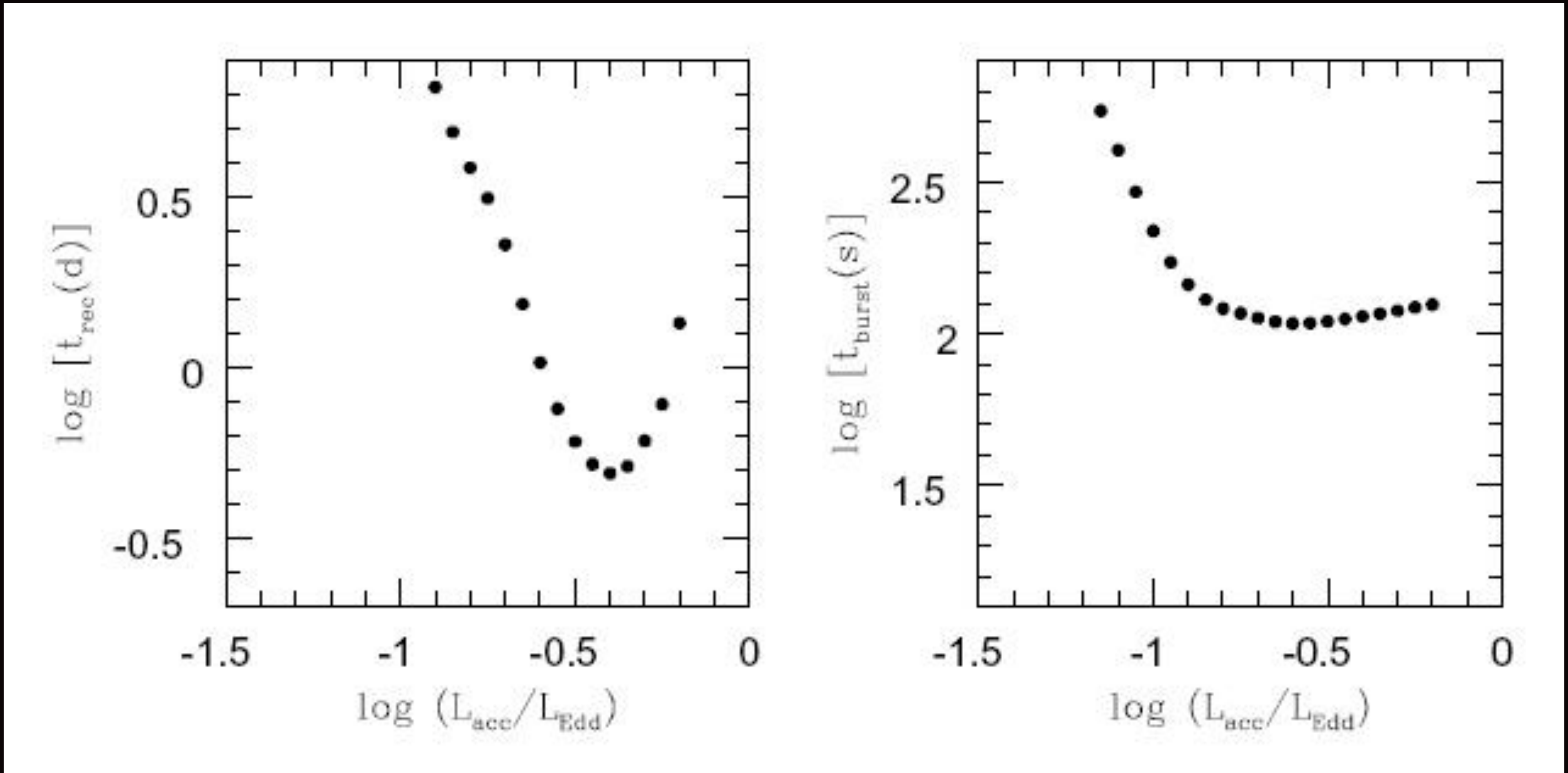
Still, if they are possible, then one can “hide” bursts due to high redshift.

Solid dots – bursts.

Blanc field – stable burning.

astro-ph/0401549

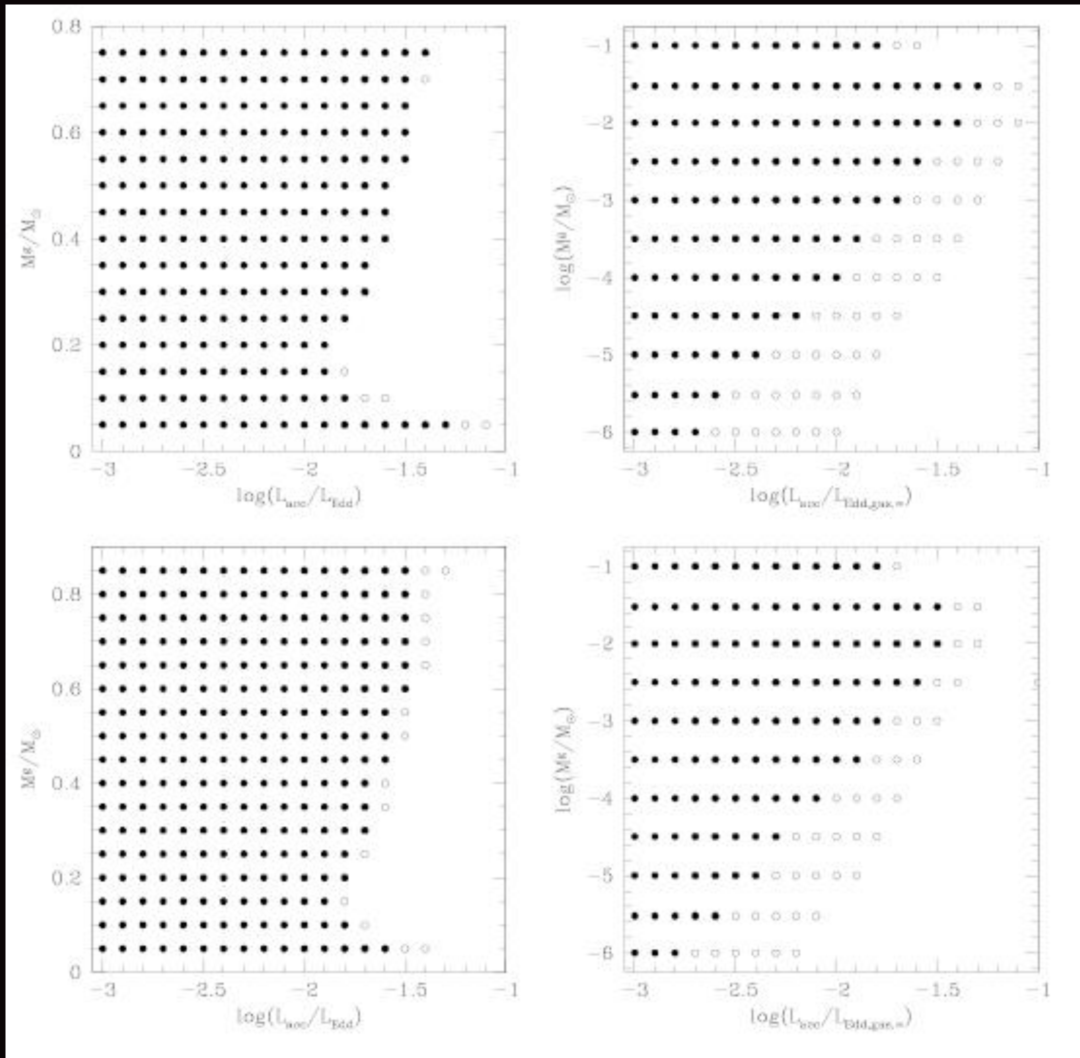
# Timing characteristics of surface bursts




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

astro-ph/0401549

# Stability respect to flares inside an object

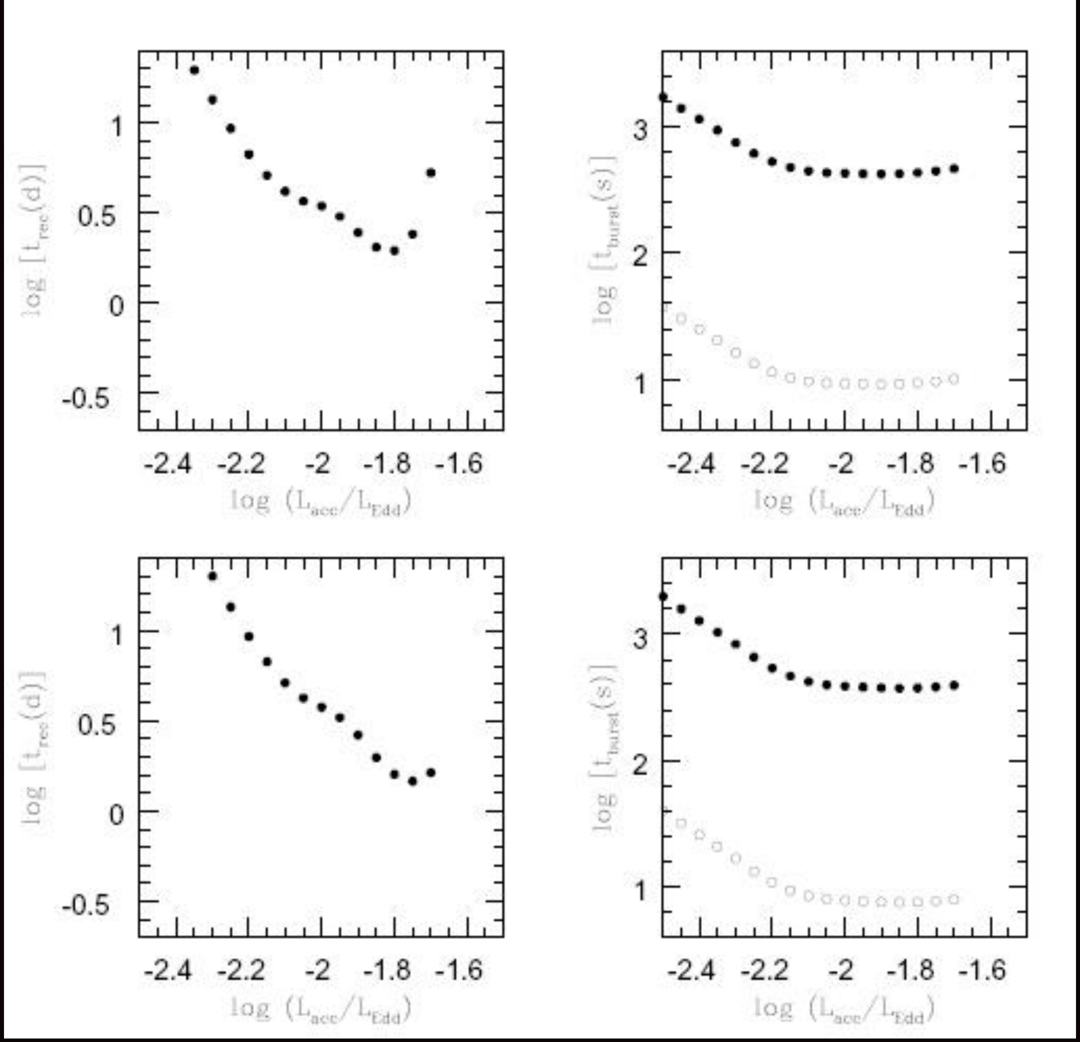



Fermion stars

Bozon stars

astro-ph/0401549

# Timing characteristics of internal bursts




Fermion stars

Bozon stars

$M_{gas}$=0.3 solar mass

astro-ph/0401549

# 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.**

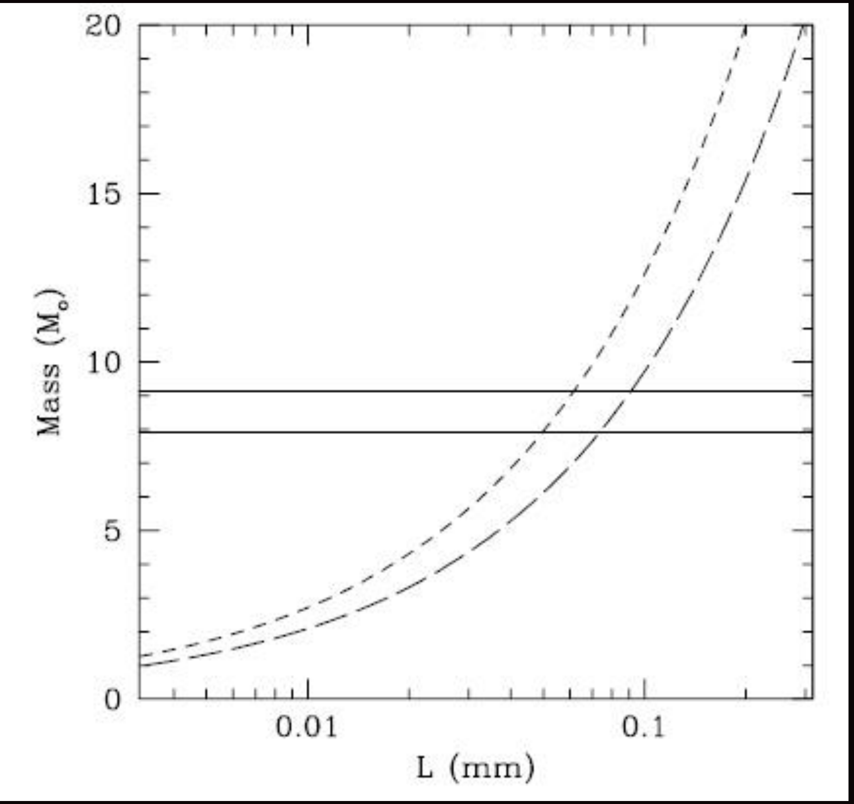
# Brane worlds and black holes

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.

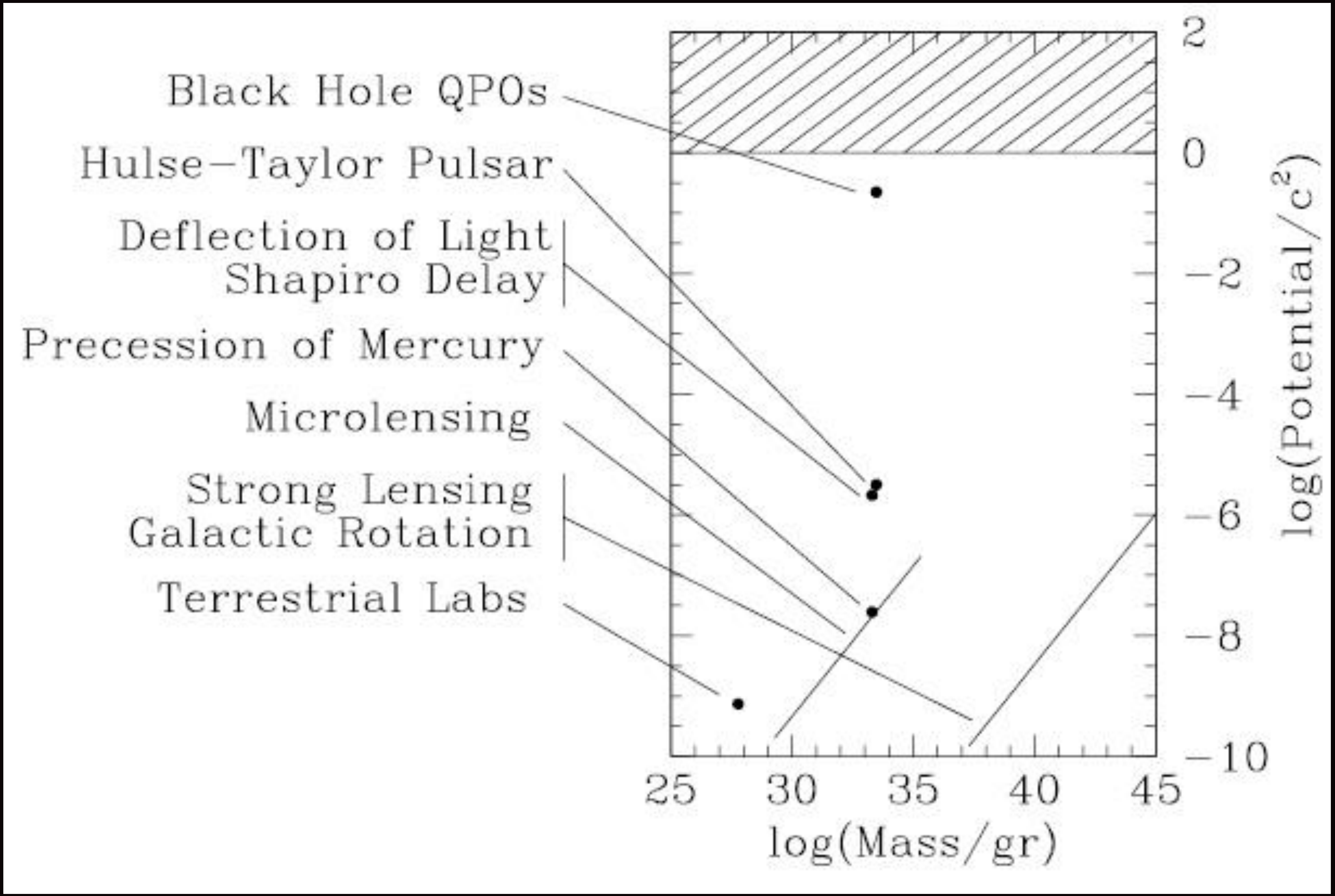
Age estimated by the time of the last galactic crossing.

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

(see also astro-ph/0401466)

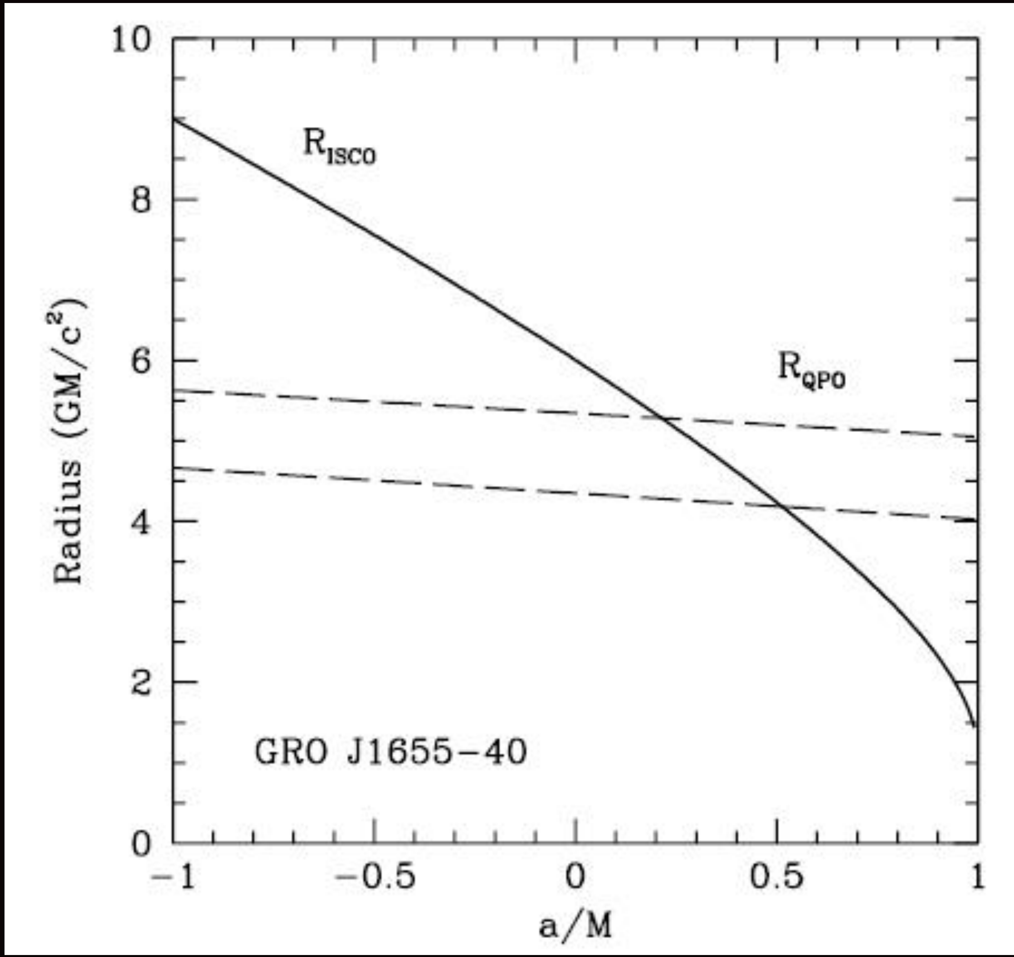


# BH spin and testing the GR




astro-ph/0402213

# QPO in GRO 1655-40




If the interpretation of QPOs in this source is correct, than we can “look inside” 3Rg.

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 $f_{QPO}<f_{AZIM}=(GM)^{1/2}/2\pi R^{3/2}$

astro-ph/0402213

# 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 criticizm, 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 activley critisized by theorists.

Problems with formation mechanisms and stability.

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

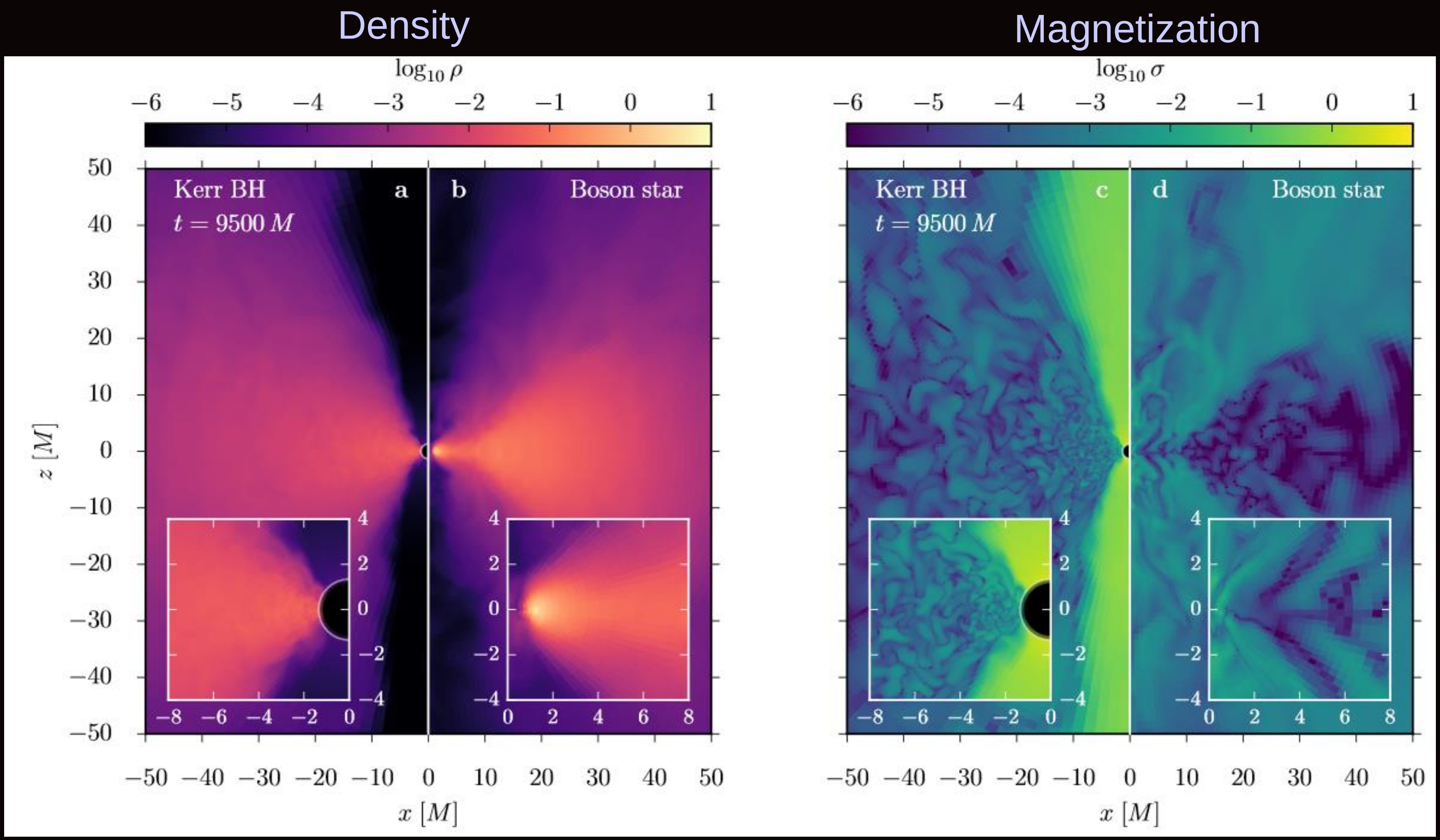
| Model | Taxonomy | Formation | Stability | EM signatures | GWs |
|---|---|---|---|---|---|
| Fluid stars | UCOs | ✗ | ✓ [18, 25, 33, 56–58] | ✓ | ✓ [18, 25, 30, 56] |
| Anisotropic stars | ClePhOs [59–61] | ✗ | ✓ [62, 63] | ✓ [35, 61, 64] | ✓ [35, 64] |
| Boson stars & oscillatons | UCOs, (ClePhOs?) [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: $r>9/8\ R_{sh}$

Valid for ordinary fluids.

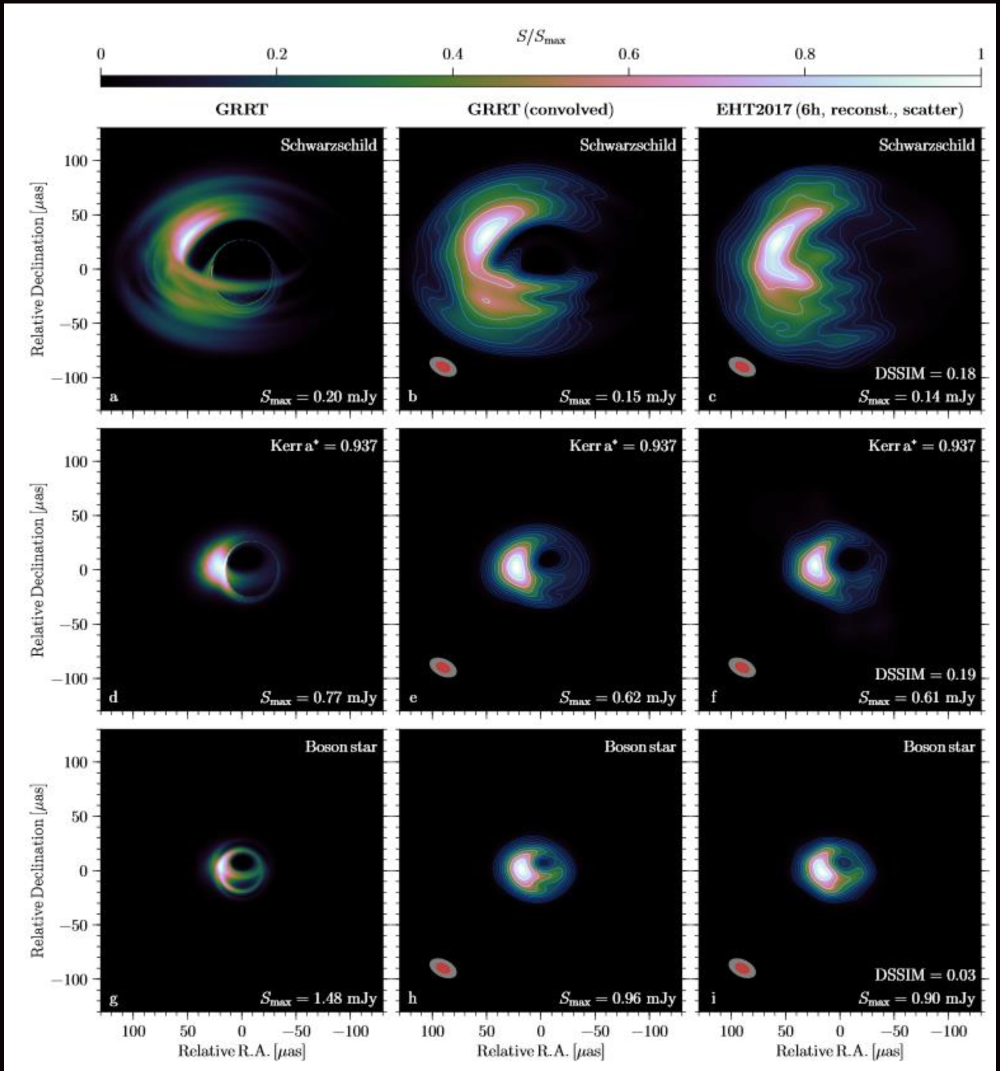
1707.03021

# BHs vs. boson stars




1809.08682

# 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".

1809.08682

# 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

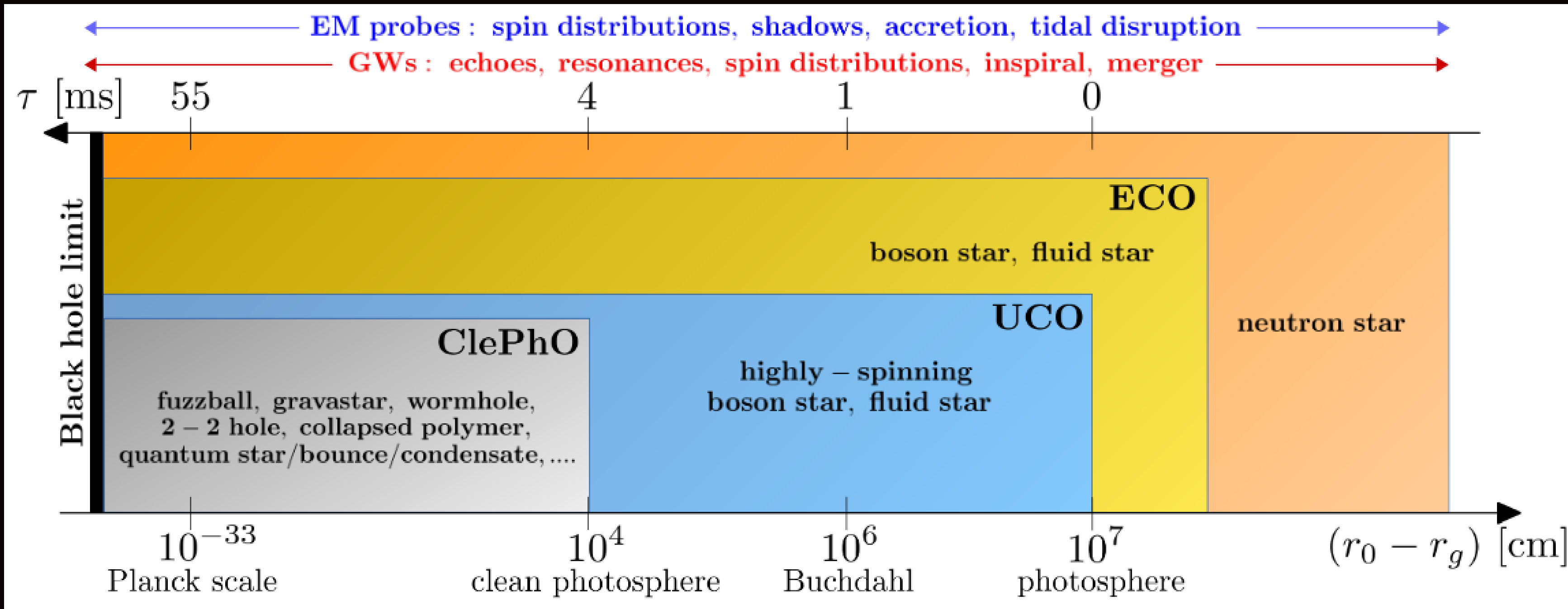
Do not produce
Hawking radiation.

Can be distinguished
in coalescence.

See recent developments
in 1512.07659


Mazur, Mottola gr-qc/0109035

# Probing vicinity of a horizon




ECO – more massive than a NS

UCO – have a photosphere (radius < photon sphere)

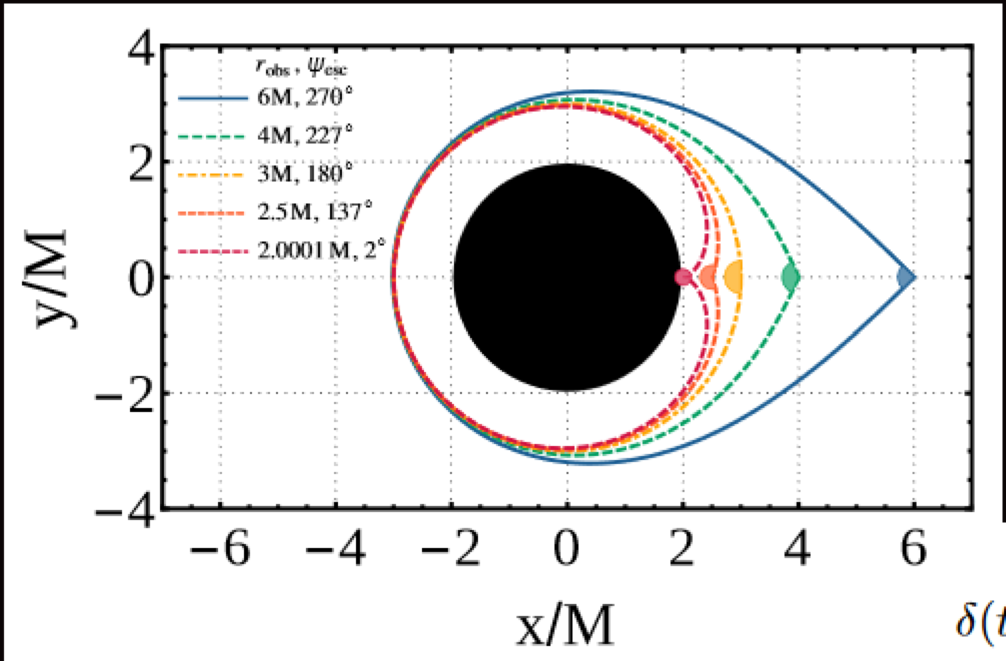
ClePhOs – have surface too close to the horizon

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

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

1707.03021 (see also a shorter version in 1709.01525)

# Emission propagation in the vicinity of a BH horizon




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

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

$$r_{\rm max} \sim 2M\left(1 + \frac{4f_0M^2}{r_0^2\sin^2\psi}\right)$$

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

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

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

1707.03021

# What can low luminosity rule out?

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

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

$\Delta E \sim \left[1 - (1-\epsilon)^N\right] \delta M$  $r_0 = 2M(1+\epsilon)$

$\Delta E \sim \epsilon N \delta M$ if $\epsilon N \ll 1$,

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

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

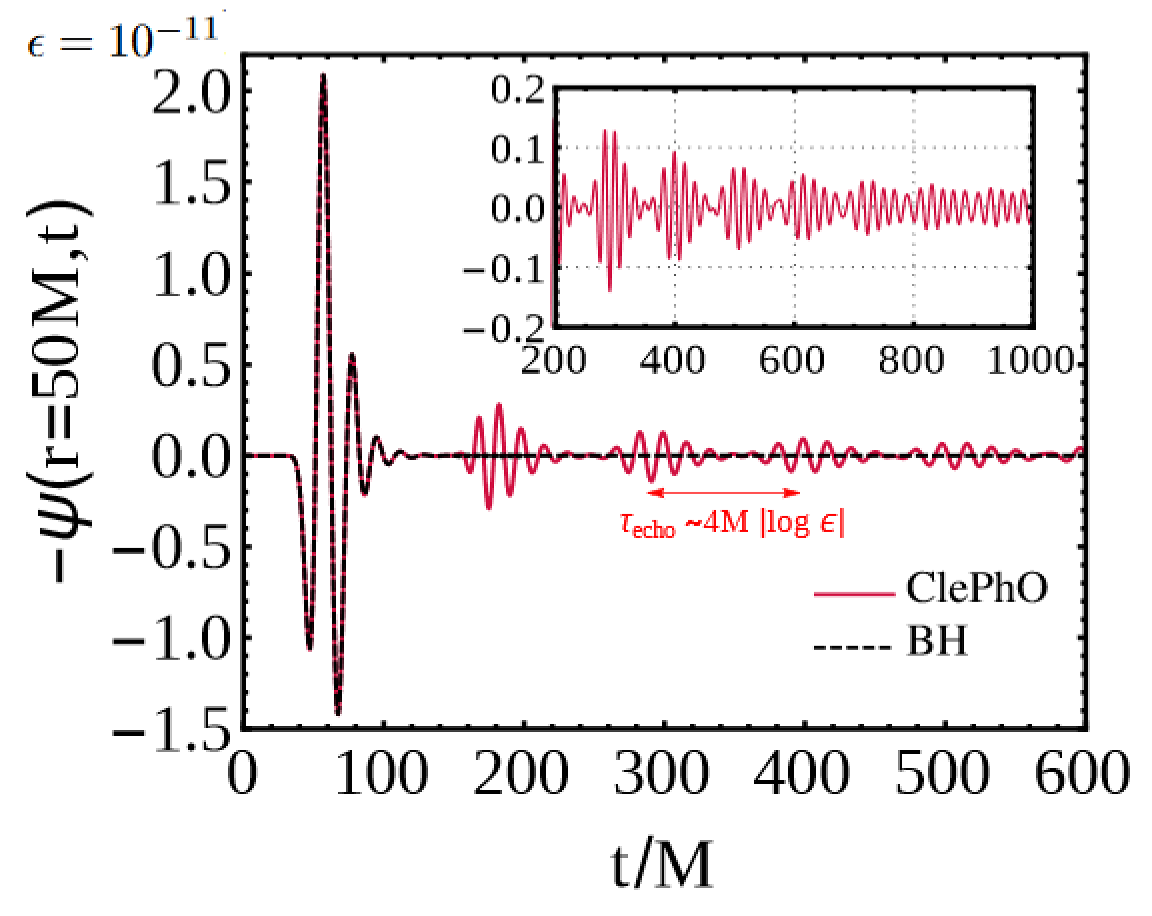
Thus, it is difficult to rule out $\epsilon \ll 10^{-16}$

with electromagnetic observations.

1707.03021

# Echos in CLePhOs

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




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

1707.03021

# GWs: BHs vs. ECOs

| | | BH | ECO | ClePhO |
|---|---|---|---|---|
| ringdown | GW echoes | ✗ | ✓(only UCOs) | ✓($\tau_{\rm echo} \sim M\lvert\log\epsilon\rvert$) |
| | Modified prompt ringdown | ✗ | ✓ | ✗ |
| | Extra modes | ✗ | ✓ | ✓ |
| 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) | ✓ | ✗ | ✗ |
| | Tidal Love number (5PN) | $k = 0$ | $k \lesssim \mathcal{O}(k_{\rm NS})$ | $k \sim [\log\epsilon]^{-1}$ |
| | Resonances | ✗ | [80, 96] | $\omega M \sim [\log\epsilon]^{-1}$ |

$\tau_{\rm echo} \sim M\lvert\log\epsilon\rvert$

1707.03021

# 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).