Topics

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Black hole
Celestial object category

Higgs boson
Subatomic particle

Vangelis
Search term

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Beta: Measuring search interest in *topics* is a beta feature which quickly provides accurate measurements of overall search interest. To measure search interest for a specific *query*, select the "search term" option. ?

Interest over time ?

☑ News headlines ☐ Forecast ?

</>

Regional interest ?

Black hole Higgs boson **vangelis**

Region | City

Cyprus	100
Greece	77
Hungary	68
Chile	55
Romania	50
Portugal	46
Poland	45

▸ View change over time ?

</>

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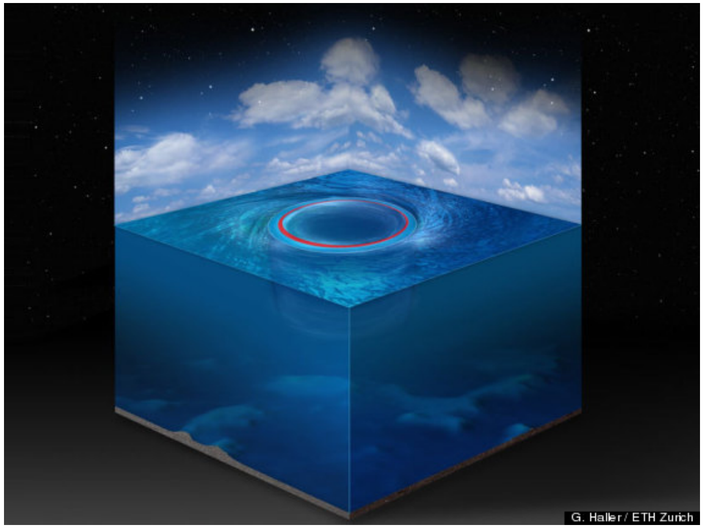
'Black Holes' In Ocean Exist, Scientists Say



‘CNN Black Hole-based Malaysian airplane theory'

The many faces of BHs

Astrophysics

Supermassive BHs
final stage of stellar collapse
symbiosis with galaxies

Gravitation

BHs are "elementary particles" of gravity
No-hair theorems
Cosmic Censorship
gravitational waves

Gauge/gravity duality

Holographic principle,
AdS/CFT correspondence
condensed matter (!)
Quark-gluon plasma

Particle physics

Mini BHs at LHC
theories with extra dimensions
BHs as particle detectors
and dark matter probes

Beyond General Relativity

Tests of Einstein's theory in strong-field regime
effective quantum-gravity theories at low energy
dark matter and dark energy problems
singularities

Fluid dynamics

Acoustic geometries
Analogue Hawking radiation
superresonance

Newton’s gravity

Action at a distance

Action is instantaneous

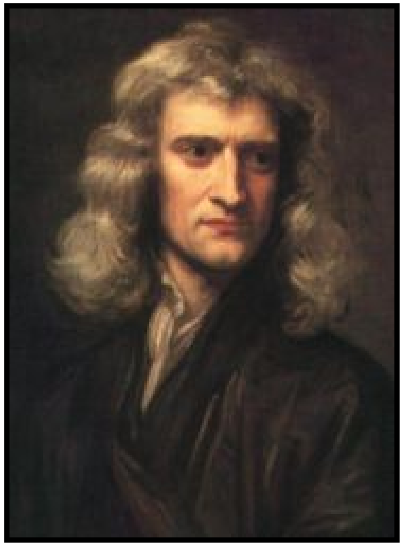
Every object falls identically

Ioannes Philliponus (~600, Alexandria): "... let fall from the same height two weights of which one is many times as heavy as the other... the difference in time is a very small one"

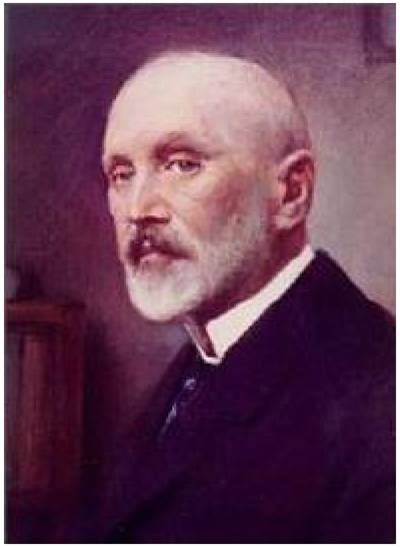
Simon Stevin (1548-1620, Antwerp):
Demonstração experimental (1586)

Galileo (1564-1642, Pisa)

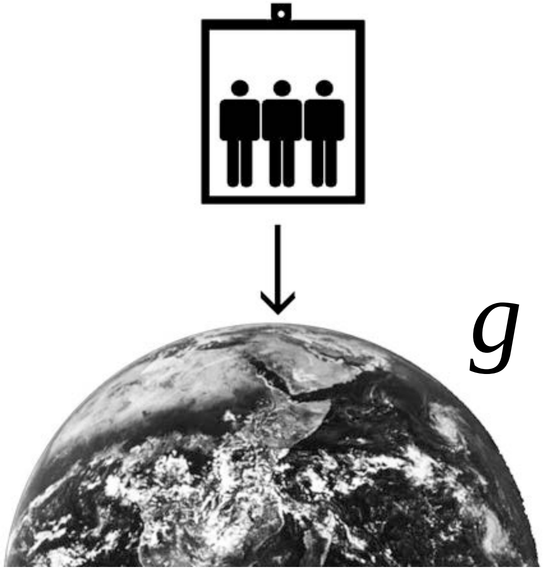
Newton (1643-1727, Cambridge): pendulum experiments– wood, gold, silver, lead, etc.



Roland von Eotvos (1848-1919, Budapest): Torsion balance (1889,1908)
equivalence ~10^{-9}.



Equivalence Principle

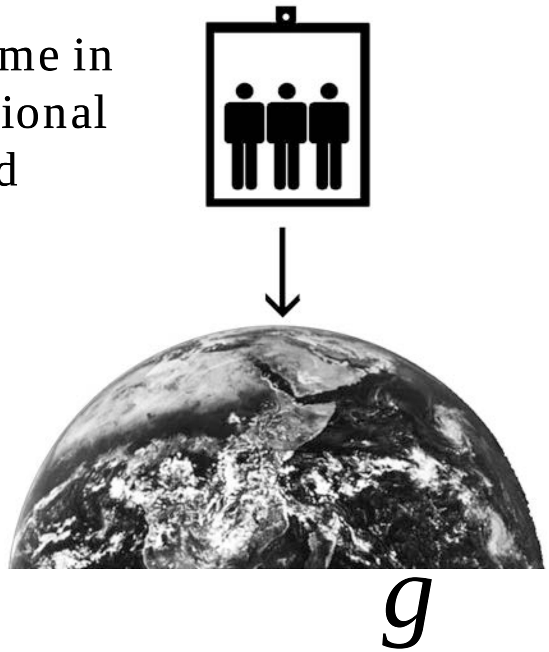


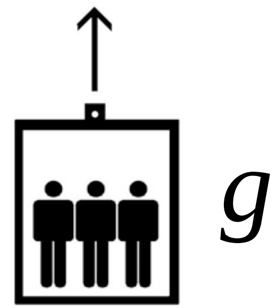
Freely falling frame

Constant velocity frame in empty space

Equivalence Principle

Rest frame in gravitational field



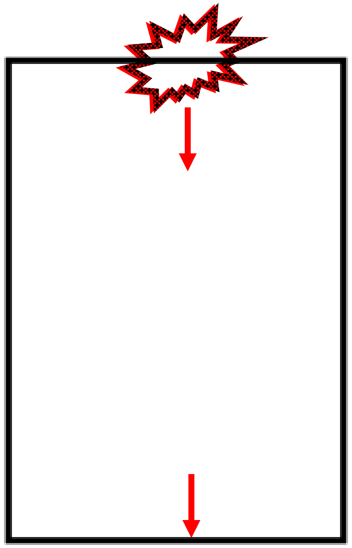


Accelerated frame in empty space

Einstein: No experiment can distinguish between gravitational field and acceleration field

Redshift

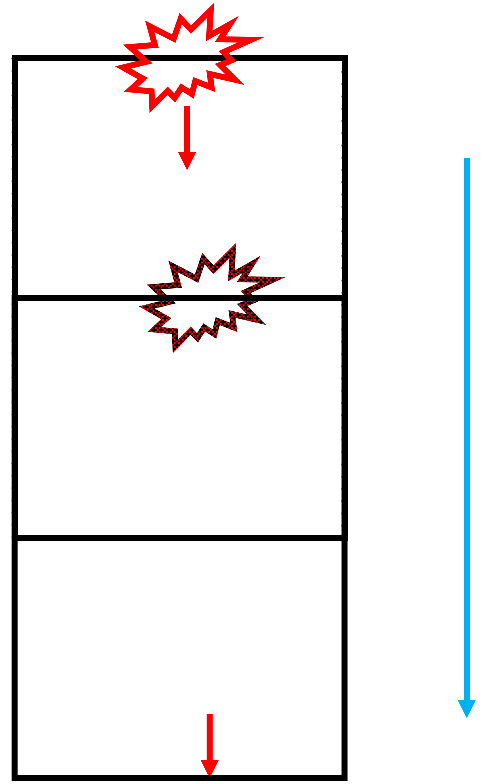
Freely falling observer:
Same frequency (color)



Free fall

Redshift

Equivalence principle:
gravity causes a blueshift

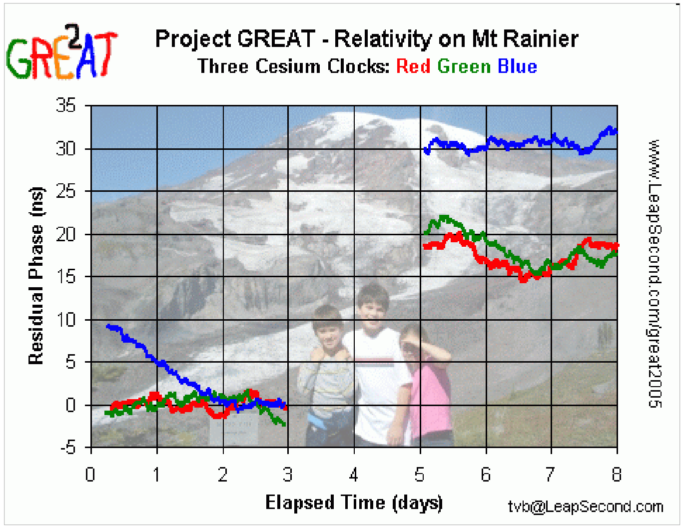


Accelerated observer

Pound-Rebka (1959)

Jefferson laboratory, Harvard

Time dilation



Global Positioning System (GPS)

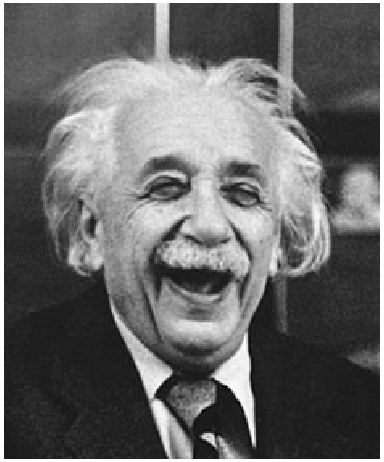
1915. Albert Einstein completes theory of gravitation, known as General Relativity, in Nov. 1915.

1919. May 29 eclipse confirms that gravity bends light. Results are made public in November; at 40, Albert Einstein is now a celebrity.

Roça Sundy, Príncipe Island

Einstein: Gravity is curvature

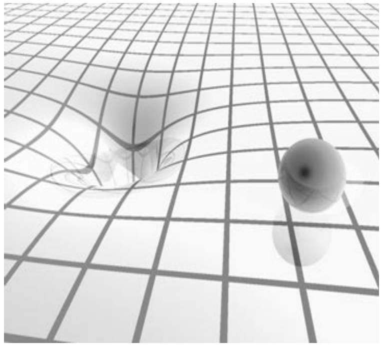
"Spacetime tells matter how to move, matter tells spacetime how to curve"



$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Any mass-energy curves space-time:

Free objects follow curvature



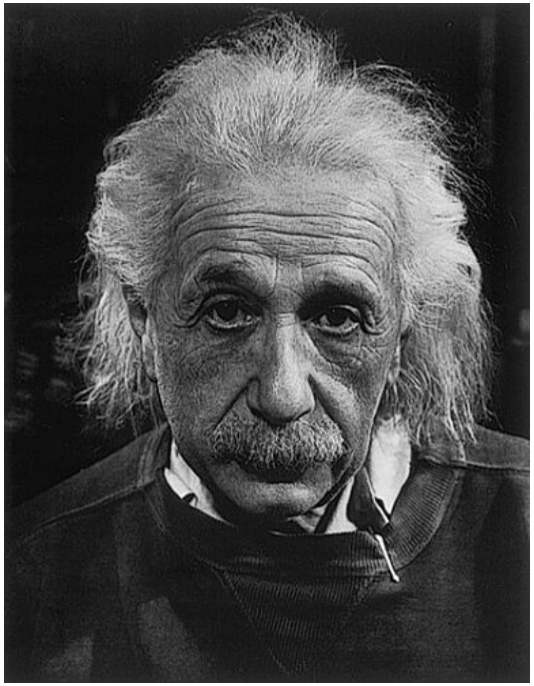
Was Einstein right?

Gravitational waves

Black holes

...was Einstein right?

In 1916, Einstein shows that GWs are a consequence of the linear theory.



In 1936, with Nathan Rosen, submits paper

Do gravitational waves exist? to Physical Review.

"Together with a young collaborator I arrived at the interesting result that gravitational waves do not exist, though they had been assumed a certainty [...] This shows that the non-linear general relativistic wave field equations can tell us more, or, rather, limit us more than we had believed up to now."

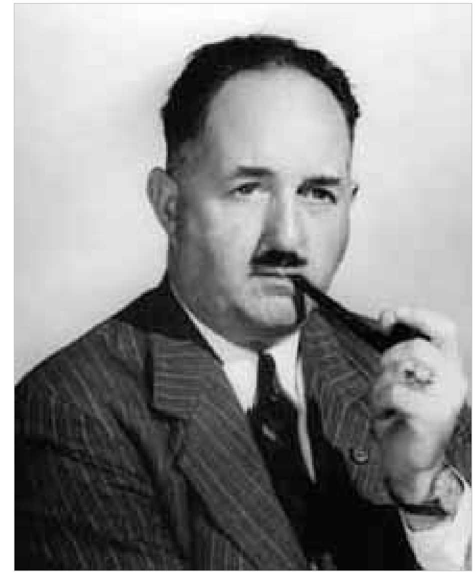
Einstein to Born, 1936

The paper was rejected (by Robertson).

Einstein was understanding:

The paper was rejected (by Robertson).

Einstein was understanding:



"I see no reason to waste my time with the opinion – in any case erroneous – of your anonymous expert"

Einstein reply to Physical Review editor

Chapel Hill Conference, 1956.

Feynman proposes thought experiment

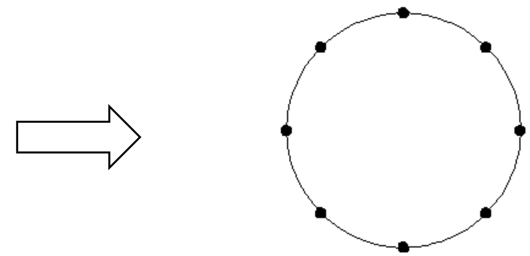
showing that GWs carry energy.

1960. Jan 1st, PRD publishes a work by Joseph Weber titled "Detection and Generation of Gravitational Waves". First practical proposal to detect GWs.

$$\delta L = h_+ \, L$$

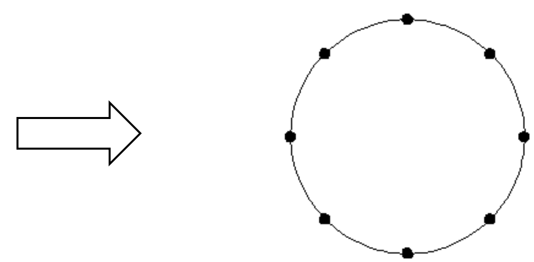
Polarization "+" :

$$h_+$$



Polarization "x":

$$h_\times$$



Or, if you wish...

...try it right here...

Gravitational waves:

Travel at the speed of light

Interact very weakly

$\lambda \sim$ Source size

Detectors “listen” to any direction

Do they exist?

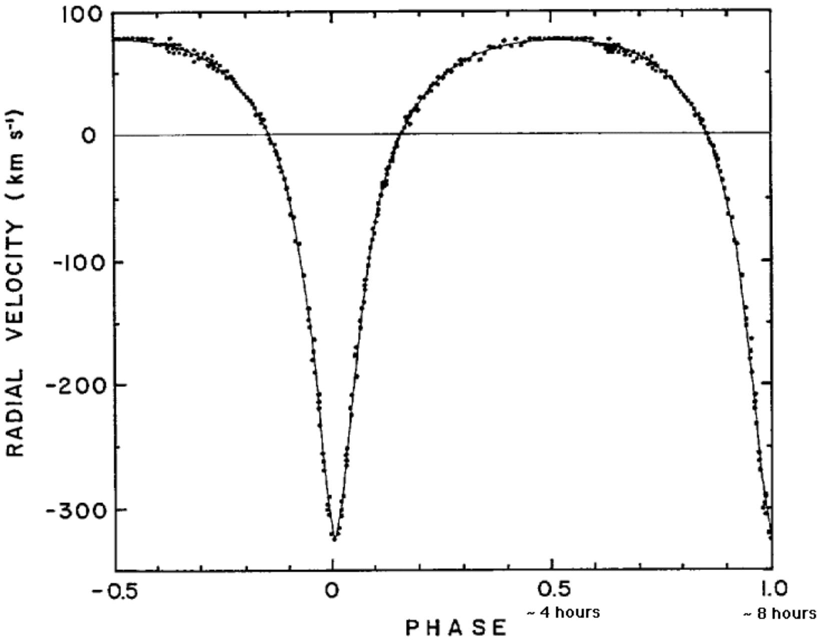
The discovery of pulsars

In August 1967, Jocelyn Bell, then a graduate student at Cambridge, finds a radio signal in the constellation Sagitta (the Little Arrow) pulsating with a period of 1.33 seconds. She found this to appear 4 minutes earlier every day, indicating a sidereal source.

For this discovery, Anthony Hewish earns the Nobel (“No-Bell”) Prize in Physics 1974.

Sound of PSR B1919+21, as observed at Arecibo on the 13th of June 2006:

The discovery of PSR B1913+16



In 1974, Russel Hulse and Joe Taylor discovered PSR B1913+16, in the constellation Aquila (the Eagle), during a systematic 430-MHz survey of the Galactic plane at Arecibo. *First binary pulsar*!

Five Keplerian parameters can be easily measured: orbital period (P_b), projected size of the orbit (x), eccentricity (e), longitude of periastron (ω) and time of passage through periastron (T_0).

Individual masses (m_1 and m_2) and inclination (i) cannot be measured, but...the mass function can be measured to excellent precision, as it depends on two observable parameters:

$$f(m_1, m_2, i)/\mathrm{M}_\odot \equiv \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2}$$

$$= x^3 \left(\frac{2\pi}{P_b}\right)^2 \left(\frac{1}{T_\odot}\right)$$

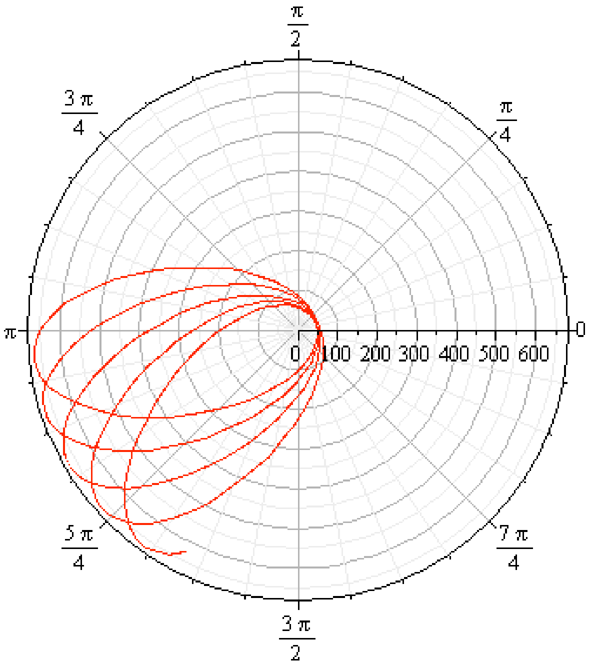
$$T_\odot \equiv \frac{\mathrm{GM}_\odot}{c^3} = 4.925490947\,\mu s$$

One equation, three unknowns! ☹

In addition, timing precision allows the measurement of several relativistic effects.

Periastron advances 4.226607(7) degrees/year. Daily periastron advance same as Mercury's in a century...

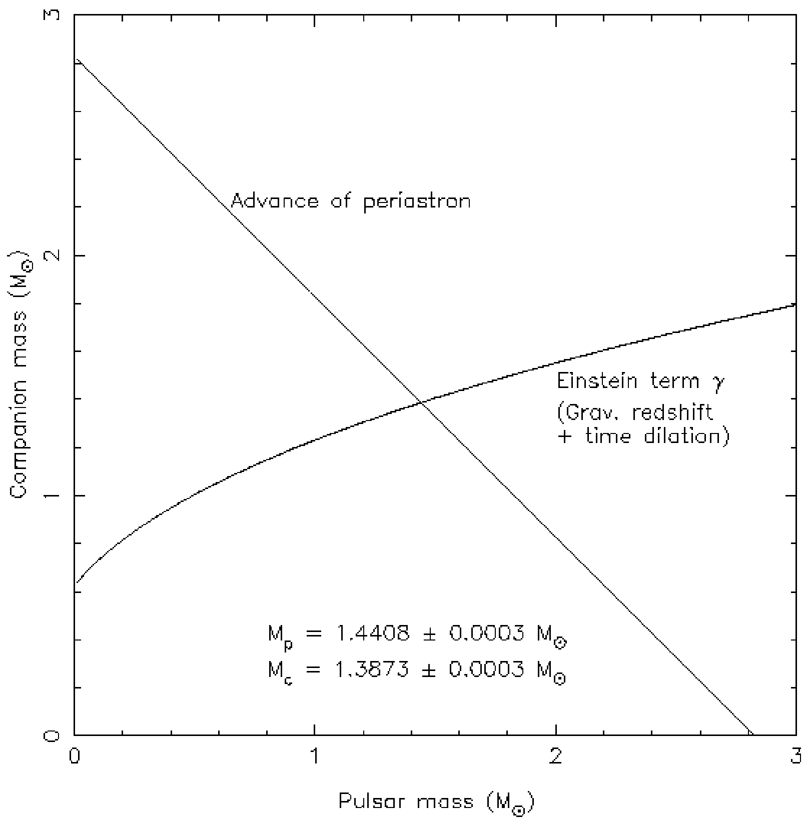
Einstein delay: $\gamma = 0.004294(1)$ s, due to slowdown of time near the companion!



These two effects provide two more equations and determine the mass and inclination of the system! This happens because, *according to GR*, they depend on the known Keplerian parameters *and* the masses of the two objects:

$$
\begin{aligned}
M &= m_1 + m_2\,,\; n_b = \frac{2\pi}{P_b} \\
\dot{\omega} &= 3 n_b^{5/3} (M T_\odot)^{2/3} (1 - e^2)^{-1} \\
\gamma &= n_b^{-1/3} e m_2 (2m_2 + m_1) M^{-4/3} T_\odot^{2/3}
\end{aligned}
$$

3 equations for 3 unknowns!



Masses of individual components (and inclination of the system!) well determined if we *assume* GR.

At the time, most precise measurement of any mass outside the solar system.

Weisberg, J.M., and Taylor, J.H., "The Relativistic Binary Pulsar B1913+16", in Bailes, M., Nice, D.J., and Thorsett, S.E., eds., Radio Pulsars: In Celebration of the Contributions of Andrew Lyne, Dick Manchester and Joe Taylor – A Festschrift Honoring their 60th Birthdays, Proceedings of a Meeting held at Mediterranean Agronomic Institute of Chania, Crete, Greece, 26 – 29 August 2002, ASP Conference Proceedings, vol. 302, (Astronomical Society of the Pacific, San Francisco, 2003).

PSR B1913+16

Third relativistic effect is measurable: orbital period is shortening due to GW emission. Depends only on quantities that are already known:

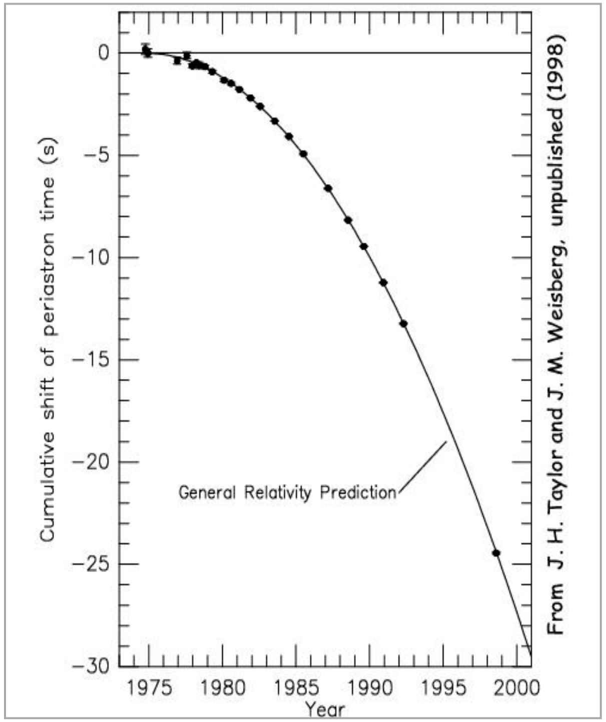
$$\dot{P}_b = -\frac{192}{5} n_b^{5/3} f_e m_1 m_2 M^{-1/3} T_\odot^{5/3}$$
$$f_e = \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)(1-e^2)^{-7/2}$$

Prediction:

the orbital period decreases at -2.40247×10^{-12} s/s (or 75 μs per year!)

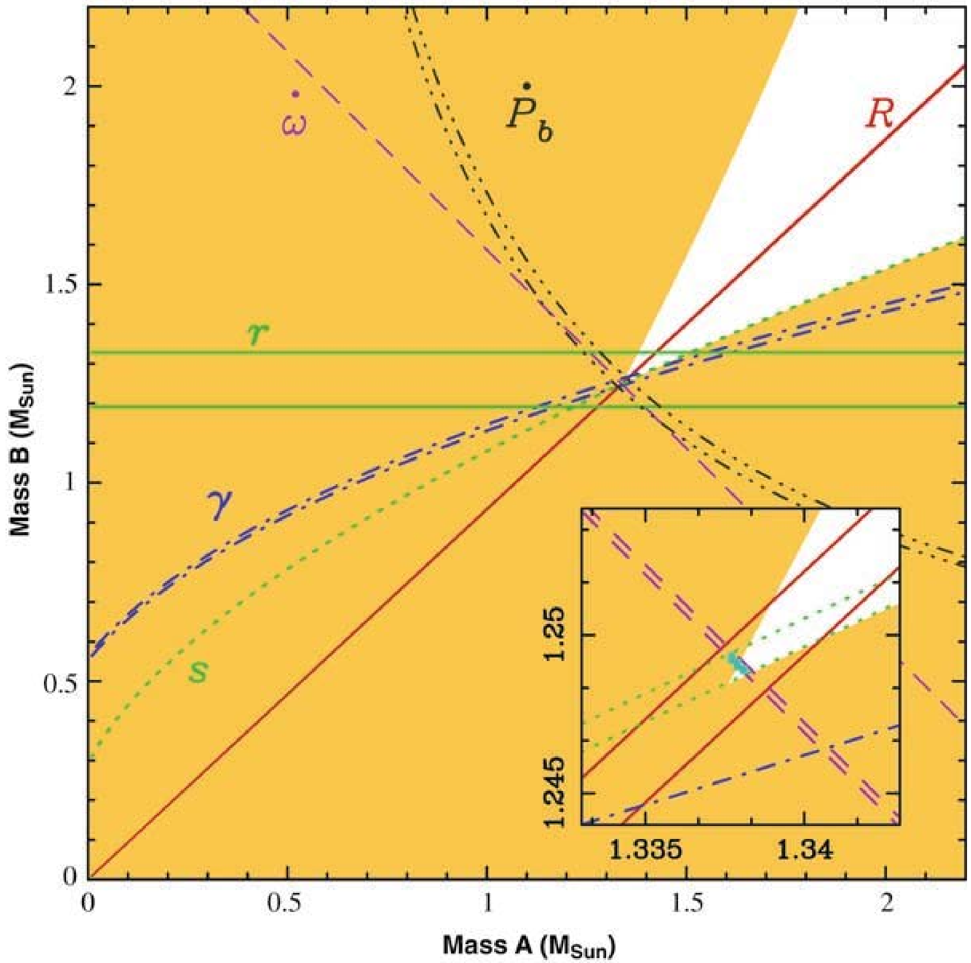
Test not possible in the Solar System.

Orbital decay detected: rate of $-2.4085(52) \times 10^{-12}$ s/s.



Gravitational waves exist!!

The double pulsar



Kramer et al. 2006, Science, 314, 97

- For double pulsar J0737−3039, *7 mass constraints (previous, plus mass ratio and 2 constraints from Shapiro delay)*
- *5 tests of GR* – including some of the most precise ever!
- Best test of GR for quadrupolar GW emission – one order of magnitude better than for the original binary pulsar!

The end?

"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."

- Lord Kelvin, 1900

GR NOT well tested in the strong-curvature regime!

$$\frac{\Phi_{\rm Newton}}{c^2} = \frac{GM_\odot}{c^2 r_{\rm periastron}} \sim 10^{-6}$$

Milisecond binary pulsar

Current experiments 10^{-6} BHs

Gravity: → **Curvature**

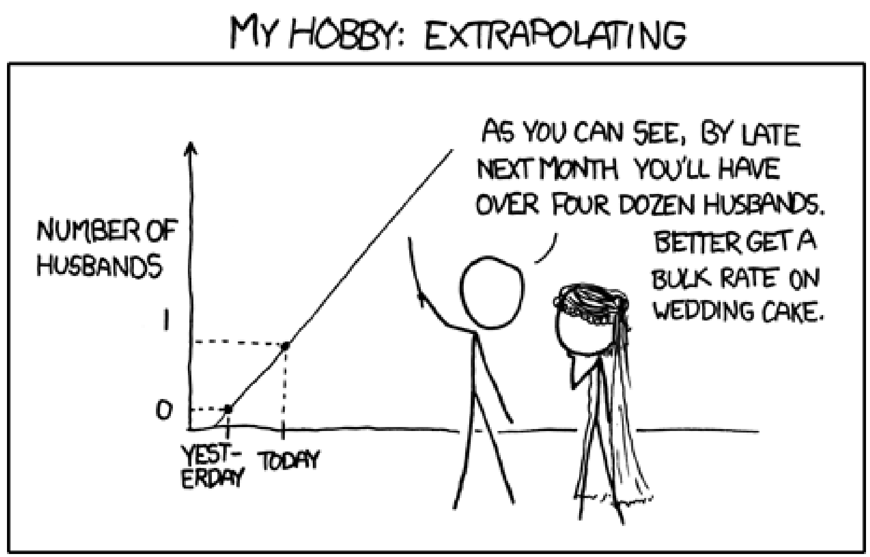
GR NOT well tested in the strong-curvature regime!

Particle physics:

Subnuclear physics 10^{-6} Atomic physics

← **Length**

Extrapolating GR to strong-field regime describing QCD with QM!



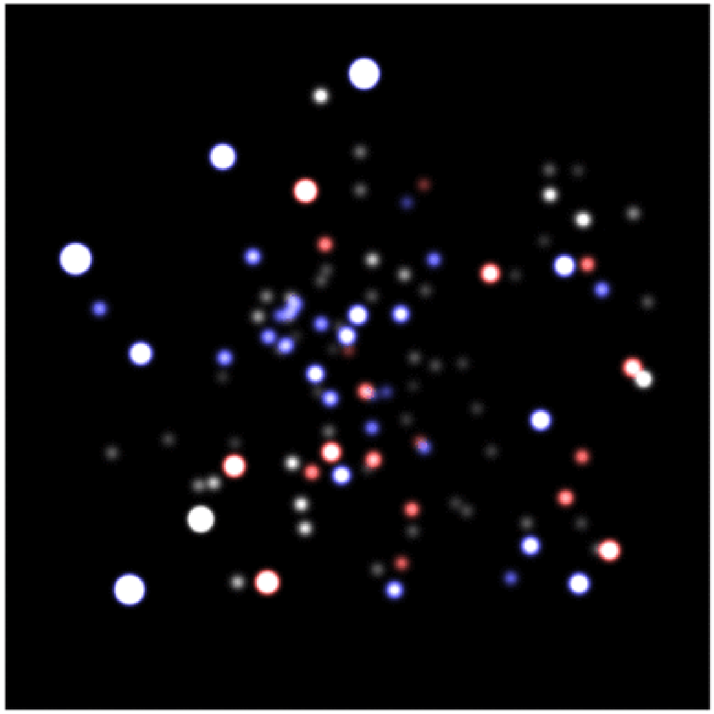
Exciting times for BH physics!

New electromagnetic observations

GW astronomy:

“Spectroscopy for the new century”

Test GR against alternative theories



Credit: ESO/MPE/M.Schartmann (2011)

Gillessen et al, Nature 481, 51 (2012)

Credit: ESO/MPE/M.Schartmann (2011)

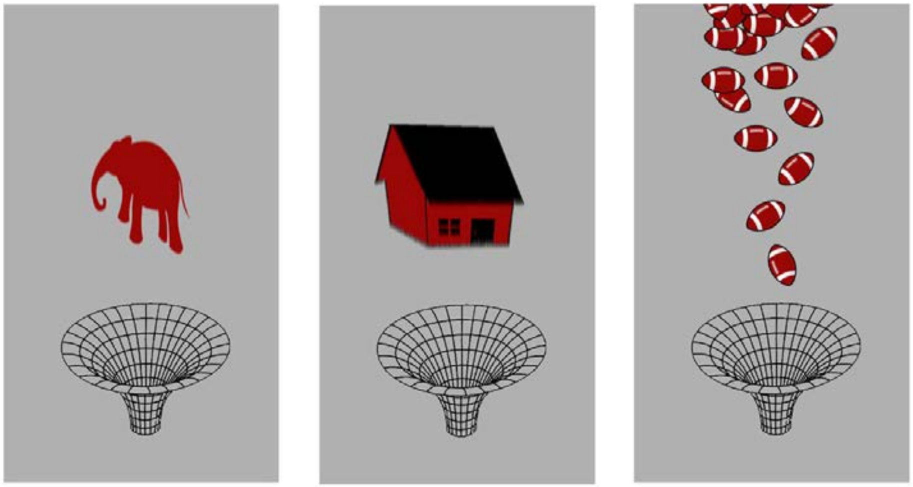
Gillessen et al, Nature 481, 51 (2012)

Black holes have no hair

One star made of matter and other of antimatter, produce identical BHs.

A BH has only three quantities in common with the star which created it:

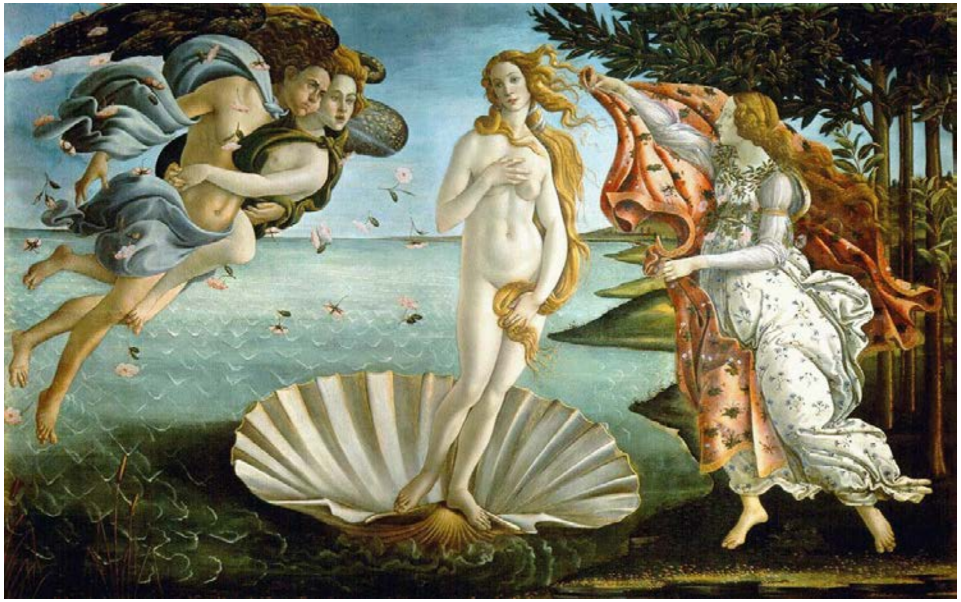
mass, spin and electric charge



$$
\begin{aligned}
ds^2 &= \frac{\Delta - a^2 \sin^2\theta}{\Sigma} dt^2 + \frac{2a(r^2 + a^2 - \Delta)\sin^2\theta}{\Sigma} dt d\phi \\
&\quad - \frac{(r^2 + a^2)^2 - \Delta a^2 \sin^2\theta}{\Sigma} \sin^2\theta d\phi^2 - \frac{\Sigma}{\Delta} dr^2 - \Sigma d\theta^2
\end{aligned}
$$

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

Singularity at r=0, infinite tidal forces, quantum effects are important



...Cosmic Censorship?

Perhaps all collapsing objects do conceal the nakedness of their singularities behind the cloak of an event horizon. But even if they do, according to the work for which Hawking is most famous that cloak may not last forever, and one day the nakedness of the singularity could be exposed to the Universe at large, with all that that implies.

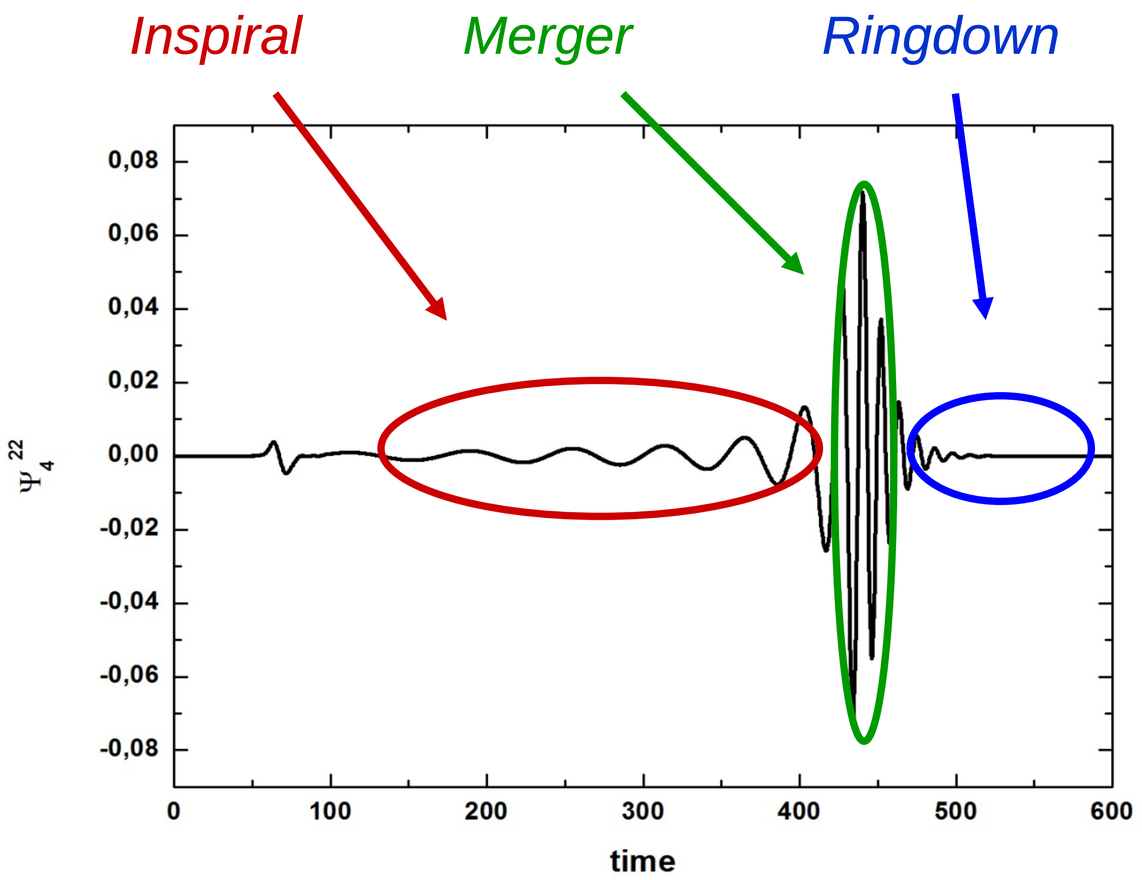
Why study black hole dynamics

Gravitational-wave detection, GW astrophysics

Mathematical physics

High-energy physics

Particle Physics

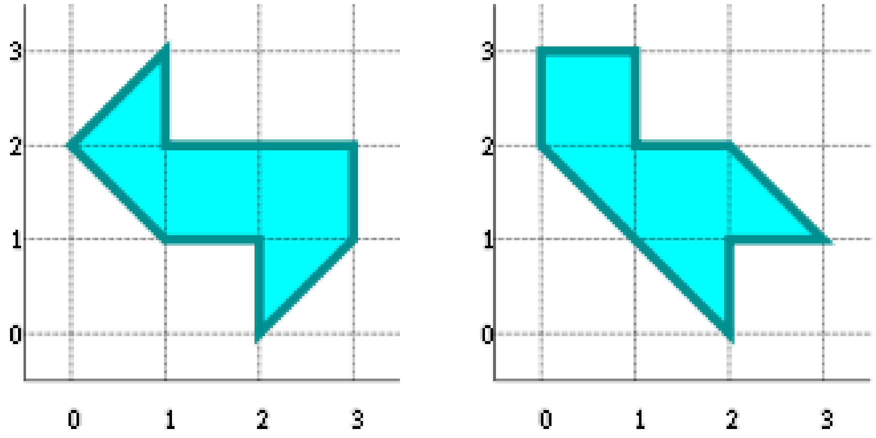


Inspiral
Merger
Ringdown
0,08
0,06
0,04
0,02
0,00
-0,02
-0,04
-0,06
-0,08
Ψ_4^{22}
0
100
200
300
400
500
600
time

“Can one hear the shape of a drum?”

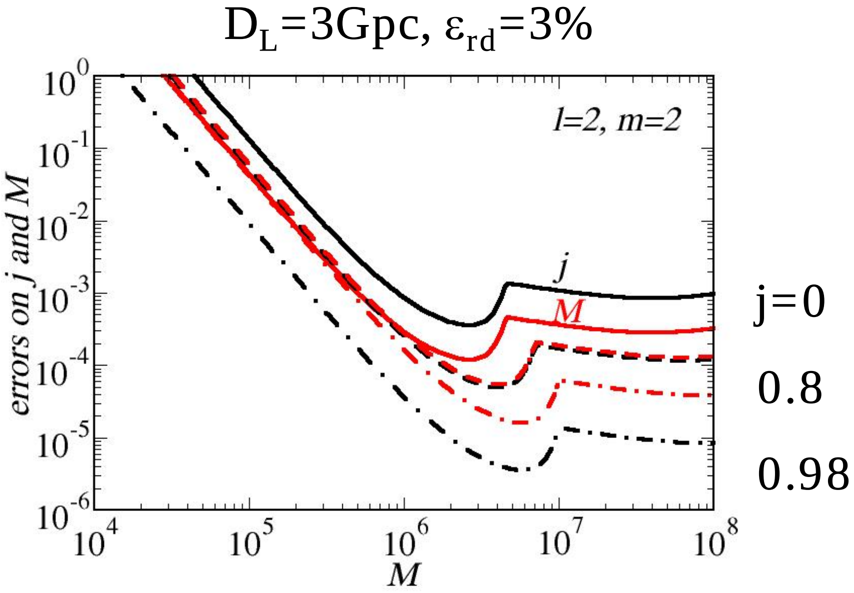
Mark Kac, American Mathematical Monthly, *1966*

$$A = (2\pi)^d \lim_{R\to\infty} \frac{N(R)}{R^{d/2}}$$



Gordon, *Webb & Wolpert*, Inventiones mathematicae, *1992*

Can one hear the shape of a BH?



$$\begin{aligned} \epsilon &= 10^{-2}\% \\ M &= 10^{6} M_{\odot} \qquad \sigma_{j,M} = 1\% \\ j &= 0.8 \end{aligned}$$

Berti, Cardoso & Will 2006; Kamaretsos et al 2012

Why dynamics: mathematical physics

Cosmic Censorship: do horizons always form?

*

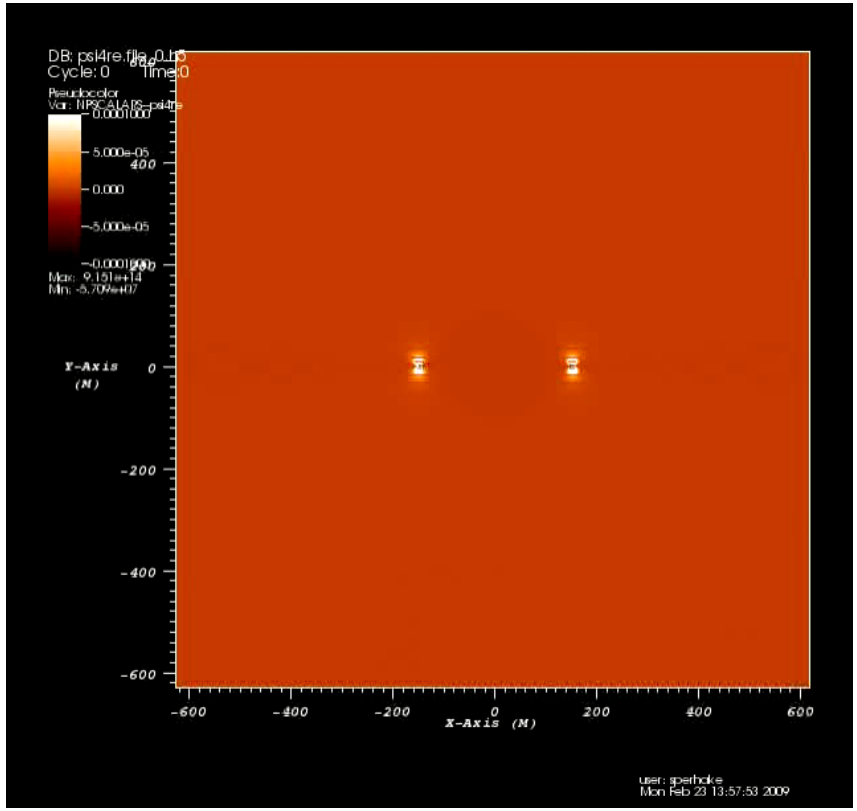
Are black objects always stable? Phase diagrams...

*

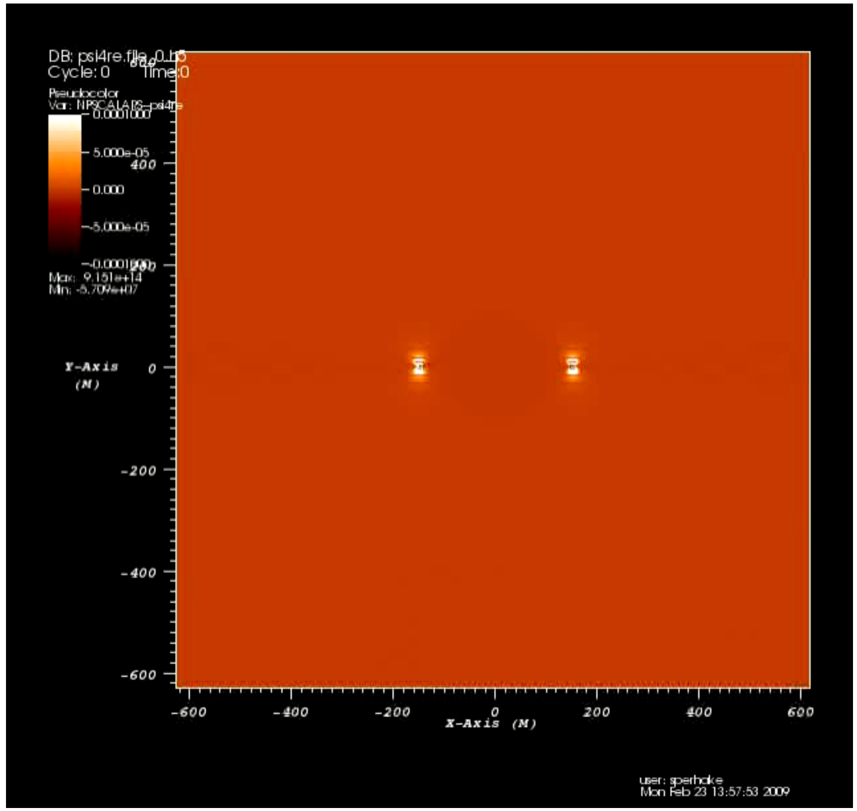
Universal limit on maximum luminosity c^5/G (10^59 erg/sec)

*

Critical behavior, resonant excitation of QNMs; analytical tools, etc



Sperhake et al PRL 2009, 2013



Sperhake et al PRL 2009, 2013

Strong field gravity and fundamental fields

Massive scalars

Interesting as effective description

Proxy for more complex interactions (vector or tensor, accretion disks...)

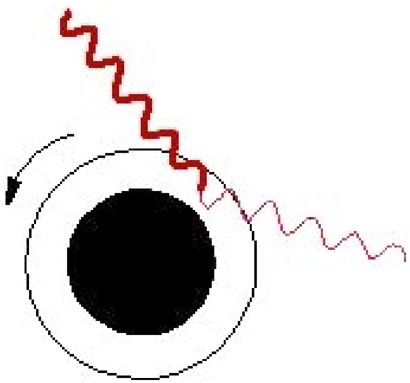
Arise as interesting extensions of GR* (BD or generic ST theories; f(R))

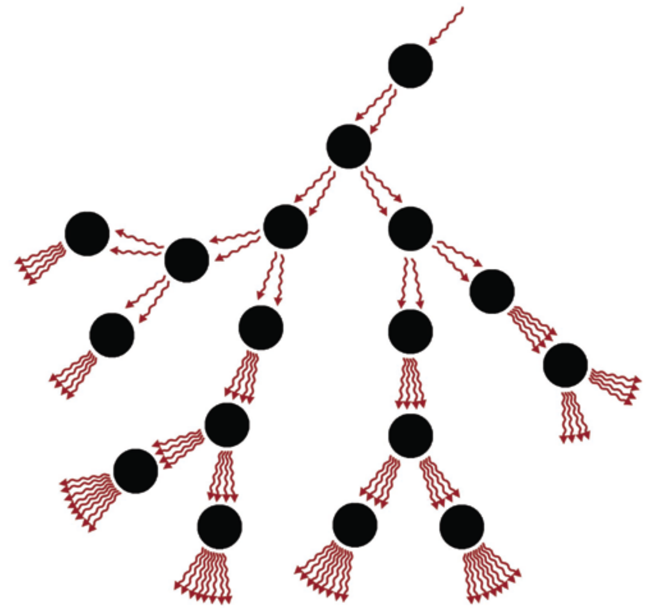
Dark matter candidates I (Boson stars, soliton stars)

Dark matter candidates II (Axiverse scenarios-moduli and coupling constants in string theory, Peccei-Quinn mechanism in QCD)

* *poorly constrained for massive fields*

Long-lived scalar states and superradiance





$$\Phi \sim e^{-i\omega t}$$

$$\omega < \Omega_{BH}$$

Zel'dovich '71

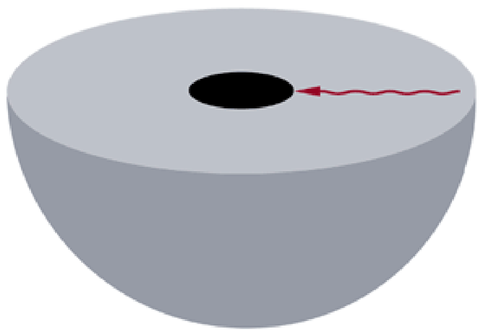
No fission-like process

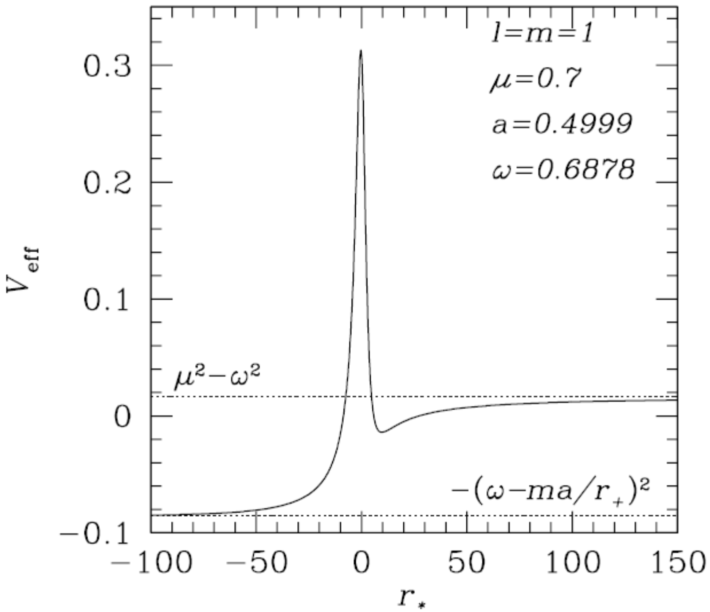
$$\sigma \sim r_+^2 < 0$$

$$\ell_{\text{free path}} \sim \frac{1}{\sigma n}$$

$$\ell_{\text{free path}} \leq R \rightsquigarrow \frac{NM}{R} \gtrsim N^{\frac{1}{2}}$$

Long-lived scalar states and superradiance





$$\omega_{\rm res}^2 = \mu_s^2 - \mu_s^2 \left(\frac{\mu_s M}{l+1+n}\right)^2$$

$$\omega_I = \mu_s \frac{(\mu_s M)^8}{24} \left(a/M - 2\mu_s r_+\right)$$

Black hole bombs

Press and Teukolsky '72; Cardoso et al '04

Kerr is linearly unstable

Damour et al '76; Detweiler '80

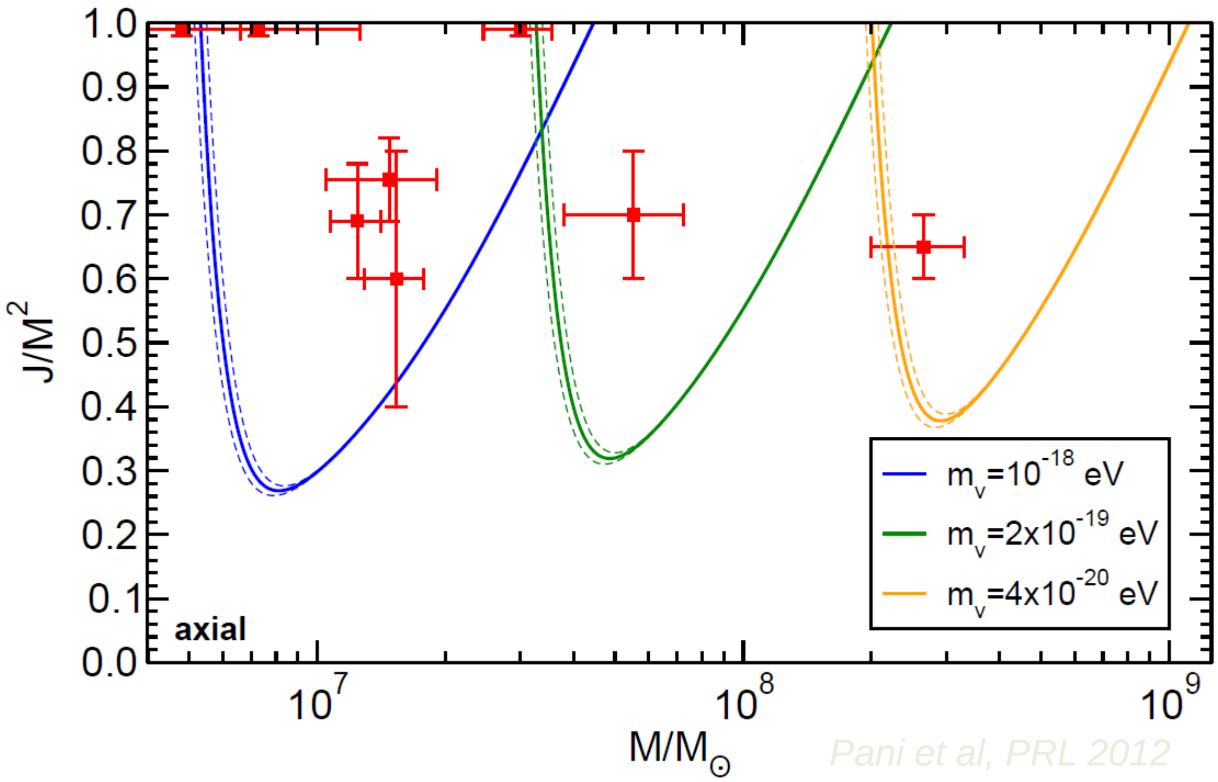
Instability

Unstable

Decay

Stable

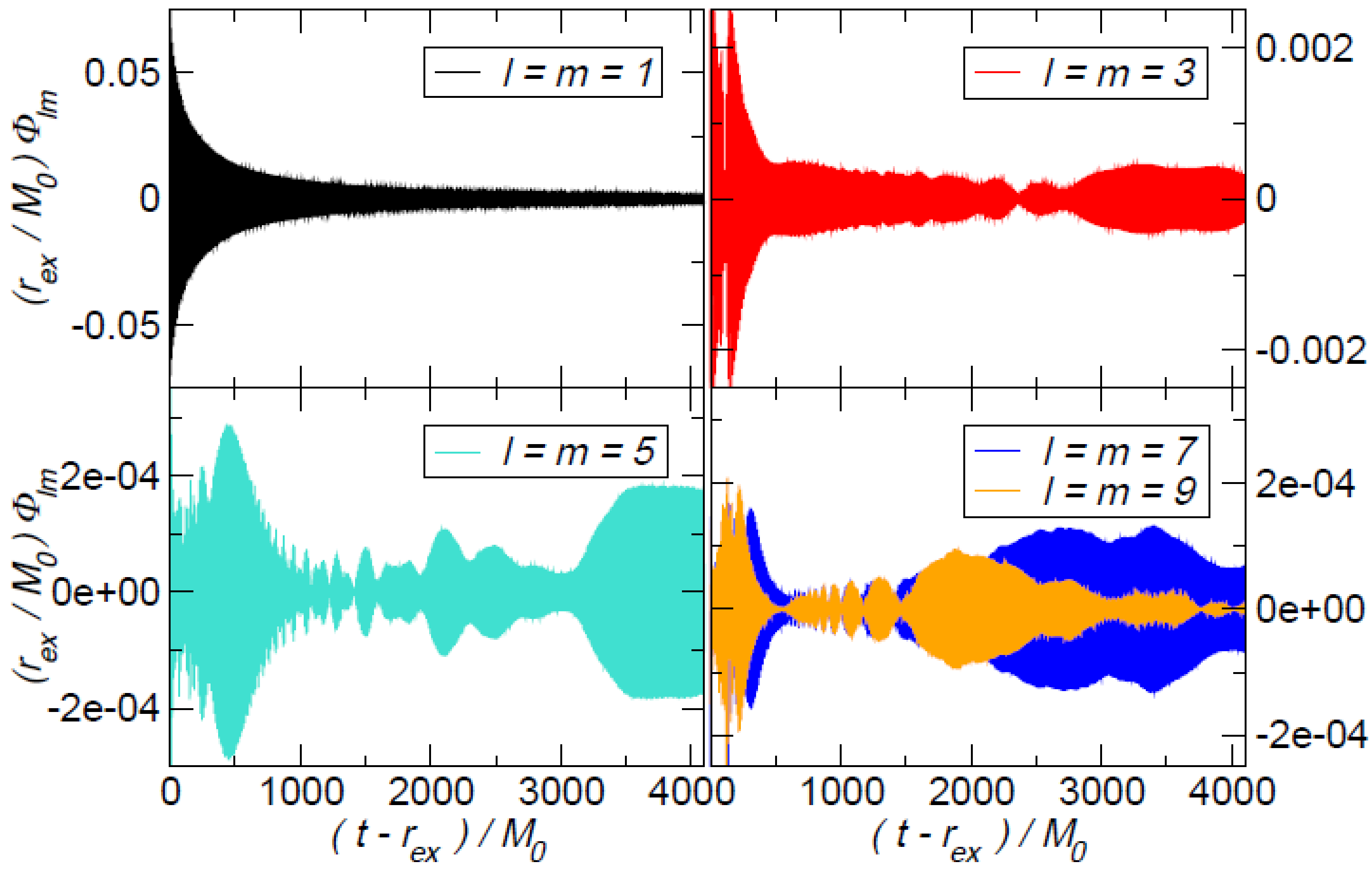
Bounding the mass of particles



Depend very mildly on the fit coefficient and on the threshold

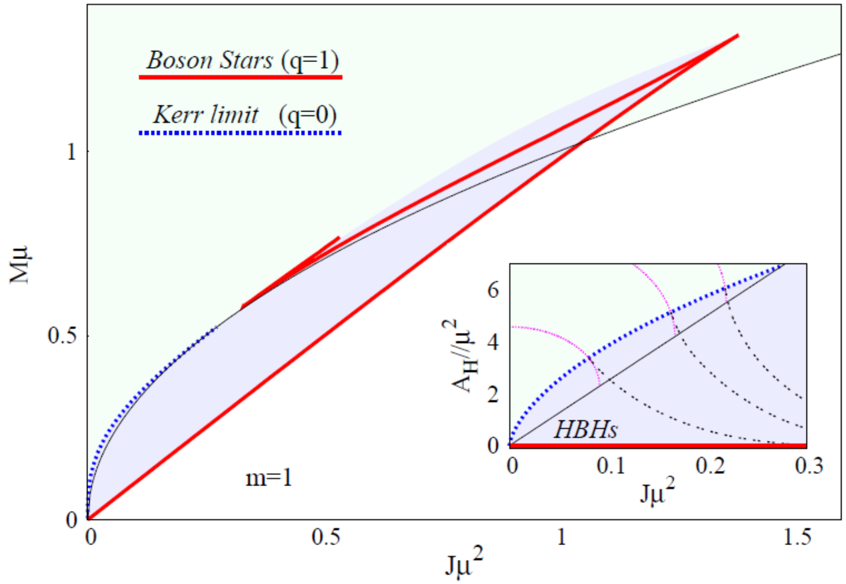
$\tau_{\mathrm{Salpeter}} \rightarrow$ timescale for accretion at the Eddington limit

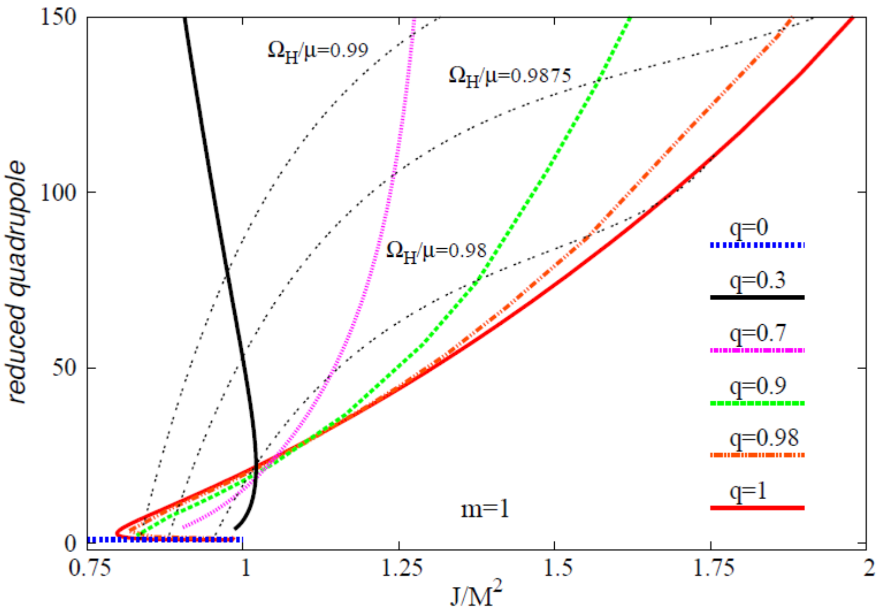
Final state I: turbulence and collapse?



Okawa, Witek, Cardoso, in preparation

Final state II: hairy black holes?

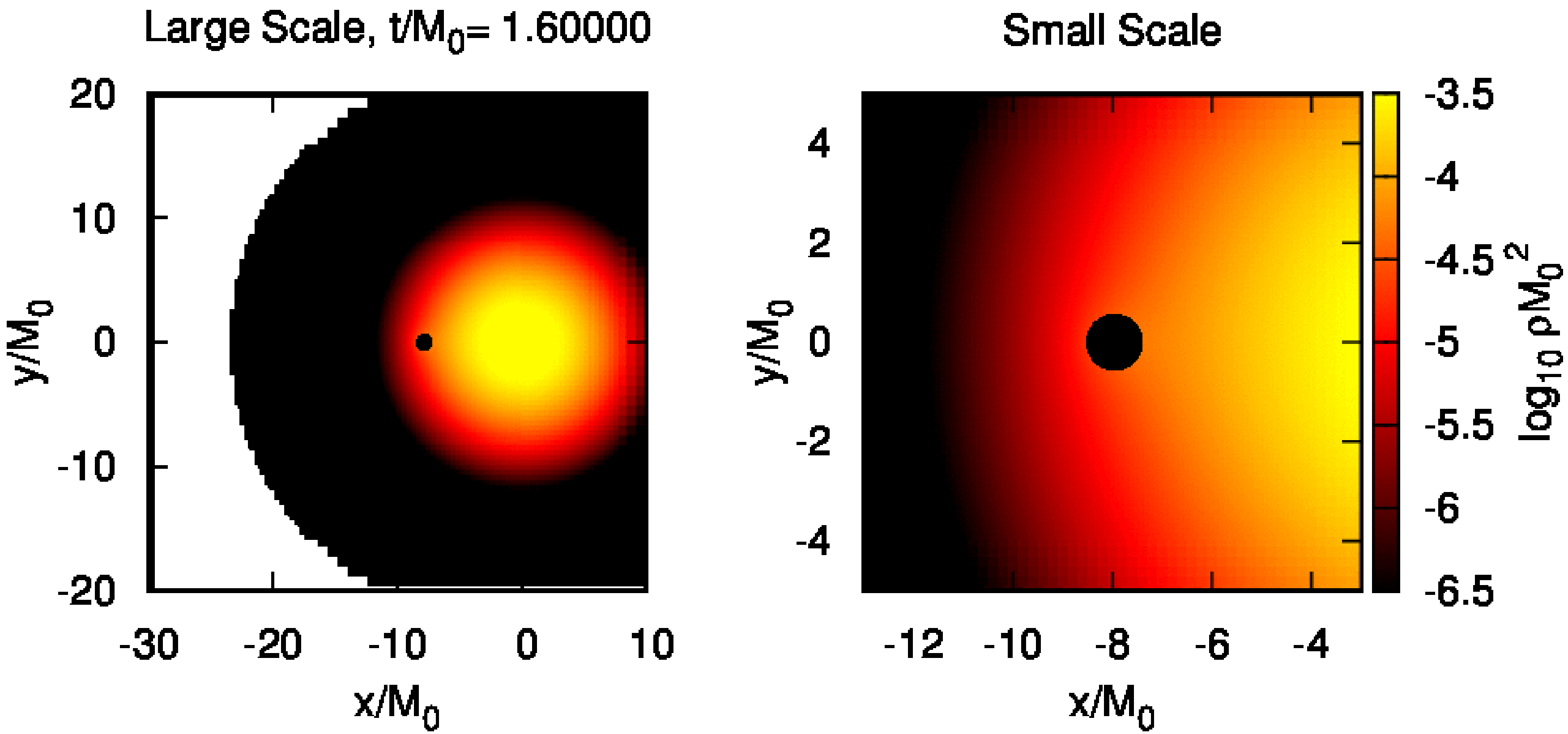




Herdeiro, Radu arXiv: 1403.2757

Interaction with scalar clouds

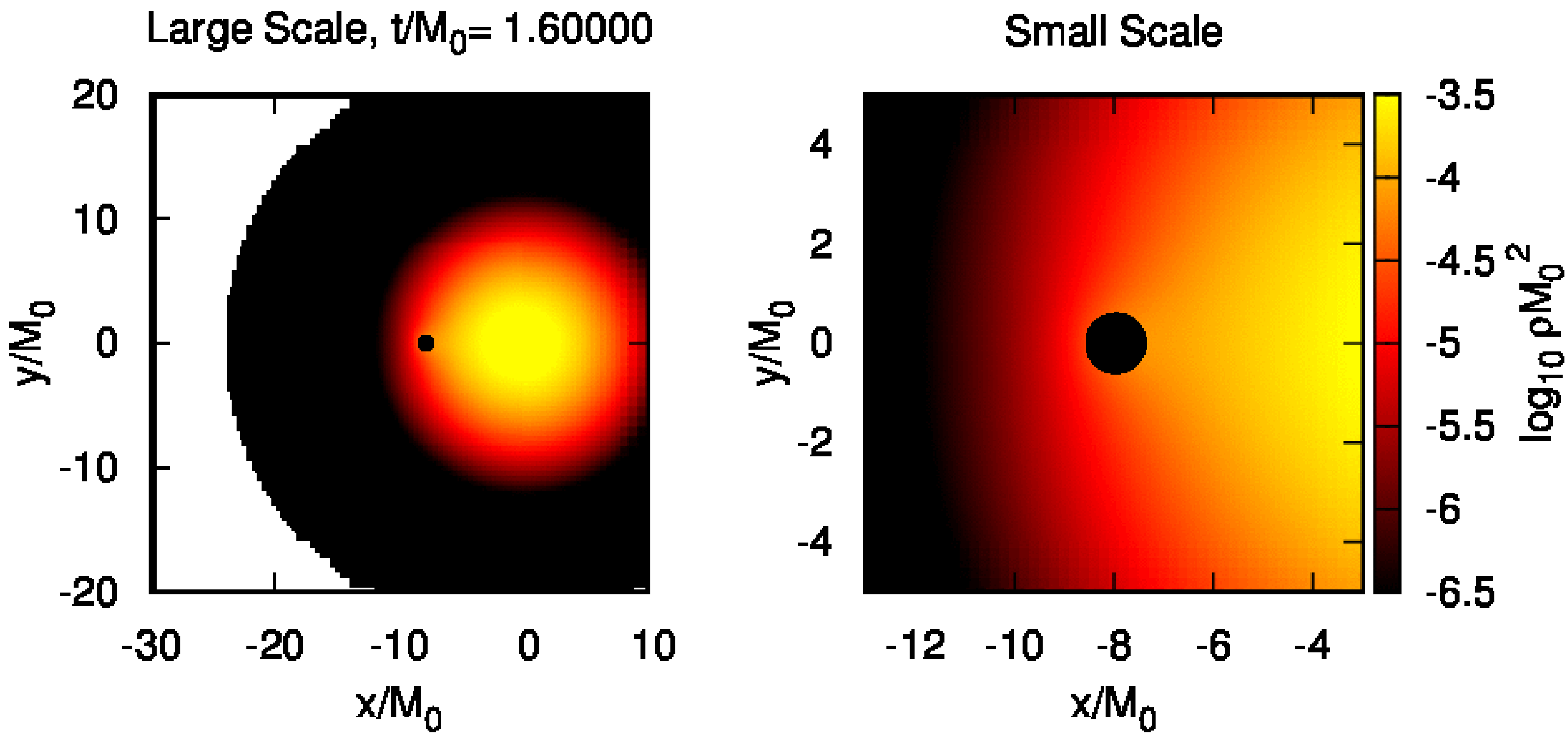
I. Dynamics of hairy solutions



Okawa, Cardoso, in preparation

Interaction with scalar clouds

I. Dynamics of hairy solutions

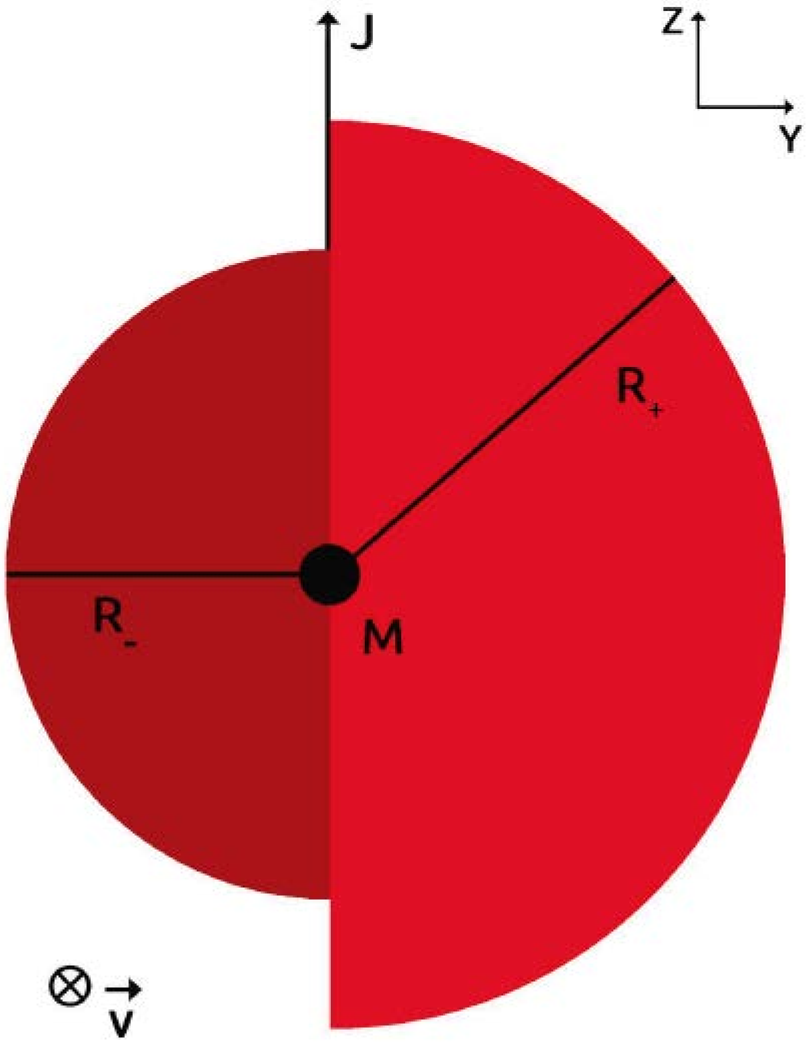


Okawa, Cardoso, in preparation

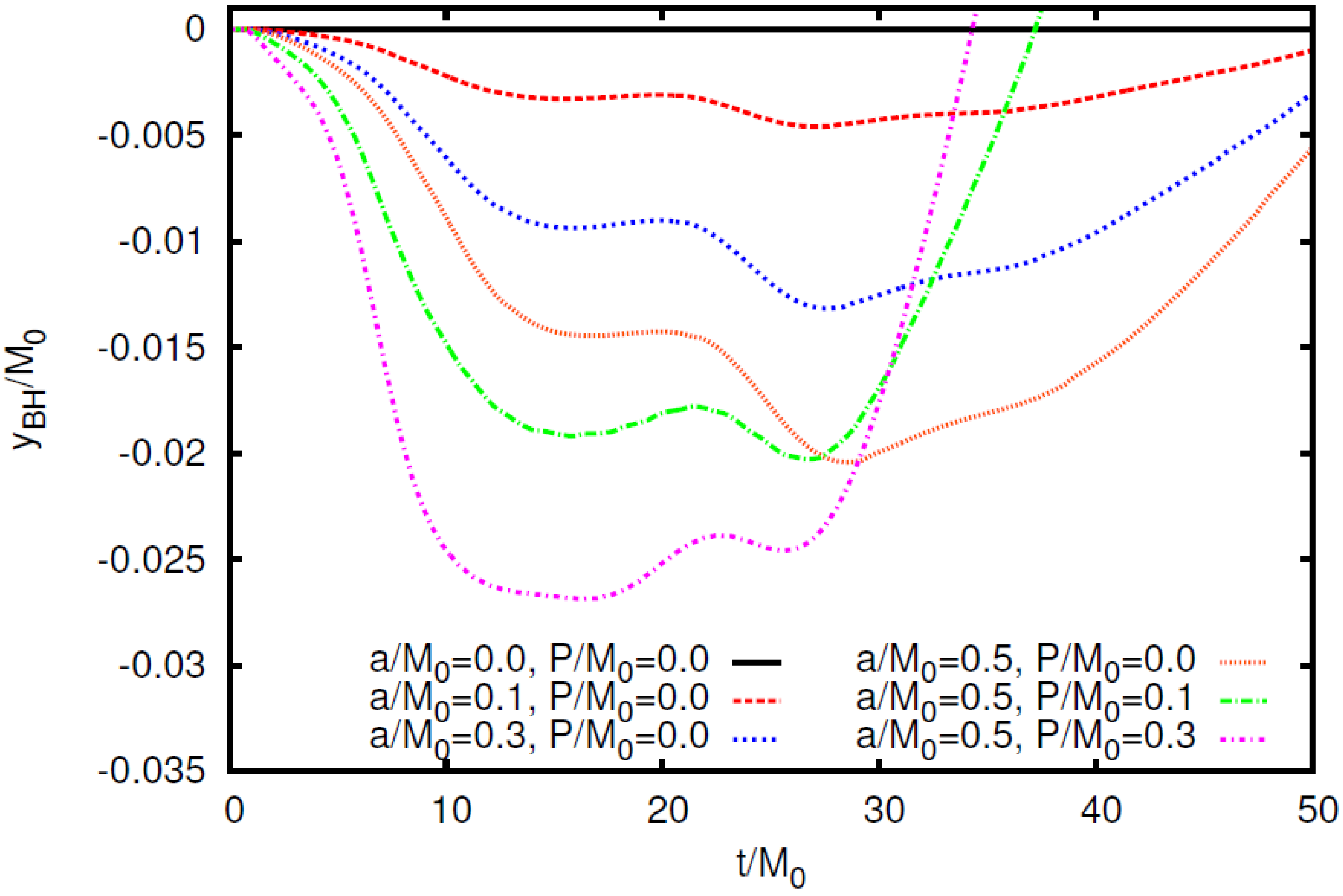
Interaction with scalar clouds II. BH (anti-) Magnus effect

Curiosity: the German Physical Society, with headquarters here at Bad Honnef, was founded by 6 students of Heinrich Gustav Magnus

Interaction with scalar clouds II. BH (anti-) Magnus effect



Interaction with scalar clouds II. BH (anti-) Magnus effect



PRELIMINARY RESULTS

GR is one of the most elegant constructions of human mind...strong field gravity is a fascinating topic

From precise maps of our Universe to tests of Cosmic Censorship, and constraints on dark matter candidates, the possibilities are almost endless....

“Nature’s imagination far surpasses our own.”
Richard Feynman (1964)

Gravitational waves exist!!