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Event Horizon Telescope - BH imaging as GR tests with P. Hess, W. Greiner†, M. Bleicher, T. Schönenbach

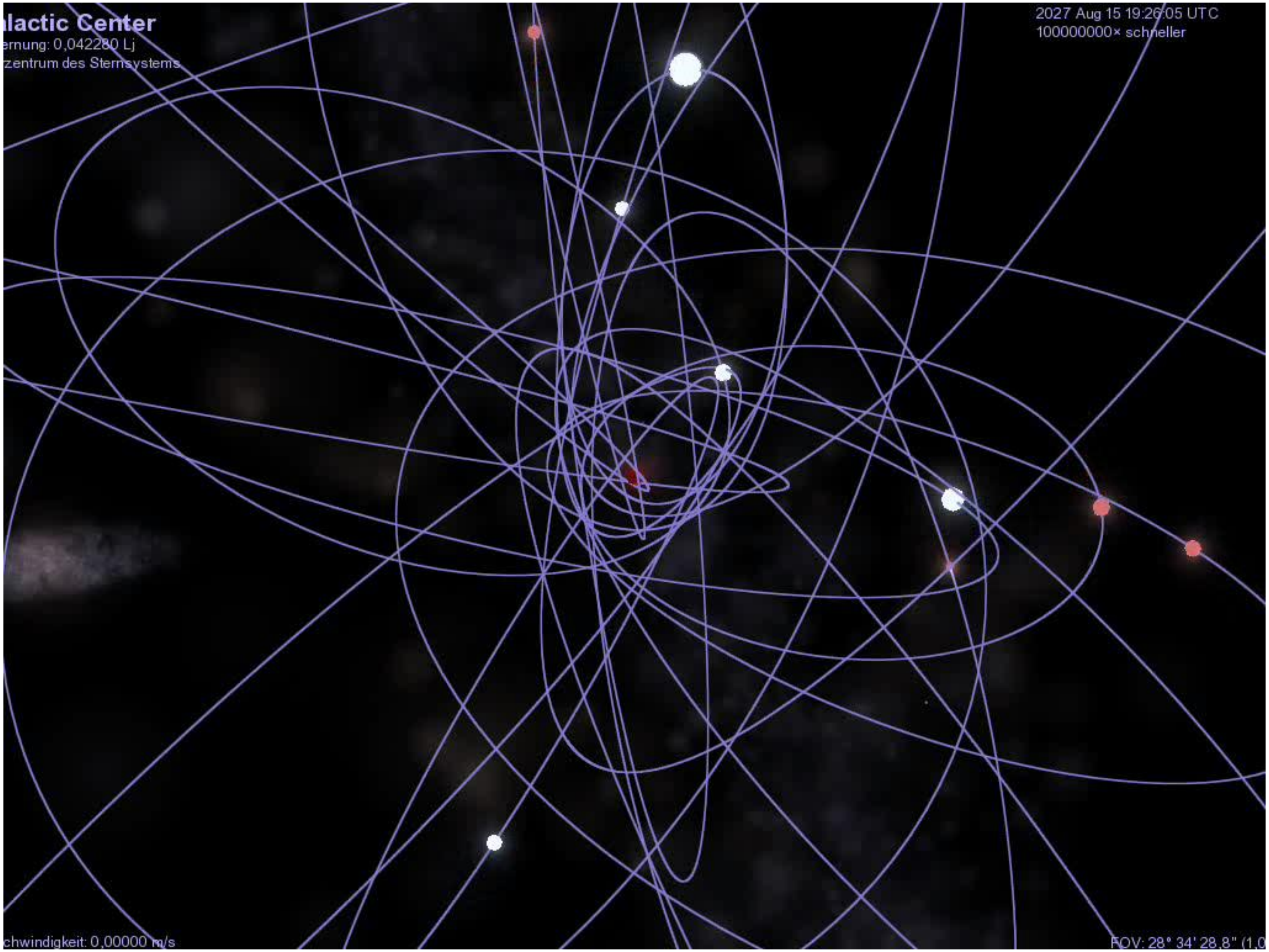
- Black Hole imaging of the Galactic Center and in M87
- status
- tests of observational signatures of GR and pc-GR

GW detections –LIGO results with A. Müller

- unique science cases
- status
- GW and electromagnetic detection

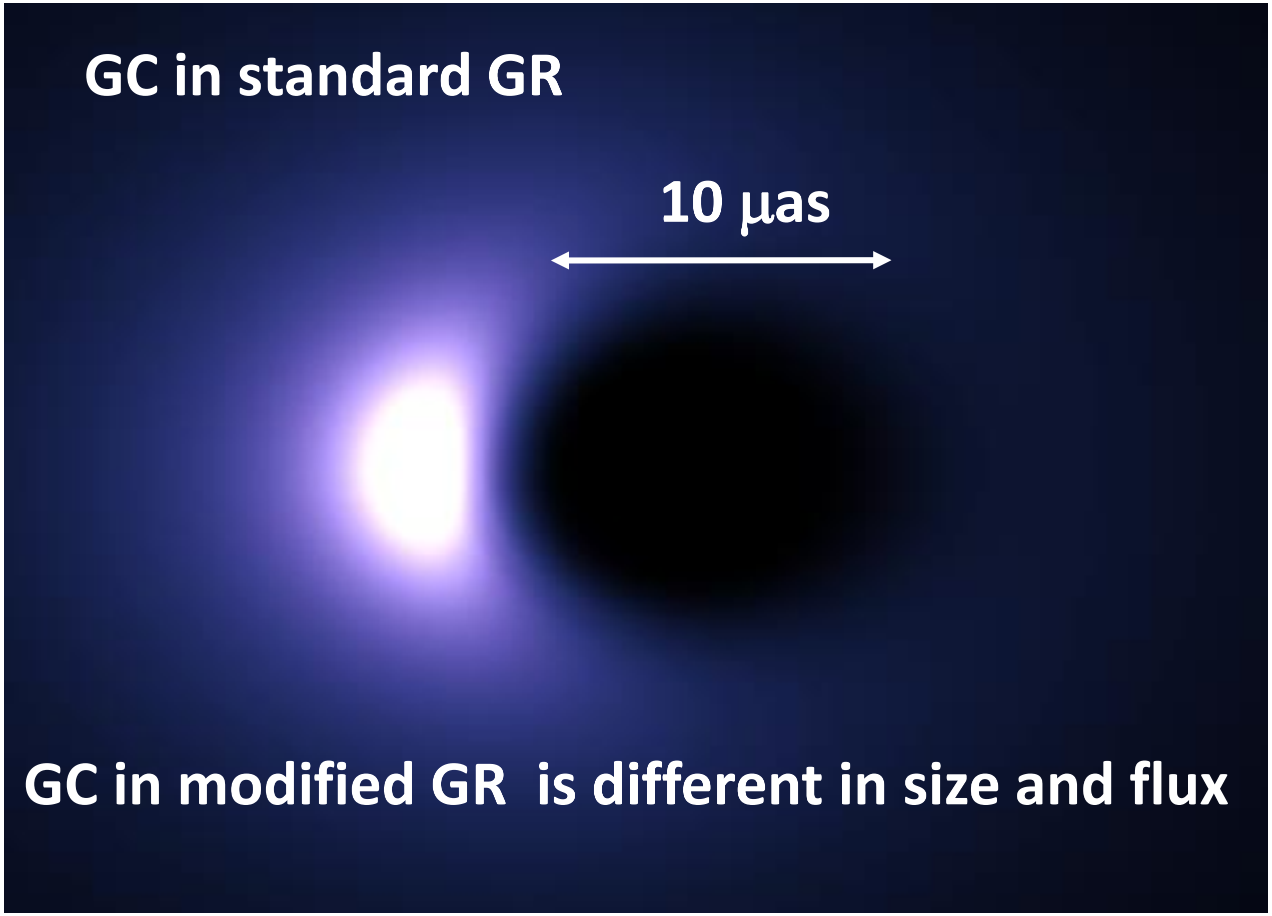
The black hole in the Galactic Center

the first indirect proof for the existence of Black Holes

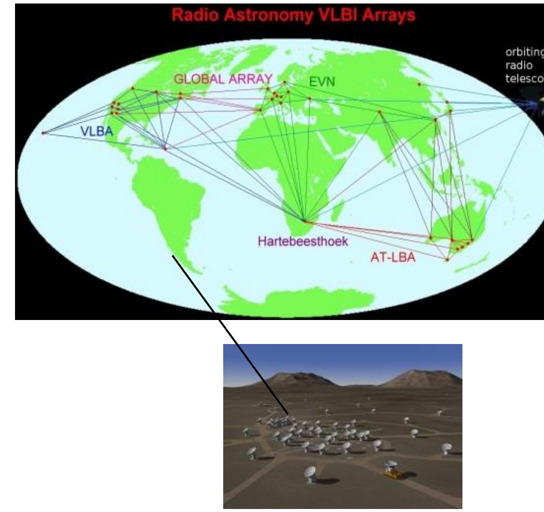


3 Millionen Solar Masses within 3 Light Hours

EHT - Black Hole imaging in the GC as GR tests



VLBI + ALMA

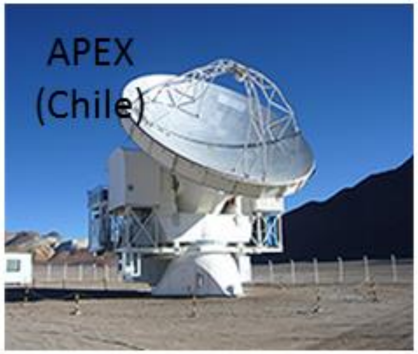


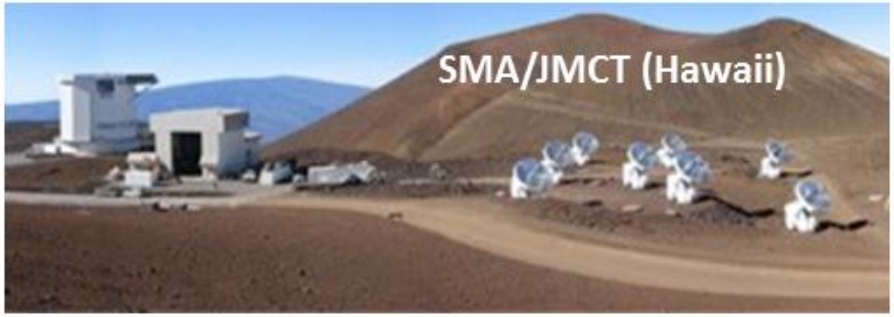
Δx = 10 μas = $1R_S$

observing:
- sub-mm shadowing
- emissivity profile

delayed since 2014
successful observations between April 5th-15th, 2017 (© Goddi)
SP data added in Winter 2017 – data processing still ongoing

2017 EHT Campaign





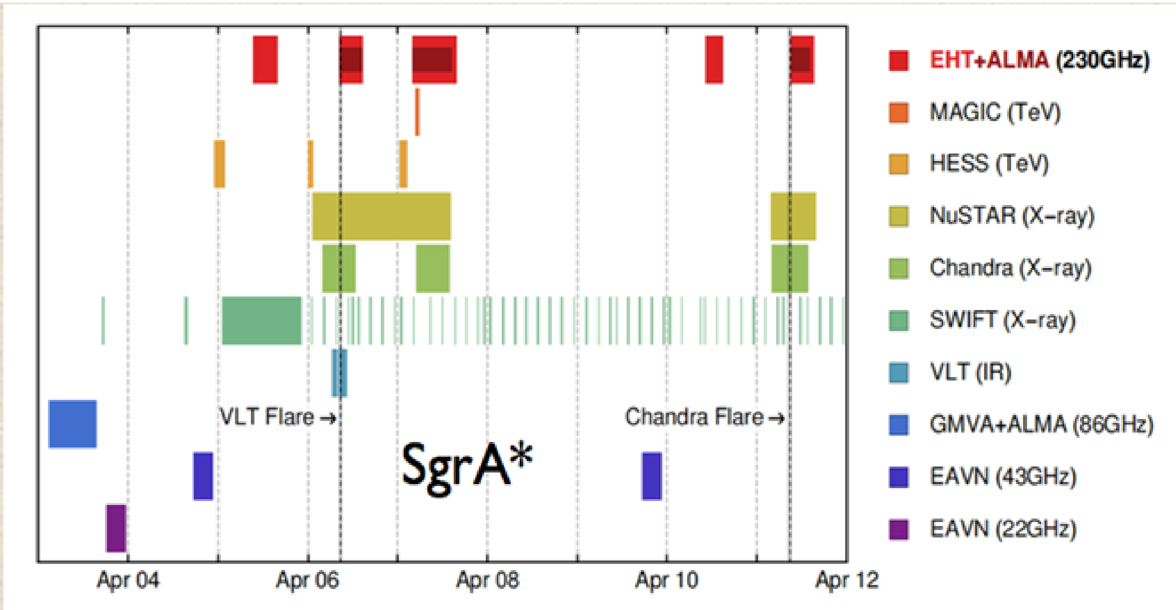
- **230 GHz mmVLBI observing during 5 nights in April with ALMA, APEX, IRAM 30m, LMT, SMT, SMA, JCMT, SPT**

- **Very successful campaign (instruments, teams, weather!)**

- **Data correlation ongoing**

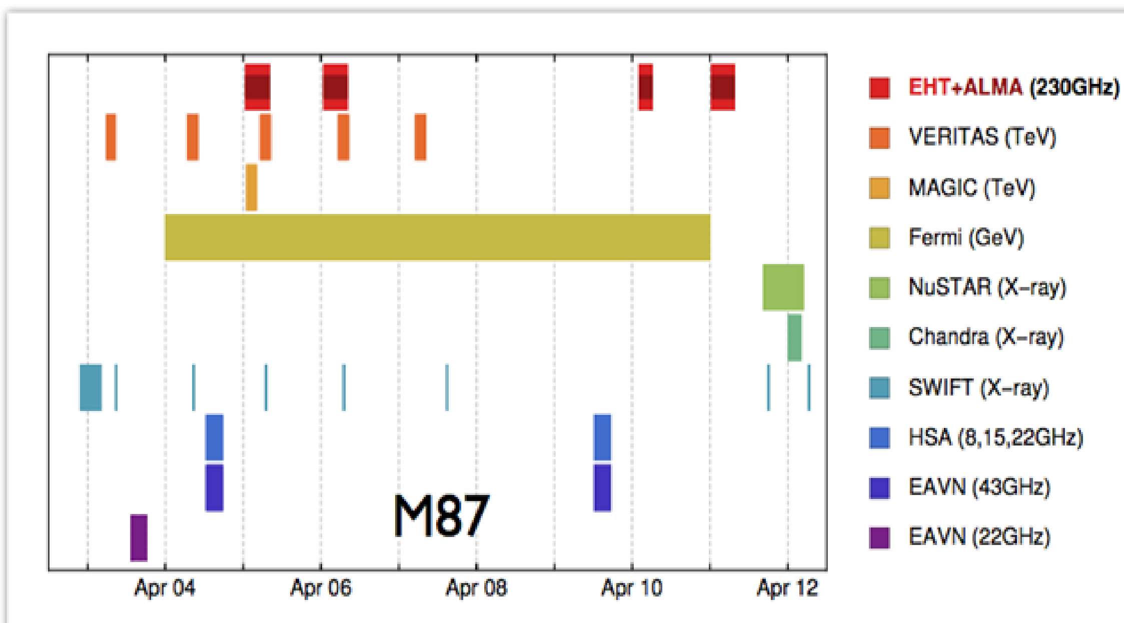
- ***Fringes for calibrators on all baselines*!**

MWL observations during EHT Campaign



April 2017 campaign

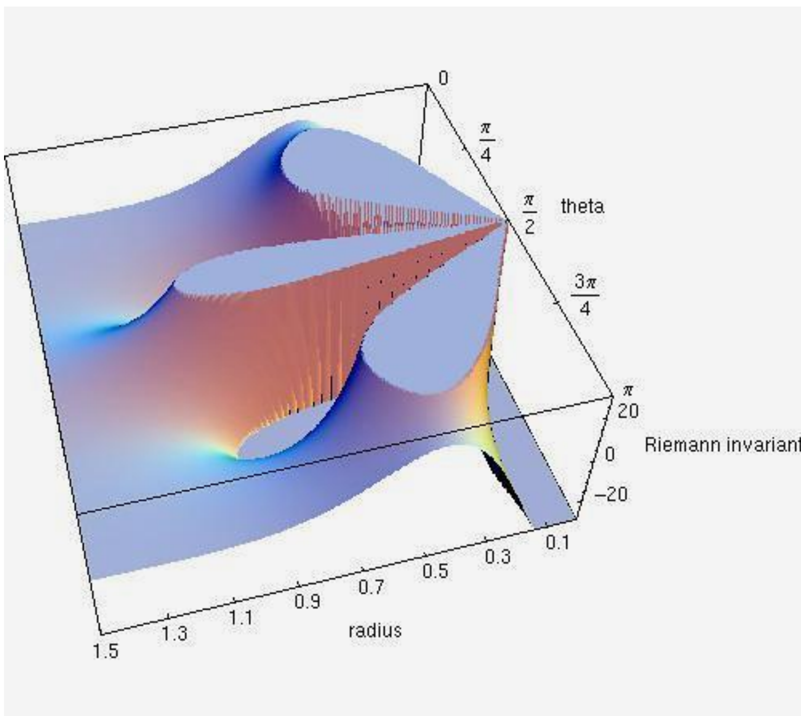
MWL Campaign



Motivation going beyond standard GR

GR theory has up to now withstood all experimental tests

nevertheless, there are extreme situations in GR, like
- the formation of a coordinate singularity at the Schwarzschild radius
- regions not accessible for observations



Kretschmann-scalar

shows how the curvature in the vicinity of the BH behaves

far away from the BH: space time is flat

close to the BH: space time curves strongly

at r=0: curvature diverges

these are reasons to search for possible extensions to GR, i.e. pc-GR

The Pseudo-Complex Theory

Hess, Greiner et al. 2009-2017+

1. the effective potential

2. last stable orbits

3. observational tests

Acceptance of pc-GR in astronomical community

1. pc-GR is part of the Athena+ proposals for ESA´s Large Mission Programme 2015-2025

2. pc-GR is part of the ALMA white paper for direct imaging of black holes

there is growing interest from galactic and extragalactic experts to perform tests going beyond standard GR

The Pseudo-Complex Theory – Einstein equation and metric tensor

$$R^{\mu\nu} - \frac{1}{2} g^{\mu\nu} R = -\frac{8\pi\kappa}{c^2} T^{\mu\nu} \sigma_-$$

$$\sigma_- = \frac{1}{2}\left(1 - I\right) \qquad \sigma_- \sigma_+ = 0 \qquad \sigma_-^2 = \sigma_-$$

- new Einstein equation
- energy momentum tensor allows for repulsion at small r[m]

$$g_{00} = \frac{r^2 - 2mr + a^2 \cos^2\theta + \frac{B}{2r}}{r^2 + a^2 \cos^2\theta}$$

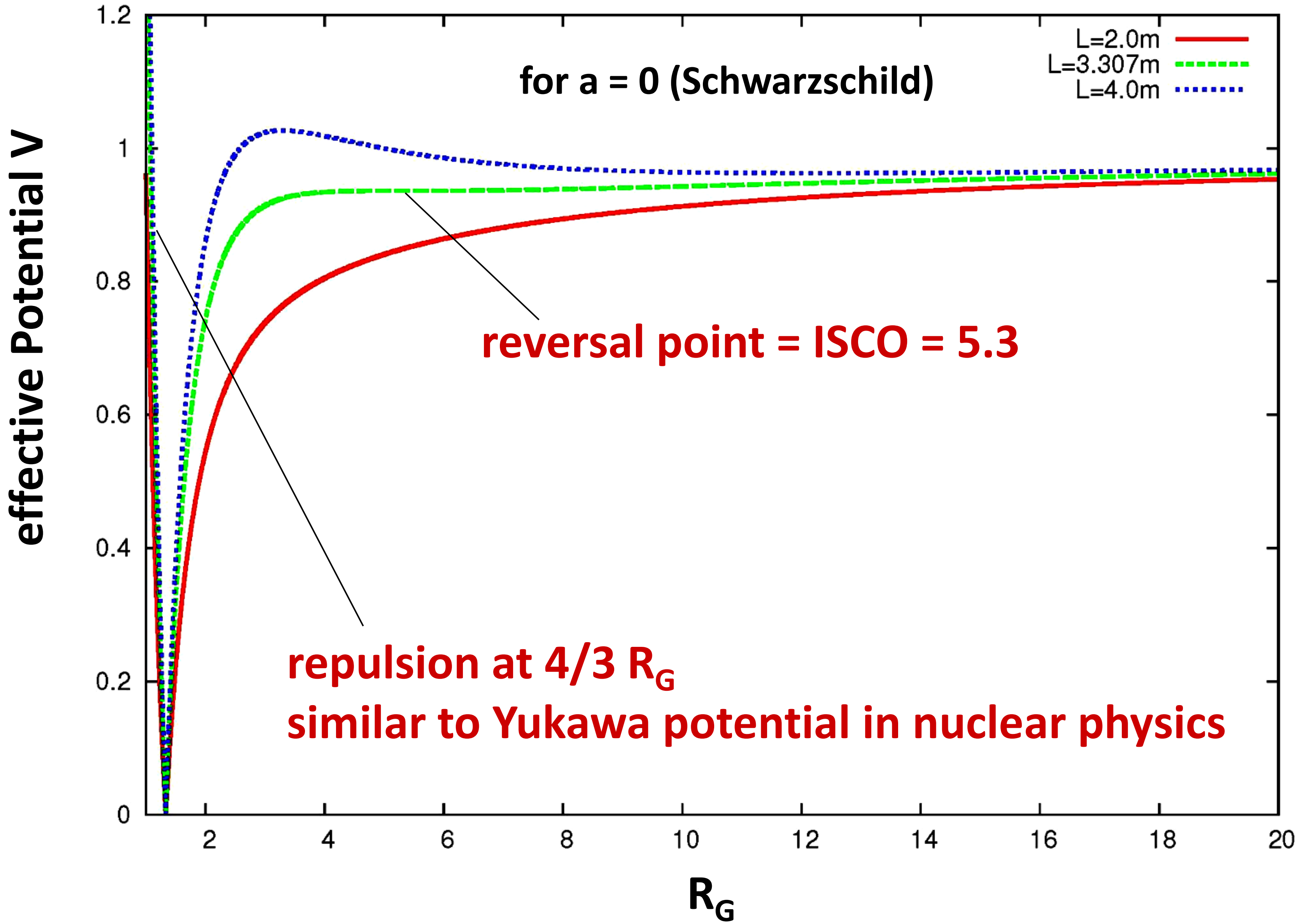
g_{00}: metric tensor

B: new pseudo-complex variable

a: spin parameter

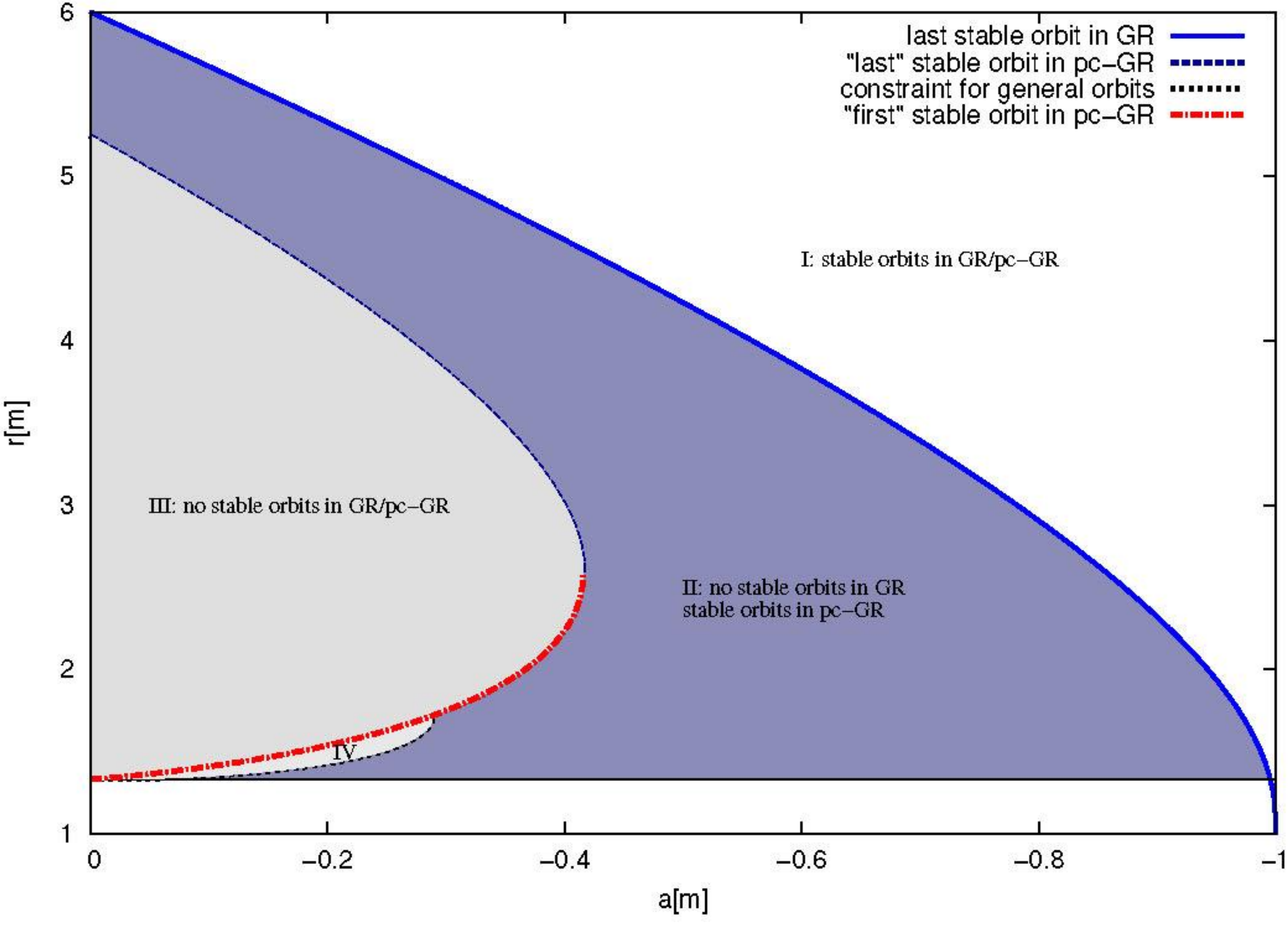
no coordinate singularity at r = 2m for a = 0

Effective potential of test particle in pc-GR

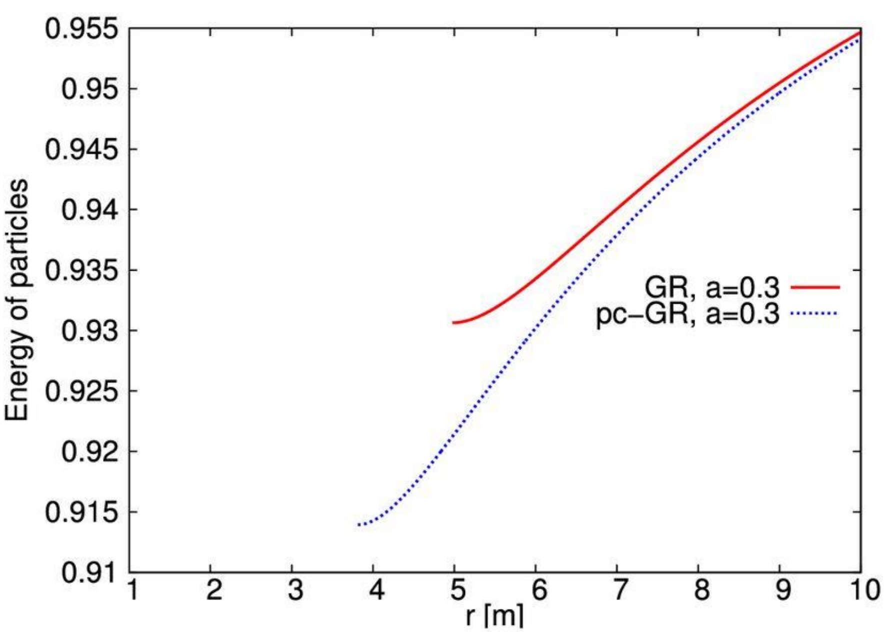


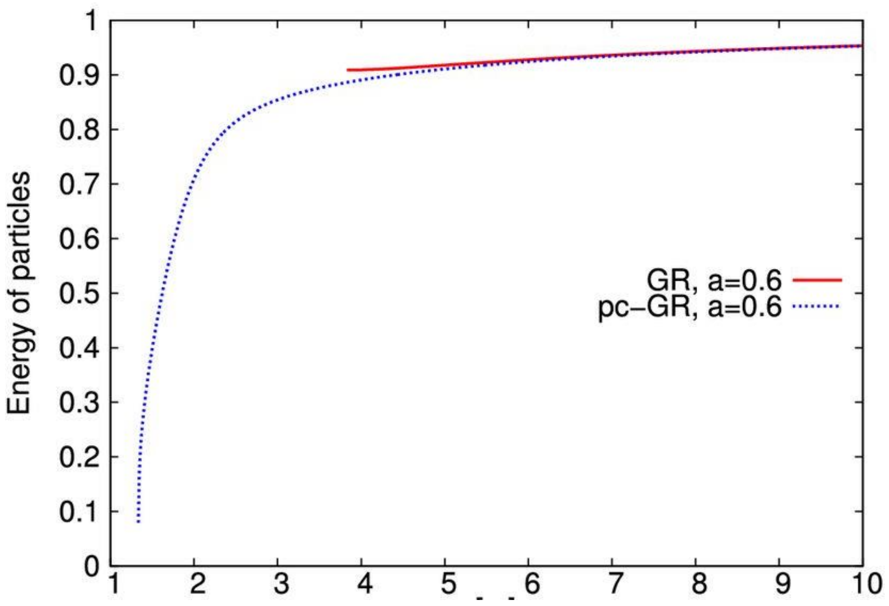
Last stable orbits

Schönenbach_etal[2013]



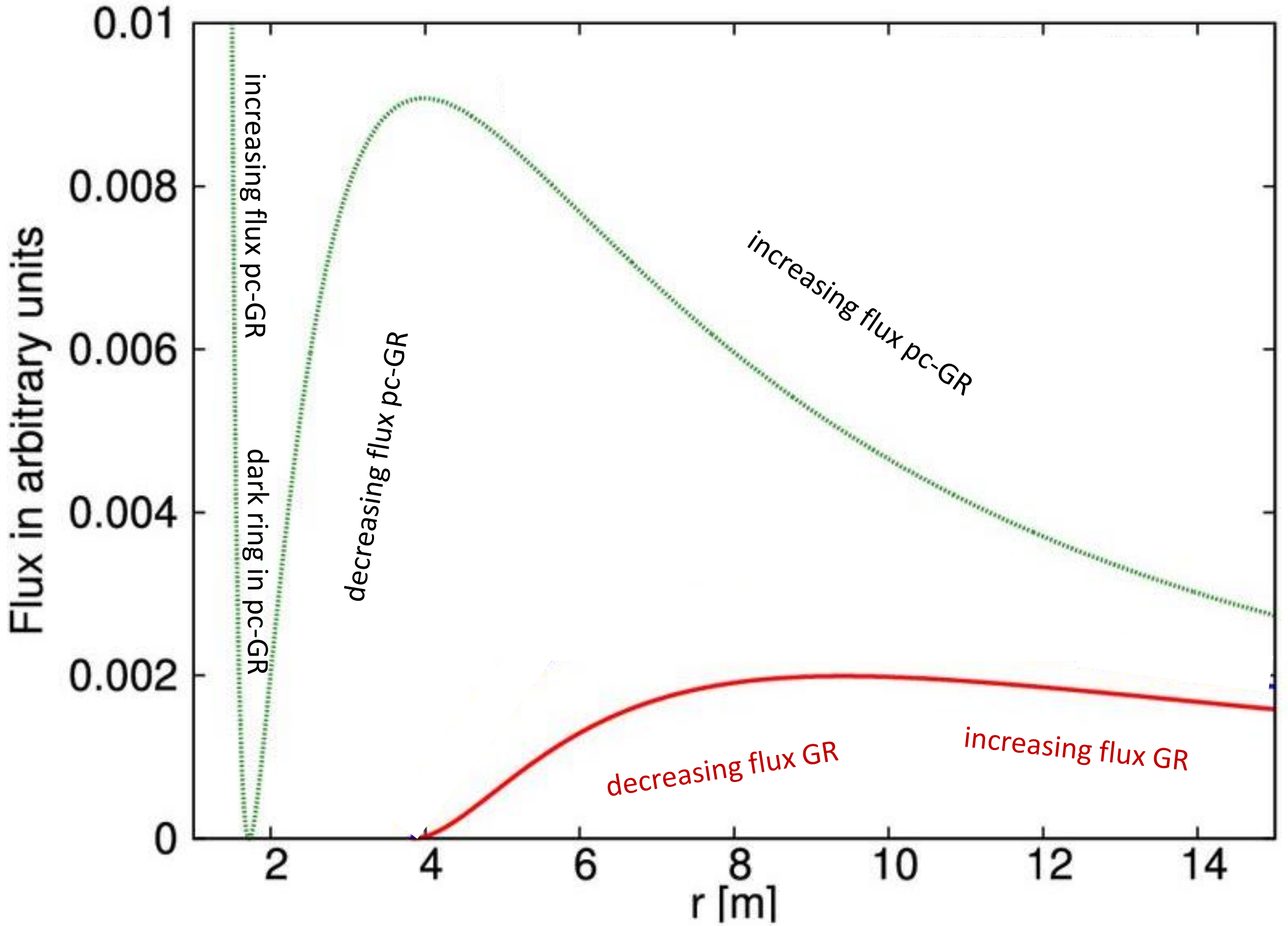
Normalized energy of particles on stable prograde circular orbits in pseudo-complex GR (Hess, Greiner[09], Schönenbach[14])





in the pc-GR case, more energy is released as particles move to smaller radii

flux function for GR and pc-GR

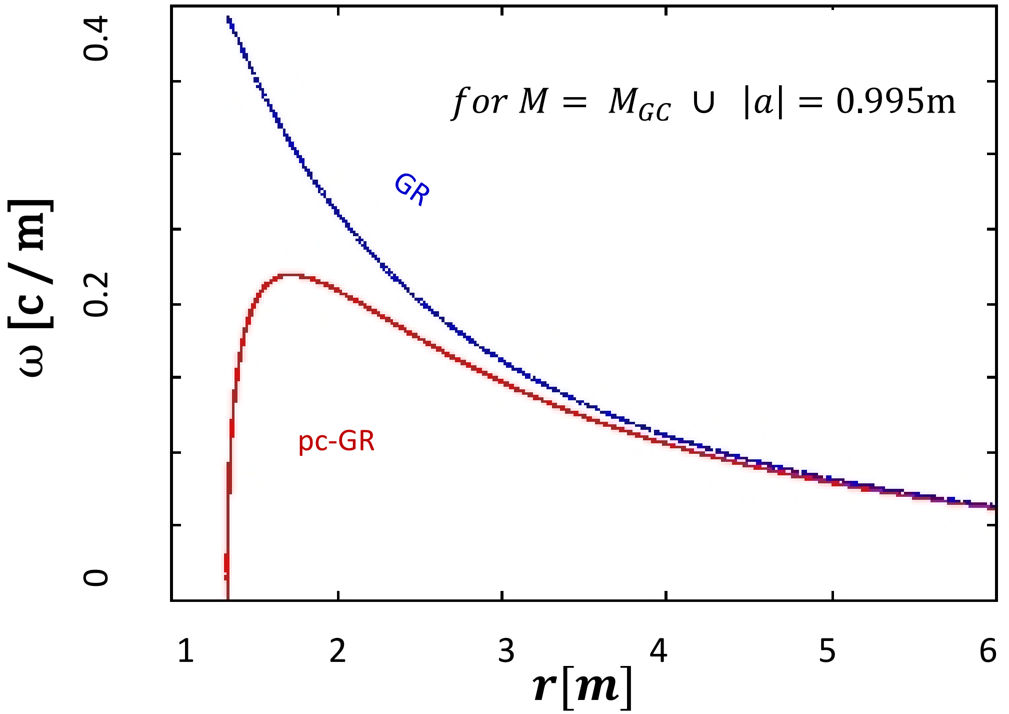


- pc-GR black holes is brighter
- appearance of zero flux in pc-GR

Radial dependence of the angular frequency $\omega(r)$

angular frequency $$\omega\pm = \frac{c}{-a\pm\sqrt{\frac{2r}{h(a,m)}}}$$

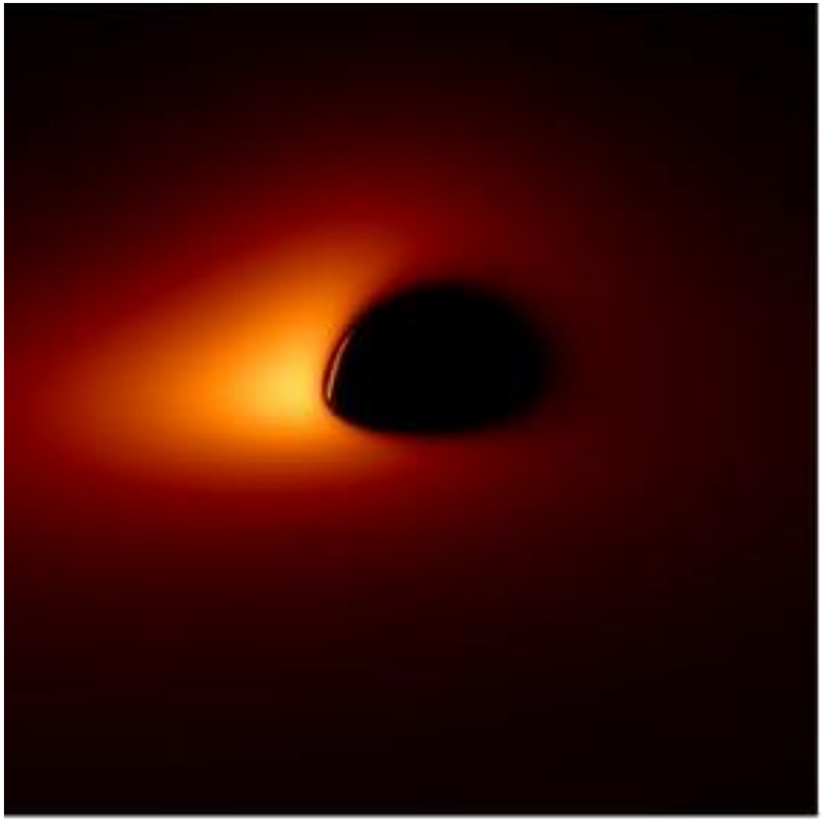
time derivative gives flux $$d_{|r}\omega\pm = d_{|r}\frac{c}{-a\pm\sqrt{\frac{2r}{h(a,m)}}} \sim flux$$



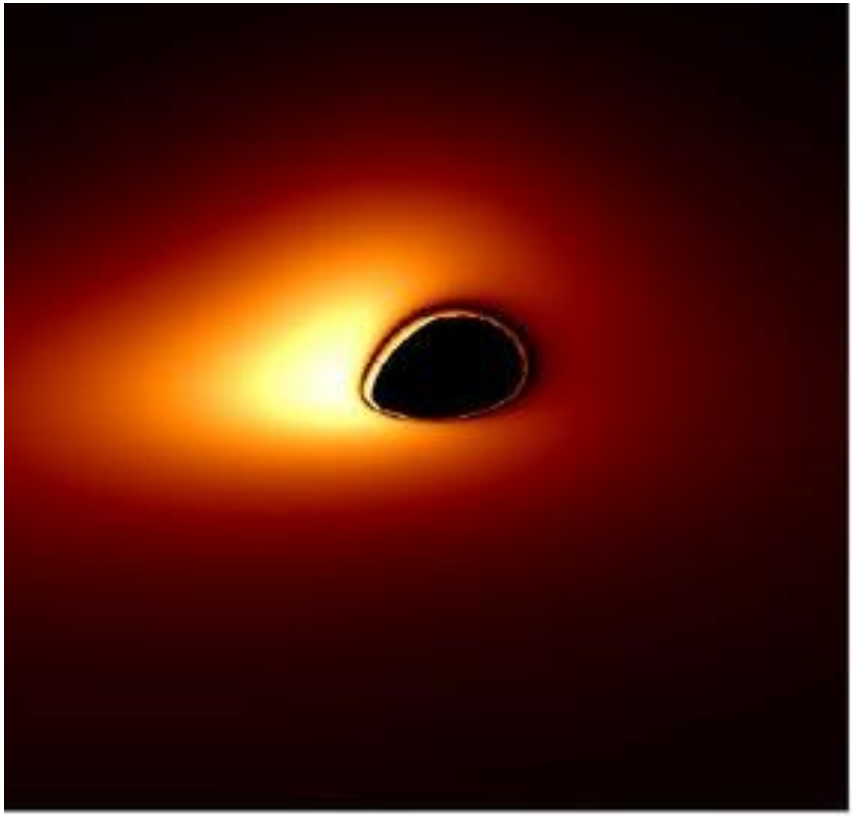
orbital frequency is reduced in pc-GR

for the mass of the GC a maximum frequency of 0.219c/m exists, corresponding to a orbital period of 9.4 min

Geometrically thin accretion disc around a rotating compact object viewed from an inclination of 70°



(d) standard GR $a = 0.9m$

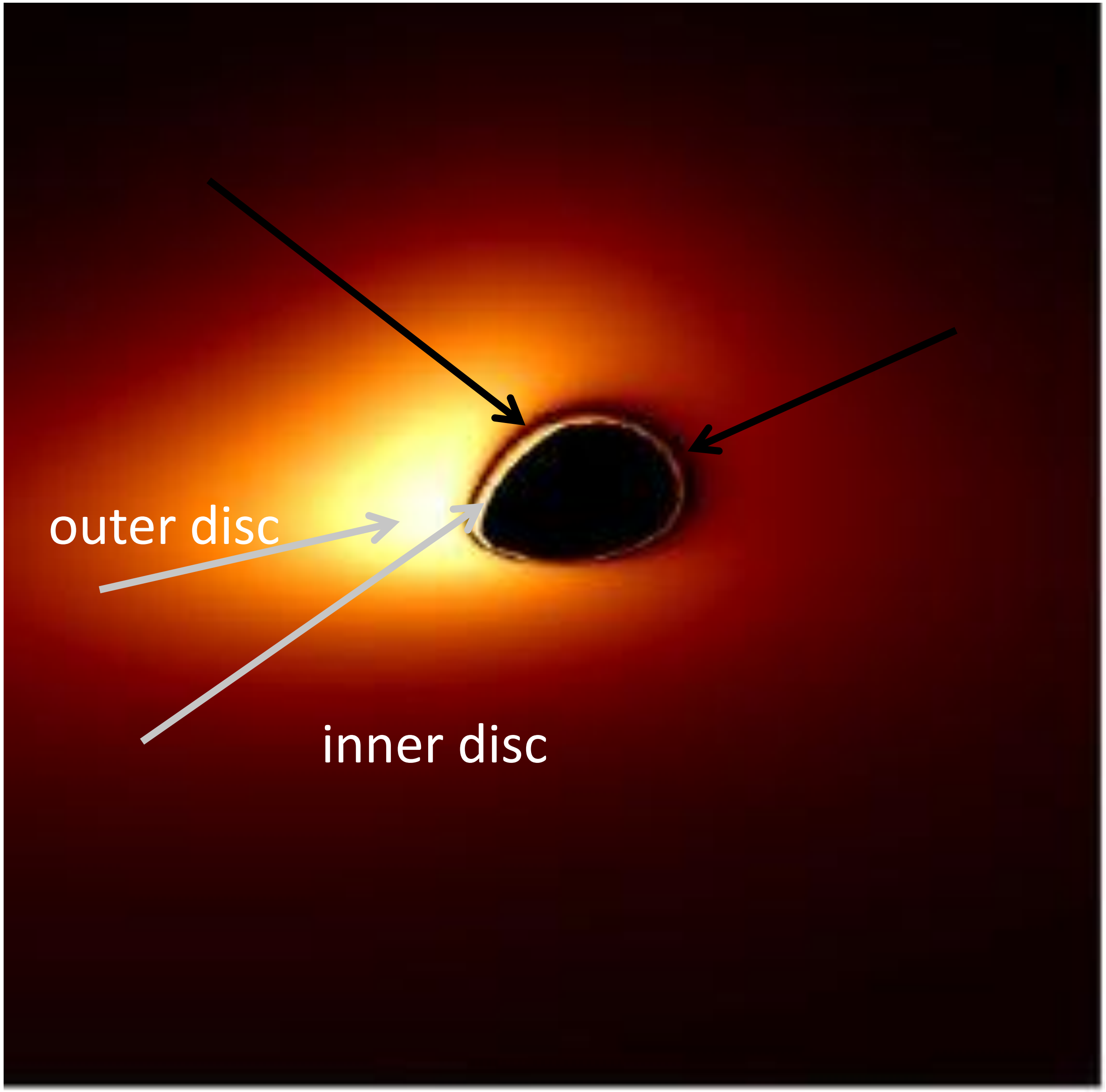


(d) pc-GR $a = 0.9m$

most prominent difference: pc-GR images are brighter

next significant difference: occurrence of a dark ring in pc-GR

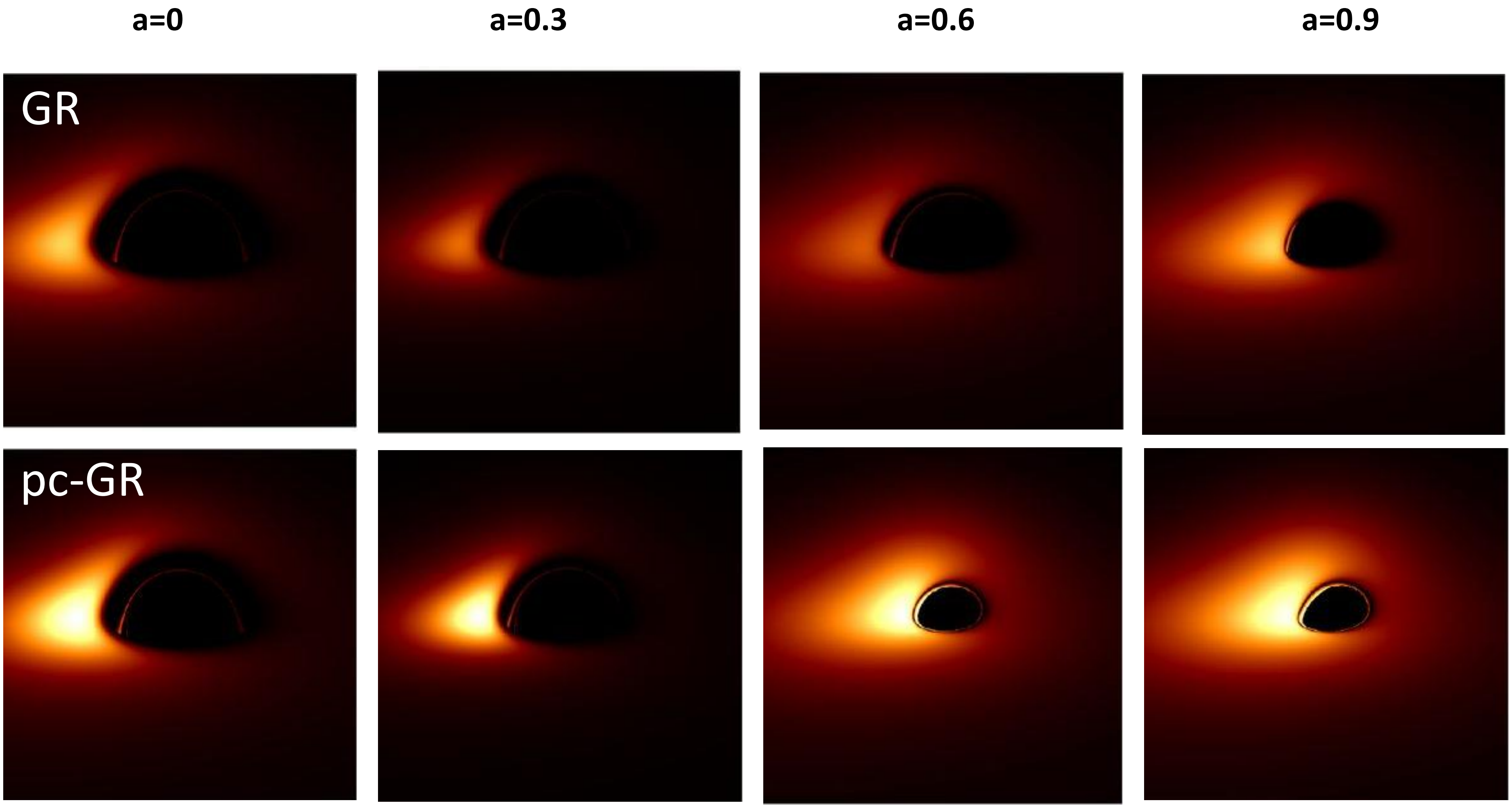
- the ring appears due to the fact that the angular frequency has a maximum at 1.72 m
- at 1.72m the flux vanishes, going further inside, the flux increases again, which is a new feature in pc-GR



(d) pc-GR $a = 0.9m$

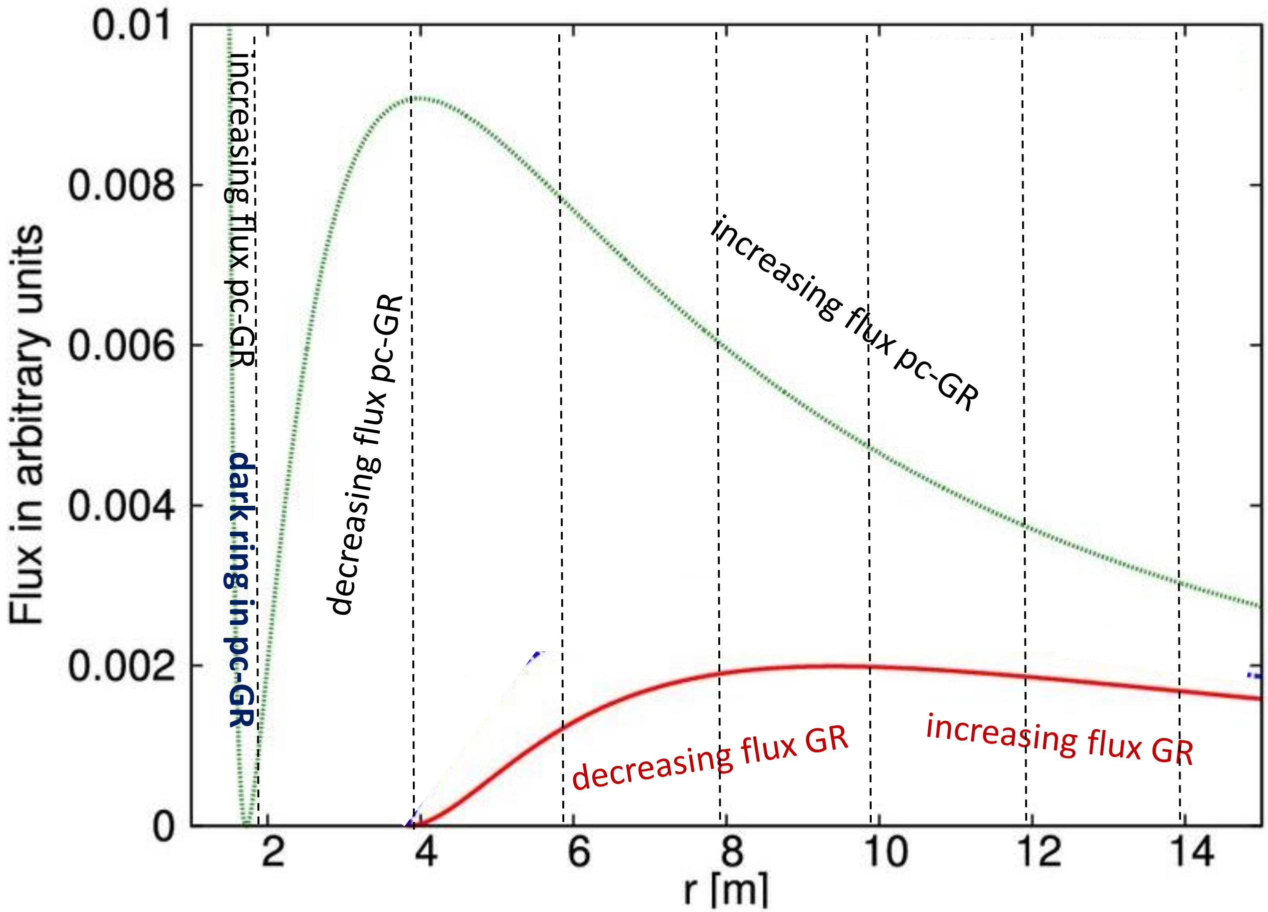
dark ring at 1.72m as new feature of pc-GR

ray-tracing in GR and pc-GR



most prominent difference: pc-GR images are brighter
next significant difference: occurrence of a dark ring in pc-GR

OBSERVED EHT intensity slices will provide robust GR test



$$I_\nu^{obs} = g^3 \; I_\nu^{rest}$$

$$g \equiv \frac{1}{1+z} = \frac{\upsilon_{obs}}{\upsilon_{em}} = \frac{\hat{p}^t_{obs}}{\hat{p}^t_{em}}$$

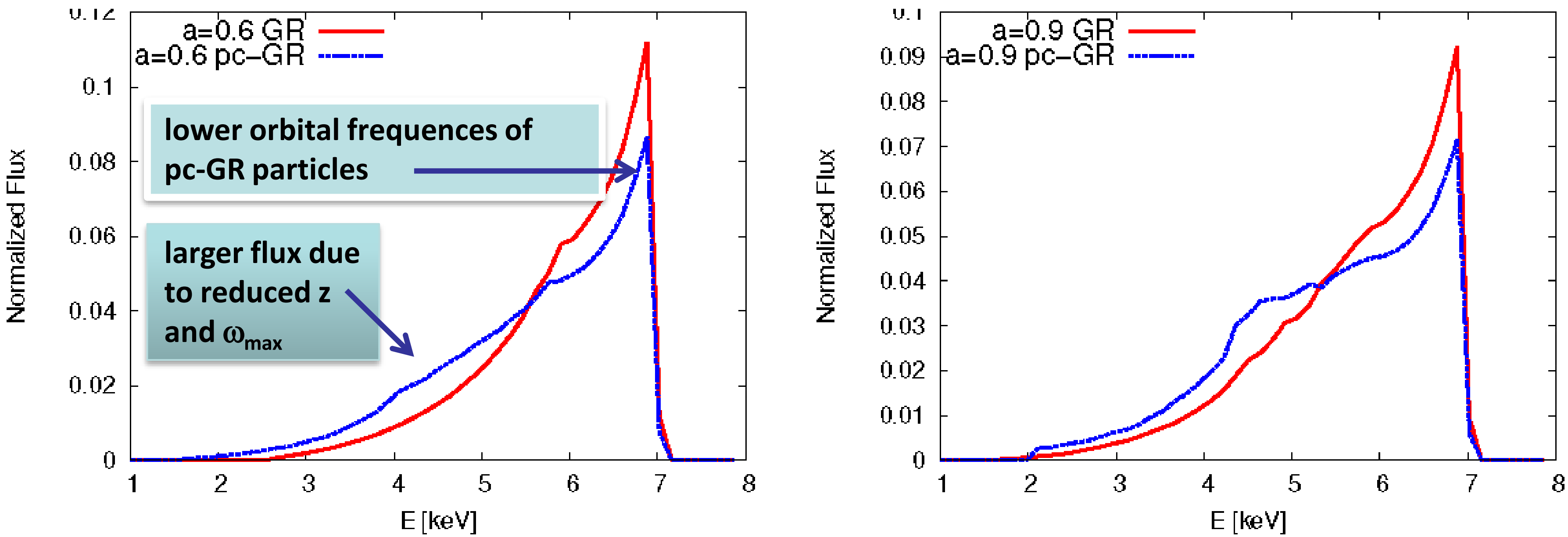
$$\frac{I_\upsilon^{obs}(pc) \quad (m)}{I_\upsilon^{obs}(GR) \quad (m)} \sim 100..1$$

the ultimate test of pc-GR:

- analyze EHT flux slices into the direction of the center of the black hole
- determine relative flux ratios between GR and pc-GR as a function of r
- these flux ratios differ by a factor of 100, a rare phenomenon in astrophysics

EHT images provide a solid proof of pc-GR or standard GR

relativistic Fe K line differences



(c) $a = 0.6$ (d) $a = 0.9$

as pc-GR discs are brighter, the integrated line flux is larger in pc-GR

the line profiles are clearly different from standard GR

this offers a second robust measurements to test pc-GR versus GR

Summary

motivated by the **upcoming EHT observations** of the BH in the GC and in M87, ray-tracing methods have been applied both to standard GR and pc-GR

the correction terms in pc-GR include:

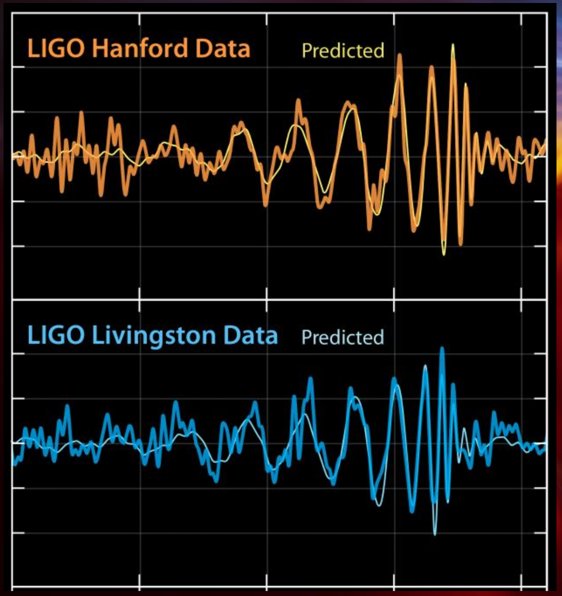
- a modified concept of the ISCO, allowing particles to get closer to the BH
- a reduced gravitational redshift and slower orbital motions
- the appearence of a maximum orbital frequency and a related zero flux emission at ω = const
- brighter accretion discs in pc-GR

the emissivity profiles of matter when approching the BH are different in GR and pc-GR allowing **a robust first test of GR and pc-GR**, especially to the appearance of a dark ring in pc-GR

the Iron **Kα emission-line profiles are also differen**t and those are good observables to test regions of strong gravity

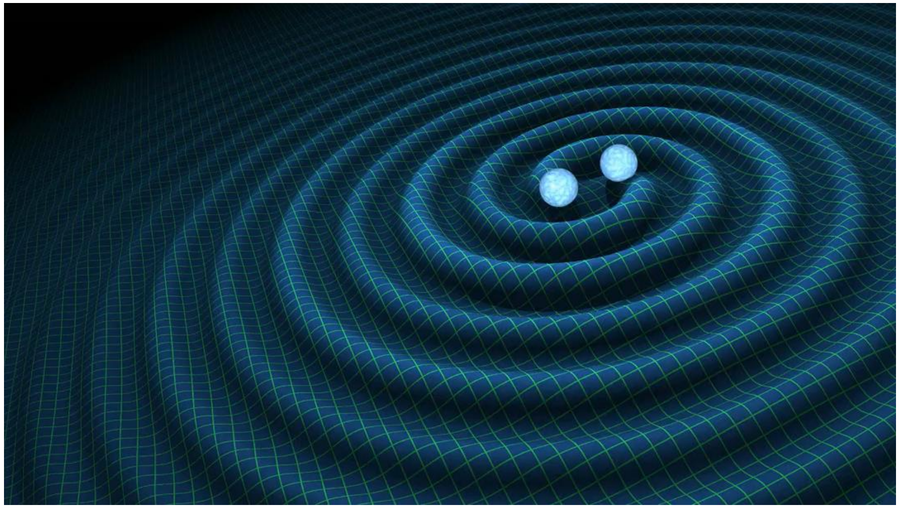
the observable differences between GR and pc-GR are remarkable different and will provide new tests of GR going beyond the 4 classicial tests of Einsteins GR theory

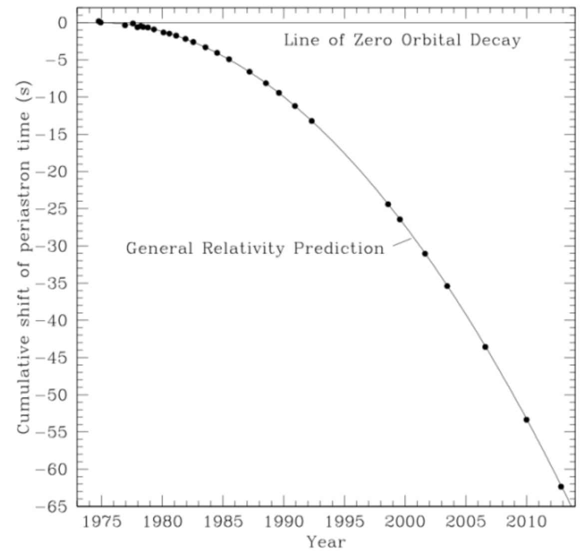
Gravitational Wave detections



Bilder: ESO, LIGO

Gravitational Wave signatures





1916: predicted by Einstein and **1934 withdrawn by him due to the weakness of the expected signal.**

Changes in the metric of the space-time, expansion with v=c

GW result into relative changes in length of $10^{-18--21}$

- a length of 1 km length is changing by 10^{-20} cm

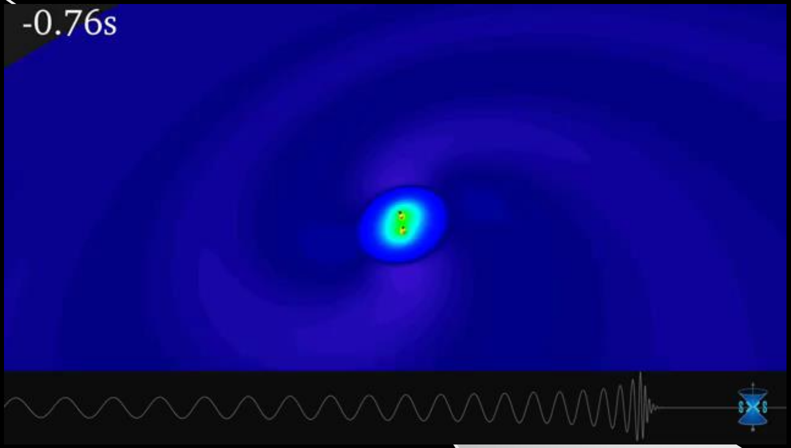
1974: first indirect proof with binary pulsar Hulse und Taylor

the orbital period is becoming shorter, as GWs are emitted

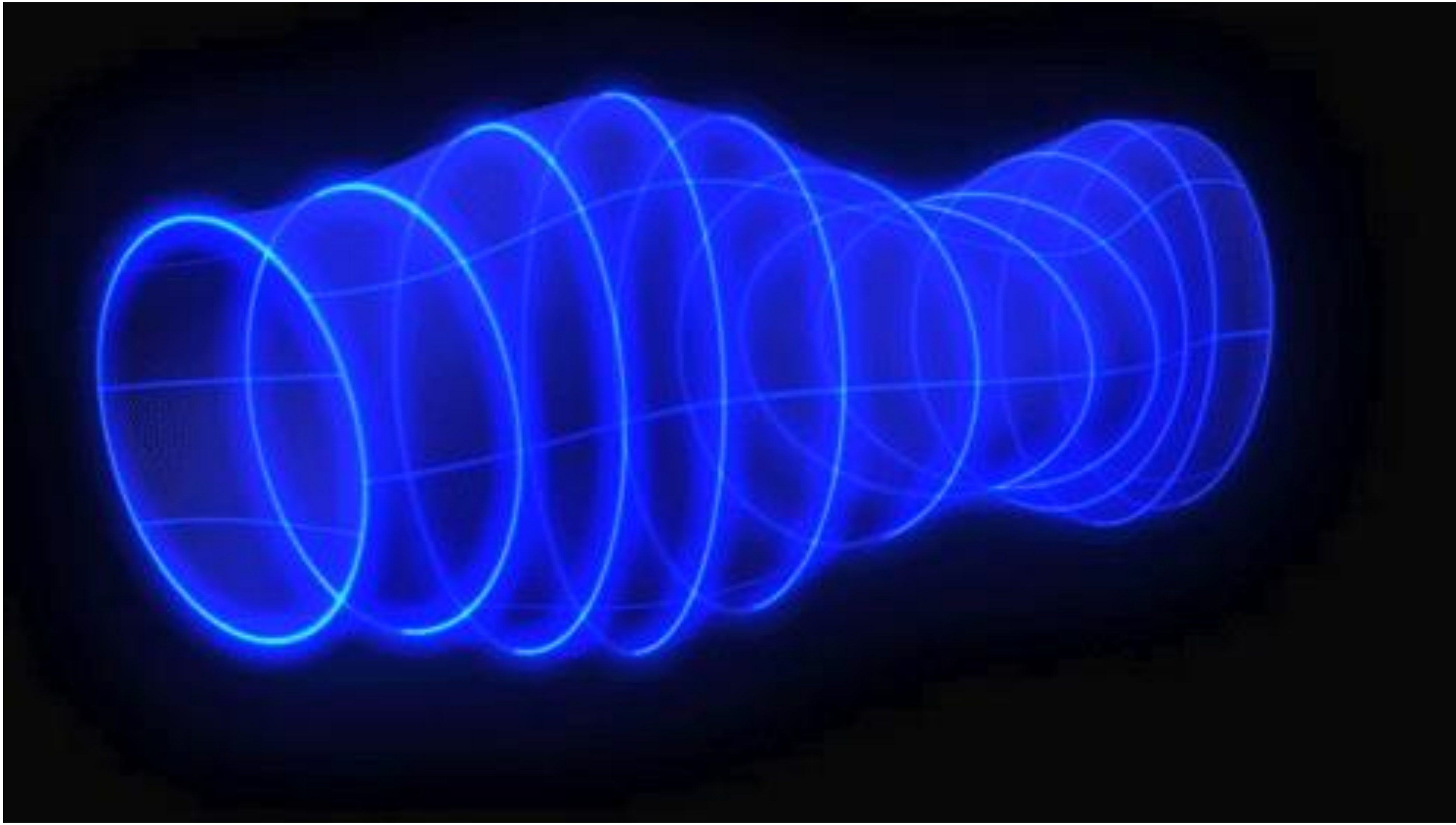
- L_GW(Hulse-Taylor) = 10^{40} Watt
- L_GW(earth-sun) = 120 Watt

Simulation of two merging black holes

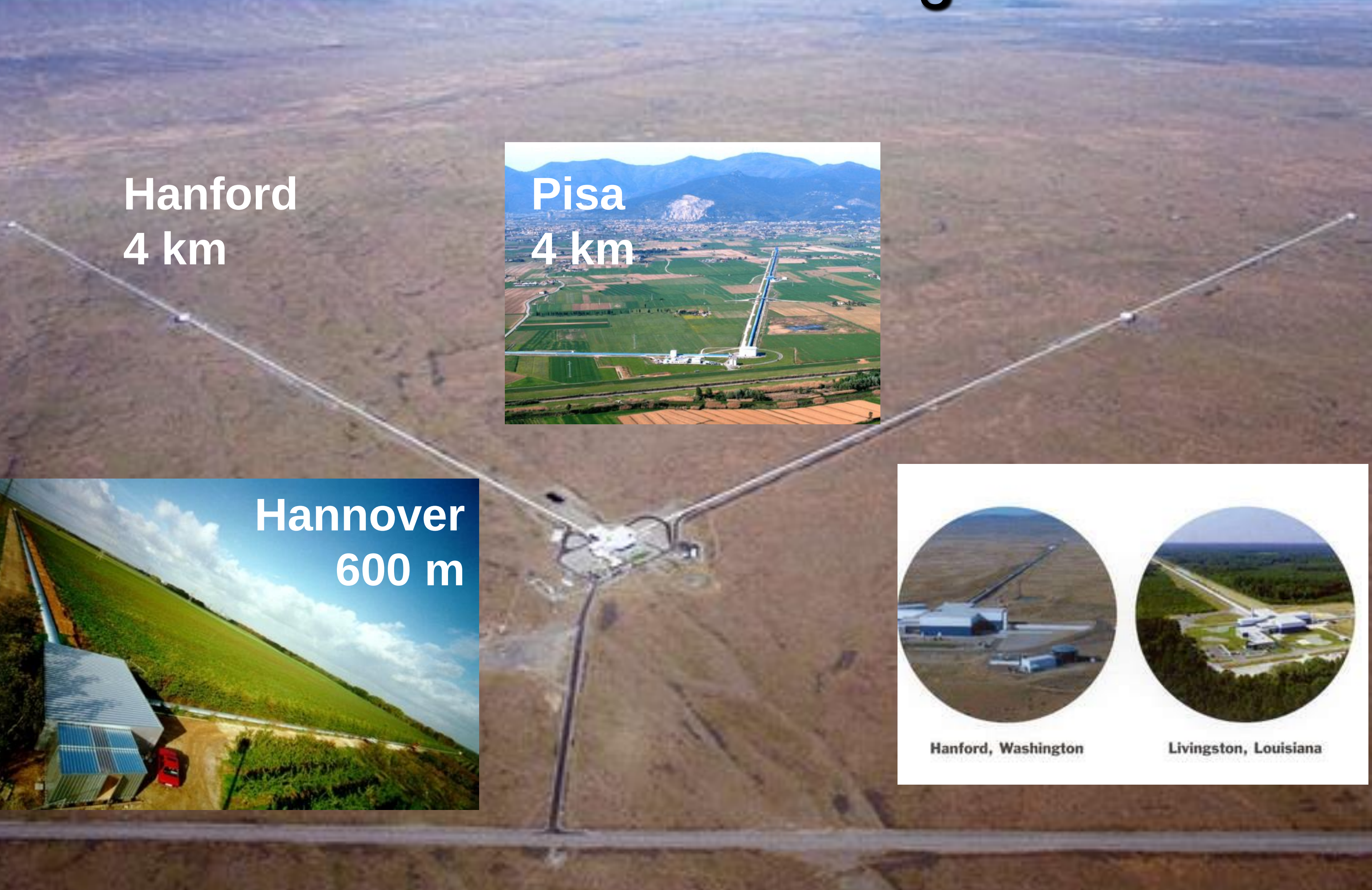
- Millisecond-timescale
- Below the black holes: curved space-time
- Gravitational-Hole
- Color-code indicates time delay green: normal; yellow: 20-30% slower; red: extreme slow in observers frame
- last 0,76 s unitl merging
- Sinus-amplitude until t = –0,07s
- t = –0,017 s frequeny and amplitude is increasing
- t = 0 s black hole – black- hole merger
- ring-down after merger



Gravitational Wave ´Crawler´



Gravitationswellen-Laserinterferometer LIGO=Hanford+Livingston



Still a problem with 30 $M_\odot$

Big problem for stellar evolution models

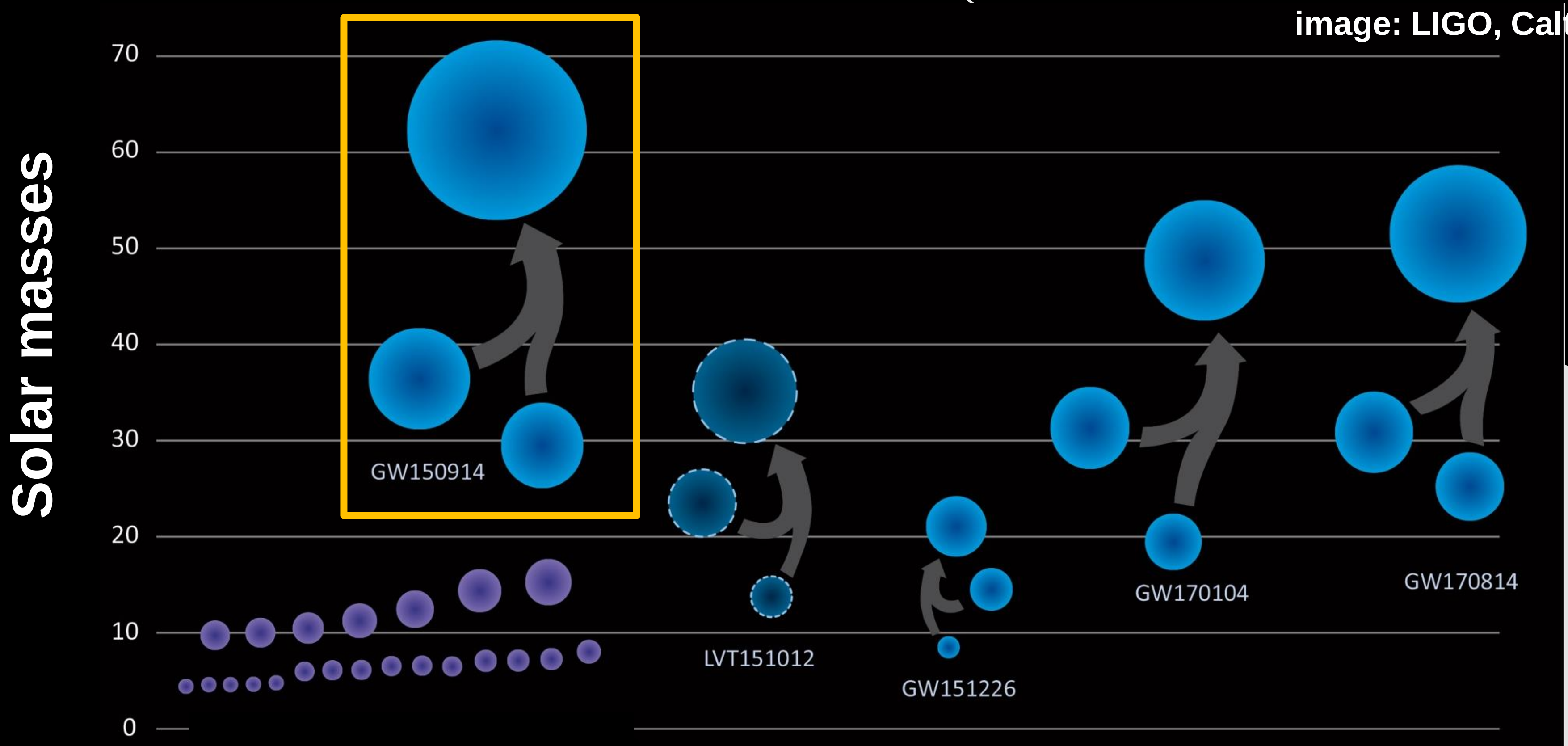
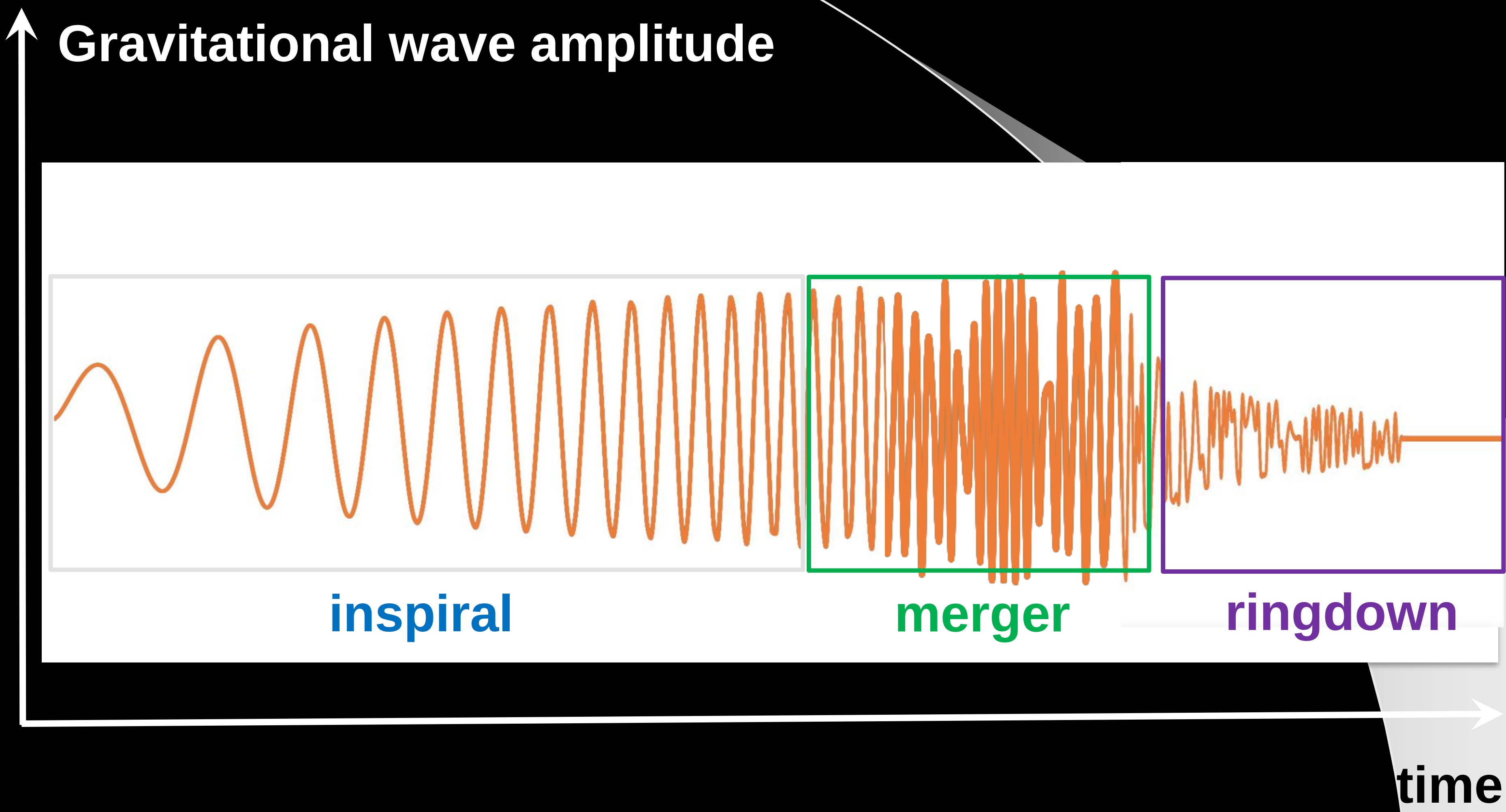
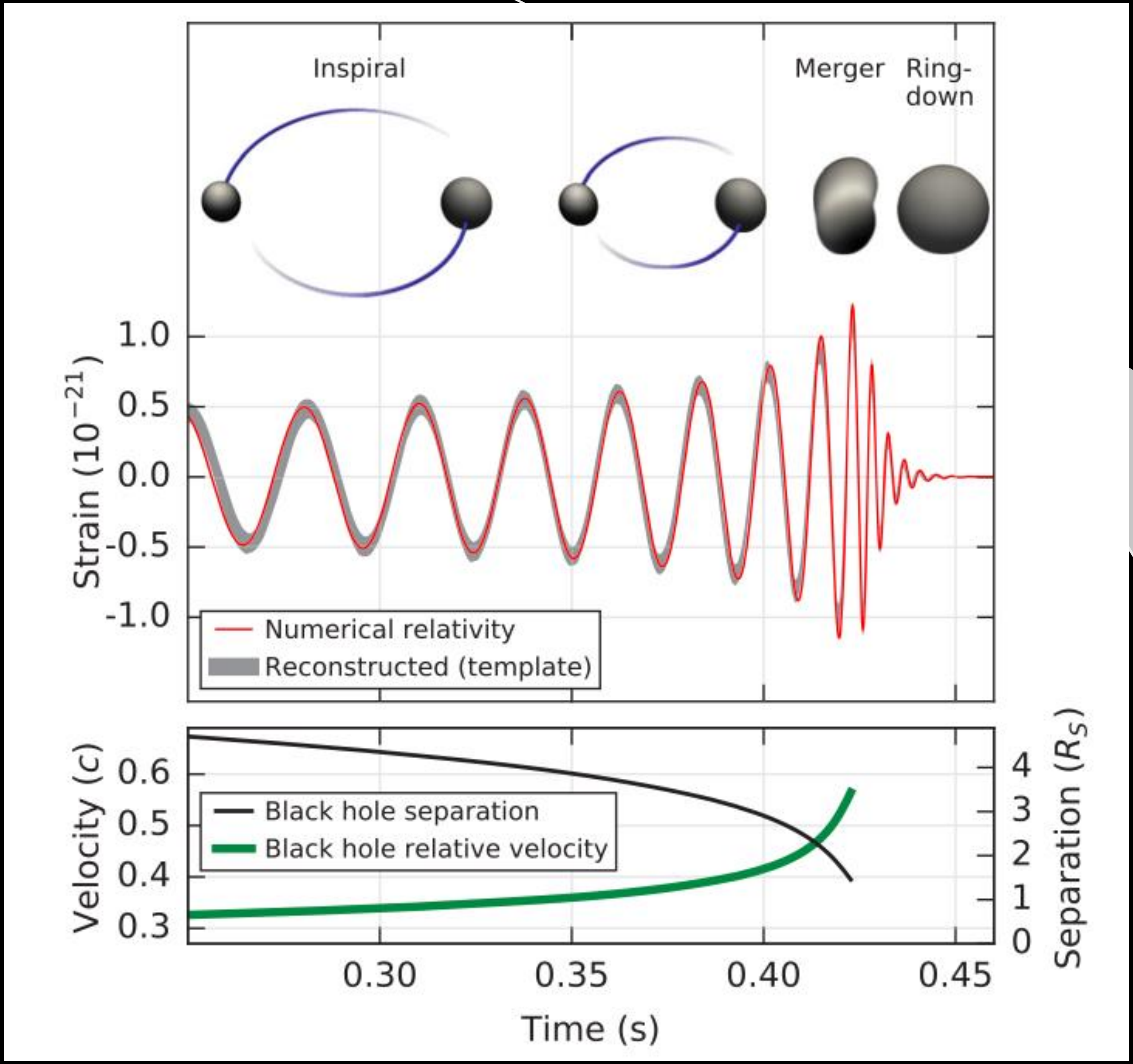


image: LIGO, Caltech

The Chirp-Signal



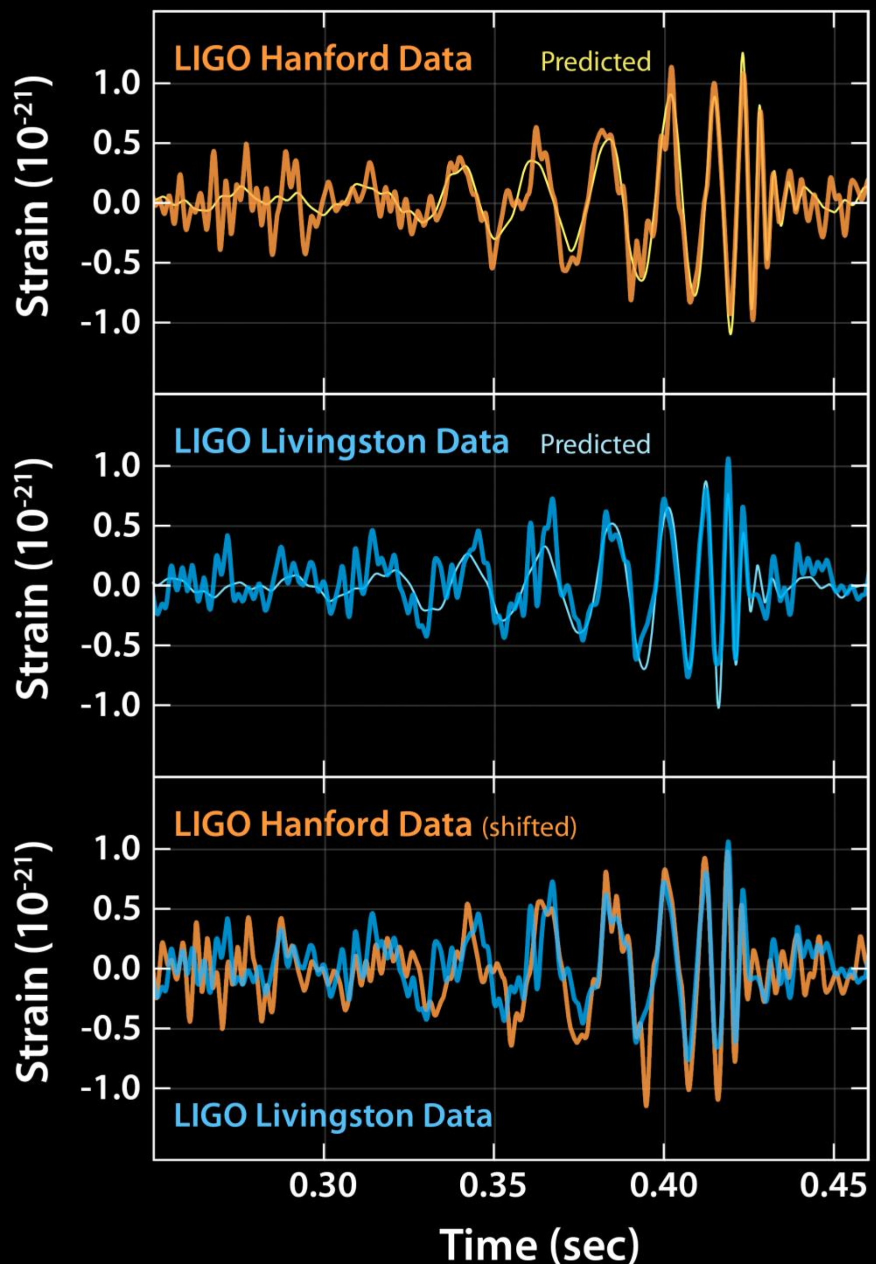
GW150914 signal and Interpretation



LIGO collaboration

GW150914
14.09.2015

LIGO, CalTech



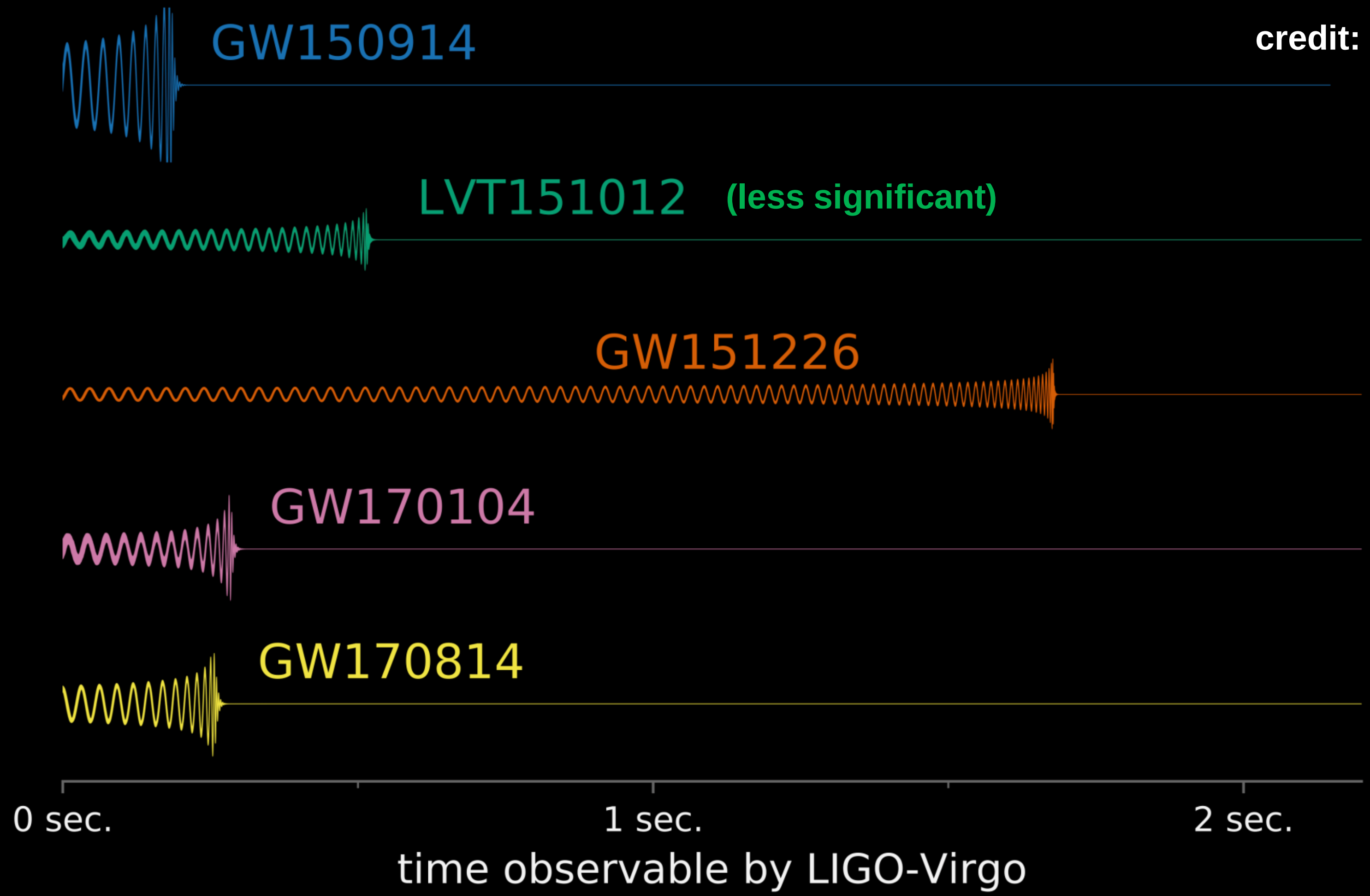
Strain = relative length change

35-250 Hz

Merging of 2 black holes with 29 und 36 $M_\odot$

GW energy release äquivalent to 3 $M_\odot$

Summary of all GW events to date



Nobel Price 2017

www.ligo.caltech.edu

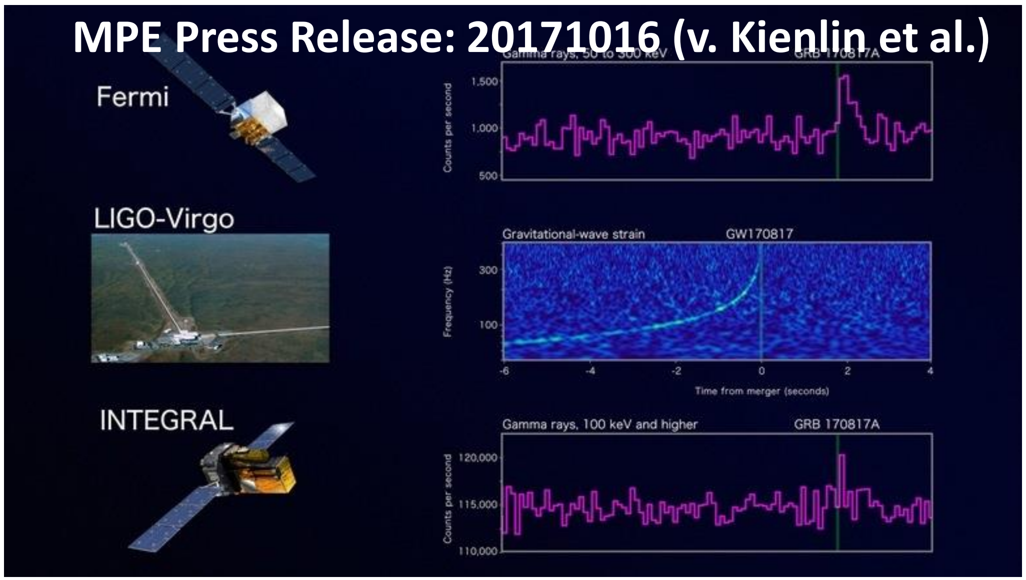
First Gravitational Wave and electromagnetic detections

Nobel Price 2017
R. Weiss, B. Barish , K. Thorne

First GW detection: 14. September 2015 (LIGO)

First GW and electromagnetic radiation: 16. October 2017

Neutron star – neutron star merging: Fermi Gamma-Ray burst .and. GW signal detection on 17.8.2017

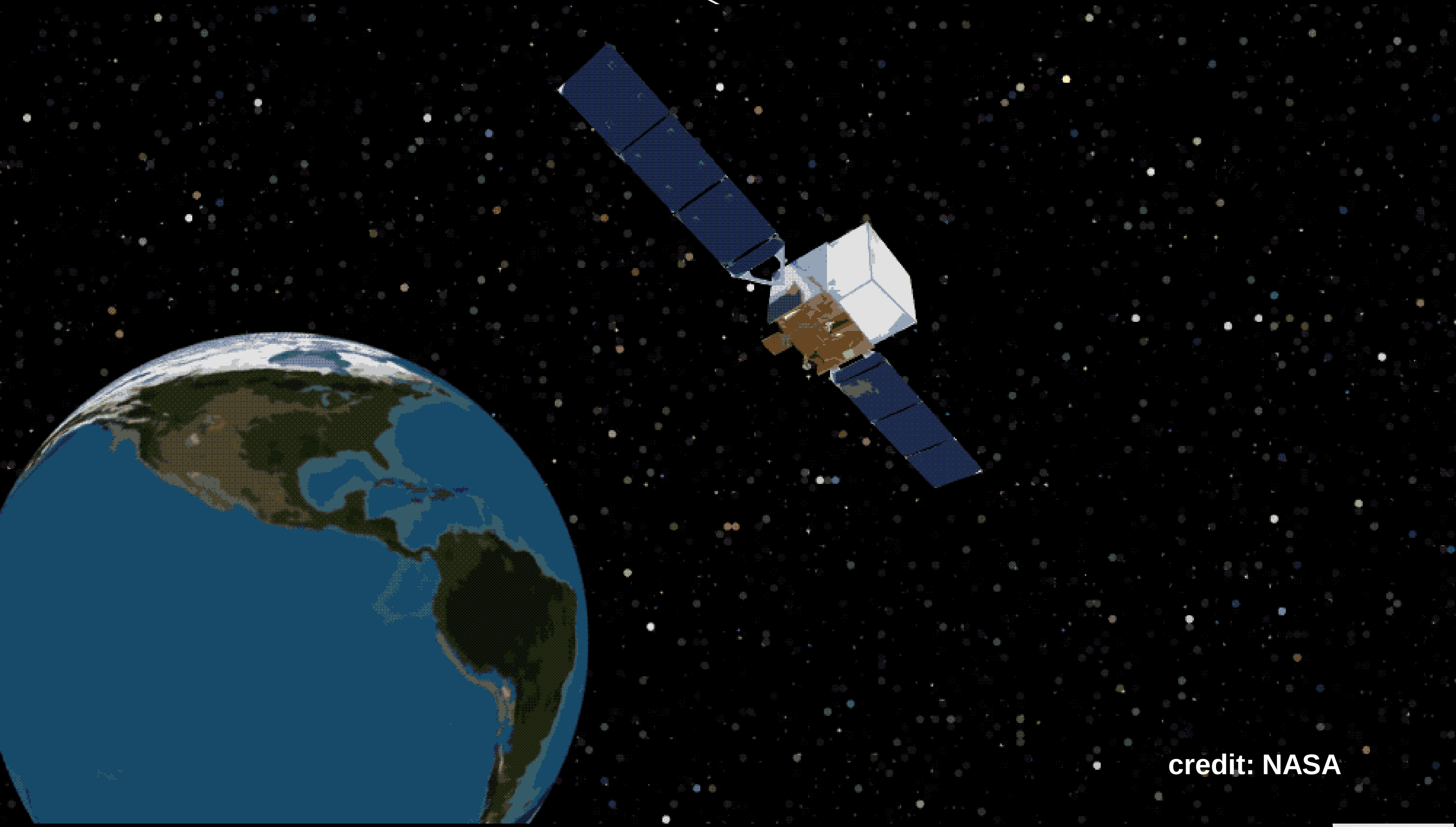


The sound of gravitational waves

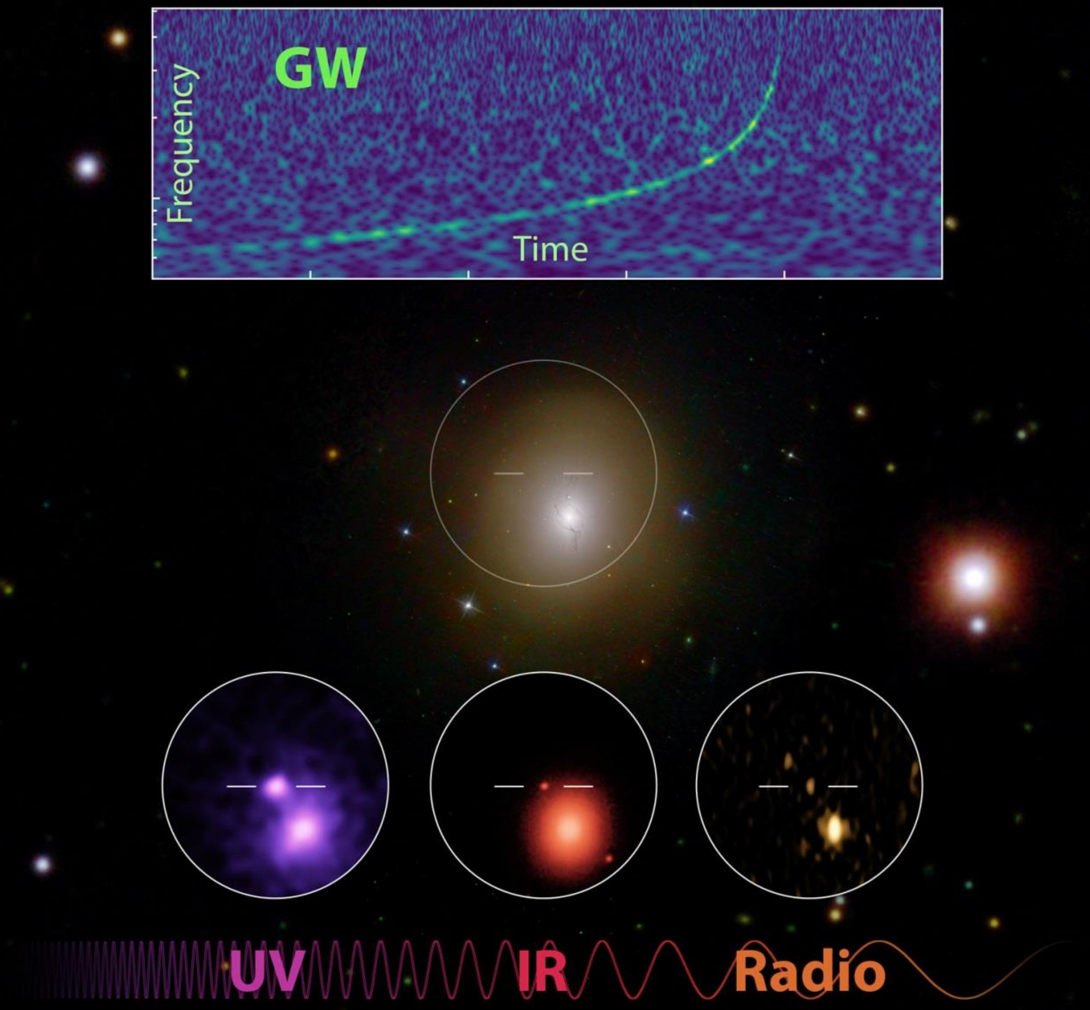
GW150914

GW170817

Fermi ´saw´ gamma ray birst 2 seconds later

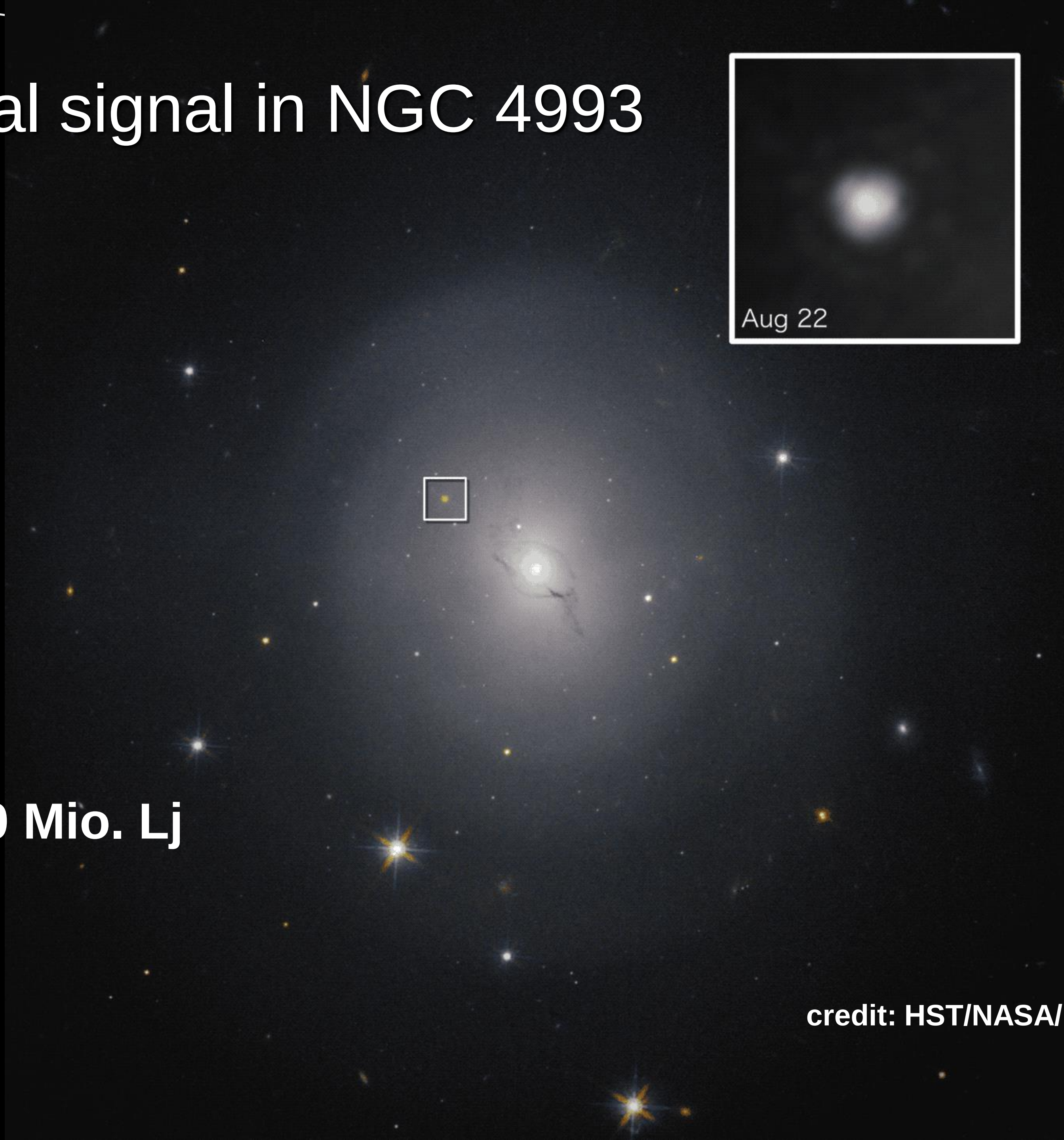


EM emission: opt., UV, IR, Radio



credit: Caltech

Optical signal in NGC 4993



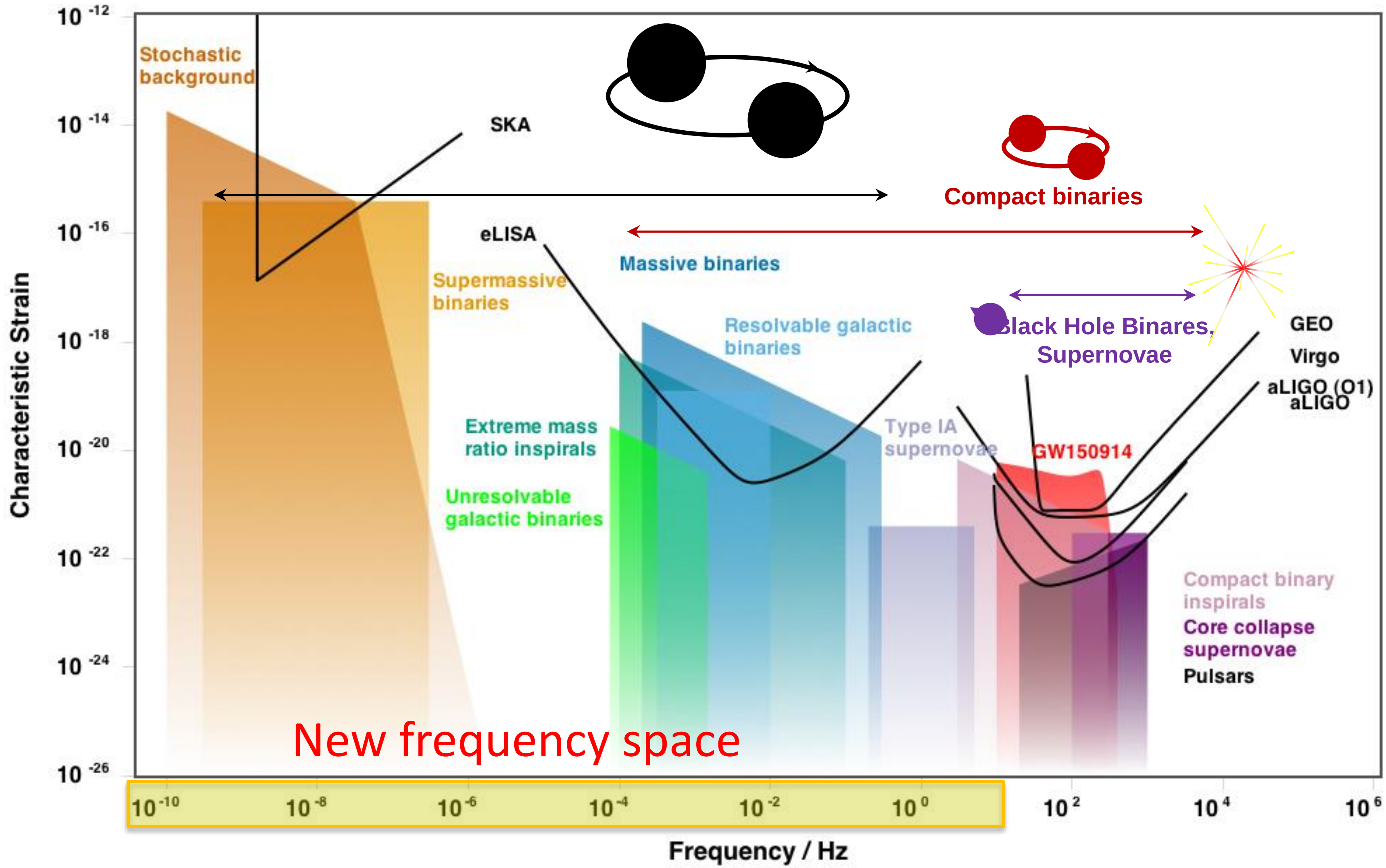
D = 130 Mio. Lj

credit: HST/NASA/ESA

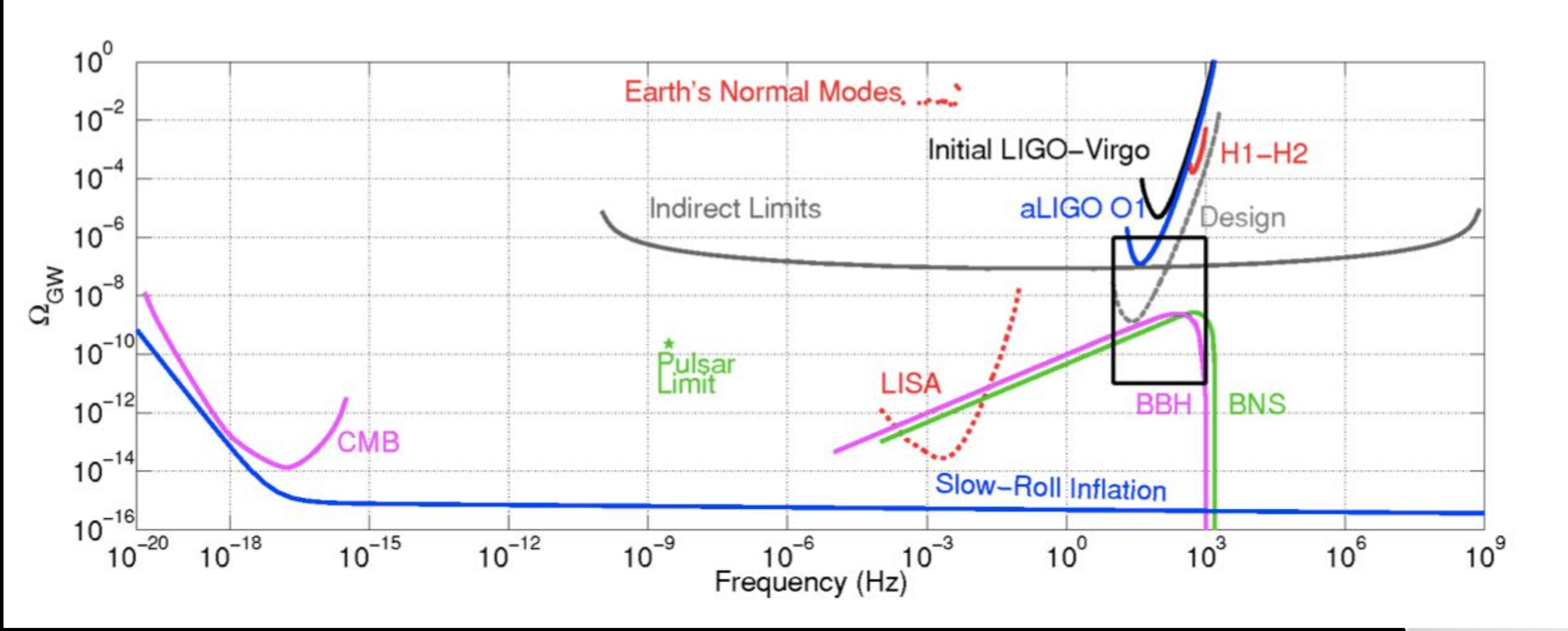
Future detections

- Supernovae in Milky Way (high frequency)
- Supermassive black holes (low frequency)
- White Dwars (low frequency)
- Big Bang: primordial gravitational waves

GW-sources and frequences



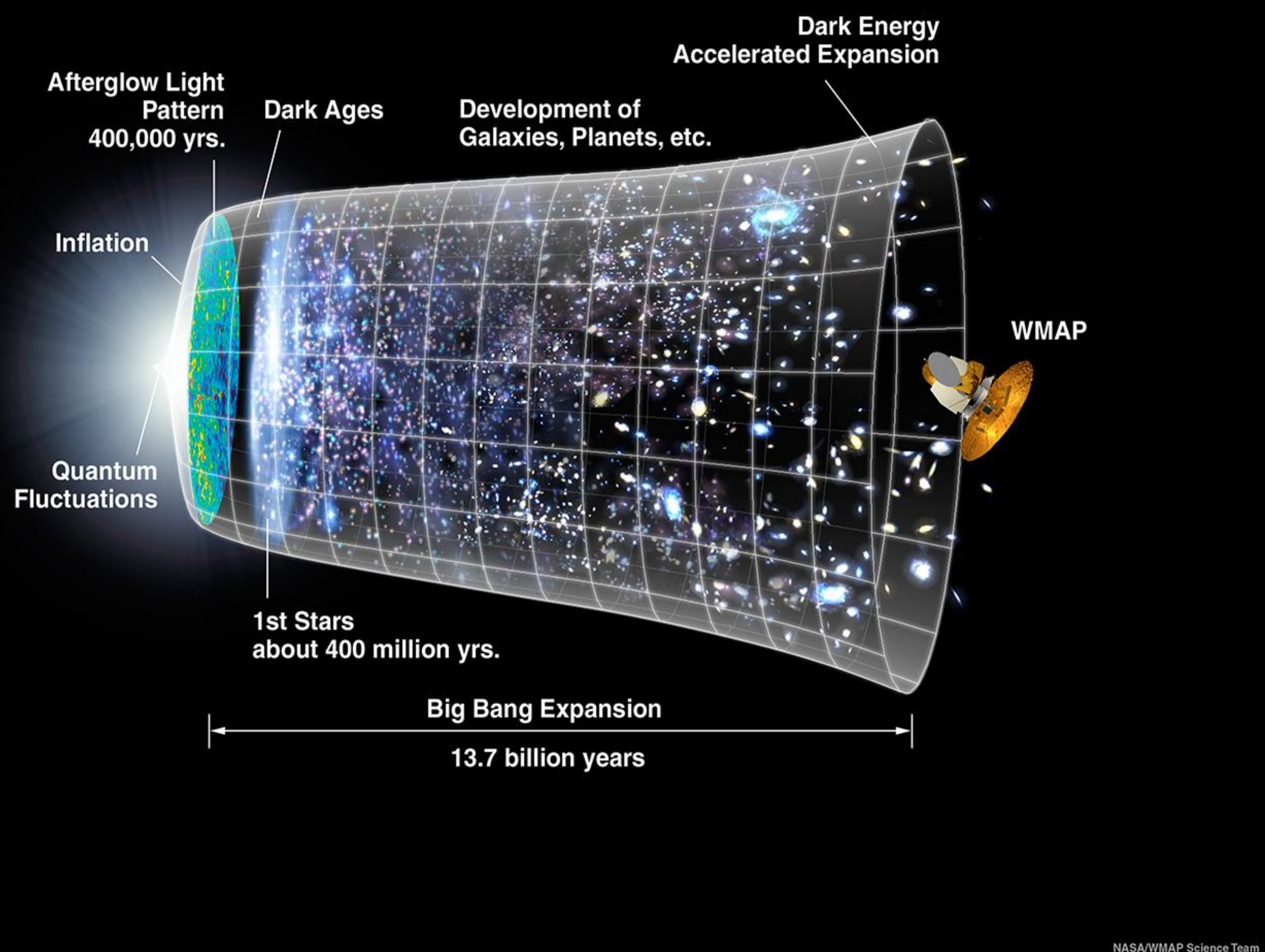
Gravitational waves from the Big Bang



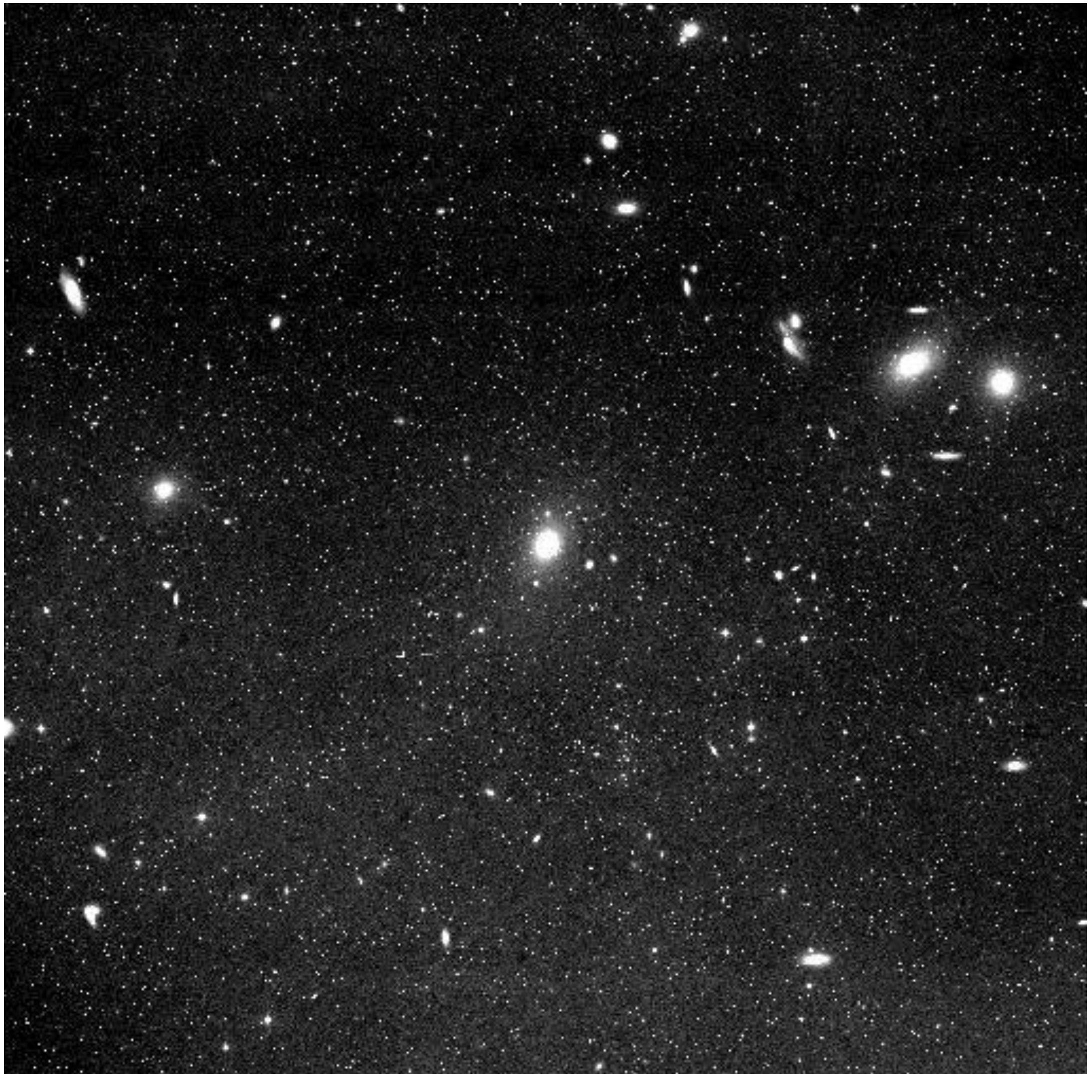
- GW-Amplitude $h \sim \sqrt{\Omega_{GW}}$

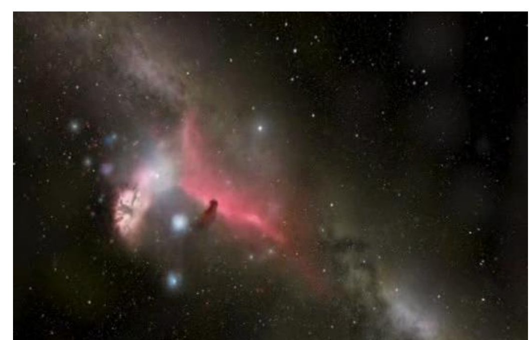
credit: LIGO

Gravitational Wave Symphony



Virgo-Galaxienhaufen: 50 Millionen Lichtjahre





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- unique science cases
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THANKS FOR YOUR ATTENTION