# Observational evidence of gravitational collapse of a hyper-massive neutron star post-merger to GW170817


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http://web.science.uu.nl/itf/Seminars/NvKampenColloquium.htm

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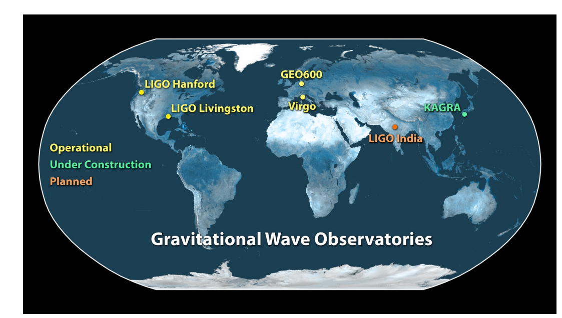
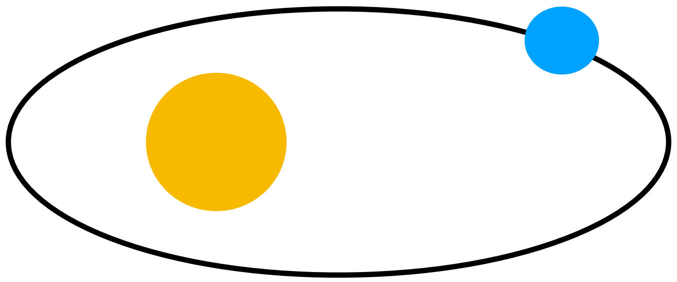



**Conclusions and Outlook**

# Binary motion

Gravitational force



Kepler's elliptical orbits: closed

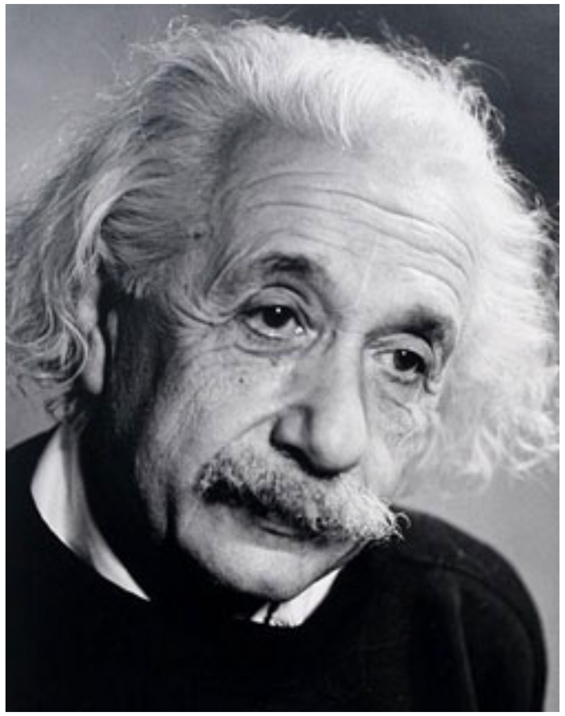
harmonic in 1/r

$$F_N = -\frac{Gm_1m_2}{r^2}\left(r = \left|\bar{r}_1 - \bar{r}_2\right|\right)$$

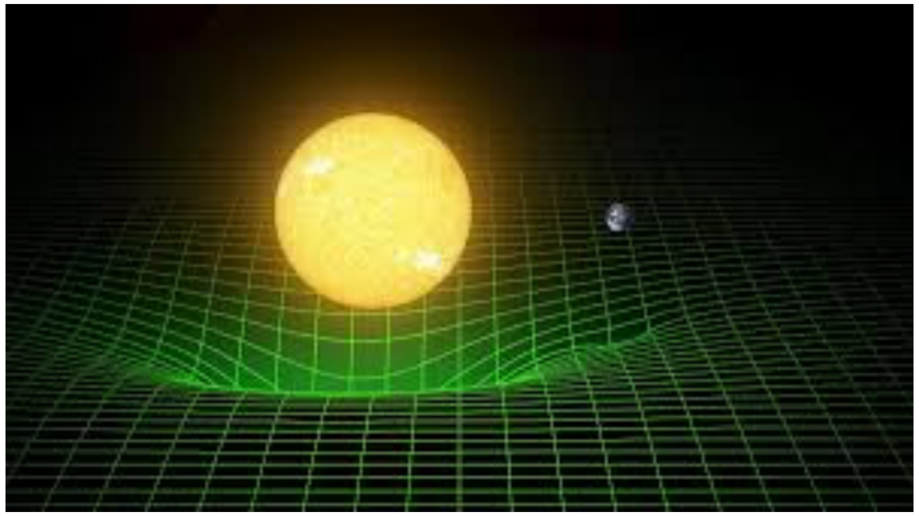
given Newton's constant G.

Works well for Earth's and all other planetary orbits except Mercury, closest to the Sun

# Spacetime curvature



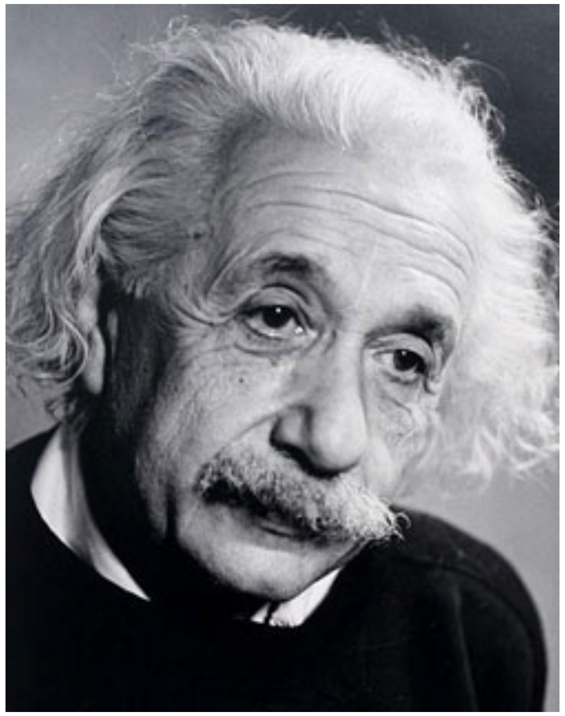
Motion in curved geometry



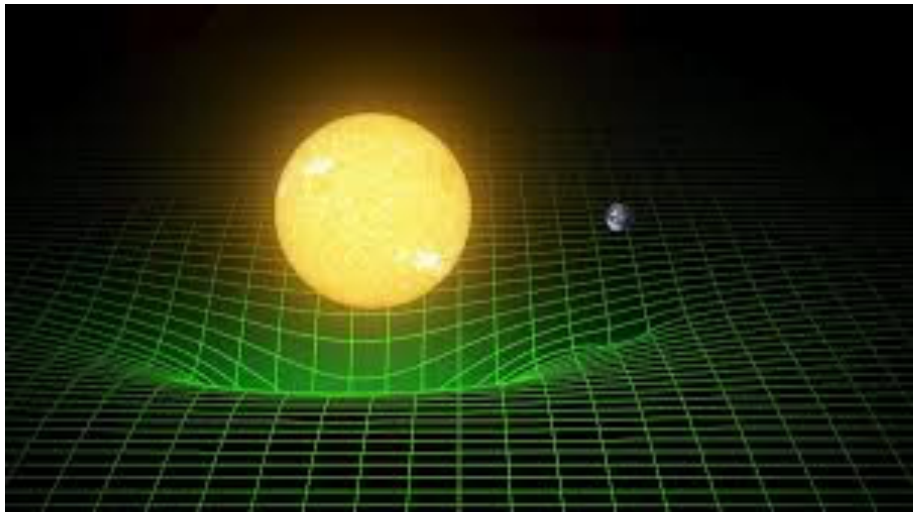
$$R_g = \frac{GM}{c^2} = 1.5\times 10^5 \left( \frac{GM_\odot}{c^2} \right) \mathrm{cm}$$

Deviation set by gravitational radius of the Sun.

# Binary motion by curvature



New small parameter:

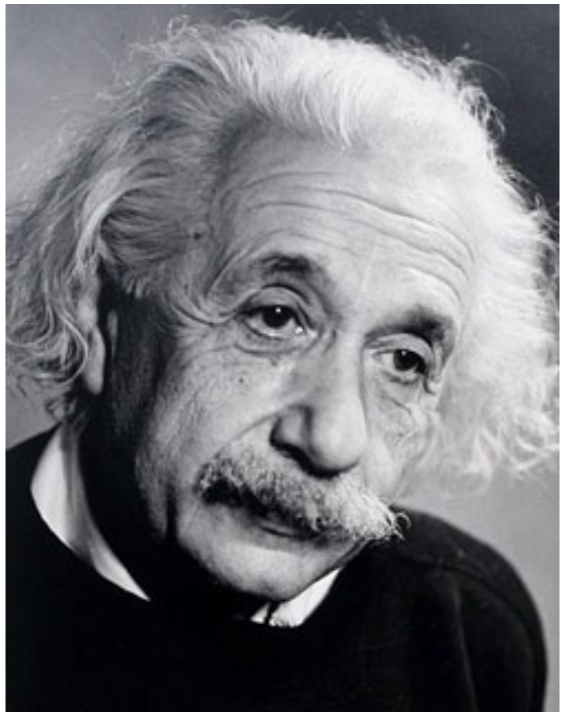


$$\epsilon = \frac{R_g}{r} = 2.5 \times 10^{-8}$$ *Mercury*

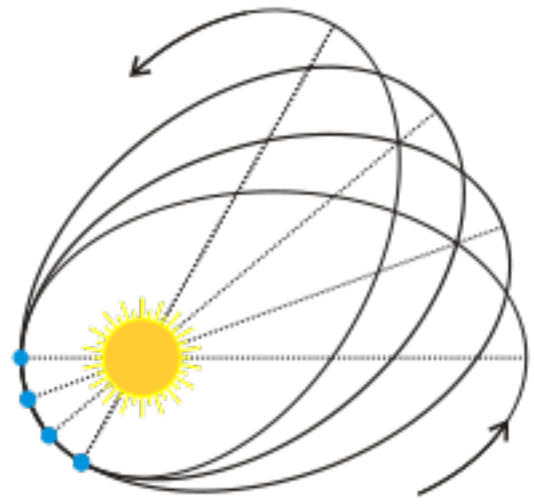
$$1.4 \times 10^{-8}$$ *Venus*

$$10^{-8}$$ *Earth*

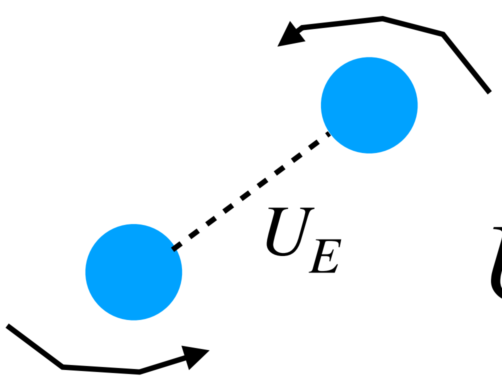
# Anharmonic binary motion



Einstein's gravitational binding energy

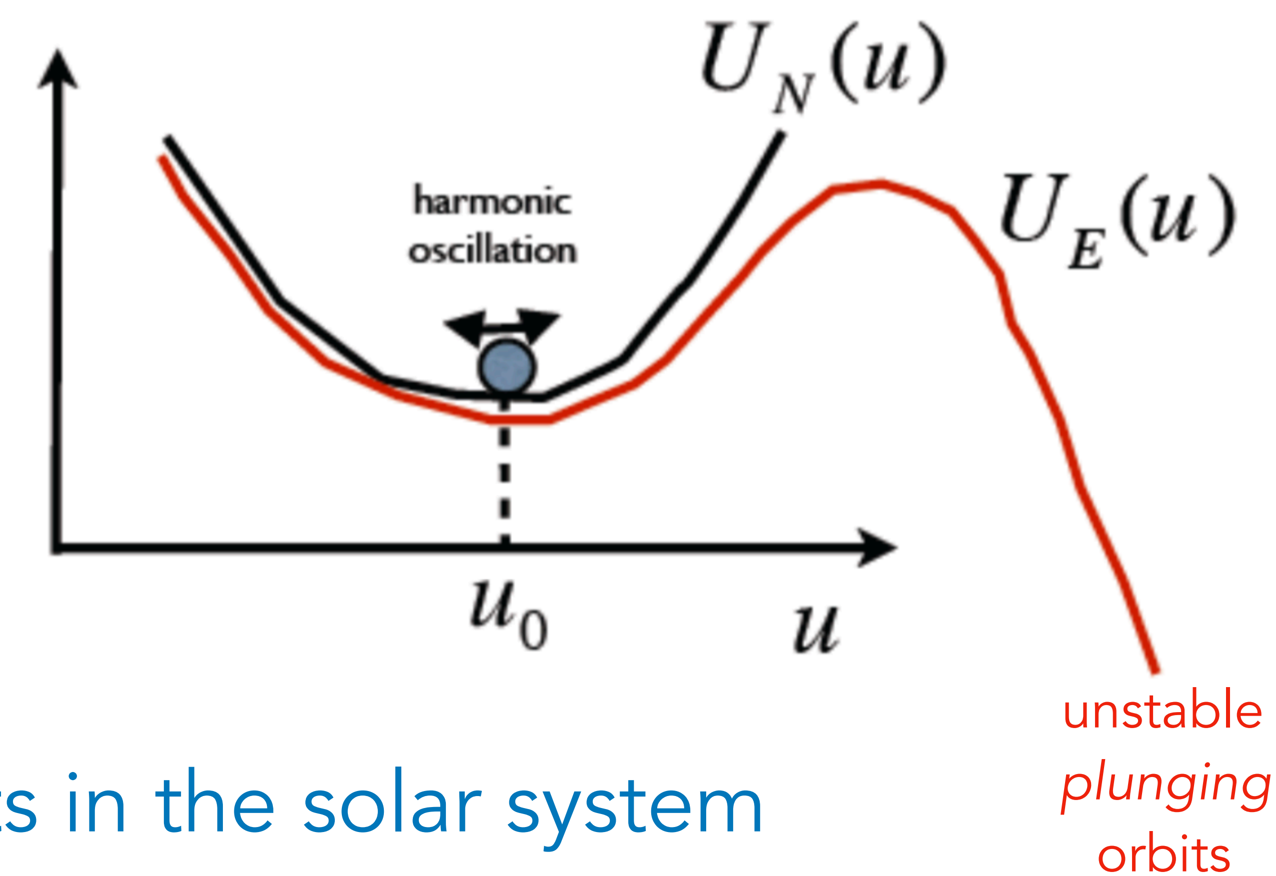


Mercury's orbit: open

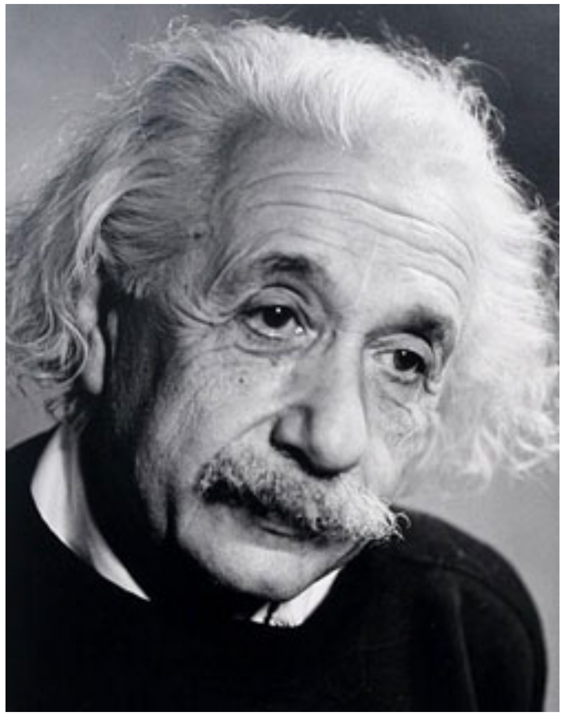



$$U_E = U_N - R_g u^3$$

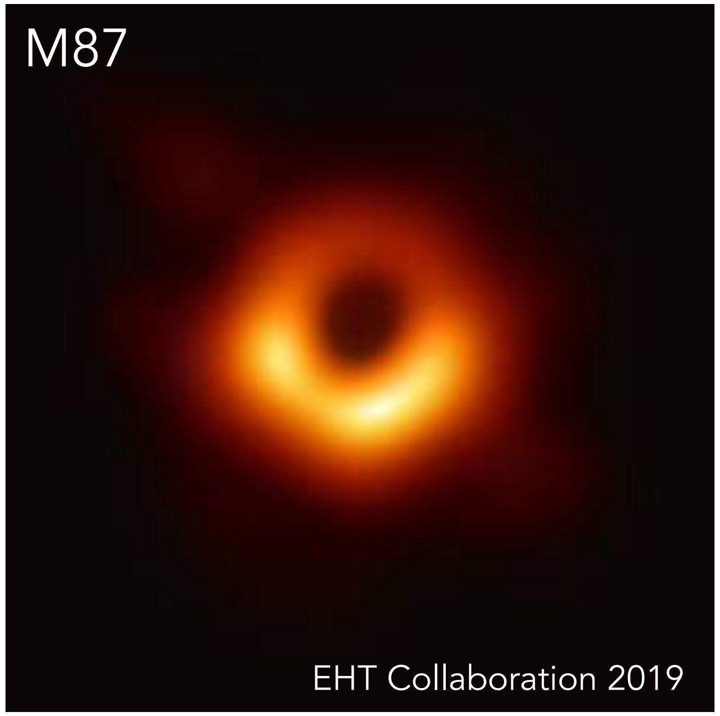
$$\left(u = r^{-1}\right)$$




Perfect, for *all* planets in the solar system



Covariant embedding of binding energy in the Einstein equations ($G$,$c$):




$$\text{Spacetime curvature } = 8\pi\frac{G}{c^4} \times \text{ stress-energy of matter}$$

Predicts black holes, dynamical spacetimes …

# Gravitational radiation

*GWs sourced by a rotating tidal field:*

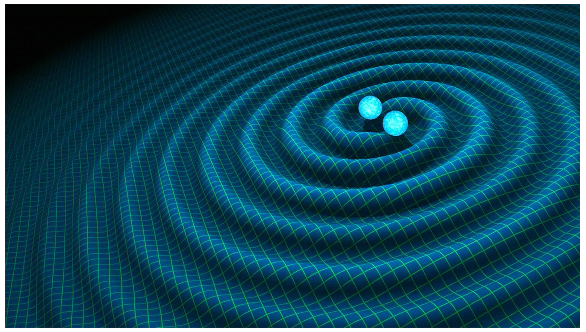
Wobble in spacetime


www.ligo.caltech.edu, exaggerated_effects_of_gravitational_waves_on_earth.mp4

$$\Omega = 2\Omega_b$$

(spin-2: π symmetry in tidal field)

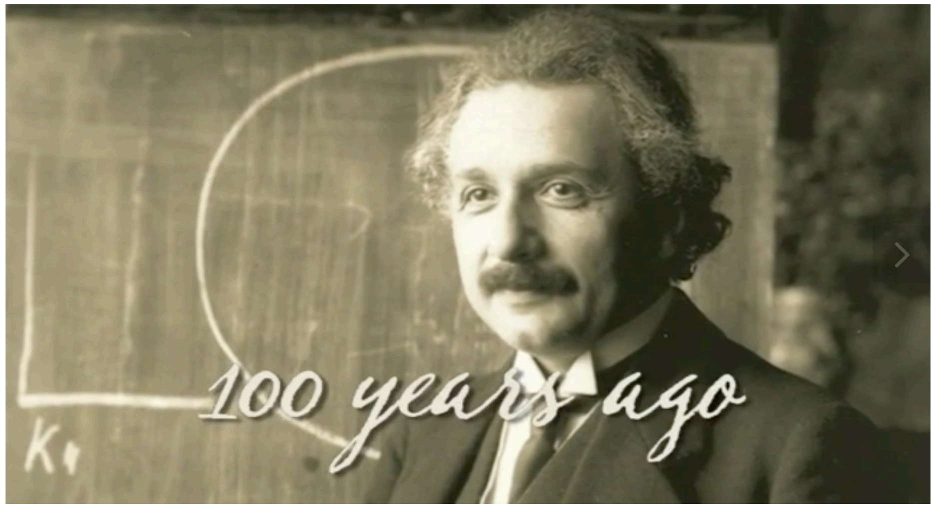
$$\omega = R_g \Omega$$



$$L_{gw} \sim \epsilon^2 \omega^2$$

Visual effect amplified by about $10^{22}$

# Unit of GW-luminosity




Dimensional analysis by c and G:

$$L_0 = \frac{c^5}{G} = 3.64 \times 10^{59}\,\mathbf{erg/s},$$

General relativity

Conveniently expressed in geometrical units ($G$ =1, $c$ =1)

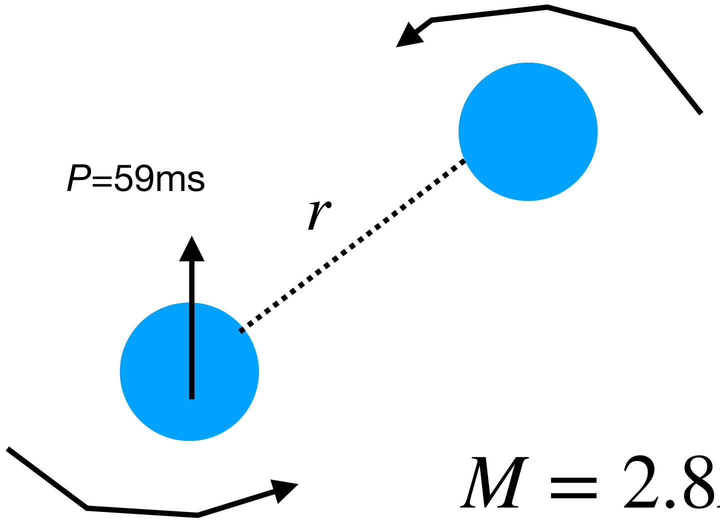
$$L_0 = \left(\frac{c}{R_{g,\odot}}\right) M_\odot c^2 \simeq 200{,}000\, M_\odot c^2 \mathbf{s}^{-1}$$

In geometrical units (c=G=1):

$$L_0 = 1$$

# Arecibo: ‘Goldeneye’ of radioastronomy

# *First*, a whisper: Hulse-Taylor binary neutron star system PSR 1913+16




$$1.07 \le \frac{r}{R_\odot} \le 4.53$$

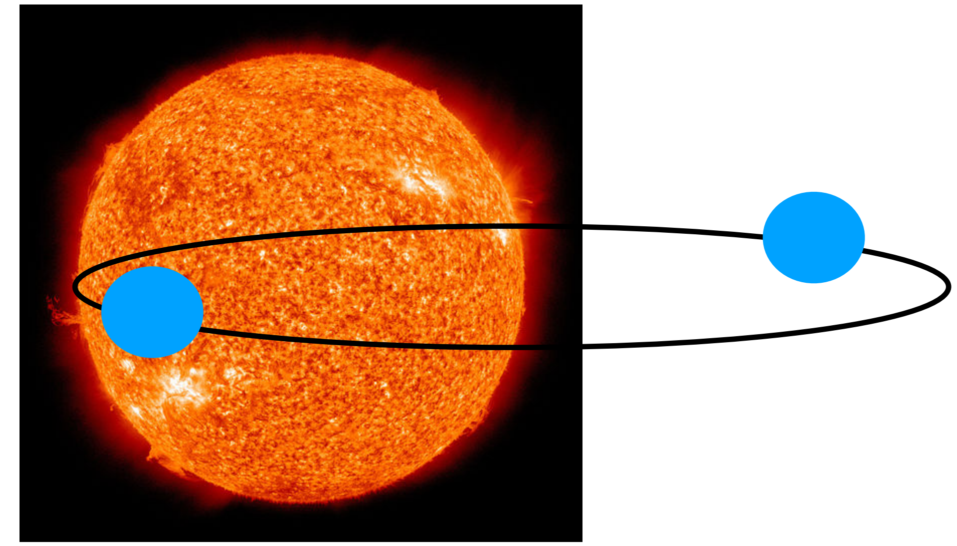
Periastron                Apastron

$$M = 2.8 M_\odot, P_{orb} = 7.75\textbf{hr}$$

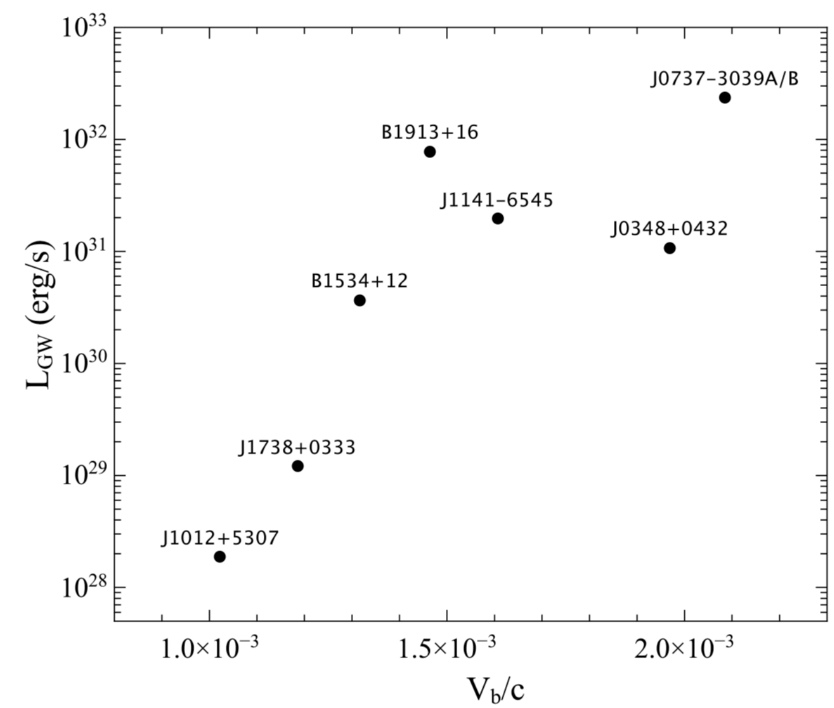
$$L_{gw} \simeq 2\,\%\,L_\odot \simeq 2 \times 10^{-28} L_0$$

Enhanced significantly by ellipticity over circular case

$$L_\odot = 3.838 \times 10^{26}\textbf{W}$$



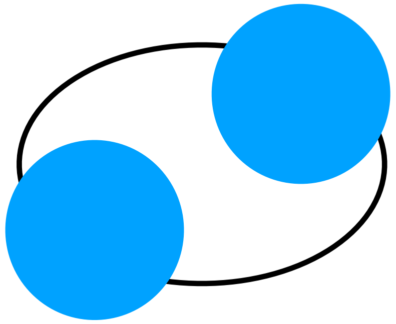
Periastron advance: 4.2 deg/yr



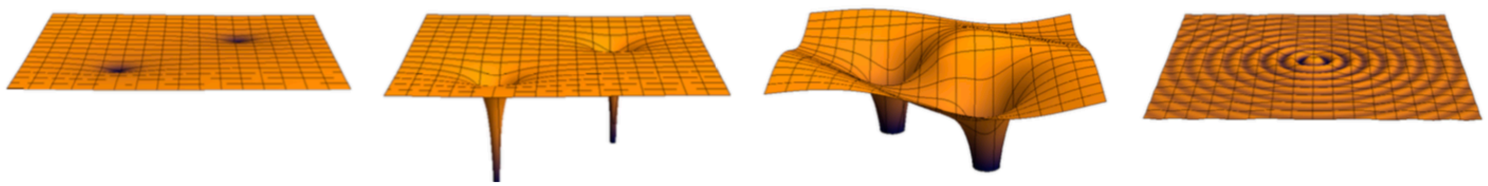

Wex, N., arXiv:1402.5594 (2014)

**Orbital evolution: indirect calorimetry on GWs**

# Binary coalescence



## Merging sequence of coalescence:



Wex, N., arXiv:1402.5594 (2014)

## Close to coalescence:

Orbital semi-major axis *a* = 100 km:

$$h_{iso} = \frac{L_{gw}^{\frac{1}{2}}}{\Omega_b D} \simeq 2 \times 10^{-23}$$

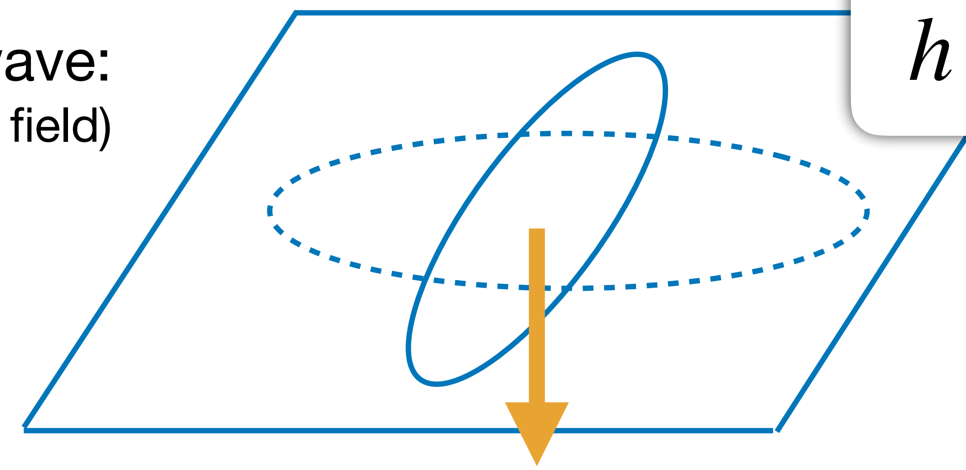
at source distance *D* = 100 Mpc

(1 pc = $3 \times 10^{18}$**cm** $\simeq 3$ **lyr**)

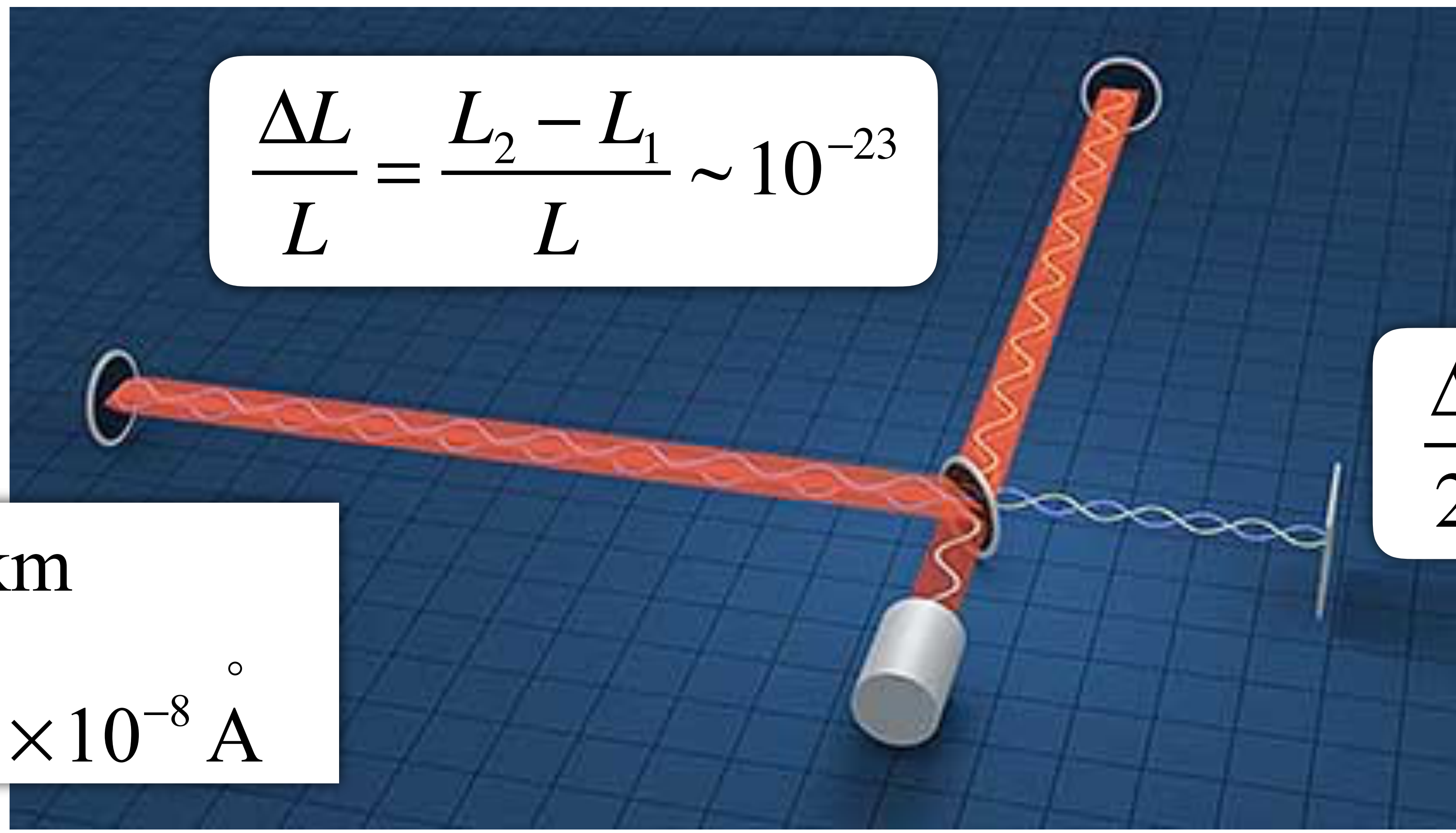
Time-to-coalescence: $t_c = \frac{5a^4}{256 M_1 M_2 M}$ : $t_c \simeq 1\mathbf{s} \left(\frac{a}{100\mathbf{km}}\right)^4$

# LIGO: capturing whispers in spacetime by laser interferometry

Spin-2 GW wave:
(e.g. sourced by a tidal field)



$$h \sim 10^{-23}$$



$$\frac{\Delta L}{L} = \frac{L_2 - L_1}{L} \sim 10^{-23}$$

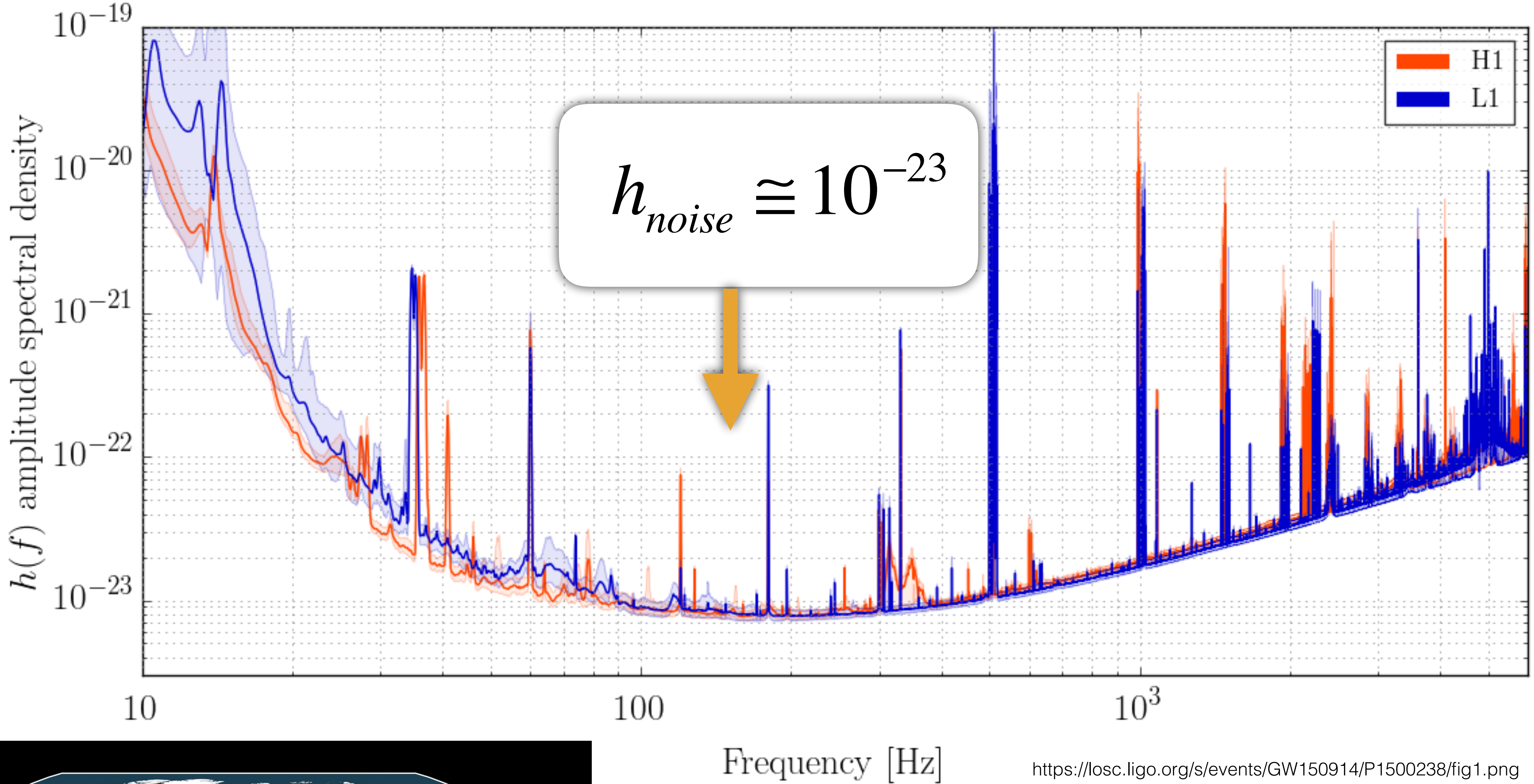
$$\frac{\Delta\varphi}{2\pi} = \frac{\Delta L}{\lambda} \sim 10^{-7}$$

$$L = 4\ \text{km}$$

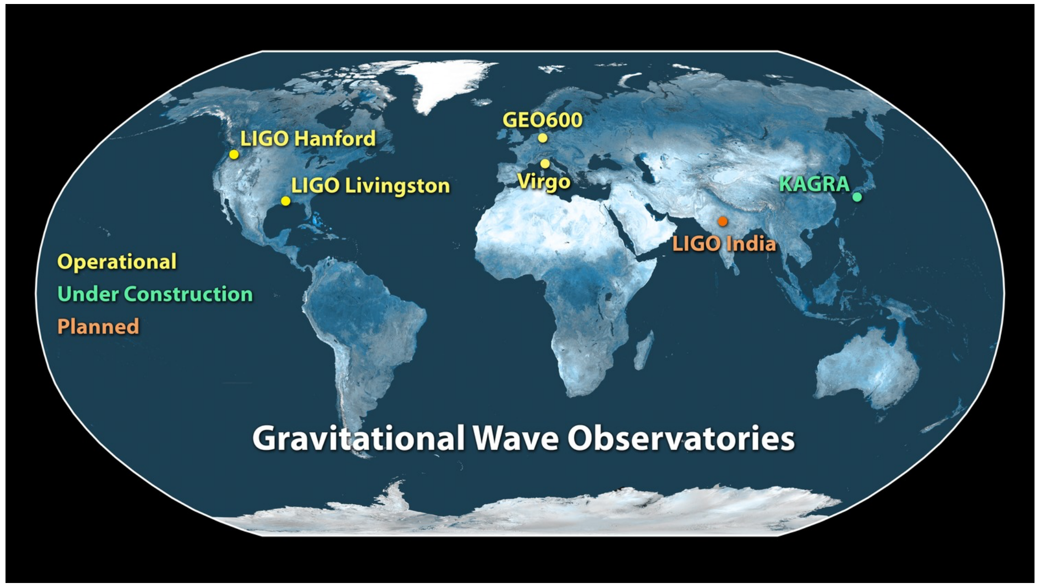
$$\Delta L \sim 4 \times 10^{-8}\ \mathring{A}$$

Many photons, advanced mirrors, seismic suspension, integrate over many wave periods, ⋯ , data-analysis, ⋯

# LIGO detector performance (Observational run O2)



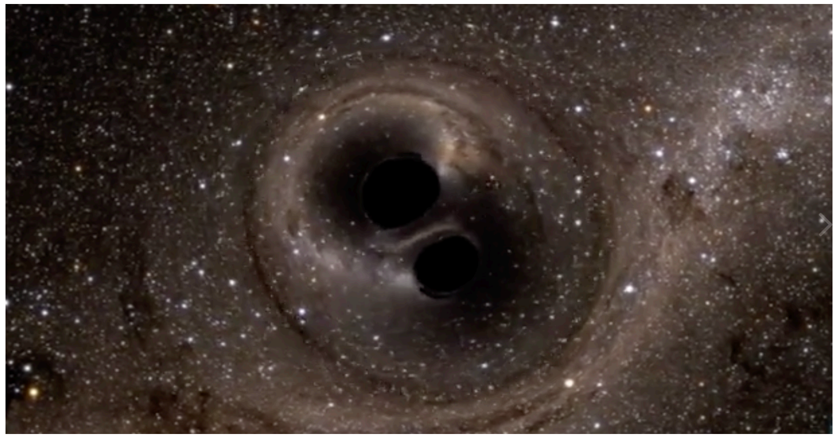

https://losc.ligo.org/s/events/GW150914/P1500238/fig1.png

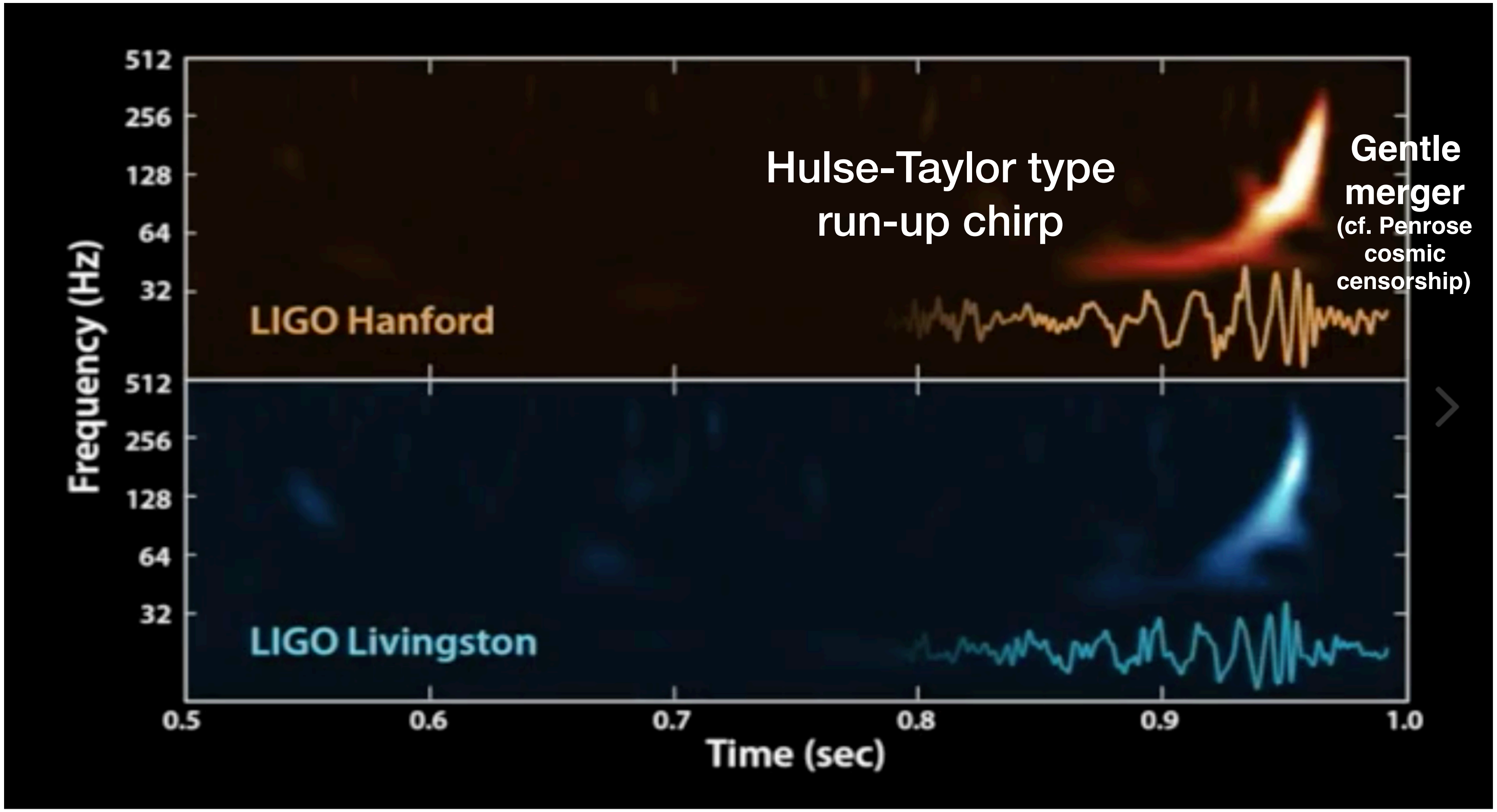



## LIGO-Virgo and KAGRA

Abbott, B.P., et al. 2017, arXiv:1304.0670

Akutsu et al., 2017, arXiv:1710.0423






$$E_{GW} \cong 3M_{\odot}c^2, L_{GW} \cong 200\ M_{\odot}c^2\mathrm{s}^{-1} \cong 0.1\% L_0$$

# A new window:

PRL **116,** 061102 (2016) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

**Observation of Gravitational Waves from a Binary Black Hole Merger**

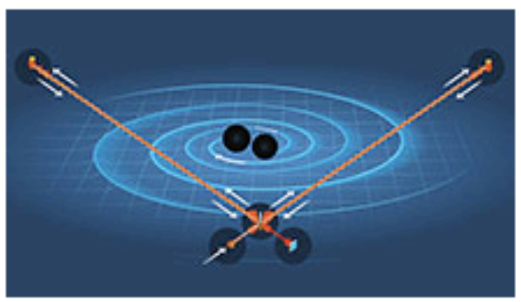
B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

> 1000 authors

## 2017 Physics Prize



© Johan Jarnestad/The Royal Swedish Academy of Sciences

### 2017 Nobel Prize in Physics

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves".*

→ More about the 2017 Physics Prize

Rainer Weiss. © Nobel Media. Ill. N. Elmehed

### "Space is enormously stiff. You can't squish it."

Rainer Weiss explains why measuring the effect of gravitational waves is so very hard to achieve.

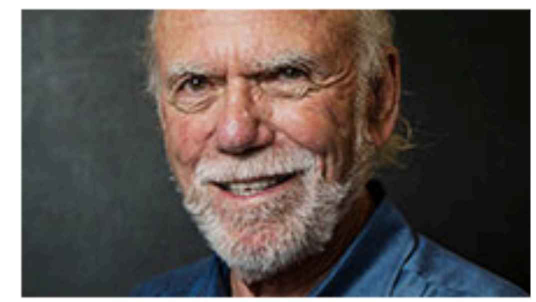
→ Interview with Rainer Weiss

Kip S. Thorne. © Nobel Media. Ill. N. Elmehed

### "Huge discoveries are really the result of giant collaborations"

Kip S. Thorne on how this year's Nobel Prize in Physics was a remarkable team effort.

→ Read or listen to the interview



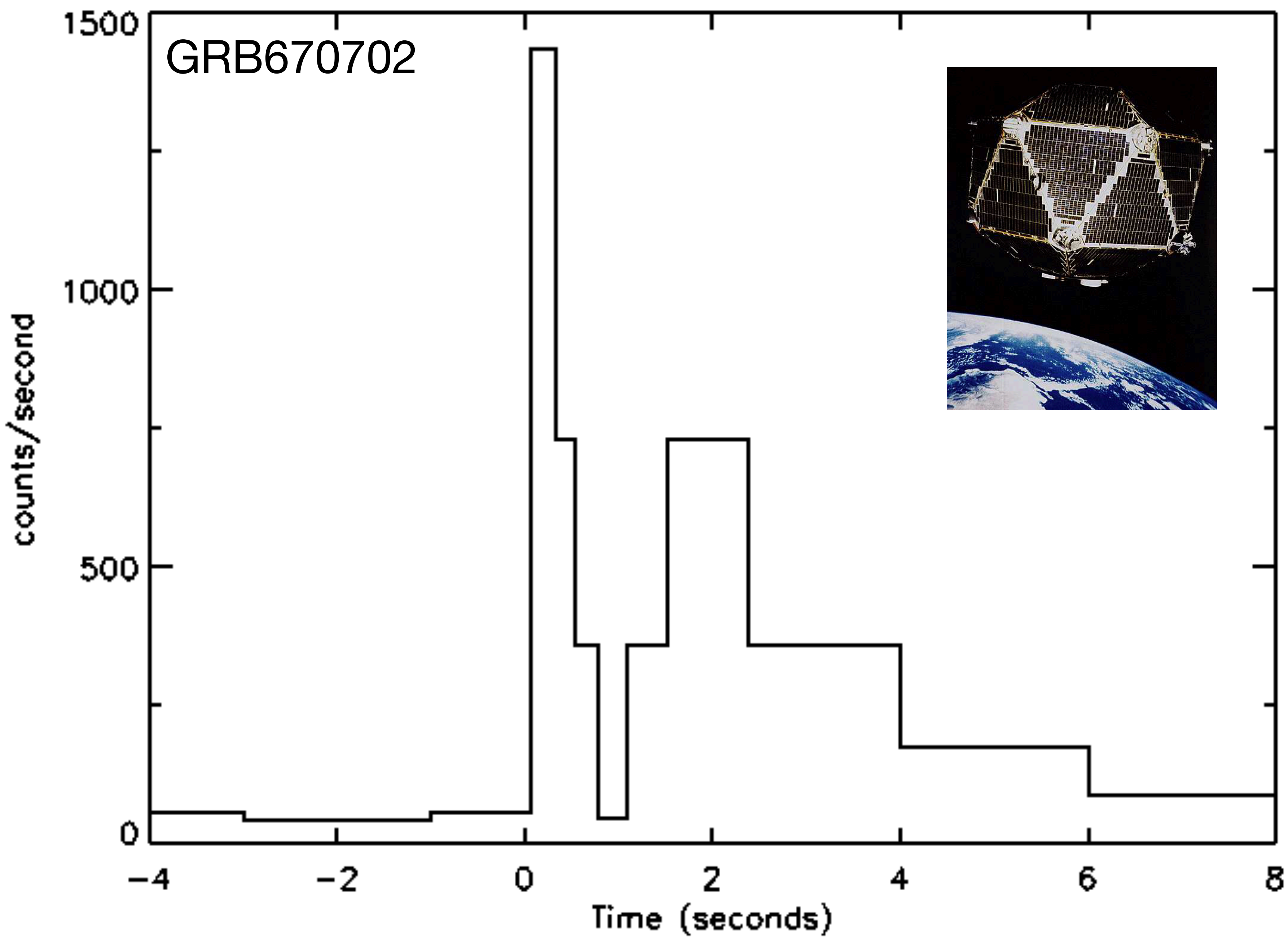
Barry C. Barish © Nobel Media. Ill. N. Elmehed

### "The actual size of the signal was about one thousandth the size of a proton!"

Barry C. Barish about the LIGO detector in a short interview after the announcement.

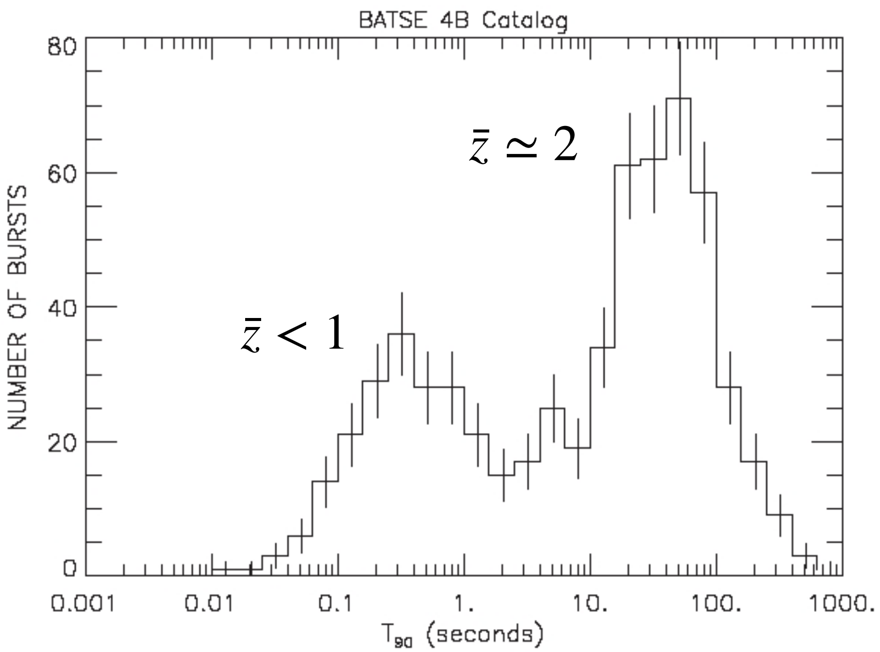
→ Interview with Barry C. Barish

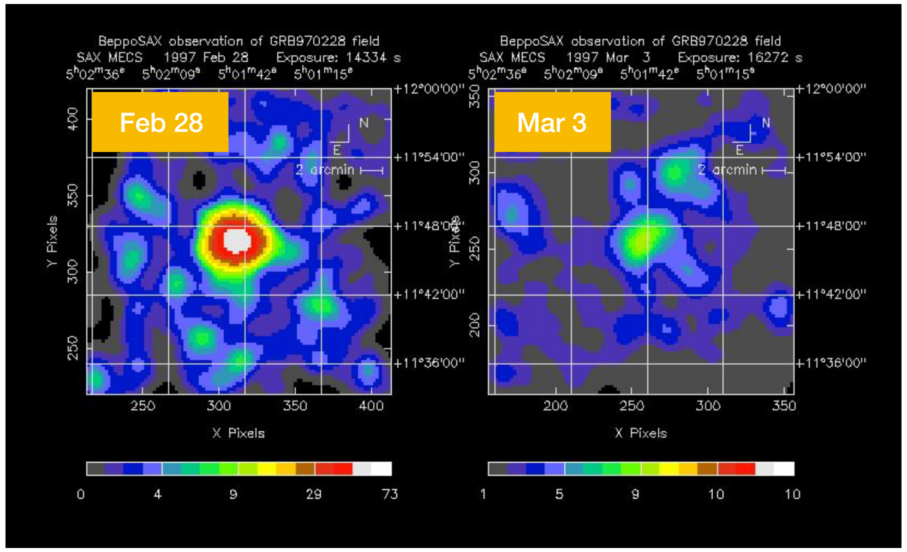
# Serendipitous discovery of gamma-ray bursts




Klebasadel, Strong & Olson (1973)

# GRBs: status overview




X-ray afterglow to GRB970228

$(T_{90} = 69\mathbf{s})$

$z = 0.695$

| | long | short |
|---|---|---|
| Mean cosmological redshift | $z \simeq 2$ ★ | $z < 1$ |
| Host galaxy | Spiral | Elliptical |
| Progenitor | Massive star | Compact binary coalescence |
| Central engine | NS/BH? | NS/BH? |

★ *Around max cosmic star formation rate*

# Magnetically launched relativistic jets from NS or BH?

Extreme $L_\gamma$ in magnetically launched jets from intermittent engines - lifetime of activity set by lifetime of spin?

(cf. O'Dea 2002)

Intermittent central engine with energy reservoir $E_J$

(van Putten, 2015)

*Accreting BH-disk system?*

Blandford-Zjanek 1977

Blandford & Payne 1982 …

*Strongly magnetized NS (Magnetar)?*

Usov 1982

Duncan & Thompson 1992 …

Observed model prediction:

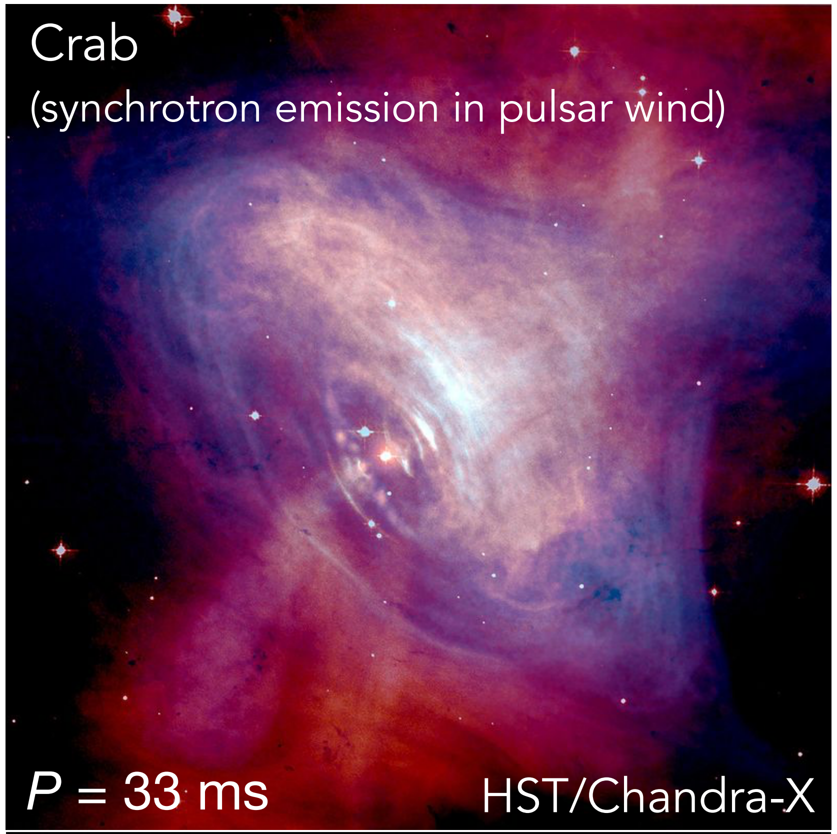
Energy output ~ photon peak energy x duration$^{1/2}$

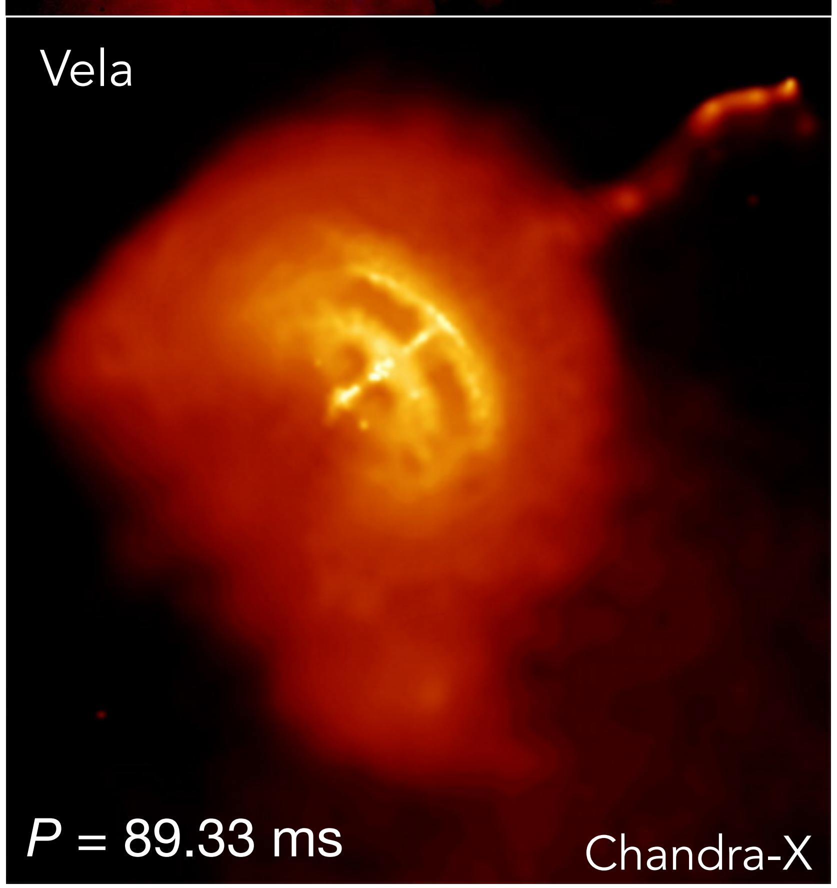
van Putten et al., 2008
Shahmoradi & Nemiroff 2014

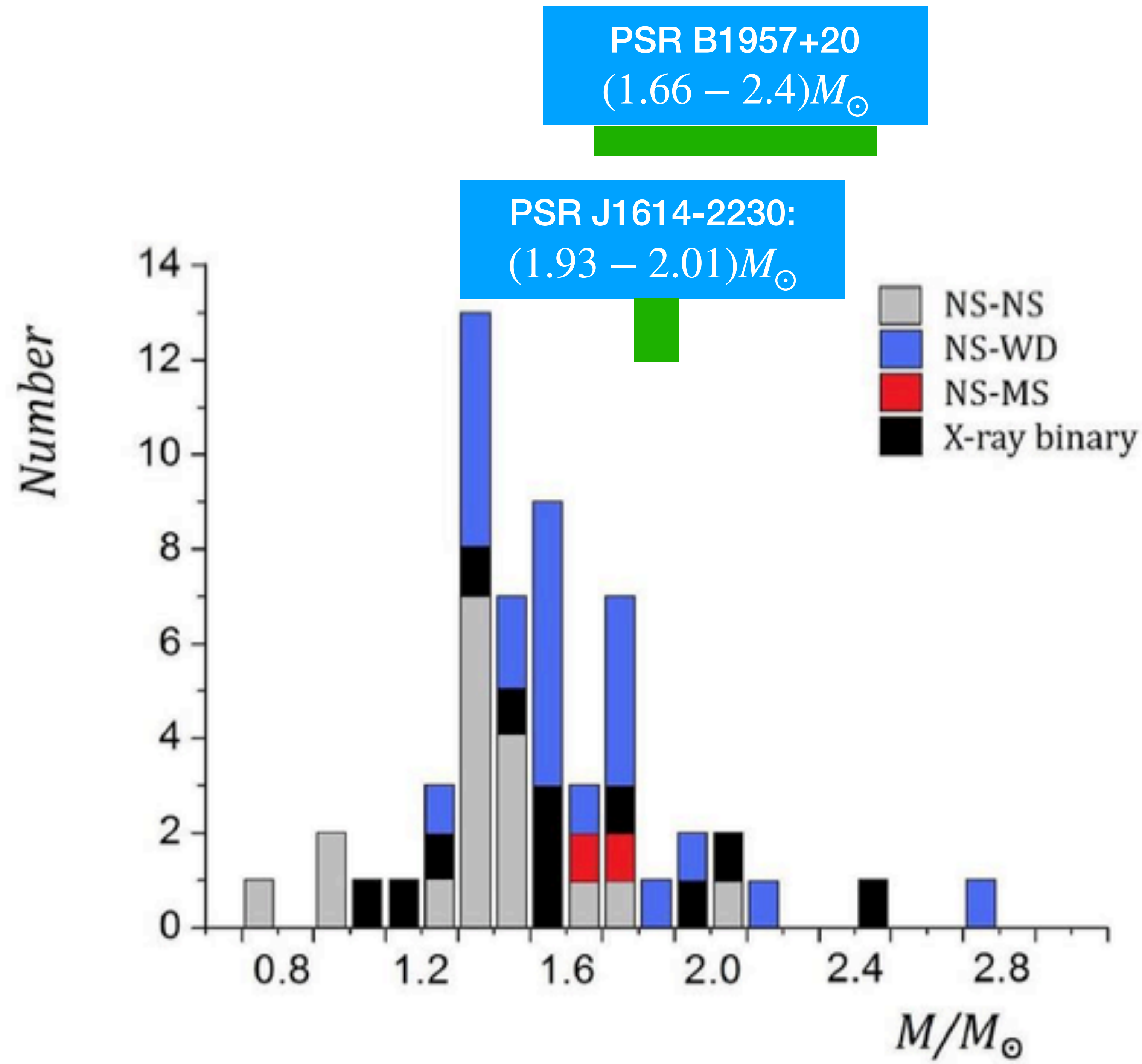
*"These arguments led to the conclusion that the birth of a magnetar is competing with BH as being source of the GRB power (the so-called "central engine")."* Bernardini, G.B., 2015

# Remnants of massive stars: NS

*Discovered as radio pulsars by Jocelyn Bell, Antony Hewish and Martin Ryle:*




In Handbook of Supernovae, edited by Athem W. Alsabti and Paul Murdin; arXiv:1607.0698v1

# Remnants of massive stars: NS or BH?

## Conventional approaches:

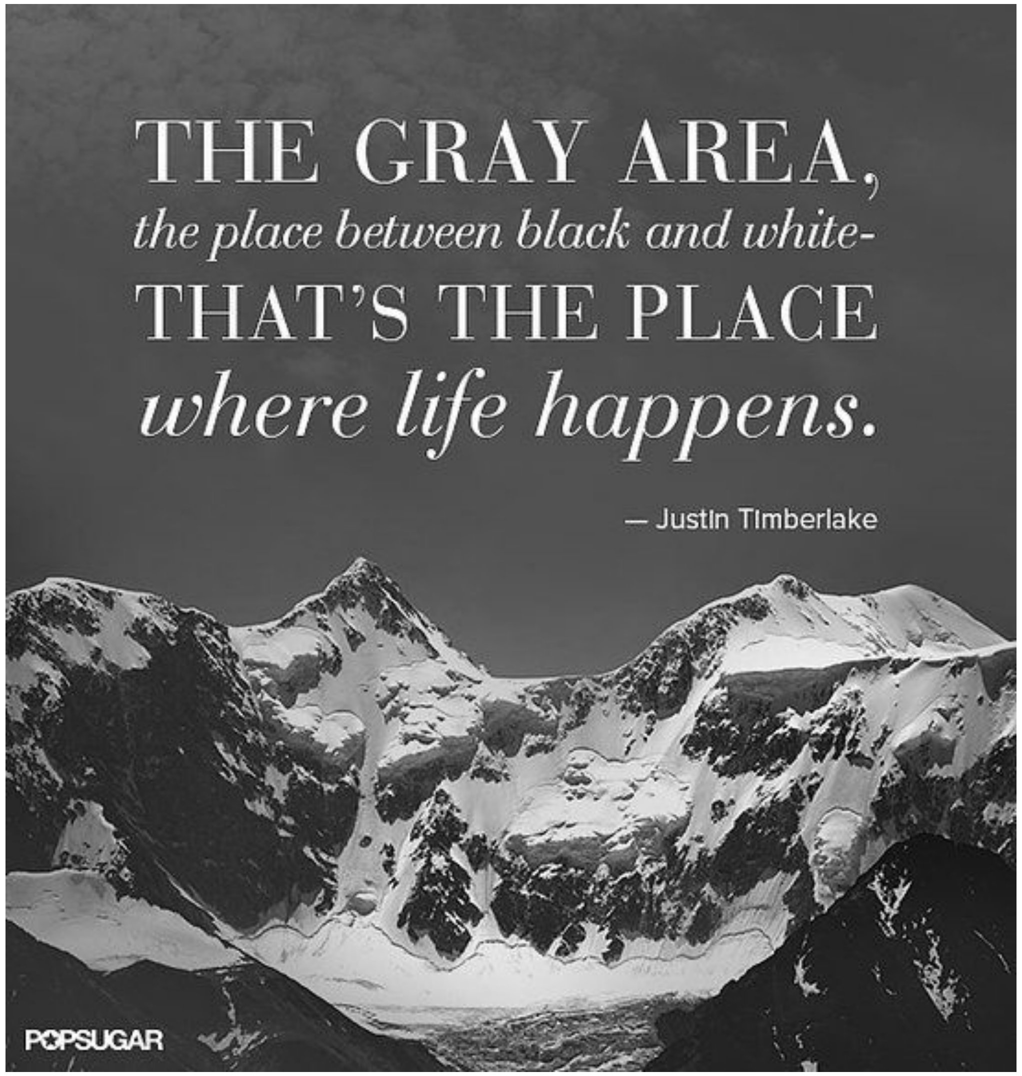
*By mass:*

$M \gtrsim 3M_\odot$ : **BH**

$2M_\odot \lesssim M \lesssim 3M_\odot$ : **NS or BH**

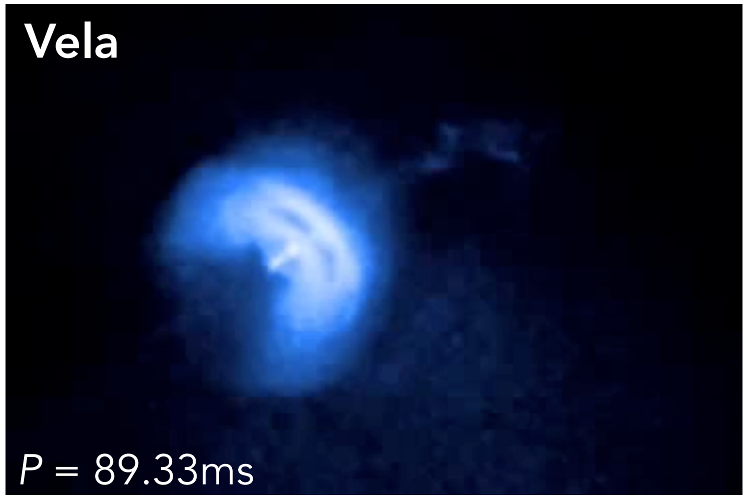
*By radio emission:*

Radio pulsar: **NS**




Limited understanding of the equation of state of neutron star matter and limitations of EM-observations, e.g., SS433, remnant SN1987A, GRB-supernovae

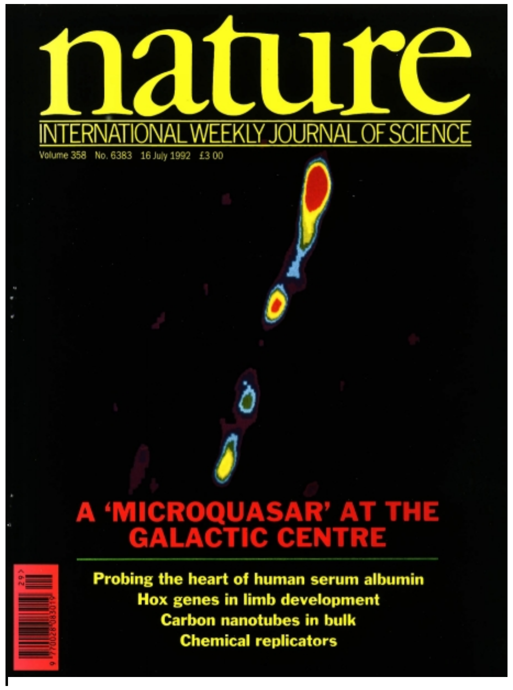
# Beyond mass: Power of spin



Credit: NASA/CXC/Univ of Toronto/M.Durant et al. 2013

**Spin-powered:** neutron star

$$E_J \simeq \frac{1}{5} M R^2 \Omega^2 \leq \frac{GM^2}{5R} \simeq \frac{1}{5} M c^2 \left( \frac{R_g}{R} \right) \lesssim 3\,\%\, M$$

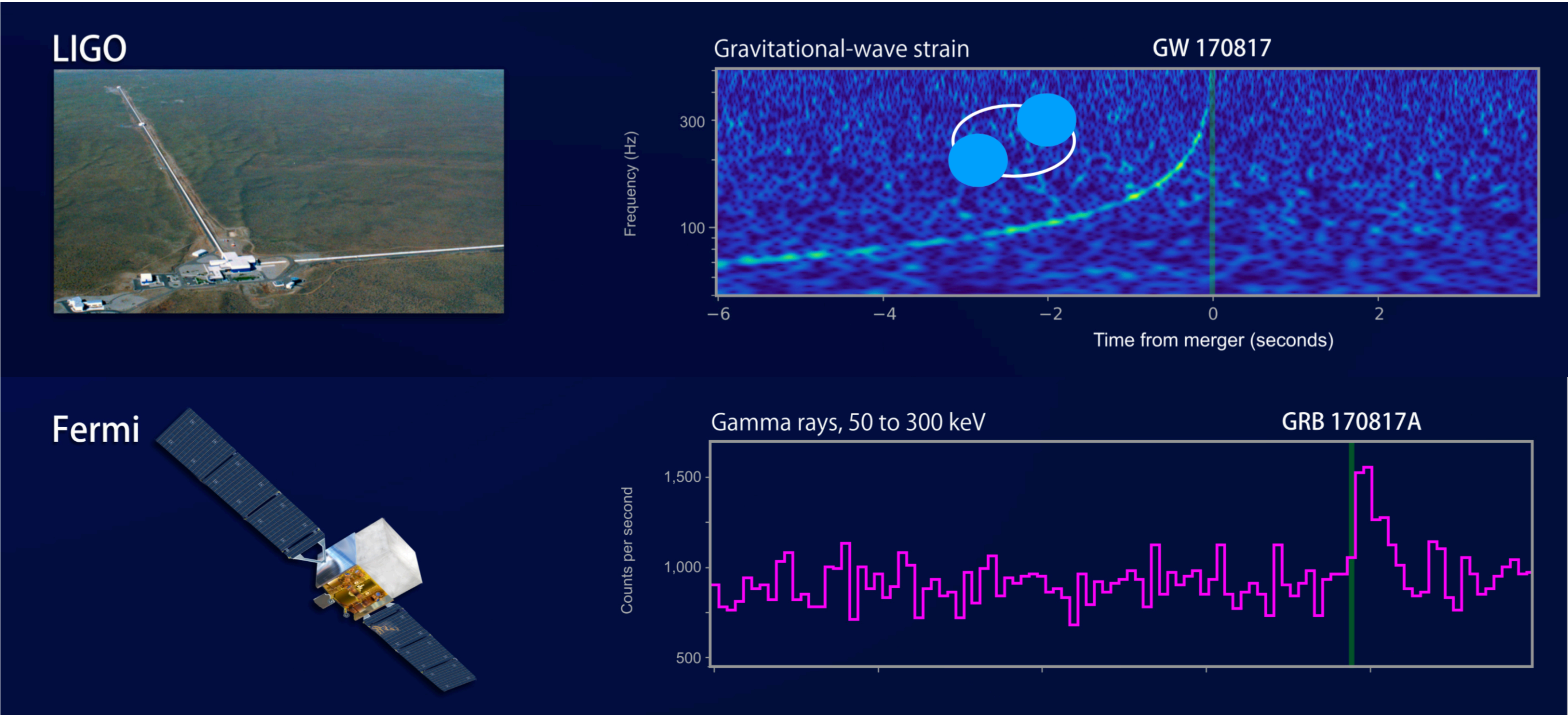


Mirabel & Rodriguez (1994)

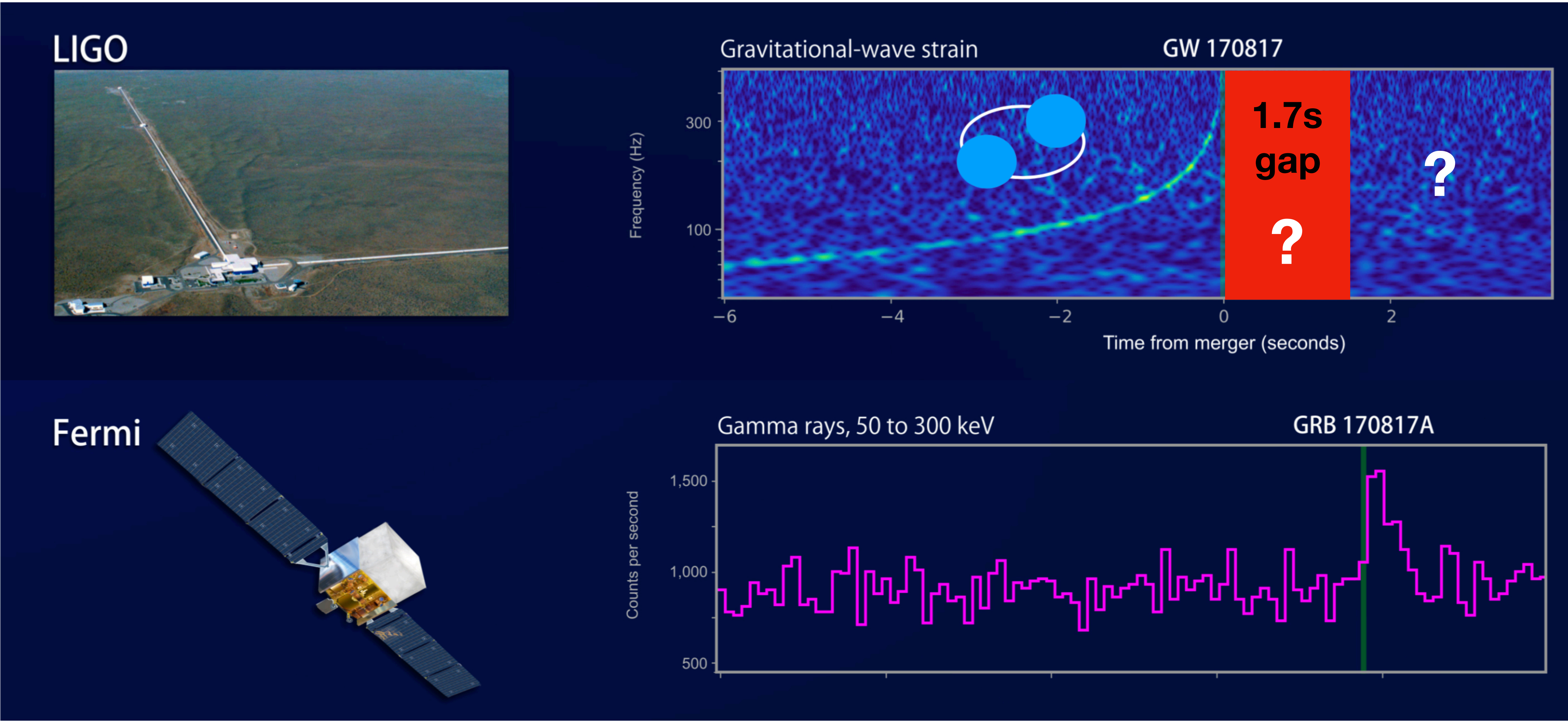
**Spin-powered:** black hole

$$E_{rot}^{max} \lesssim 29\,\%\, M_\odot c^2$$

# GW170817: New multi-messenger event



# GW170817: What happened?



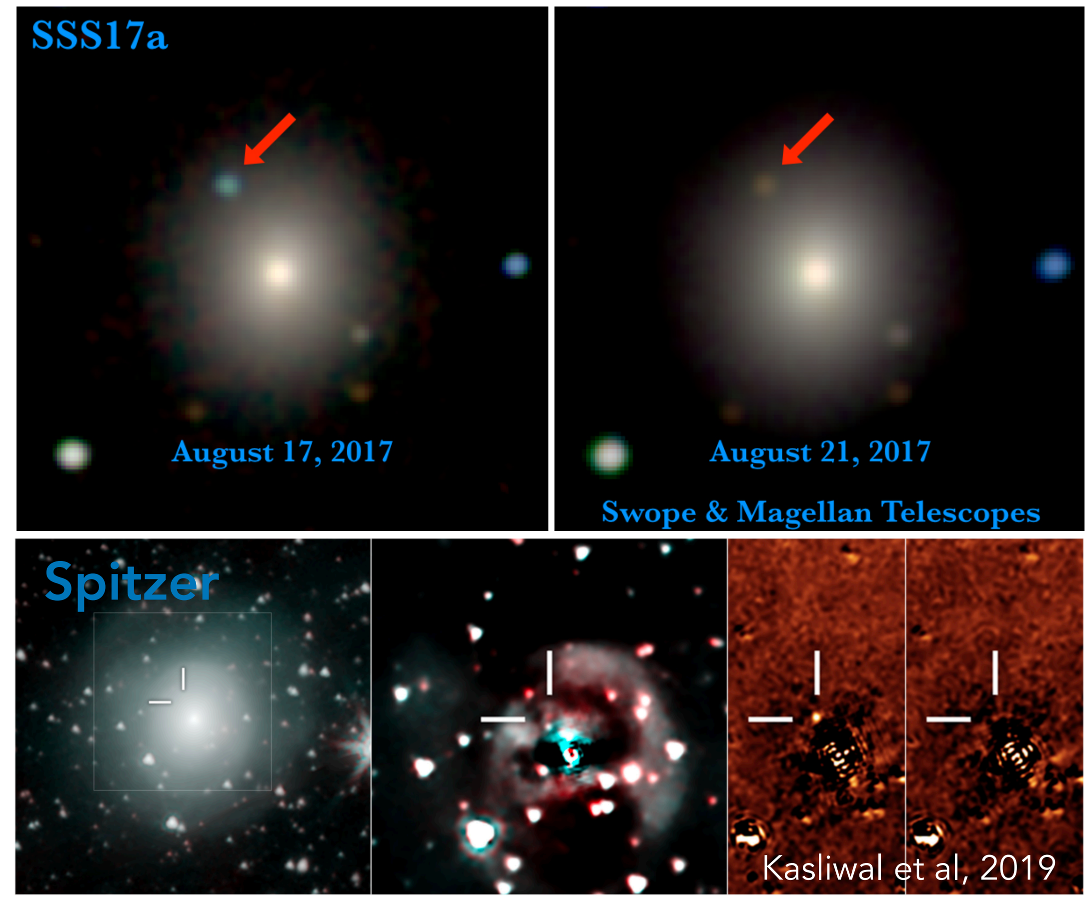

Lifetime hyper-massive NS? NS or BH remnant?

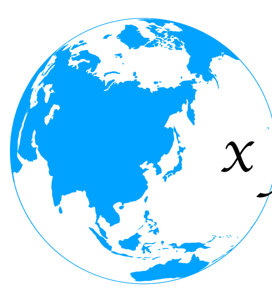
# Cosmic Gold: post-merger kilonova

*Primordial:*
H, He, Li

*Core-collapse SNe:*
~ up to La (slow *n*-capture)

*All else?*
Ejecta from DNS mergers (rapid n-capture)



*x few hundred:*


Smartt et al. 2017

# GW170817: Merging sequence with post-merger calorimetry in EM

NS + NS $\rightarrow$ HNS $\rightarrow$ GRB170817 + kilonova + remnant

$\mathscr{E}_{\rm gw} = 2.25\% M_\odot c^2$

(LIGO 2017)

$E_j \simeq 10^{49-50}$**erg** $E_k \simeq 4.5 \times 10^{51}$**erg**

(Mooley et al. 2019)

Ultra-relativistic jet and baryon-rich disk wind powering GRB170817A and the kilonova

Calorimetry in EM, $\mathscr{E}_{EM} \simeq 0.5\,\%\,M_\odot c^2$, insufficient to constrain remnant

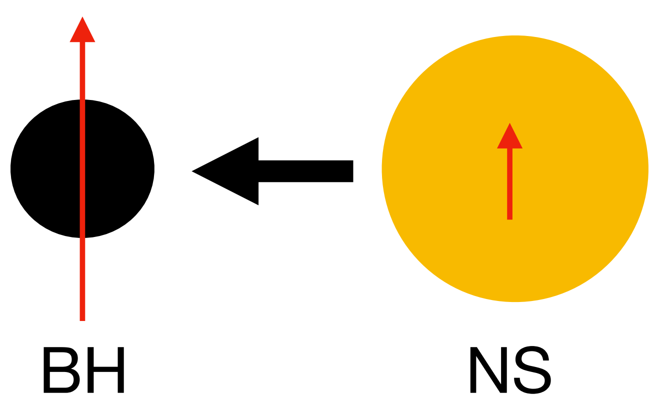
# Ballerina effect in gravitational collapse: “boosting” spin energy

*Ballerina effect*

*“What I do is very difficult.*
*It is very hard on the body.*
*If I am lucky I have a good ten*
*years ahead of me, if I am lucky.”*
Alex Cortes (Big Apple Circus)

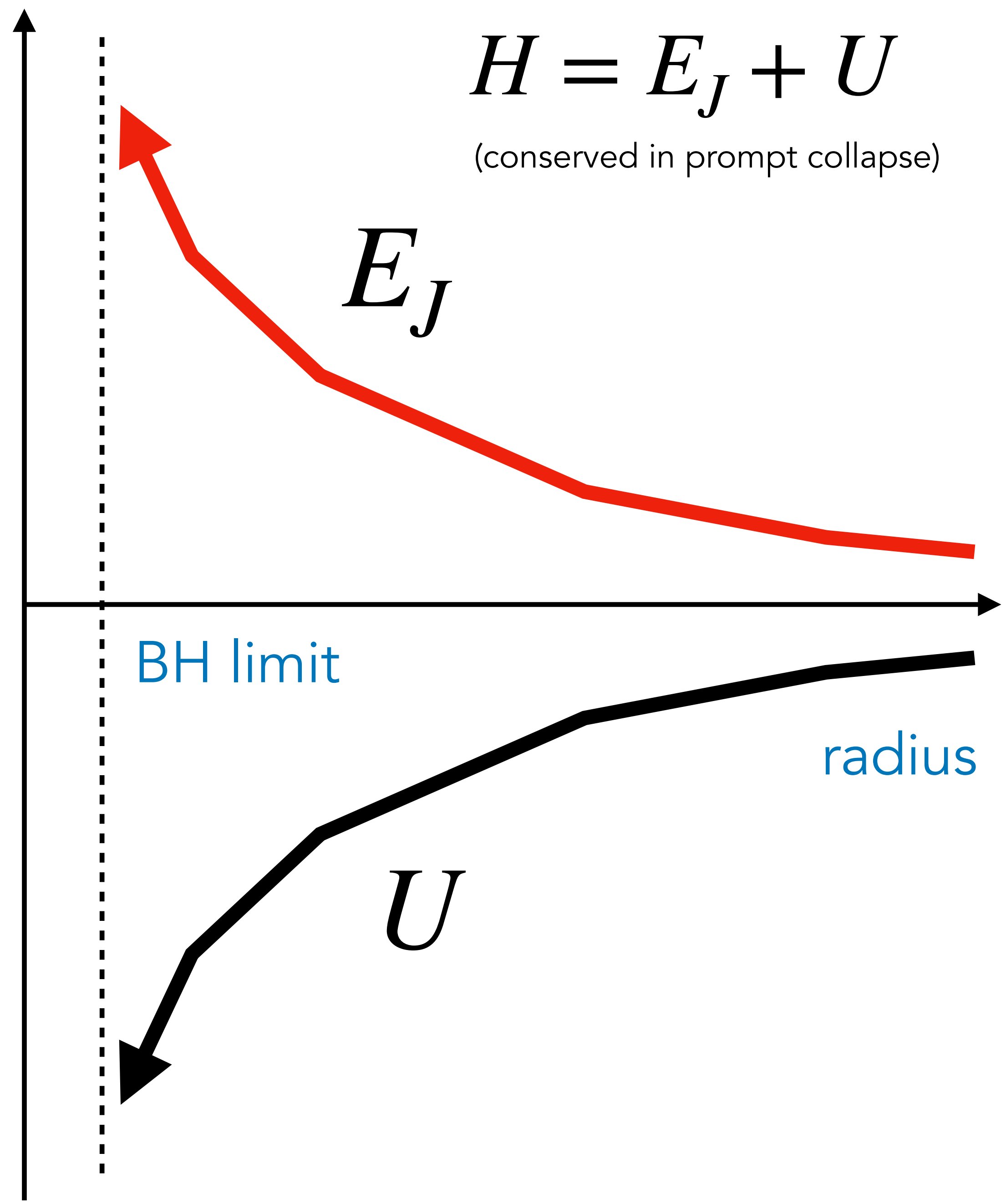
Radial contraction

(self-gravity of the human body is negligible)

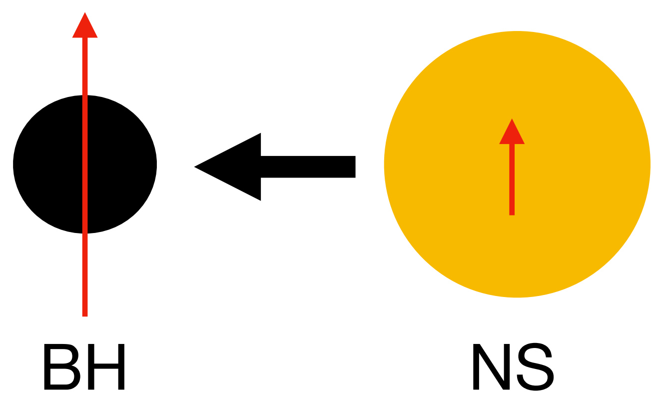



Gravitational collapse

Total energy = spin energy + binding energy



# "Boosting" spin energy in prompt collapse to a Kerr BH

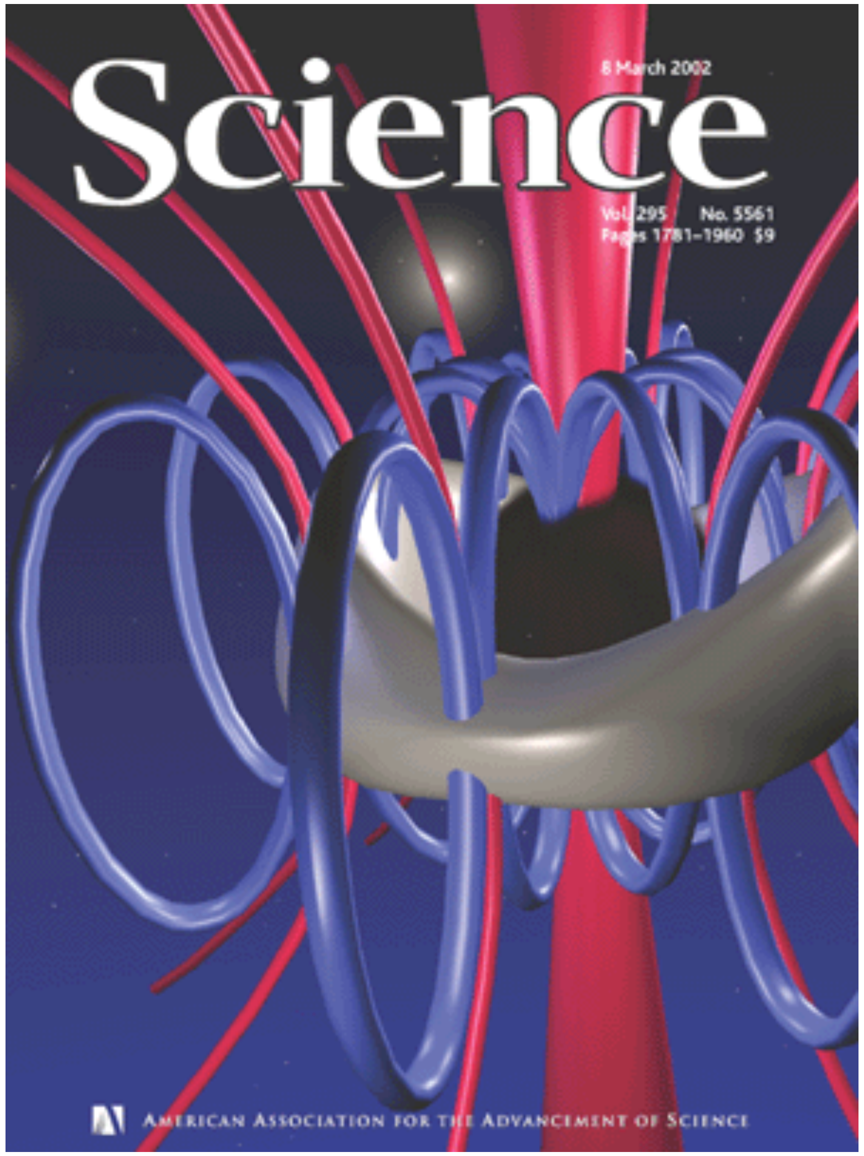



Gravitational collapse

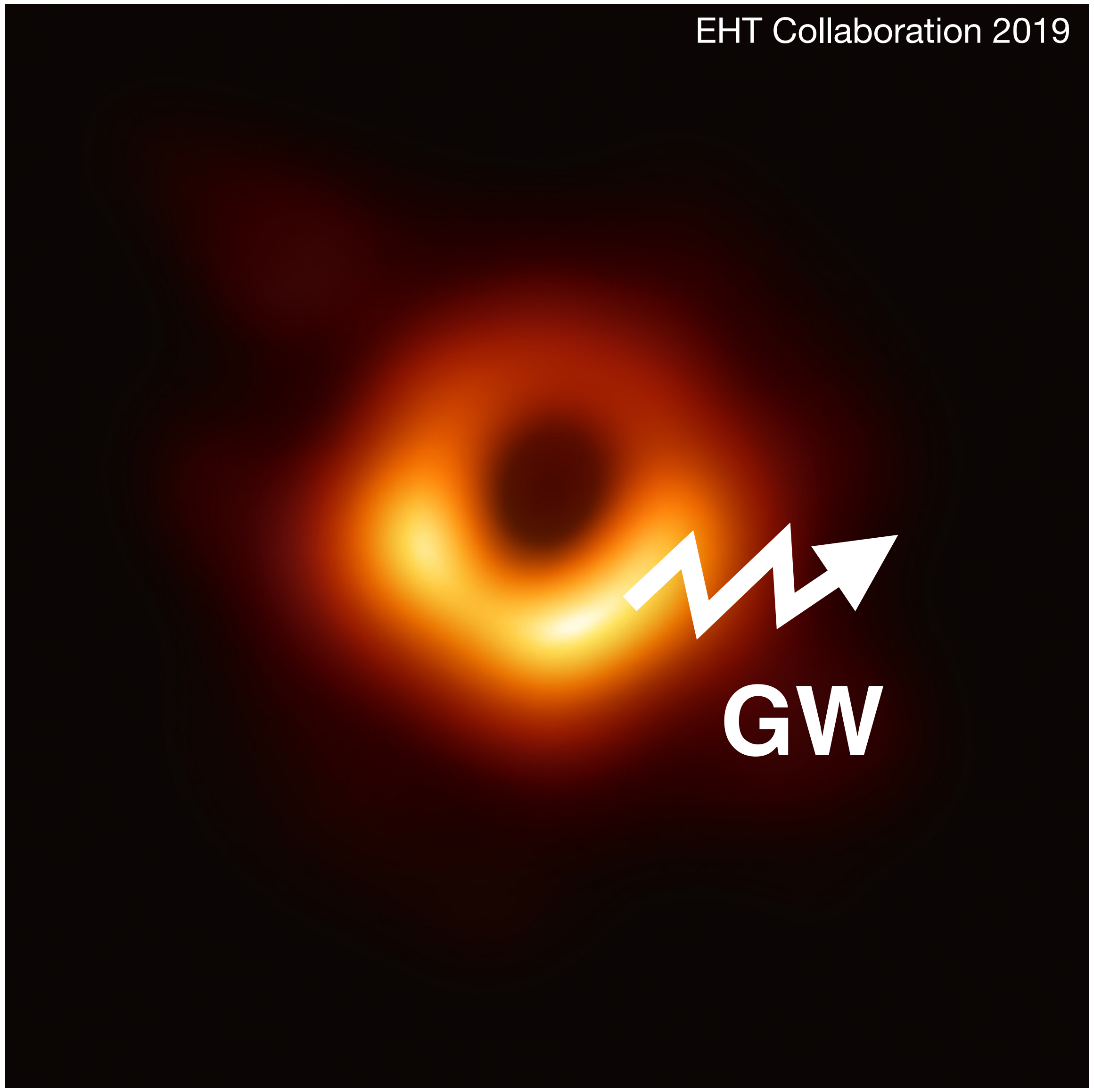
$$E_J^{max}\Big|_{\mathbf{BH}} \gtrsim 10\; E_J\Big|_{\mathbf{NS}}$$

Allows extreme "boosts" $O(10^2)$ in
non-extremal NS → near-extremal Kerr BH

# Non-axisymmetric BH-disk or torus?




van Putten, & Levinson, 2002, Science, 295,1874




Clumps beyond what is expected from gravitational lensing

A non-asymmetric disk or torus is luminous in gravitational radiation

**Direct GW-calorimetry on GW signal of duration $T_s$:** "*The emitted gravitational radiation can be detected by gravitational wave experiments and provides a method for identifying Kerr black holes in the Universe.*" (van Putten & Levinson, 2002, Science, 295, 1874)

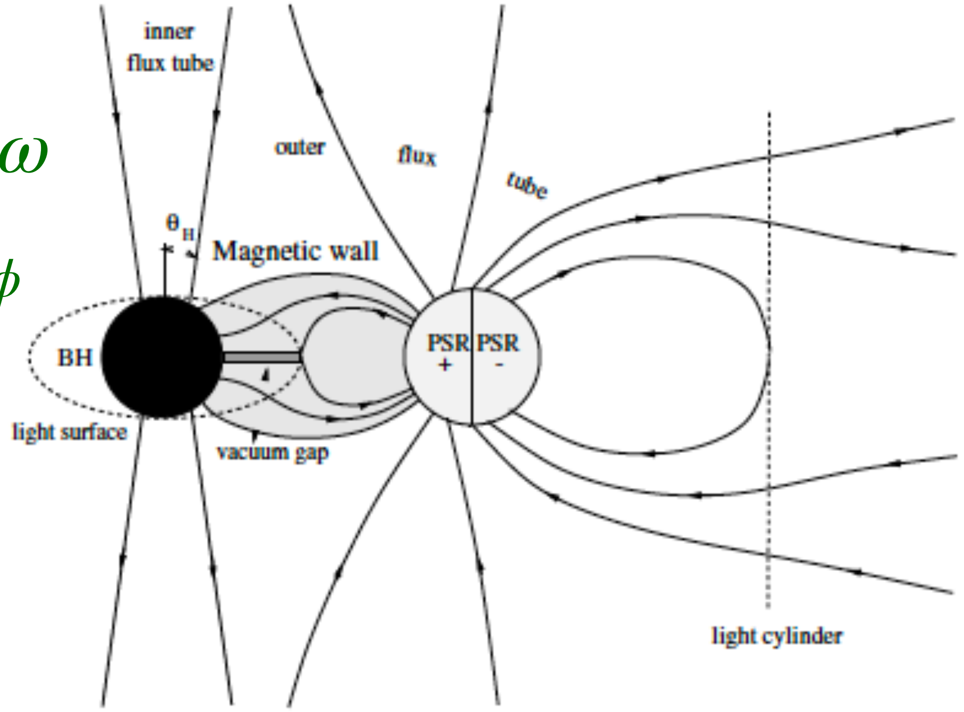
# GRBs: liberate spin energy of a near-extremal Kerr BH?

*Launching high-energy outflows:*

Frame dragging induced potential energy $E = J_p \omega$

Leptons along open magnetic flux tubes $J_p = eA_\phi$

(van Putten, 2000, PRL 84 3752)




van Putten & Levinson, 2003, ApJ, 584, 937

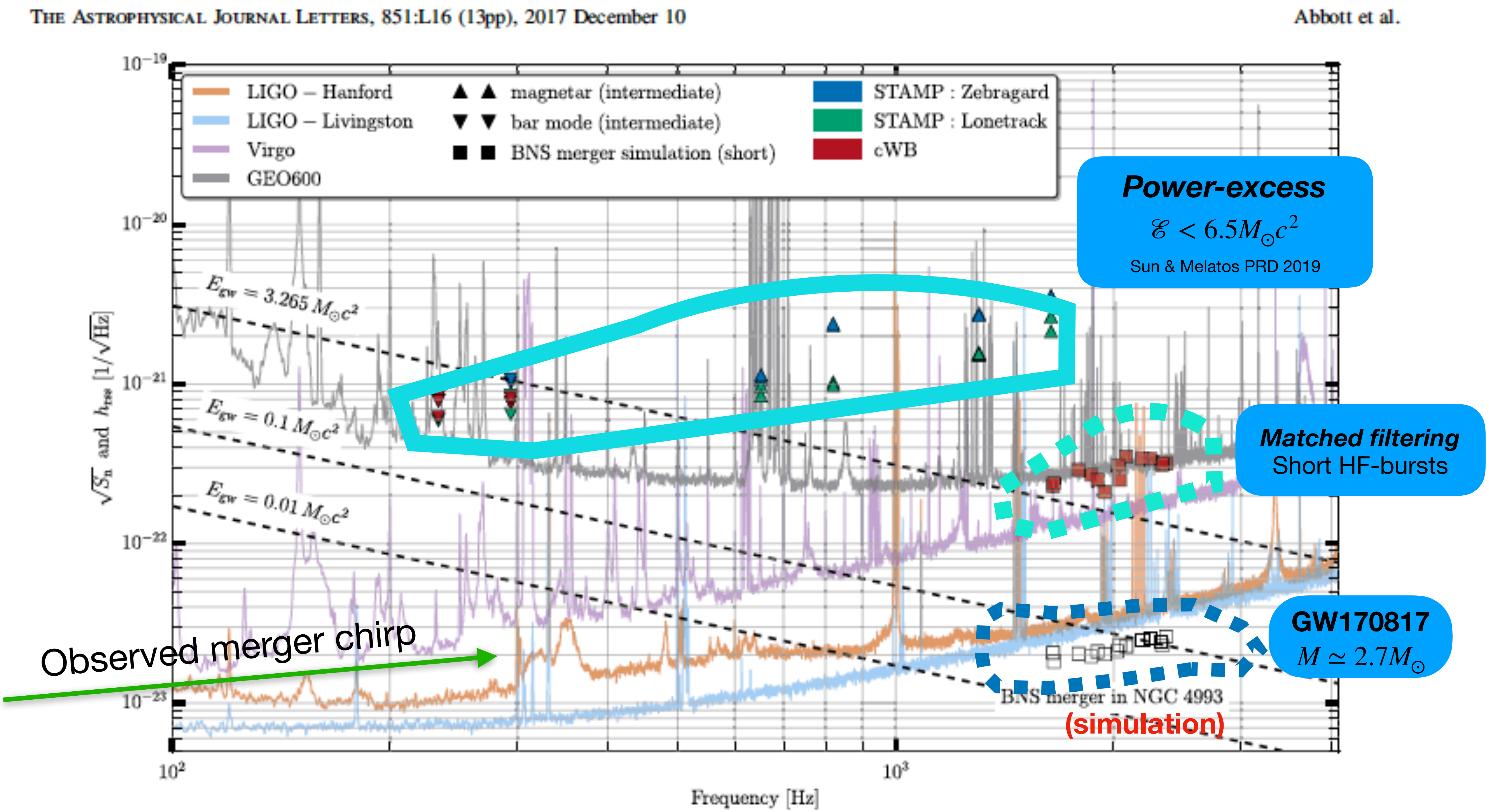
Rotating BH surrounded by high-density disk or torus:

Burst duration set by lifetime of spin $T_s$:

$$T_s \simeq 1.5\mathbf{s} \left(\frac{\sigma}{0.1}\right)^{-1} \left(\frac{z}{6}\right)^4 \left(\frac{M}{M_\odot}\right)$$

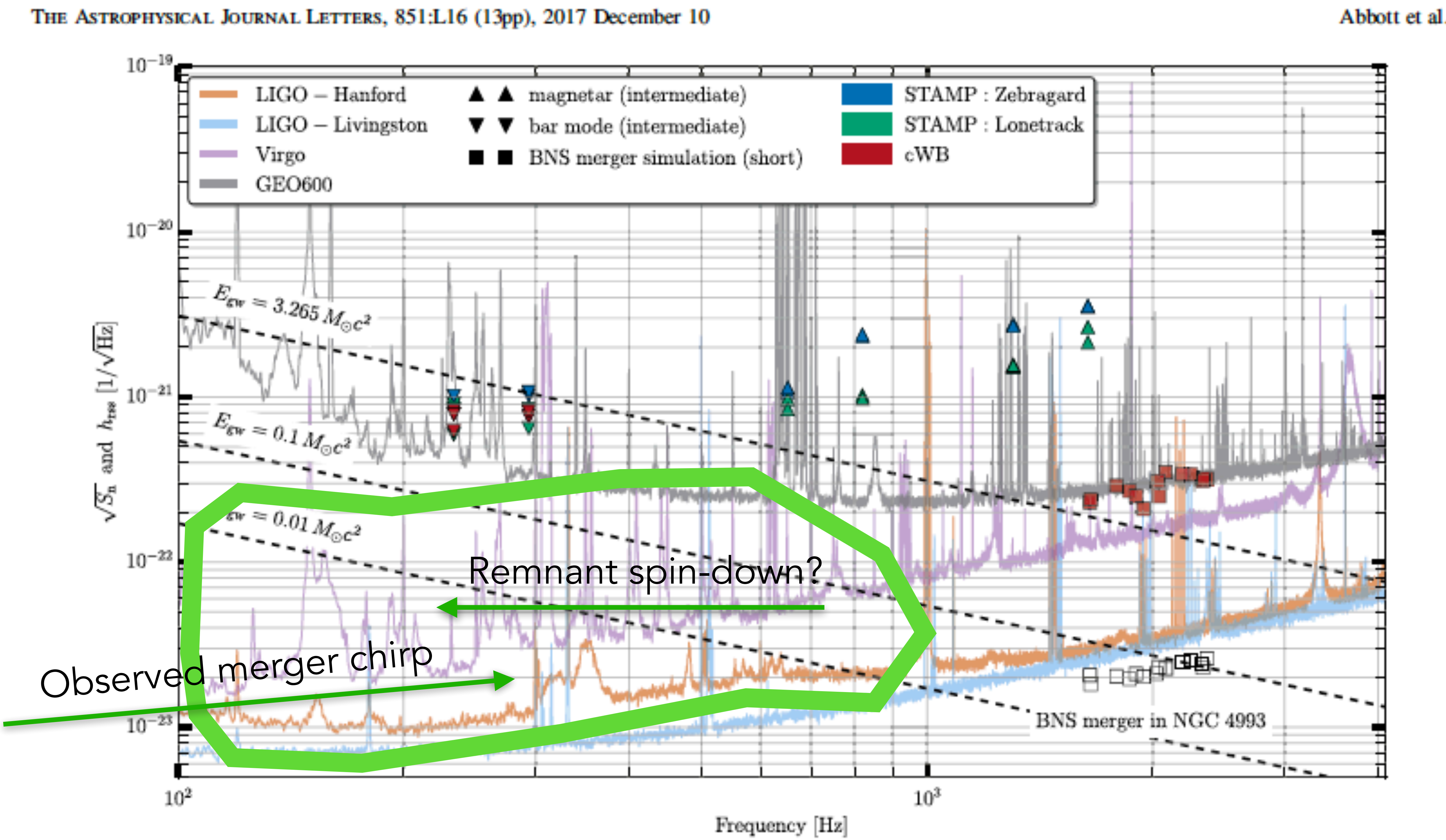
$$z = \frac{r}{M}, \quad \sigma = \frac{M_T}{M}$$

# LIGO-Virgo search for un-modeled post-merger signals



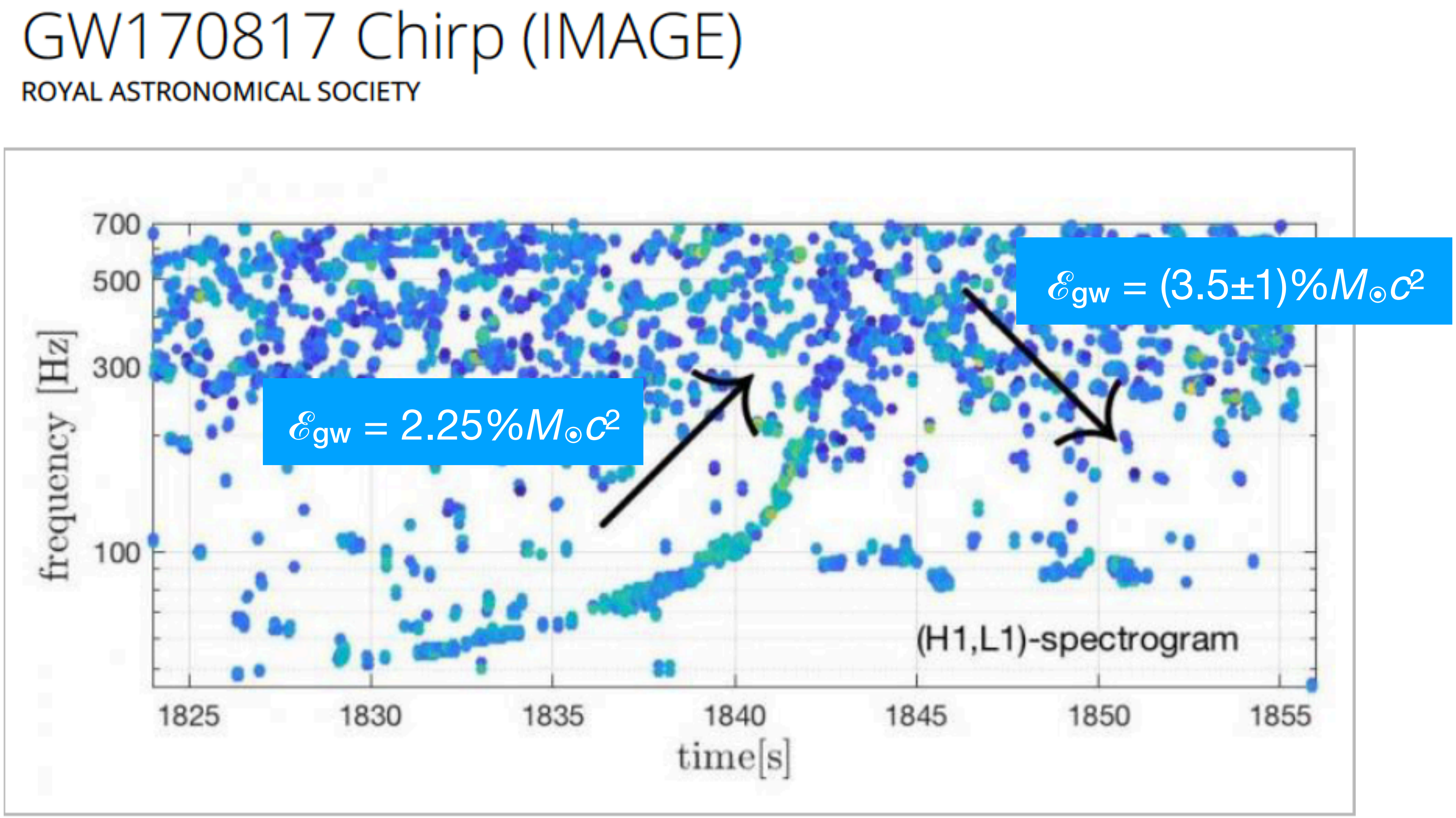

$$h_{\text{un-modeled}} \sim 10^{-22} - 10^{-21} = O(10^{1-2}) \times h_{GW170817}$$

# Challenge: search the abyss




$$h \sim 10^{-23} - 10^{-22} \sim h_{GW170817}$$

# Extended Emission: pre- and post-merger calorimetry in GWs



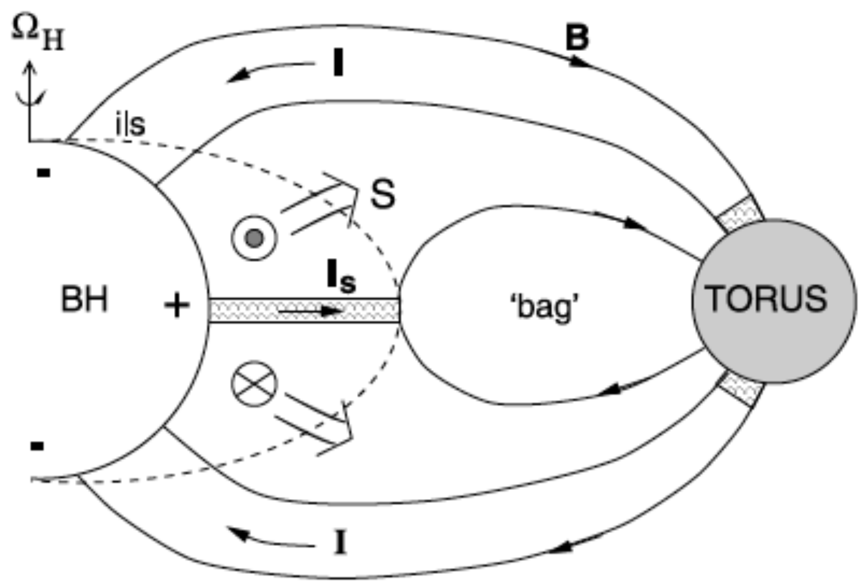

Nov 14 2018

van Putten & Della Valle, 2019, MNRAS, 482, L46
van Putten Della Valle & Levinson, 2019, ApJ, 796, L2

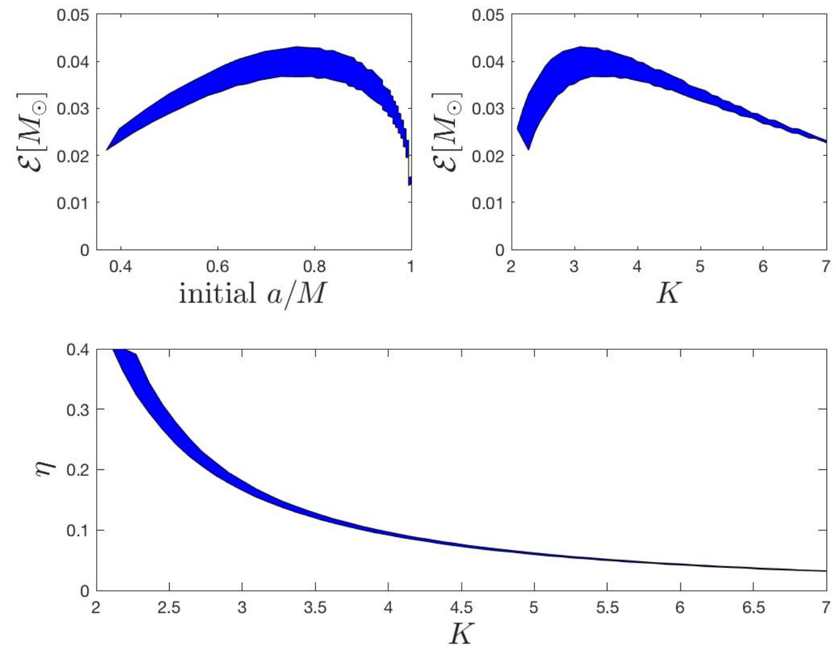
# Model $\mathscr{E}_{gw}$ from spin energy $E_J$ of a Kerr BH

*"Additional spin-up torques from a rapidly spinning rotating black hole can arrest the disk's inflow."* van Putten & Ostriker ApJL 552 L31 (2001)

$E_J$




van Putten, 1999, Science, 285, 115




van Putten, Della Valle & Levinson, 2019

$$L_H = -\dot{M},\ T = -J_H$$

multiple $K$ of ISCO radius

$f_{GW,i} = 650$**Hz (observed):**

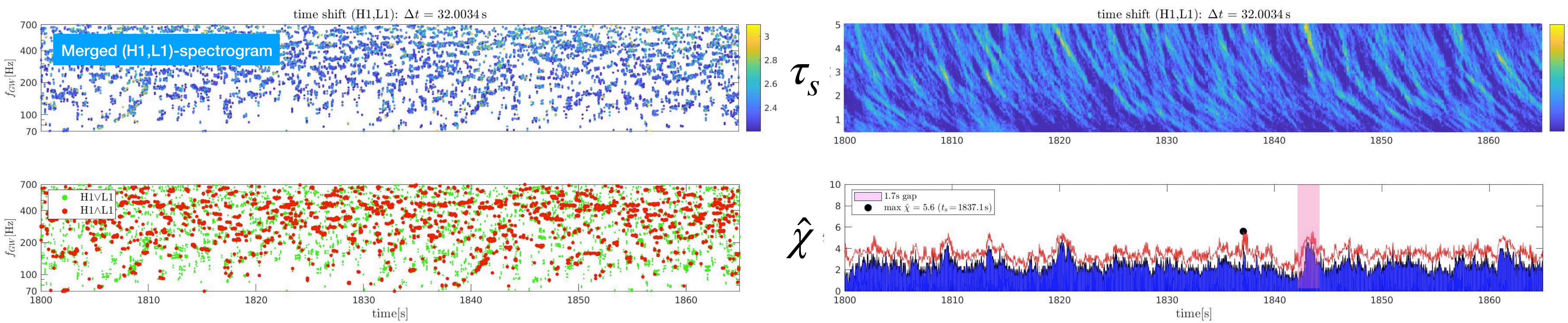
$$K \simeq 3,\ \eta \simeq 15\,\%$$

GW by non-axisymmetric torus of ~3$R_{\rm ISCO}$ about BH with $a/M$~0.75

$$\mathscr{E} \simeq 3\,\%\,M_\odot c^2$$

**Theory and observations agree.**

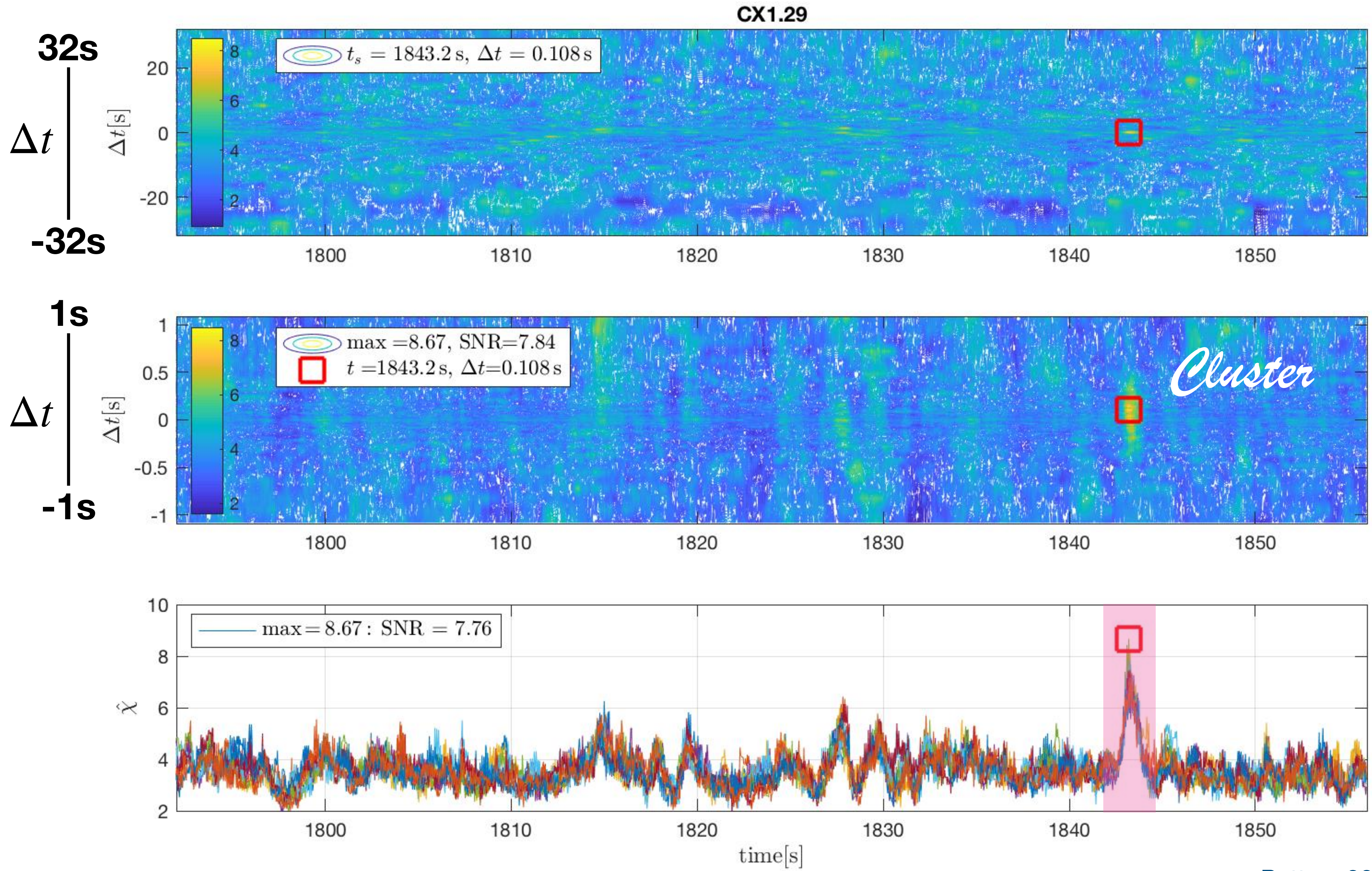
# Time-slide correlation analysis




Cluster in 1.7s gap
between GW170817
and GRB170817A

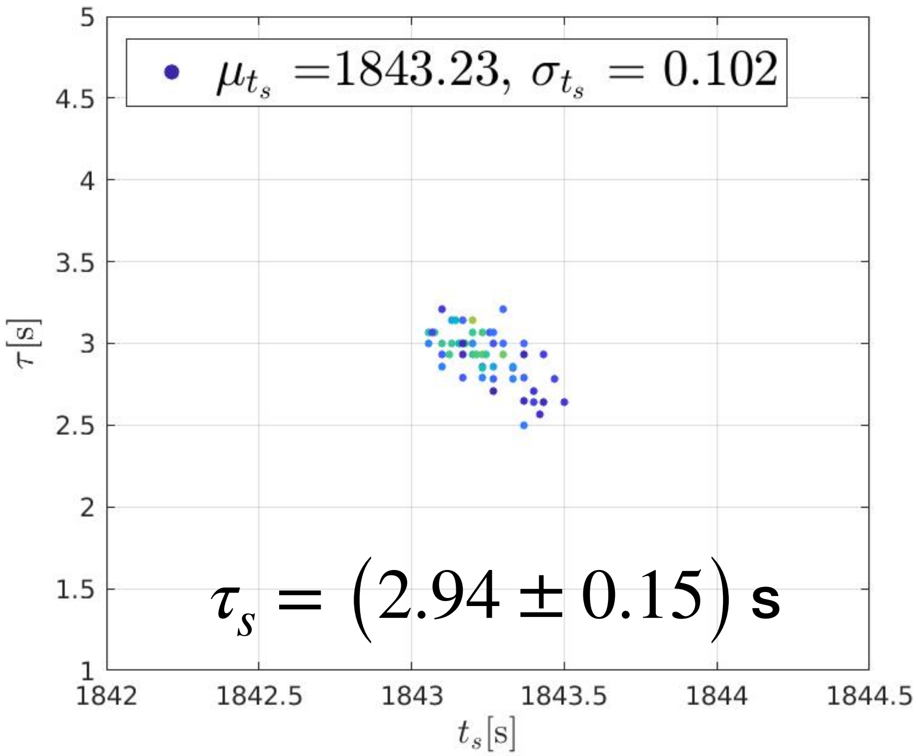
Scan for descending chirps over 3+1 parameters
(high resolution at 1B tries over 2048 s data)

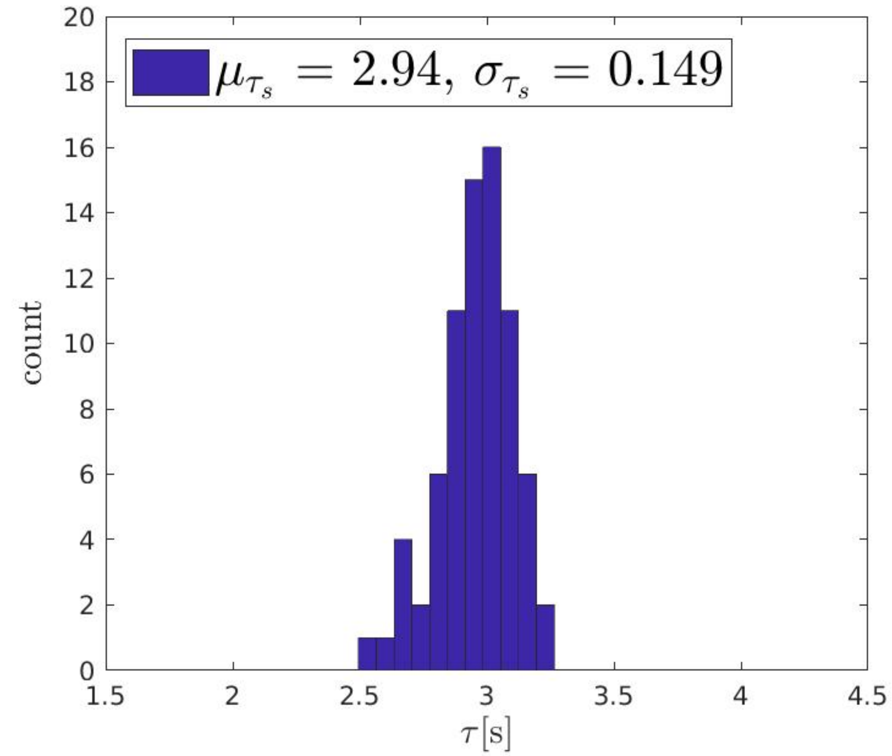
# “Hot spot”: Cluster of correlated behavior about $\Delta t \simeq 0$




van Putten, 2019, in prep.

# Parameter estimation and significance of a cluster PDF




Two-time causality condition on the cluster in $(t_s, \Delta t)$:

$$\textbf{Global } \max\chi \textbf{ in 1.7s gap}: \; p_1 = \frac{1.7\text{s}}{100\text{hr}}$$

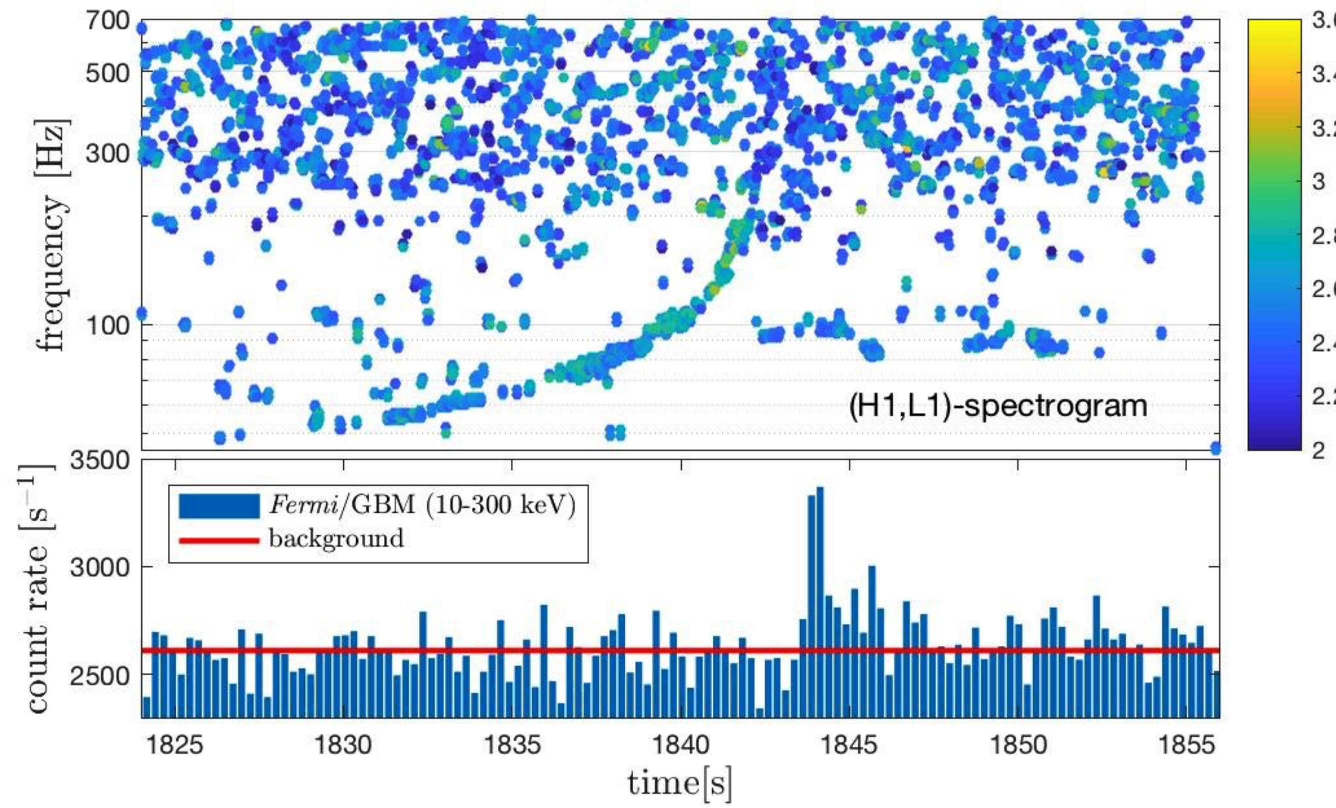
$$|\Delta t| < \tau_{template} = 0.5\text{s} : p_2 = \frac{\tau_{template}}{\max \Delta t} = \frac{0.5}{32}$$

$$p = p_1 p_2 \simeq 7.4 \times 10^{-8}:$$

Gaussian equivalent significance: 5.38 σ


van Putten, 2019, in prep.

# Merging sequence by multi-messenger calorimetry


NS + NS → HNS → BH-disk → BH + GWs + GRB170817 + kilonova

$\mathscr{E}_{gw} = 2.25\% M_\odot c^2$

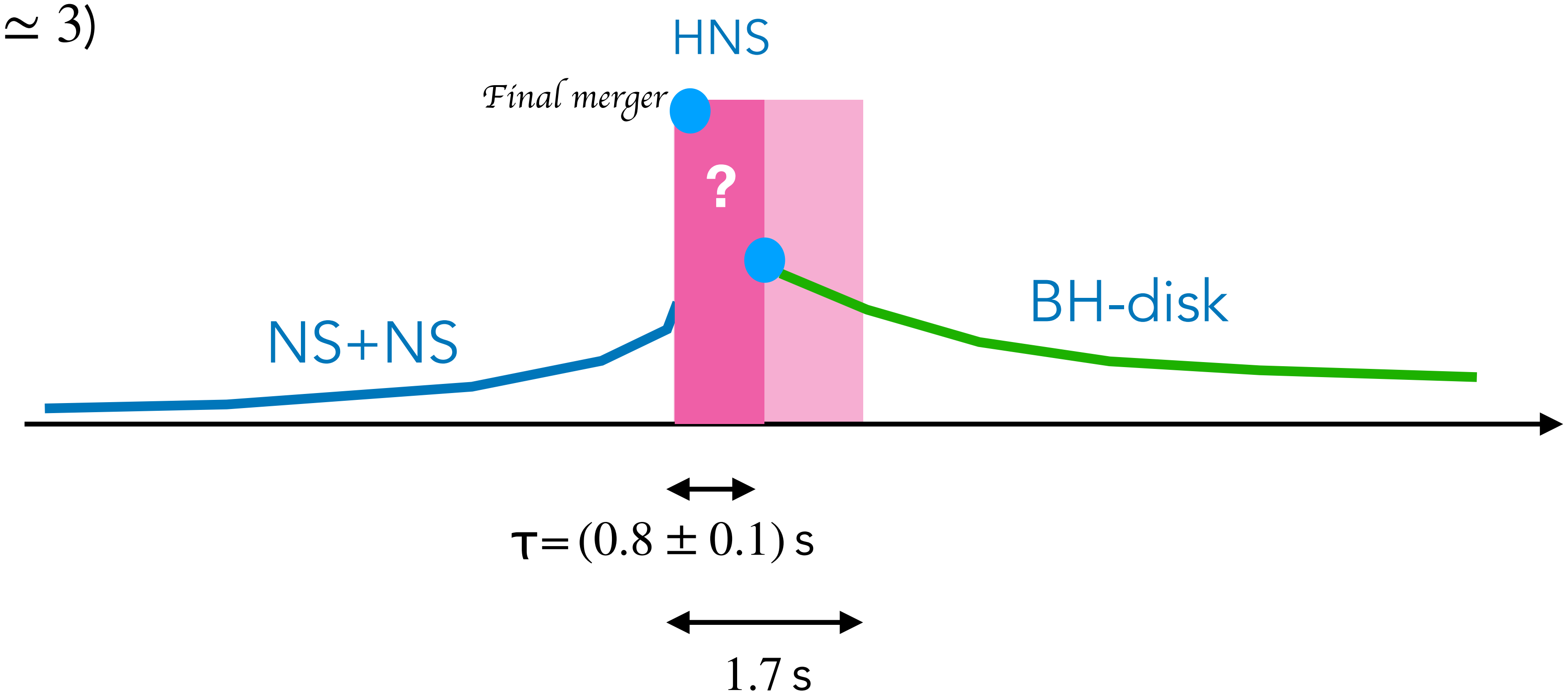
$t_c = 0.8 \pm 0.1$ s $\quad$ $\mathscr{E}_{gw} = (3.5 \pm 1)\% M_\odot c^2$

$\mathscr{E}_{EM} = 0.5\% M_\odot c^2$

Also from kilonova studies: $t_c = 0.9^{0.31}_{-0.28}$ s (Gill & Rezolla 2019)

# Conclusions and outlook

**NS-BH?** First-ever calorimetric evidence in GWs of a Kerr black hole in a *descending chirp* with $\mathcal{E}_{gw} = (3.5 \pm 1)\,\%\, M_\odot c^2$ at 5.38σ with $\tau_s = (2.94 \pm 0.15)$ s in spin-down against a tick torus ($K \simeq 3$)




**Lifetime HSN?** $\tau \leq (0.8 \pm 0.1)$ s of HNS formed in the immediate aftermath of GW170817, 30% overweight ($M \simeq 2.6 M_\odot$):

*Softening of EOS by slow kaon condensation?* (Kaplan & Nelson 1986, Brown et al. 1987,1992, …)

*Quiet gravitational collapse?*

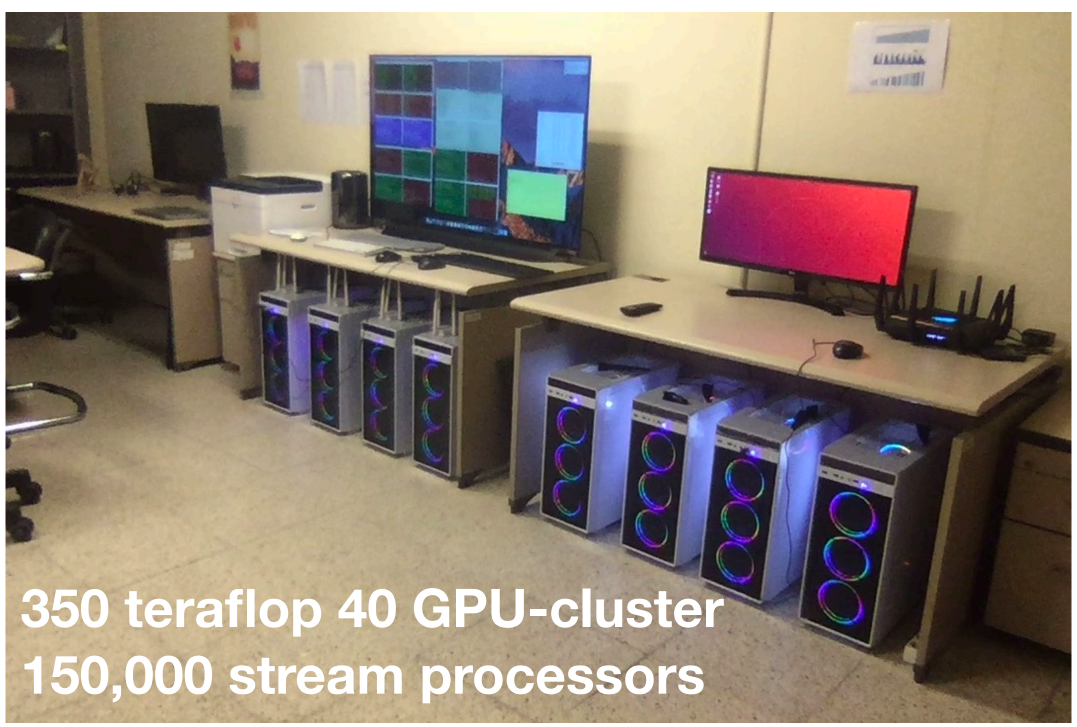
*Spin-down of initially near-extremal HNS (near centrifugal hang-up) in immediate aftermath of GW17017?*

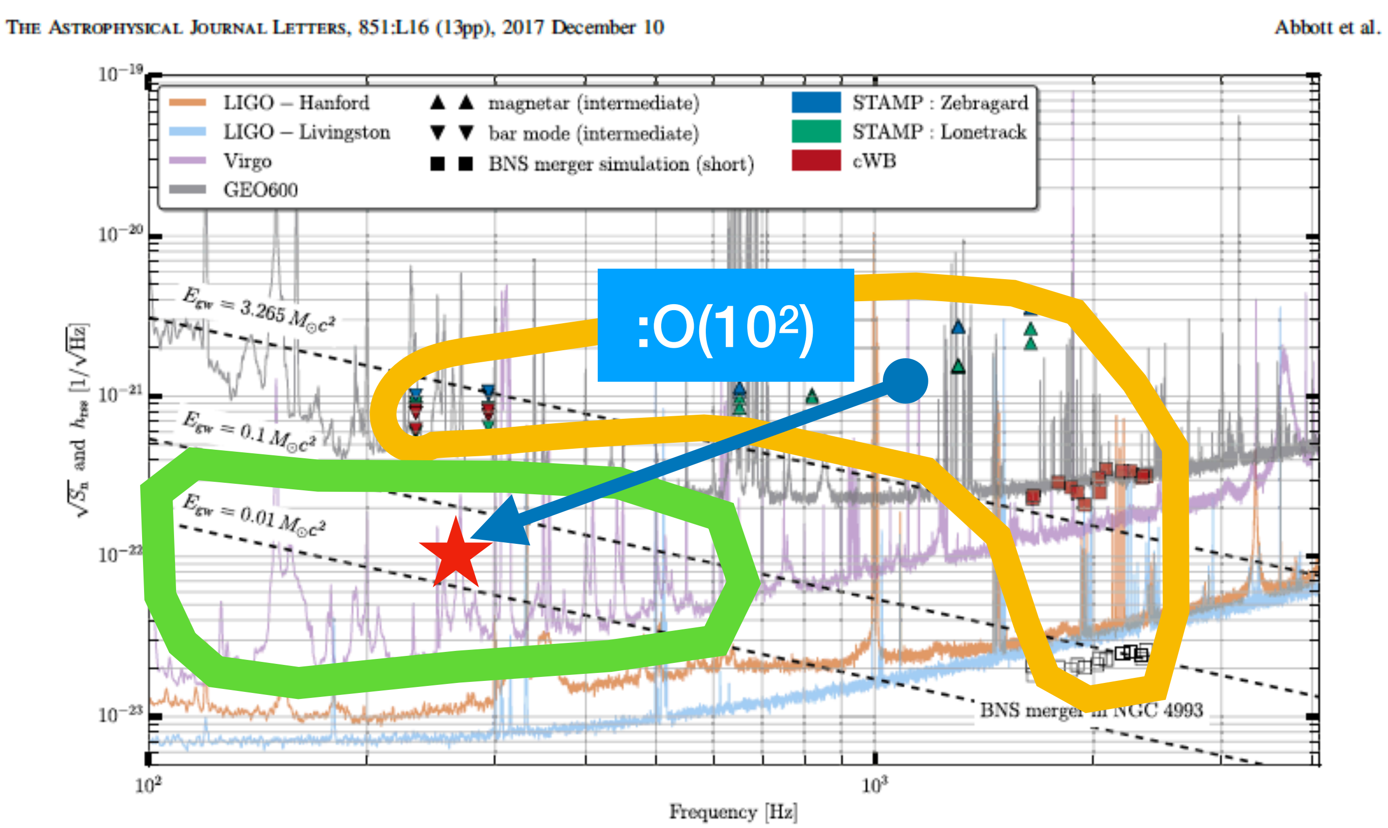
*Short GW-burst with Extended Emission (SGWBEE)?*

# Conclusions and outlook

- ***Type Ib/c SNe?*** (10% of all SN, <1% is parent population of normal long GRBs)
  Expect similar $\mathscr{E}_{gw}$ - rare yet possibly more frequent than rates of mergers and GRBs
  (van Putten, Levinson, Frontera, Guidorzi, Amati & Della Valle, 2019, to appear)

- ***Deep search in the abyss?***
  Pursue blind searches by GPU-accelerated butterfly filtering O($10^2$) below power excess



*Thank you*

# Extra slides and supporting information

- From M87 to micro-quasars and GRBs: common engine SGRBEE and LGRB?
- Quadrupole GW-radiation formula: $L_{gw}$ from a non-axisymmetric torus
- Butterfly filtering and $\chi$-image analysis
- Signal injection experiments
- Single-detector observing of EE in H1 and L1
- EQ170223: Earthquake response of H1