GW-observations of the central engine of core-collapse supernovae in the Local Universe

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Outline

CC-SN event sequences

Lessons learned from GW170817

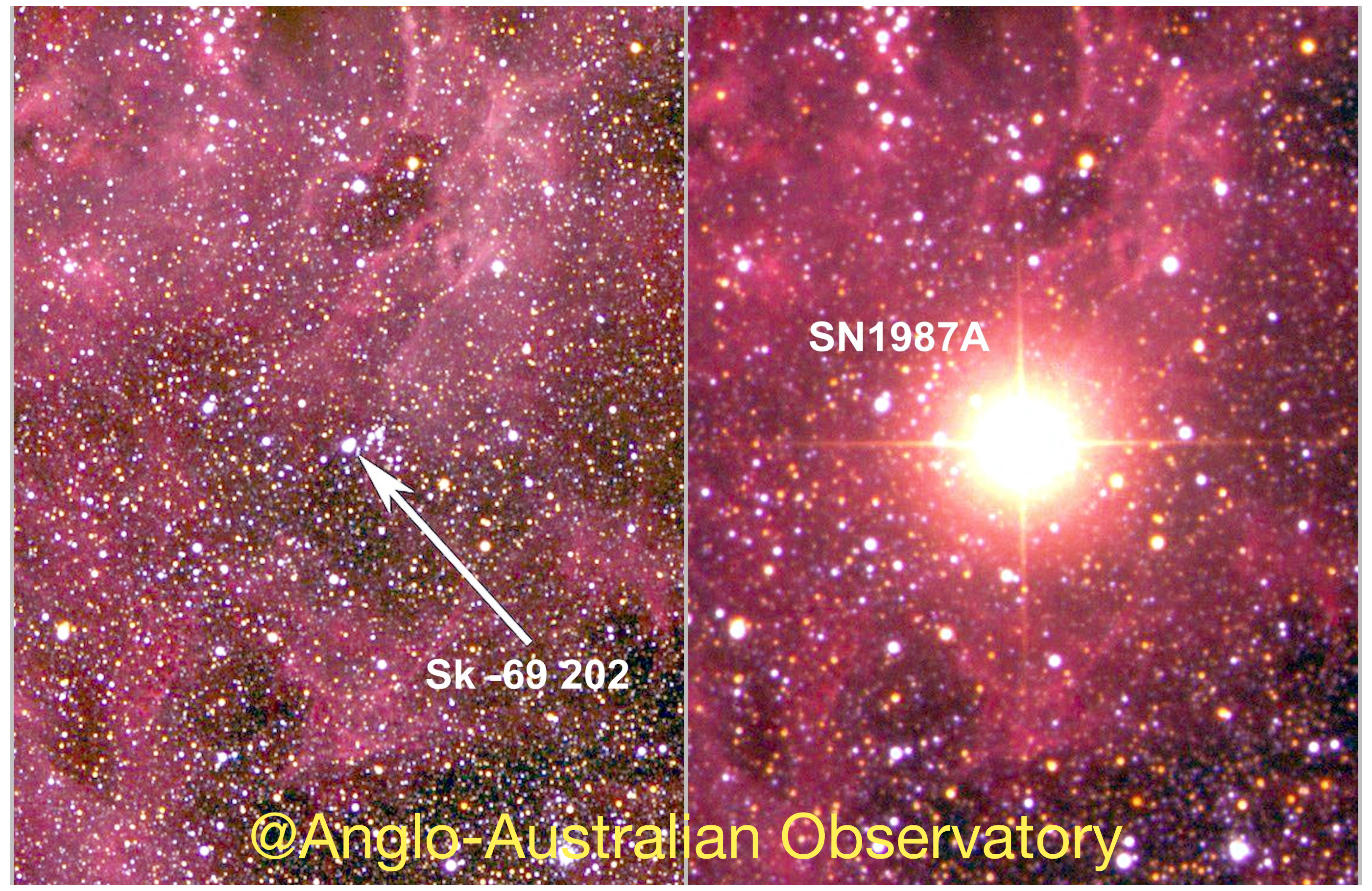
Detector-limited horizon distance to long-duration transients

Conclusions and outlook

CC-SN event sequences

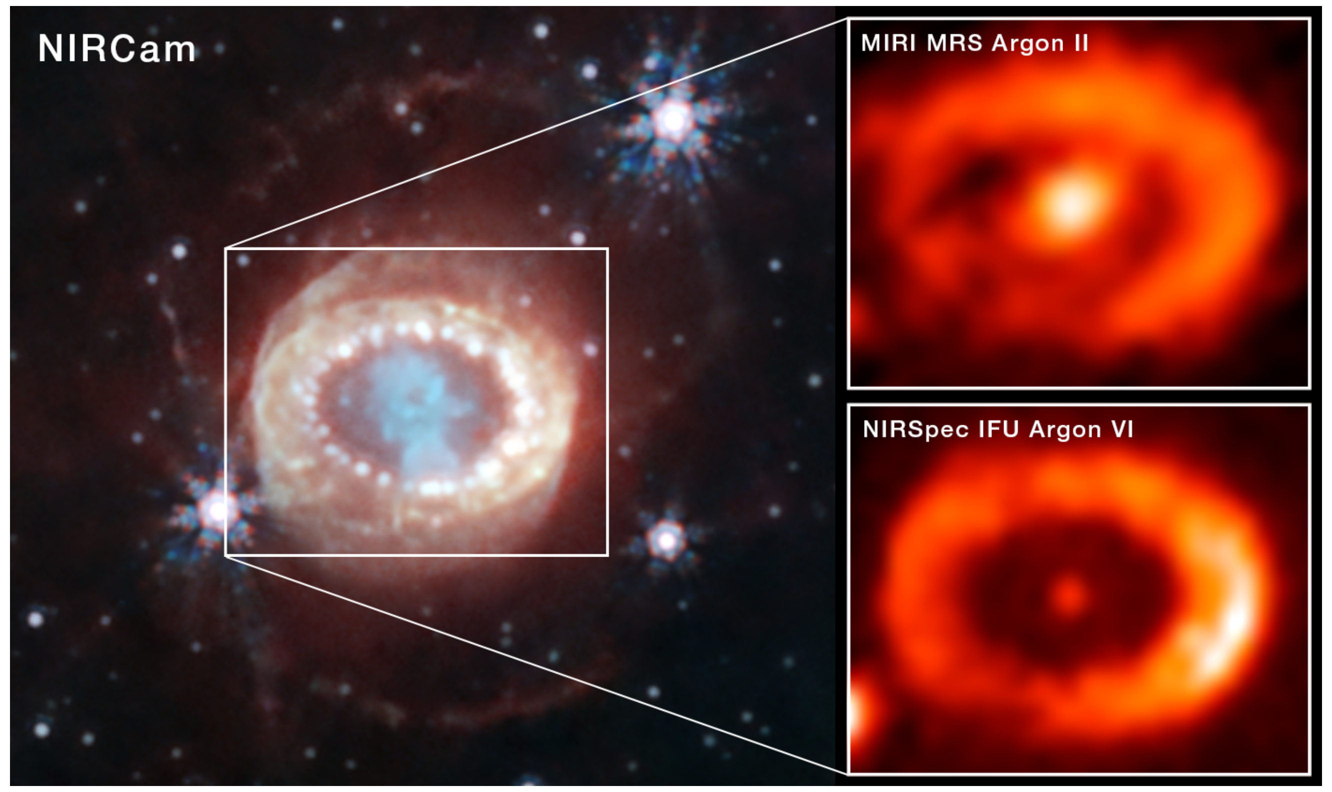
Sanduleak –69 202
$M \simeq 18 M_\odot$

→



NS
→

+37 yr/JWST



CC-SN event sequences

Progenitor mass?

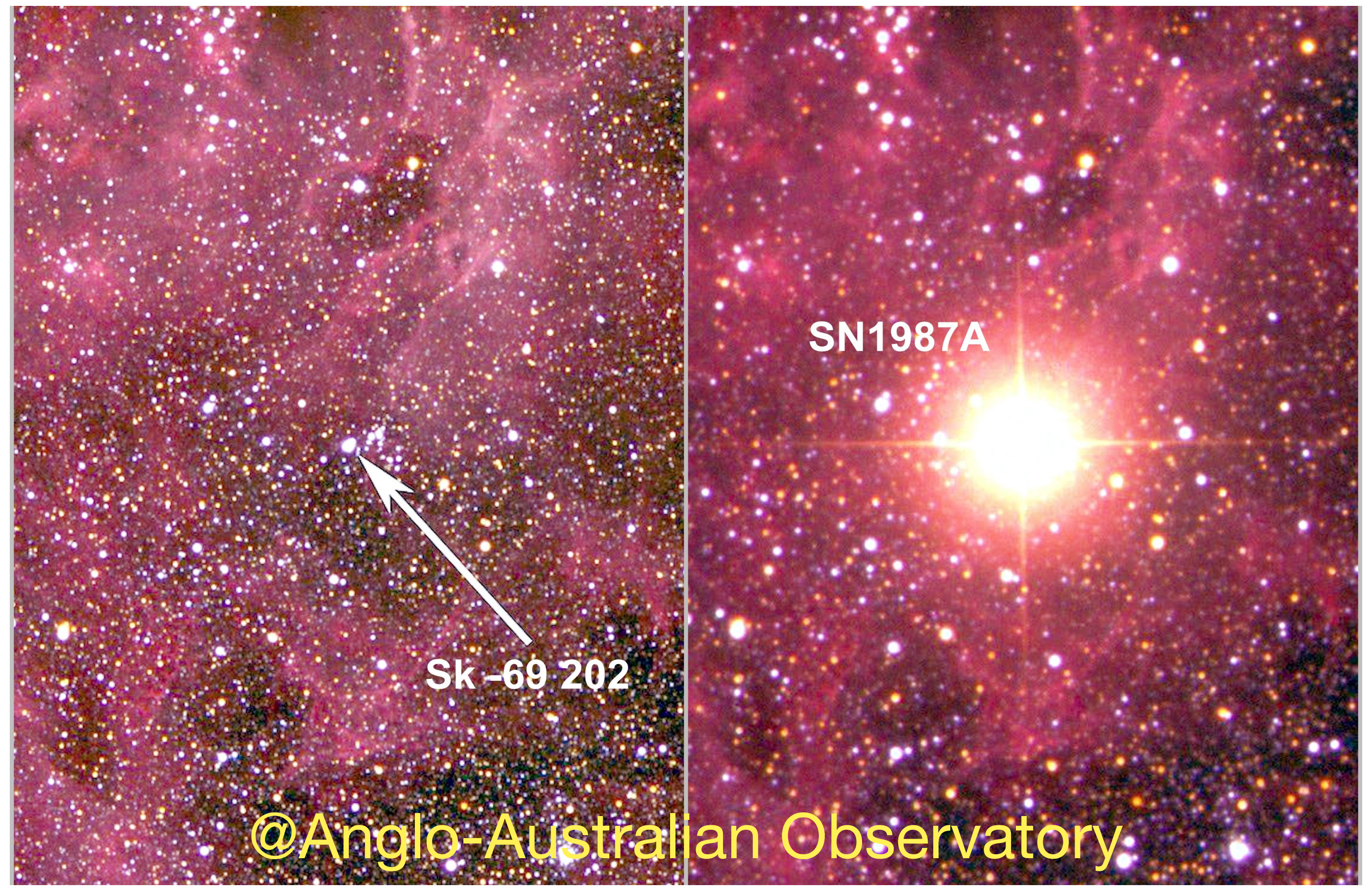
Central engine(s)?

Final Remnant?

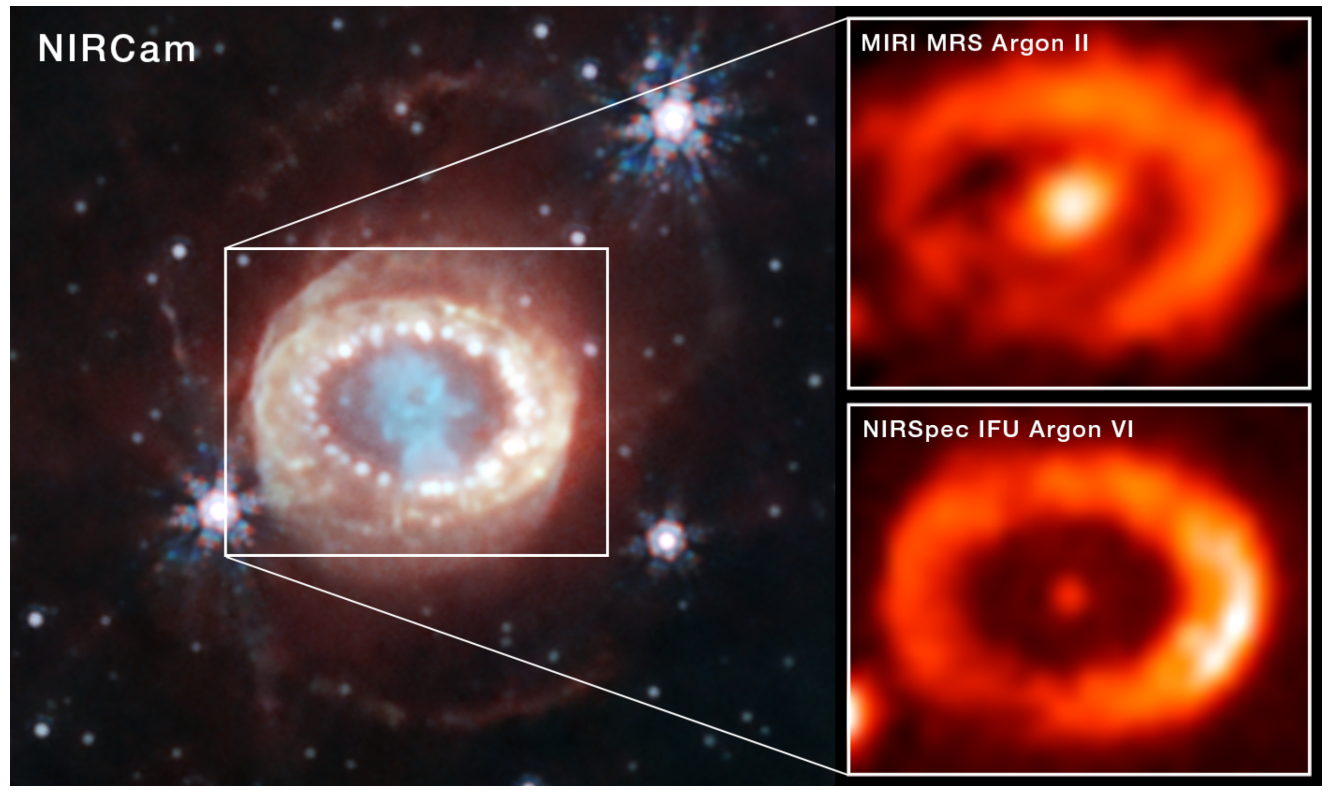
Sanduleak –69 202

$M \simeq 18 M_\odot$

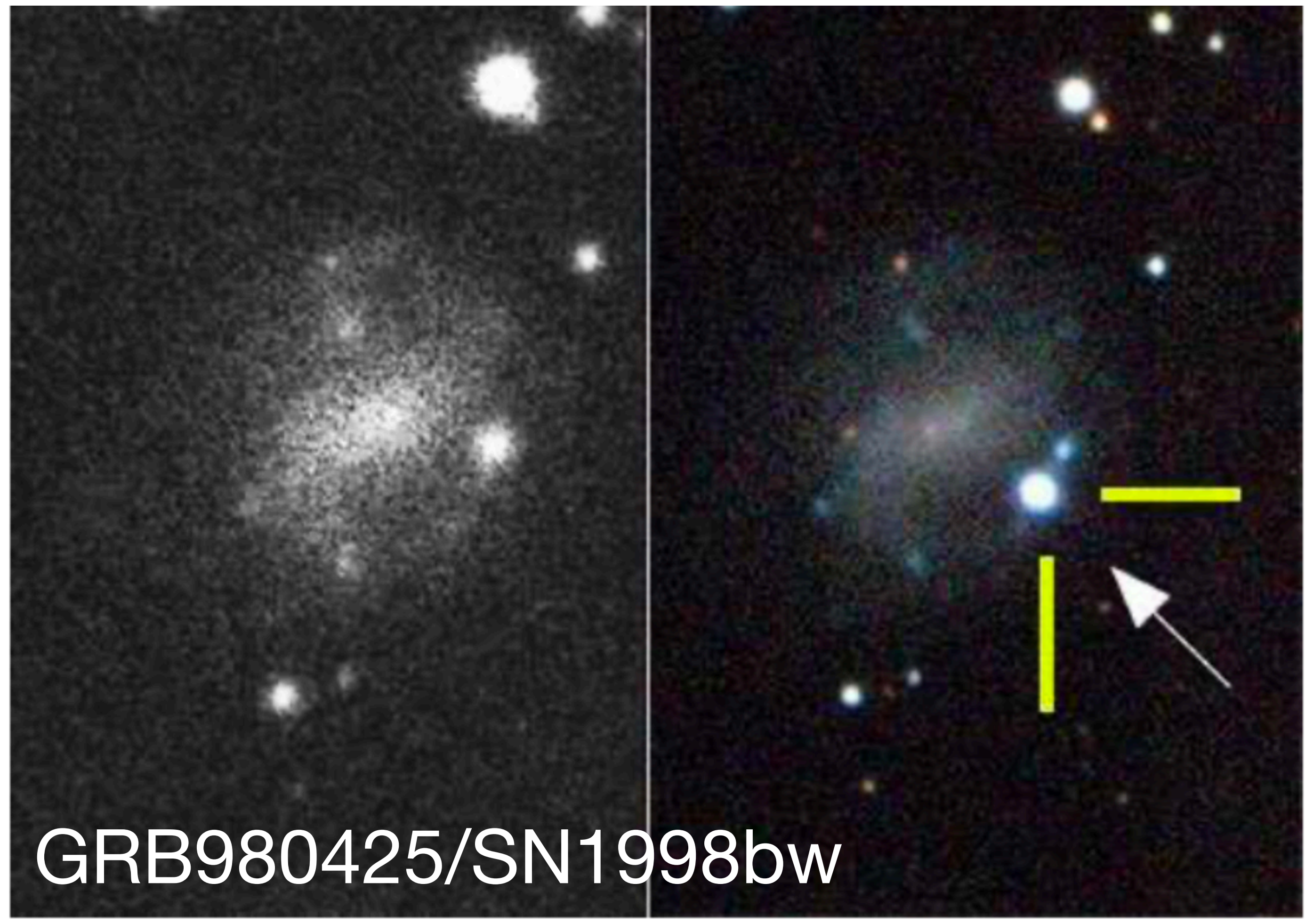
Run-up



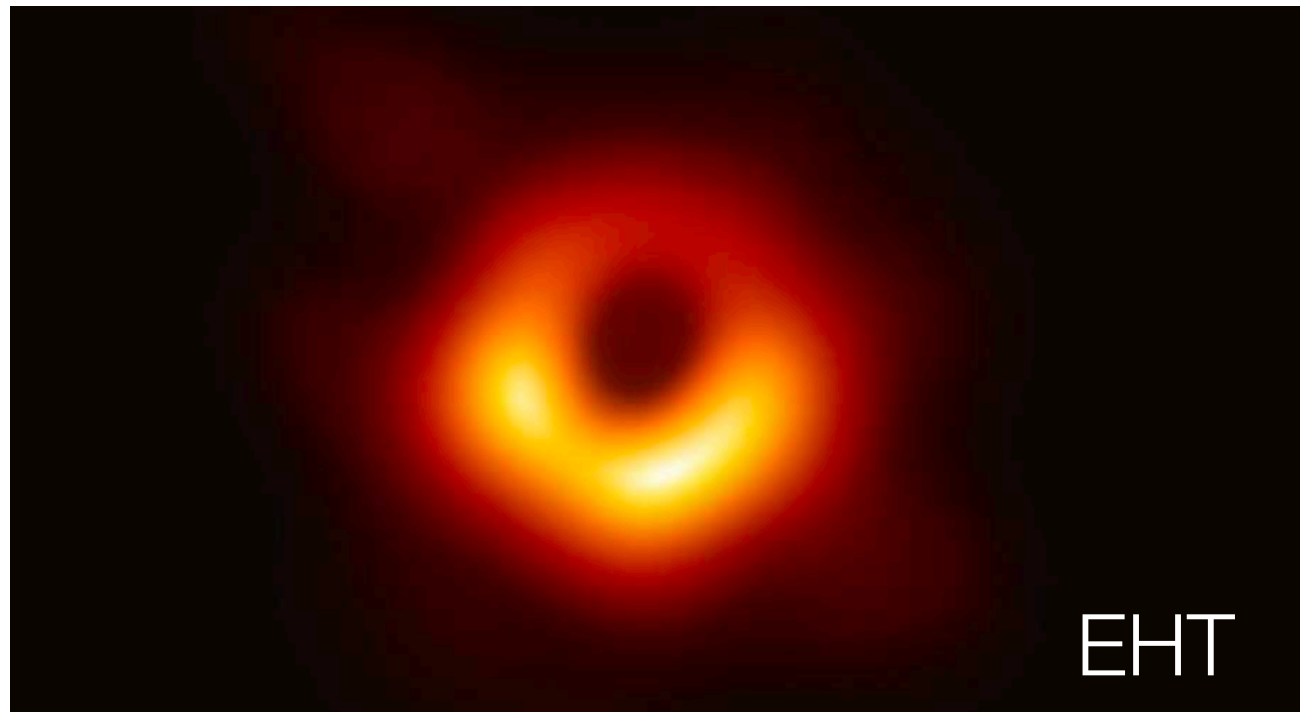
NS



$M \overset{?}{>} 20 M_\odot$



BH?



CC-SN event sequences

Progenitor mass?

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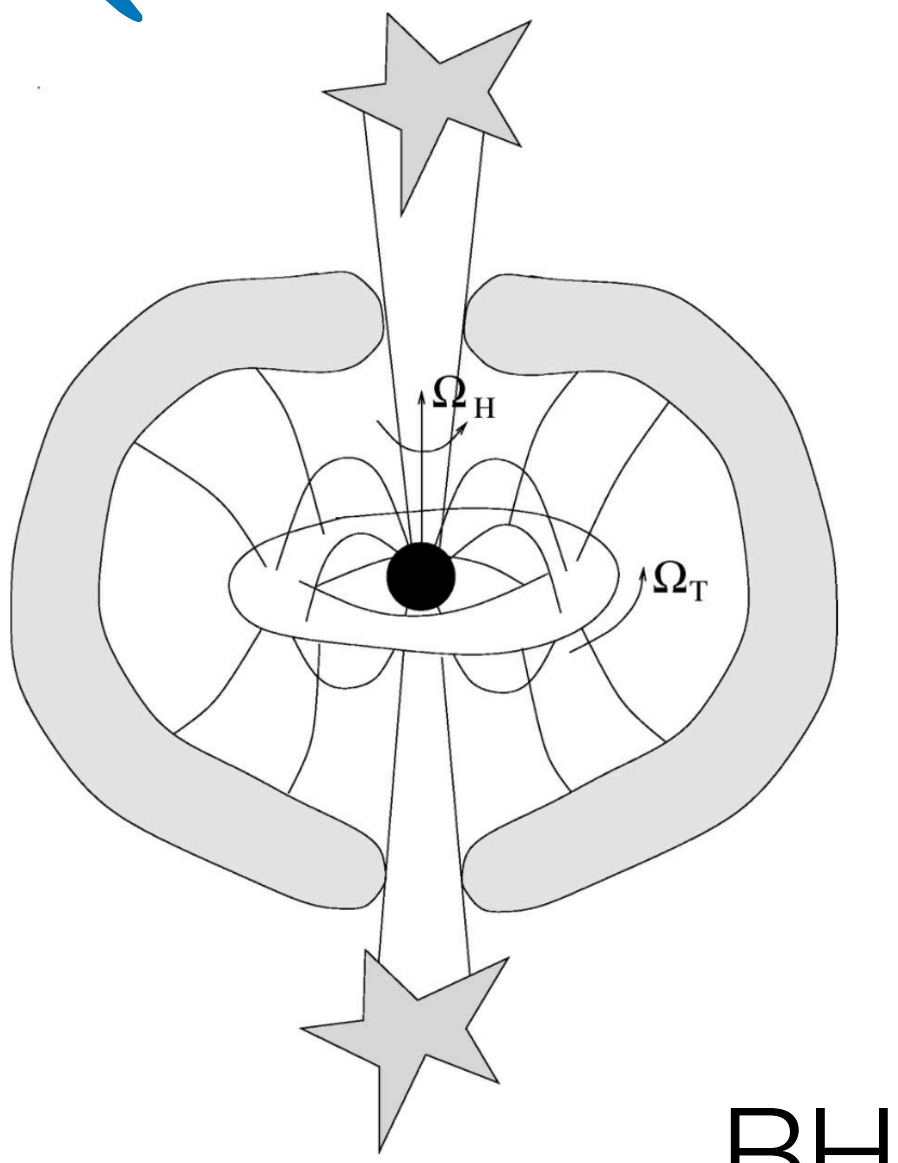
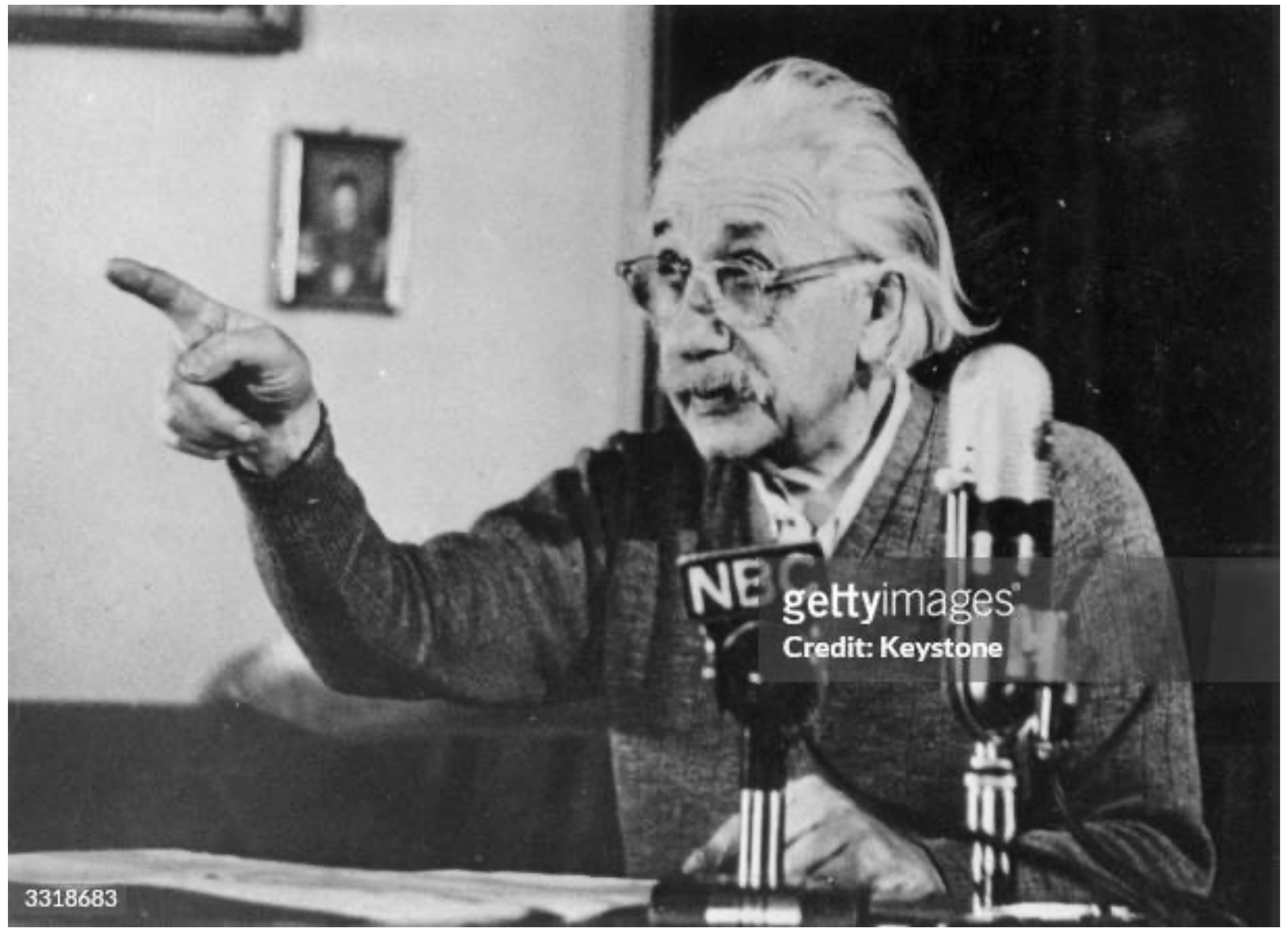


BH

van Putten, Levinson, Lee, Rigimbau, Punturo & Harry, 2004, PRD 69 044007
van Putten, Levinson, Frontera, Guidorzi, Amati & Della Valle, 2019, EPJ Plus 134, 537

Distinct outlook on GW-emission by frequency and energy

Probe by gravitational radiation



$$L_0 = \frac{c^5}{G} \simeq 200{,}000\, M_\odot c^2 \mathrm{s}^{-1} \simeq 3.6 \times 10^{59}\ \mathrm{erg\ s}^{-1}$$

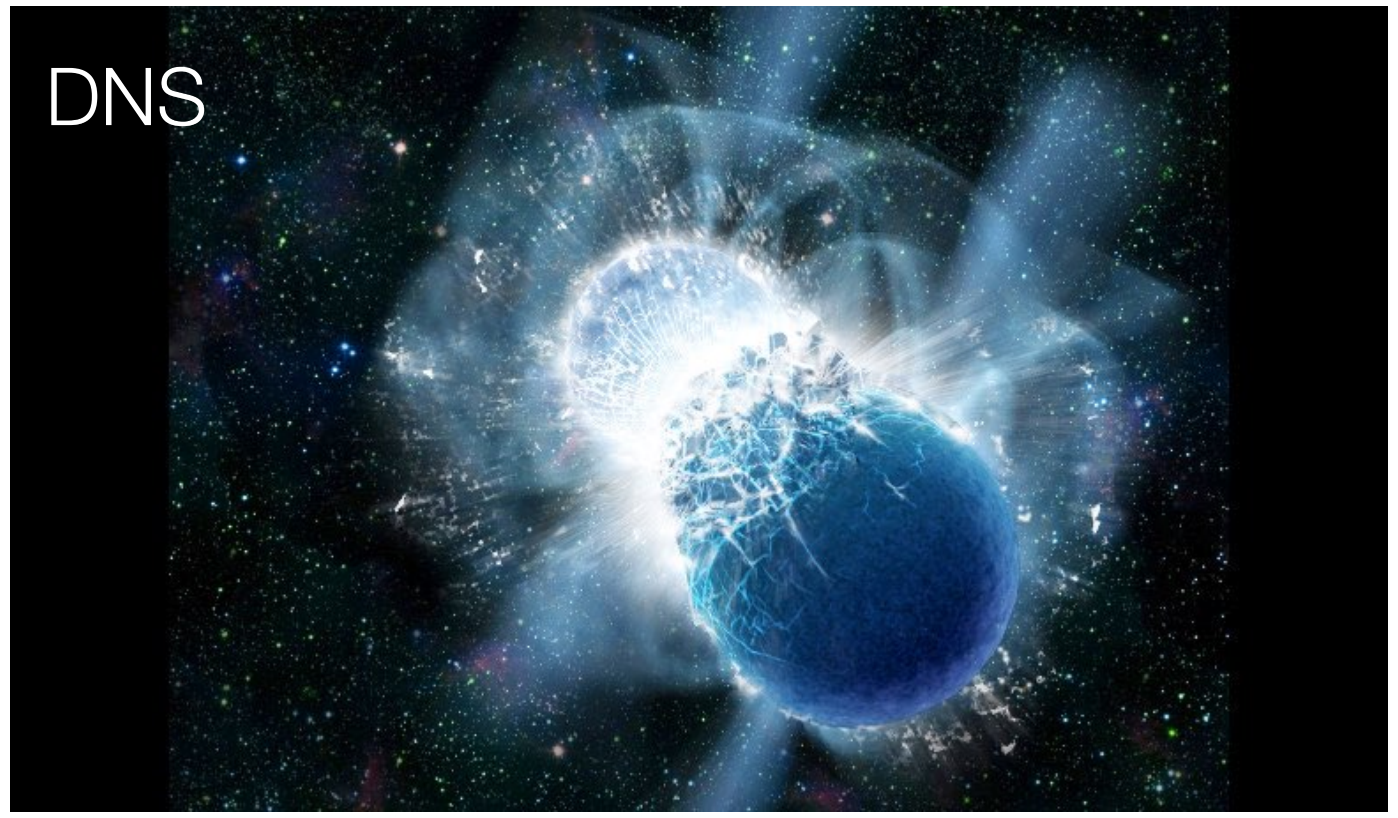
Quadrupole GW-emission from BH central engines

$$L_{gw} = \frac{32}{5}\left(\frac{\delta m}{M}\right)^2 \left(\frac{M}{a}\right)^5 L_0 \sim 10^{51} \mathrm{erg\ s}^{-1}$$

van Putten PRL 2001; van Putten & Levinson 2003

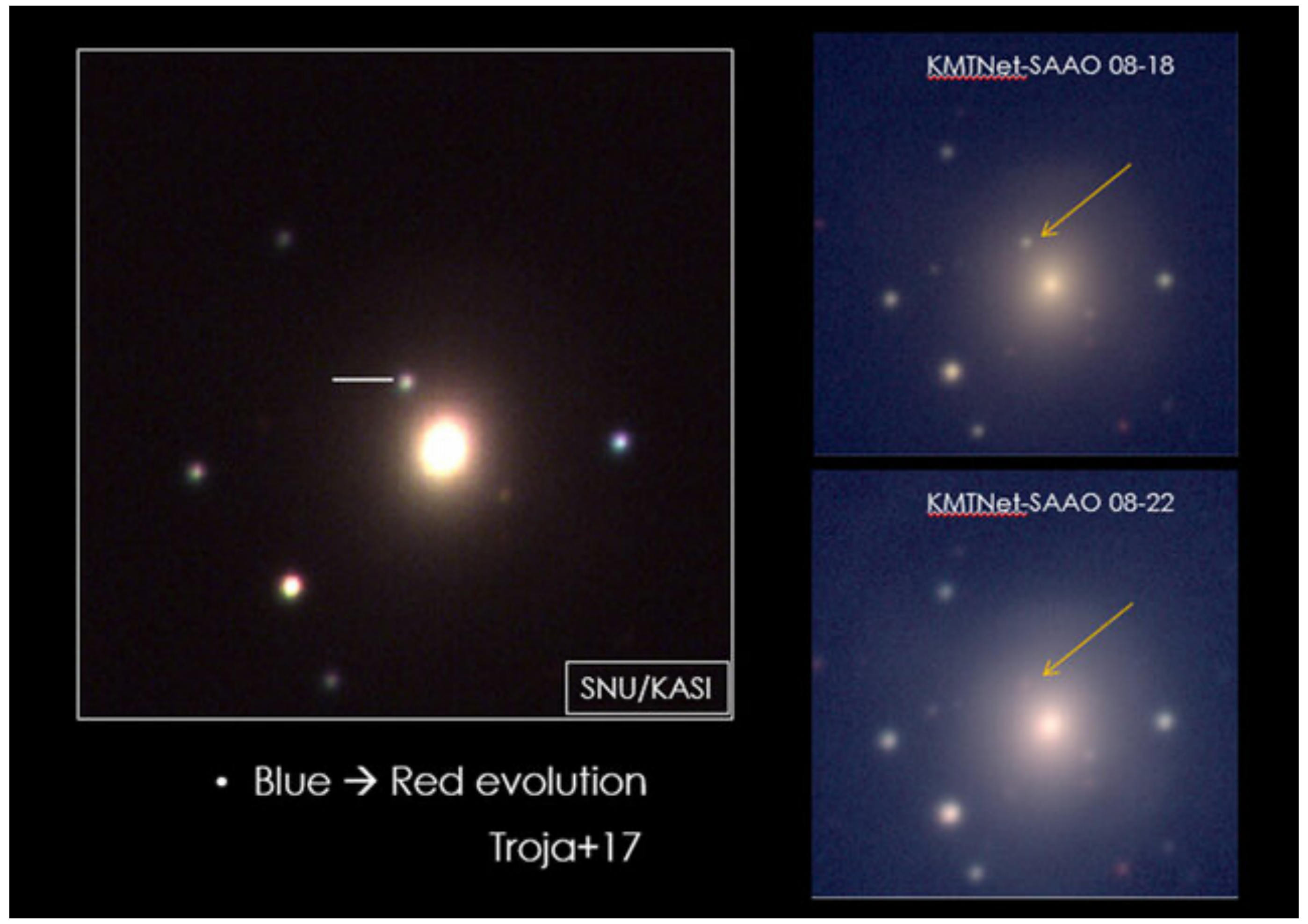
Lessons learned from GW170817

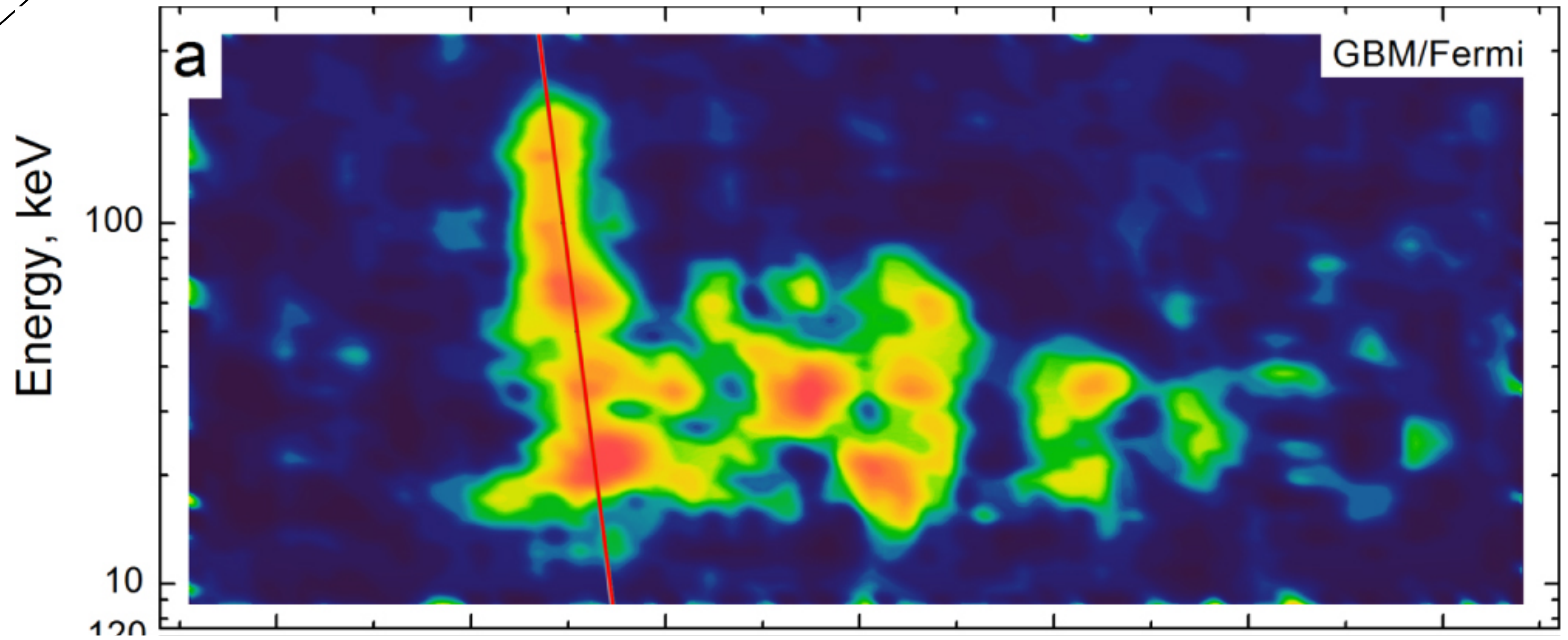
Event sequence GW170817?



HMNS?

AT2017gfo / KMTNet



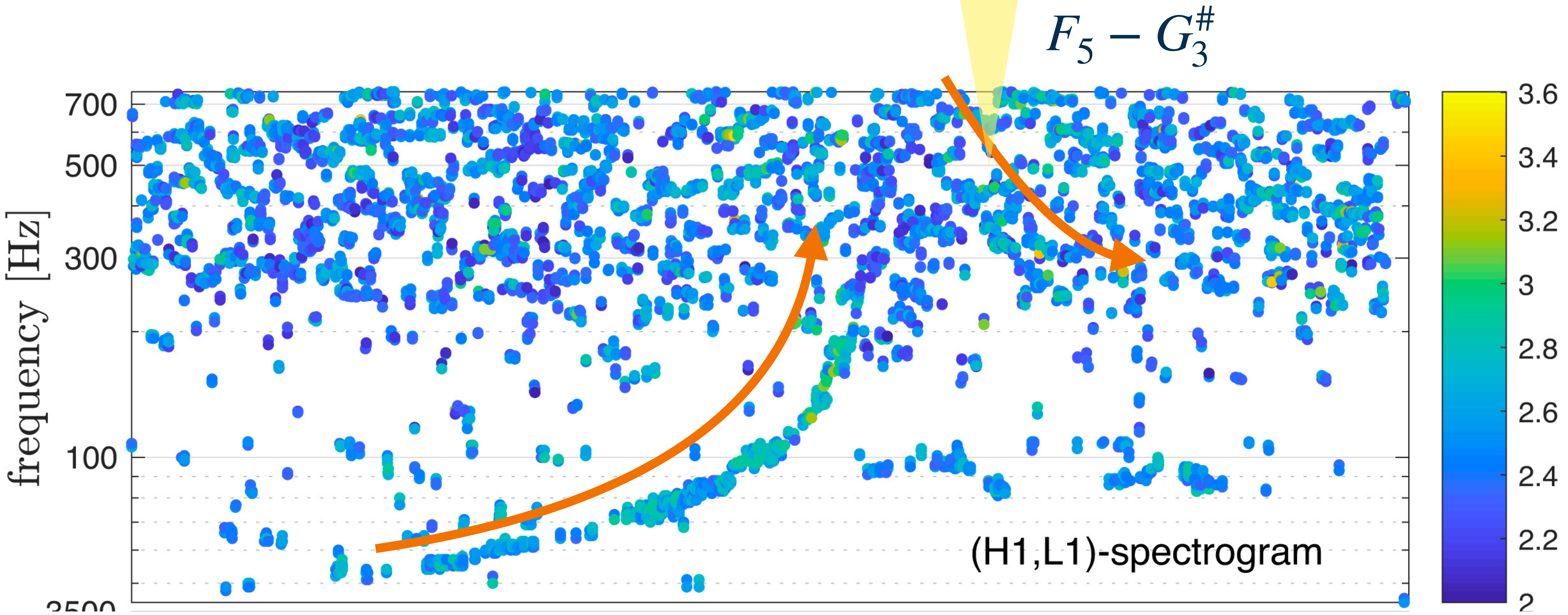


Pozanenko et al., 2018

NS/BH?

GW170817-GW170817B/GRB170817A

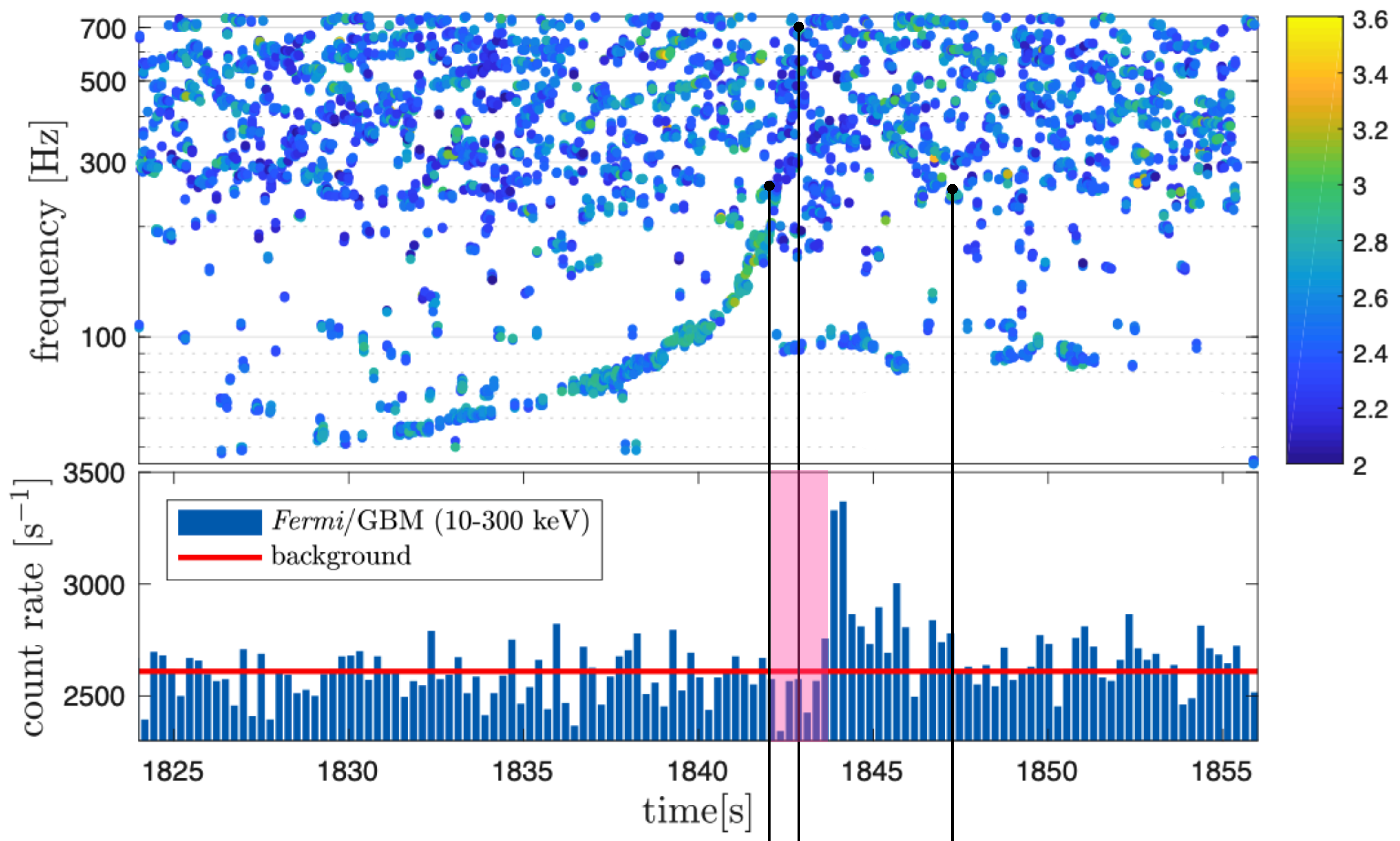
GW170817B
5.5σ detection by merged
& independent H1, L1-analysis



van Putten, 2023, 32nd Texas Symposium Relativistic Astrophysics (invited)
van Putten & Della Valle, 2023, A&A, 669, A36

… event timing and energy

$\mathcal{E}_{GW} \simeq 3.5\,\%\, M_\odot c^2$ exceeds E_J^{HMNS} by 4x

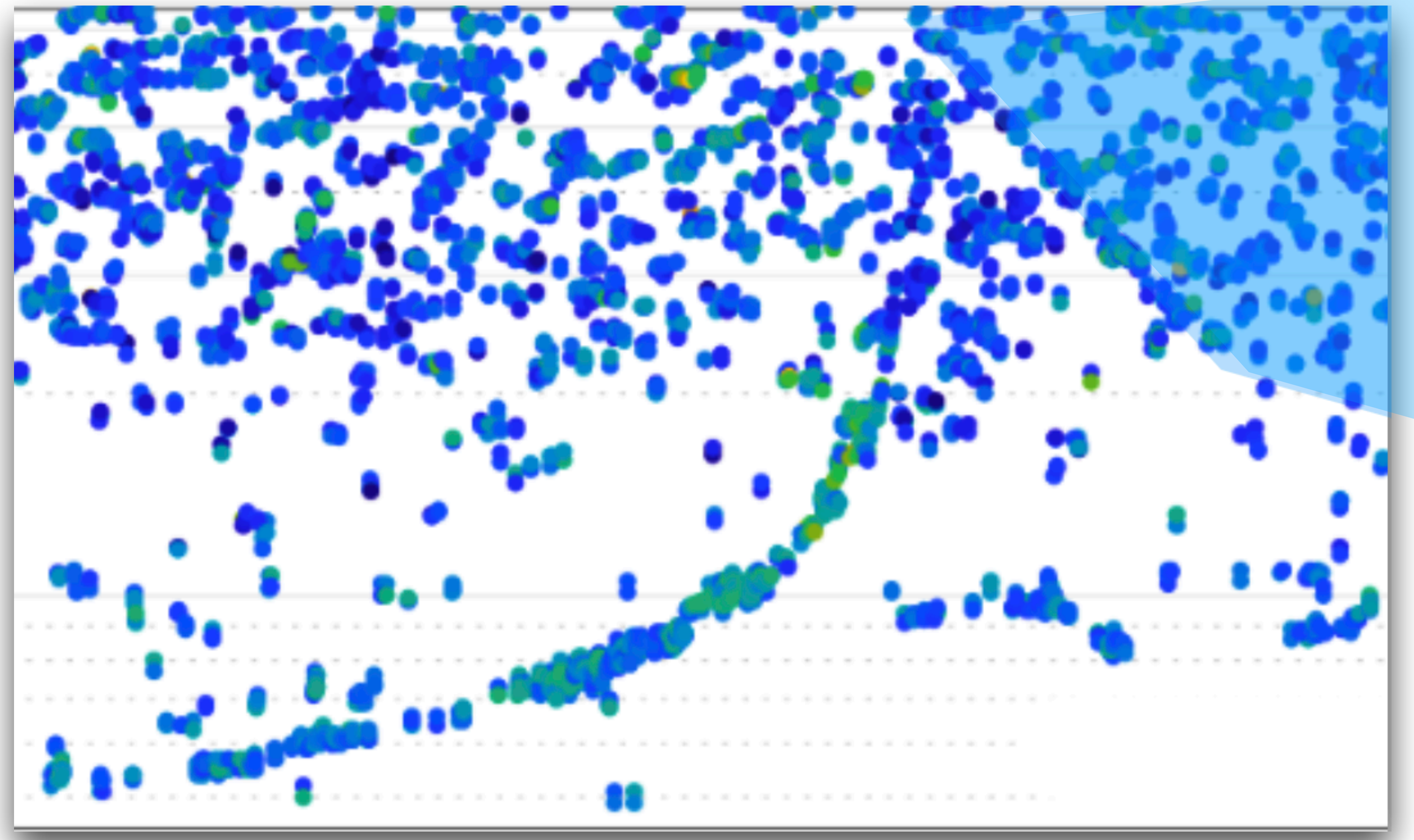


van Putten & Della Valle 2019 MNRAS 482 L46

$t_{delay} = 0.92$s 3.7s $T_{GW170817B} = 3.7$ s

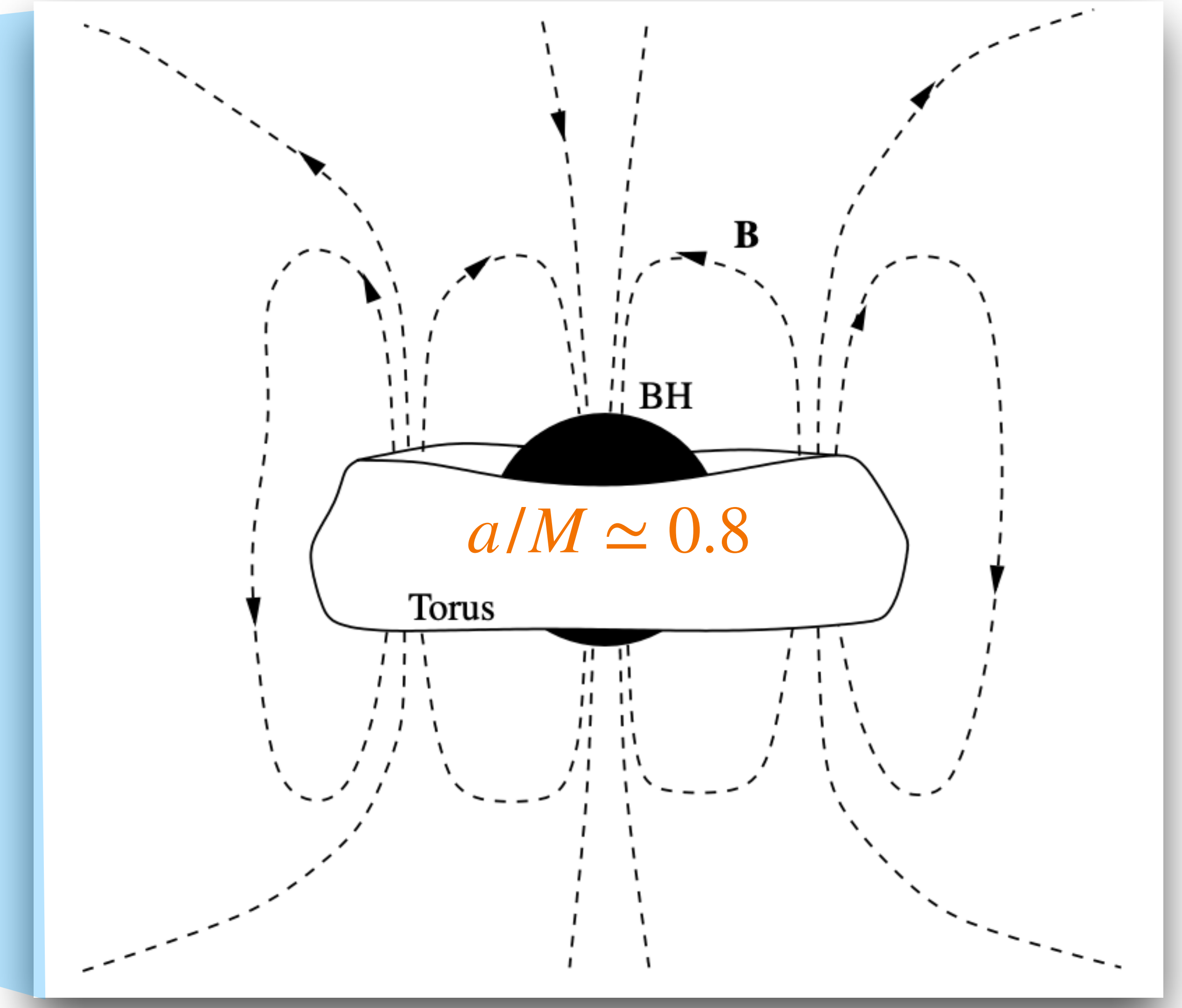
.. central engine and remnant

$F_5 - G_3^{\#}$



van Putten & Della Valle (2019)

E_{GW}



Radiative cooling mostly in GW-emission (PTP 2012)

DNS merger → HMNS → BH remnant

Scaling relation for BH central engines

$$200\,\mathrm{Hz}\left(\frac{2.5\,M_\odot}{M}\right) \lesssim f_{gw} \lesssim 700\,\mathrm{Hz}\left(\frac{2.5\,M_\odot}{M}\right)$$

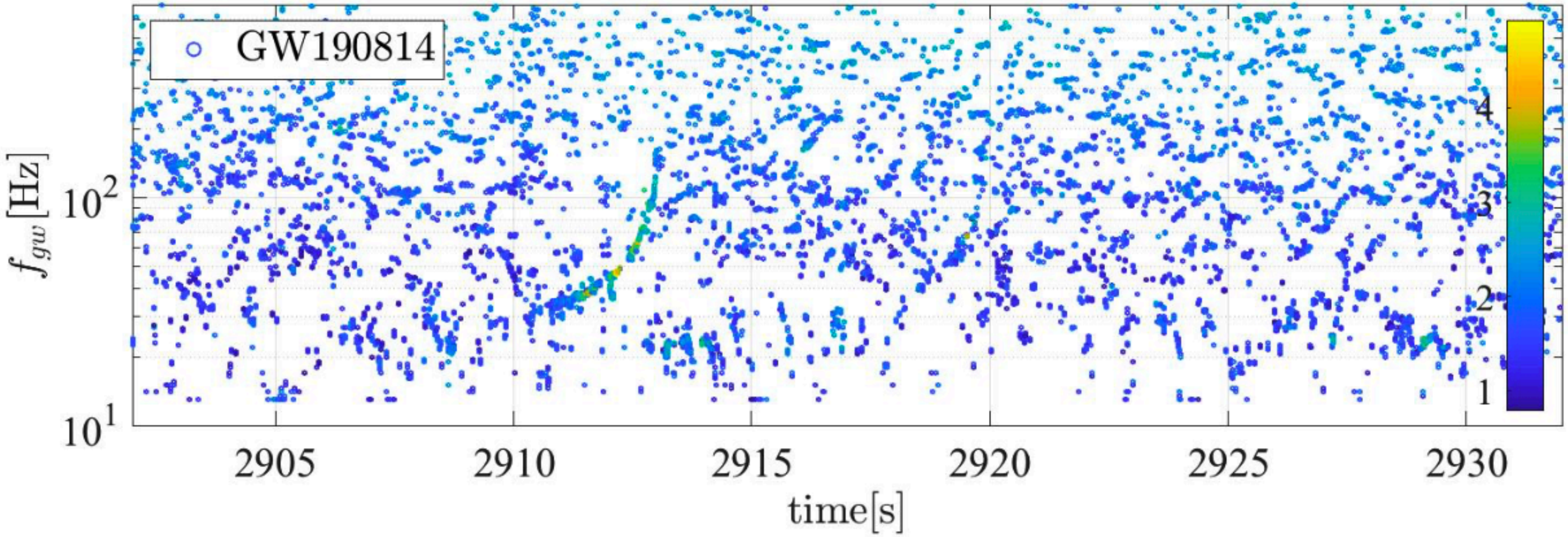
$$E_{GW} \simeq 3.5\,\%\,M_\odot c^2 \left(\frac{M}{2.5M_\odot}\right)$$

Abchouyeh, van Putten & Amati, 2023, ApJ, 952, 157
van Putten, Della Valle & Abchouyeh, in prep.

Detector-limited horizon distance to long-duration transients

… by un-modeled search

$$D = 240\,\mathrm{Mpc}$$



Horizon distance for CC-SNe?

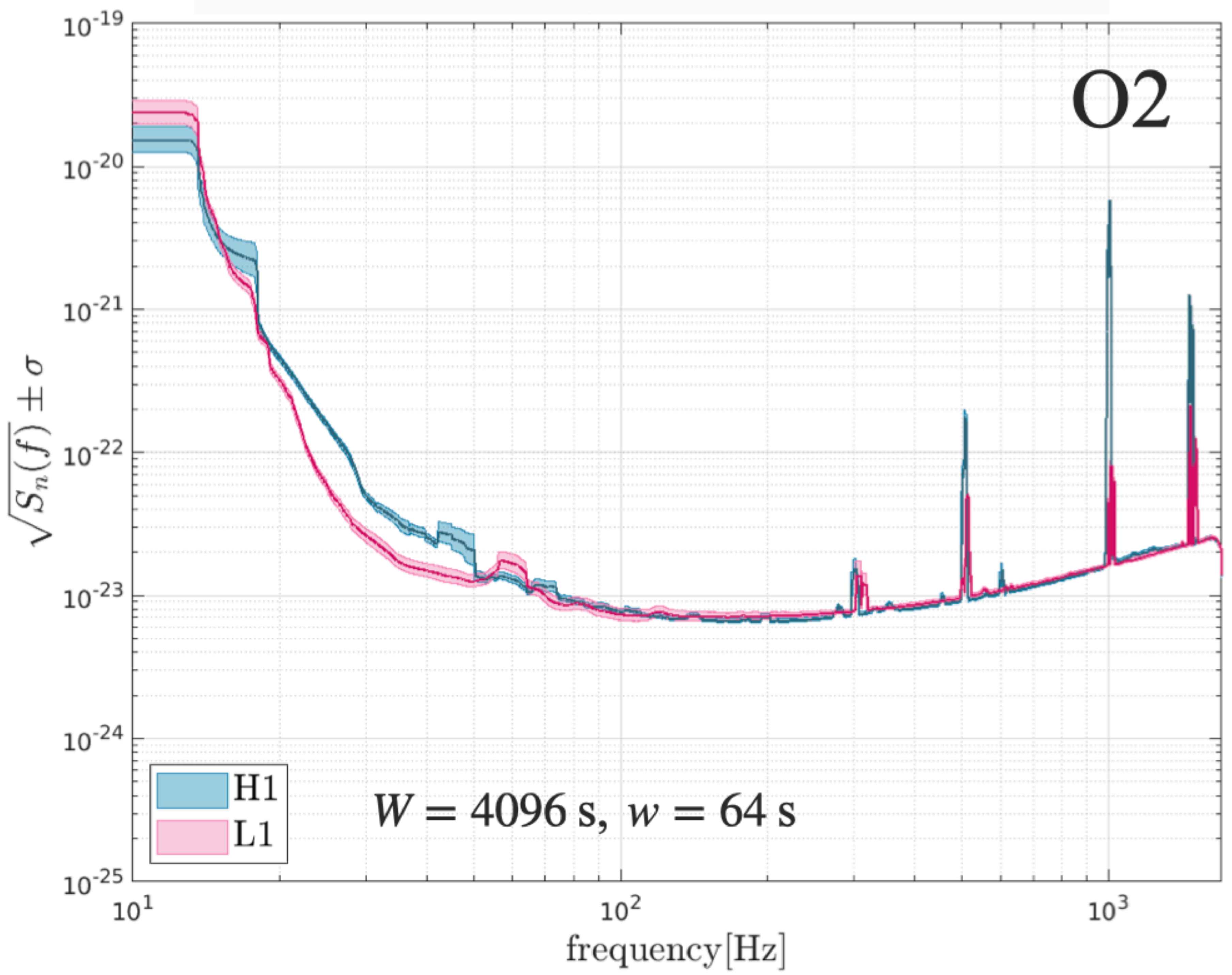
Progenitors $M_* \gtrsim 20M_\odot$ are expected to produce BH central engines of mass $M \gtrsim 5M_\odot$

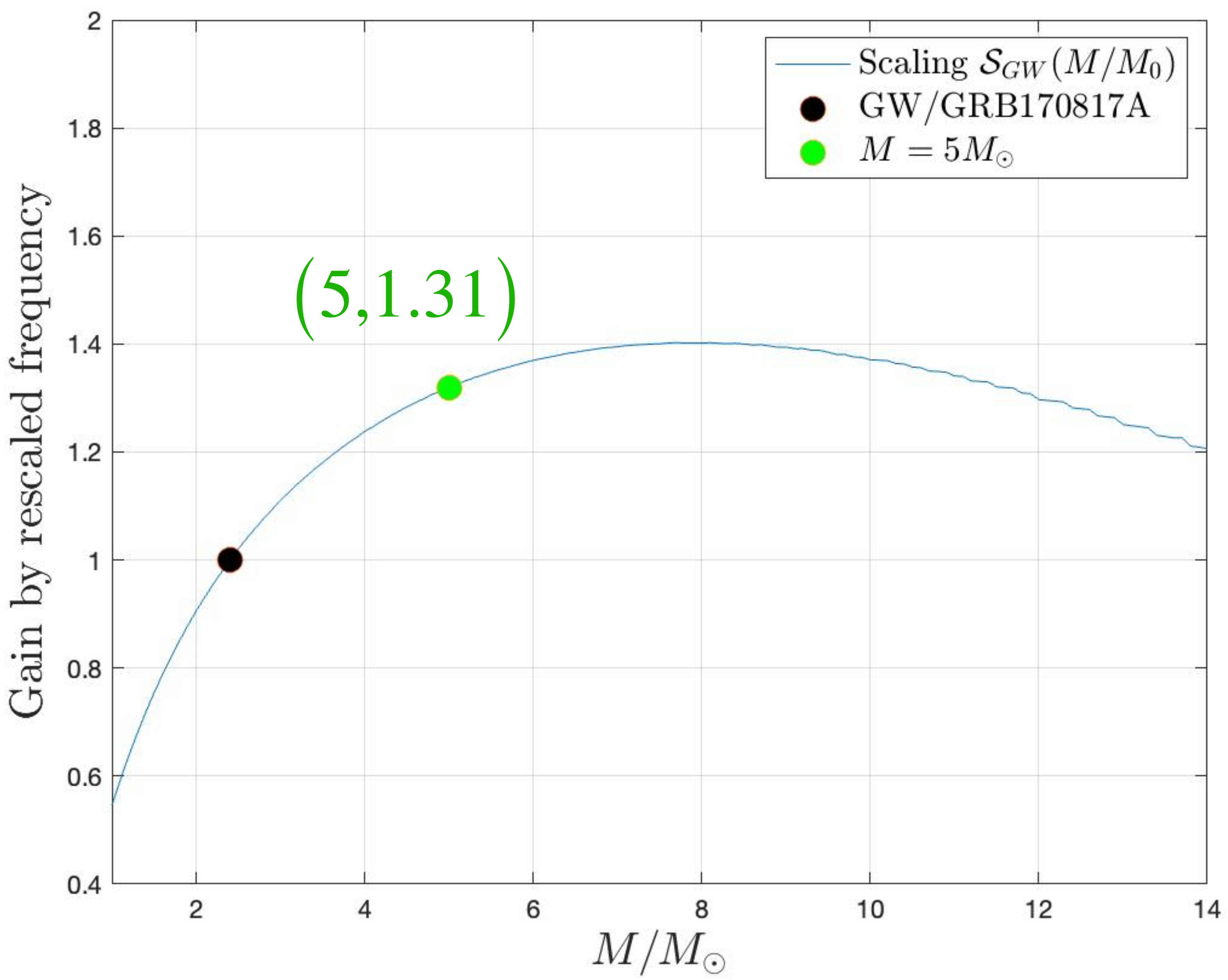
Compared to GW170817B/GRB170817A, this poses three advantages

- k_S: Scale to lower GW-frequency, overlap with bandwidth of maximal sensitivity $B \simeq \left(100 - 250\right)\,\mathrm{Hz}$
- k_E: Scale to more GW-energy, assuming similar Kerr parameter $a = J/M$
- k_D: Scale to more distant horizon distance by detector sensitivity improvement O4 over O2

van Putten, Della Valle, Abchouyeh, in prep.

Horizon distance (I)





$k_s = 1.31$: gain by frequency scaling, moving closer to the trough of optimal sensitivity

$k_E = \dfrac{M}{2.5M_\odot}$: gain by energy scaling in $h_{char} = \dfrac{\sqrt{2}}{\pi D}\sqrt{\dfrac{E_{GW}}{|S|}} \simeq \dfrac{M}{D}\sqrt{\dfrac{\mathcal{E}_{GW}}{M}} \propto M$

van Putten, Della Valle, Abchouyeh, in prep.

Horizon Distance (II)

For CC-SN, expect $M \gtrsim 5M_\odot$

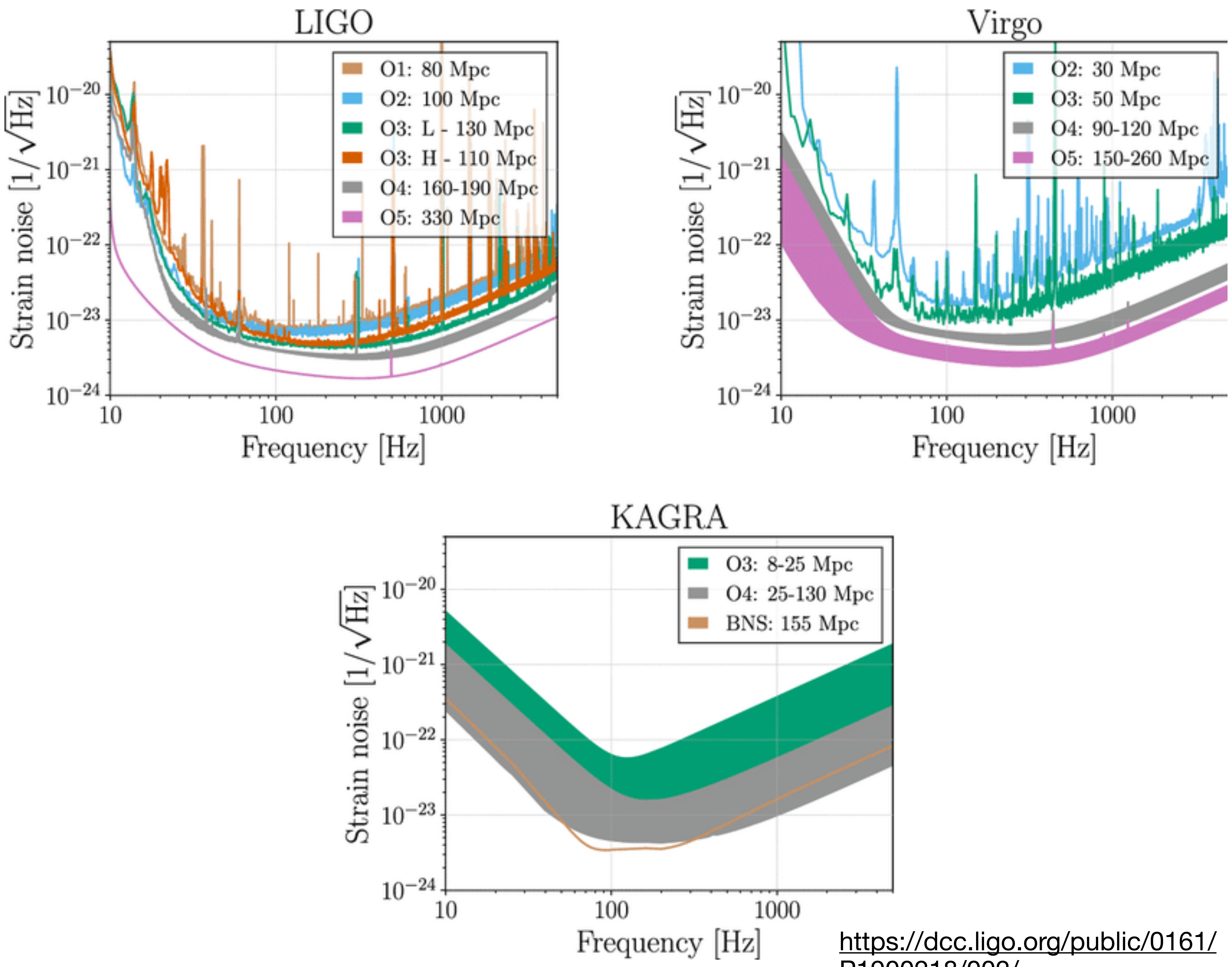
$$k_s \gtrsim 1.31$$

$$k_E = \frac{M}{2.5M_\odot} \gtrsim 2$$

$$k_D = \frac{[\mathrm{O4}]}{[\mathrm{O2}]} \simeq 1.6$$ (detector improvement)

Total gain over GW170817B/O2

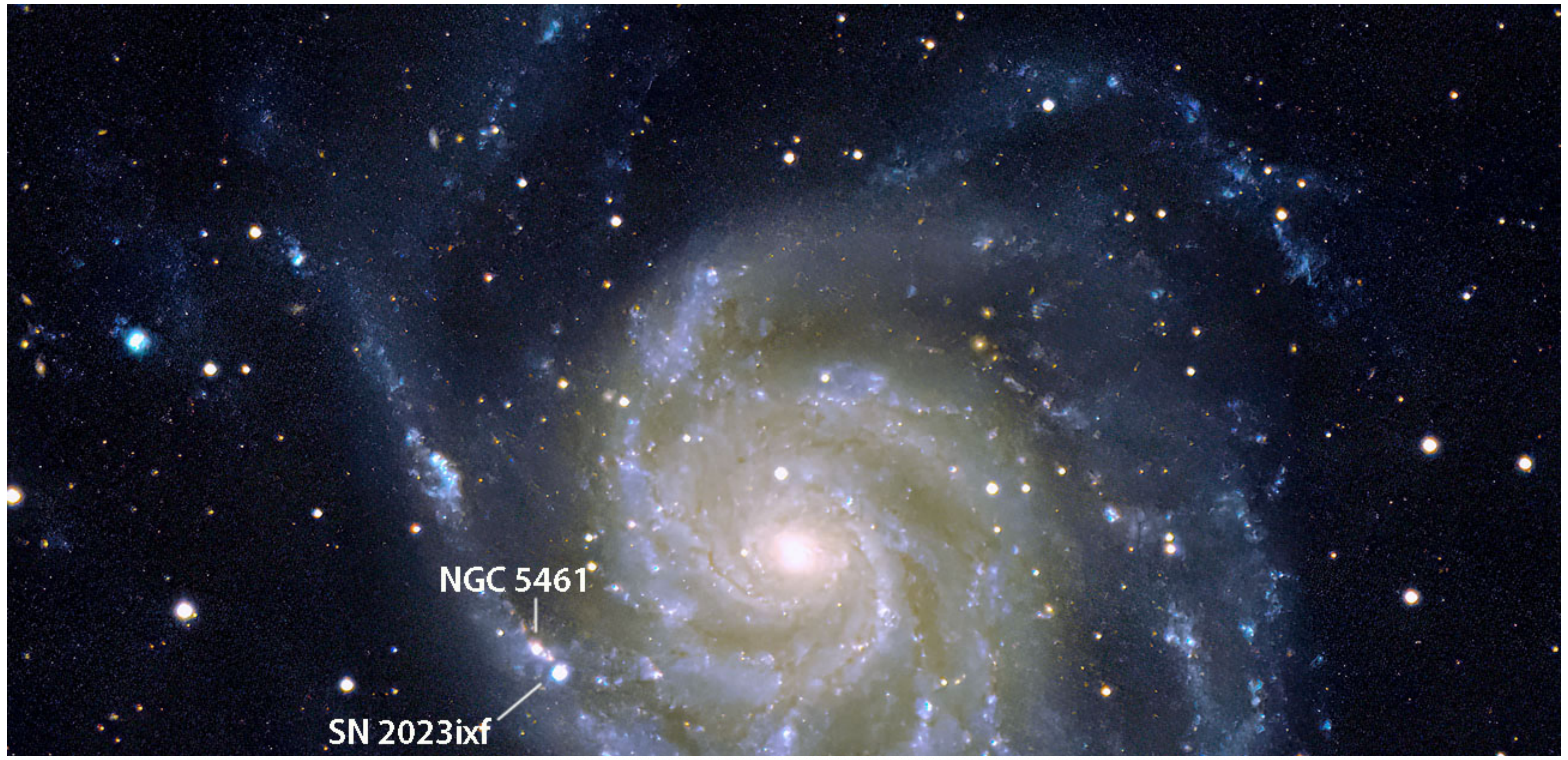
$$k = k_S k_E k_D = 4.33$$

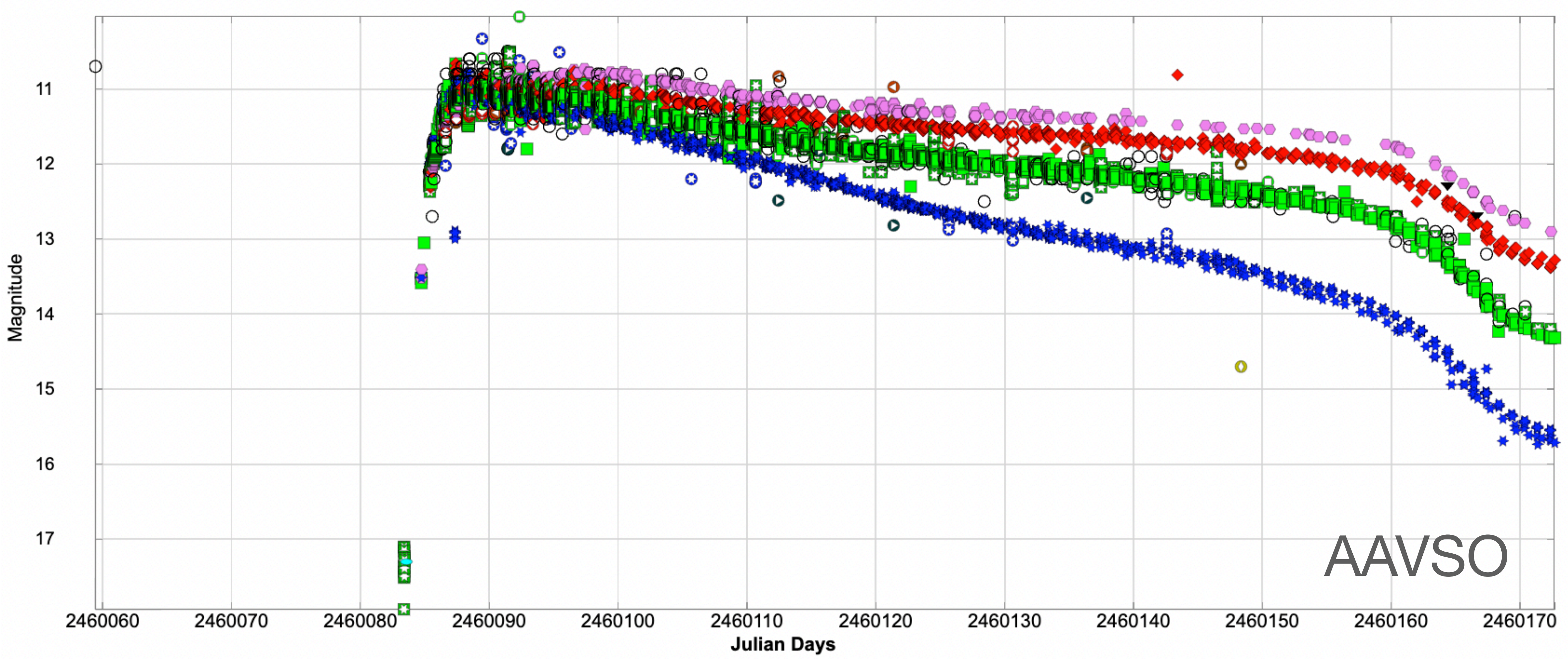


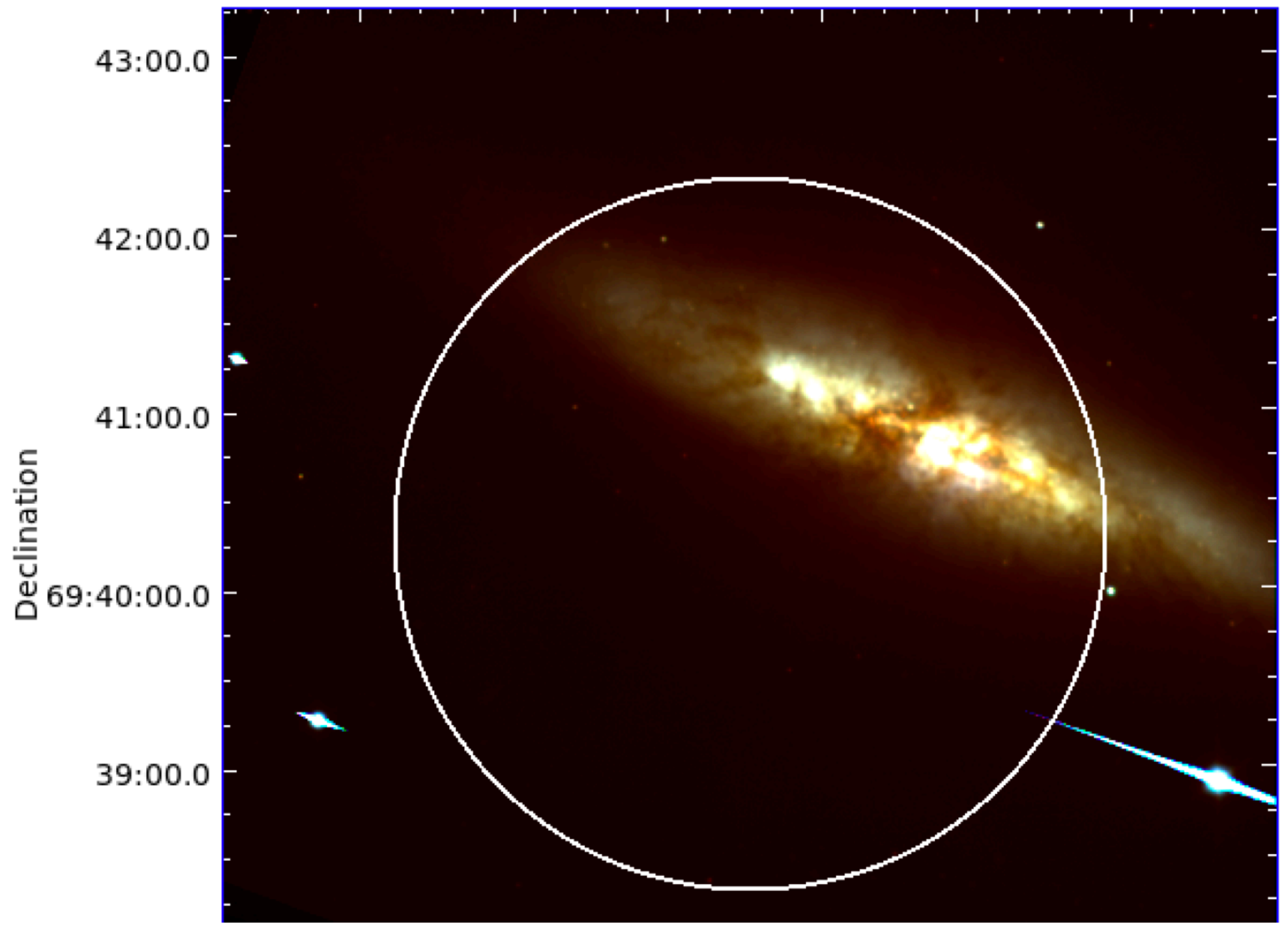
https://dcc.ligo.org/public/0161/P1900218/002/SummaryForObservers.pdf

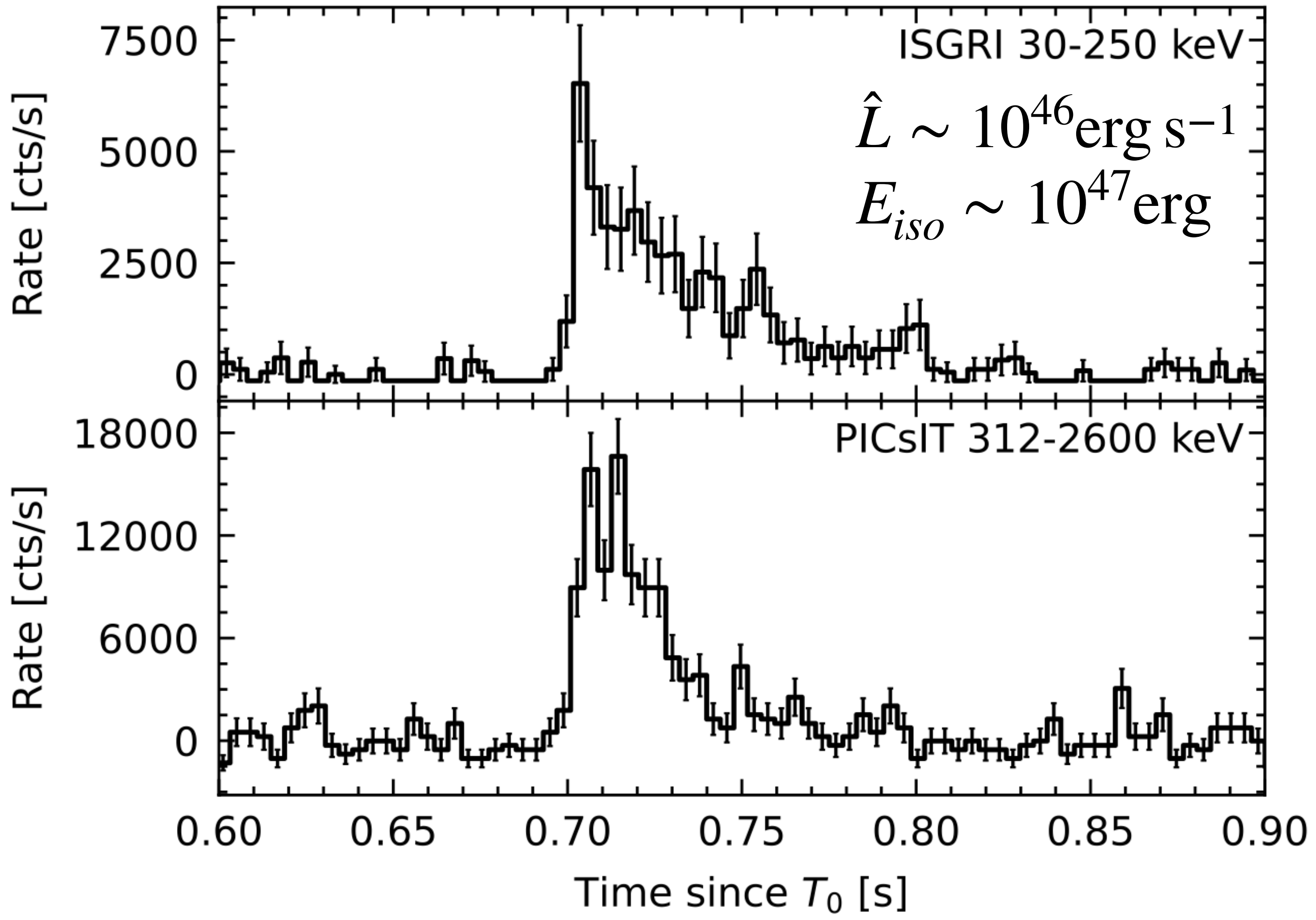
O4 horizon distance to BH central engines $\sim 160\,\mathrm{Mpc}$

SN 2023ixf ($D \simeq 7\,\mathrm{Mpc}$)









Mereghetti , S., et al., 2023, arXiv:2312.14645v1

… observational opportunity

M101 is 6 times closer than GW170817
O4 is 1.6 times more sensitive than O2

Detection threshold by scaling of $\sim 1\,\%\,M_\odot c^2$ in probe of GW170817/O2

$$\mathcal{E}_{GW,th} \simeq \frac{1\,\%\,M_\odot c^2}{120} \simeq 0.01\,\%\,M_\odot c^2 = 10^{-4} M_\odot c^2 \text{ (<1 kHz)}$$

Use-case

- Confidently detect or rule out BH spin-down (<1kHz)
- Put new astrophysical bound(s) on new-born NS (>1kHz)

Conclusions and outlook

Un-modeled GW-observations: new probe of CC-SNe event sequence "*progenitor mass - central engine - final remnant*"

Identify un-expected signals in the run-up (e.g. Imshennik & Ryazhskaya, 2004, Astron. Lett., 30, 14)

Detect or rule out BH central engines

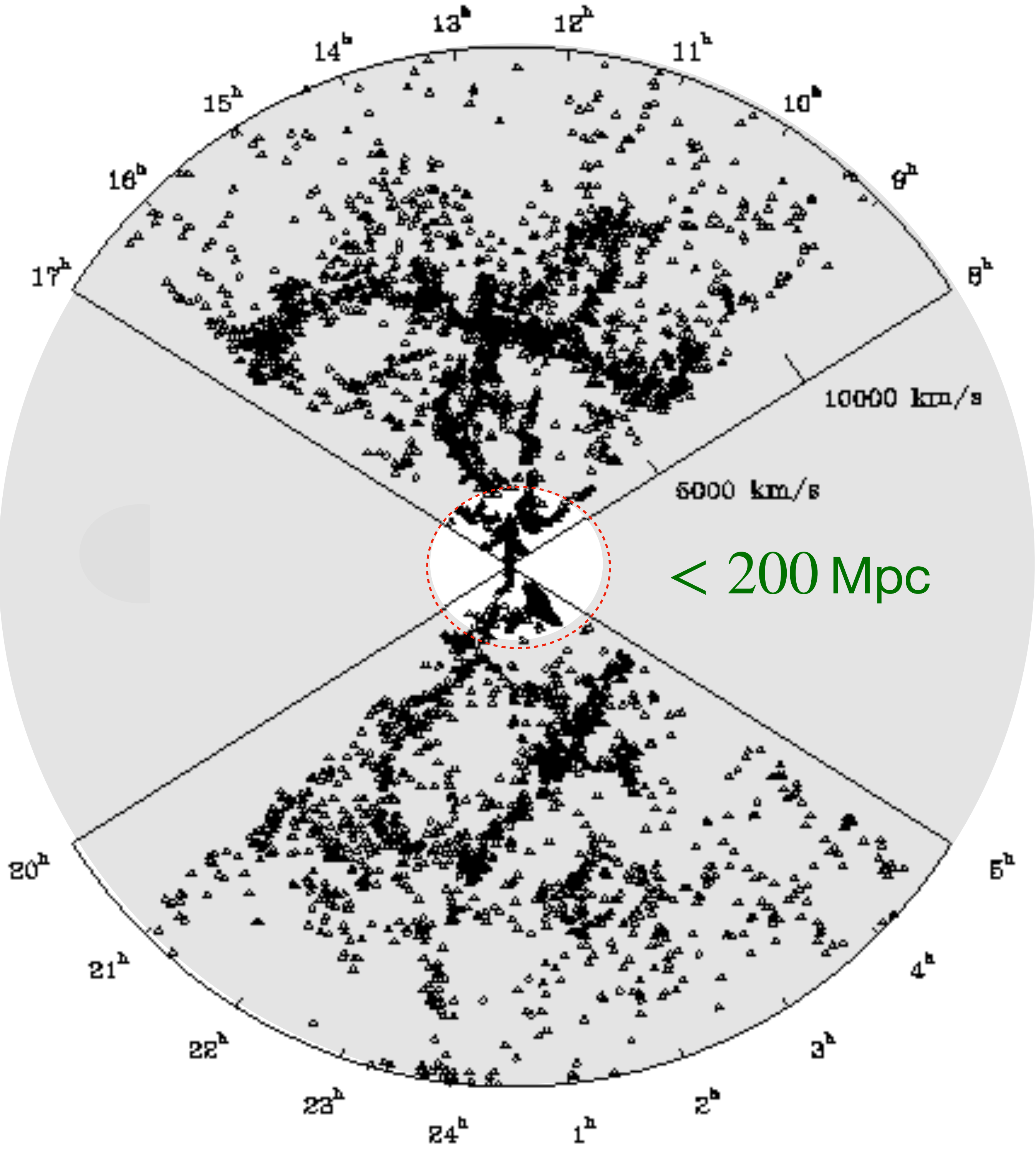
$$200\,\mathrm{Hz}\left(\frac{2.5\,M_\odot}{M}\right) \lesssim f_{gw} \lesssim 700\,\mathrm{Hz}\left(\frac{2.5\,M_\odot}{M}\right)$$ (scaling of GW170817B)

O4 horizon distance: $\sim 160\,\mathrm{Mpc}$.

SN2023ixf (M101): if BH central engine is ruled out, then progenitor $< 20M_\odot$ (cf. Sanduleak –69 202 to SN1987A).

Extra slides

Detector-limited horizon distances

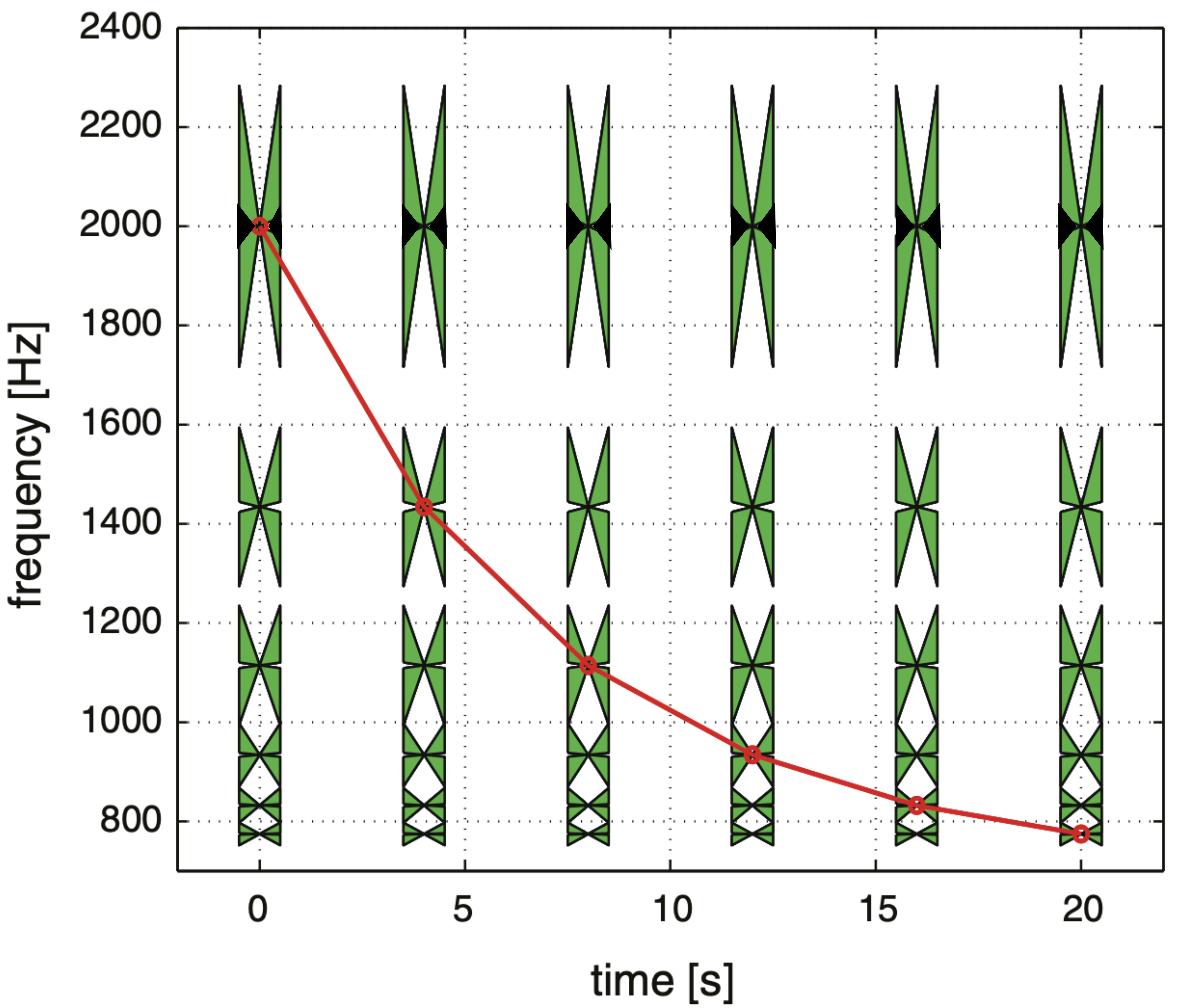


CBC realizes *detector-limited sensitivity* — limit of ideal matched filtering

Geller and Huchra 1989, Science 246, 897

Time-symmetric un-modeled searches

Equal sensitivity to ascending/descending chirps
Template bank: time-symmetric chirp-like templates

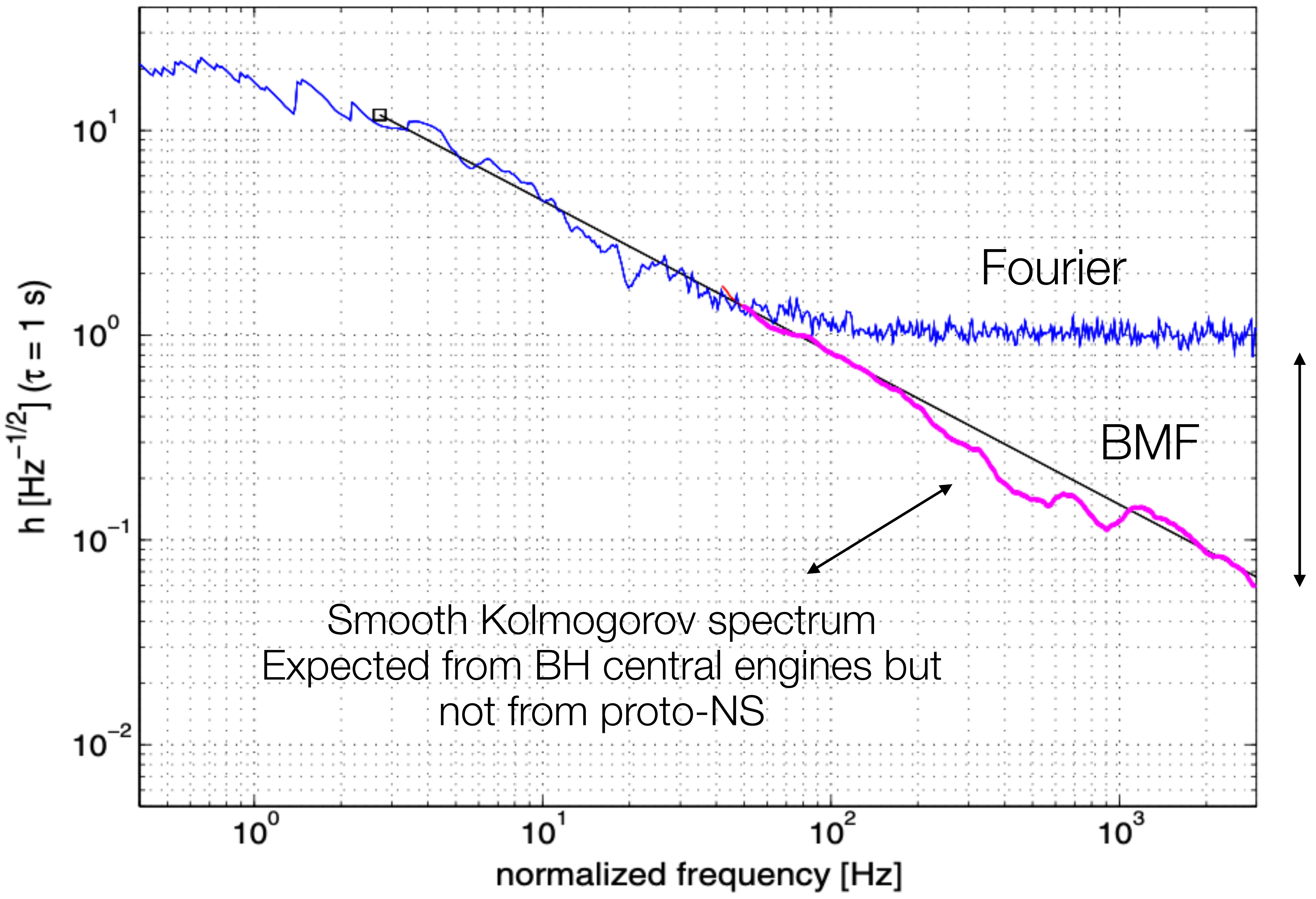


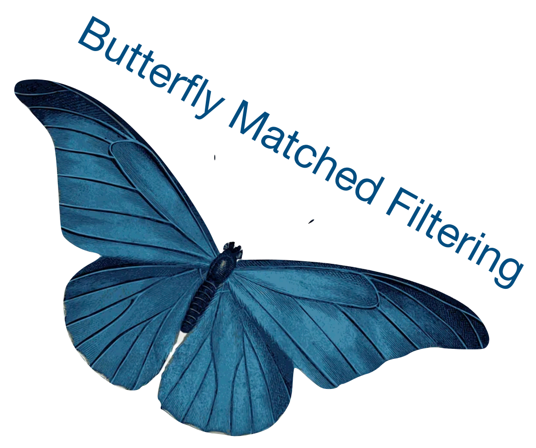
Butterfly matched filtering

BMF Kolmogorov spectra

van Putten, Guidorzi & Frontera ApJ (2014)

Bu





Gain

Sensitivity of BMF outperforms Fourier-based analysis by over one order of magnitude

BMF sensitivity gain

- Sensitivity to ascending/descending chirps on par with CBC

$$\text{gain over FFT} = \sqrt{\frac{N_n}{N_{FFT}}} \simeq \left(\frac{1}{2}(n+2)!\,\Delta N^{\frac{n}{2}}\right)^{\frac{1}{2(n+2)}} = 2.2\ (n=1)$$

- Gain $= \sqrt{2}$ gain $\simeq 3.11$ for joint (H1,L1)-observations

Equivalent to 10 years of improvement in detector sensitivity - bringing next-gen GW-detector sensitivity into view today