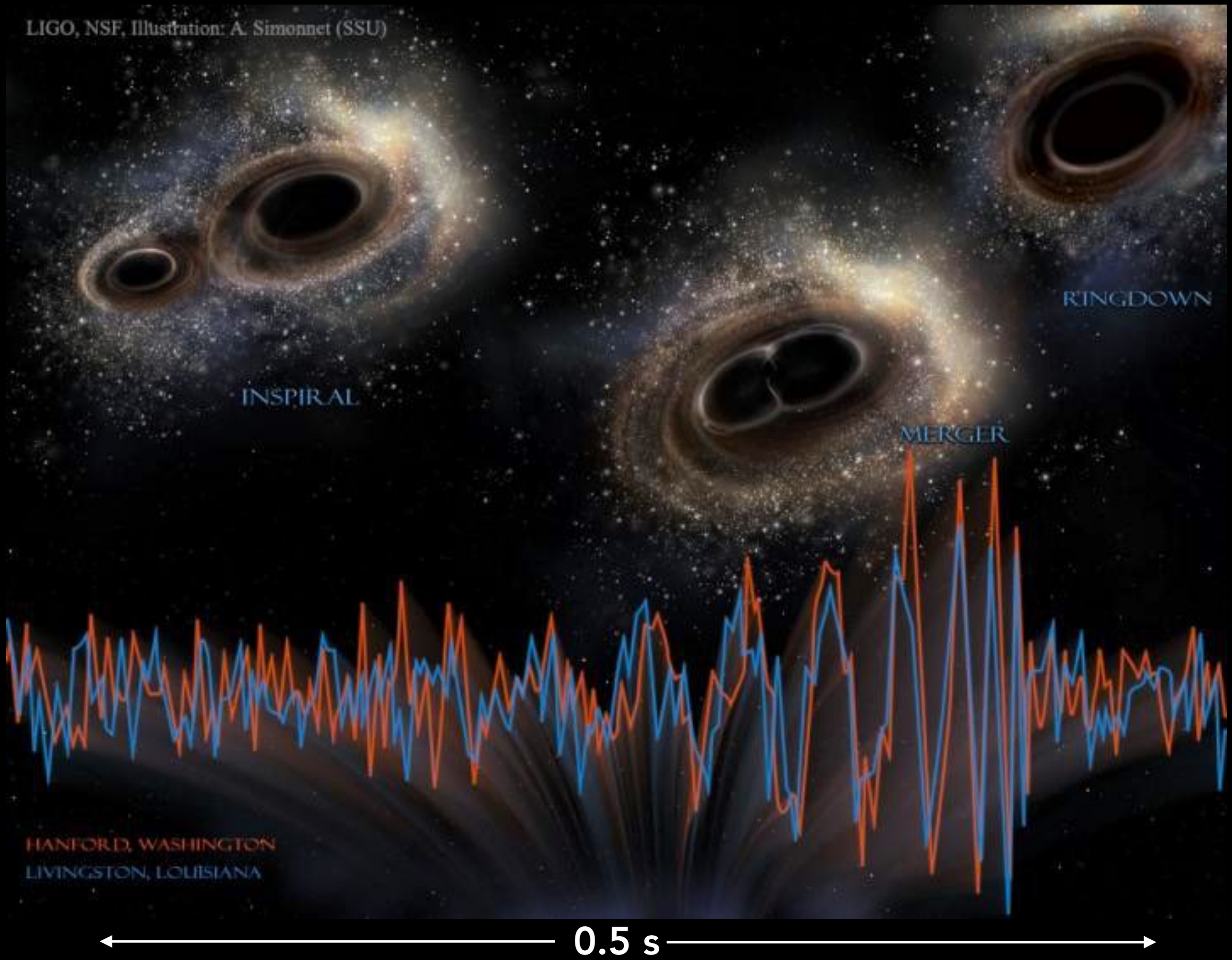
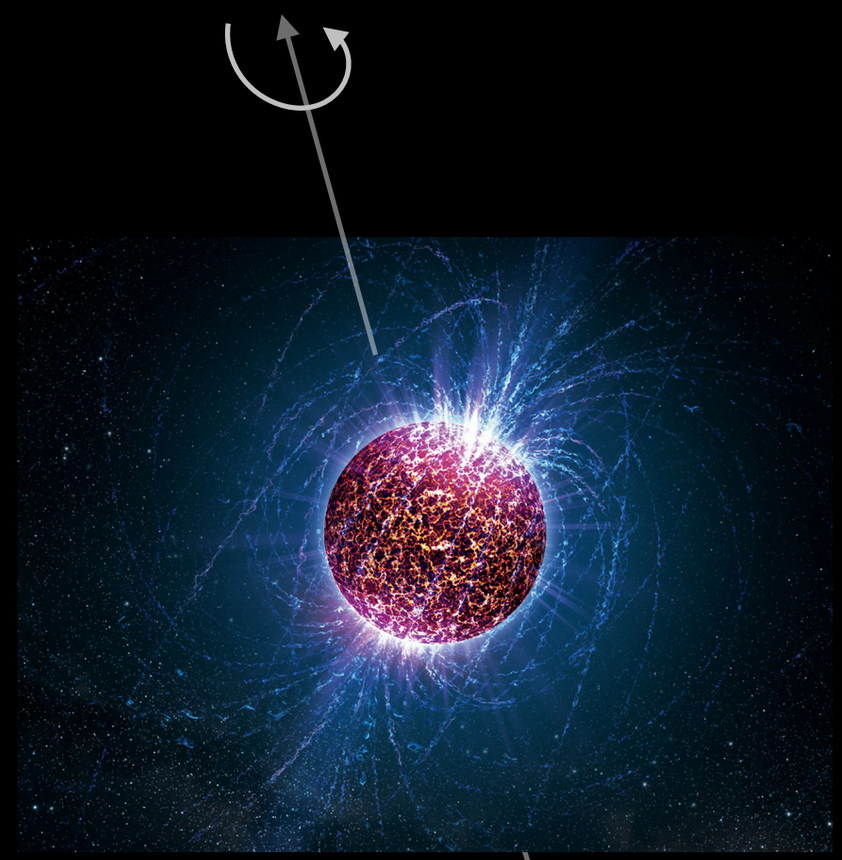
LATEST GRAVITATIONAL WAVE RESULTS

M. Alessandra Papa
Max Planck Inst. for Gravitational Physics, Hannover

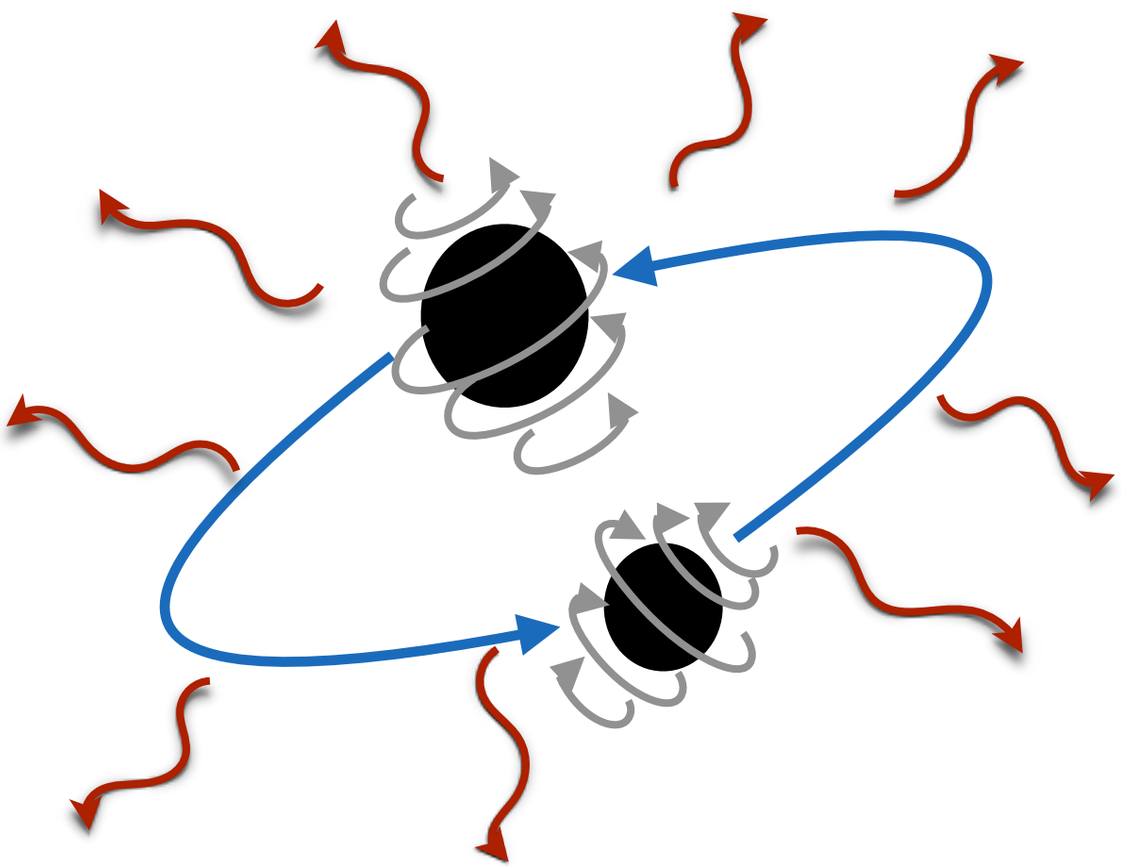

LIGO, NSF, Illustration: A. Simonnet (SSU)
INSPIRAL
MERGER
RINGDOWN
HANFORD, WASHINGTON
LIVINGSTON, LOUISIANA
0.5 s

THE NEXT BIG THING

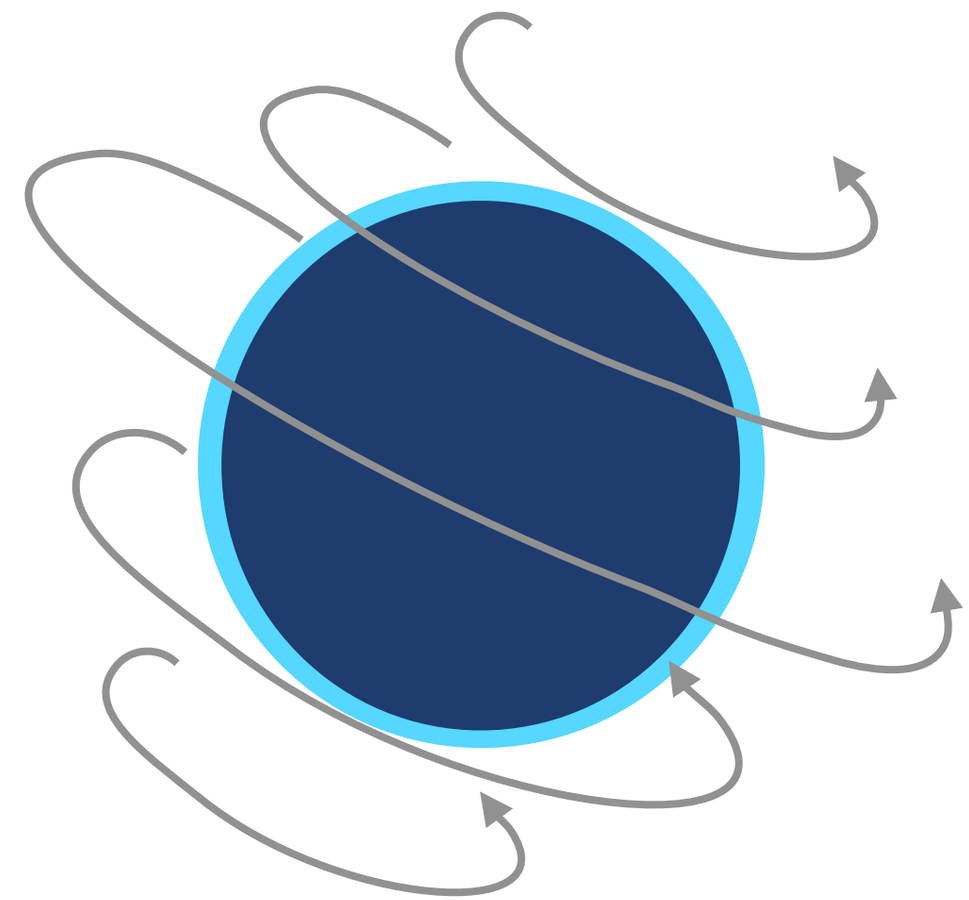


gravitational waves from
spinning neutron stars

Binary merger signals

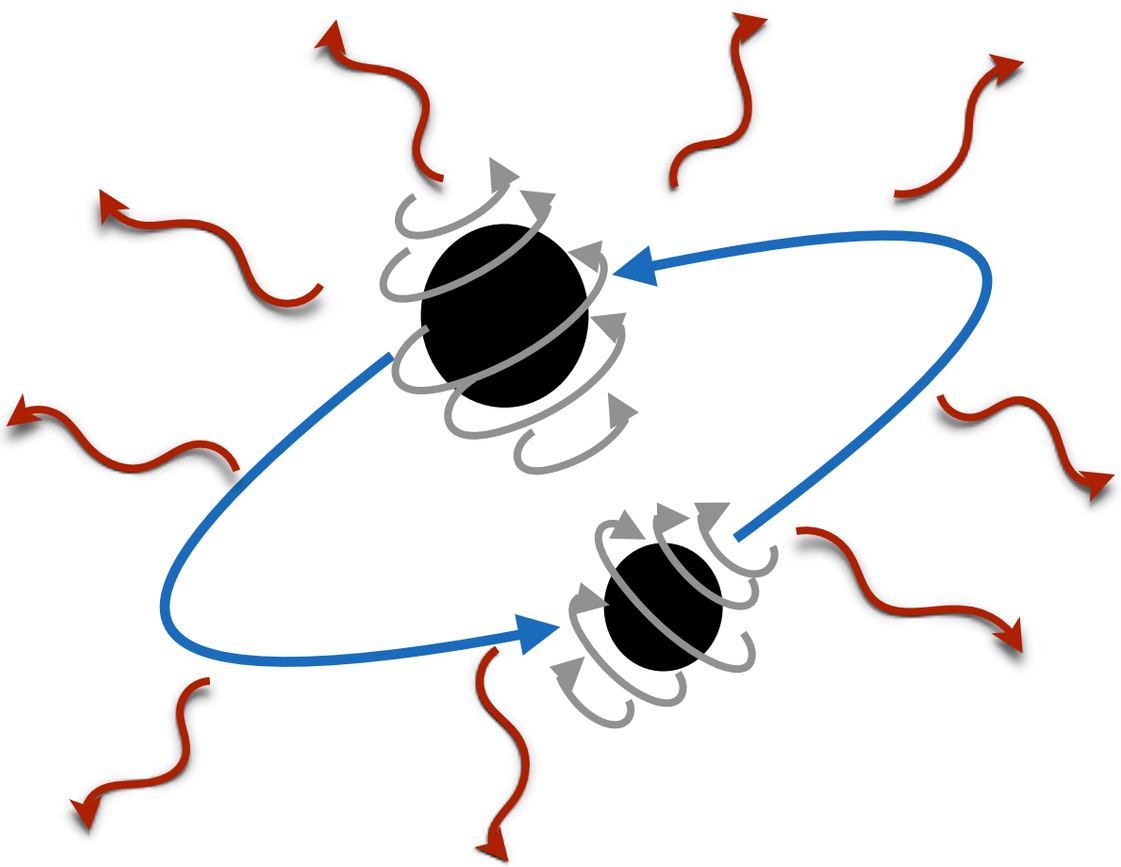


Spinning neutron star signals

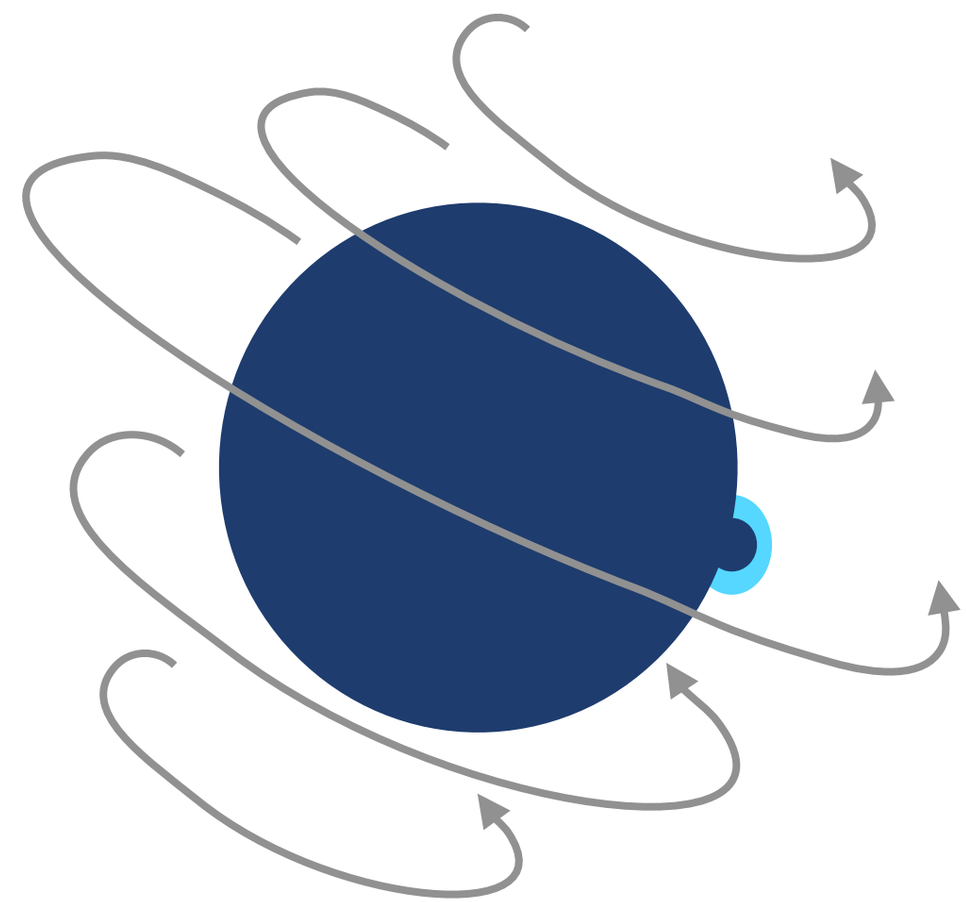


no gravitational waves

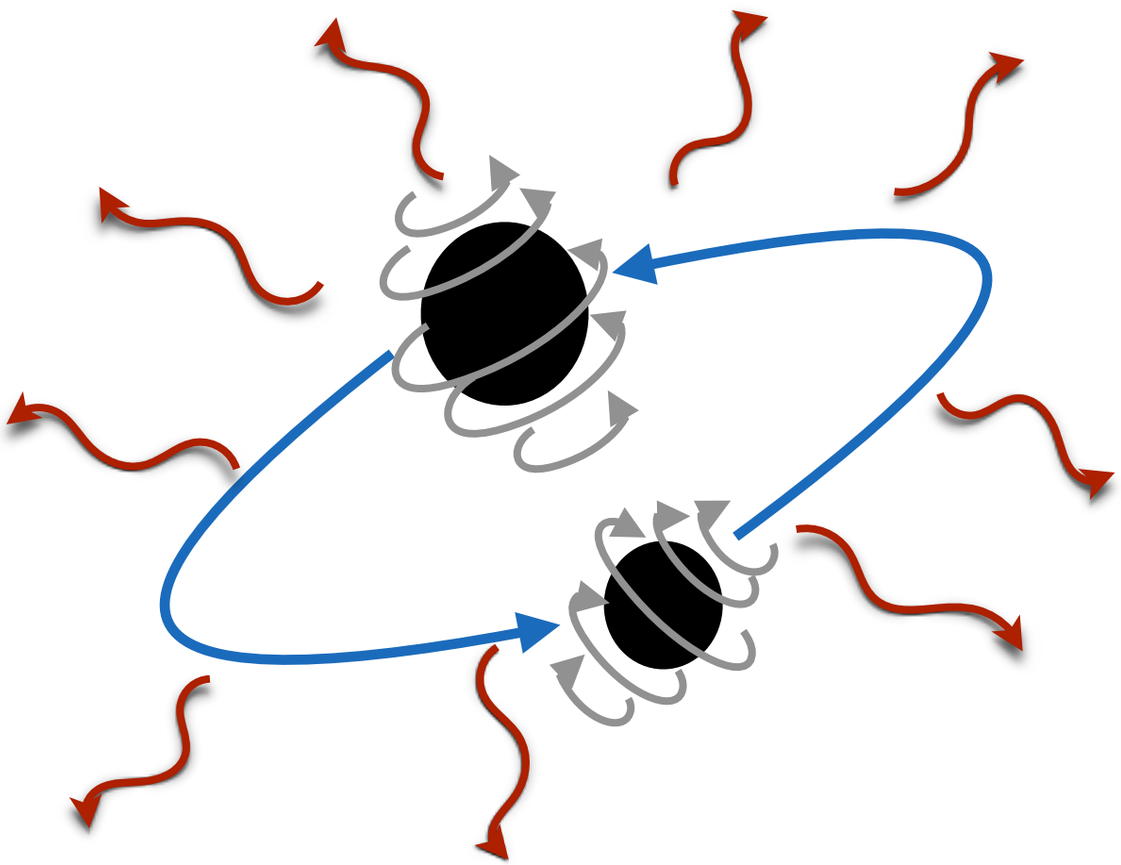
Binary merger signals



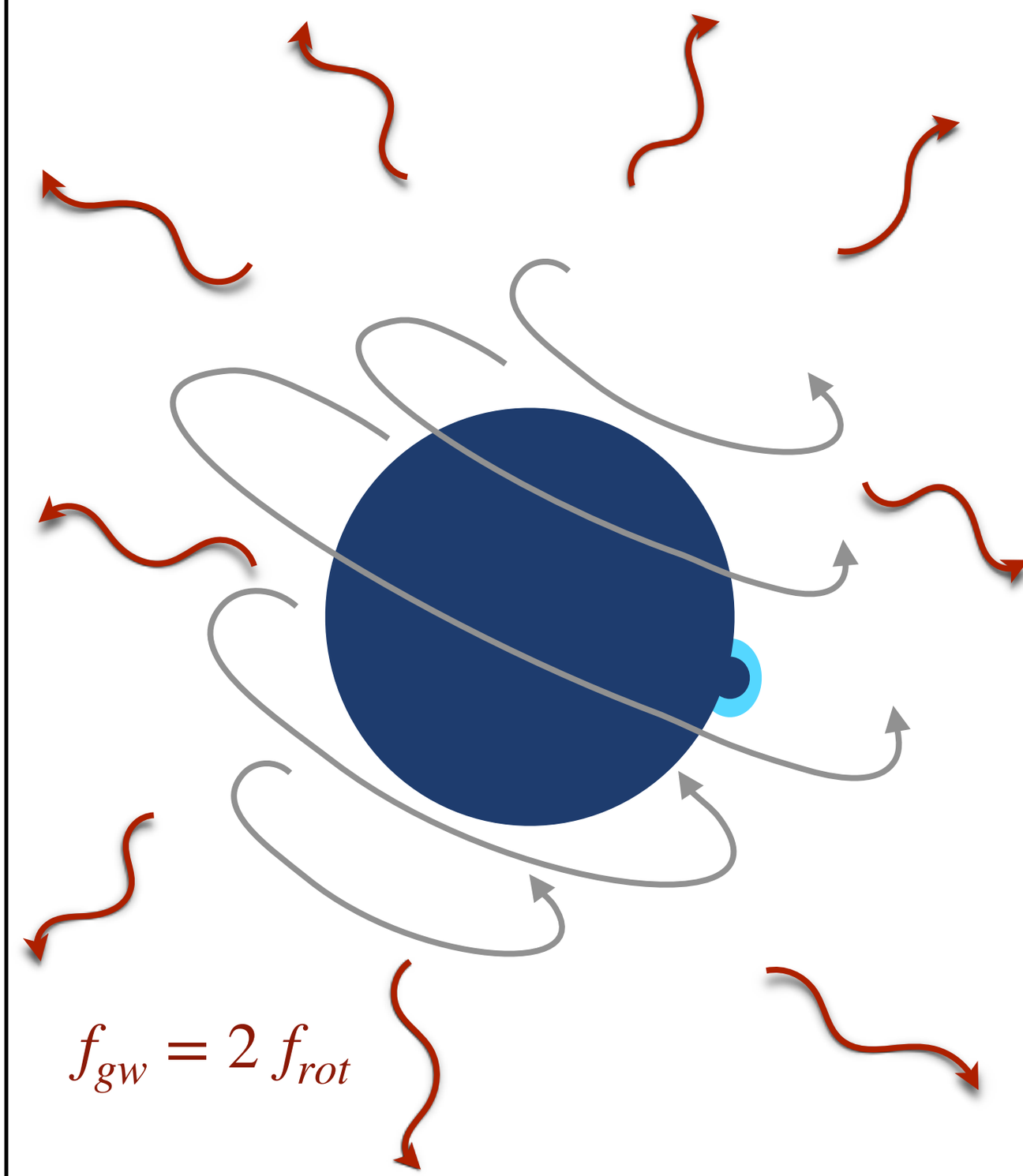
Spinning neutron star signals



Binary merger signals

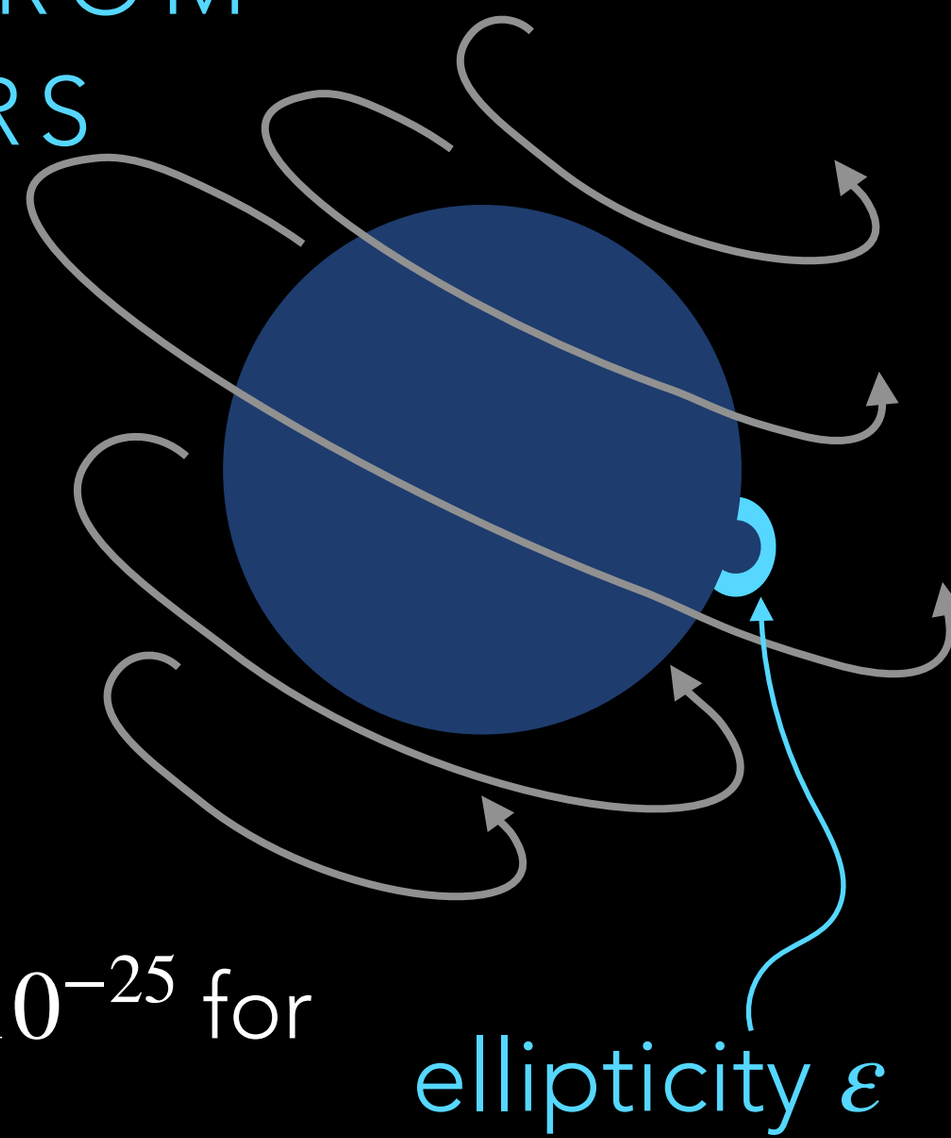


Spinning neutron star signals



gravitational waves !

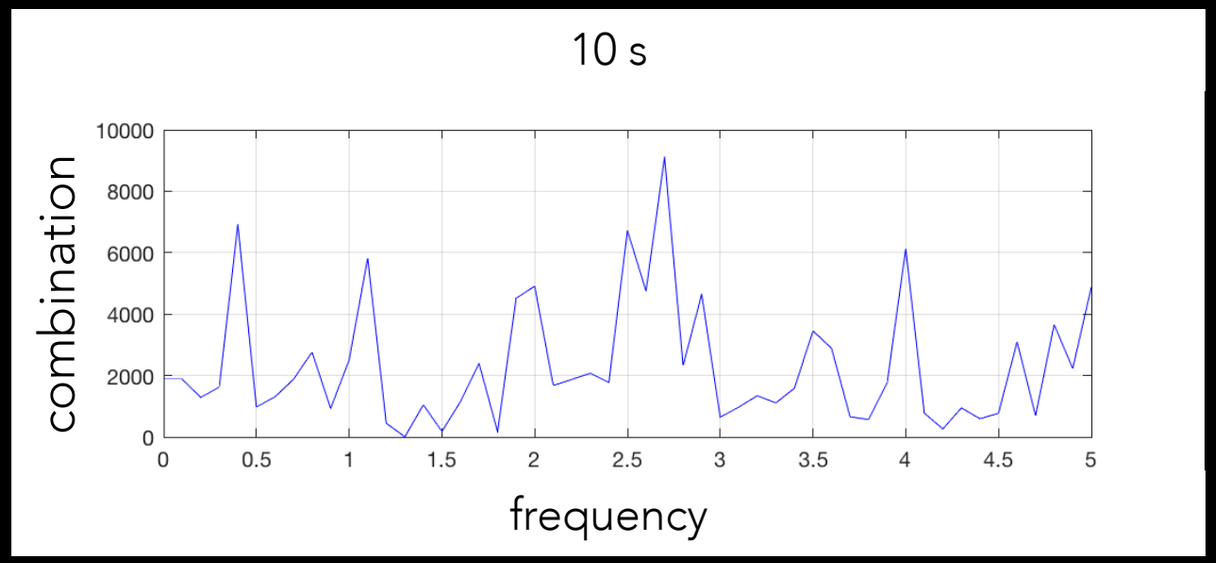
GRAVITATIONAL WAVES FROM SPINNING NEUTRON STARS

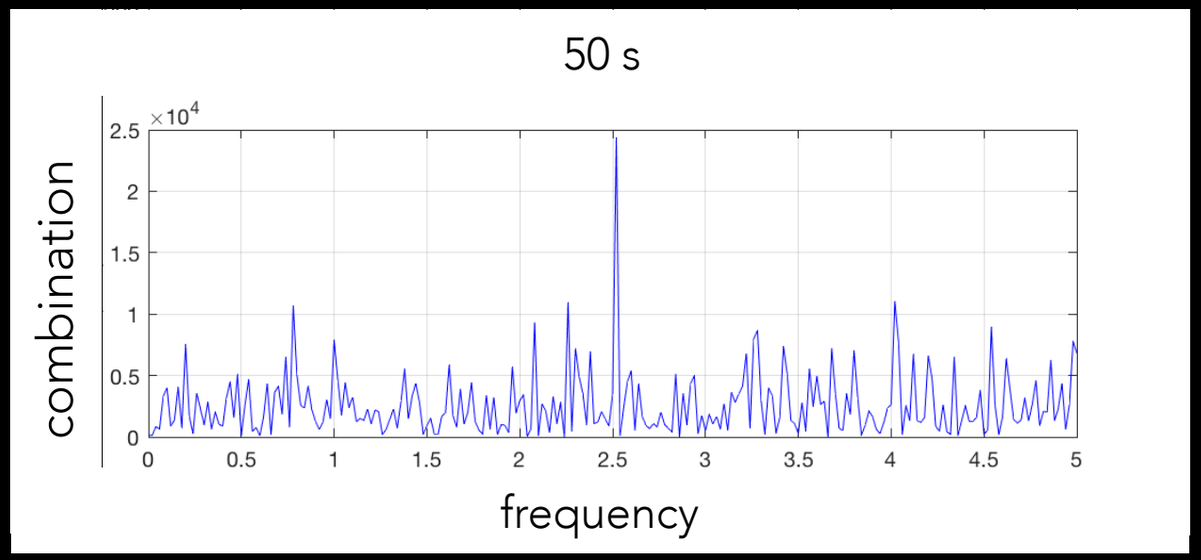


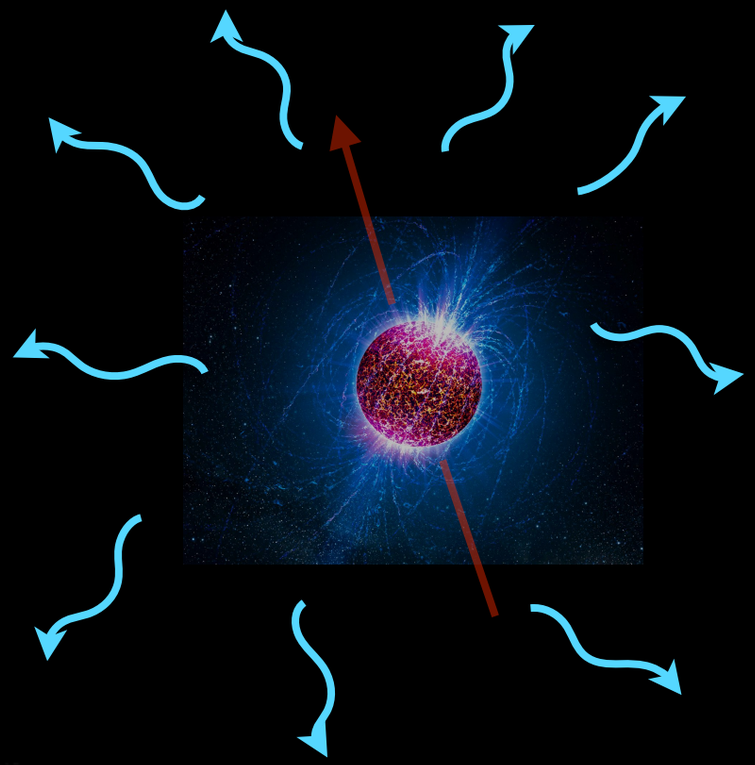
- signal always there
- very weak:
- amplitude $h_0 = \frac{2\pi^2 G}{c^4} \frac{I \varepsilon f_{gw}^2}{D} = 2 \times 10^{-25}$ for
  D=1 kpc
  $\varepsilon = 10^{-6}$
  $f_{gw} = 1$ kHz
- amplitude from binary merger $\approx 10^{-21}$

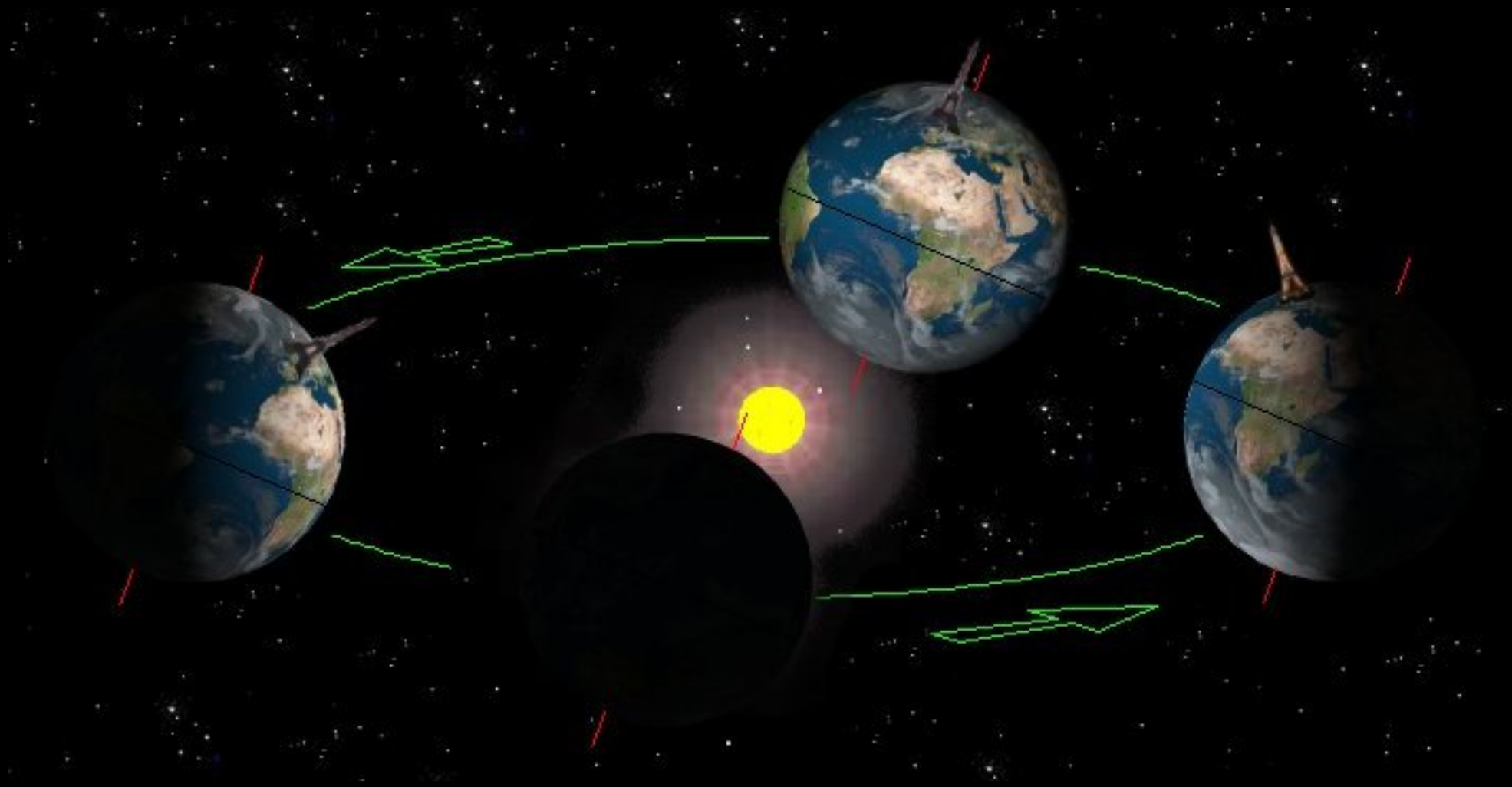
THE LONGER THE OBSERVATION IS, THE BETTER

basic idea: combine the data, the signals adds coherently, the noise does not



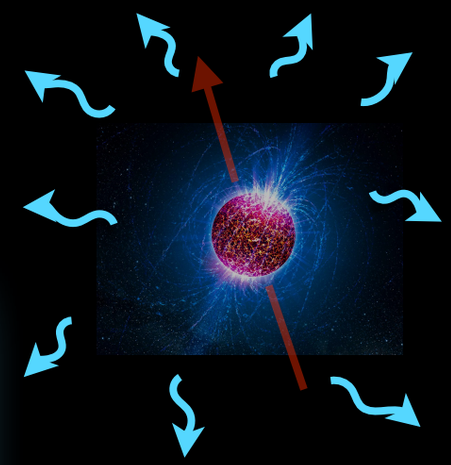


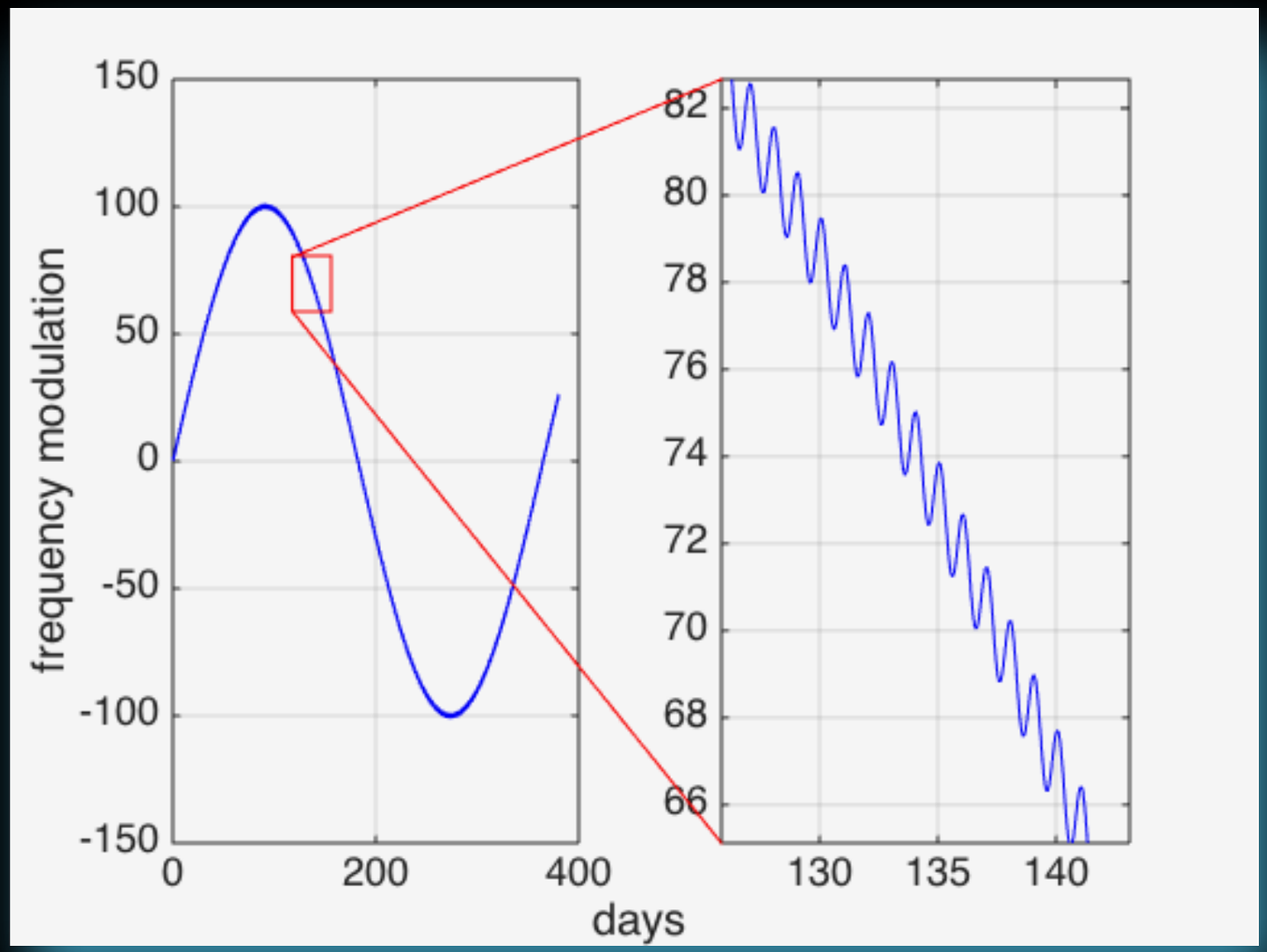


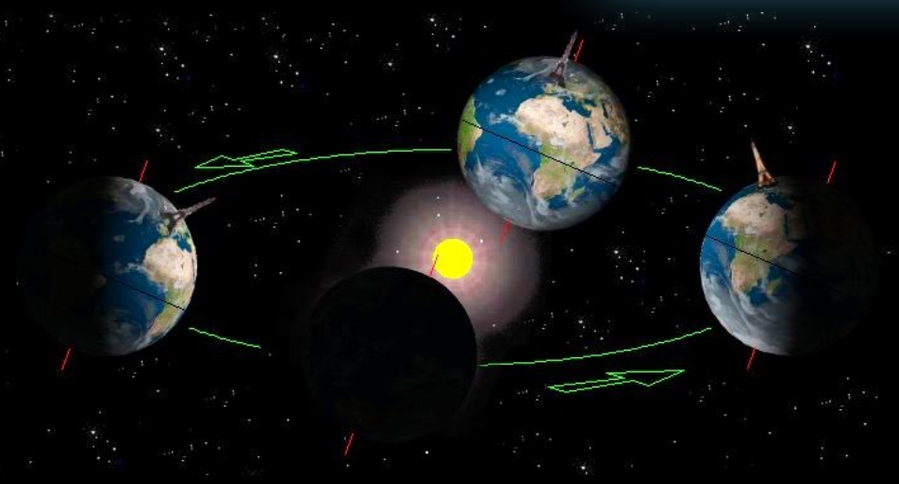


obviously not to scale !

SIGNAL AT THE DETECTOR IS MODULATED







obviously not to scale !

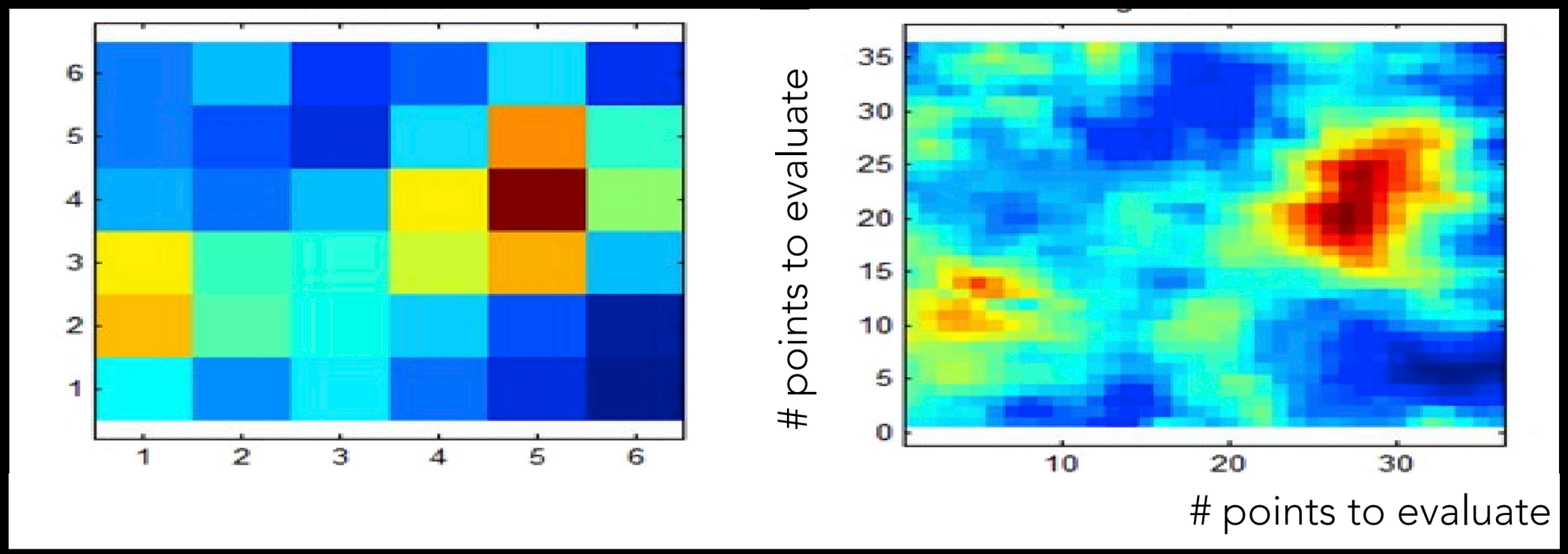
RESOLUTION GROWS WITH OBSERVATION LENGTH

- if now does not know the source of the signal, the data needs to be differently combined for every tentative frequency value and for every sky position

- number of points to evaluate quickly grows with observation time ($\propto T^5$ for a typical all-sky search)

duration X

duration 6X



same patch of sky

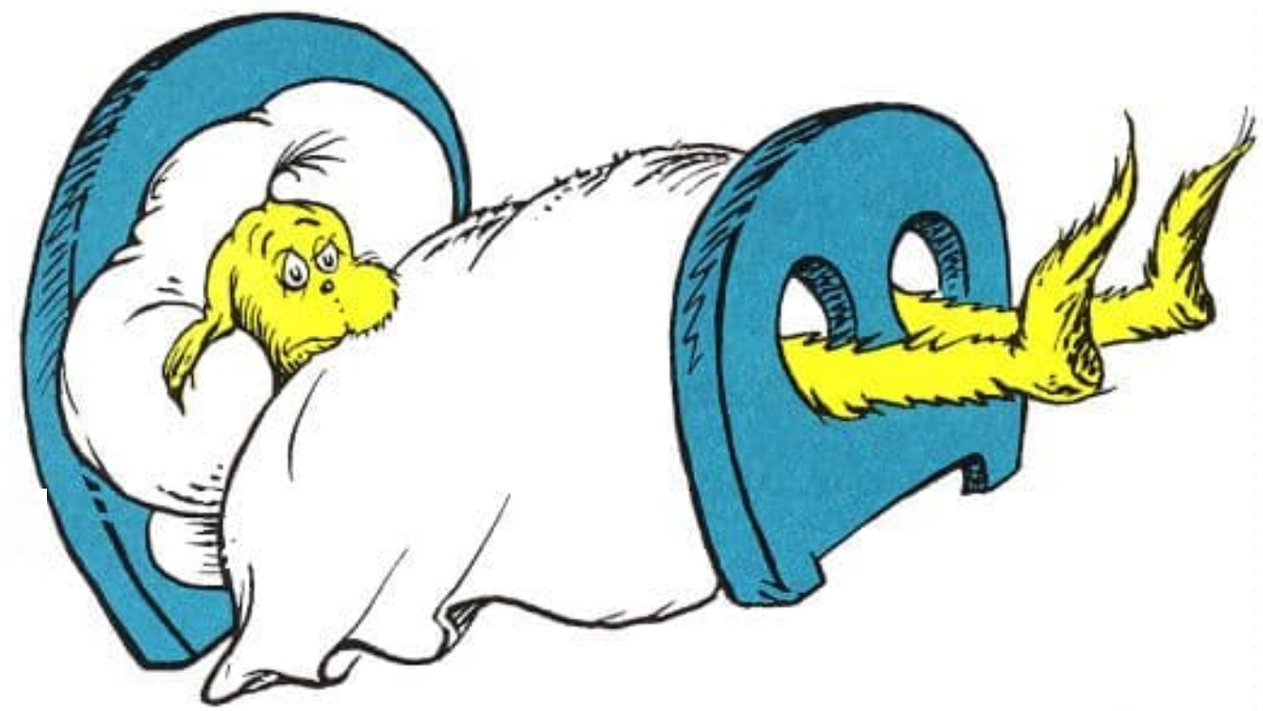
MOST CHALLENGING DETECTION PROBLEM OF GW ASTRONOMY

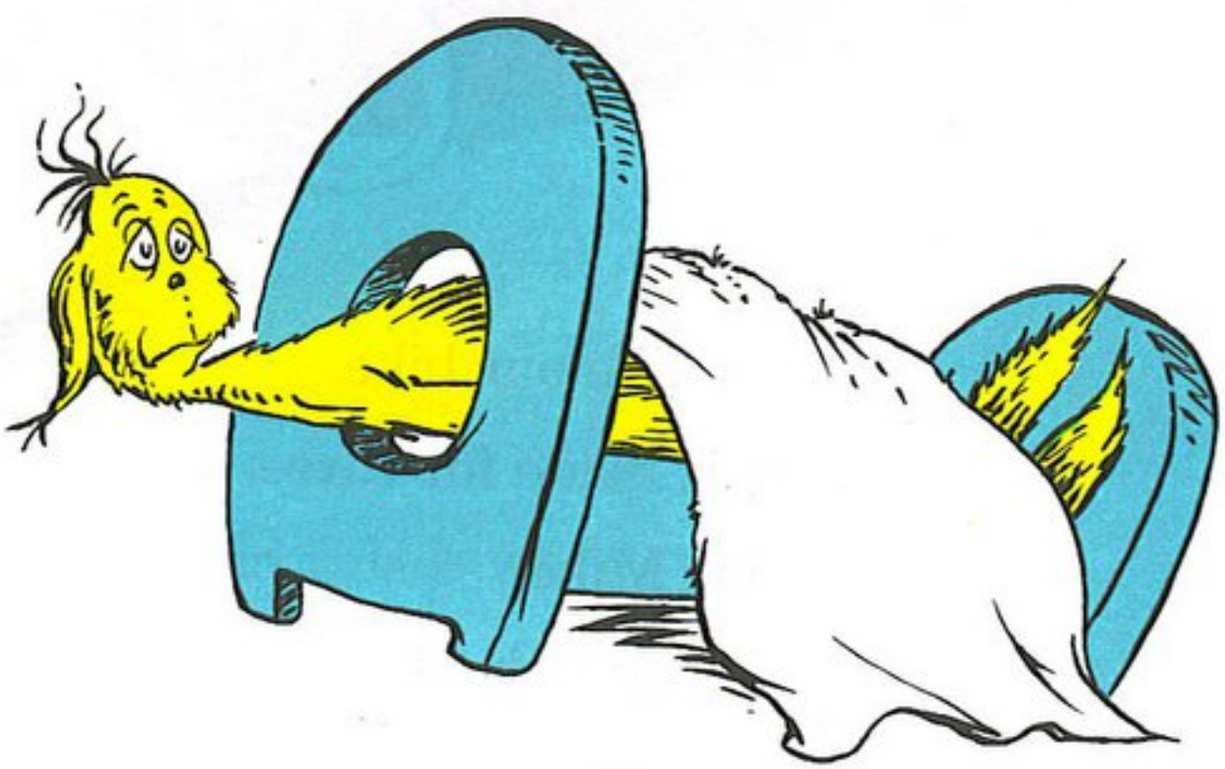
$\approx 10^{26}$ waveforms resolvable with 1 year of data

OPTIMAL SEARCH METHODS CANNOT BE USED

- have to develop new methods

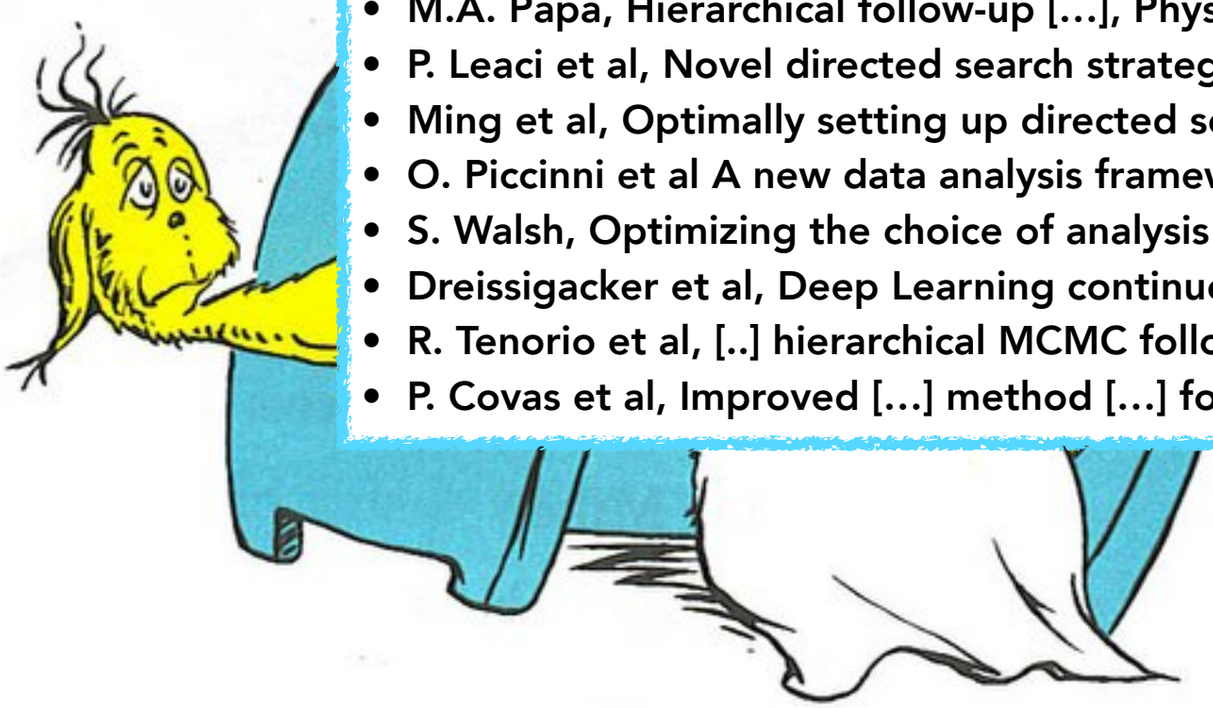
- sacrifice depth and/or breadth of search, depending on target





OPTIMAL SEARCH METHODS CANNOT BE USED

- P. Brady et al, Searching for periodic sources […], Phys.Rev.D 57 (1998)
- B.Krishnan et al, The Hough transform search for …, Phys.Rev.D 70 (2004)
- C. Cutler et al, […] multiple detectors and multiple GW pulsars, Phys.Rev.D 72 (2005)
- R. Prix, […] metric of the multi-detector F-statistic, Phys.Rev.*D* 75 (2007)
- H. Pletsch, Parameter space correlations of the optimal statistic […], Phys.Rev.D 78 (2008)
- H. Pletsch et al, Exploiting global correlations…, Phys.Rev.Lett. 103 (2009)
- B. Knispel et al, Pulsar Discovery by Global Volunteer Computing, *Science* 329 (2010)
- B. Owen, How to adapt […] for r-modes, Phys.Rev.D 82 (2010)
- R. Prix et al, […] Optimal StackSlide method at fixed computing cost, Phys.Rev.D 85 (2012)
- V. Dergchev, Novel universal statistic […], Phys.Rev.D 87 (2013)
- P. Astone et al, Method for all-sky searches of continuous […], Phys Rev D 90 (2014)
- B. Behnke et al, Post processing methods […], Phys.Rev.D 91 (2015)
- S. Walsh, Comparison of methods […], Phys.Rev.D 94 (2016)
- M.A. Papa, Hierarchical follow-up […], Phys.Rev.D 94 (2016)
- P. Leaci et al, Novel directed search strategy …, Phys.Rev.D 95 (2017)
- Ming et al, Optimally setting up directed searches […], Phys Rev 97 (2018)
- O. Piccinni et al A new data analysis framework […], Class.Quant.Grav. 36 (2019)
- S. Walsh, Optimizing the choice of analysis methods […], Phys.Rev.D 99 (2019)
- Dreissigacker et al, Deep Learning continuous gravitational waves […], Phys.Rev.D 102 (2020)
- R. Tenorio et al, [..] hierarchical MCMC follow-up […], Phys.Rev.D 104 (2021)
- P. Covas et al, Improved […] method […] for stars in binary systems, arXiv:2208.01543 (2022)

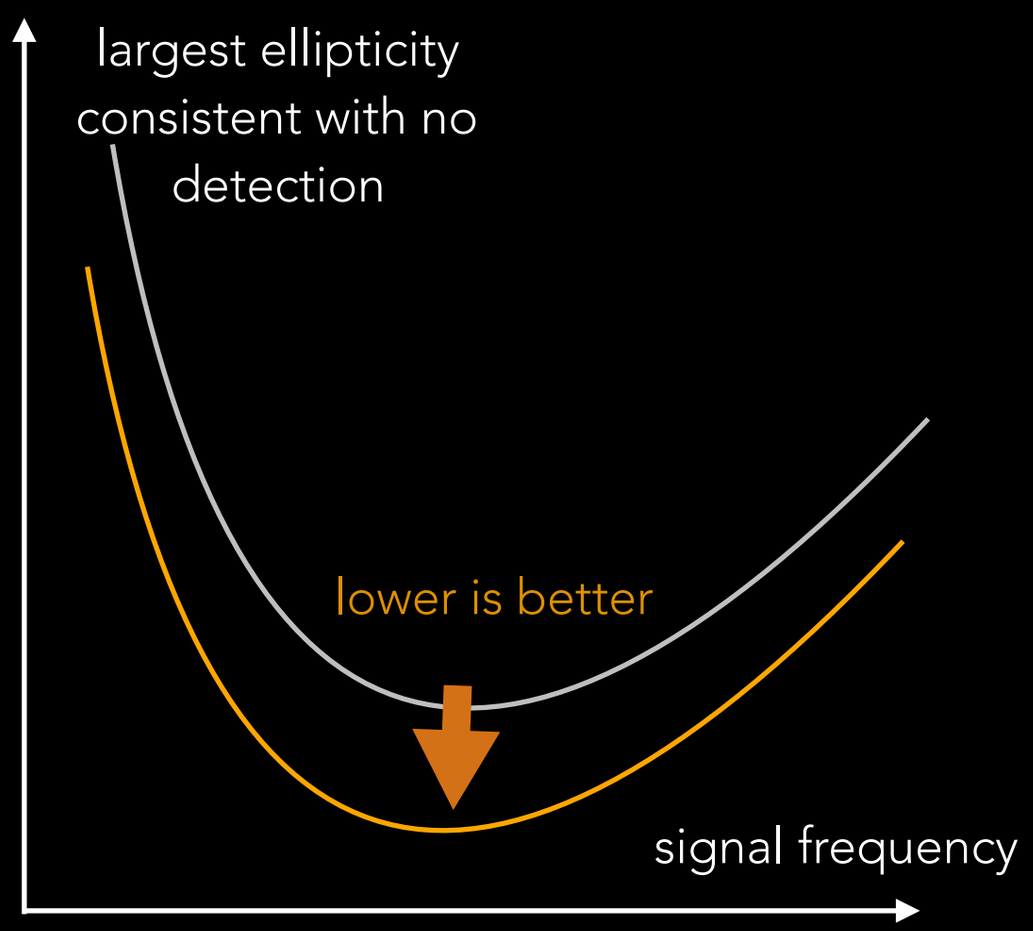


TARGETS

- interesting objects (known pulsars)
- regions (galactic centre, globular clusters, young SN remnants)
- all-sky

THE PRIMARY GOAL IS TO MAKE THE FIRST DETECTION

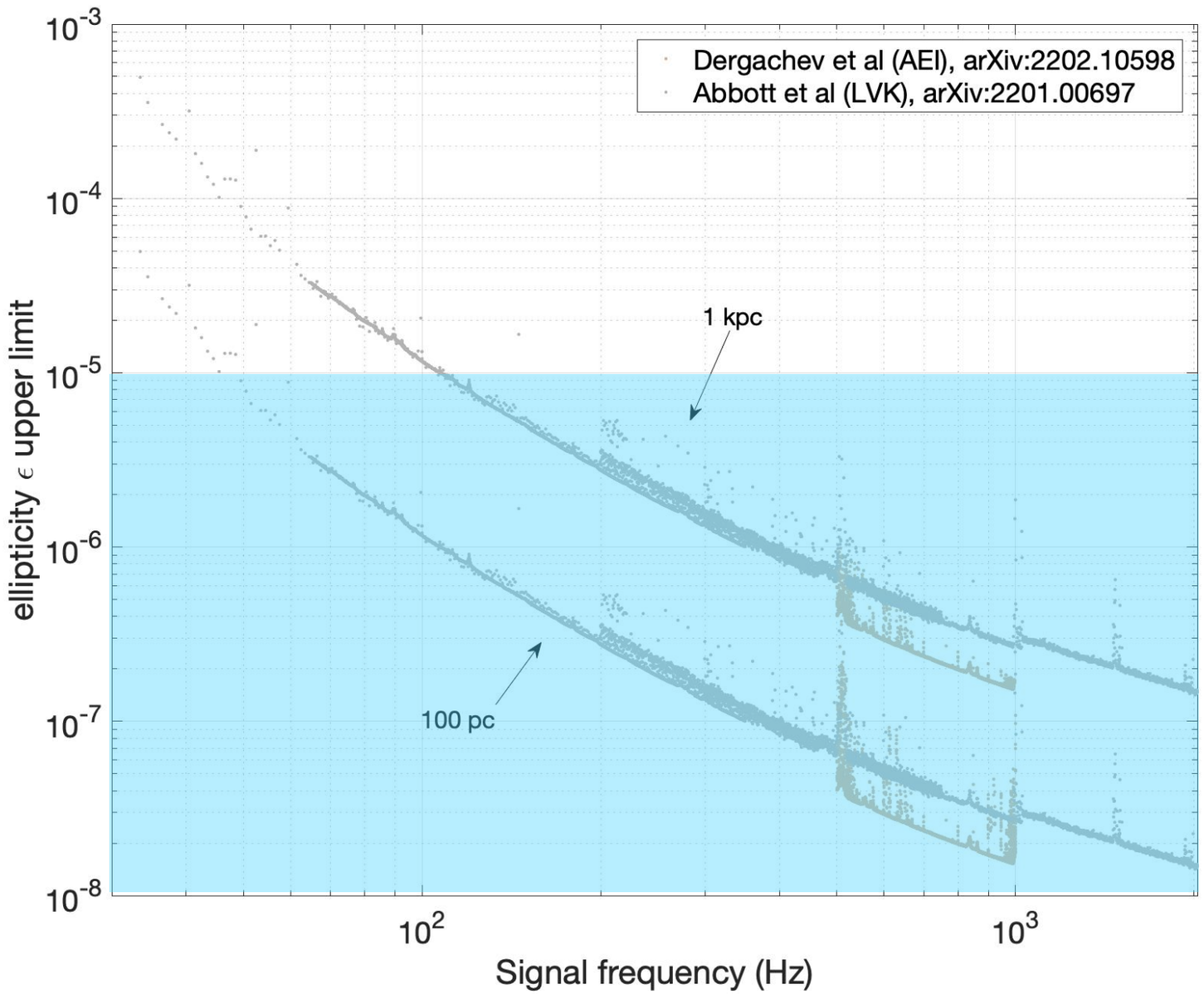
- very sensitive searches but so far no detection
- can constrain signal amplitude



ALL-SKY SURVEYS

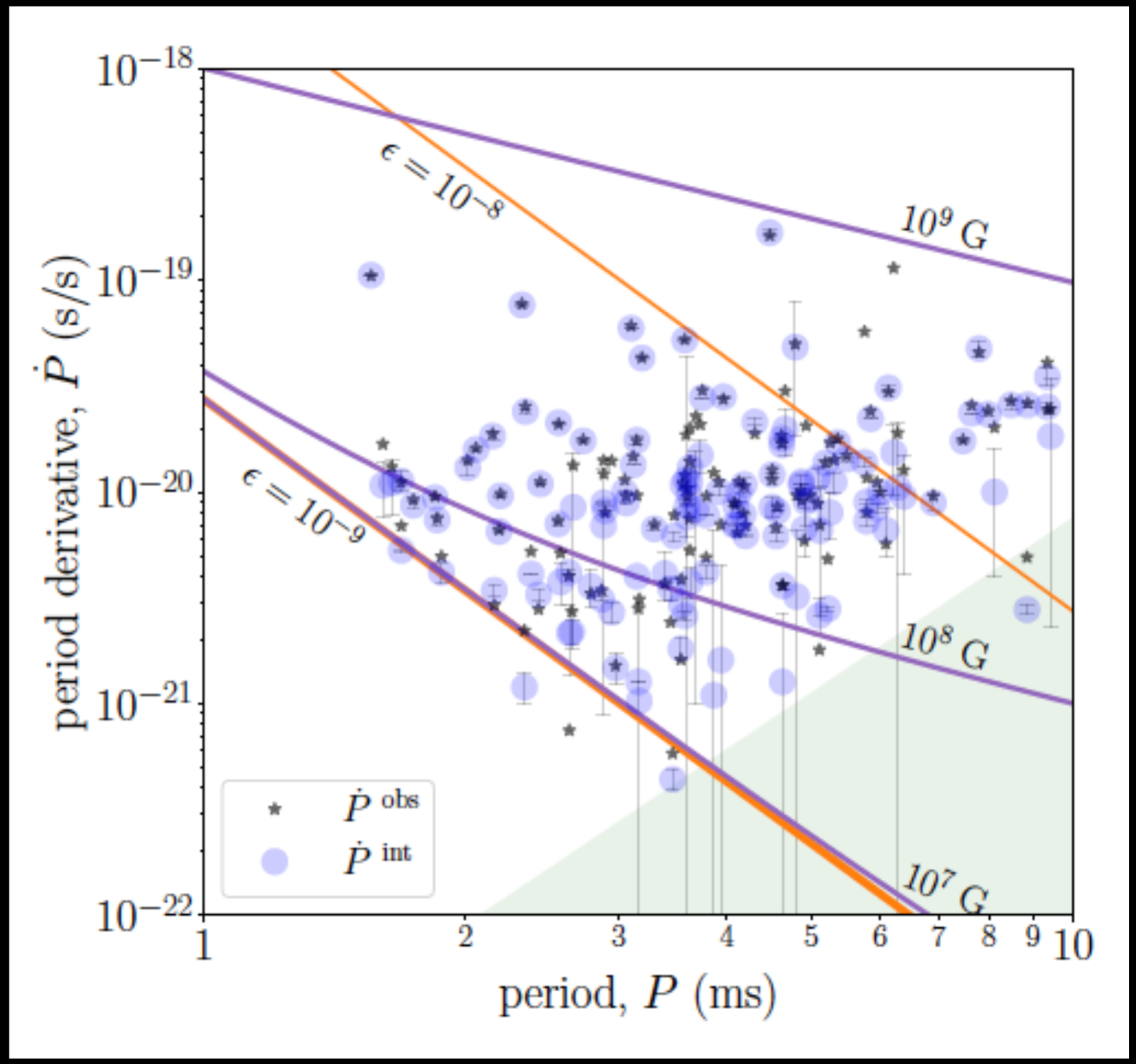
SEARCHING FOR ONE THAT IS NEARBY AND BUMPY ENOUGH BE DETECTABLE

O3 DATA



plausible ε values

EVIDENCE OF MINIMUM ELLIPTICITY ?



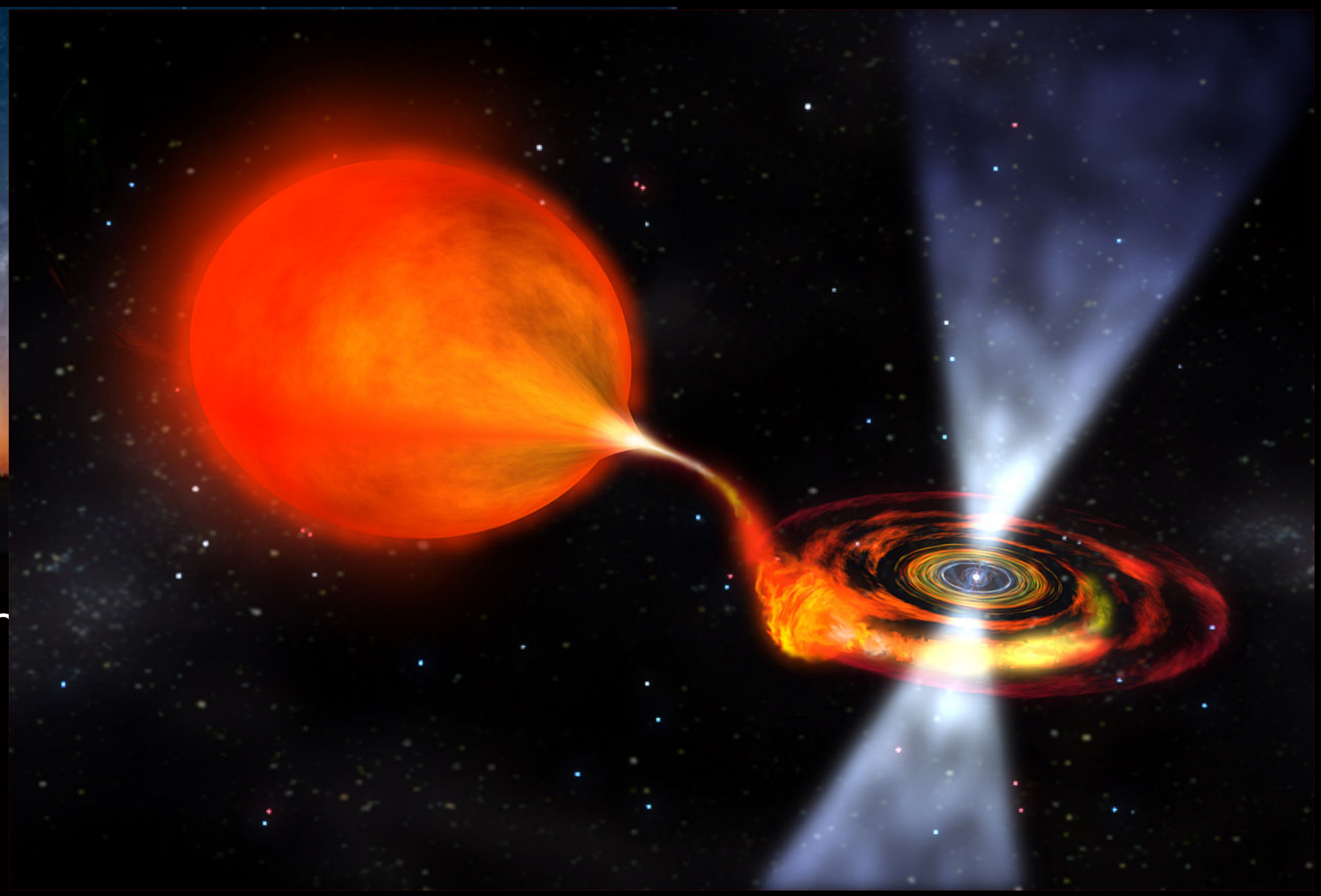
Woan et al, ApJ 863 (2018)

INTERESTING DIRECTIONS IN THE SKY

Center of our galaxy

INTERESTING DIRECTIONS IN THE SKY

Cer



bright LMXB

INTERESTING DIRECTIONS IN THE SKY

Cent

Young supernova remnant

YOUNG SUPERNOVA REMNANT

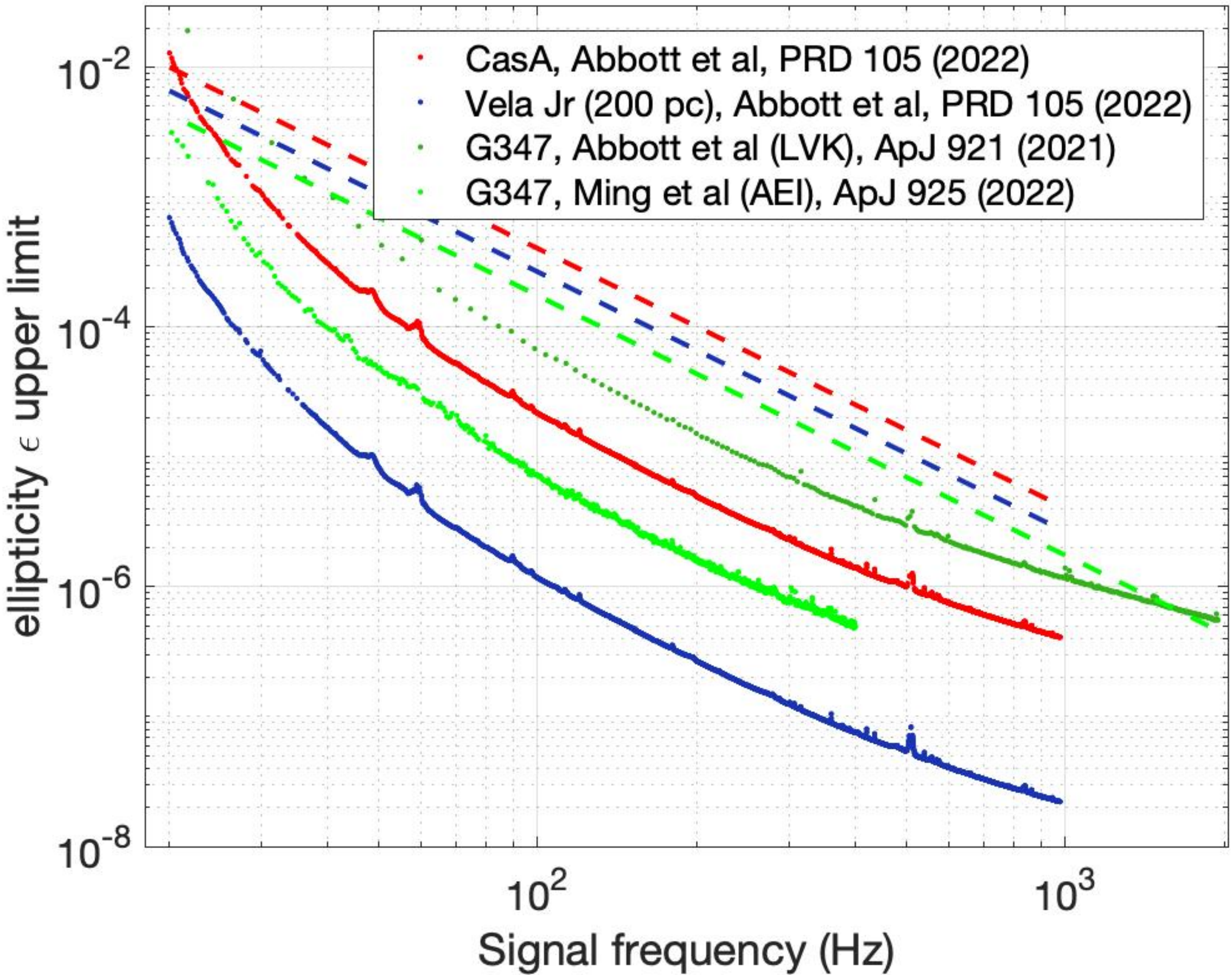
distance D, age τ, evolving solely due to GW emission

$$h_0^{spdwn} = \frac{1}{D}\sqrt{\frac{5GI}{8c^3\tau}}$$

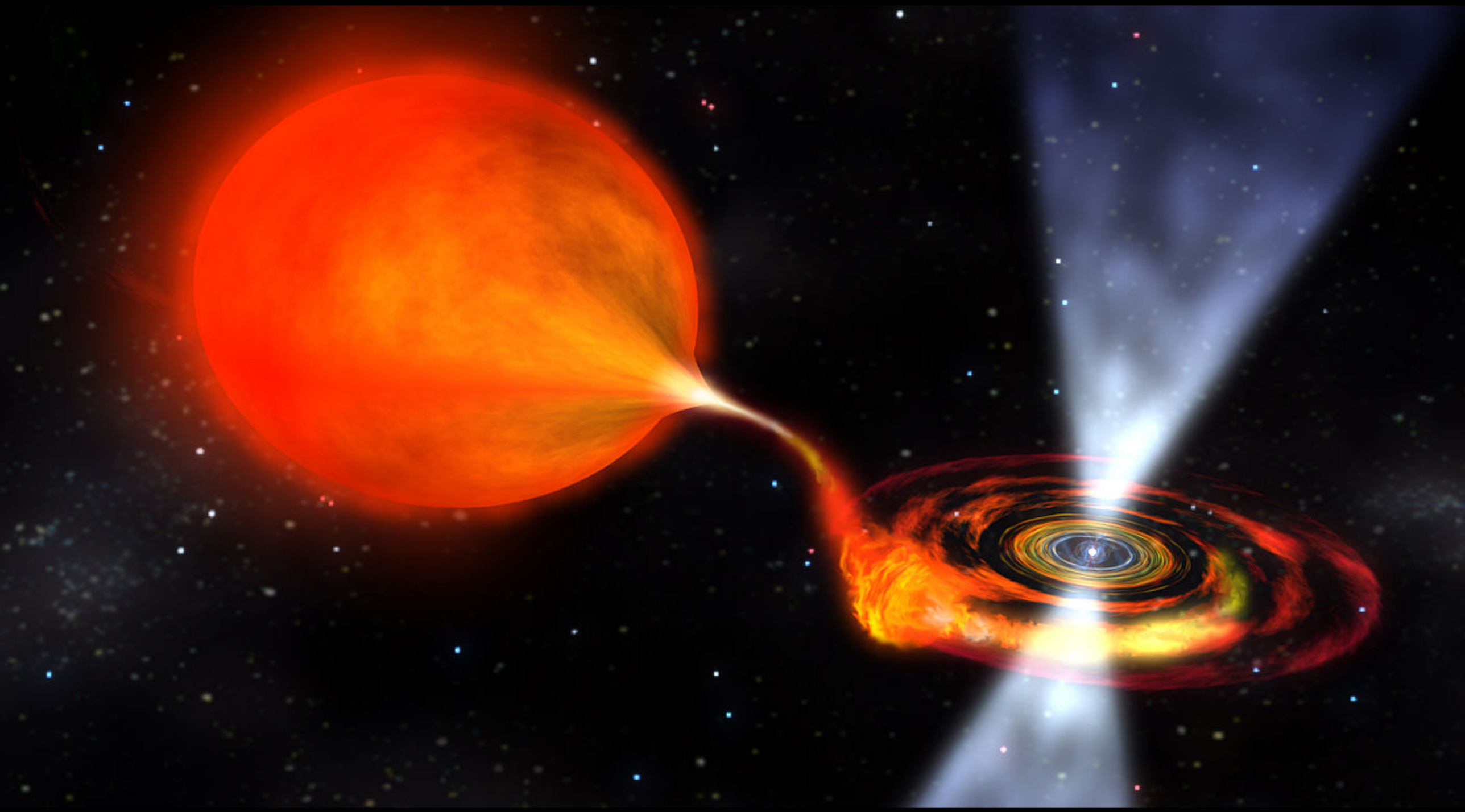
CLOSE-BY SUPERNOVA REMNANTS

SNR (G name)	Other name	RA+dec (J2000)	D (kpc)	τ (kyr)
1.9+0.3	—	174846.9−271016	8.5	0.1
15.9+0.2	—	181852.1−150214	8.5	0.54
18.9−1.1	—	182913.1−125113	2	4.4
39.2−0.3	3C 396	190404.7+052712	6.2	3
65.7+1.2	DA 495	195217.0+292553	1.5	20
93.3+6.9	DA 530	205214.0+551722	1.7	5
111.7−2.1	Cas A	232327.9+584842	3.3	0.3
189.1+3.0	IC 443	061705.3+222127	1.5	3
189.1+3.0	IC 443	061705.3+222127	1.5	20
266.2−1.2	Vela Jr.	085201.4−461753	0.2	0.69
266.2−1.2	Vela Jr.	085201.4−461753	0.9	5.1
291.0−0.1	MSH 11−62	111148.6−603926	3.5	1.2
330.2+1.0	—	160103.1−513354	5	1
347.3−0.5	—	171328.3−394953	0.9	1.6
350.1−0.3	—	172054.5−372652	4.5	0.6
353.6−0.7	—	173203.3−344518	3.2	27
354.4+0.0	—	173127.5−333412	5	0.1
354.4+0.0	—	173127.5−333412	8	0.5

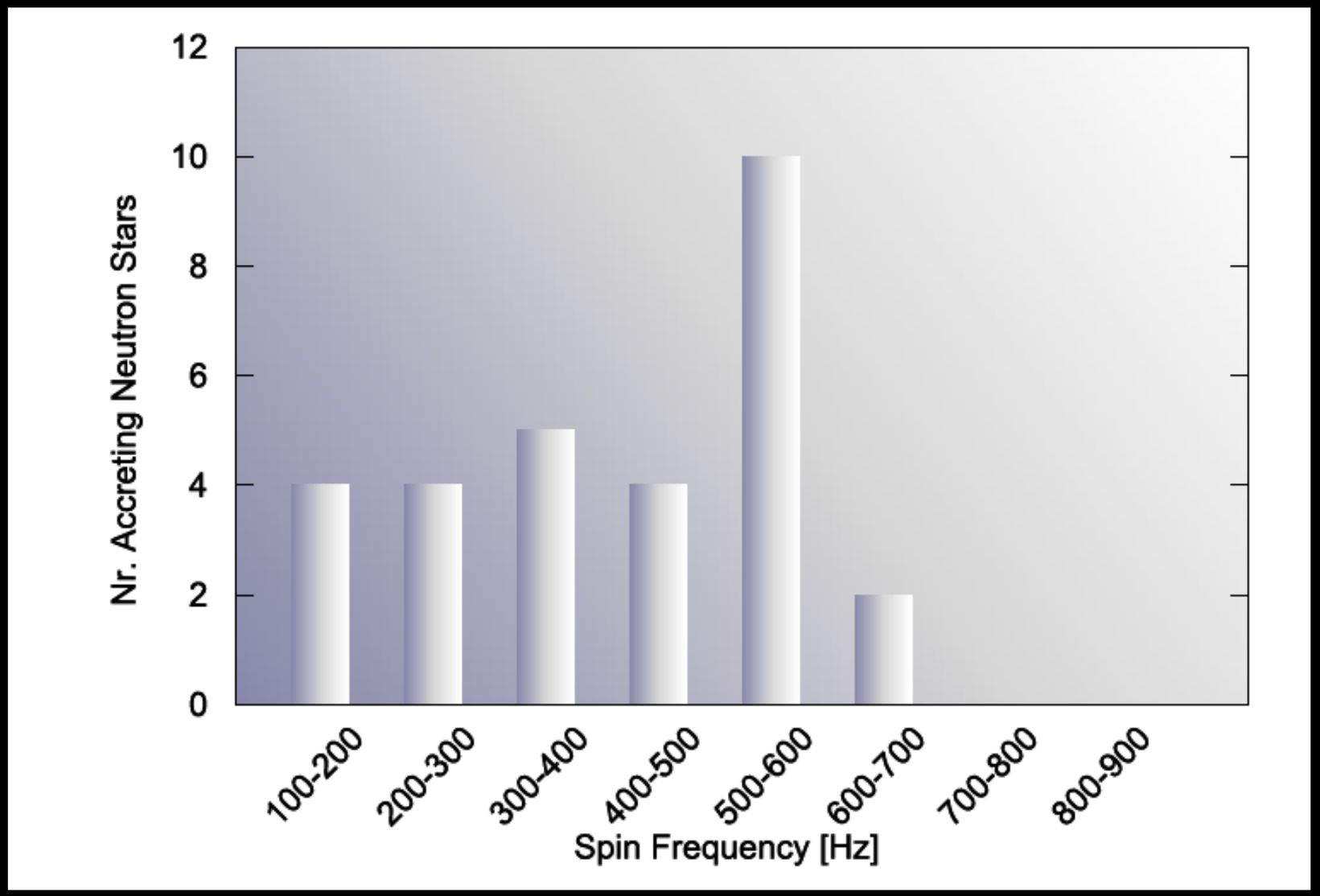
- Ming et al, Optimally setting up directed searches [...], Phys Rev 97 (2018) , Phys Rev D 93 (2016)


CasA, Abbott et al, PRD 105 (2022)
Vela Jr (200 pc), Abbott et al, PRD 105 (2022)
G347, Abbott et al (LVK), ApJ 921 (2021)
G347, Ming et al (AEI), ApJ 925 (2022)
ellipticity ϵ upper limit
10^-2
10^-4
10^-6
10^-8
10^2
10^3
Signal frequency (Hz)

ACCRETING NEUTRON STARS

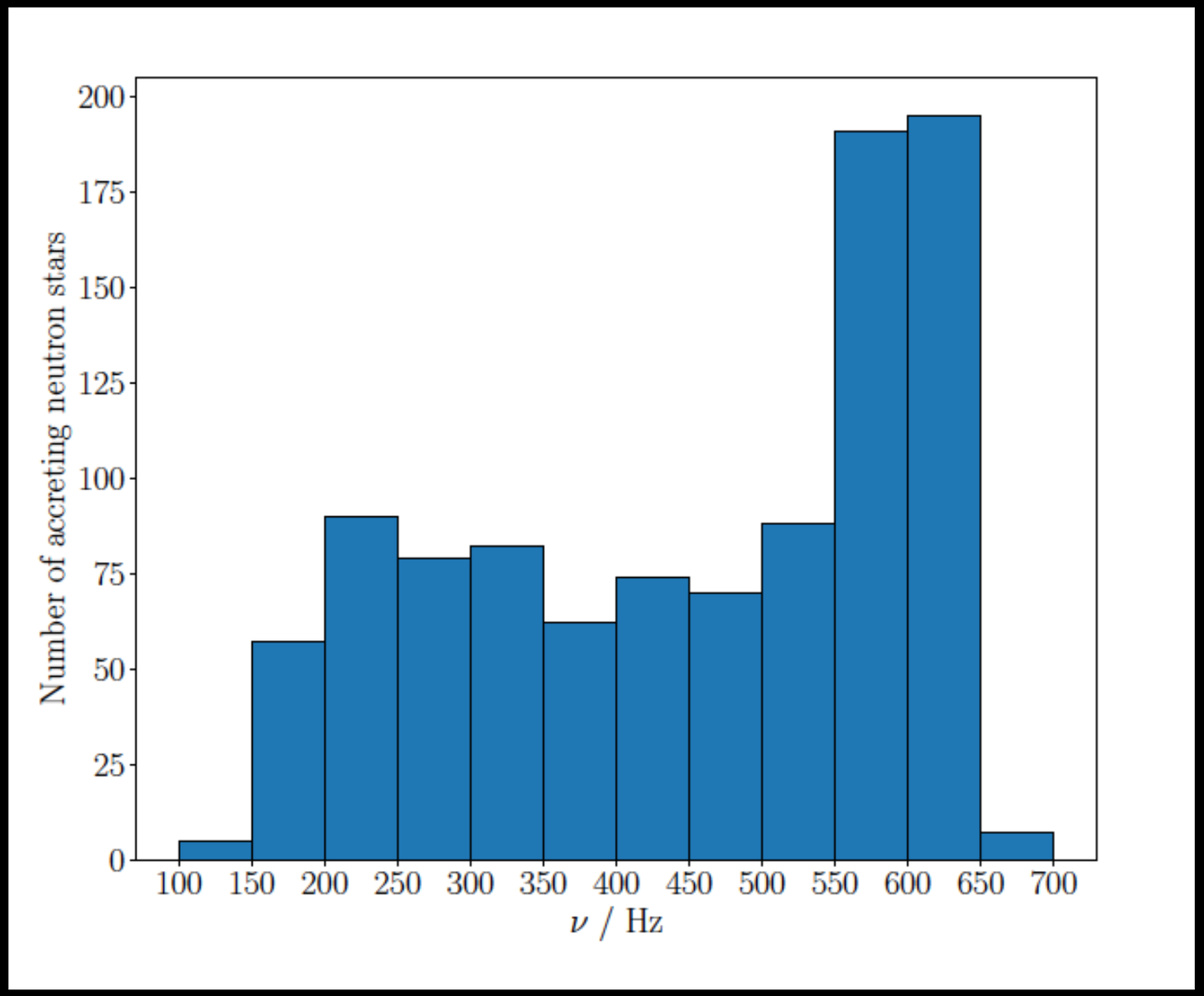


SPINS OF ACCRETING NEUTRON STARS



Patruno Haskell Andersson, ApJ 850 (2017)

SYNTHETIC POPULATION WITH GRAVITATIONAL WAVE EMISSION

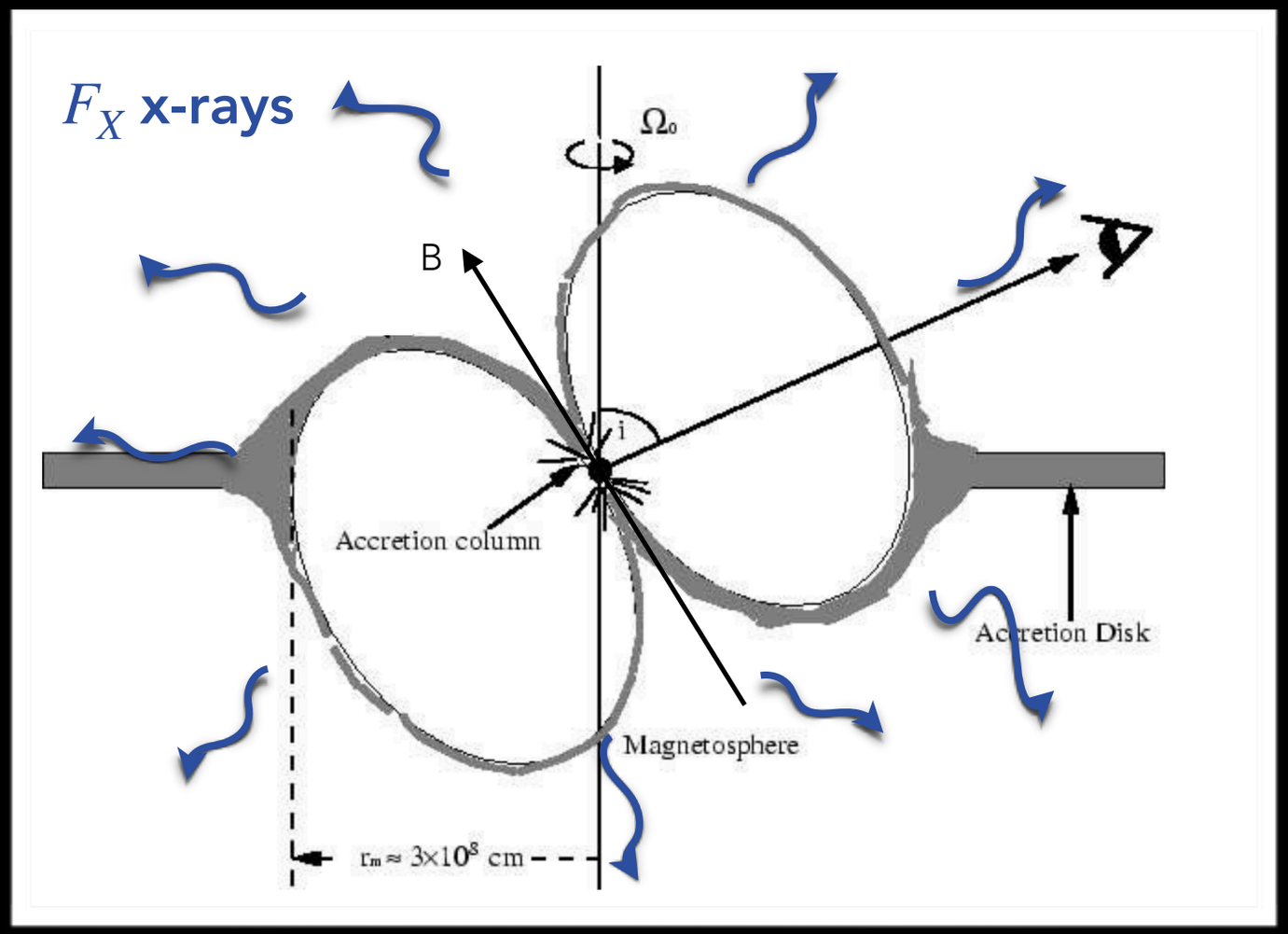


F. Gittins, N. Andersson, *Mon.Not.Roy.Astron.Soc.* 488 (2019)

TORQUE BALANCE

$$h_0^{torq.bal.} = 3.4 \times 10^{-26}\, X^{-\frac{1}{2}}\, M^{-\frac{1}{4}}\, r_m^{\frac{1}{4}}\, F_X^{\frac{1}{2}}\, R^{\frac{1}{2}}\, f_{GW}^{-\frac{1}{2}}$$

for R=10 km, M=1.4 $M_\odot$, f_{GW}=600 Hz, r_m = 10 Km, $F_X/X = 3.9 \times 10^{-7}$erg cm^{2}s^{-1}



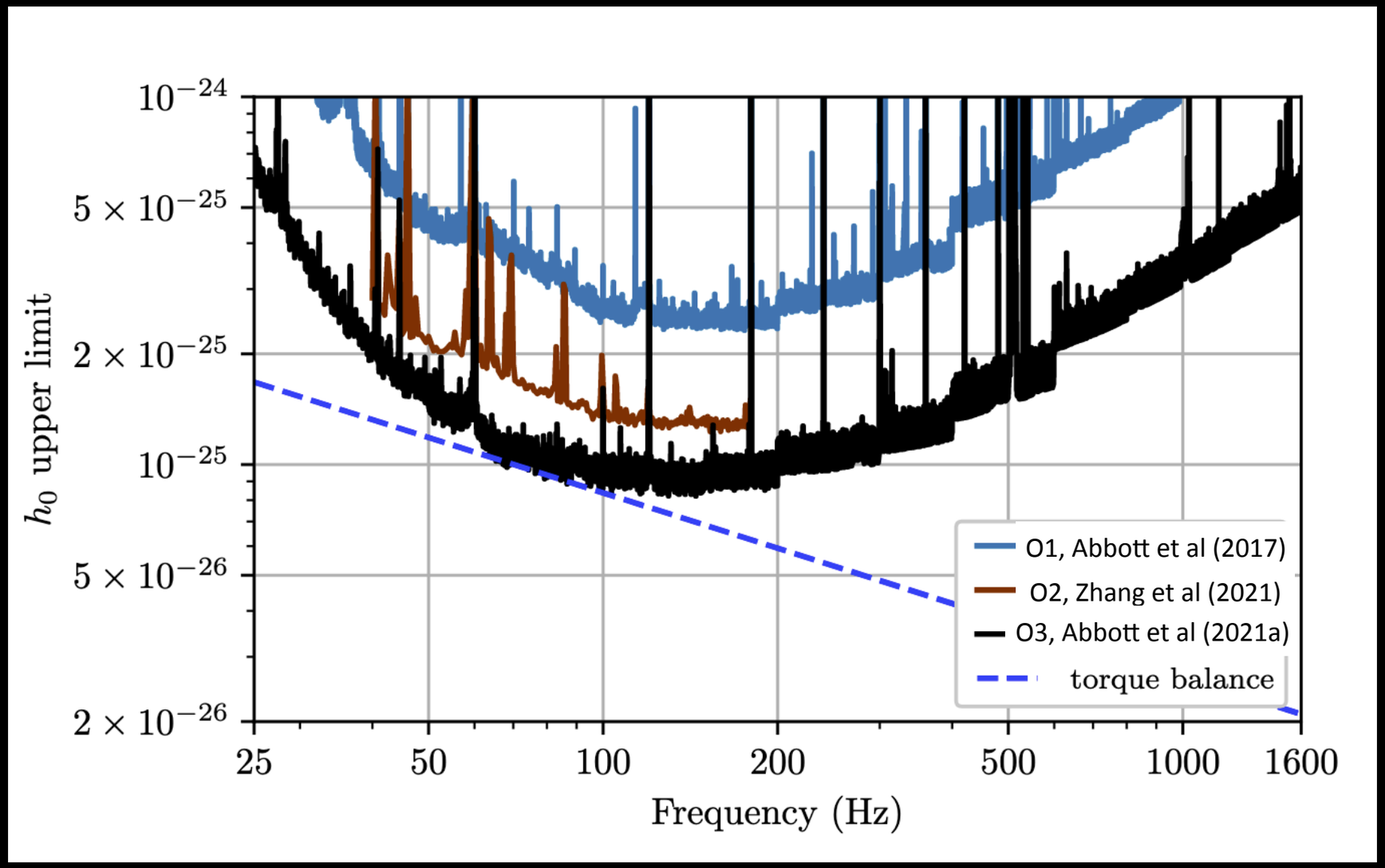
$$h_0 = \sqrt{\frac{5G}{2\pi^2 c^3}\frac{\dot{E}_{GW}}{d^2 f_{GW}^2}}$$

torq. bal. if $\dot{E}_{GW} = \pi f_{GW} N_{acc}$

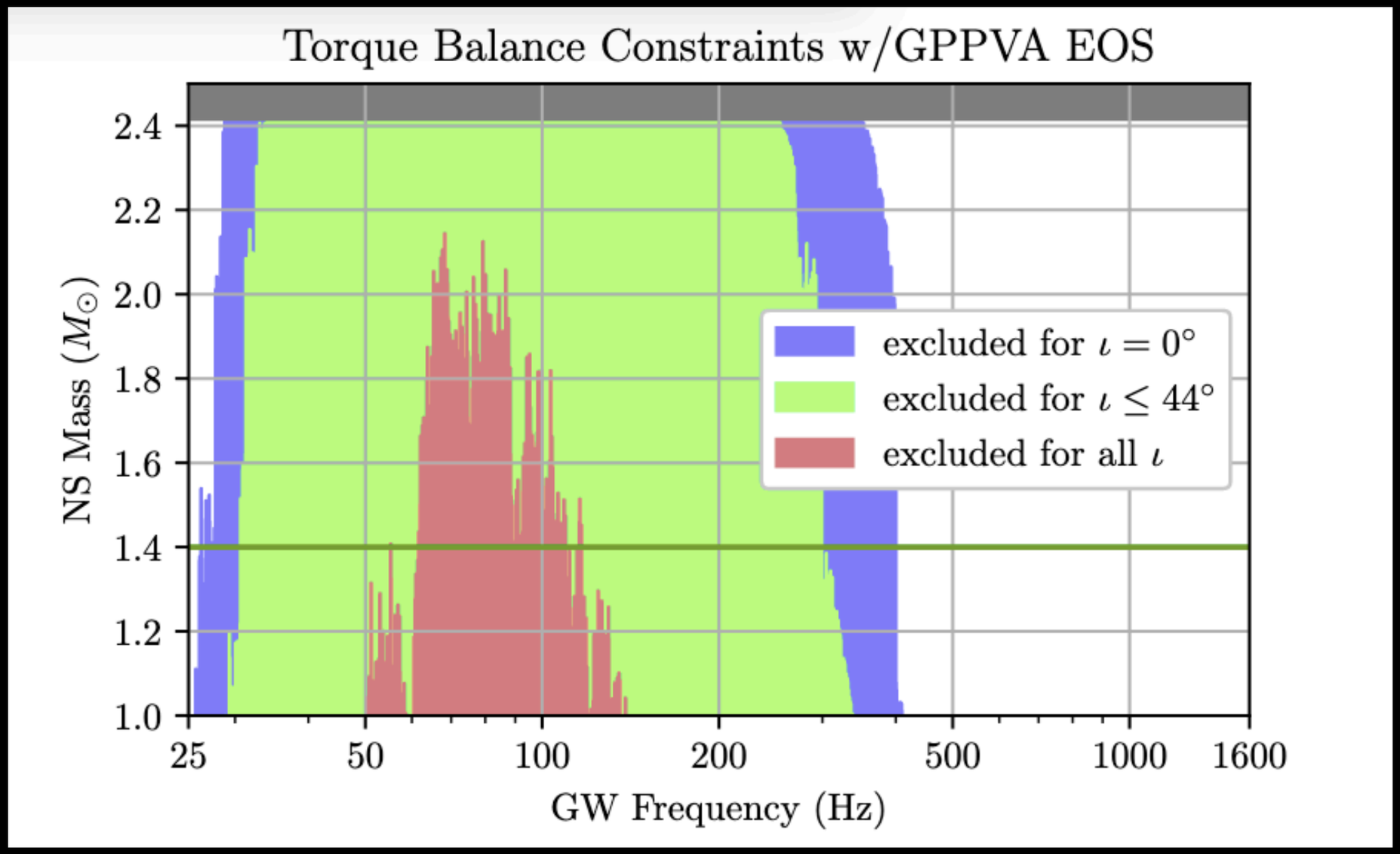
$$N_{acc} = \dot{M}\sqrt{GMr_m}$$

$$4\pi d^2 F_X = X\frac{GM\dot{M}}{R}$$

SCORPIUS X-1
BRIGHTEST X-RAY SOURCE (AFTER SUN)



Abbott et al, *arXiv:2209.02863 (2022)*



Abbott et al, *arXiv:2209.02863 (2022)*

"The only guarantee for failure is to stop trying."

–JOHN C. MAXWELL