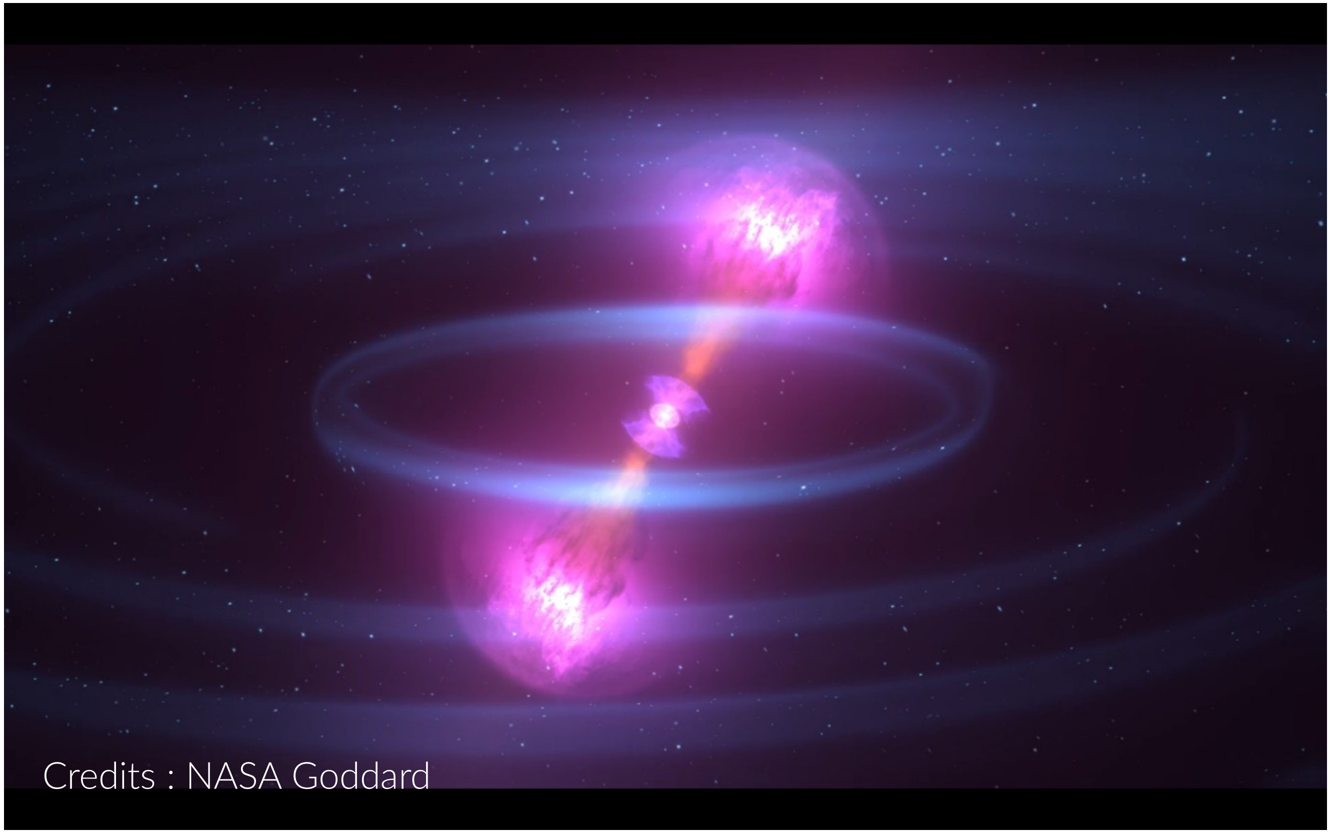
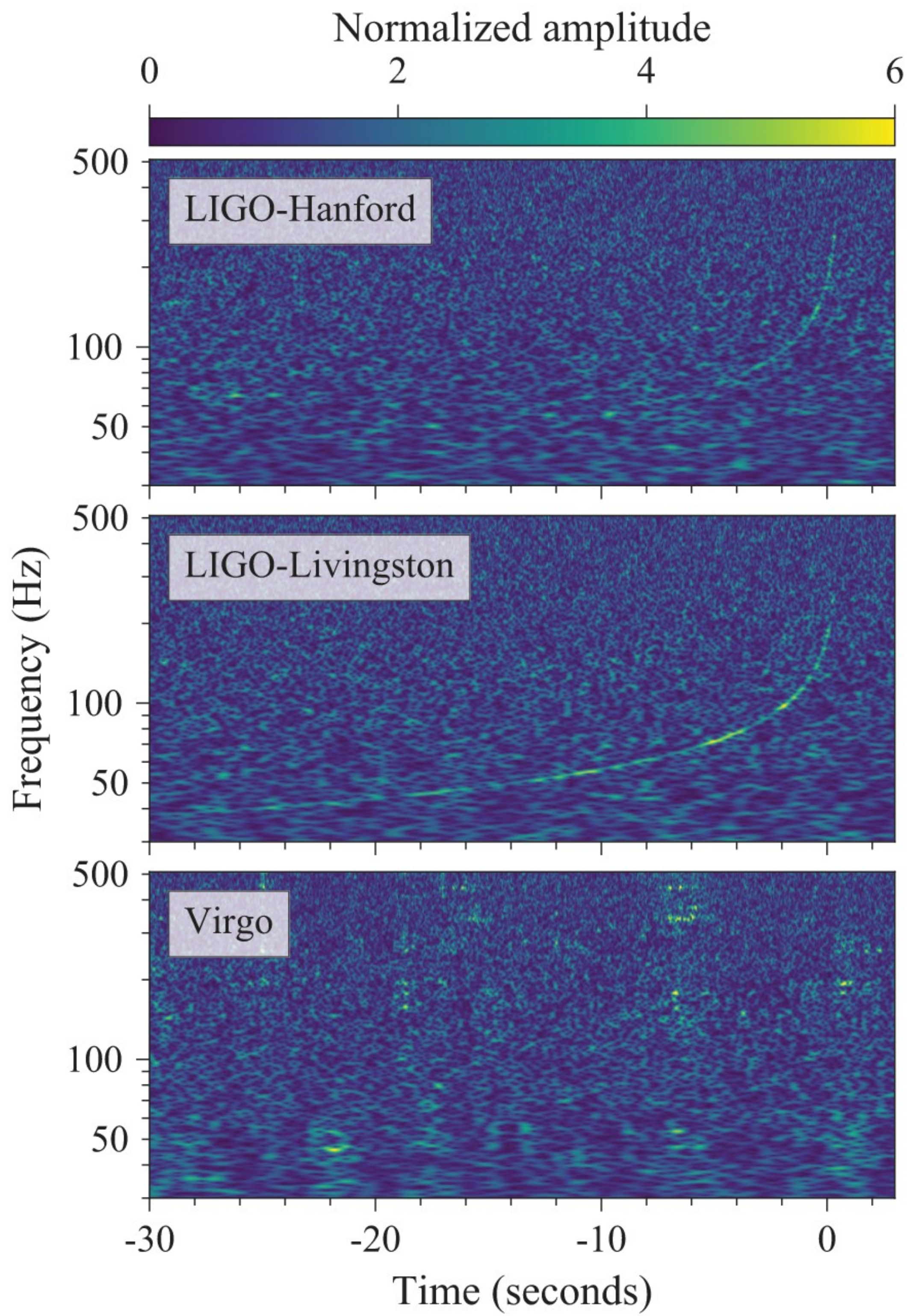
GW170817: Anatomy of the GW chirp

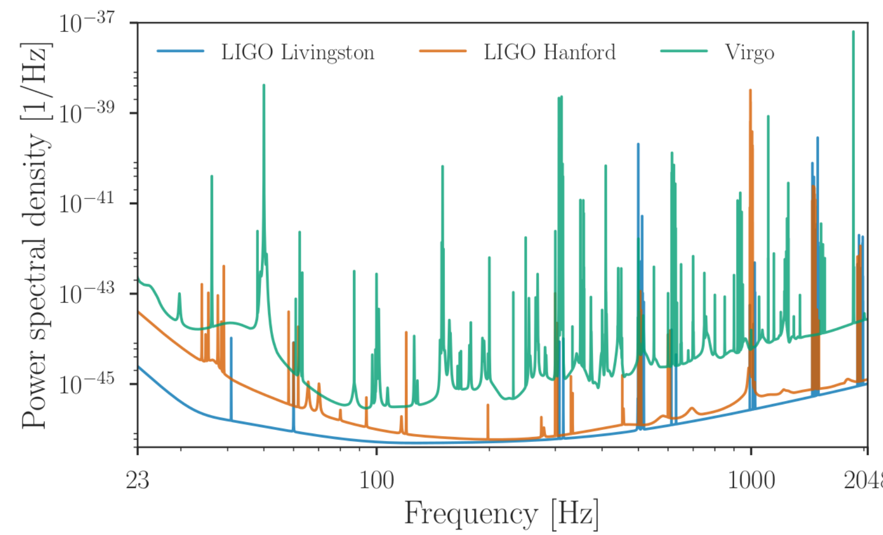


Eric Chassande-Mottin
AstroParticule et Cosmologie (APC)
CNRS Univ Paris Diderot

Outline

- **GW170817 from a GW-only perspective**
  - Basics about the chirp and some details about its analysis
  - What can we learn from the GW signal alone?
  - Next steps and prospects





$$\tau \sim 100\,\mathrm{s}$$

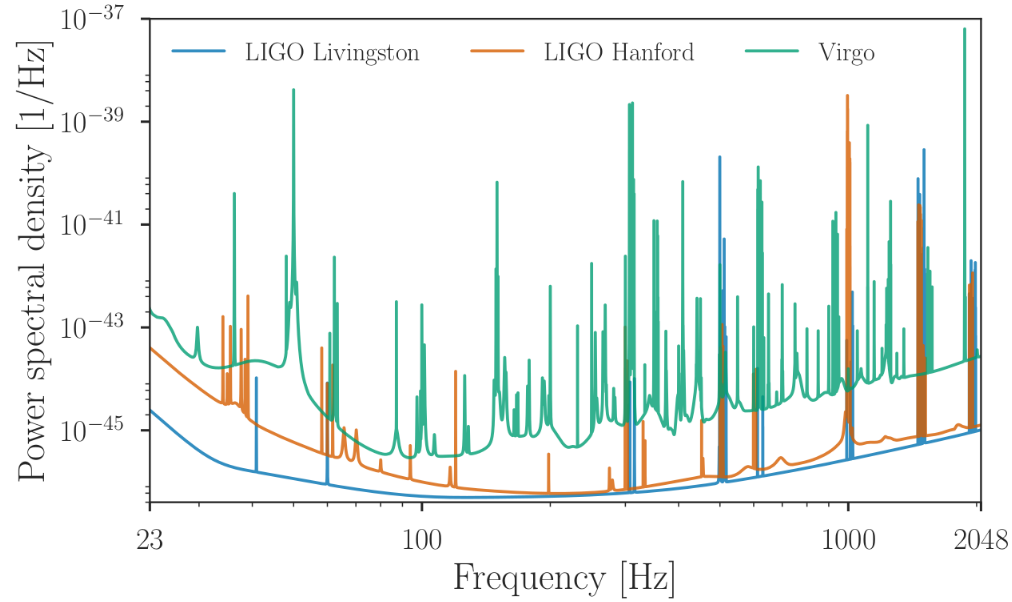
$$\mathrm{SNR} \sim 30$$

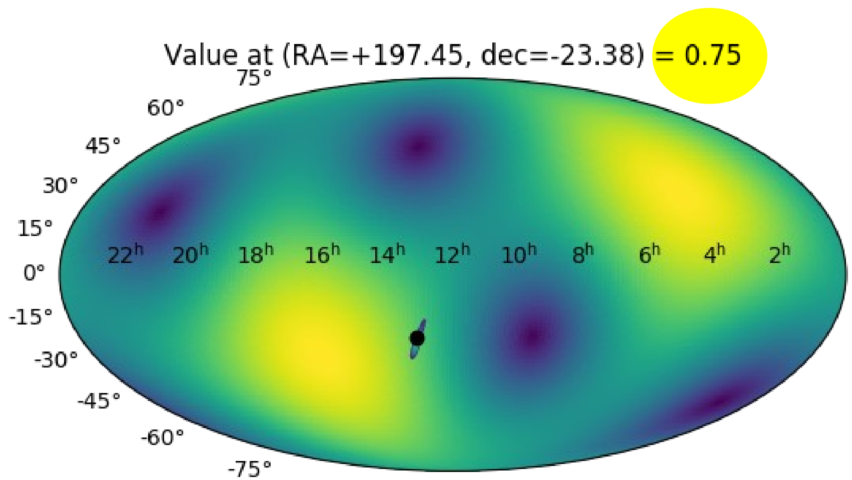
$$\tau \propto \mathcal{M}_{\mathrm{det}}^{-5/3}$$ chirp mass

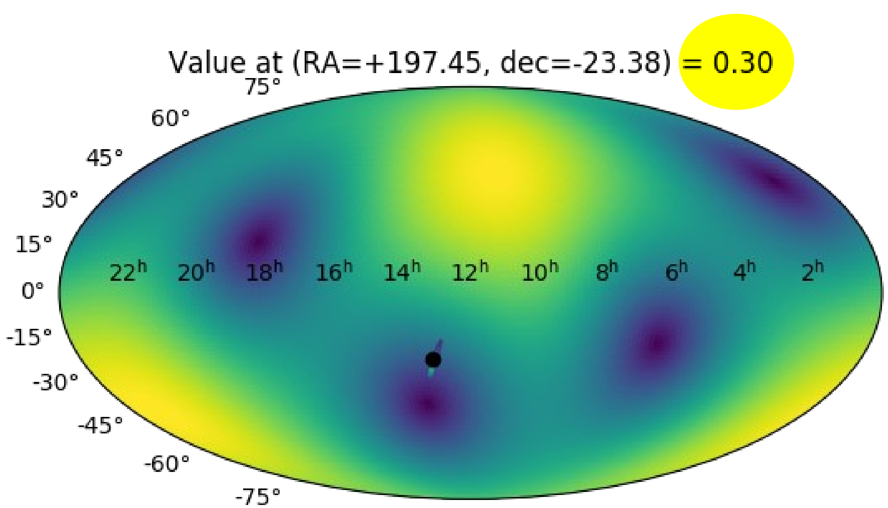
$$\tau \lesssim 1\,\mathrm{s} \quad \text{for BBH}$$

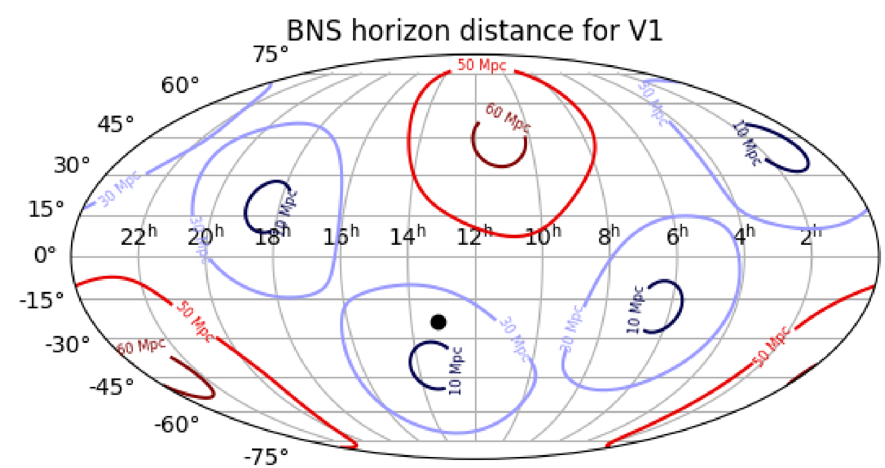
$$\mathrm{SNR}_{\mathrm{total}} = 32.4$$

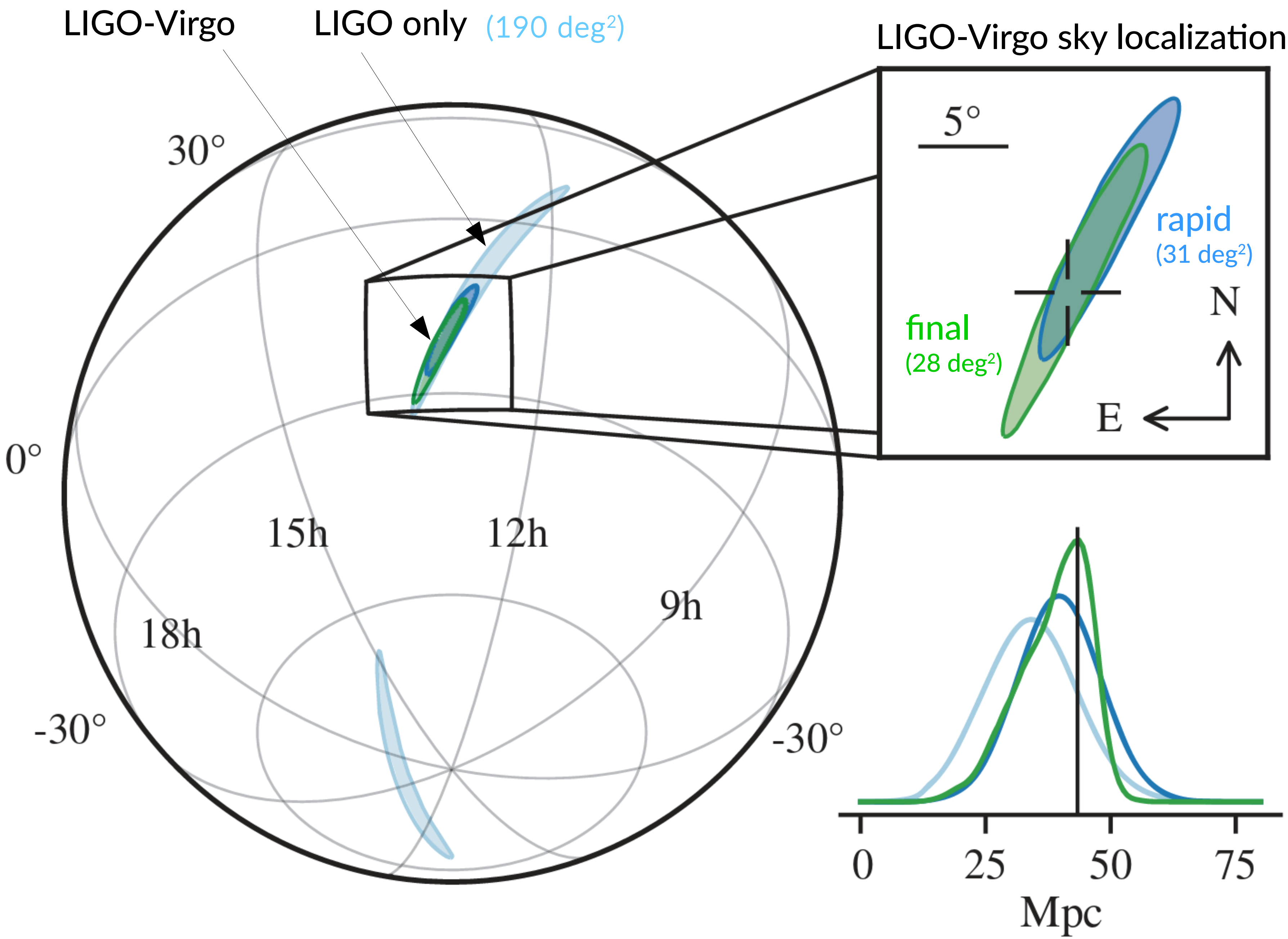
$$\mathrm{SNR}_{H1} = 18.8$$
$$\mathrm{SNR}_{L1} = 26.4$$
$$\mathrm{SNR}_{V1} = 2.0$$











LIGO-Virgo
LIGO only
(190 deg²)
LIGO-Virgo sky localization
5°
rapid
(31 deg²)
final
(28 deg²)
N
E
30°
0°
-30°
-30°
15h
12h
18h
9h
0
25
50
75
Mpc

Alert timeline

t_c + 40 min: 1st LV announcement

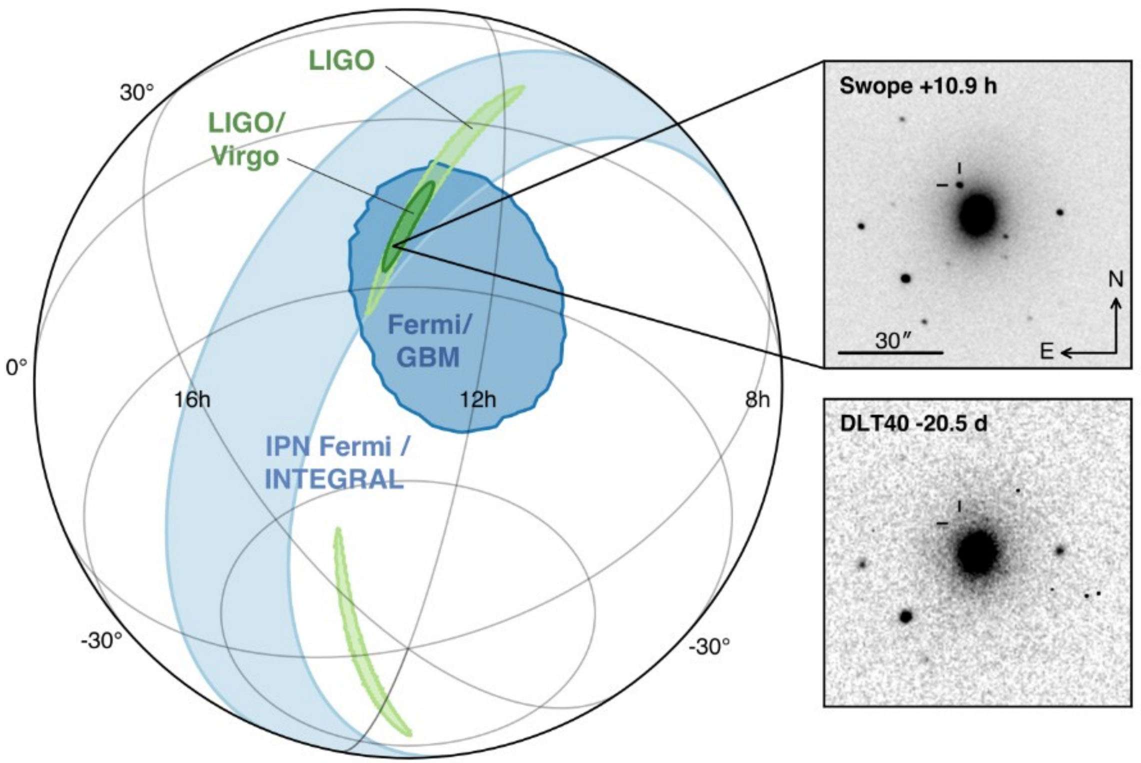
candidate BNS in H1 associated with GRB
large glitch in L1
issue with V1 data transfert

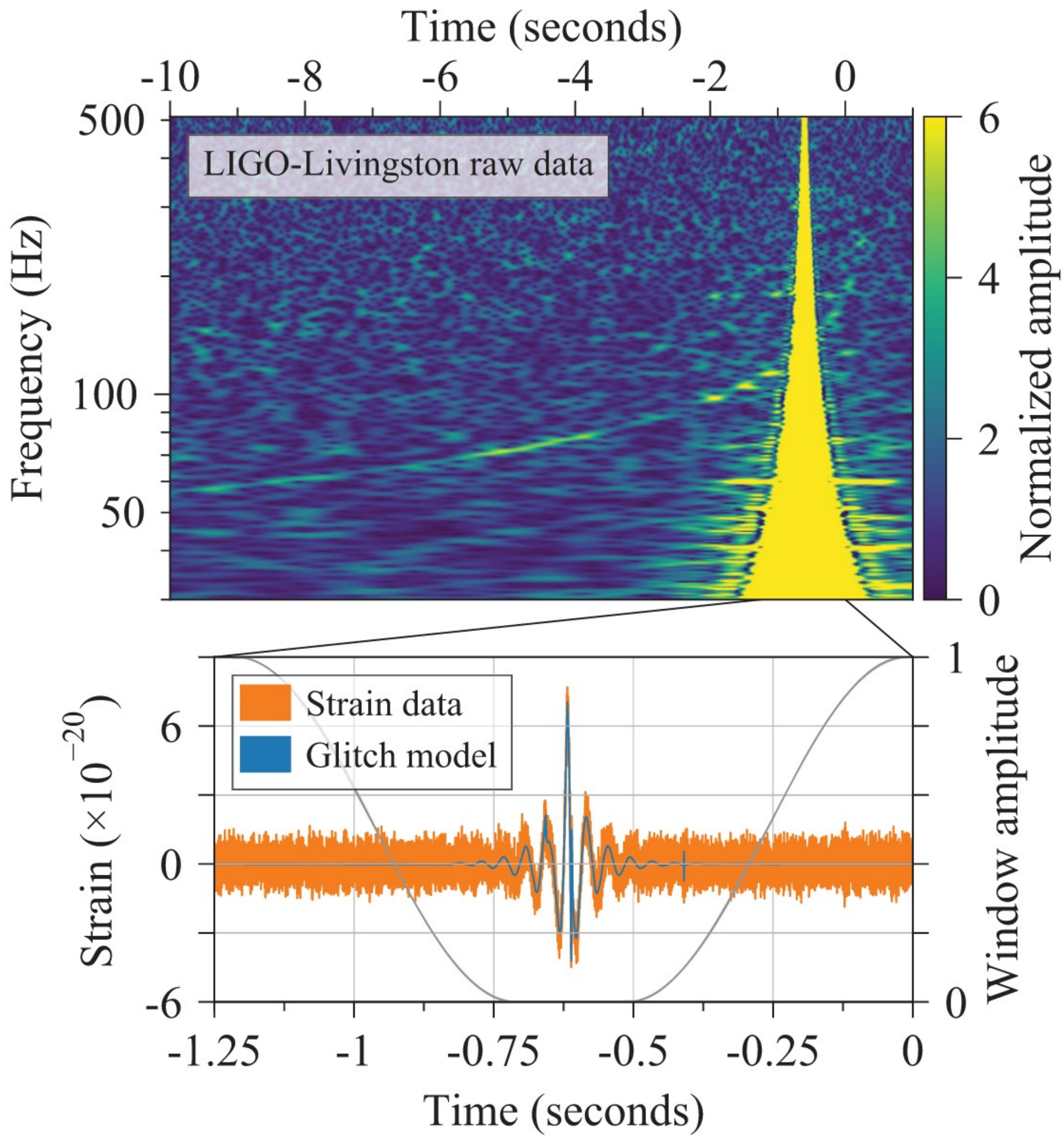
t_c + 1h05 : Fermi report
preliminary localization = 1100 deg^2

t_c + 1h30 min: LV update
H1-only loc. and distance = 37 ± 12 Mpc

t_c + 5h : LIGO Virgo loc. = 30 deg^2

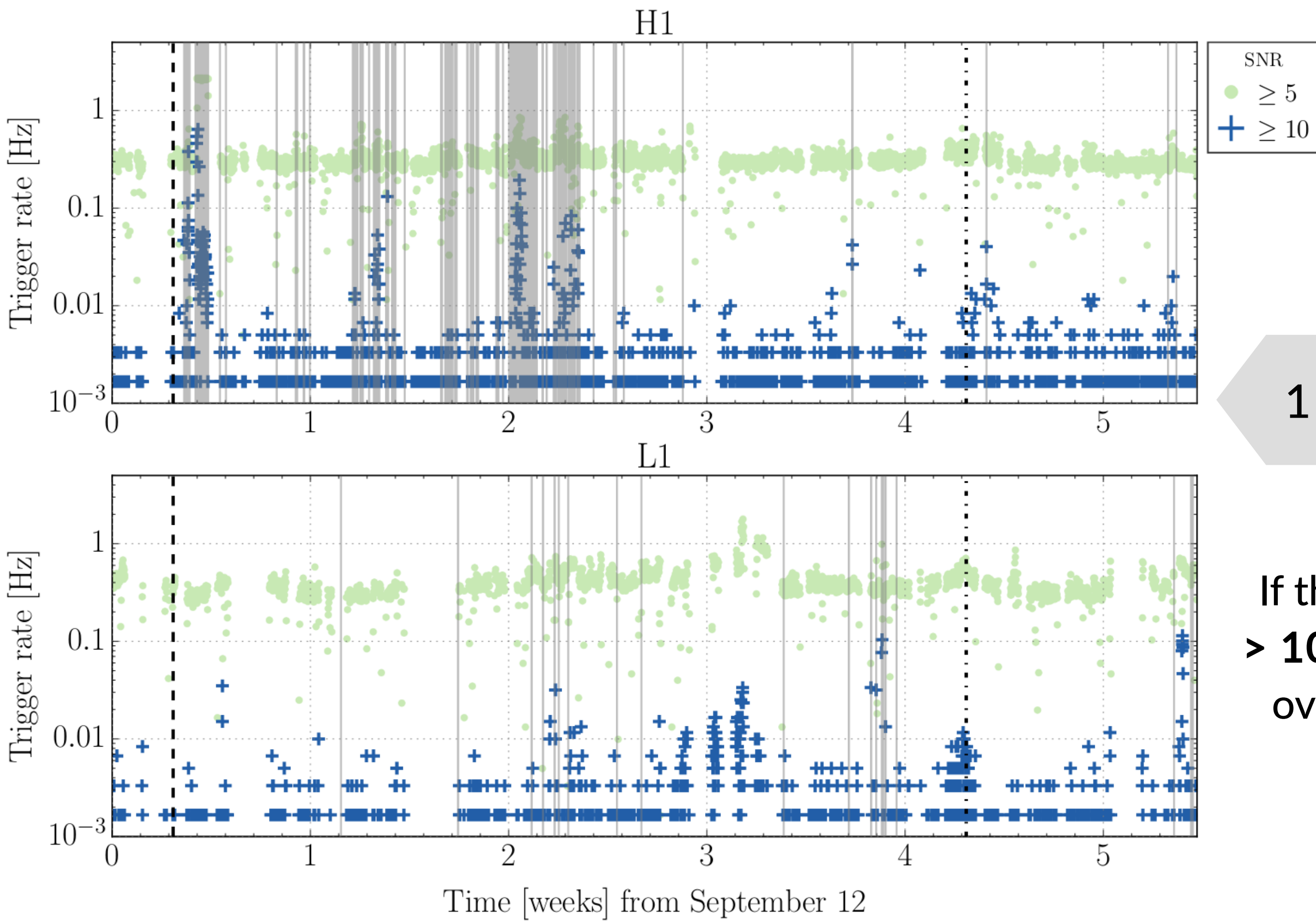
distance = 40 ± 8 Mpc
Too late for Australia and South Africa!





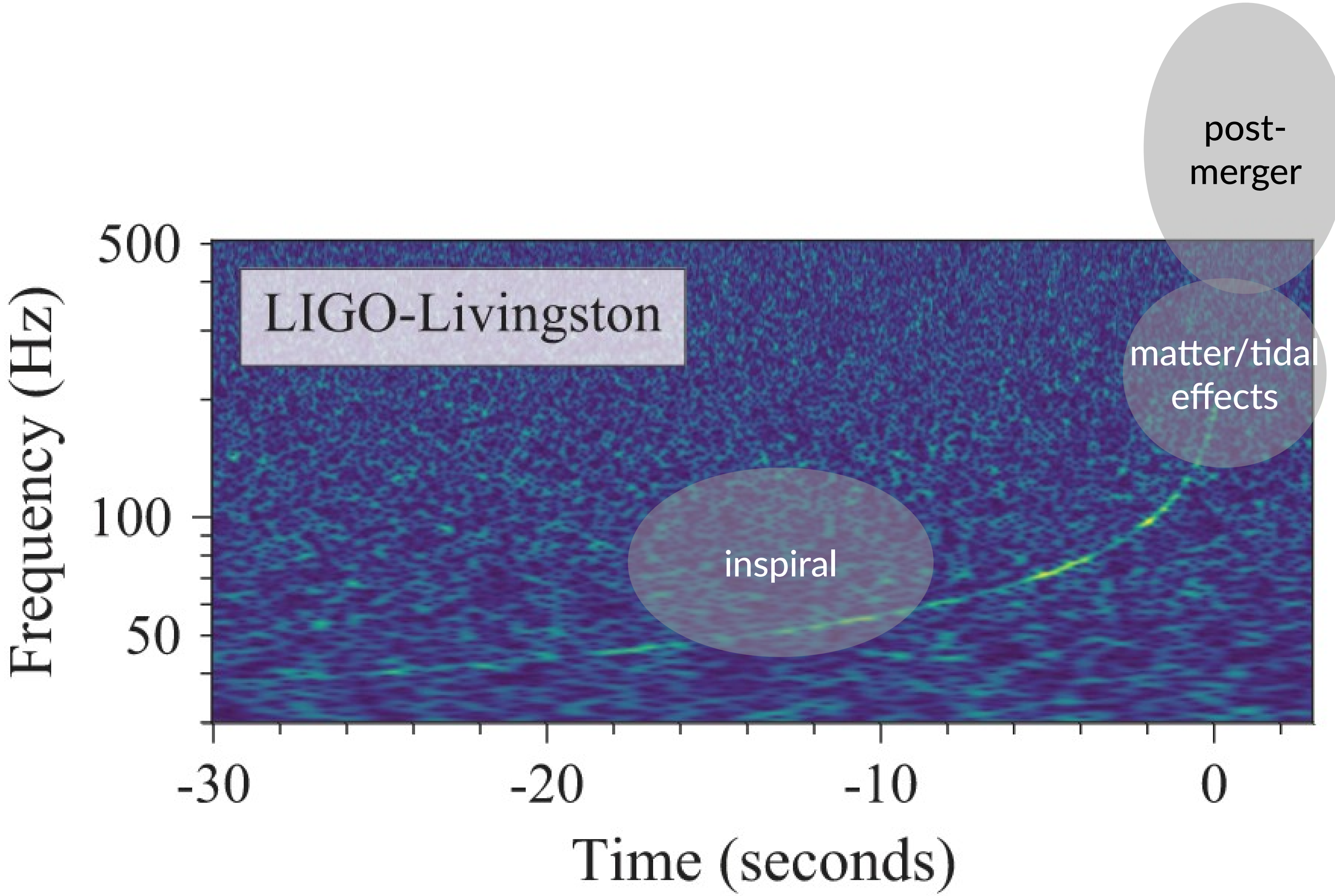
DAC saturation in test mass position feedback control

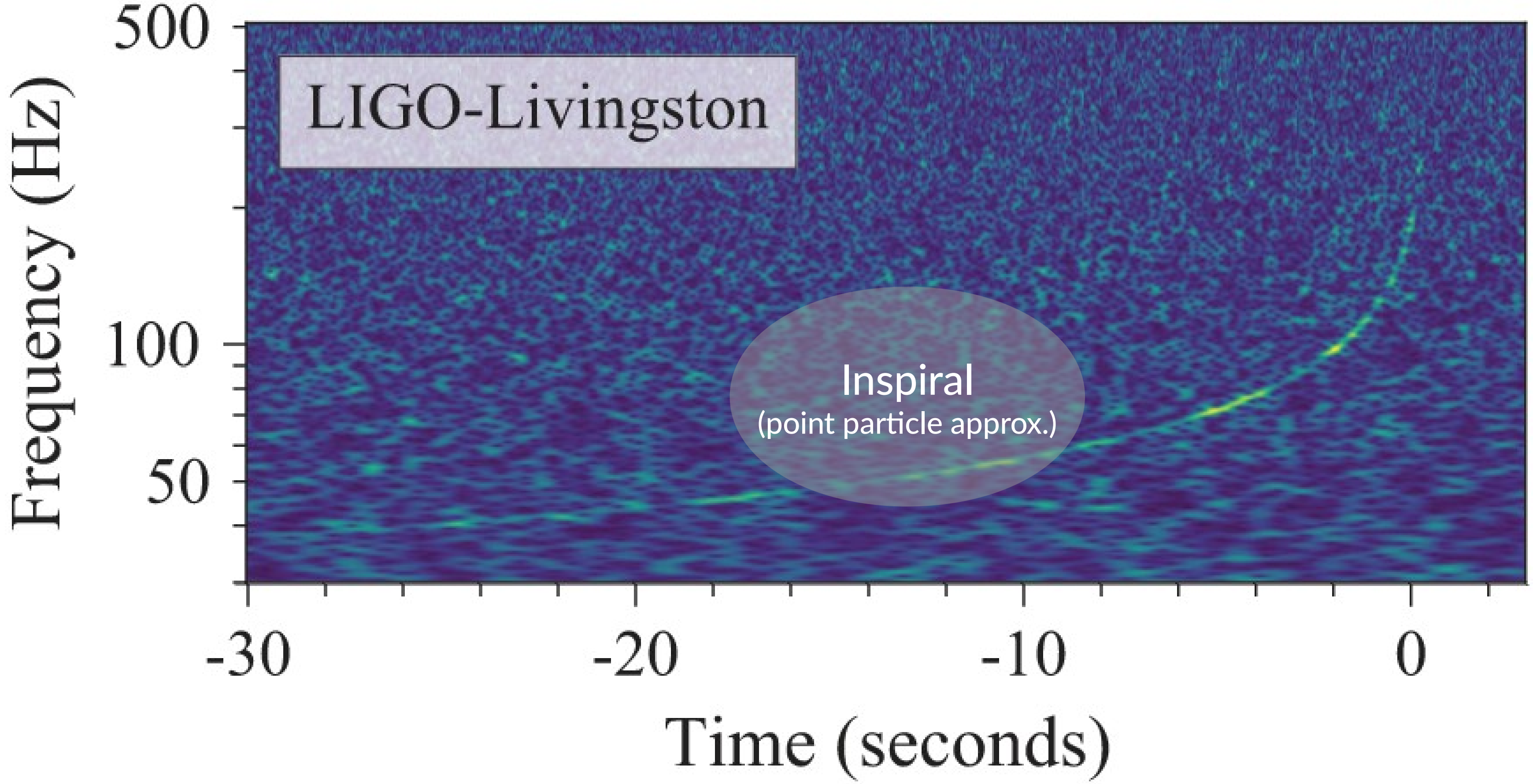
Glitch rate during O1



1 per ~20 mins

If the glitch rate remains the same,
> 10 % probability that a loud glitch overlaps with a 100-s GW signal


post-
merger
matter/tidal
effects
inspiral
LIGO-Livingston
500
100
50
Frequency (Hz)
-30
-20
-10
0
Time (seconds)



500
100
50
Frequency (Hz)
LIGO-Livingston
Inspiral
(point particle approx.)
-30
-20
-10
0
Time (seconds)

Source parameters (1)

- GW signal is described by **15 parameters** (masses and spins + time/space location and orientation)
- Parameter estimates obtained by **fitting the waveform** coherently in all detectors using Bayesian sampling methods
- Waveform phase determined to lowest order by **chirp mass** $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$

    Phase matching: measurement accuracy scales with $1/N_{cycles}$

    With $N_{cycles} \approx 3000$ from 30 to 1000 Hz

    detector-frame chirp mass $\mathcal{M}^{\mathrm{det}} = 1.1977\,\mathrm{M}_\odot \pm 0.07\%$

… then mass ratio, spins and matter effects

Source parameters (2)

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \qquad \mathcal{M}^{\rm det} = 1.1977\,{\rm M}_\odot \pm 0.07\%$$

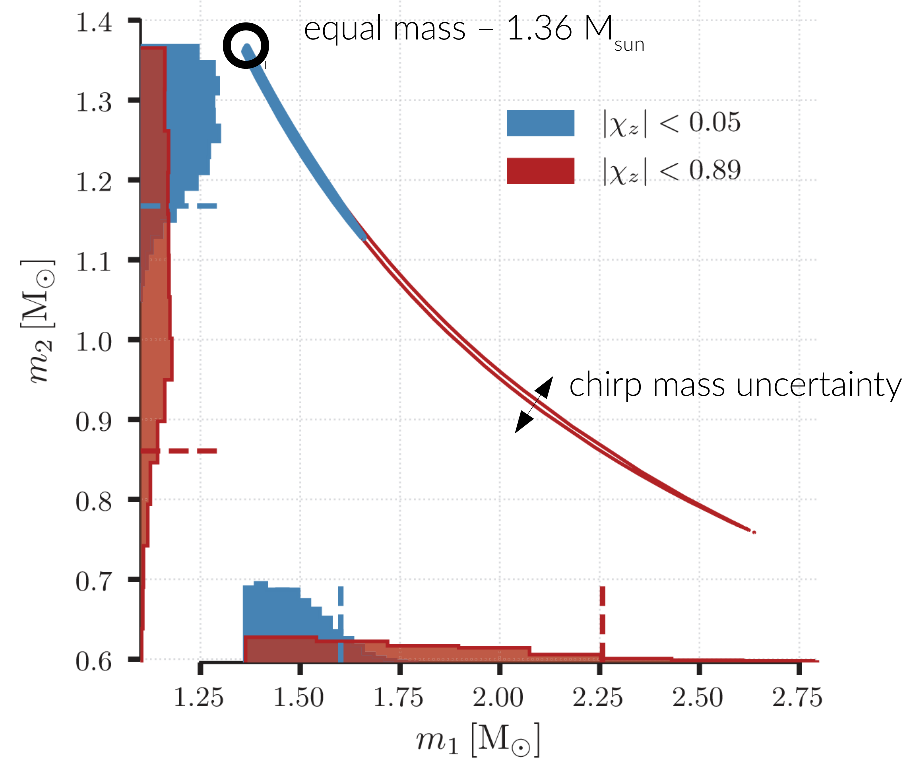
- Some of the parameters are **degenerate**, e.g., distance vs inclination

$$h_+ \propto \frac{1 + \cos^2\theta_{JN}}{D_L} \qquad D_L = 40\,{\rm Mpc} \pm 35\%$$

- Can be converted to **source frame** by assuming a ref. cosmology (Planck)

$$z = 0.008 \pm 37.5\%$$

$$\mathcal{M} = \mathcal{M}^{\rm det}/(1+z) \qquad \mathcal{M} = 1.188\,{\rm M}_\odot \pm 0.33\%$$



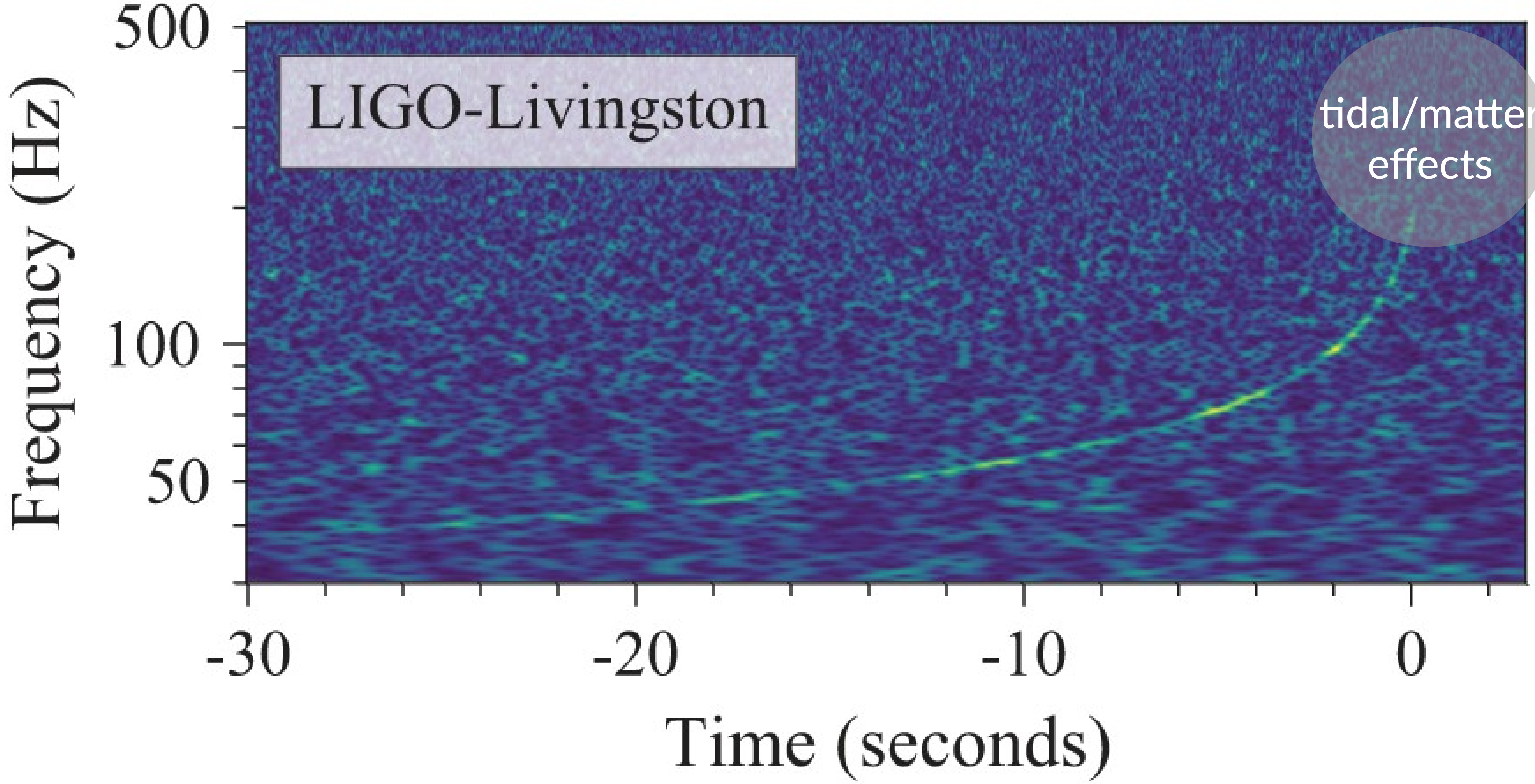
	Low-spin priors ($|\chi| \leq 0.05$)	High-spin priors ($|\chi| \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

Abbott et al, Phys. Rev. Lett. 119, 161101 (2017)

Updated, more precise estimates coming soon
(better calibration, waveforms models, use of EM information)

Tidal deformation by the gravity gradient due to companion
changes the grav. potential and thus the orbital motion/GW signal

Effect observable in the final tens of GW cycles before merger
f_{GW} > 400 Hz – Keplerian orbital radius ~ 60 km
comparable to NS radius



Constraints on NS deformability

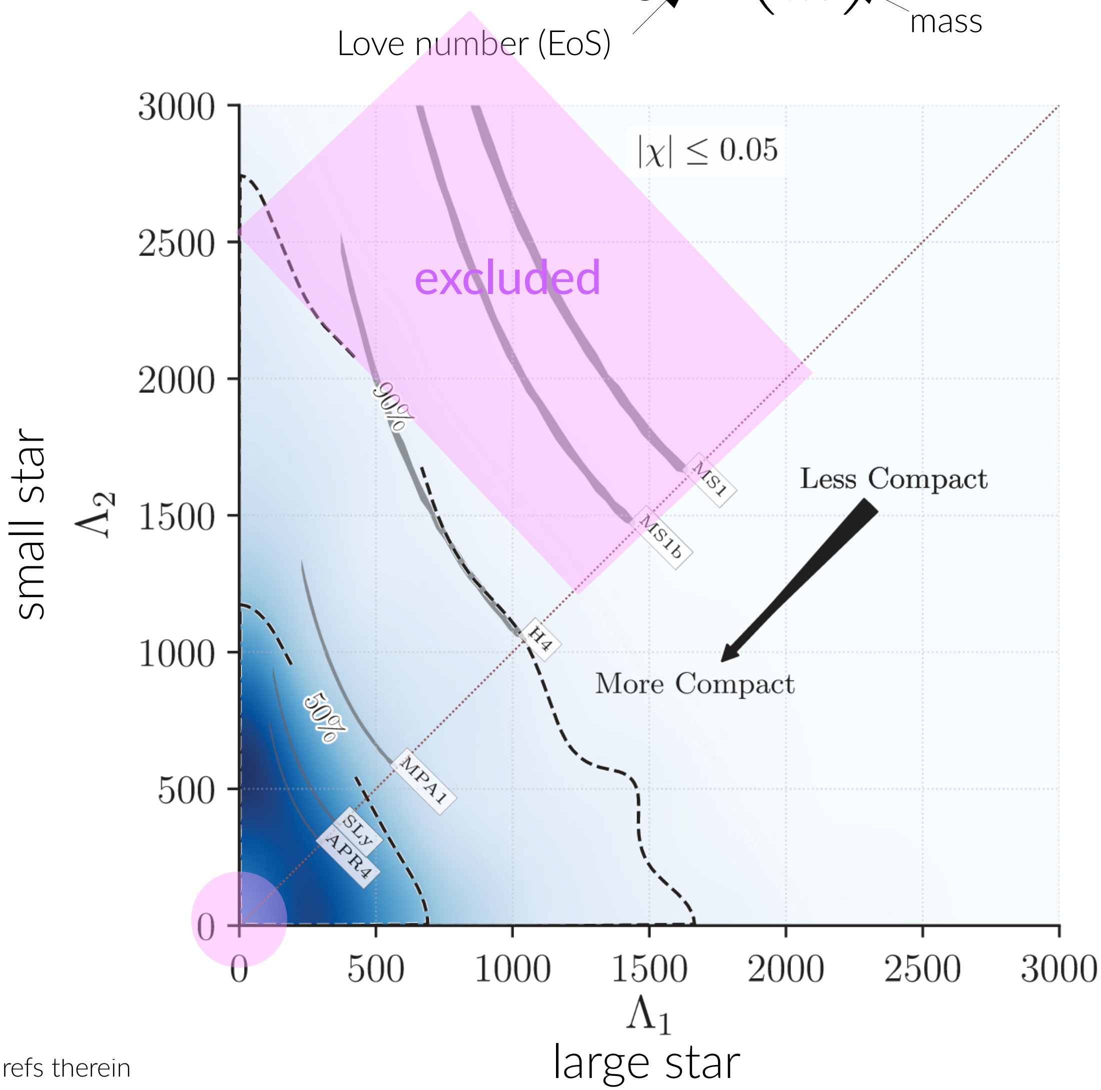
and EoS of cold dense matter

Tidal deformability $\Lambda = \frac{2}{3} k_2 \left(\frac{R}{m} \right)^5$ $k_2 = 0$ for BH

NS radius (EoS)

mass

Love number (EoS)



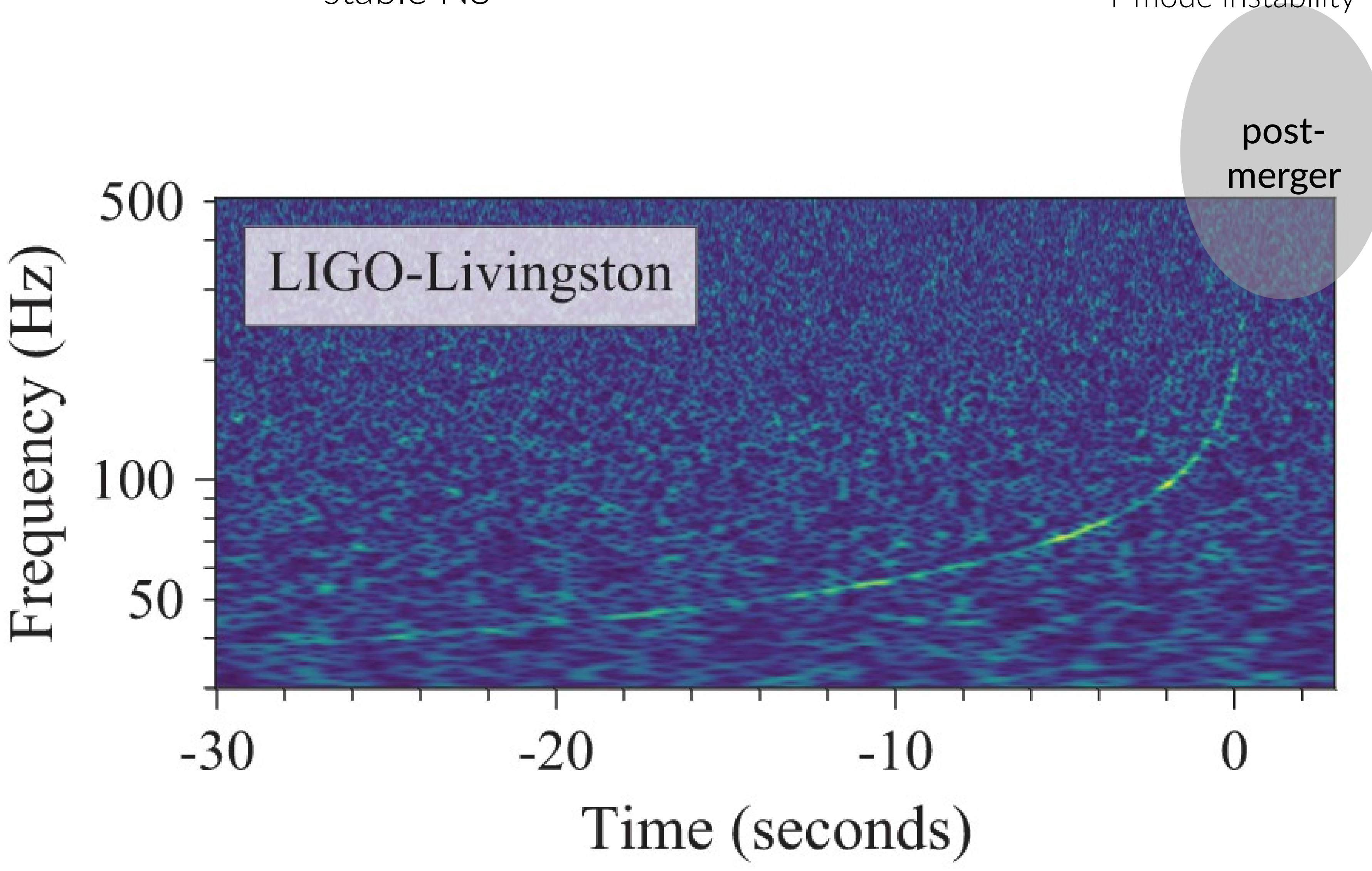
Update **coming soon**
(better param estimates,
waveforms systematics,
direct constraints on EoS)

Selection of EoS from J. S. Read et al
Phys. Rev. D79, 124032 (2009) and refs therein

Post-merger scenarios

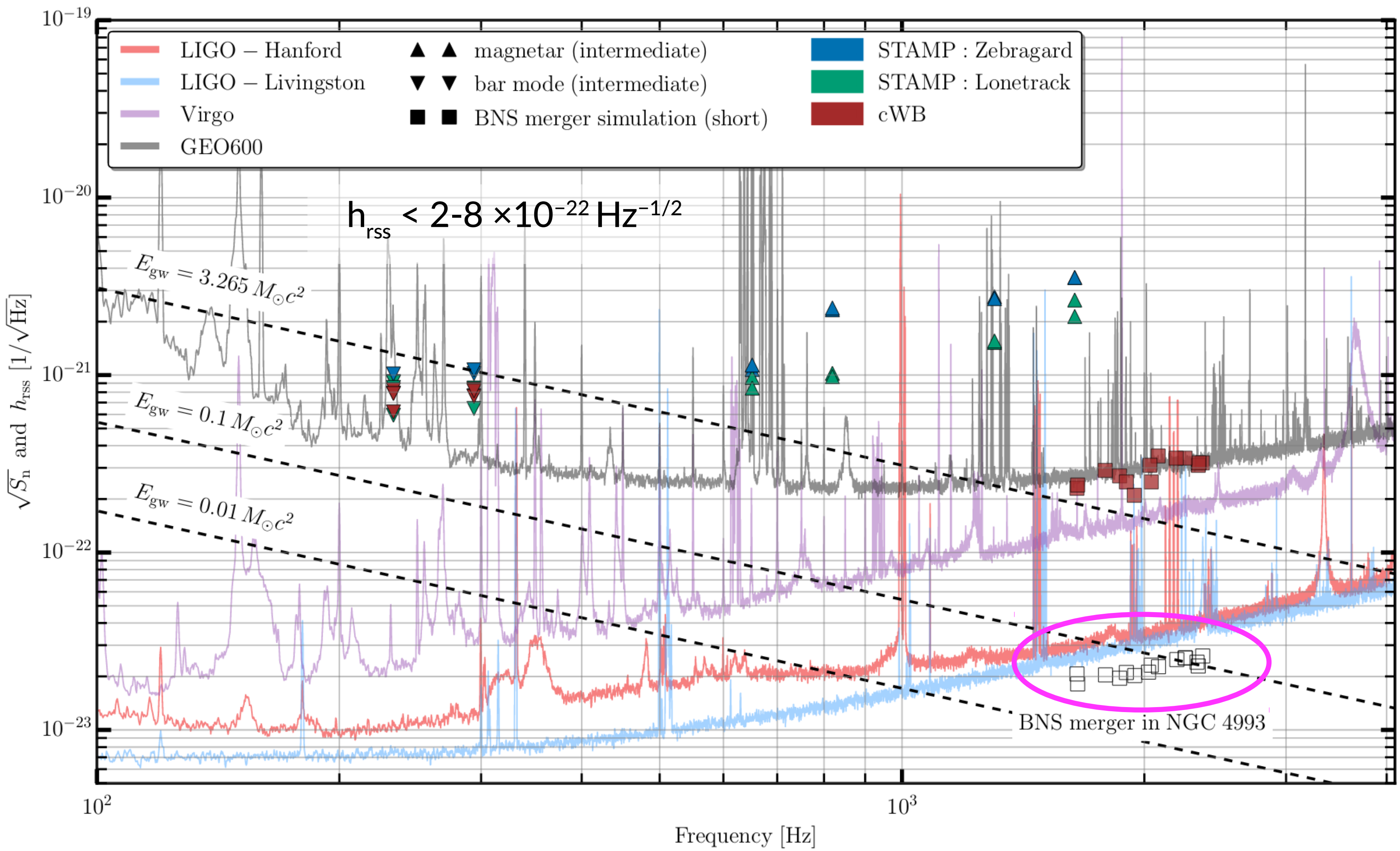
- prompt collapse to a black hole → quasi normal mode at 6 kHz
- hypermassive NS; livetime ~ 1 s [preferred] → f-mode at 2-4 kHz
- supramassive NS; livetime ~ $10 - 10^4$ s
- stable NS

→ magnetar, bar mode or r-mode instability



Agnostic search for GW transients (up to 4 kHz) with short (< 1 s) and intermediate (< 500 s) durations

No evidence for a post-merger signal



Deeper and more complete search (including long duration, days) **coming soon**

Abbott et al,
Astrophys. J. Lett. 851, L16

Implications of GW170817

(besides GRB astrophysics)

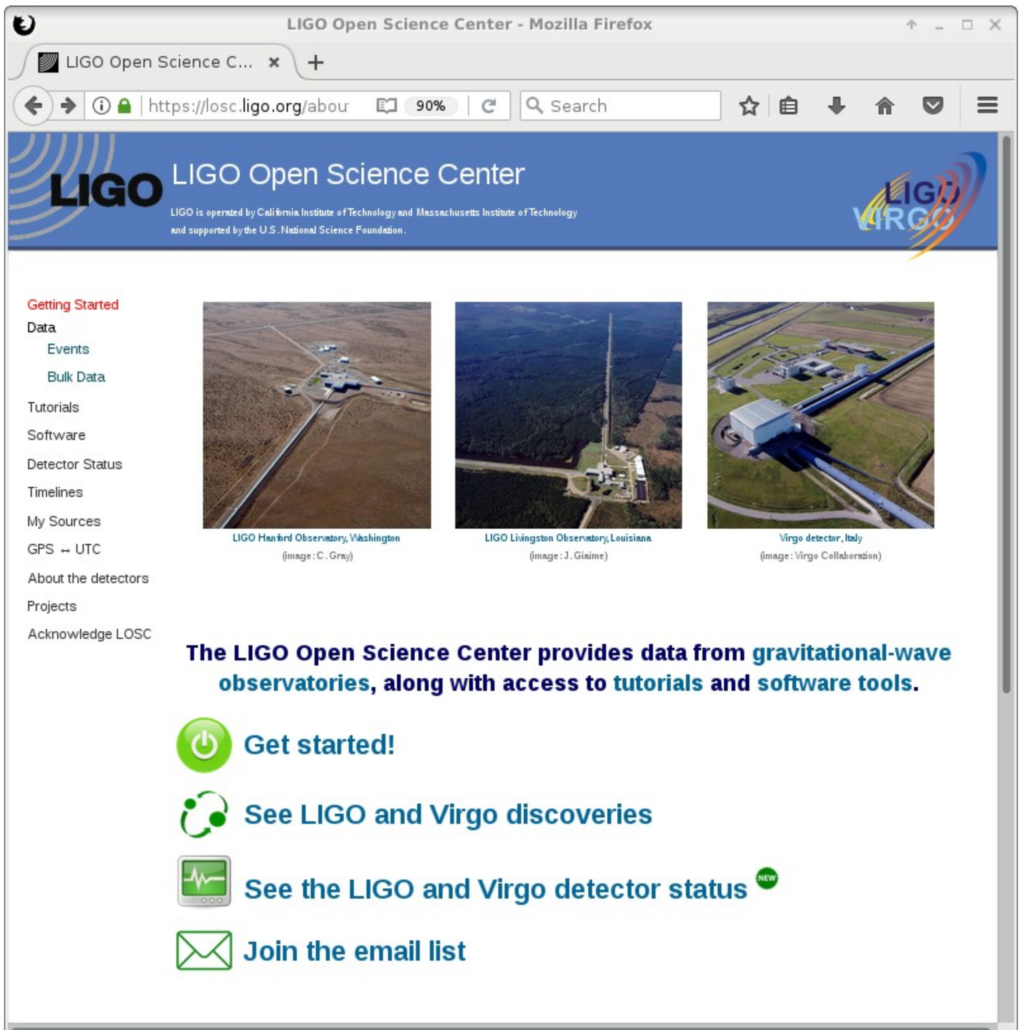
- Coincidence with GRB170817A within 1.7 s
- Very stringent constraints on the speed of gravity $|c/c_g - 1| < 5 \times 10^{-16}$
- Incompatible with a large set of alt. gravity scalar-tensor theories brought forward to explain dark energy

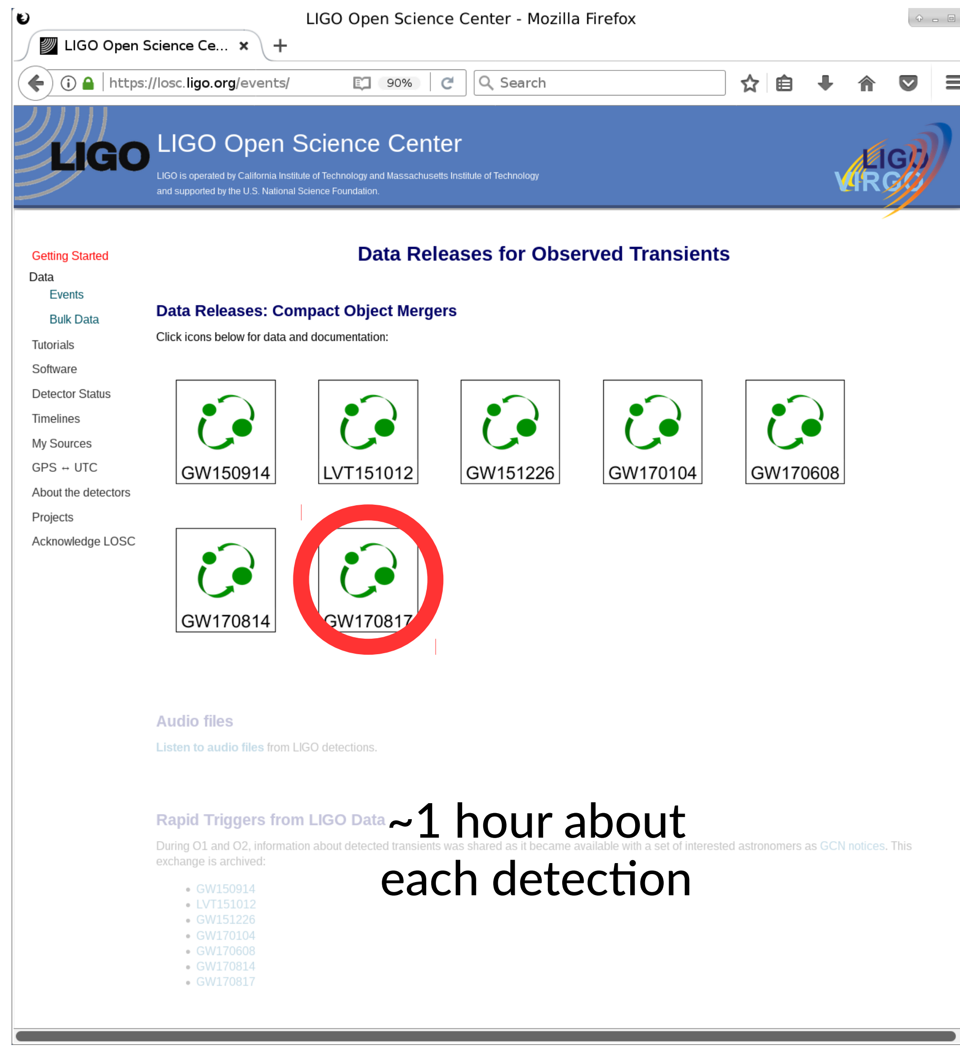
	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [42] Brans-Dicke/$f(R)$ [43, 44] Kinetic Gravity Braiding [46]	quartic/quintic Galileons [13, 14] Fab Four [15, 16] de Sitter Horndeski [45] $G_{\mu\nu}\phi^{\mu}\phi^{\nu}$ [47], Gauss-Bonnet
beyond H.	Derivative Conformal (20) [18] Disformal Tuning (22) DHOST with $A_1 = 0$	quartic/quintic GLPV [19] DHOST [20, 48] with $A_1 \neq 0$
	Viable after GW170817	Non-viable after GW170817

https://arxiv.org/abs/1710.05901
https://arxiv.org/abs/1710.05877

Open data for open science

https://www.losc.ligo.org





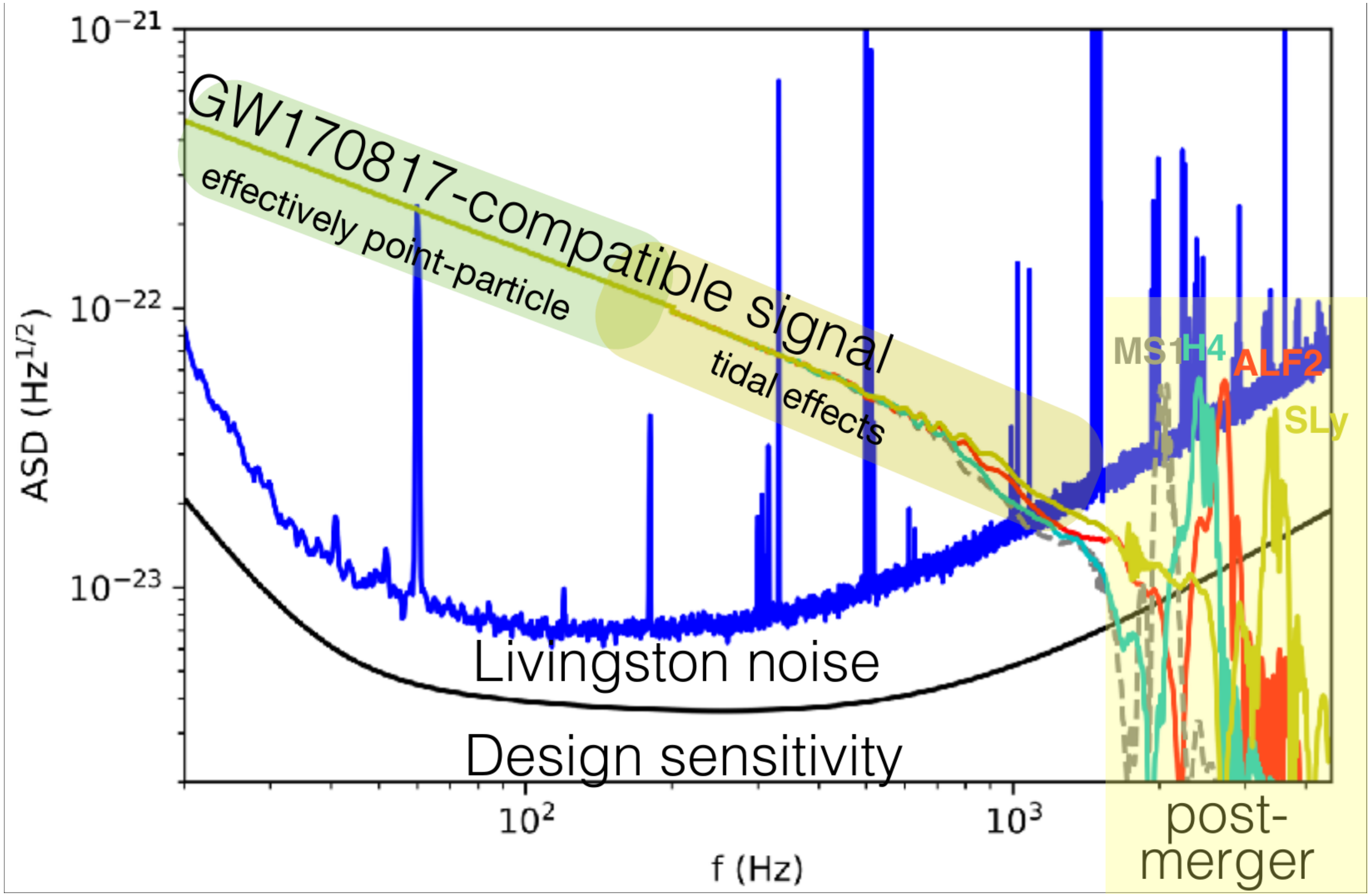
~1 hour about each detection

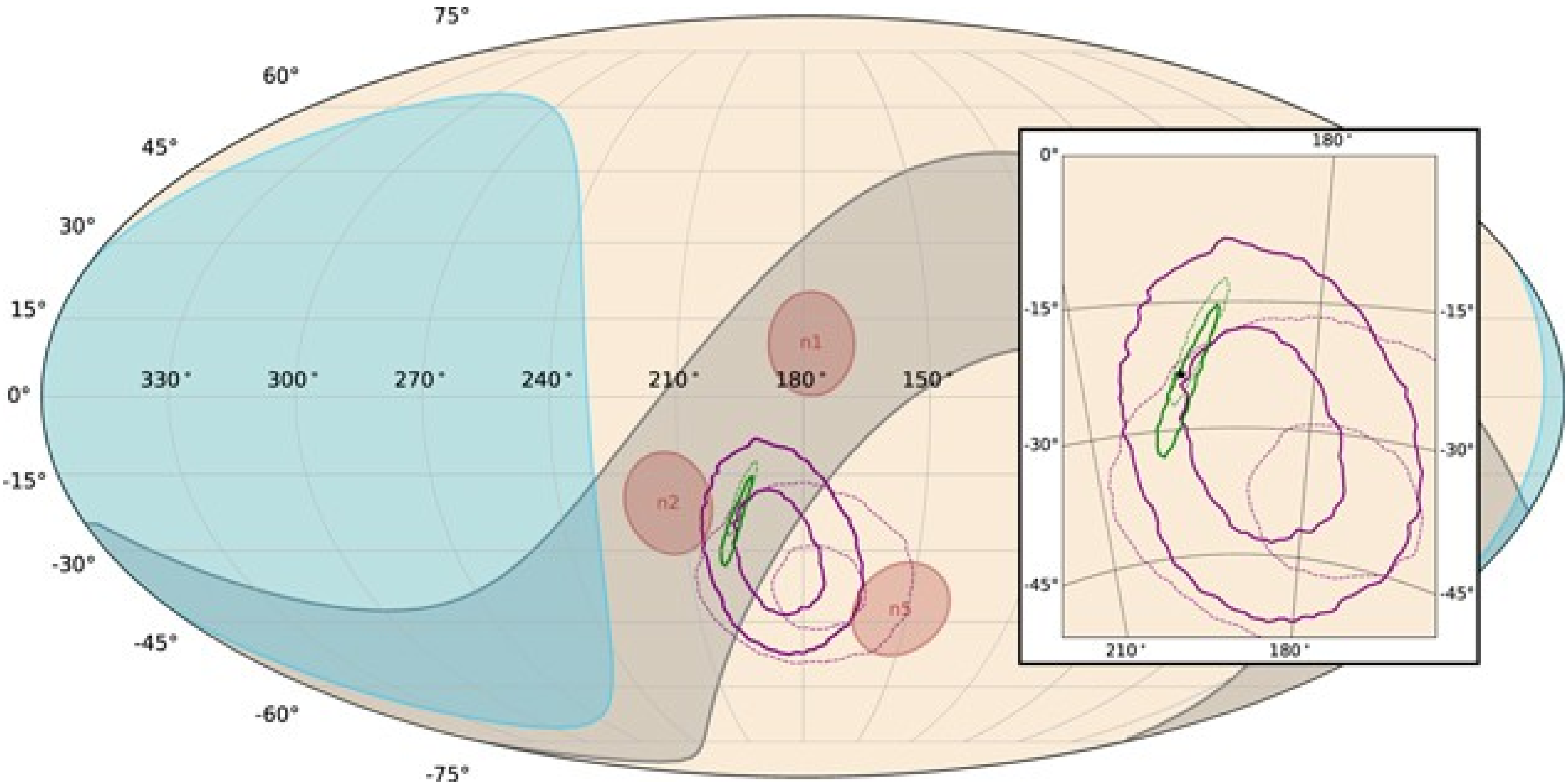
Open data workshop with online tutorials and videos

Concluding remarks

- Plenty of physics with the GW170817 chirp
  - Binary parameters obviously but also physics of NS/EoS of dense matter and tests of post-merger scenarios
  - Tests of General Relativity (GW polarizations, dipole radiation, etc)
- Importance of seeing the same source in GW and EM for fundamental physics
  - Unanticipated implications on fundamental physics (alt. models for gravity, limit on num of spacetime dimensions)
- Future is bright
  - 1–50 BNS expected in O3 (12 months)
  - 4-80 BNS/yr for 2020+ at/near design sensitivity

EoS of cold dense matter





1st Fermi localization with dashed lines

Priors

- Masses (detector frame): uniform in [0.5,7.7] M_{sun} and chirp mass in [1.18, 2.17] M_{sun}
- Spins: uniform in mag up to 0.05 (low spin) and 0.89 (high spin), isotropic/uncorrelated
-