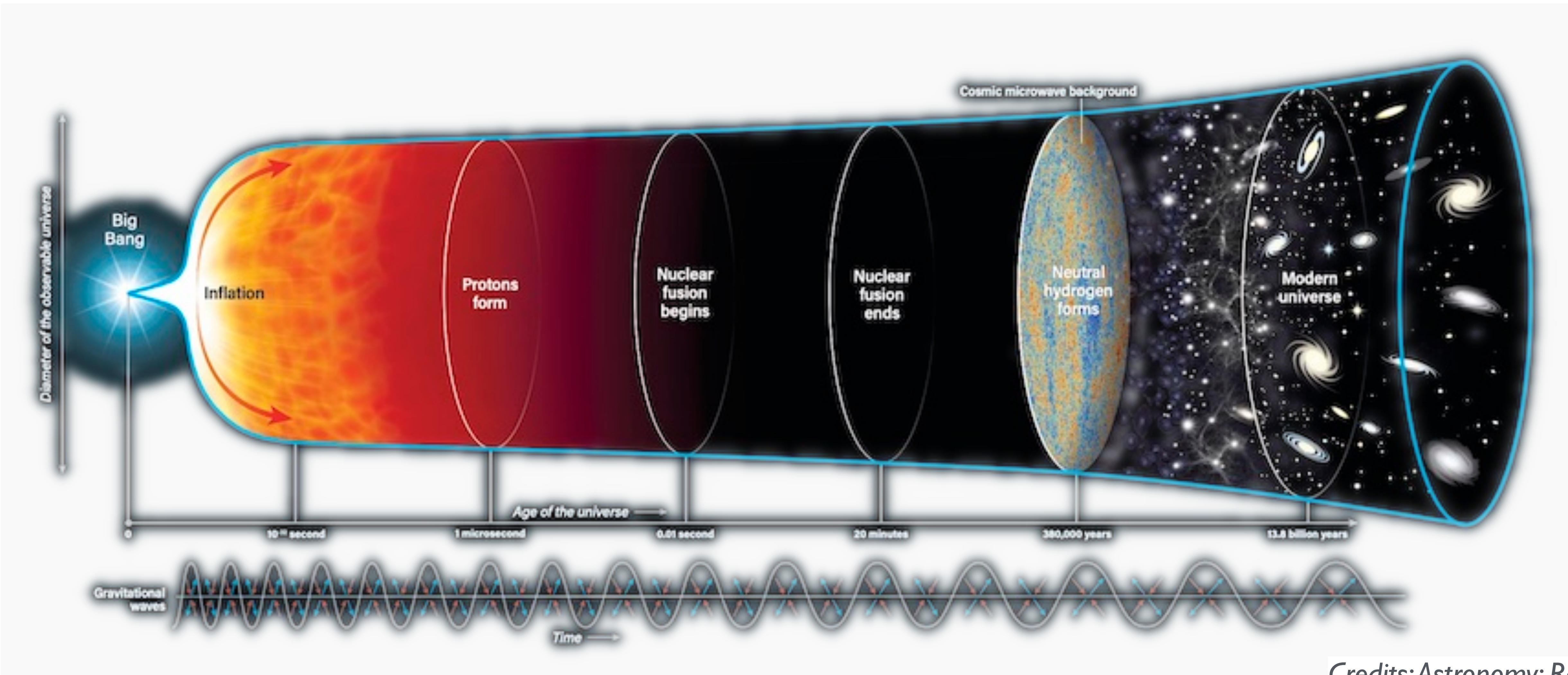
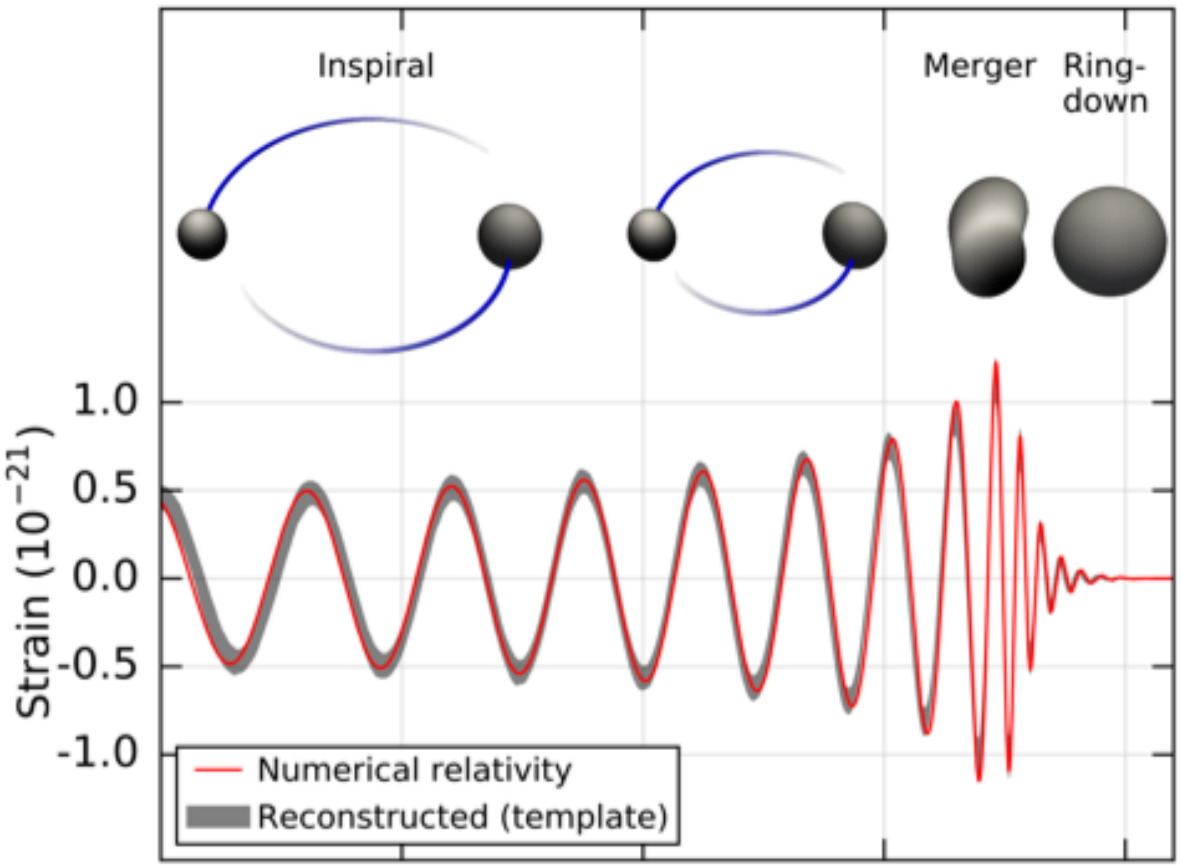
Cosmology with gravitational waves: Latest results and prospects

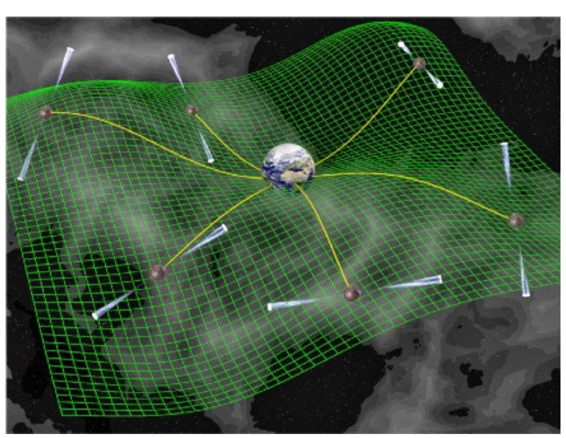


Credits: Astronomy: Roen Kelly, after BICEP2 Collaboration

Danièle Steer

Individual resolvable sources

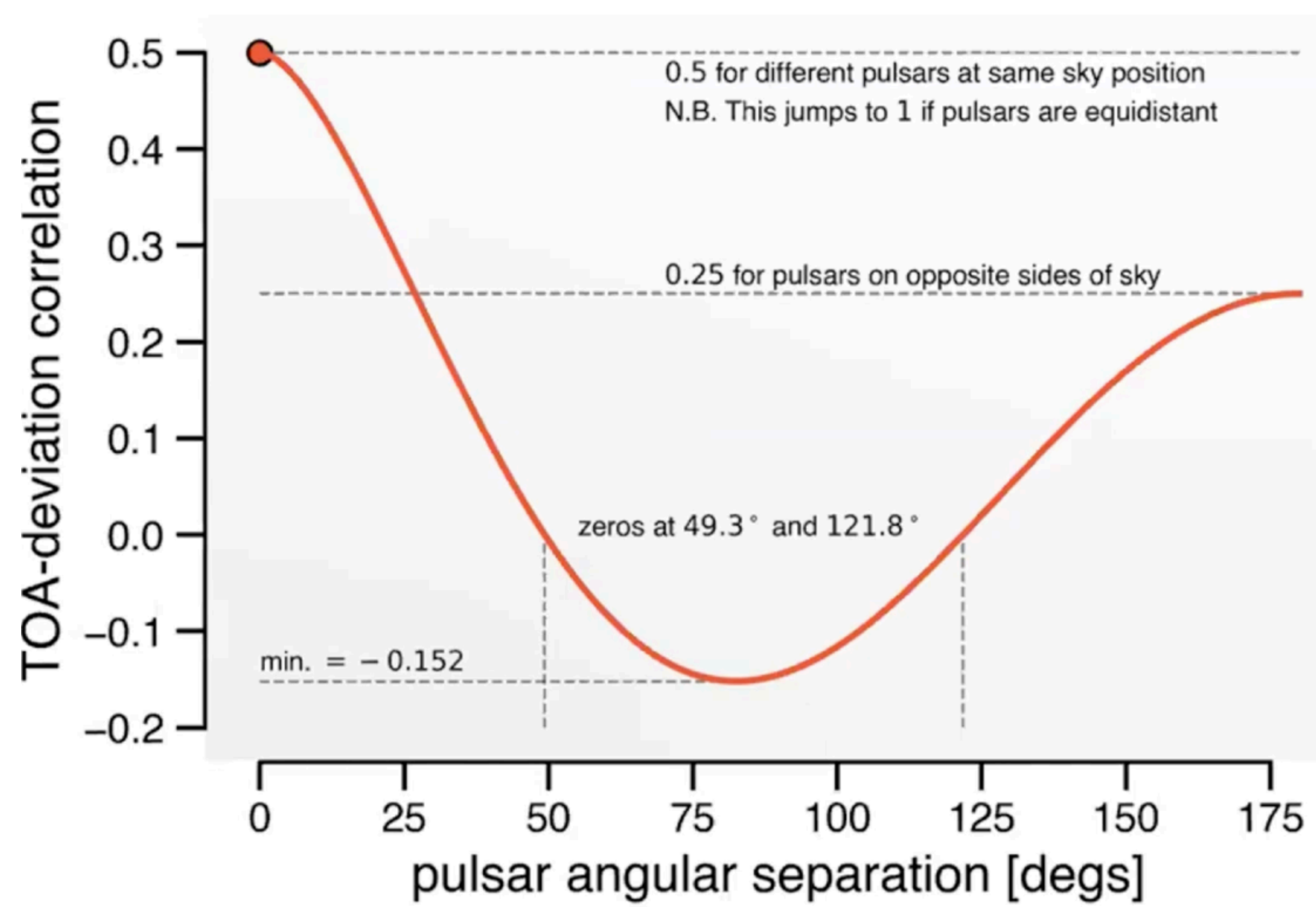




[Credit: D. Champion]

GW background

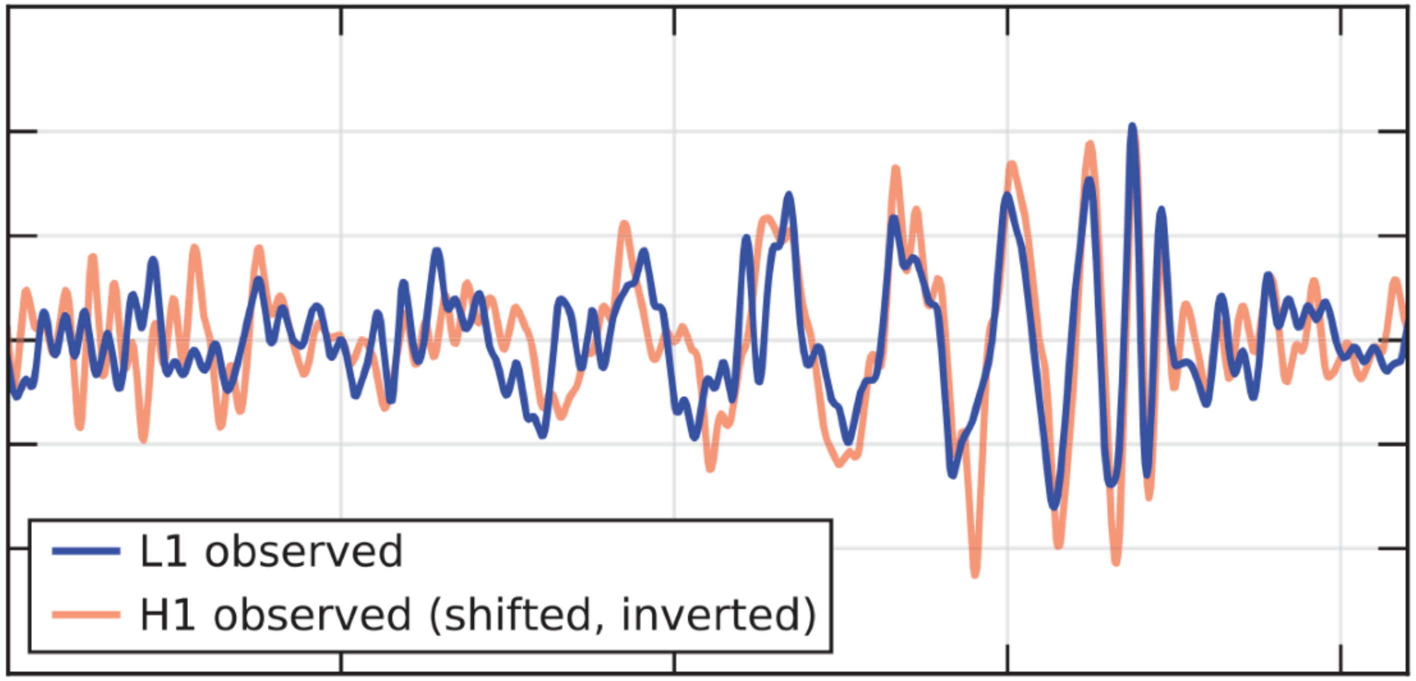
[Hellings&Downs, 1983]

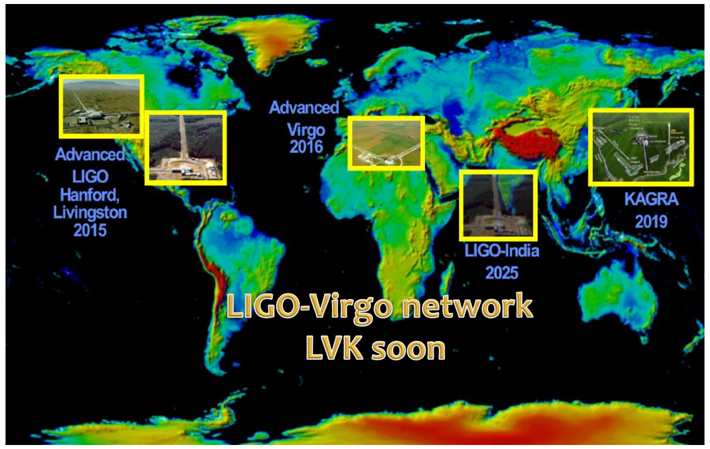


GW150914,
z ~ 0.1

[LIGO-Virgo, PRL 116, 061102]

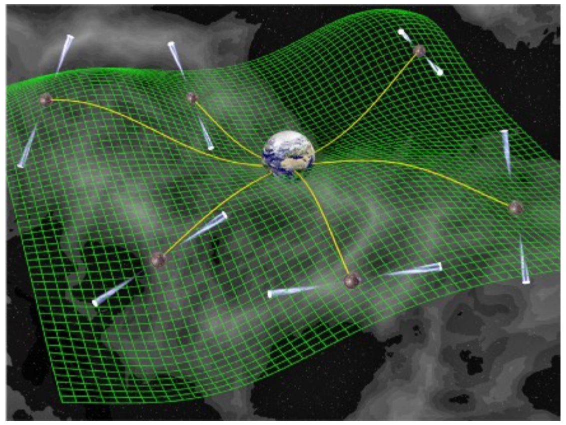
+ over 90 detections since then

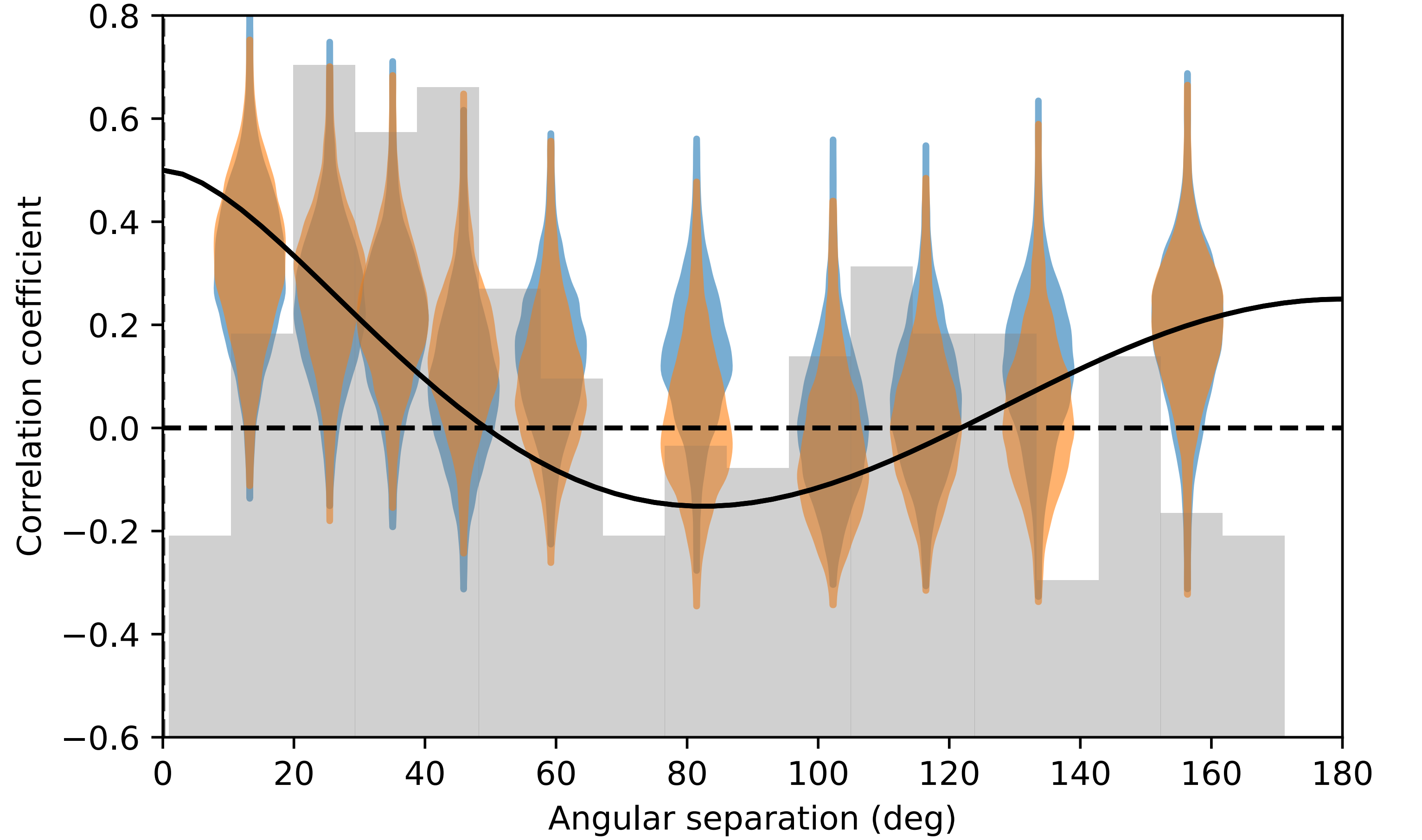


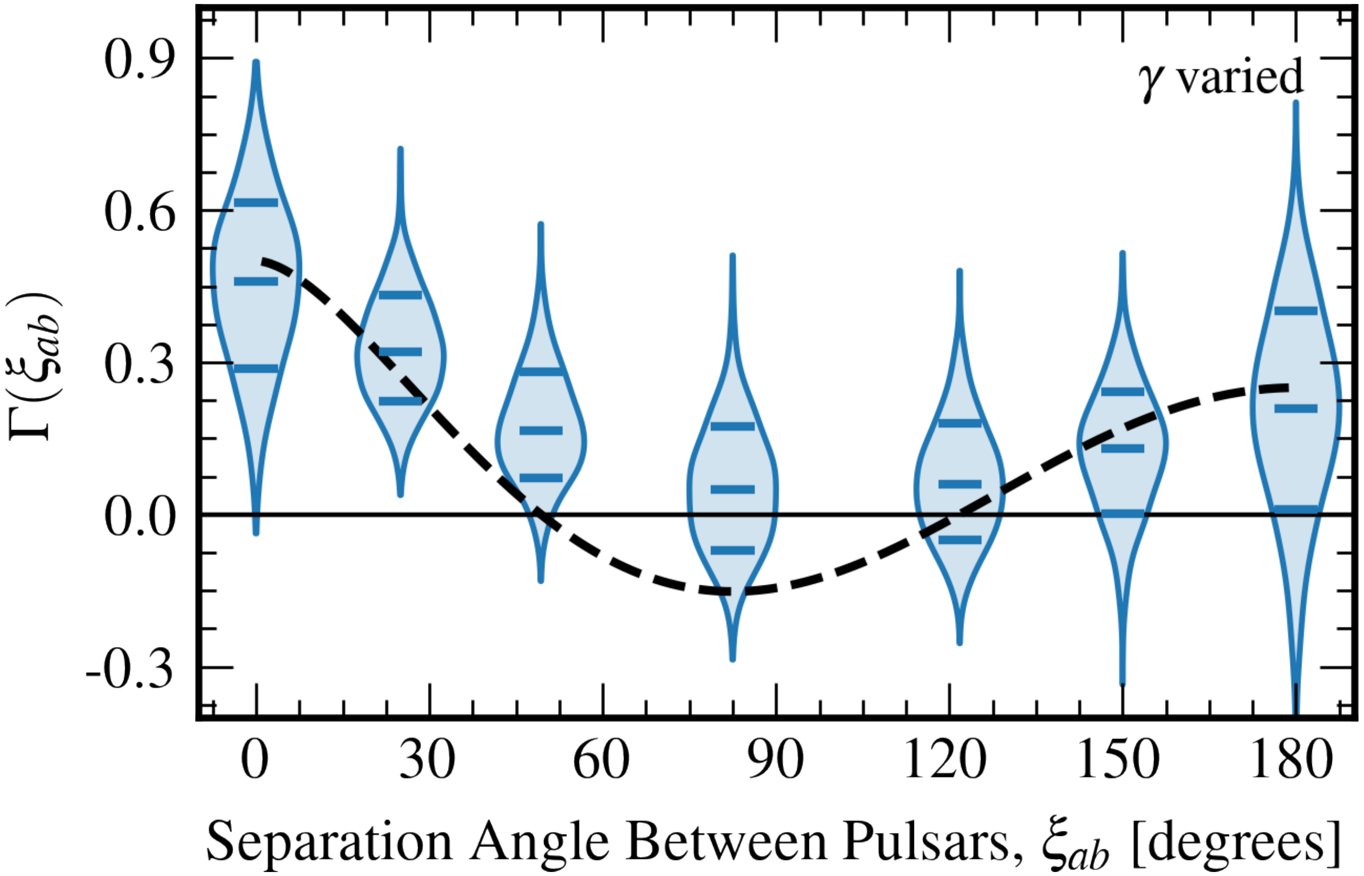


Pulsar Timing Array (EPTA); 25 pulsars

[EPTA III: search for GWs 2306.16214]





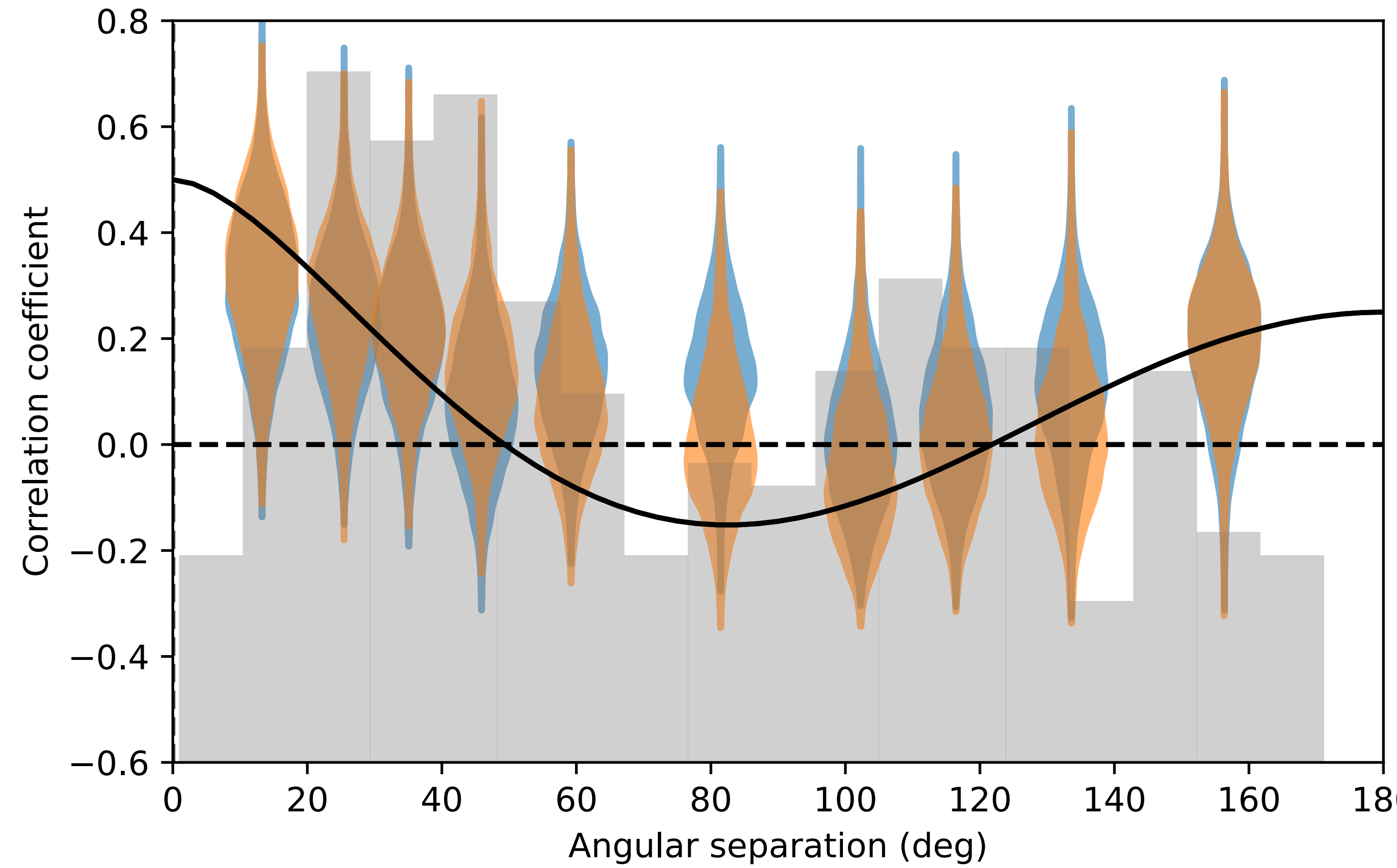


NANOGrav collaboration,
15 year data set
68 pulsars

[NANOGrav, Evidence for a GW background, 2306.16213]

Pulsar Timing Array
(EPTA); 25 pulsars

[EPTA III: search for GWs 2306.16214]



Compelling **evidence** for a GW background:

$3.5 - 4\sigma$ (NANOGrav)

$\sim 3 - 3.5\sigma$ (EPTA+IPTA)

$\sim 2\sigma$ (PPTA)

(CPTA)

Within 1-2 years, IPTA, combined data => detection?

Gravitational waves and cosmology

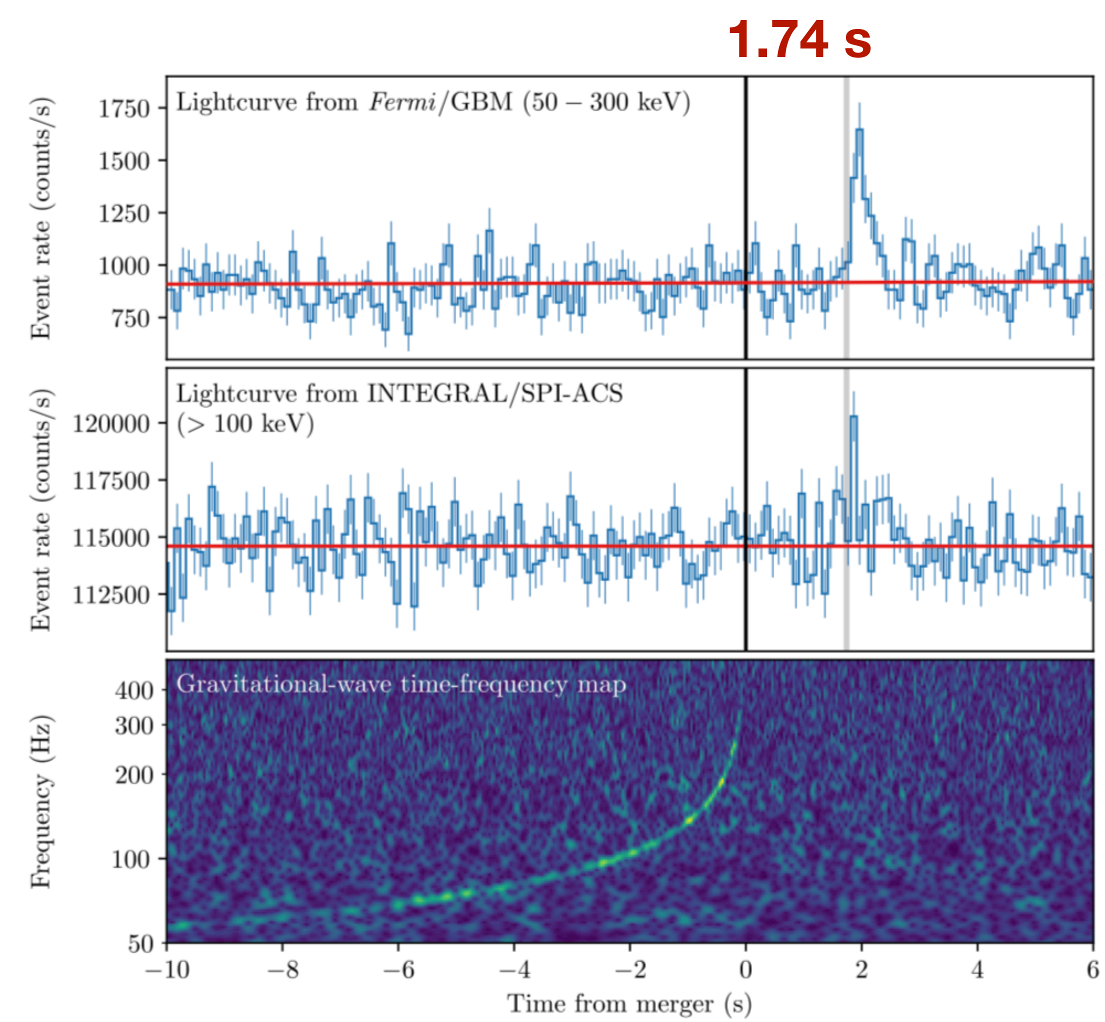
Individual sources
and populations of sources
at cosmological distances
e.g. binary neutron stars (BNS),
binary black holes (BBH),
neutron star- black-hole binary (NS-BH)
Topological defects e.g. cosmic string bursts…

late-time universe

– Expansion rate $H(z)$
– H_0 , Hubble constant
– Ω_m
– beyond ΛCDM
dark energy $w(z)$ and dark matter
– modified gravity (modified GW propagation)
– astrophysics; eg BH populations, PISN mass gap?
….

LVK O3, $z_{\rm max} \lesssim 0.9$

BNS-GW170817, $z \sim 0.01$



B. P. Abbott +, APJL, 848:L13 (2017)

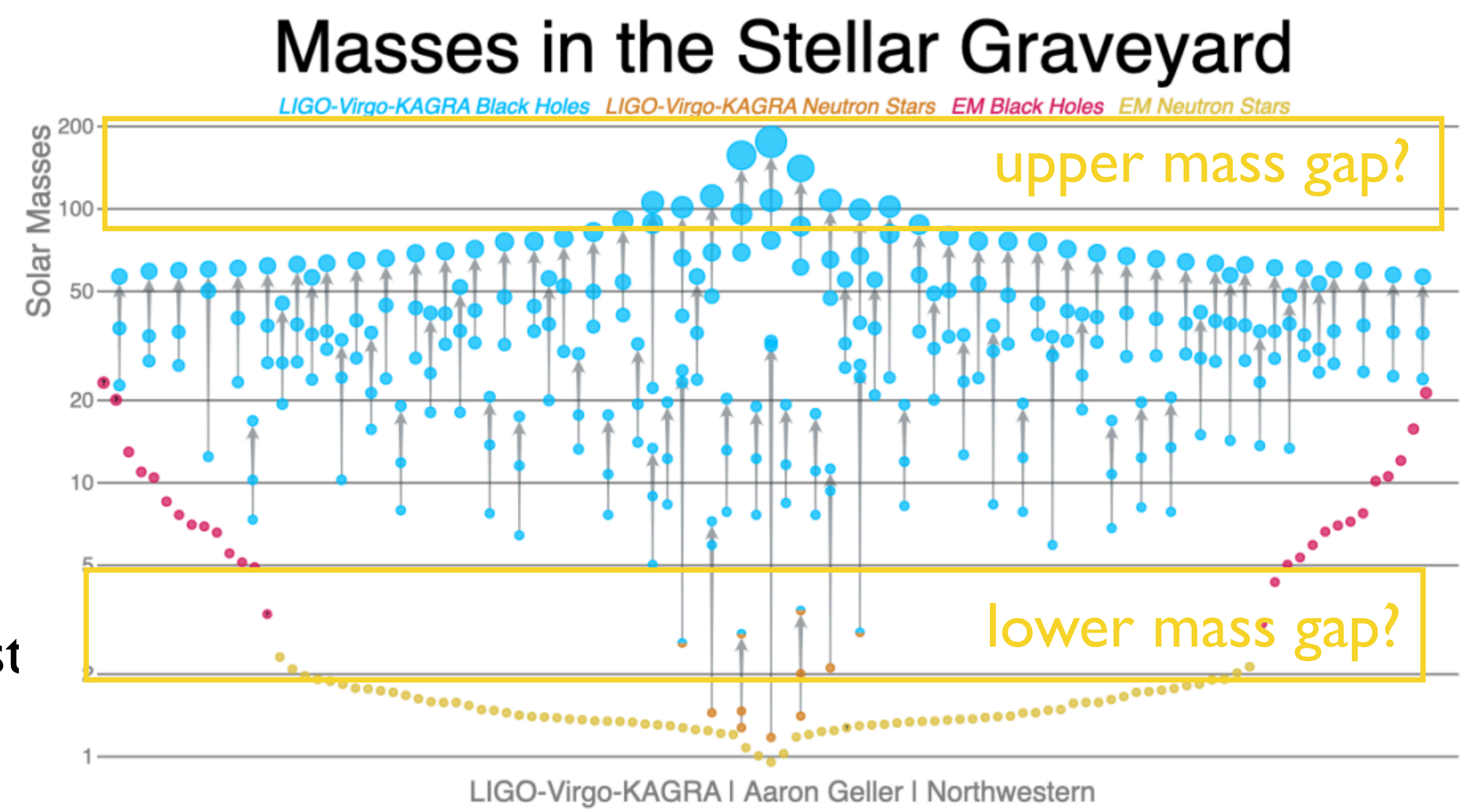
$$-3 \times 10^{-15} \leq \frac{c_{GW} - c}{c} \leq +7 \times 10^{-16}$$

Gravitational waves and cosmology

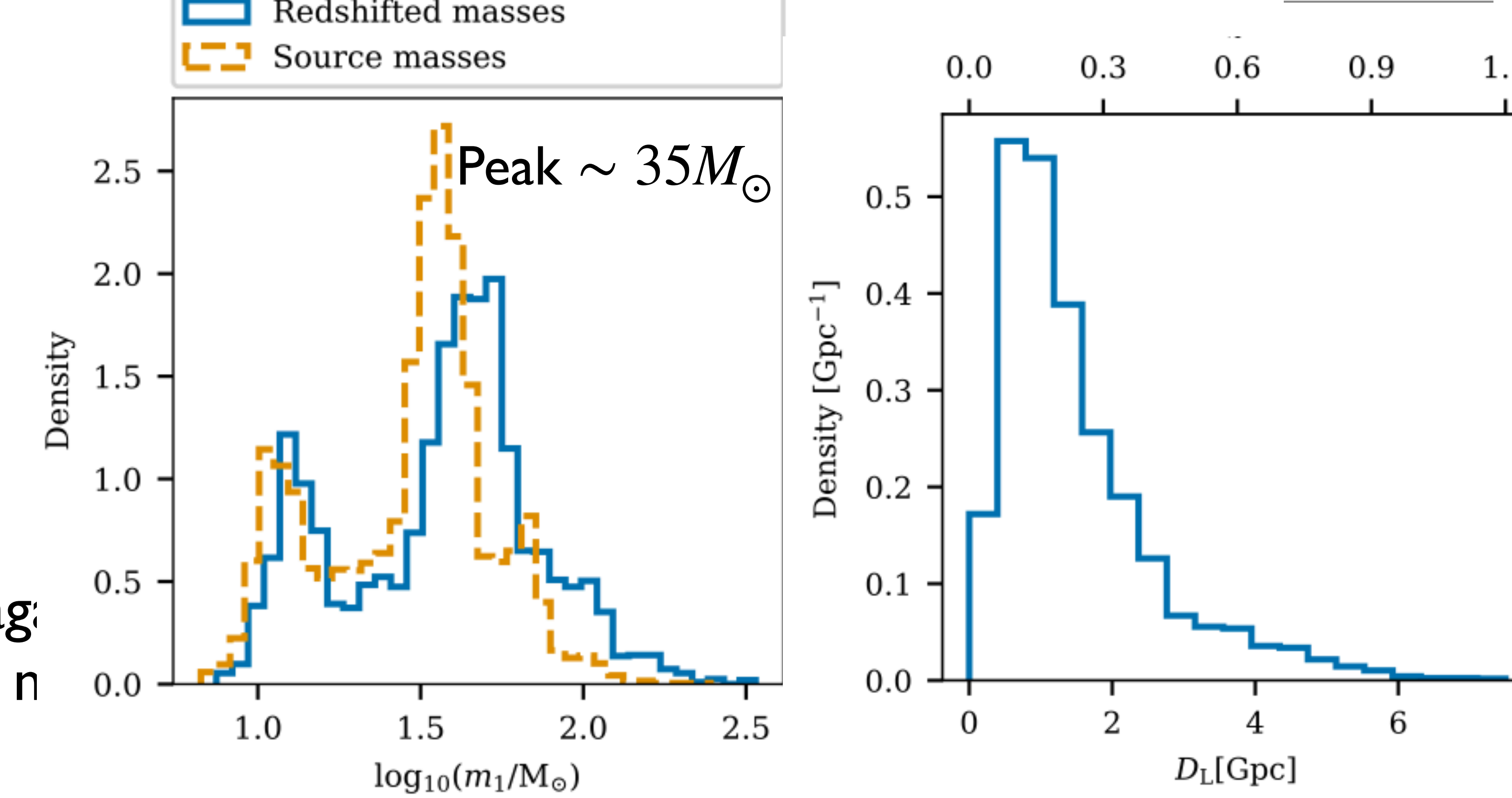
Individual sources
and populations of sources
at cosmological distances
e.g. binary neutron stars (BNS),
binary black holes (BBH),
neutron star- black-hole binary (NS-BH)
Topological defects e.g. cosmic string burst

late-time universe

– Expansion rate $H(z)$
– H_0 , Hubble constant
– Ω_m
– beyond $\Lambda\mathrm{CDM}$
dark energy $w(z)$ and dark matter
– modified gravity (modified GW propag
– astrophysics; eg BH populations, PISN n
….



2111.03604



Gravitational waves and cosmology

Individual sources
and populations of sources
at cosmological distances
e.g. binary neutron stars (BNS),
binary black holes (BBH),
neutron star- black-hole binary (NS-BH)
Topological defects e.g. cosmic string bursts…

late-time universe

– Expansion rate $H(z)$
– H_0 , Hubble constant
– Ω_m
– beyond $\Lambda\mathrm{CDM}$
dark energy $w(z)$ and dark matter
– modified gravity (modified GW propagation)
– astrophysics; eg BH populations, PISN mass gap?
….

Stochastic background
of GWs of astrophysical
and/or cosmological origin

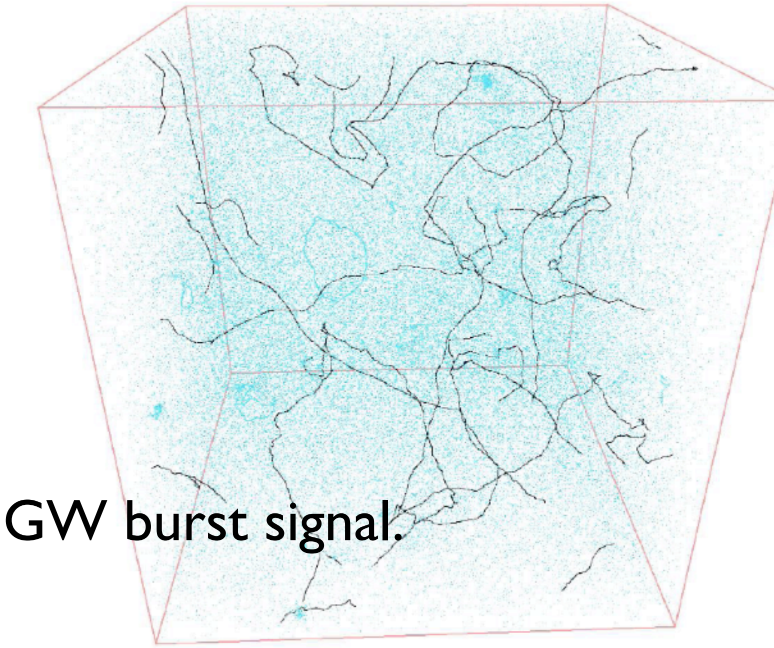
$$\Omega_{\rm gw}(t_0, f) = \frac{f}{\rho_c}\frac{d\rho_{\rm gw}}{df}(t_0, f)$$

Very early universe until today
$t \gtrsim t_{Pl}$

– population of black holes
– quantum processes during inflation
– Phase transitions in Early universe
– cosmic strings
– primordial black holes
– ultra light dark matter
…

More speculative. Early universe sources beyond standard model of particle physics!

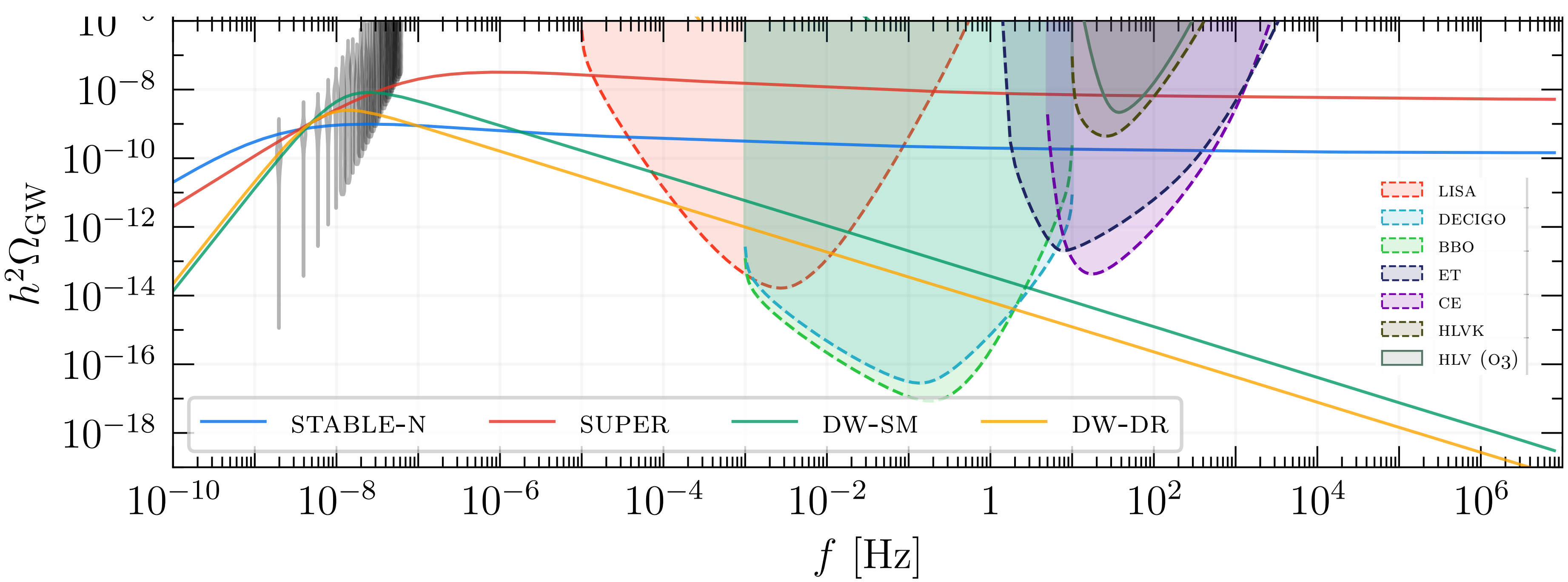
Cosmic Strings.



– Line-like topological defects, may be formed in a symmetry breaking phase transition, time t_i

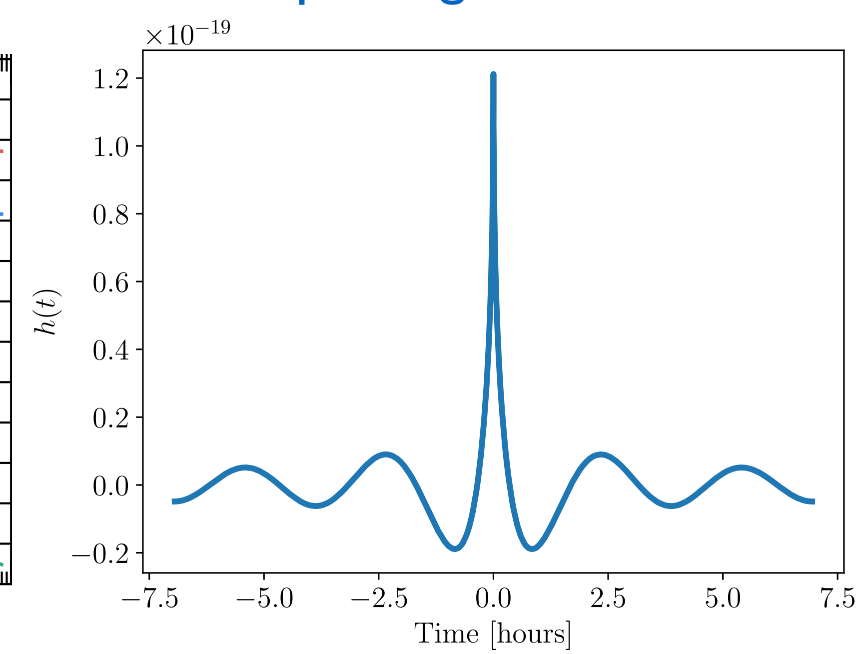
– loops are created for all times $t > t_i$, oscillate relativistically and emit GWs:
- individual loop, close by, emits a particular *short*, and periodically *repeating*, GW burst signal.
- effect of all loops is to generate a SGWB

Stochastic GW background



[NANOGrav, 2306.16219]

Repeating short burst



[Damour&Vilenkin, Auclair et al]

– Experiments, current and future, can either put constraints on, or measure

$$G\mu \sim 10^{-6}\left(\frac{T_i}{10^{16}\ \mathrm{GeV}}\right)^2$$

Gravitational waves and cosmology

Individual sources
and populations of sources
at cosmological distances
e.g. binary neutron stars (BNS),
binary black holes (BBH),
neutron star- black-hole binary (NS-BH)
Topological defects e.g. cosmic string bursts…

↕

late-time universe

↓

- Expansion rate $H(z)$
- H_0 , Hubble constant
- Ω_m
- beyond $\Lambda\mathrm{CDM}$
  dark energy $w(z)$ and dark matter
- modified gravity (modified GW propagation)
- astrophysics; eg BH populations, PISN mass gap?

….

Stochastic background
of GWs of astrophysical
and/or cosmological origin

$$\Omega_{\rm gw}(t_0,f) = \frac{f}{\rho_c}\frac{d\rho_{\rm gw}}{df}(t_0,f)$$

↕

Very early universe until today
$t \gtrsim t_{Pl}$

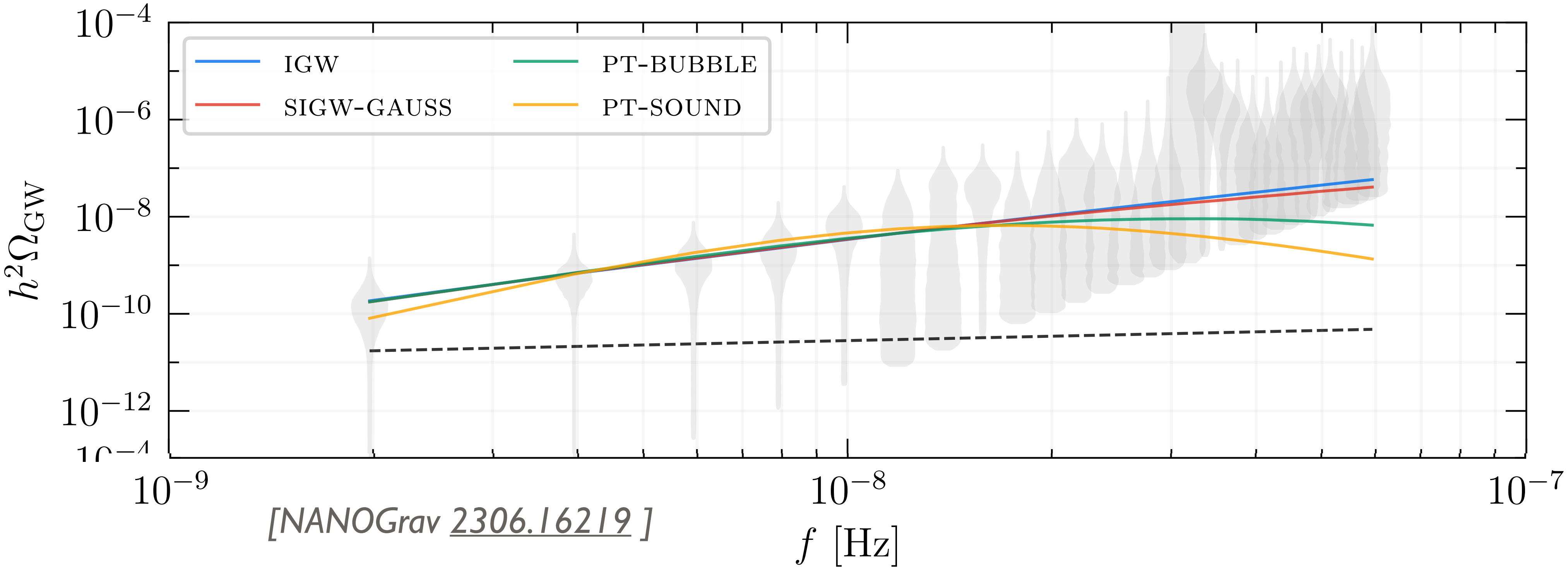
↓

- population of black holes
- quantum processes during inflation
- Phase transitions in Early universe
- cosmic strings
- primordial black holes
- ultra light dark matter

…

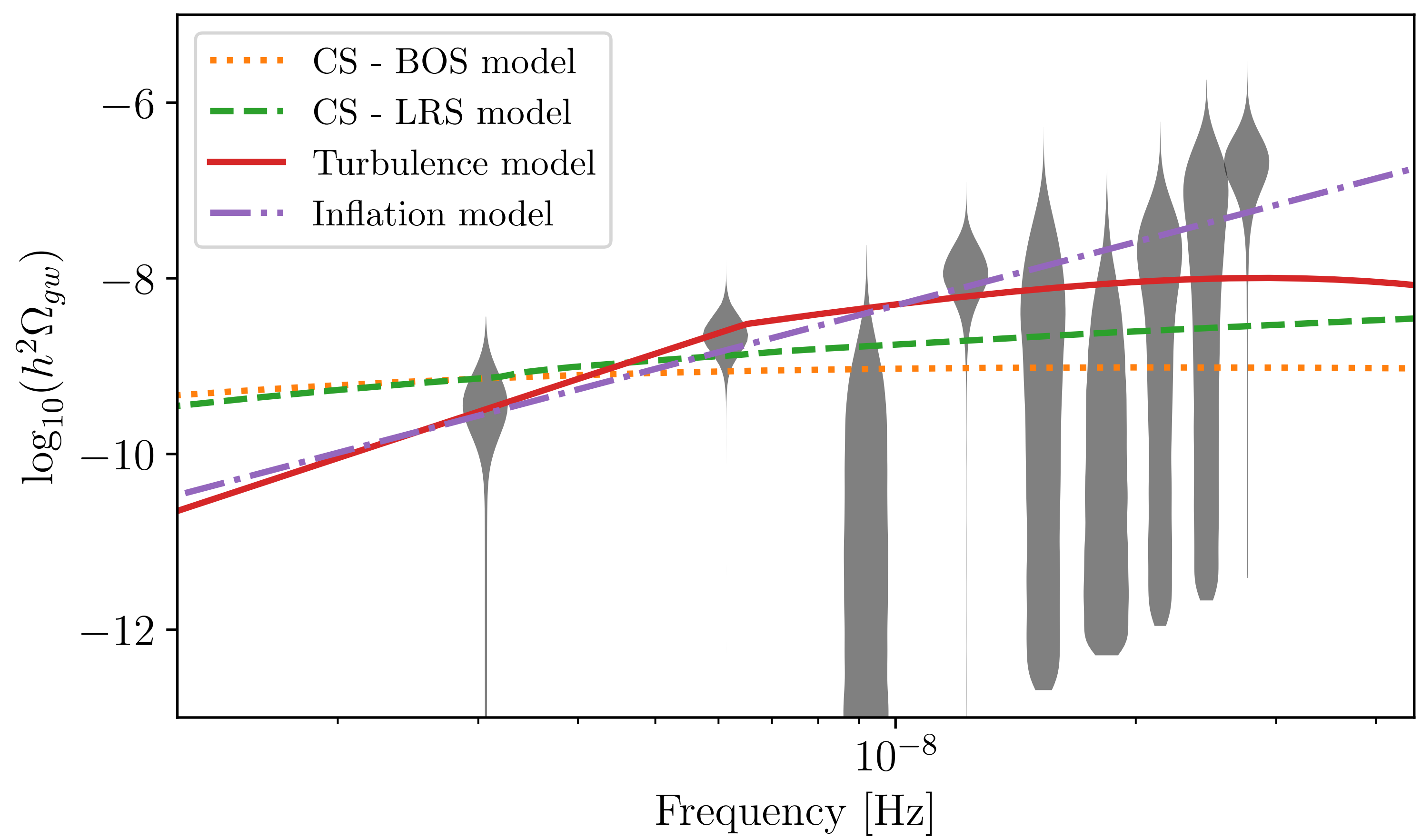
More speculative. Early universe sources beyond standard model of particle physics!

PTA results: SGWB Spectra for maximum a posteriori parameter values, all assuming primordial background to be the only source of GWs***



[NANOGrav 2306.16219]

Inflationary GWs
Scalar induced GWs
Phase transitions: bubble collisions
Phase transitions: sound waves
Astrophysical bkgd



Cosmic strings
Phase transitions: decaying MHD turbulence
Inflationary GWs

[EPTA+InPTA, 2306.16227]

Plan

1/ very very simplified comments on detectors & individual compact binary sources

2/ late time cosmology (H_0, Ω_m) constraints with LVK; future

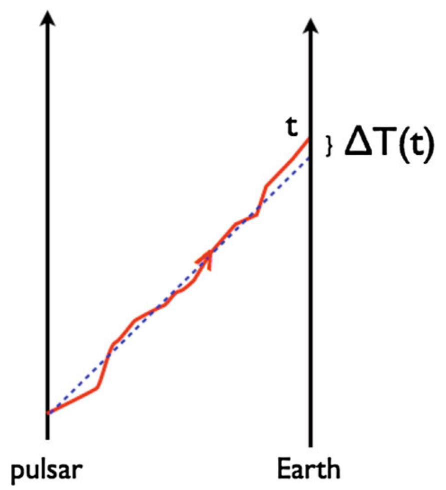
3/ PTA results – Stochastic GW background
– results on different early universe sources

*** <u>Nota Bene:</u>
Though an astrophysical background of putative SMBHB is the most plausible source of the PTA observations, analysis of the data seems to indicate a mild tension between data and predictions.
"This discrepancy presents an opportunity for new physics models to fit the data better".
• *Caution: The situation can evolve with more data.. Should "..not over-interpret the observed evidence in favour of some of the cosmological sources/new physics"*

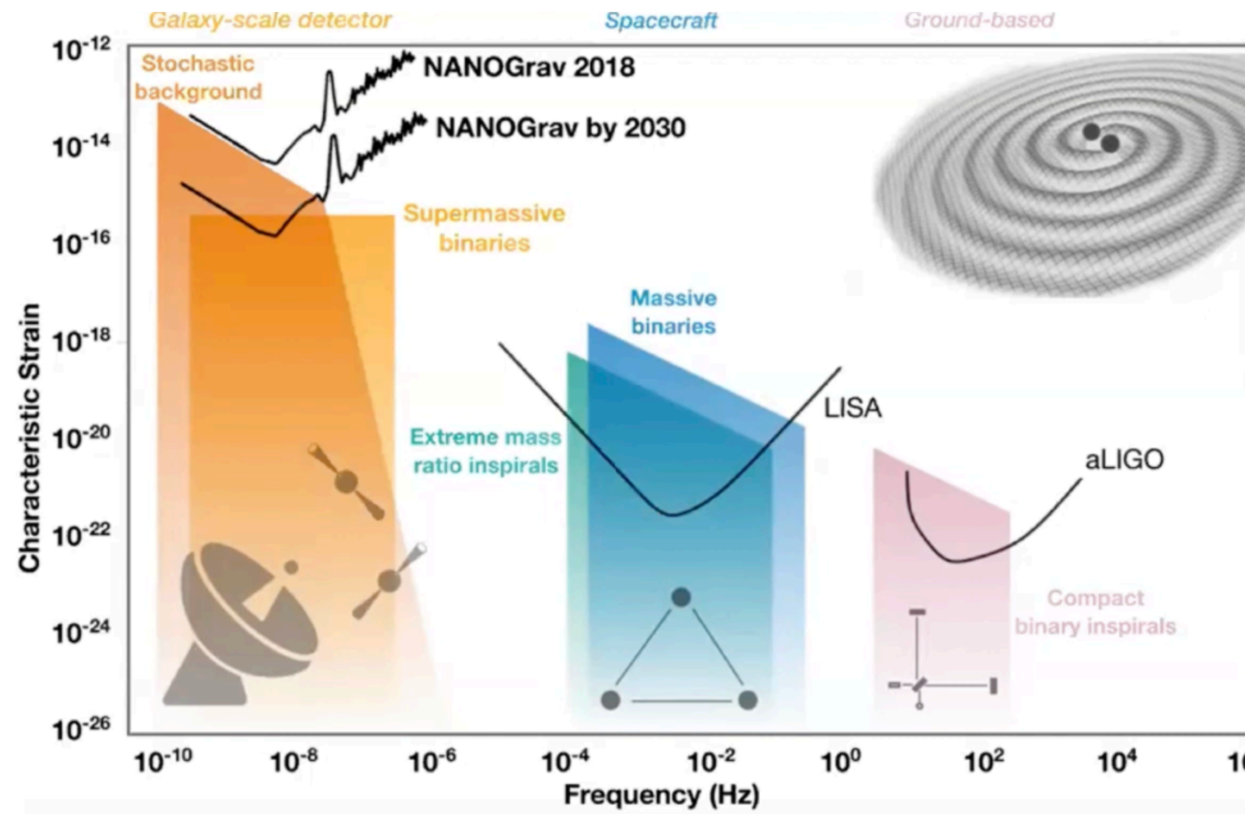
I/ On detectors & binary sources

- designed to be as sensitive as possible to time-varying changes in the separation between two freely-falling objects

PTA:

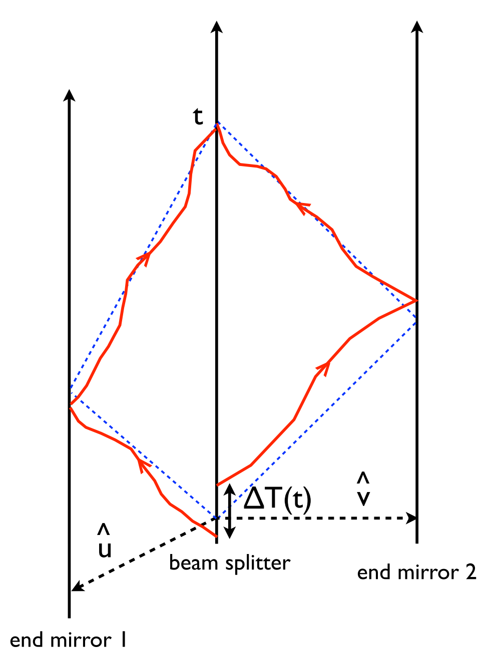


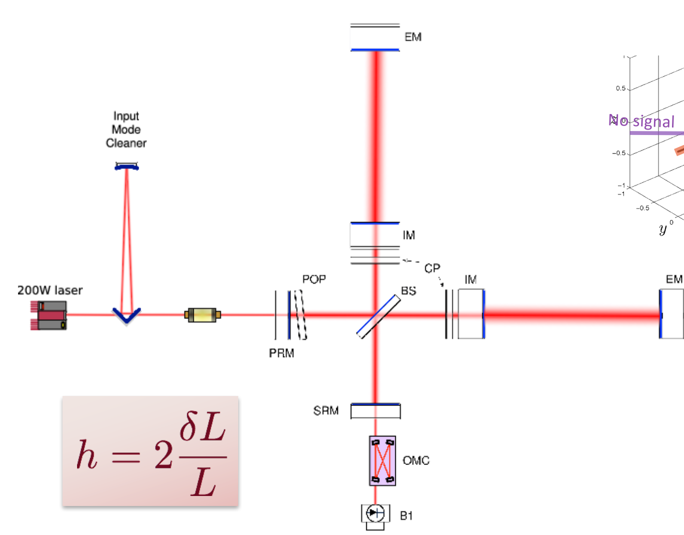
$$h_{\rm timing}(t) = \Delta T(t)$$



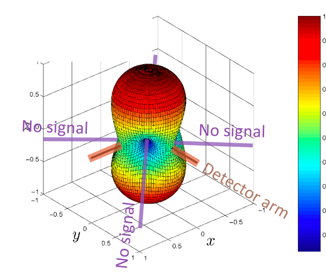
Ultra-stable millisecond pulsars used as beacons "clocks sending signals". In reality though messy astrophysical objects. … Measure TOA of pulse, and compare to expected TOA determined from detailed timing model for the pulsar

Laser interferometers.

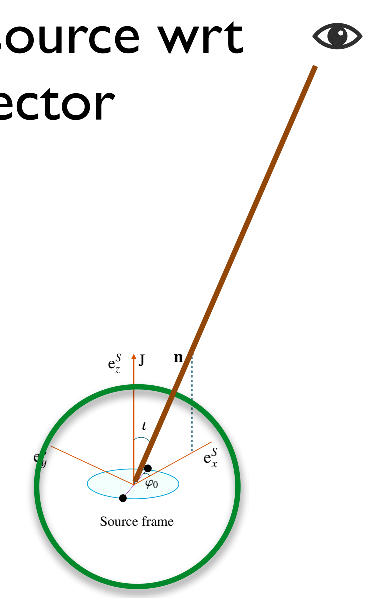




$$h = 2\frac{\delta L}{L}$$



- in both cases, response depends on the orientation of the source wrt to detector



$$h(t,\theta,\phi,\psi) = F_+(t,\theta,\phi,\psi)h_+(t) + F_\times(t,\theta,\phi,\psi)h_\times(t)$$

characteristic size of detector

$f_* = c/L$

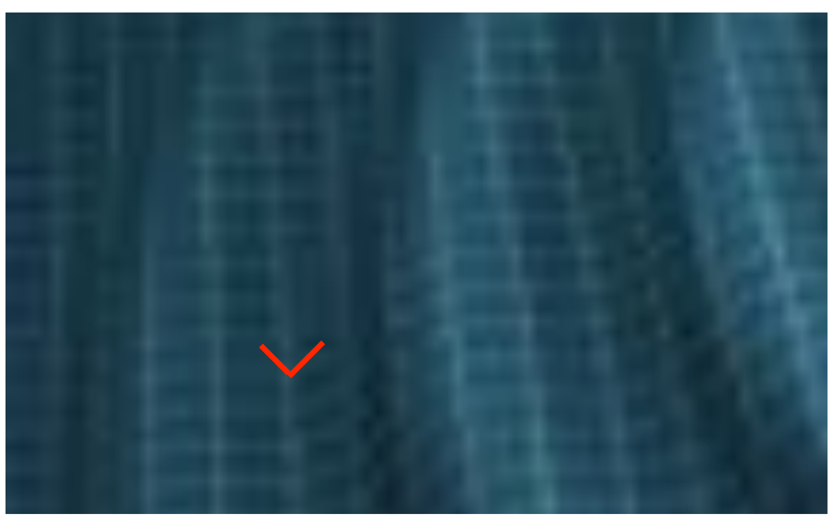
frequency to which detector is sensitive

Beam detector	L (km)	f_* (Hz)	f (Hz)	f/f_*	Relation
Ground-based interferometer	~ 1	$\sim 10^5$	10 to 10^4	10^{-4} to 10^{-1}	$f \ll f_*$
Space-based interferometer	$\sim 10^6$	$\sim 10^{-1}$	10^{-4} to 10^{-1}	10^{-3} to 1	$f \lesssim f_*$
Pulsar timing	$\sim 10^{17}$	$\sim 10^{-12}$	10^{-9} to 10^{-7}	10^3 to 10^5	$f \gg f_*$

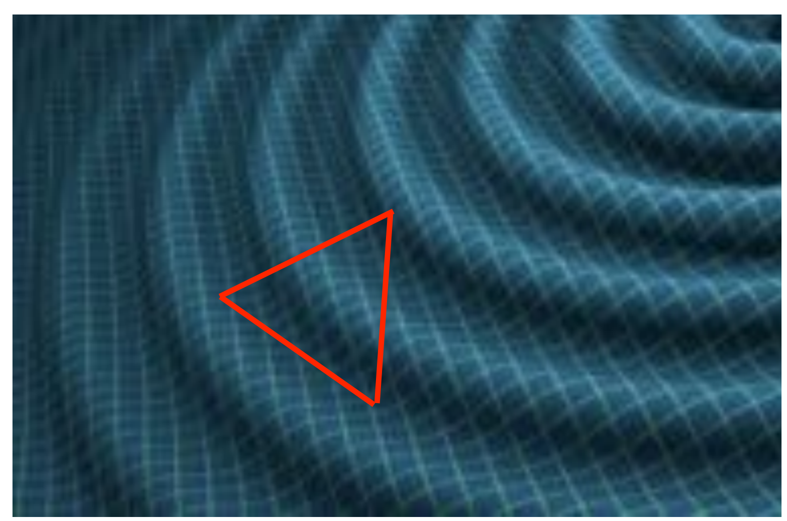
$fL \to 0$

$fL \sim 1$

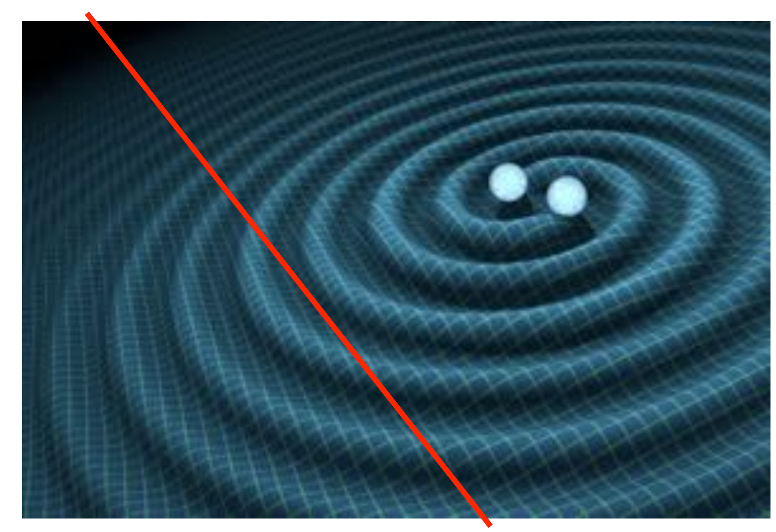
$fL \to \infty$



LVK



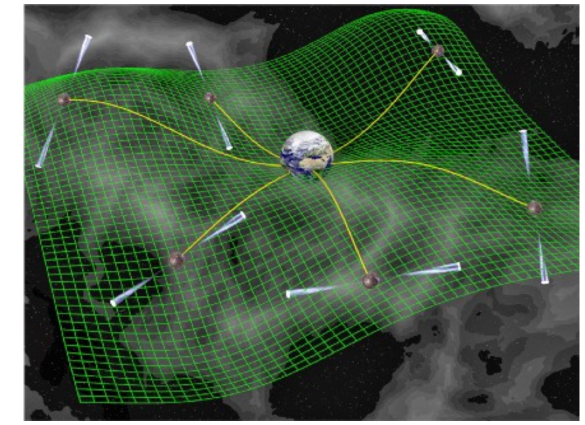
LISA



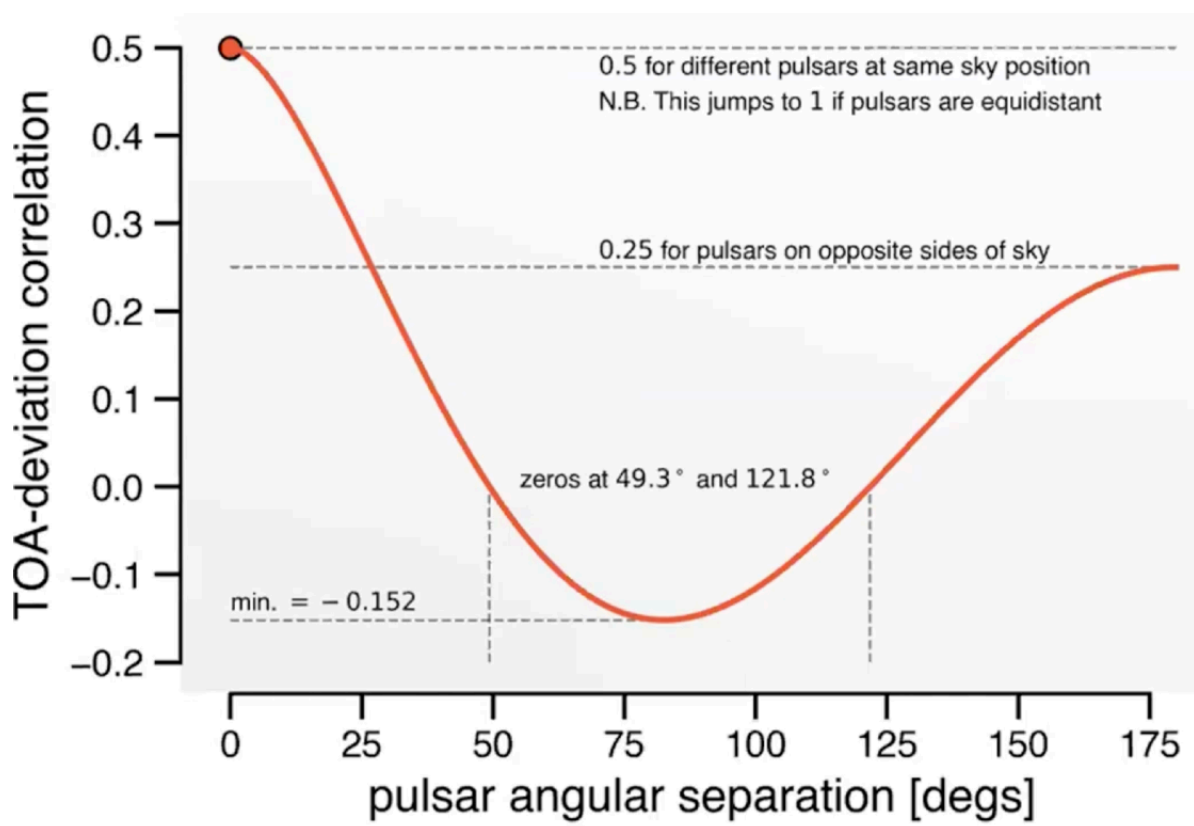
PTA

[Romano+Cornish]

• In PTA, the correlations between δt_a and δt_b simplifies in $fL \to \infty$, to a frequency-independent angular part (HD), overall amplitude depends on $\Omega_{\rm gw}(f)$

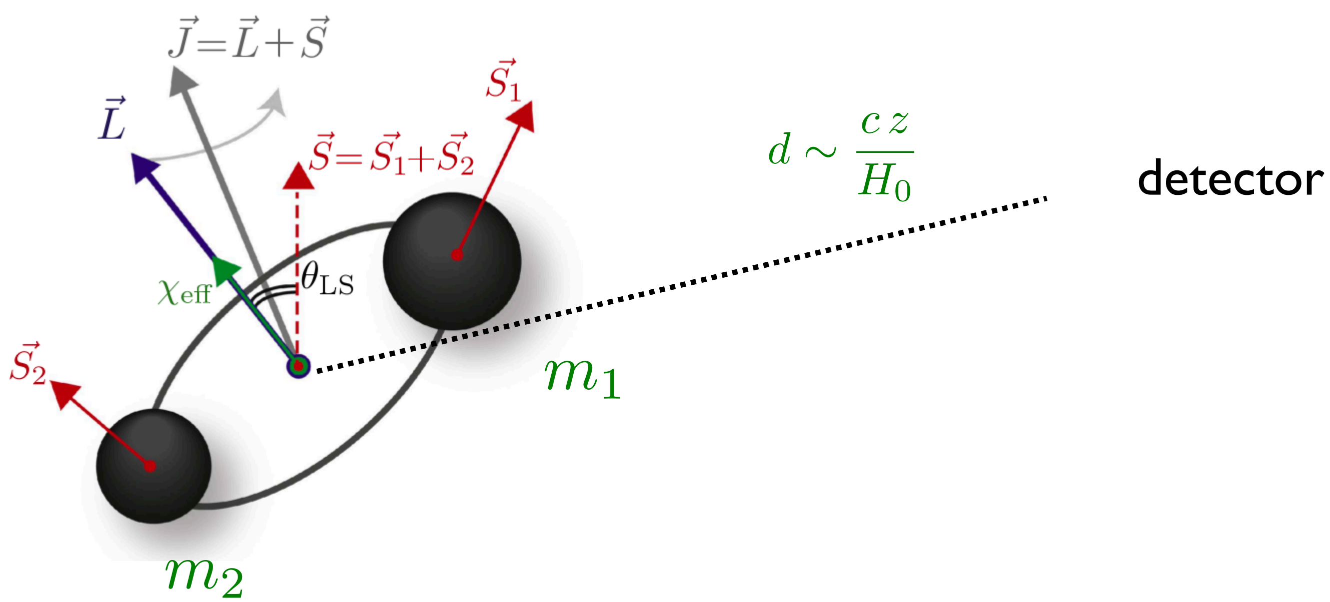


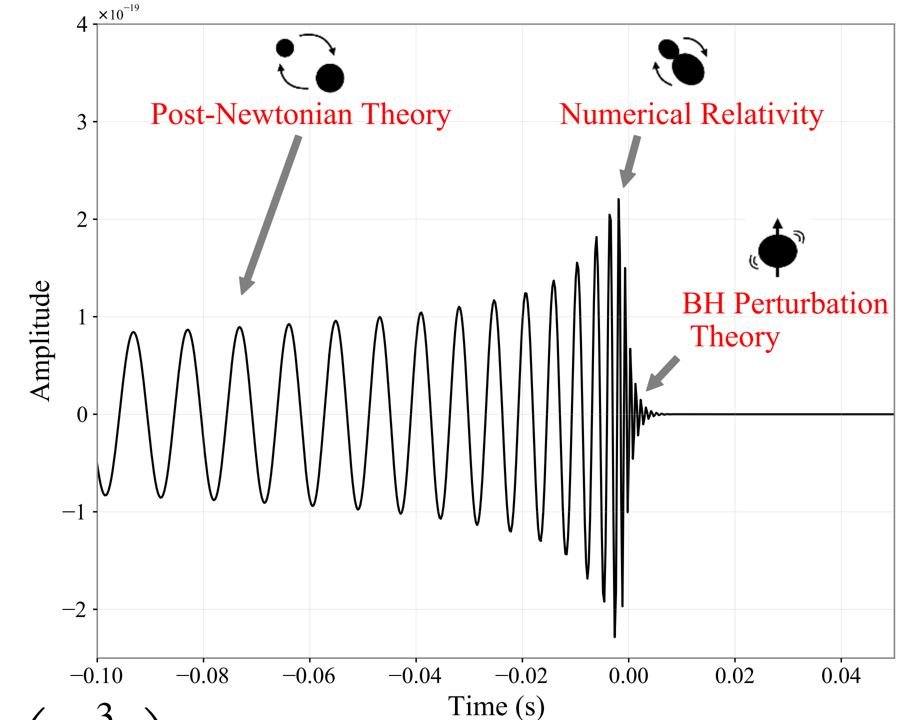
$$\sim \frac{\Omega_{\rm gw}(f)}{f^5}$$



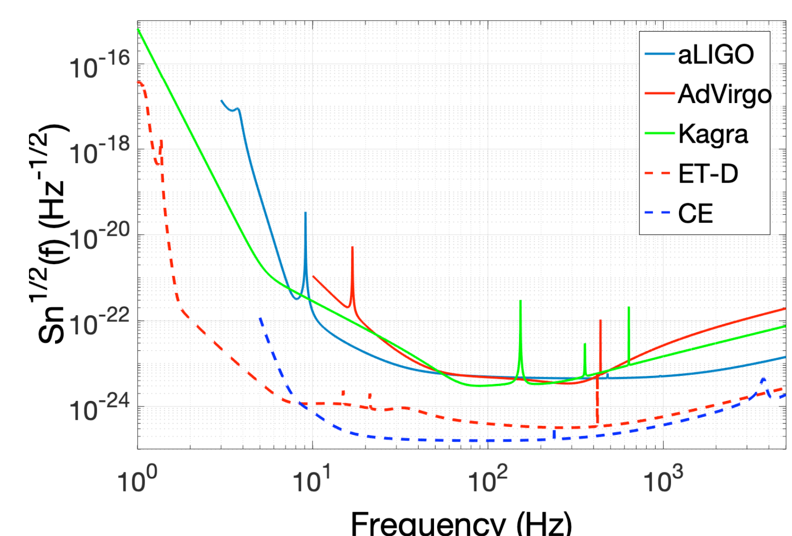
• 2023 PTA results : HD correlation detected at high significance (EPTA, Bayes factor ≈ 60). Amplitude of correlation essentially determines $\Omega_{\rm gw}(f)$

On binary system characterstic scales





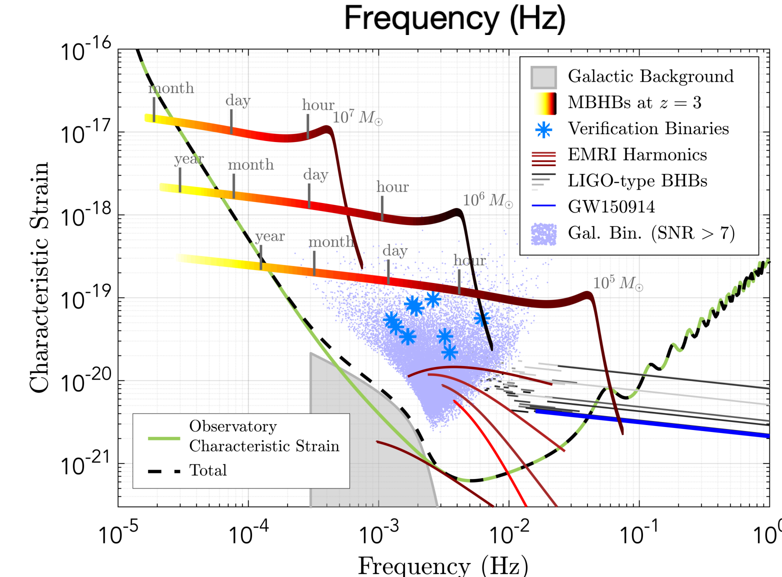
- Maximal **merger frequency** (assumed at ISCO) $f_{\rm merger} = \frac{1}{6^{3/2}\pi}\left(\frac{c^3}{GM}\right)$
  - BNS, $m_{1,2} \sim 1.4 M_\odot$ $f_{\rm merger} \sim 1.5\,{\rm kHz}$
  - stellar mass BHs, $m_{1,2} \sim 35 M_\odot$ $f_{\rm merger} \sim 60\,{\rm Hz}$
  - Supermassive BBHs, $m_{1,2} \sim 10^6 M_\odot$ $f_{\rm merger} \sim 10^{-3}\,{\rm Hz}$



*– nHz frequencies (PTA) do **not** correspond to of SMBHB coalescence, but emitted by binaries with masses $10^7 - 10^{10} M_\odot$,on broad orbit (period ~ year(s))*

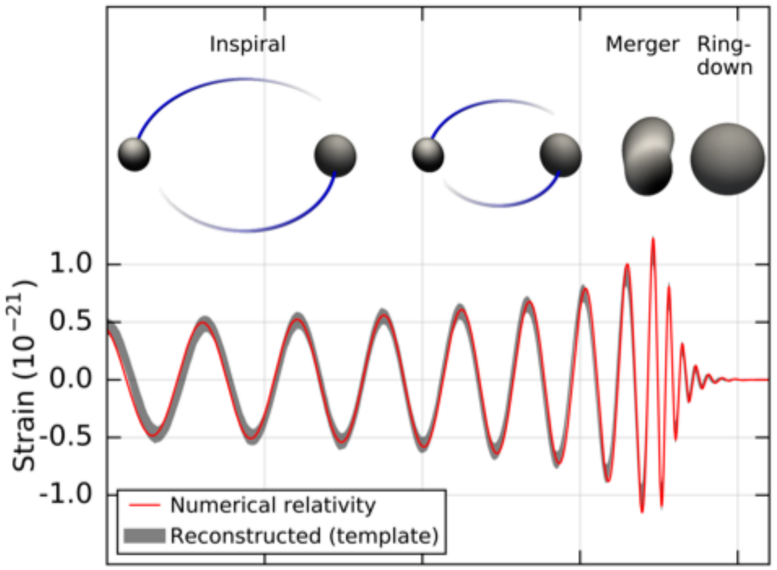
– no known astrophysical objects small and dense enough to emit at frequencies >10kHz

Any discovery of GWs these frequencies *either* exotic astrophysical objects (PBH or boson stars) *or* cosmological events in the early Universe



[Aggarwal et al, 2011.12414]

Cosmological setting



$\mathrm{fn}(d_L; \mathcal{M}_z)$

$\mathrm{fn}(t; \mathcal{M}_z)$

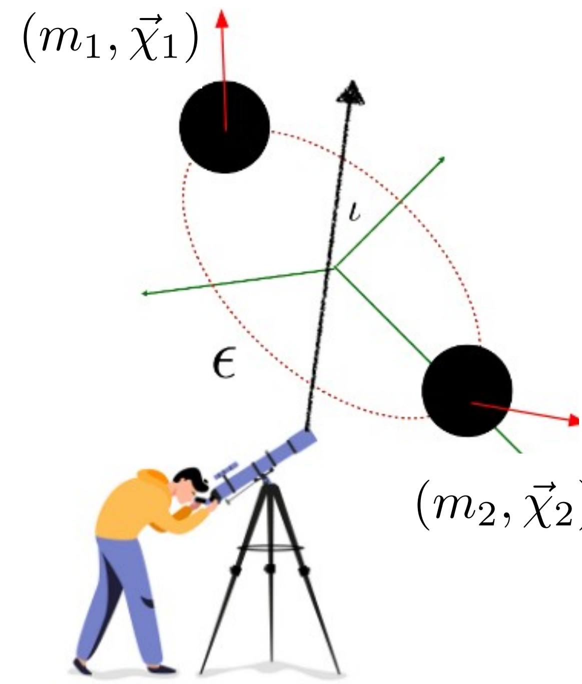
- Phase:

$$m^{\det}_{1,2}(z) = (1+z) m_{1,2}$$
$$\mathcal{M}_z = (1+z)\mathcal{M}$$

chirp mass $\mathscr{M} = \dfrac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$

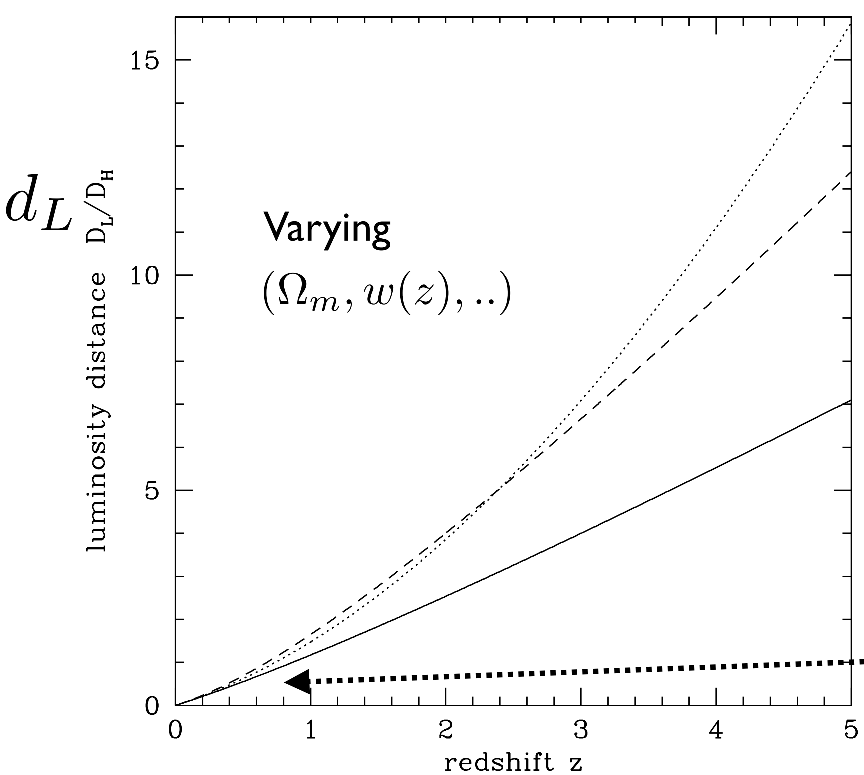
- Amplitude:

$$d_L, \mathscr{M}_z, \iota, \ldots$$



Fisher matrix analysis

$$\frac{\Delta\mathscr{A}}{\mathscr{A}} \sim 0.1 \left(\frac{10}{\rho}\right)$$
$$\frac{\Delta\mathscr{M}_z}{\mathscr{M}_z} \sim 10^{-5} \left(\frac{10}{\rho}\right)\left(\frac{\mathscr{M}_z}{M_\odot}\right)^{5/3}.$$



$$d_L(z) = \frac{c(1+z)}{H_0}\int_0^z \frac{dz'}{\left[\Omega_m(1+z')^3 + \Omega_\Lambda(1+z')^{3(1+w(z'))}\right]^{1/2}}$$

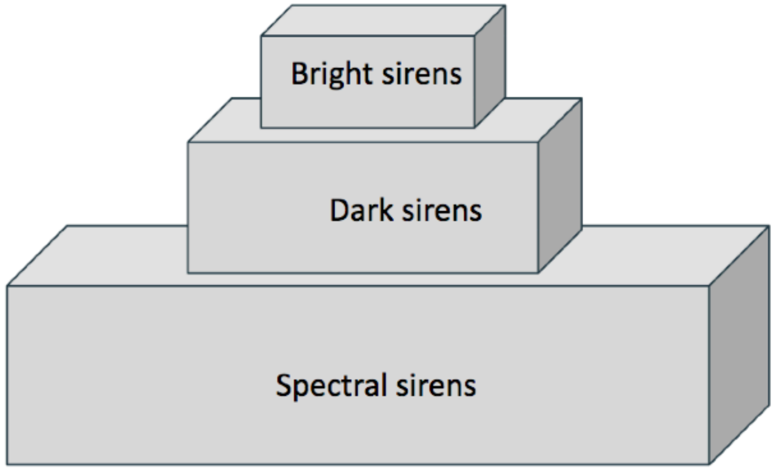
- *But* for point sources, perfect degeneracy between source masses, redshift, spins. Some extra non gravitational information necessary to determine z.

$$cz = H_0 \, D_L$$
$$\frac{\Delta H_0}{H_0} \sim \frac{\Delta z}{z} + \frac{\Delta D_L}{D_L}$$

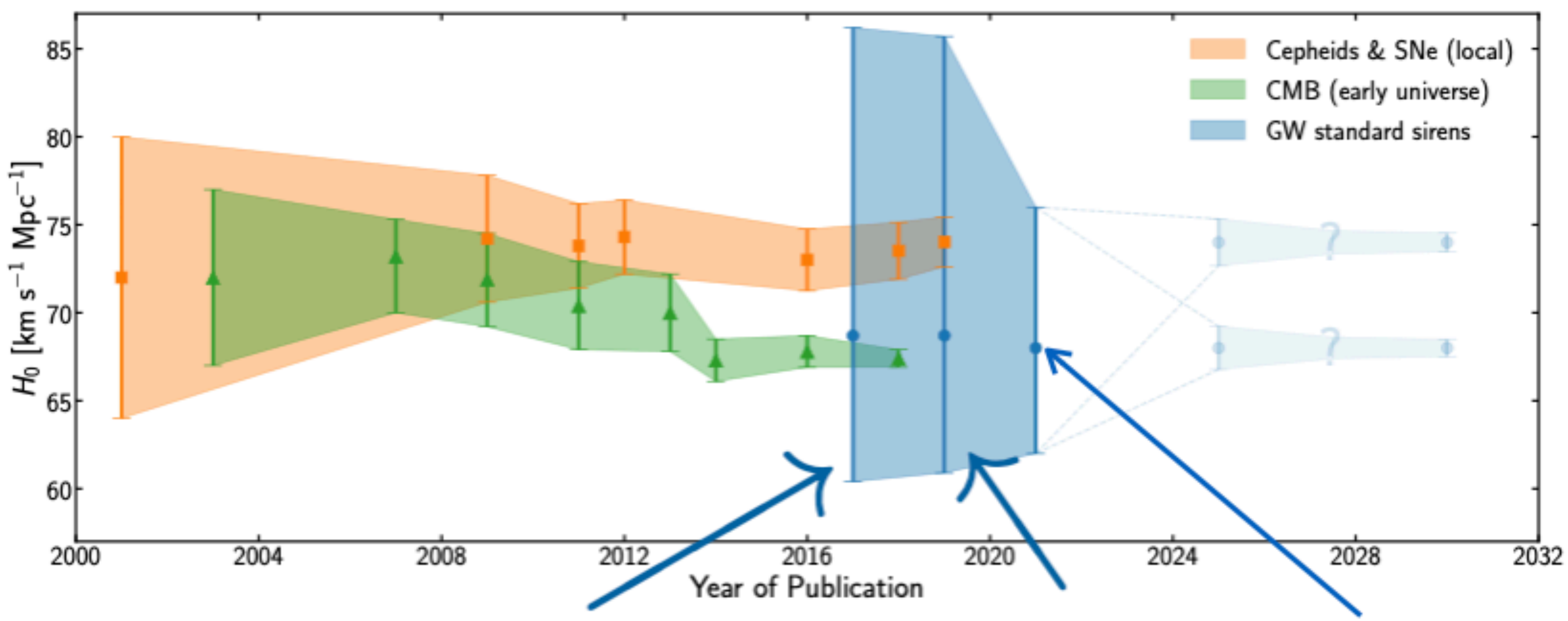
Crux of doing late-time cosmology with GWs is to determine *redshift* of the sources.

2/ late time cosmology (H_0, Ω_m) constraints with LVK; future

H0 with GWs:



As yet, cannot say anything on the ~4-sigma tension between measurements that calculate the sound horizon at decoupling (+assumption of Lambda CDM) and those that do not.



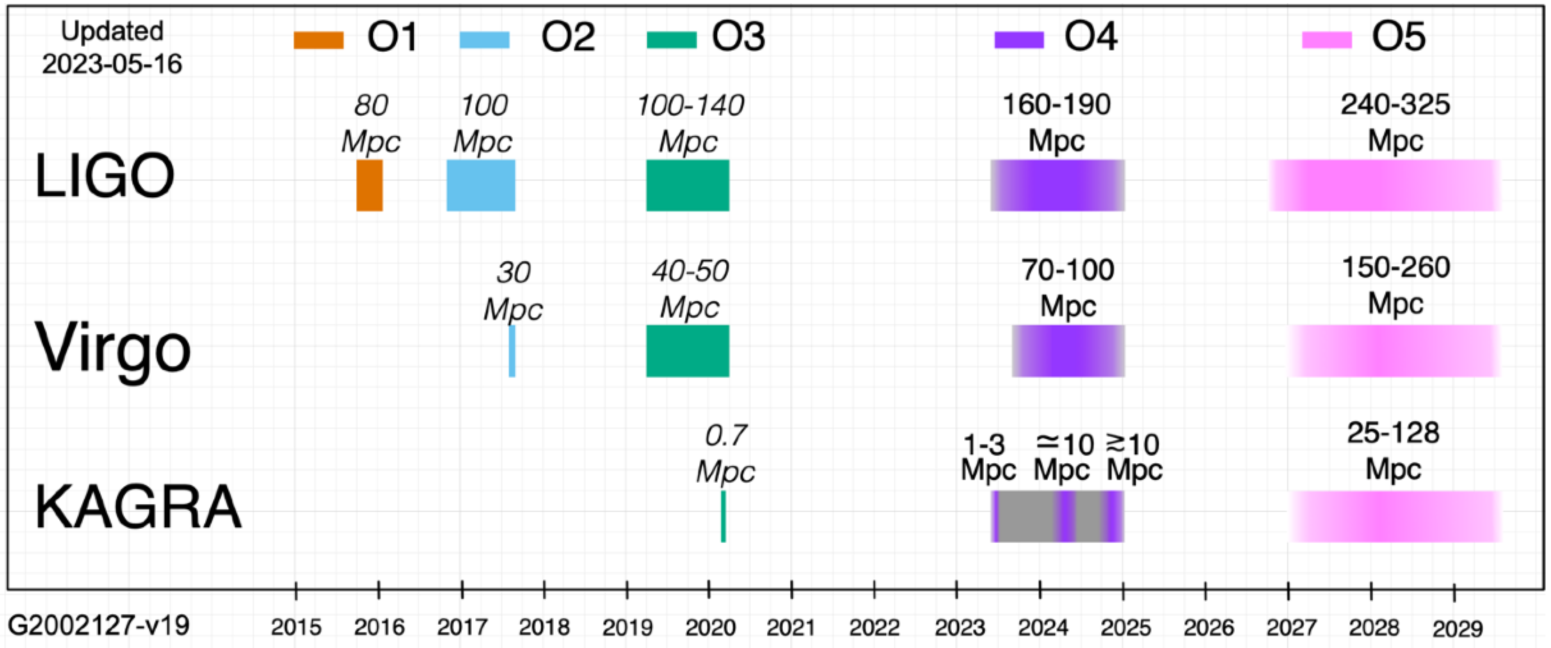
[2018 Planck collaboration]

[2112.04510, SH0ES and Pantheon+ collaborations, Reiss et al]

O1: *1710.05835*

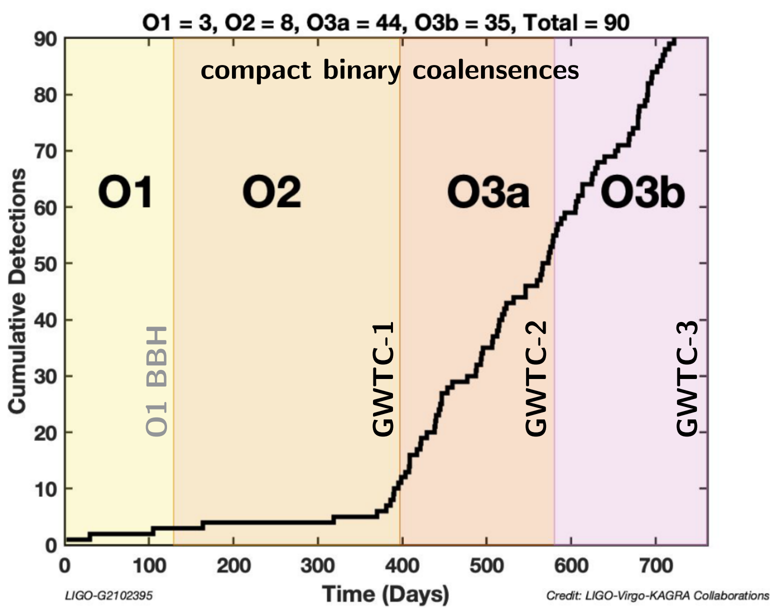
O1+O2: *1908.06060*
(4% improvement)

O1+O2+O3:
(~42% improvement)



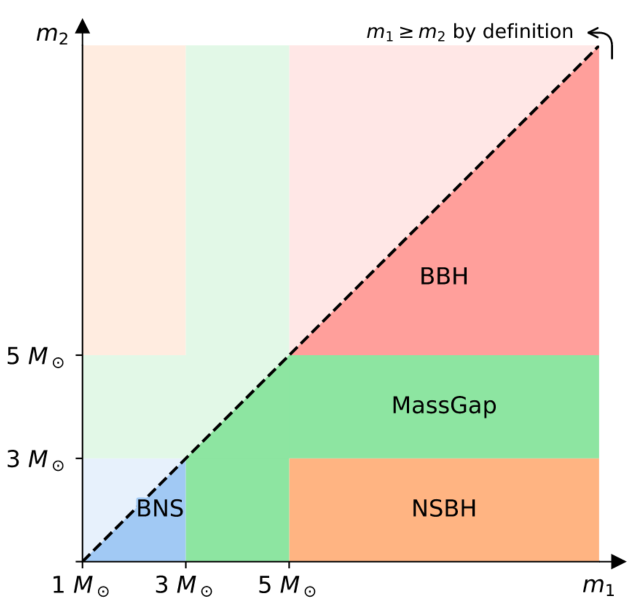
4th observing run, 24th may 2023.

- Virgo **not** started: excess noise at low frequency
  – hypothesis due to thermal noise on one mirror, which has been replaced but noise still there.
  – hope to rejoin in autumn.



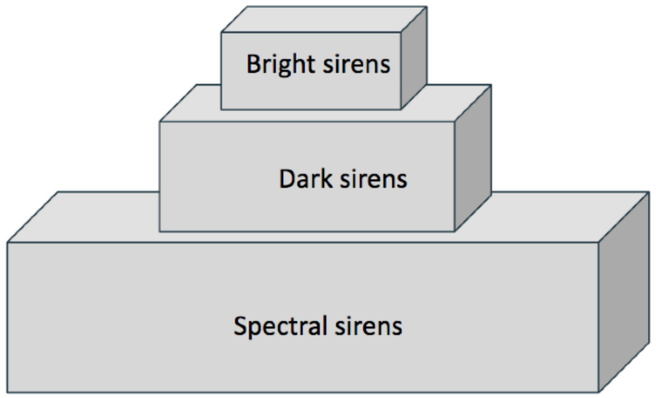
- **During O1 (~4 months):**
  - 3 confident BBHs

- **During O2 (~8 months):**
  - 7 confident BBHs (of which GW170814 in DES catalogue)
  - 1 confident BNS+EM counterpart (GW170817)



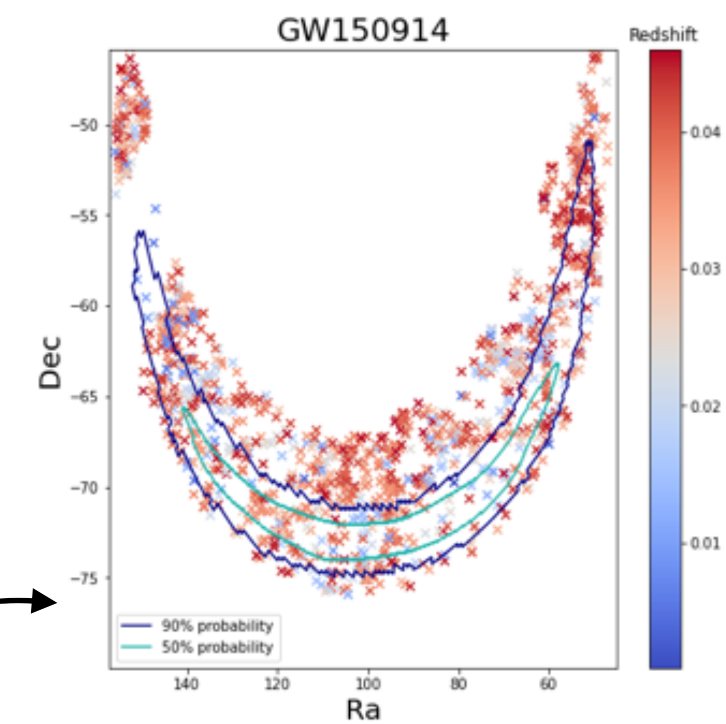
- **During O3 (~12 months)**:
  - 1 consistent with BNS masses (GW190425)
  - 4 events compatible with NSBH masses
  - 2 events compatible with BNS masses
  - ~80 confident BBHs.
  - Tentative EM counterpart from GW190521

LVK applied 3 methods to determine z



Method 1= *Bright siren* method, requires **EM counterparts**.

Potentially most accurate for cosmological parameters.
- *LVK*: only one seen so far, GW170817
- *ET*: how many are expected?
- *LISA*. BBH mergers may be accompanied by an electromagnetic counterpart (generated by gas accreting on the binary or on the remnant BH). Expected rate: ~2-20 per year! *[A.Mangiagli et al 2207.16078]*



– Method 2 = *Spectral siren* method works without counterparts, so will work also for LISA etc. But requires knowledge of underlying **astrophysical properties of sources** (mass distribution)

– Method 3 = ***Dark siren*** method uses information from **galaxy catalogues**.

But often these may not be complete, and will definitely not be at larger z.

Likelihood observing GW data d, given H0

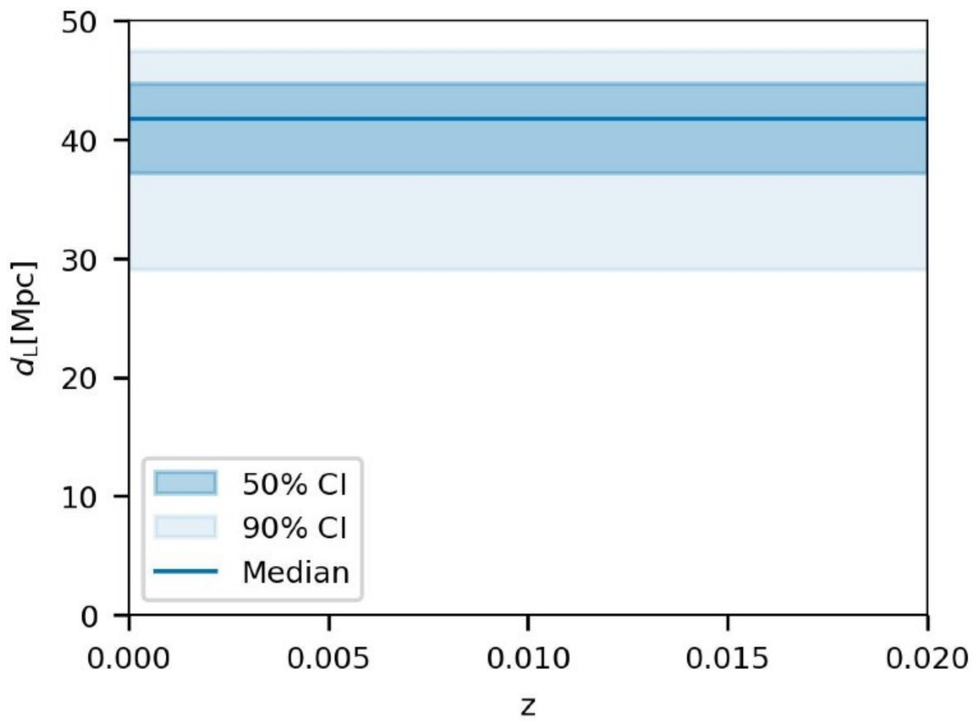
$$p(d|H_0) = p(d|H_0, G)p(G|H_0) + p(d|H_0, \bar{G})p(\bar{G}|H_0)$$

Probability that GW source host is in Galaxy catalogue

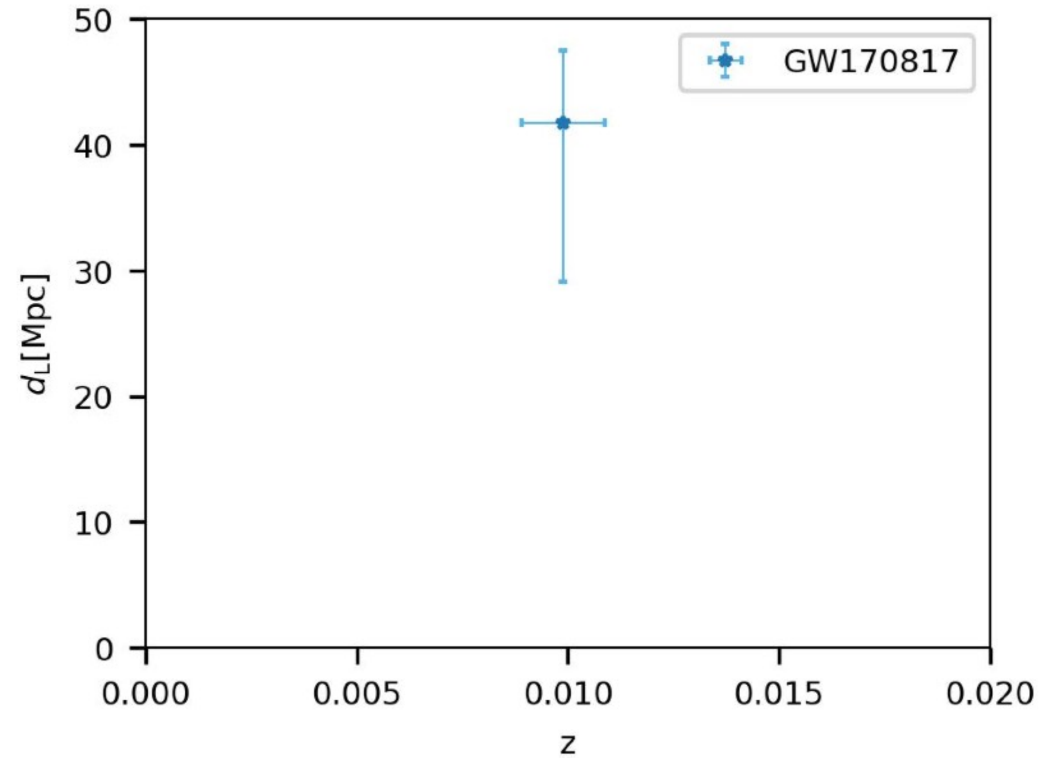
If its not in the Galaxy catalogue, then its outside.

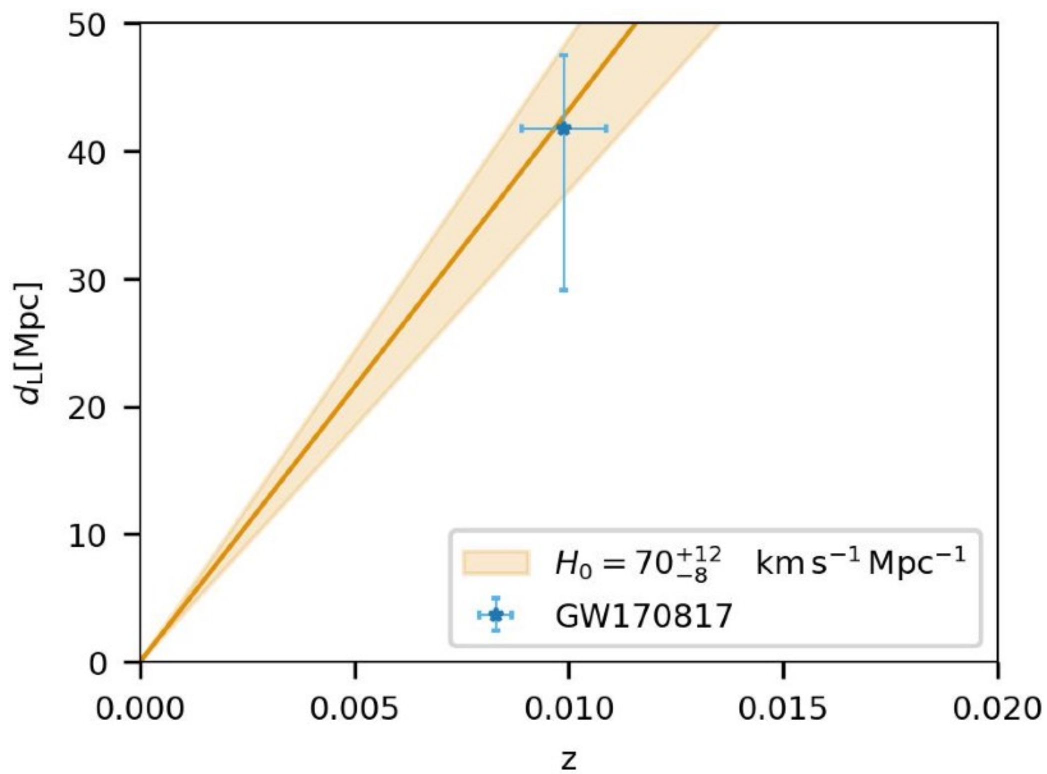
Bright sirens: Cosmology with GW170817

- BNS detected by LIGO and Virgo.
source distance ~ 40 Mpc
[LVK+, ApJL, 848 (2017)].



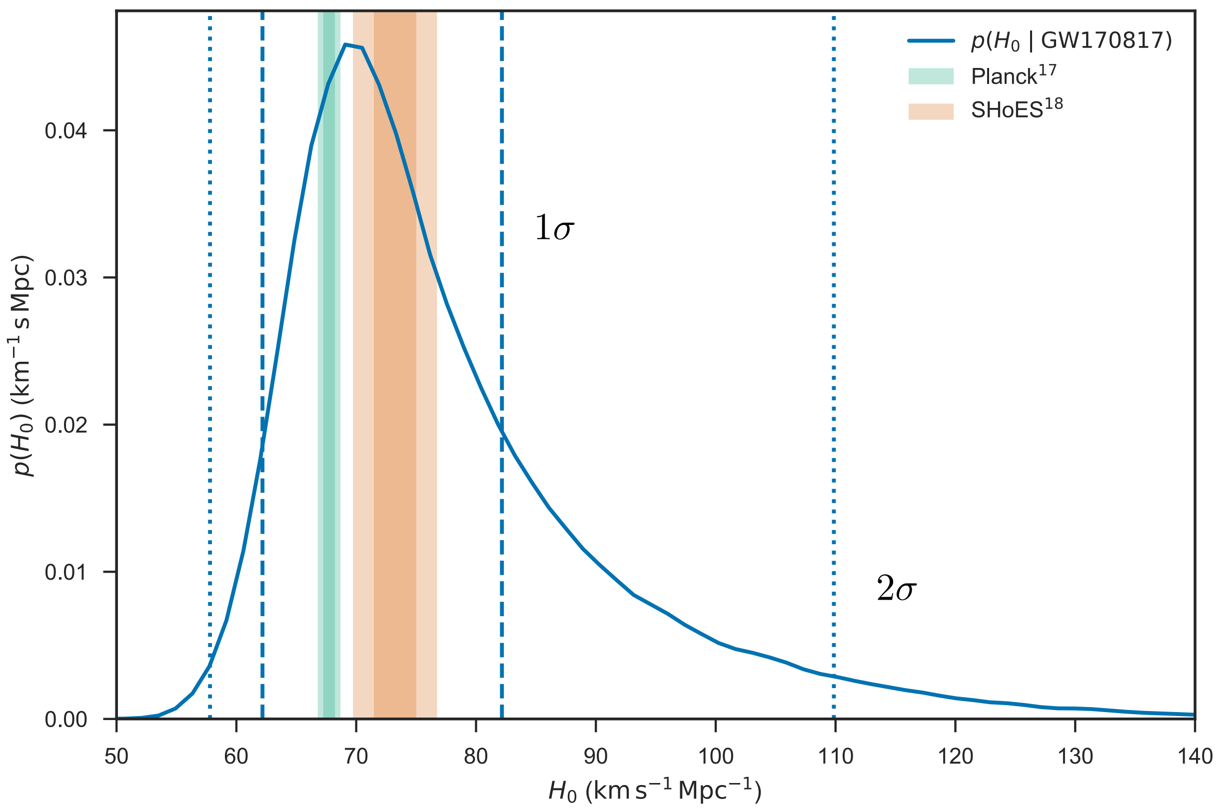
- Short Gamma-ray burst and Kilonova allowed the identification of the source host galaxy **NGC4993**.





$$H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

[1710.05835]



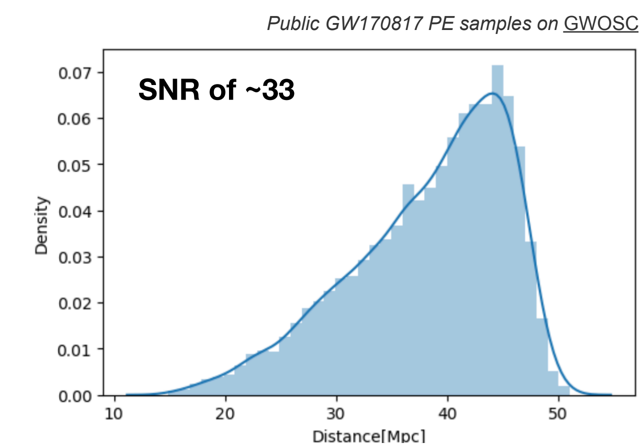
Errors:

1/ peculiar velocities

$$v_H = 3017 \pm 166\,\mathrm{km\,s^{-1}}.$$

2/ distance $d = 43.8^{+2.9}_{-6.9}\,\mathrm{Mpc}$ ~15% error

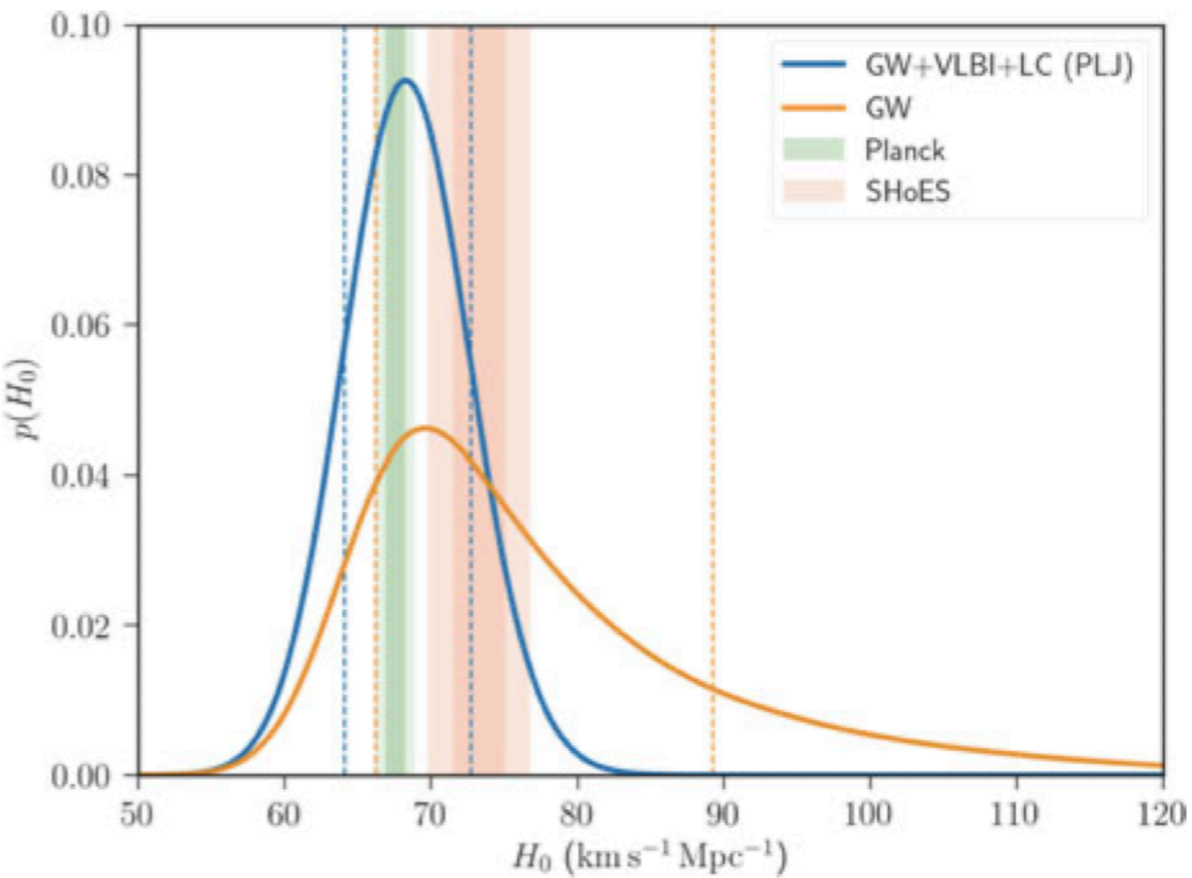
3/ statistical measurement error from noise in detectors instrumentation calibration uncertainties



- radio band observations with VLBI
==> estimate of inclination

$$15 < \iota \left(d_L/41\mathrm{Mpc}\right)$$

[Hotokezaka, 2019]



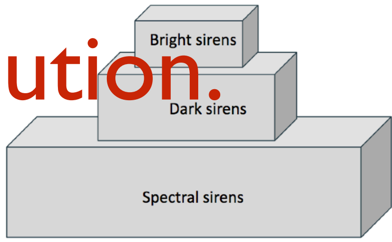
But only one such event so far...

- Pity as errors scale as $1/\sqrt{N}$

- H0 accurate to ~3% with 30 events with counterparts

Phys.Rev.D 101 (2020) 12, 122001

Spectral Sirens: Knowledge of source frame mass distribution.



- Since

$$m_{1,2}^{\rm det} = [1 + z(d_L, H_0, \ldots)] m_{1,2}^{\rm source}$$

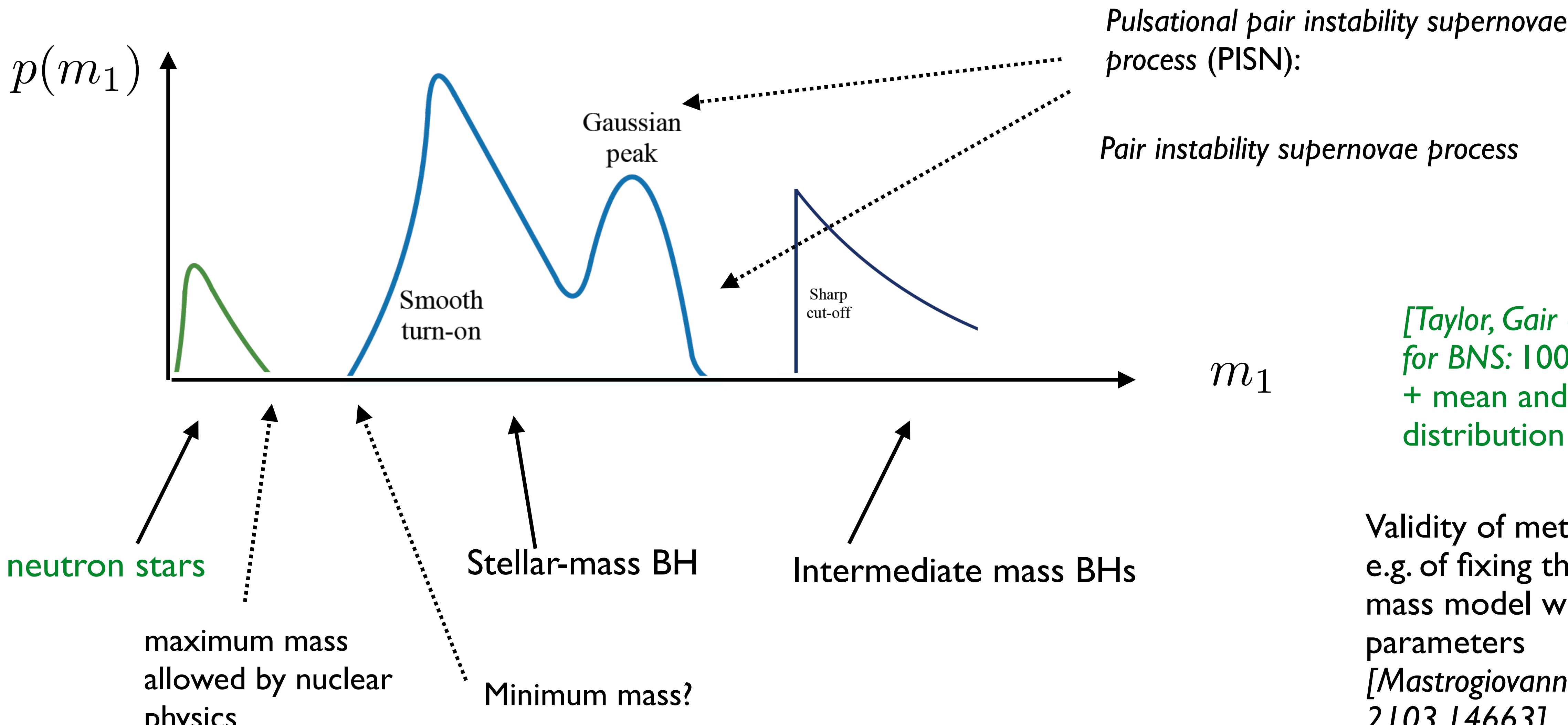
knowledge of source mass (for a population or individual source), together with given observed mass can infer z-distribution.

$$\frac{\delta z}{z} \sim \frac{\delta m_{1,2}^{\rm source}}{m_{1,2}^{\rm source}} \frac{1}{z}$$

Again, H0 error scales as $\sim 1/\sqrt{N}$

ET: BBH $10^5 - 10^6/\text{year}$

BNS $\sim 10^4/\text{year}$

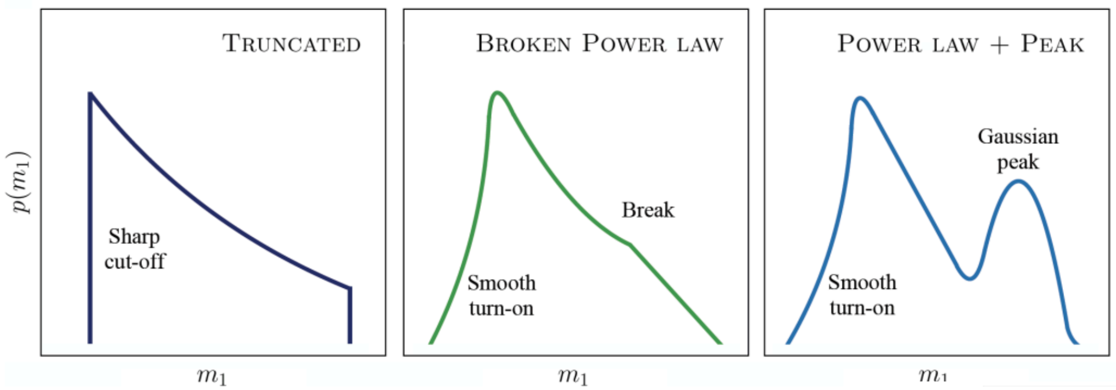


[Taylor, Gair et al, 2012]
for BNS: 100 obs -> H0 to 20% + mean and variance of mass distribution

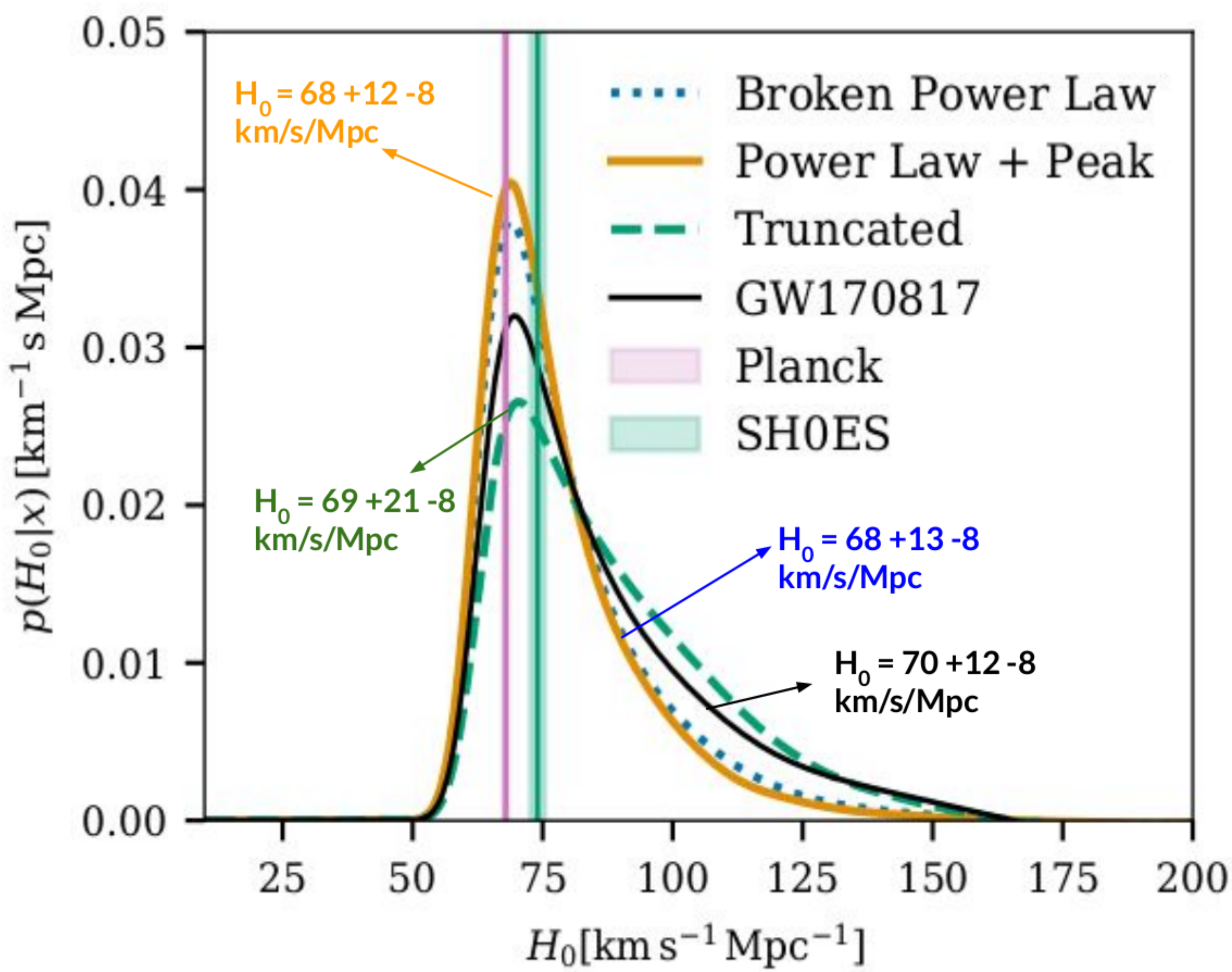
Validity of method, effect for e.g. of fixing the underlying mass model with incorrect parameters *[Mastrogiovanni et al 2103.14663]*

Applied to GWTC3 :
H_0 posterior of the 3 mass models combined with GW170817 posterior

LVK: arXiv:2111.03604



The only EM information is the counterpart of GW170817

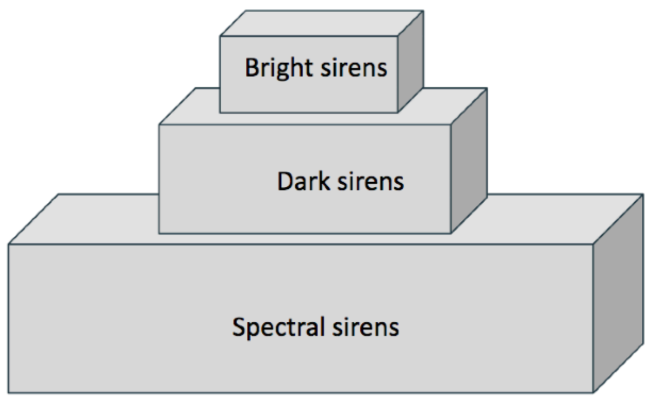


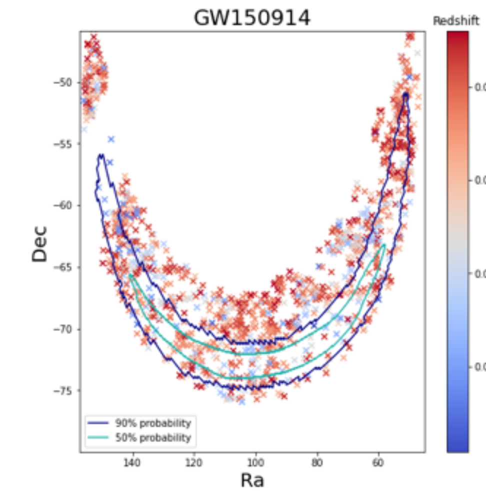
Mass model	$\log_{10} \mathcal{B}$
TRUNCATED	−1.9
POWER LAW + PEAK	0.0
BROKEN POWER LAW	−0.5

Table 3. Logarithm of the Bayes factor between the different mass models and the POWER LAW + PEAK model preferred by the data, for the case of a w_0CDM cosmology with wide priors.

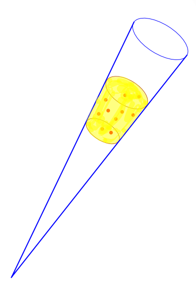
Dark sirens: cosmology aided by galaxy surveys

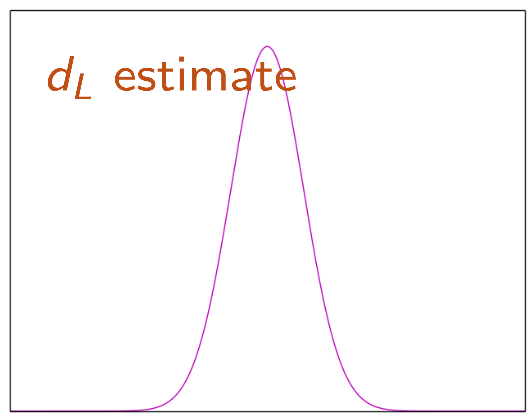
[Schutz, Nature 1986],





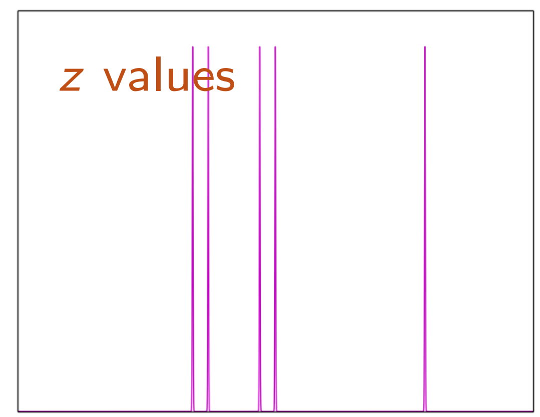
How it works: Given some GW event in some direction:





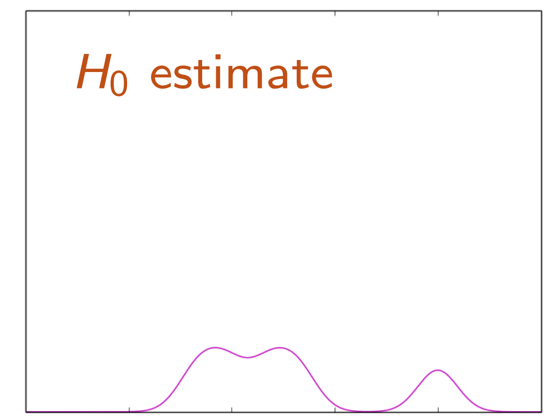
GW

+



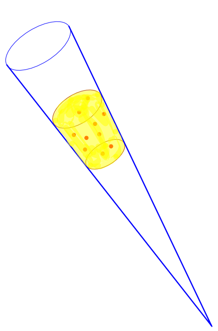
Different possible galaxies for single detection

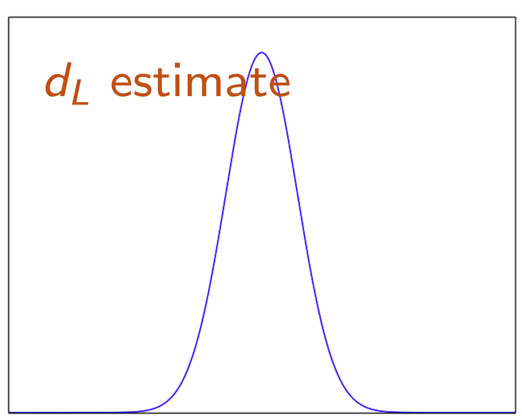
$\Rightarrow$



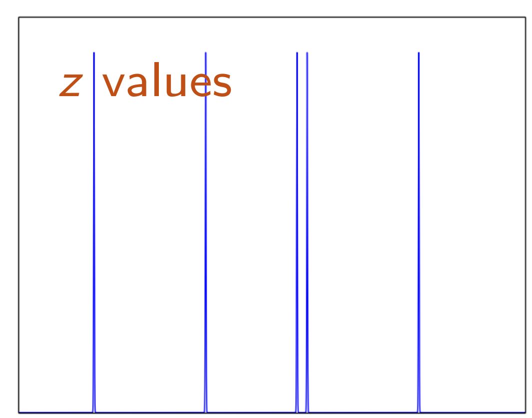
Multimodal H_0 estimate

Another event



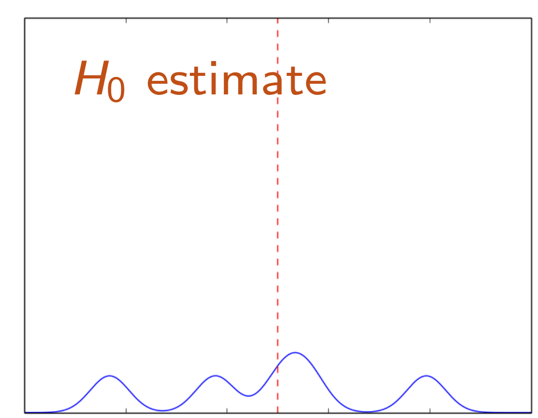


+



Different possible galaxies for single detection

$\Rightarrow$

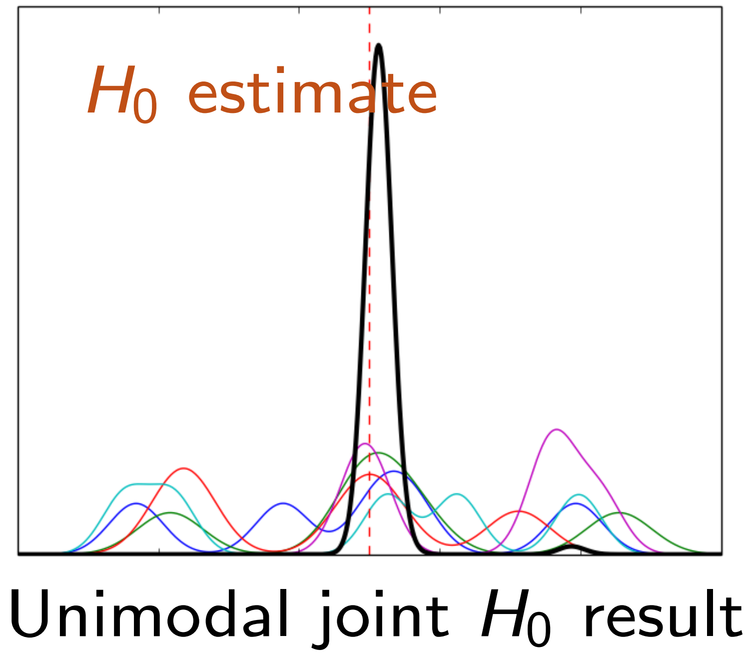


Multimodal H_0 estimate

E cosi via…

[Courtesy A.Ghosh]

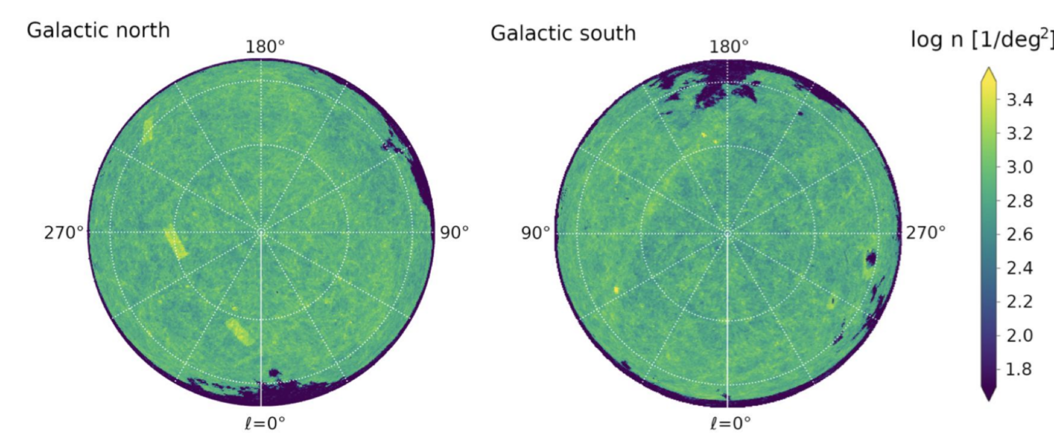
combine information from all observed detections:



[Courtesy A.Ghosh]

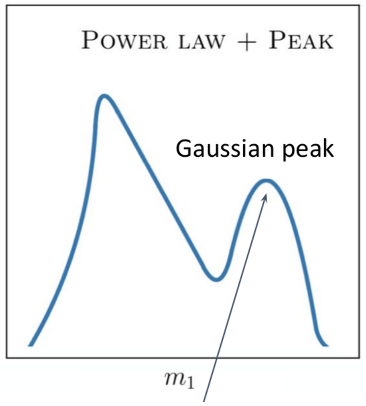
H0 with galaxy catalogues using GWTC3

- Use Glade+ all sky galaxy catalogue
    - 22 million galaxies,
    - 20% completeness up to 800 Mpc.
    - photometric redshifts with relative errors

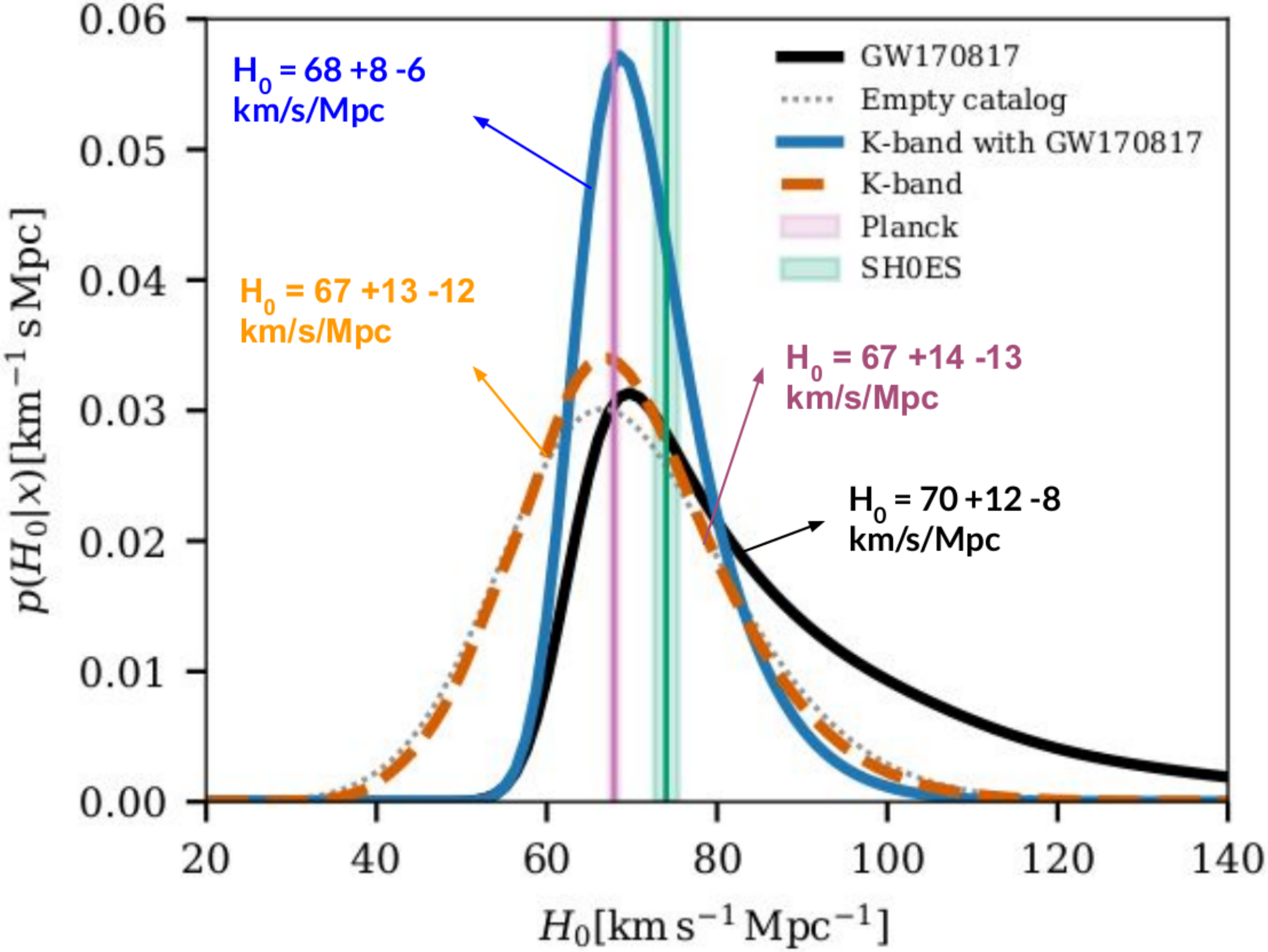


- Not many well localised GW events. Best is NS-BH GW190814 (which has no EM counterpart)

Main result of the O3 LVK cosmology paper showing various H0 posteriors.



Fix the preferred mass model (powerlaw+Gaussian peak, and use the median values obtained in the spectral siren cosmological and population analysis)



LVK: arXiv:2111.03604

Dark siren cosmology with binary black holes in the era of third-generation gravitational wave detectors

Niccolò Muttoni,[1,2,*] Danny Laghi,[1] Nicola Tamanini,[1] Sylvain Marsat,[1] and David Izquierdo-Villalba[3,4]

- simulated population of BBHs (power-law+peak) *[arXiv: 2303.10693]*

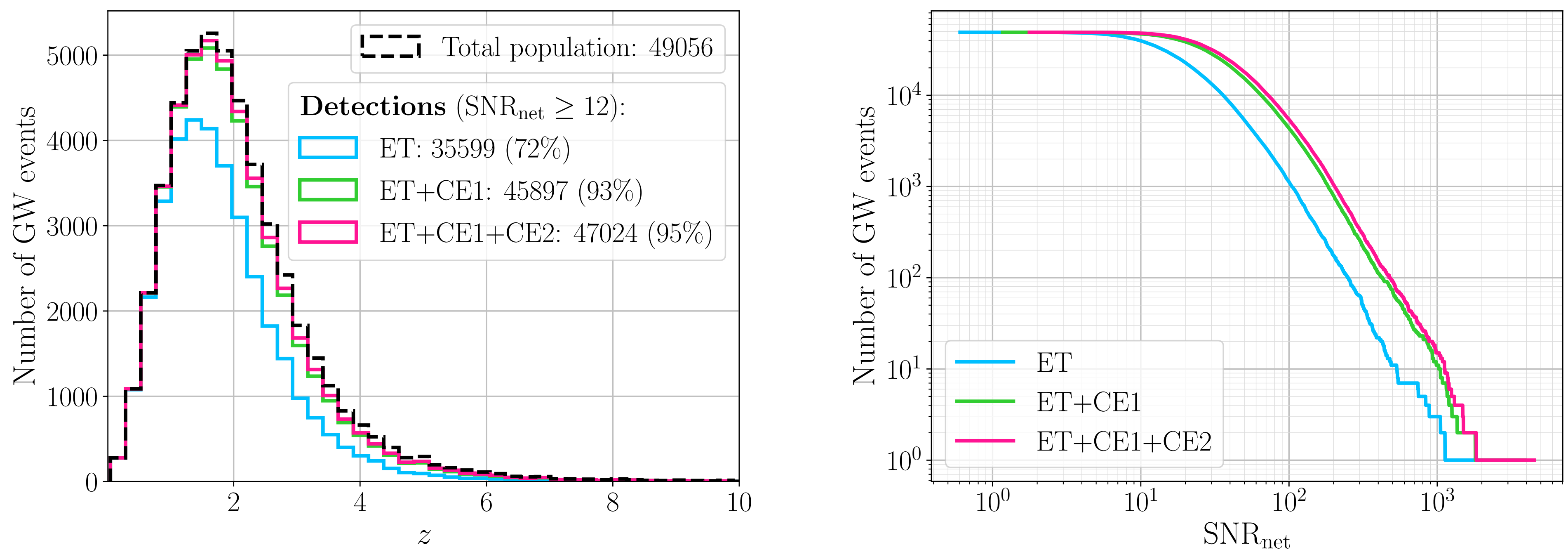


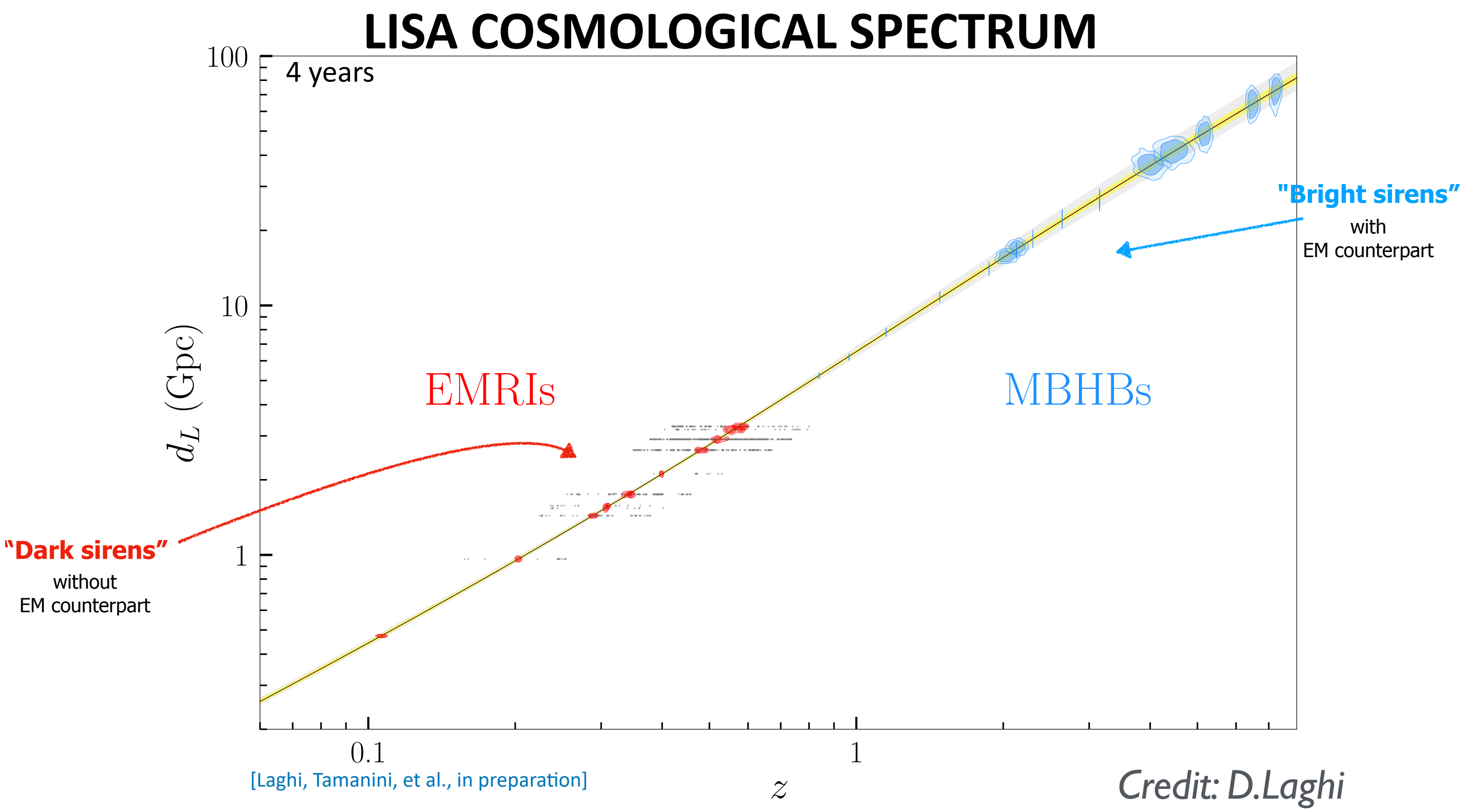
FIG. 2. Left: Redshift distributions of the total and detected population for different networks in one year of observation (full duty cycle), colors as in legend. Right: Number of detected GW events left above a given SNR_{net}, colors as in legend.

main results assume a fiducial scenario in which galaxy surveys will be complete up to z = 1 by the 3G detector era.

– *best constraints:* ET+CE1+CE2 network, H0 (Ω_m) recovered at a 0.7% (9.0%) at 90% CI

– Assuming Ω_m known perfectly a priori, a ET+CE1 => 0.3% precision in H0

Cosmology with LISA



Credit: D.Laghi

- Massive BHB, $M \in [10^5 - 10^9]M_\odot$ at $z \gtrsim 1$: very loud signals (SNR order Hundreds), and some EM counterparts are expected

- if sufficient amount of gas is present, EM emission can be produced by the accretion of the gas onto the binary during the inspiral, merger and ringdow

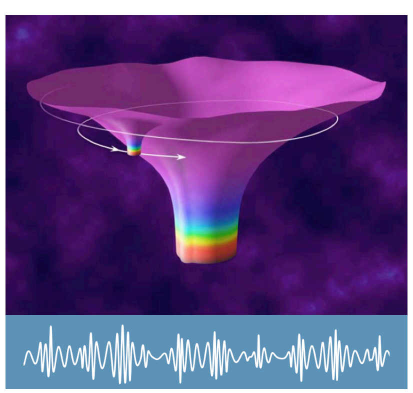
- but opinions vary on how many detectable EM many to be expected over a 4 year LISA:

$\mathcal{O}(8-20)$ *Tamanini et al. (2016)*

$\mathcal{O}(2-20)$ *Mangiagli et al., (2022)*

- H_0 at a few %?

[LISA Cosmology WG, White Paper (arXiv:2204.05434)]


Credit: Nasa

EMRI: one SMBH with a very light companion $\sim 10M_\odot$. Slow inspiral, so very accurate measurement of Parameters…but no EM counterpart. Use as dark +spectral sirens.

[Laghi et al., MNRAS (2021)]
- H_0 accuracy at 1-6 %
- Ω_m accuracy 25% at most
- w_0 accuracy 10% at least

Plan

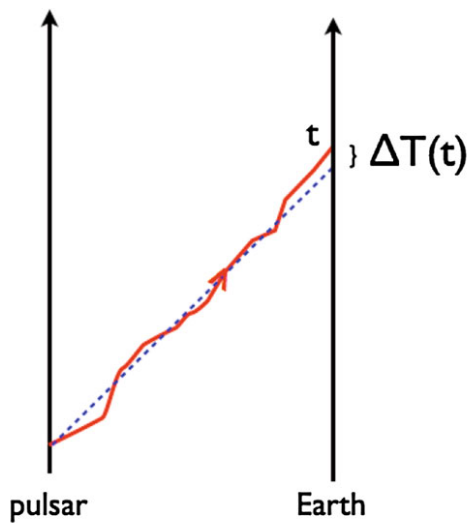
1/ very very simplified comments on detectors &
individual compact binary sources

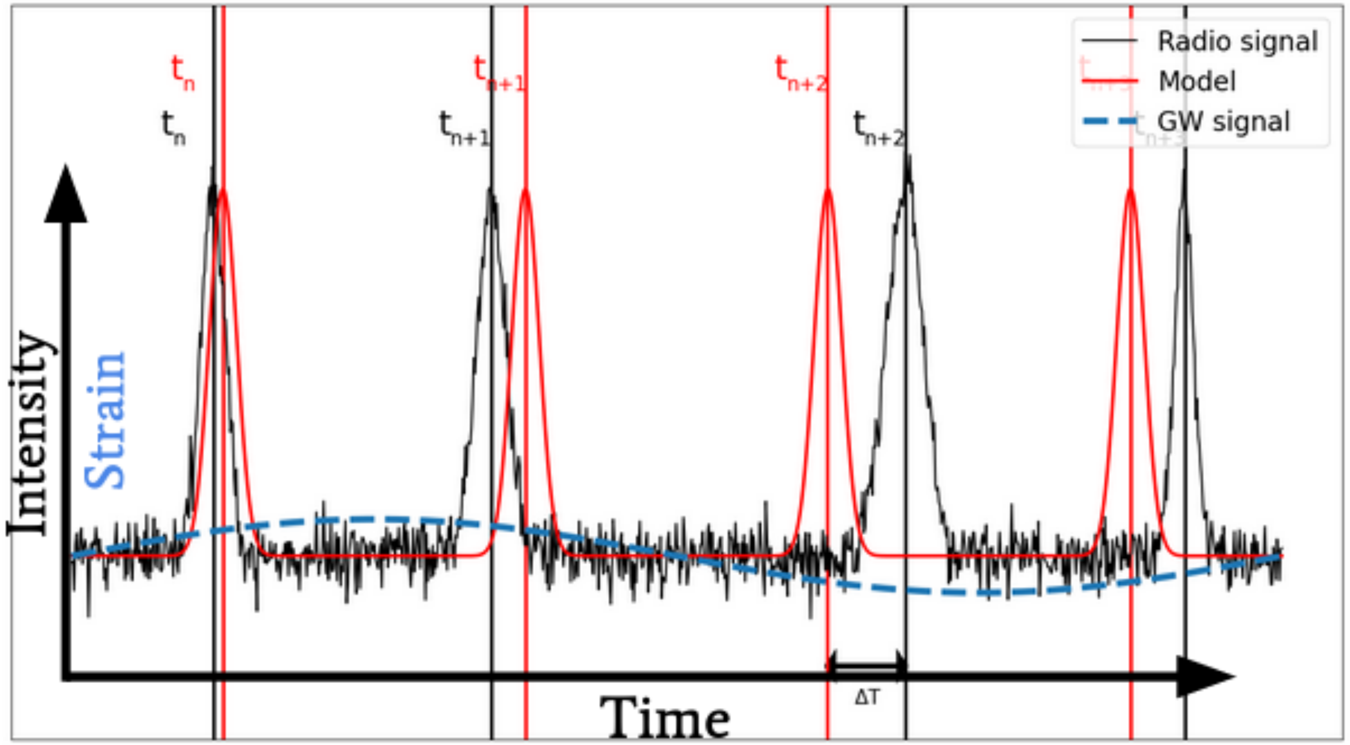
2/ late time cosmology (H_0, Ω_m) constraints with LVK; future

3/ PTA results – Stochastic GW background
– results on different early universe sources

***<u>Nota Bene:</u>
Though an astrophysical background of putative SMBHB is the most plausible source of the PTA observations, analysis of the data seems to indicate a mild tension between data and predictions.
"This discrepancy presents an opportunity for new physics models to fit the data better".
• *Caution: The situation can evolve with more data.. Should "..not over-interpret the observed evidence in favour of some of the cosmological sources/new physics"*

Aim: measure time delay of radio pulses from millisecond pulsars = stable clocks with fluctuations.





[credit: Mikel Falxa]

– For each pulsar, build a model of predicted time of arrival (TOA), including many physical effects: proper motion, sky localisation, parallax, dispersion due to interstellar medium,…

Errors in the fitting model

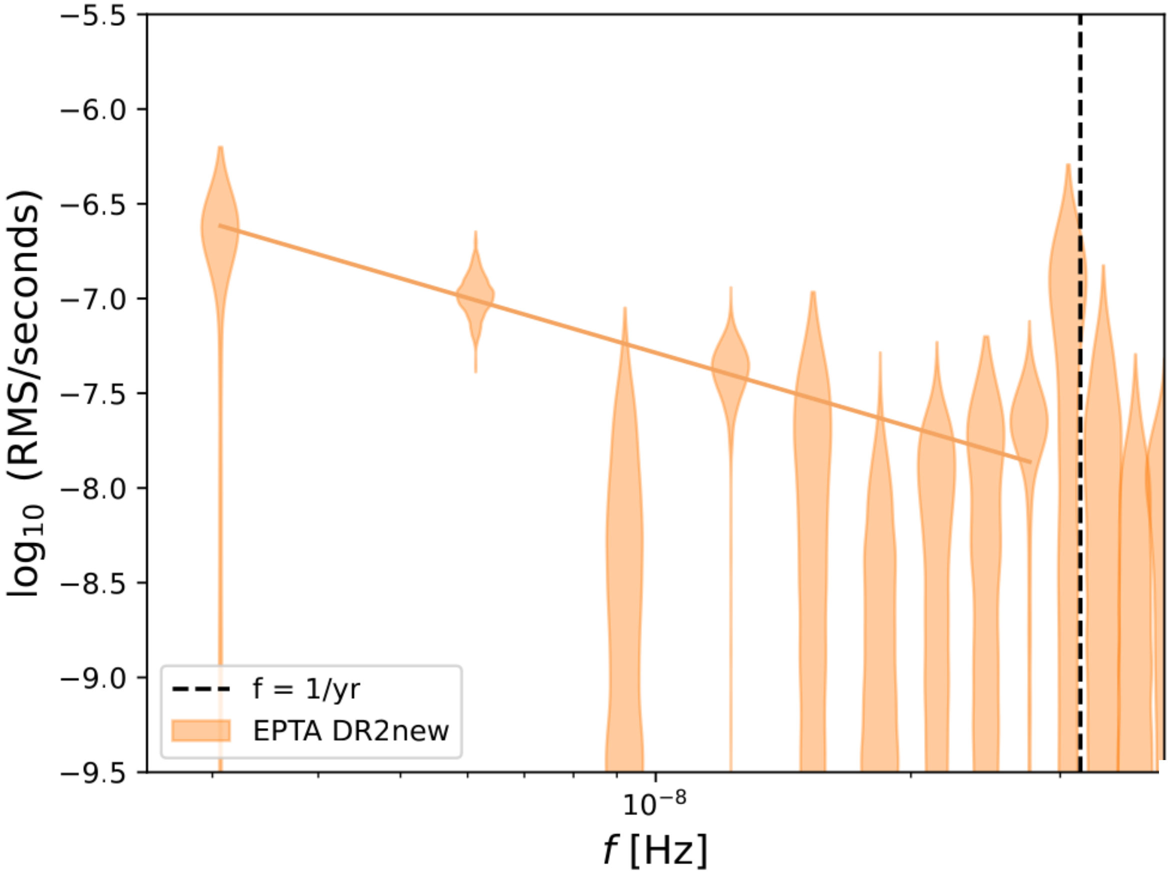
$$\Delta t = t_{\mathrm{TOA}}^{\mathrm{predicted}} - t_{\mathrm{TOA}}^{\mathrm{observed}} = \Delta t_{\mathrm{errors}} + \Delta\tau_{\mathrm{GW}} + \mathrm{noise}$$

– A GW signal is a *common* correlated signal in all pulsars, and spatially correlated across the sky (HD).
– This differentiates it from the different uncorrelated noises in each pulsar

$$\langle \Delta t_a \Delta t_b \rangle \sim \delta_{ab}\varphi_a + \Gamma_{ab}^{\mathrm{HD}} S(f)$$

$$\log_{10}\left[\left(\frac{S(f)}{T}\right)^{1/2}\right]$$

T=obsv time= 10.3 yrs (EPTA)



[EPTA+InPTA, 2306.16227]

$$\log_{10}(A_{f_0=1\mathrm{yr}^{-1}}) = -13.94^{+0.23}_{-0.48}$$

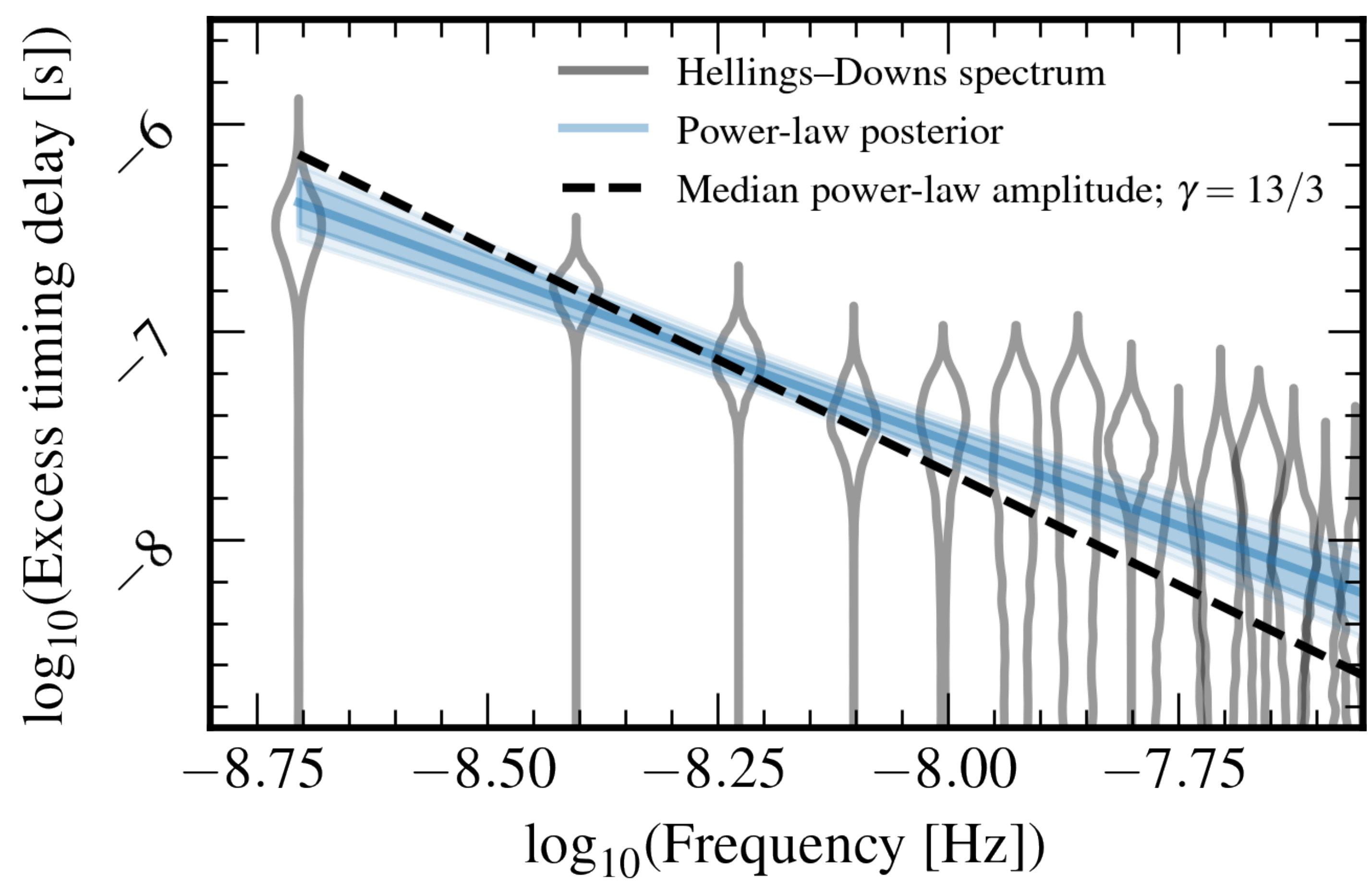
$$\gamma = 2.71^{+1.18}_{-0.71}$$

$$\gamma = 3.2^{+0.6}_{-0.6}$$

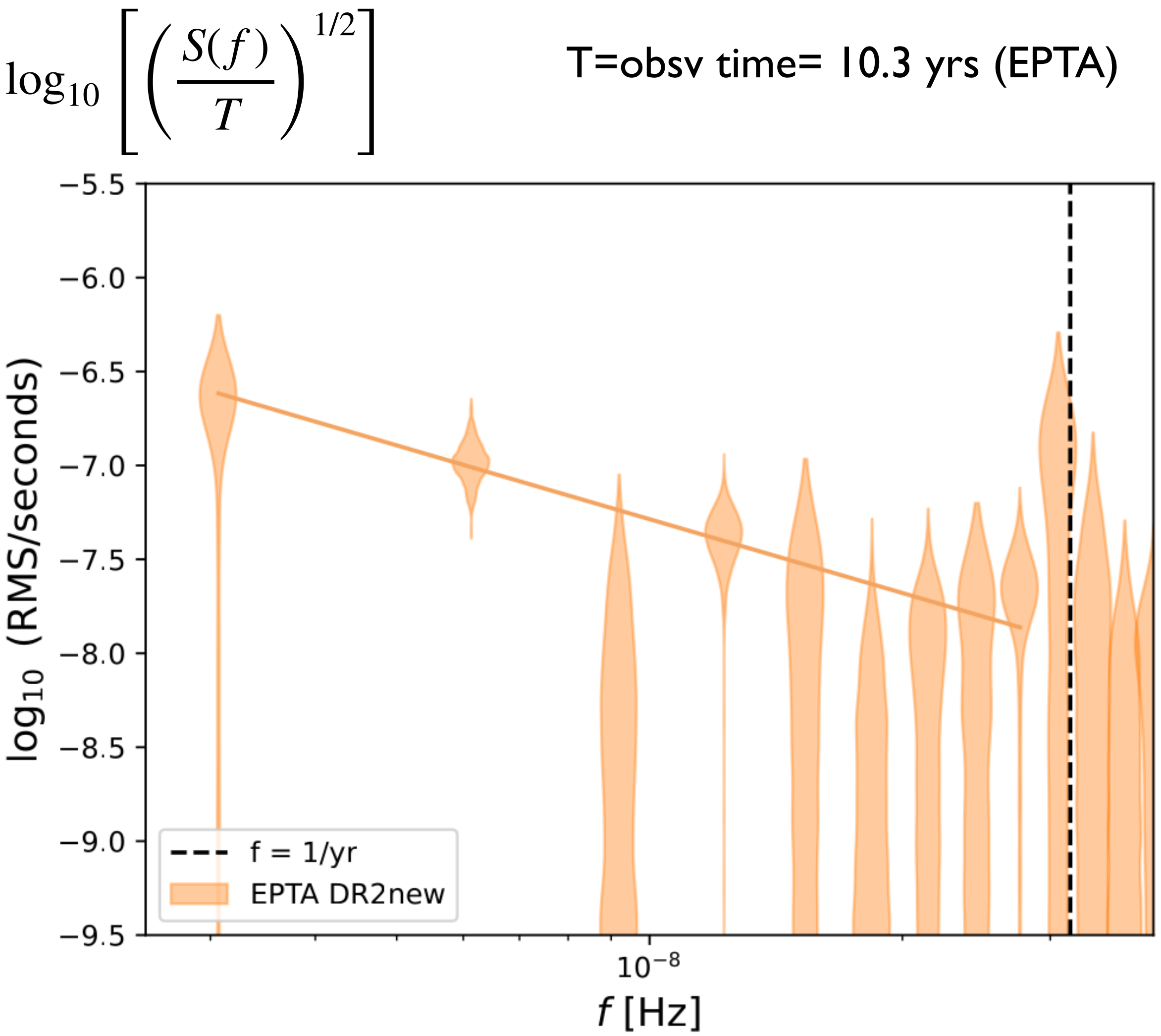
Best power-law fit to the data,

$$S(f) = \frac{A^2}{12\pi^2 f_0^{2\alpha}} f^{-\gamma}$$

T=obsv time= 16.03 yrs (EPTA)



[NANOGrav 2306.16227]



[EPTA+InPTA, 2306.16227]

$$8\pi^4 f^5 S(f) = \Omega_{GW}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2(f)$$

Best power-law fit to the data,

$$S(f) = \frac{A^2}{12\pi^2 f_0^{2\alpha}} f^{-\gamma}$$

- In presence of a SGWB,

homogenous and isotropic (inherited from FLRW universe);
unpolarised (absence of significant source of parity violation in the universe),
gaussian (formed by emission from many uncorrelated regions).

$$\langle h_r(\mathbf{k},\eta)\, h_p^*(\mathbf{q},\eta)\rangle = \frac{8\pi^5}{k^3}\,\delta^{(3)}(\mathbf{k}-\mathbf{q})\,\delta_{rp}\,h_c^2(k,\eta)$$

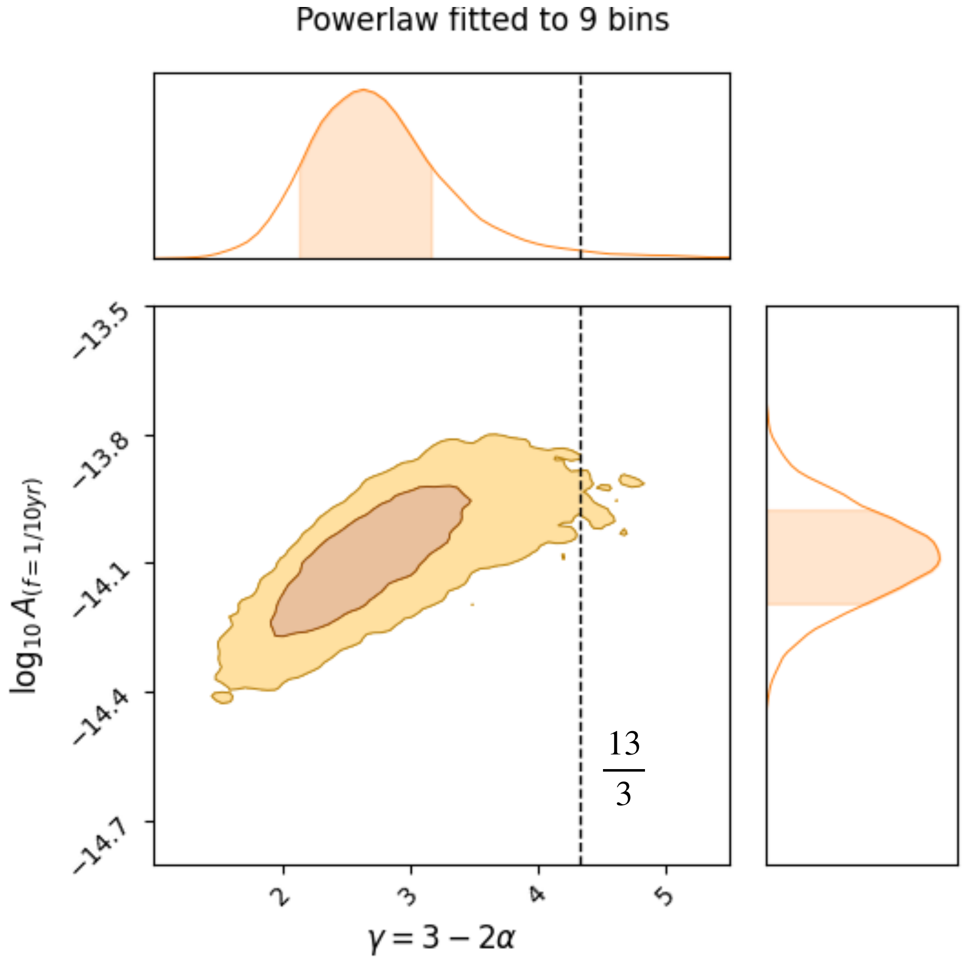
h_c = characteristic dimensionless strain amplitude per logarithmic frequency interval and per polarization state

- Modelling $h_c(f)$ by a power-law: $h_c(f) = A\,(f/f_0)^{\alpha}$, it follows that $S(f) = \frac{A^2}{12\pi^2 f_0^{2\alpha}} f^{-\gamma}$

$$\gamma = 3 - 2\alpha$$

• incoherent superposition of GWs from a population of inspiraling SMBHB, mass $10^7 - 10^{10} M_\odot$, on broad orbit (period ~ year(s)) forms a stochastic signal at nHz freqs.

[EPTA+InPTA, 2306.16227]



$$\log_{10}(A_{f=1\mathrm{yr}^{-1}}) = -13.94^{+0.23}_{-0.48}$$
$$\gamma = 2.71^{+1.18}_{-0.71}$$

• Amplitude mainly controlled by typical masses + abundances. Shape, by subparsec-scale binary evolution.

• Assuming SMBHB, in *circular* orbits, radiating *only through GW emission*, *[Phinney 2001]*

$$h_c^2(f) = \frac{4G^{5/3}}{3\pi^{1/3}c^2} f^{-4/3} \int \mathrm{d}\mathcal{M} \int \mathrm{d}z\, (1+z)^{-1/3}\, \mathcal{M}^{5/3} \frac{\mathrm{d}^2 n}{\mathrm{d}z\,\mathrm{d}\mathcal{M}}$$

Number density of merging binaries per unit redshift and chirp mass.

• So $\alpha = -2/3, \gamma = 13/3$

• interesting information on SMBHB formation models, evolution, eccentricity, stellar environments… Indeed GW emission alone is typically insufficient to merge SMBHB within a Hubble time.

• 3240 models studied, spanning different eccentricities and densities of stellar environments *[EPTA+InPTA, 2306.16227]*

[EPTA+InPTA, 2306.16227]

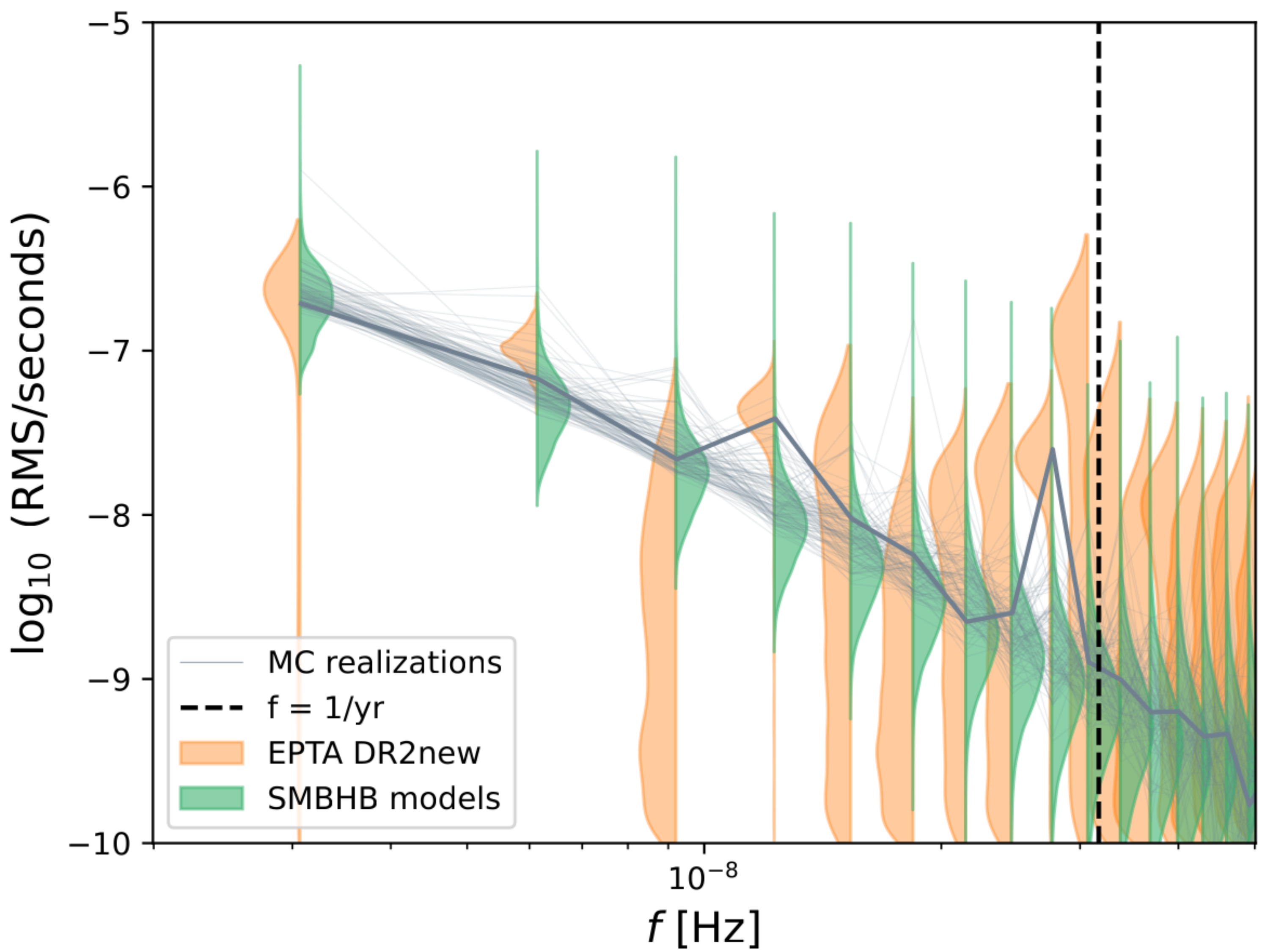


Fig. 3: Free spectrum violin plot comparing measured (orange) and expected (green) signals. Overlaid to the violins are the 100 Monte Carlo realizations of one specific model; among those, the thick one represents an example of a SMBHB signal consistent with the excess power measured in the data at all frequencies.

model prediction distributions (green) are highly non-Gaussian, with long tails extending upwards caused by rare very massive/nearby binaries that can sometimes produce exceptionally loud signals

Cosmological signals I: inflation

$$8\pi^4 f^5 S(f) = \Omega_{\rm GW}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2(f)$$

$$h_c(f) = A\left(f/f_0\right)^{\alpha}$$

$$S(f) = \frac{A^2}{12\pi^2 f_0^{2\alpha}} f^{-\gamma}$$

$$\gamma = 3 - 2\alpha$$

– standard **single field slow-roll inflation** generates a GW spectrum which is red tilted at CMB scales $n_T = -r/8 < 0$, where from Planck $r \leq 0.036$.

– Correspondingly $\Omega_{GW} \sim 10^{-16}$ at PTA frequencies…unobservable.

– Analyses differ a little between NANOGrav and EPTA, but basically have considered leaving *free* both $n_T =$ constant and r

– Assuming instantaneous reheating, that it is followed by a radiation era, and in the PTA band

$$\Omega_{\rm GW}(f) \approx 1.5 \times 10^{-16} \left(\frac{r}{0.032}\right)\left(\frac{f}{f_*}\right)^{n_T}$$

[Lasky et al 2016, Caprini & Figueroa 2018]

CMB pivot scale, $f_* \approx 7.7 \times 10^{-17}$Hz

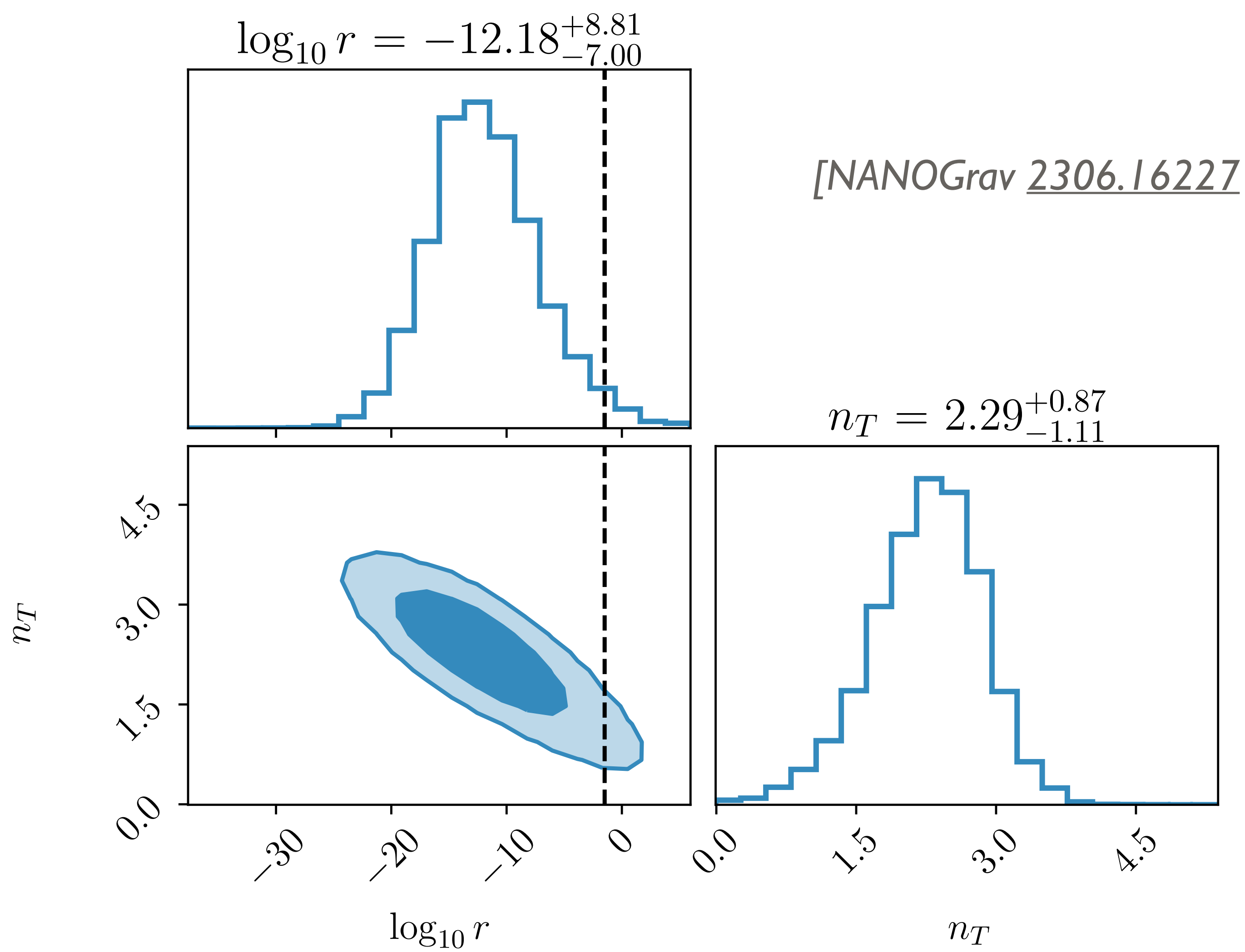
$$\gamma = 5 - n_T$$

– The 90% credible (symmetric) intervals

$$\log_{10} r = -12.18^{+8.81}_{-7.00}$$

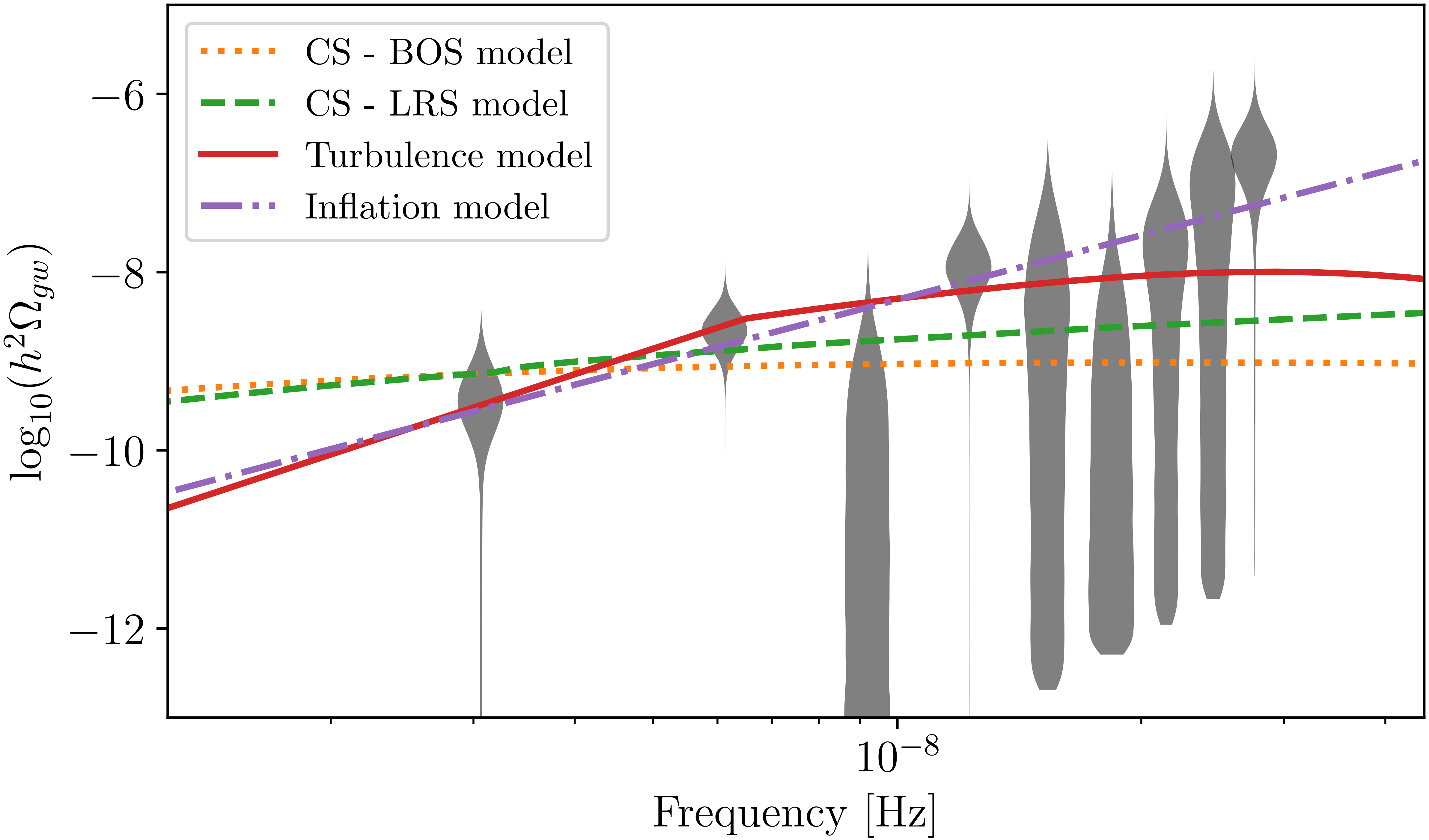
$$n_T = 2.29^{+0.87}_{-1.11}$$

– fractional energy density spectrum obtained from the maximum a posteriori parameter values:



[NANOGrav 2306.16227]

Spectra for maximum a posteriori parameter values,
all assuming primordial background to be the only source of GWs



[EPTA+InPTA, 2306.16227]

Cosmological signals II: cosmic strings

$$8\pi^4 f^5 S(f) = \Omega_{\rm GW}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2(f)$$

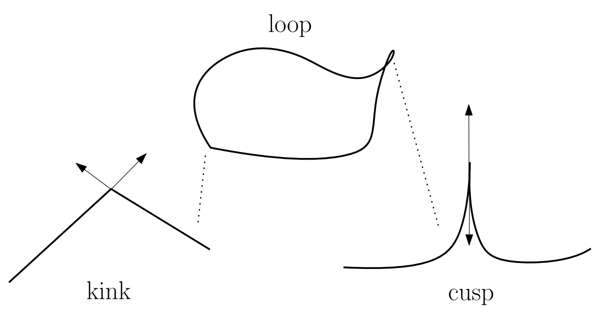
$$h_c(f) = A\left(f/f_0\right)^{\alpha}$$

$$S(f) = \frac{A^2}{12\pi^2 f_0^{2\alpha}} f^{-\gamma}$$

$$\gamma = 3 - 2\alpha$$

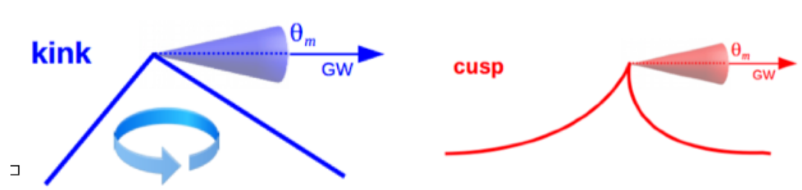
- Given a model for the distribution of cosmic string loops, all of which radiate into GWs,

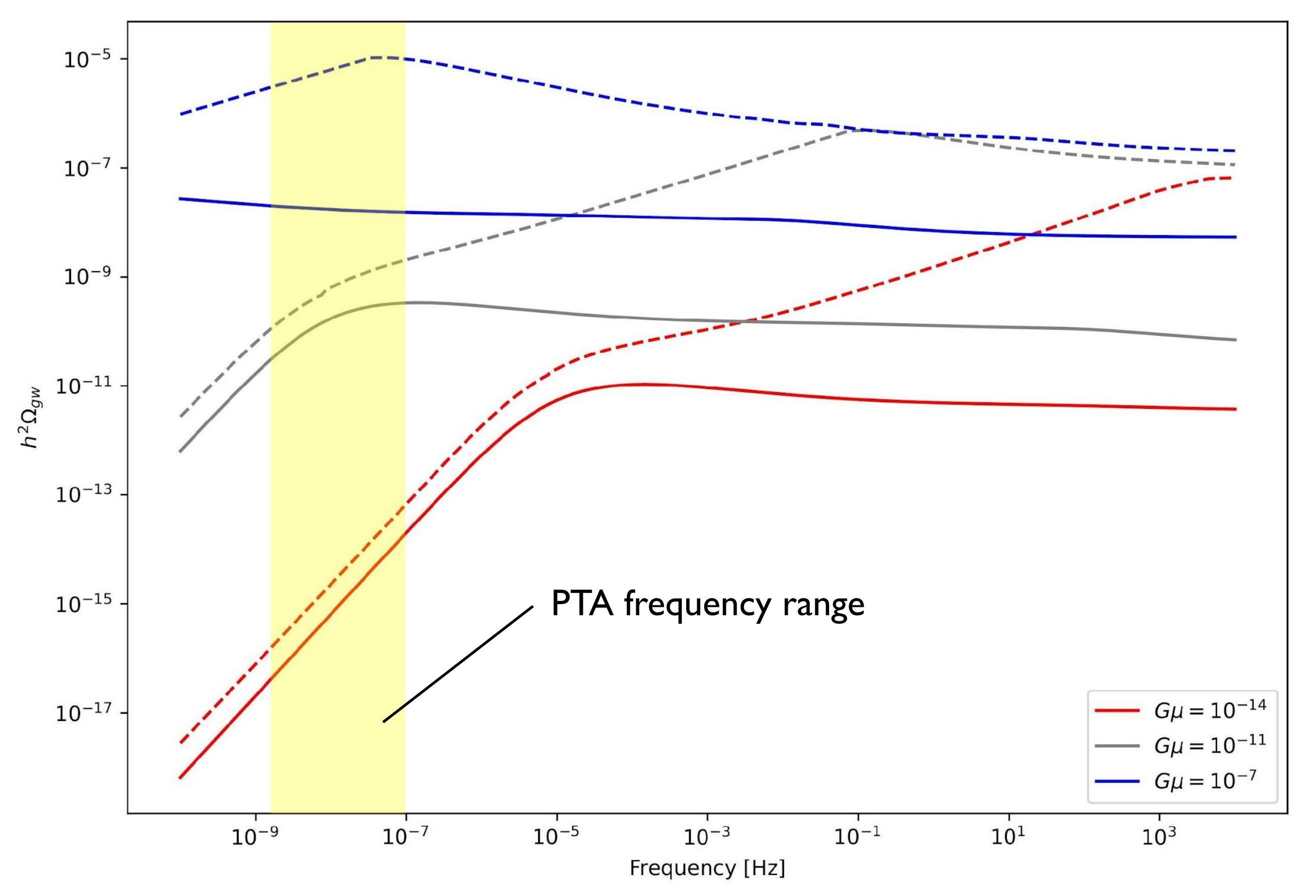
$$\Omega_{\rm GW}(t_0, f) = \frac{16\pi (G\mu)^2}{3H_0^2} \sum_b \frac{N_b \Gamma^{(b)}}{\zeta(q_b)} \times \sum_{n=1}^{+\infty} \int \frac{n^{1-q_b} \mathrm{d}\, z}{(1+z)^5 H(z)} \mathrm{n}\left[\frac{2n}{(1+z)f}, t(z)\right],$$



Sum over bursts from cusps, kinks and kink-kink collisions

$$q_c = 4/3,$$
$$q_k = 5/3.$$
$$q_{kk} = 2$$





[NANOGrav 2306.16227]

Cosmological signals II: cosmic strings

$$8\pi^4 f^5 S(f) = \Omega_{GW}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2(f)$$

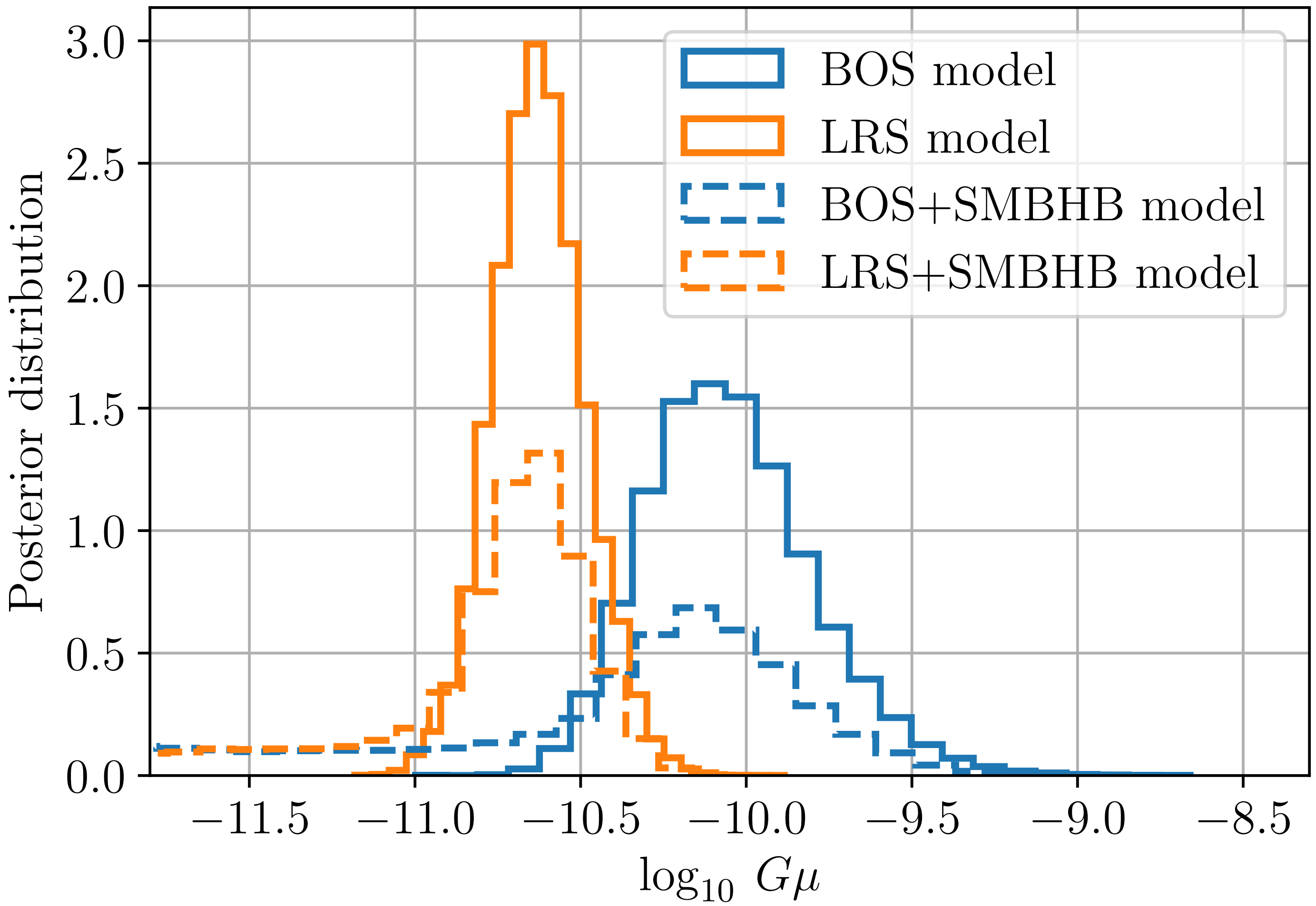
$$h_c(f) = A\,(f/f_0)^{\alpha}$$

$$S(f) = \frac{A^2}{12\pi^2 f_0^{2\alpha}} f^{-\gamma}$$

$$\gamma = 3 - 2\alpha$$

- Given a model for the distribution of cosmic string loops, all of which radiate into GWs,

$$\Omega_{GW}(t_0, f) = \frac{16\pi(G\mu)^2}{3H_0^2} \sum_b \frac{N_b \Gamma^{(b)}}{\zeta(q_b)} \times \sum_{n=1}^{+\infty} \int \frac{n^{1-q_b} \mathrm{d}\, z}{(1+z)^5 H(z)} \mathrm{n}\left[\frac{2n}{(1+z)f}, t(z)\right],$$



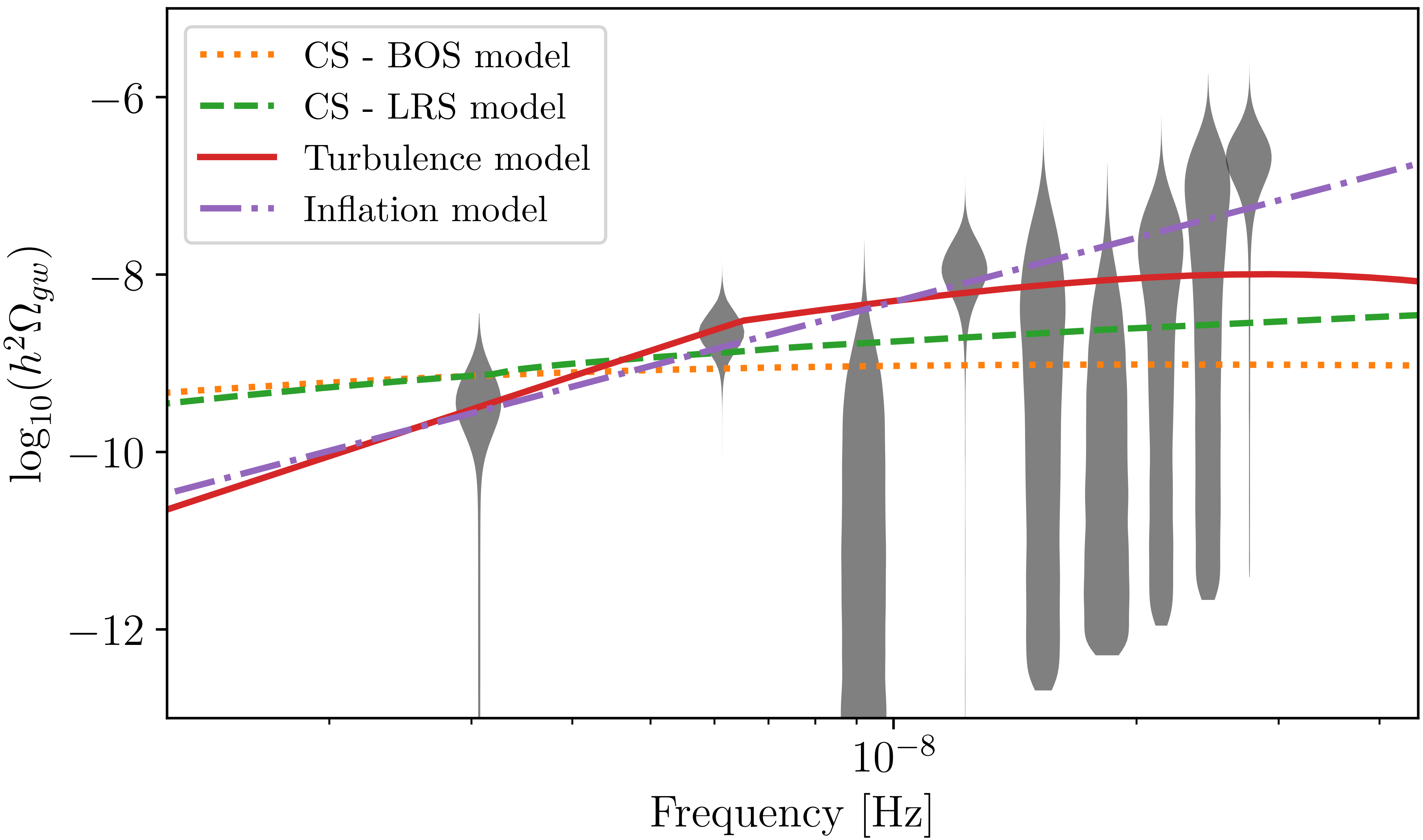
BOS model $\log_{10}(G\mu) = -10.07^{+0.47}_{-0.36}$

LRS model $\log_{10}(G\mu) = -10.63^{+0.24}_{-0.22}$

To be compared with expected LISA constraints, of order 10^{-17}, and LVK constraints BOS: $\log_{10}(G\mu) \lesssim -8$, LRS (but from the burst signal), $\log_{10}(G\mu) \lesssim 10^{-14}$

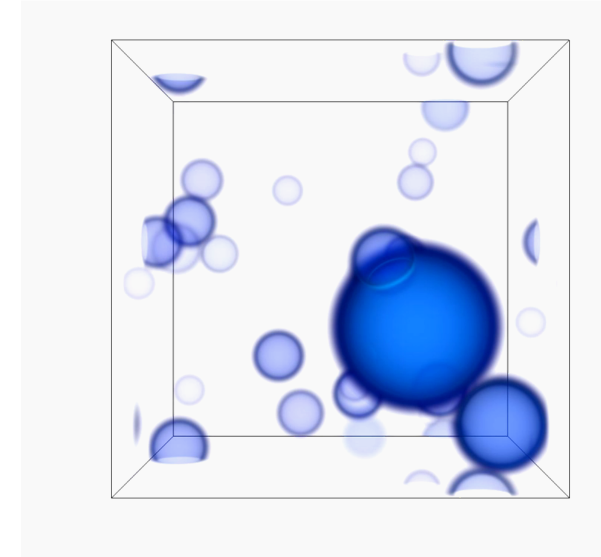
[EPTA+InPTA, 2306.16227]

Spectra for maximum a posteriori parameter values,
all assuming primordial background to be the only source of GWs



[EPTA+InPTA, 2306.16227]

Cosmological signals III: 1st order phase transition sourced by turbulence



Roper Pol et al. (2022a)

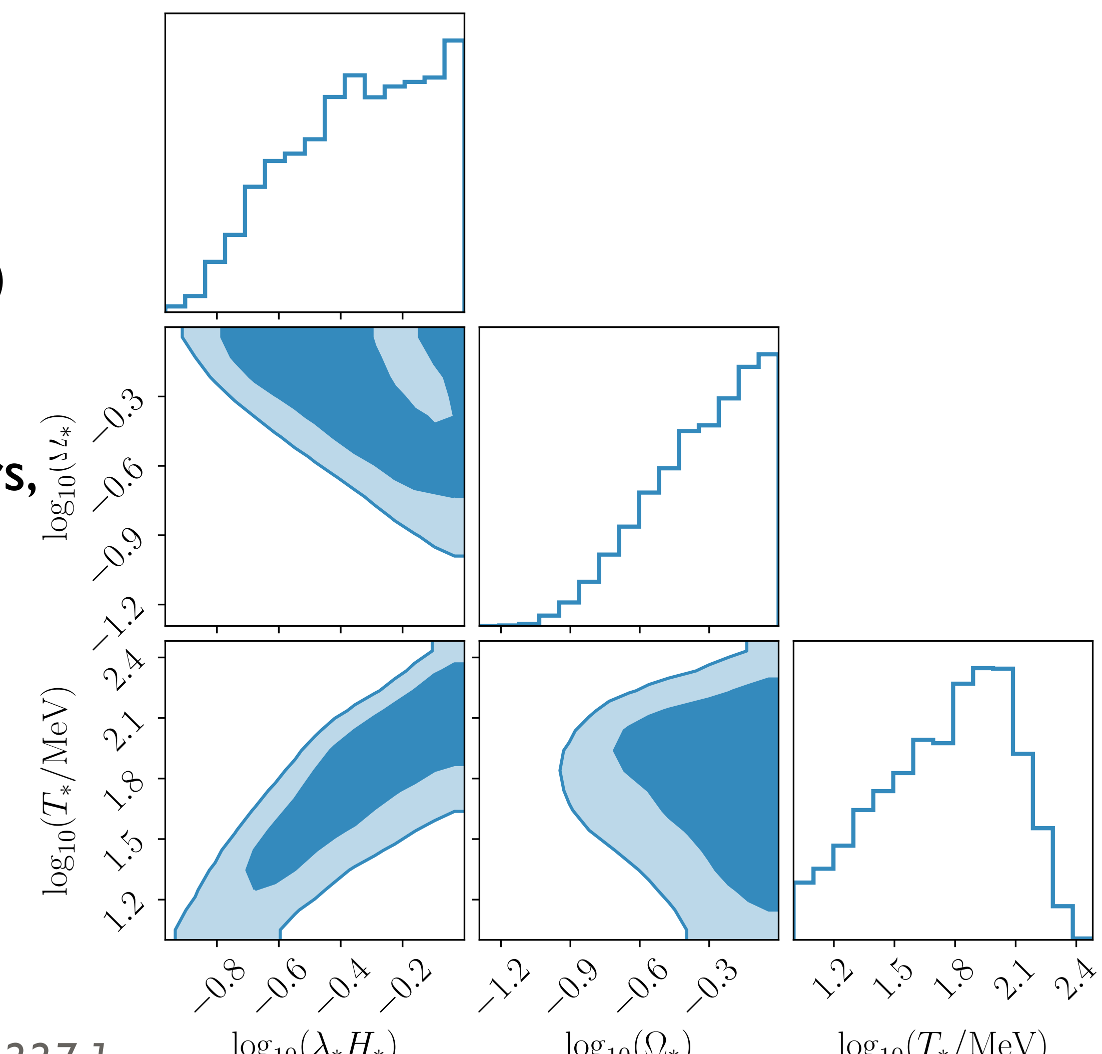
- The shape of $\Omega_{\mathrm{GW}}(f)$ depends on (at least) 3 parameters:

  T_* = temperature of universe when 1st order PT occurred (~QCD)
  $\lambda_* \mathscr{H}_*$ = characteristic length scale of turbulence relative to Hubble horizon
  Ω_*= ratio of turbulent energy density to radiation energy density (measure of strength of the phase transition)

- And defined, for turbulence, by three power laws:
  f^3 at frequencies below the inverse effective duration of the turbulence $f < 1/\delta t_{\mathrm{fin}}$,
  f at intermediate frequencies $1/\delta t_{\mathrm{fin}} < f < 1/\lambda_*$,
  $f^{-8/3}$ at large frequencies $f > 1/\lambda_*$ (Kolmogorov turbulence)

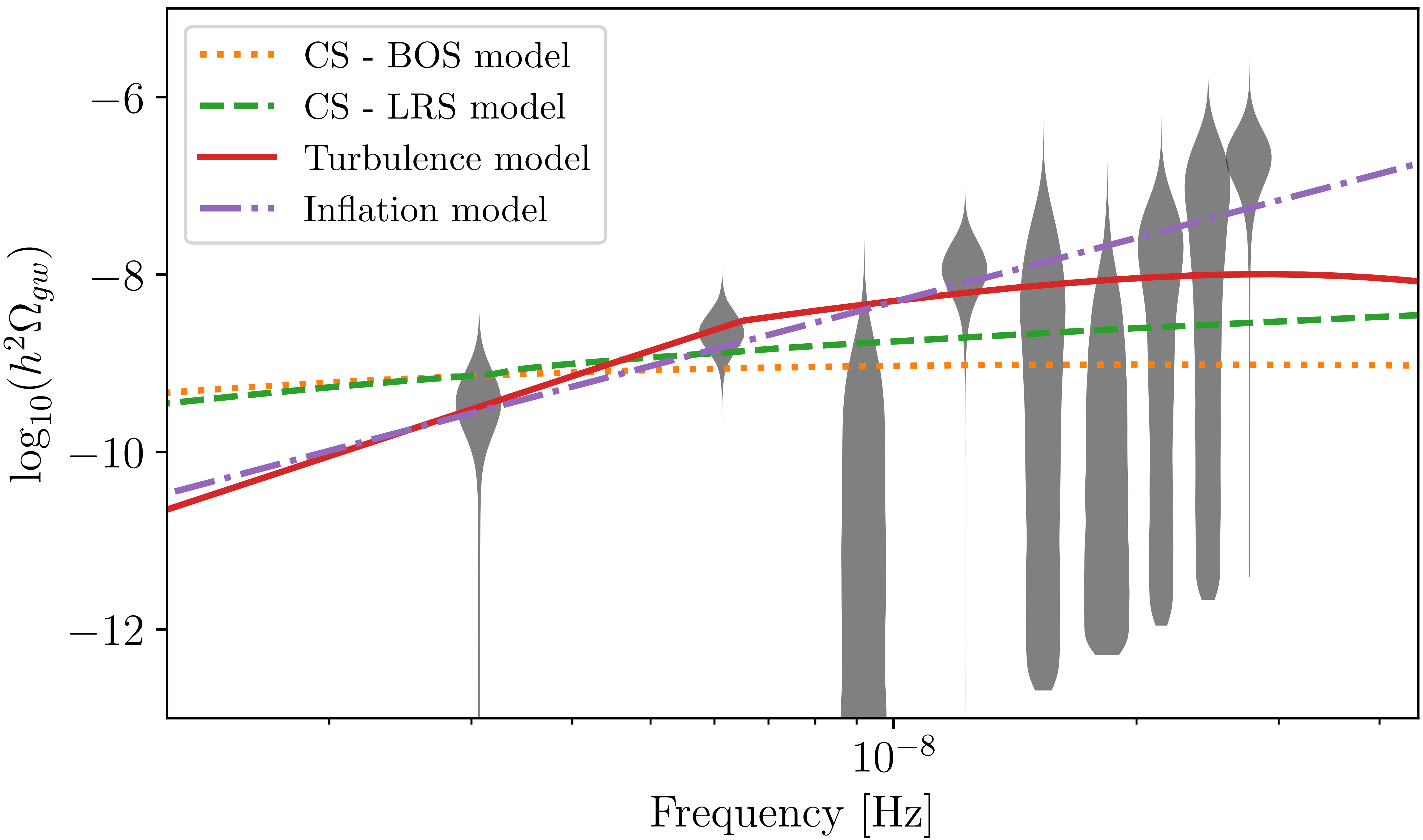
- Analysed with $\log_{10}$ -uniform priors for the model parameters,
$\log_{10}(\lambda_* \mathscr{H}_*) \in [-3,0]$
$\log_{10} \Omega_* \in [-2,0]$
$\log_{10}(T_*/1\mathrm{MeV}) \in [1,3]$

- small values of Ω_* disfavoured. At larger values, the f^3 part of the spectrum enters the PTA band with sufficiently high amplitude, and can provide a good fit to the data



[EPTA+InPTA, 2306.16227]

Spectra for maximum a posteriori parameter values,
all assuming primordial background to be the only source of GWs



[EPTA+InPTA, 2306.16227]

NANOGrav: Bayes factors

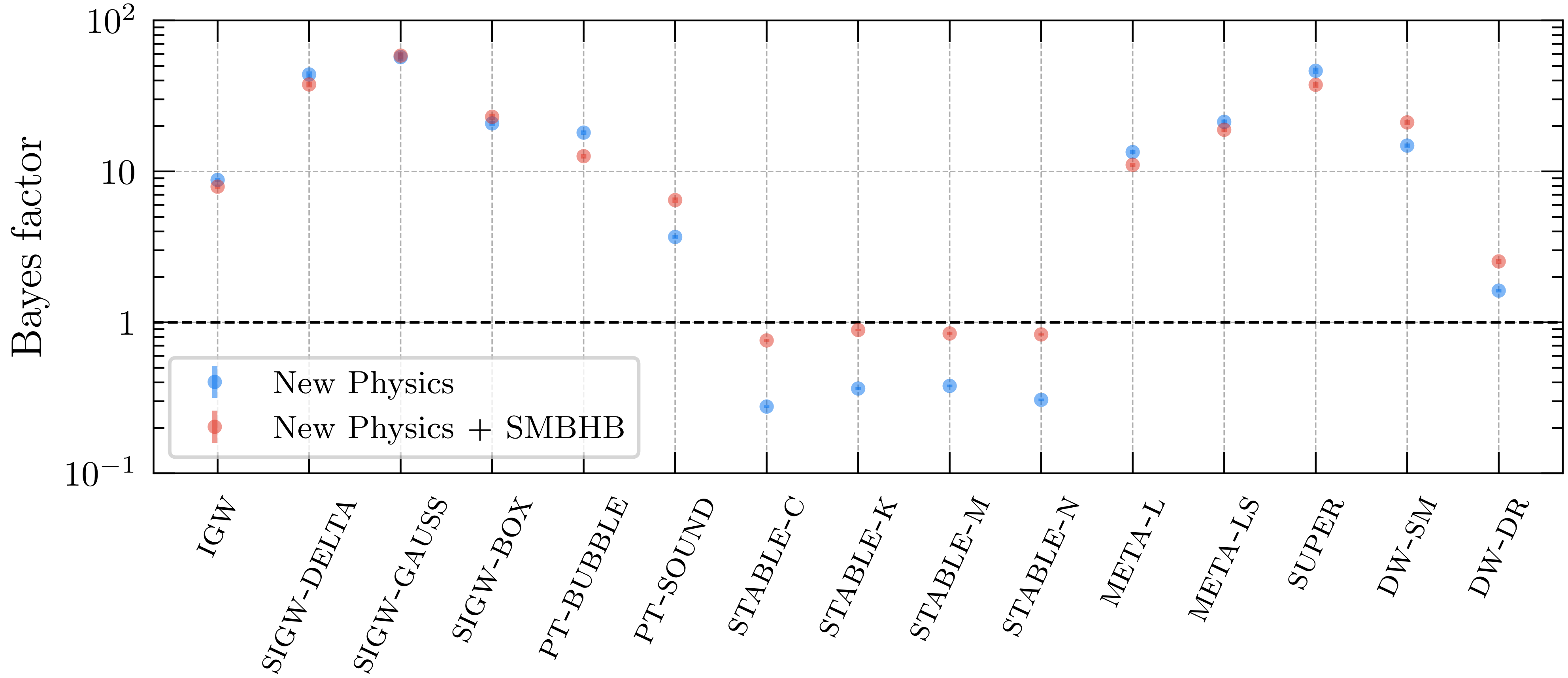
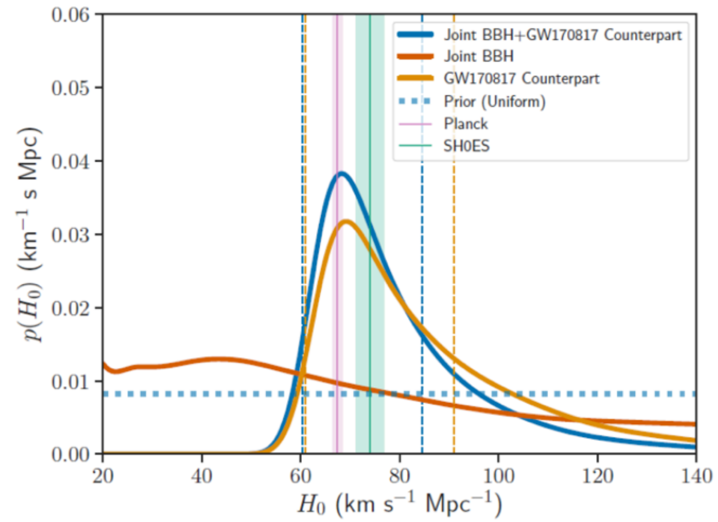


Figure 2. Bayes factors for the model comparisons between the new-physics interpretations of the signal considered in this work and the interpretation in terms of SMBHBs alone. Blue points are for the new physics alone, and red points are for the new physics in combination with the SMBHB signal. We also plot the error bars of all Bayes factors, which we obtain following the bootstrapping method outlined in Section 3.2. In most cases, however, these error bars are small and not visible.

EPTA Bayes factors follow a similar trend (but differ in the details), private communication H.Quelquejay-Leclere

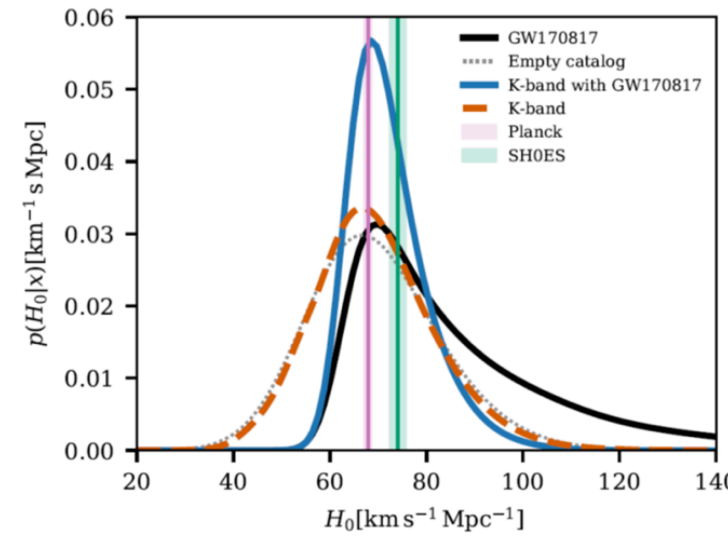
Conclusions part 1

Using GWTC-1



+30 GW events

Using GWTC-3



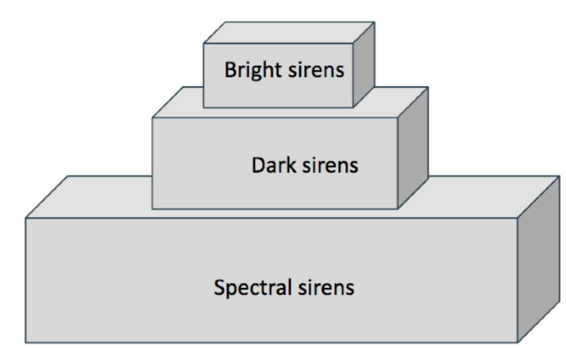
Key messages from O3:

- H0 constraint still driven by bright siren GW170817, but dark sirens are already making a significant difference
- Without very good sky localizations, results are sensitive to BH population model parameters.

For O4 and beyond: higher GW event rates & plus deeper galaxy surveys and improved (cosmo+pop) modelling

More generally:

- Different ways to extract information on H0 and modified gravity using GWs.
- Bright/dark siren (galaxy catalogue) methods will become less viable for sources at high z
- BBH, BNS populations. **Cosmology hand in hand with astrophysics**
- Same methods can be used to constrain propagation effects in modified gravity
- Number of effects to consider: overlapping sources and parameter estimation; higher order modes; precessing spins; waveform accuracy ? etc



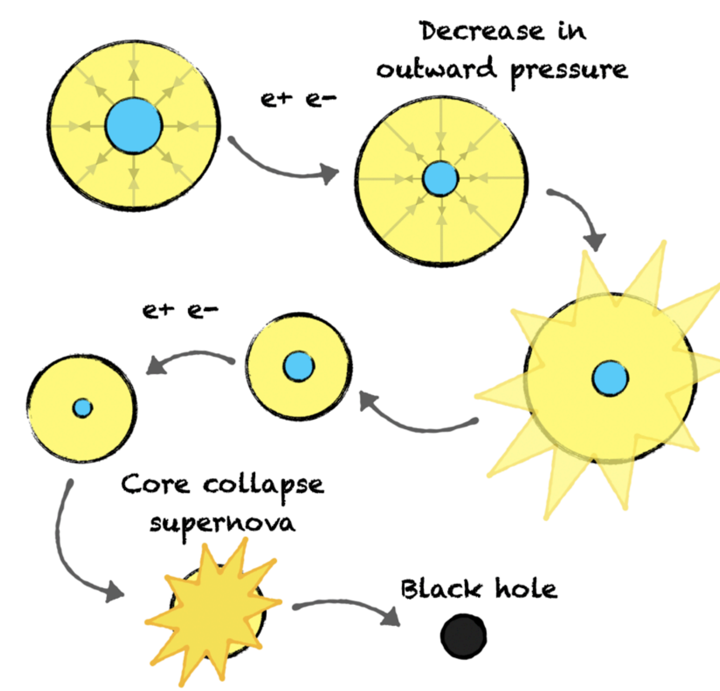
Conclusions part 2

- In the next 2 years, IPTA will have probably confirm the detector of a GW background.
- Very exciting times ahead to understand its origin, astrophysical or cosmological or both.

Expectation *[Credit: LVK BBHs population webinar 2021]*

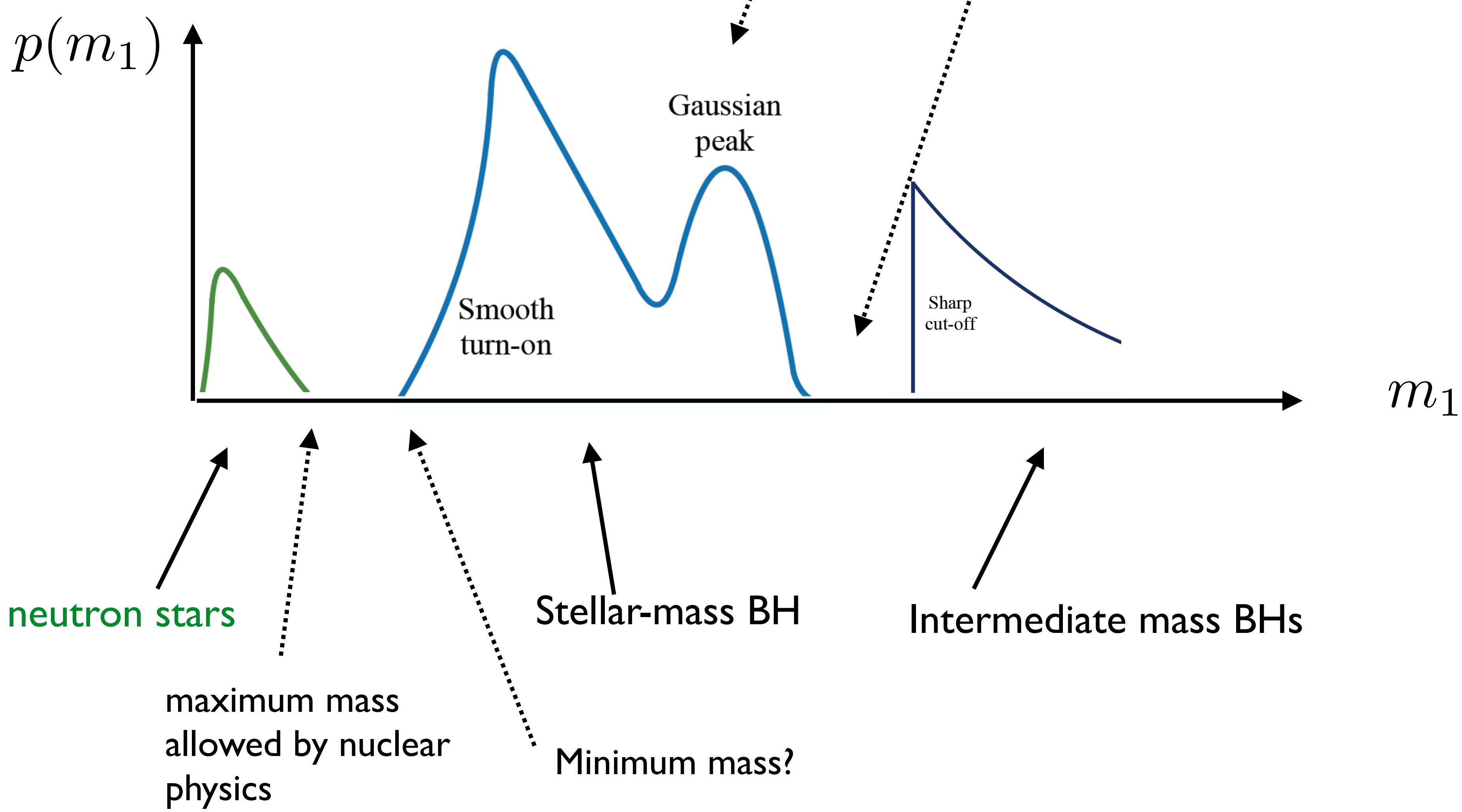
Pair instability supernovae process

- at sufficiently high temperatures, electron positron pairs produced.
- Lowers pressure inside star, which collapses.
- Expected to leave no BH remnant in range $\sim [50, 120]\ \mathrm{M}_\odot$

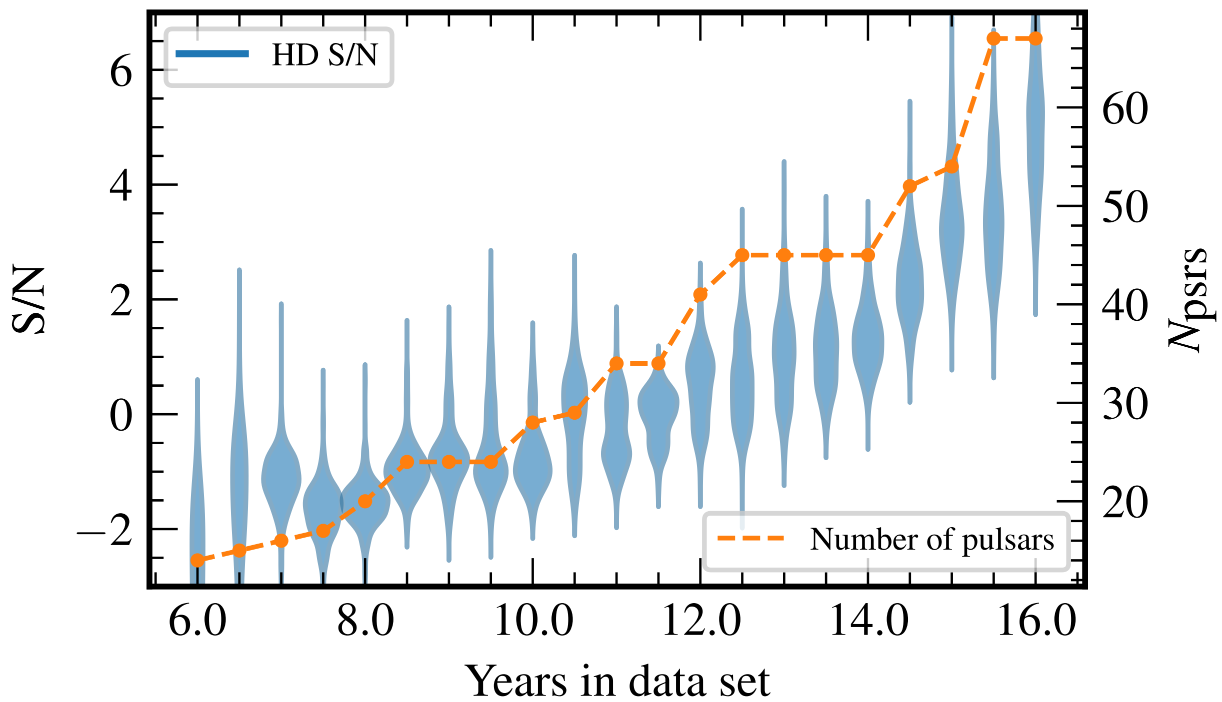


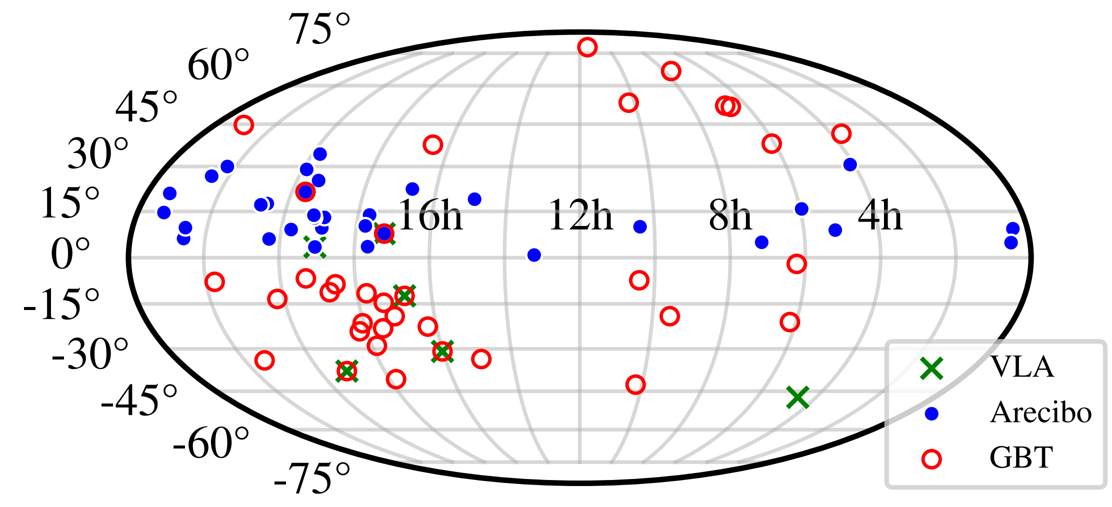
Pulsational pair instability supernovae process (PISN):

- star not totally disrupted, but only partially.
- after a series of pulses, final expectation is set of BHs $\sim [35-45]\mathrm{M}_\odot$



[Taylor, Gair et al, 2012]
for BNS: 100 obs -> H0 to 20%
+ mean and variance of mass
distribution


HD S/N
Number of pulsars
S/N
N_{psrs}
Years in data set
6.0
8.0
10.0
12.0
14.0
16.0
−2
0
2
4
6
20
30
40
50
60


75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
16h
12h
8h
4h
VLA
Arecibo
GBT