LISA+3G coherent multiband parameter estimation of SOBHB and IMBHB using PyCBC

Shichao Wu (AEI Hannover)

Collaborators: Alex Nitz, Ian Harry, Stas Babak, and Michael J. Williams

LISA AstroWG Meeting at MPA

06.11.2024

Max-Planck-Institut für Gravitationsphysik ALBERT-EINSTEIN-INSTITUT

Leibniz Universität Hannover

Syracuse University College of Arts & Sciences

UNIVERSITY OF PORTSMOUTH

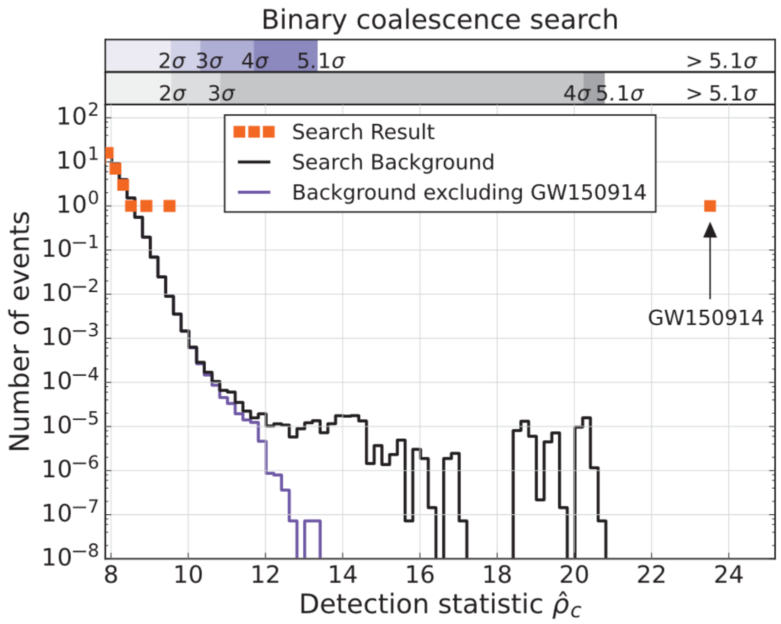
Outlines

1. PyCBC: Past, Present, and Future
2. Difficulties in the LISA+3G Multiband Observation
3. Coherent Multiband Parameter Estimation using PyCBC

1 PyCBC: Past, Present, and Future

- PyCBC was used to make the “5-sigma significance plot” for GW150914
- PyCBC is used by LVK Collaboration to routinely find new CBC signals
- PyCBC is already heavily used in studies for next-generation ground-based detectors, such as ET and CE

- Now we are extending PyCBC to be used for LISA, TianQin, Taiji, and DECIGO

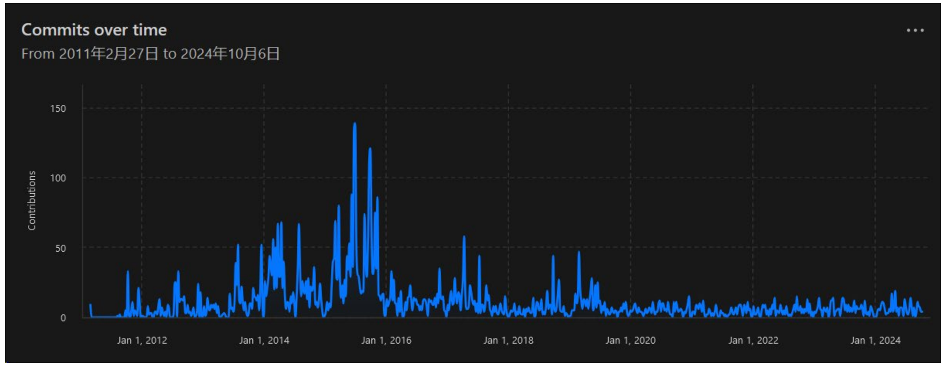


S241102cy
https://gracedb.ligo.org/superevents/S241102cy/

10.1103/PhysRevLett.116.061102
10.1103/PhysRevD.93.122003

Per-Pipeline Event Information

UID	Group	Pipeline	Search	gpstime	FAR (Hz)
G522239	CBC	spiir	AllSky	1414594067.731	1.791e-05
G522247	CBC	pycbc	AllSky	1414594067.728	1.520e-08
G522253	CBC	gstlal	AllSky	1414594067.729	2.897e-09
G522248	CBC	CWB	BBH	1414594067.738	7.325e-11
G522244	CBC	MBTA	AllSky	1414594067.728	1.509e-12

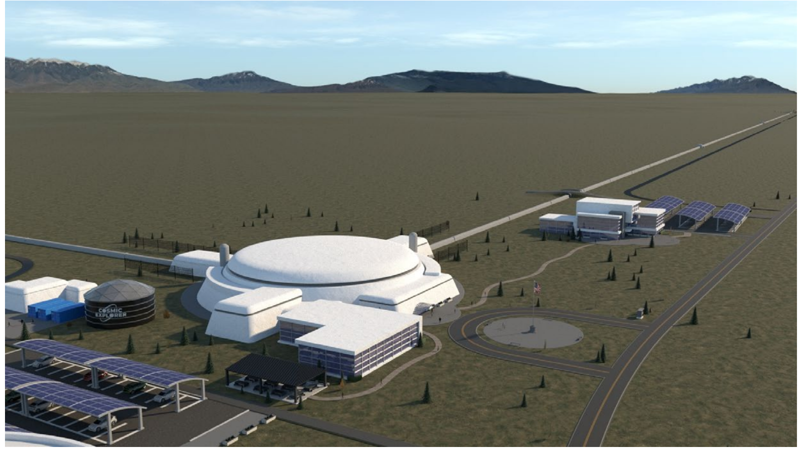


https://github.com/gwastro/pycbc/graphs/contributors

2 Difficulties in the LISA+3G Multiband Observation

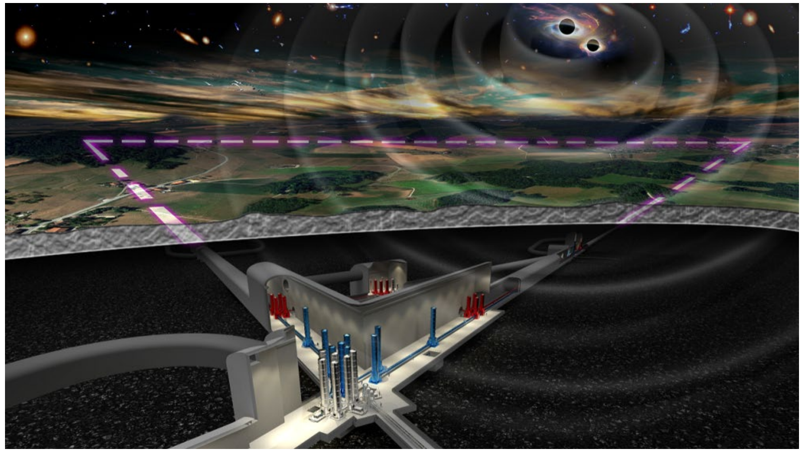
- GW detectors in the 2030s

Cosmic Explorer



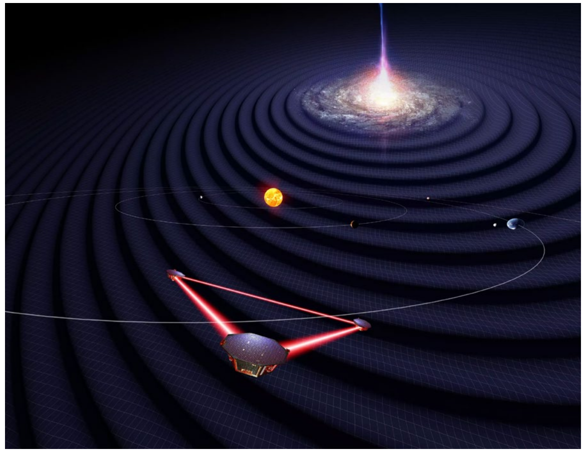
(https://cosmicexplorer.org)

Einstein Telescope



(http://www.et-gw.eu/)

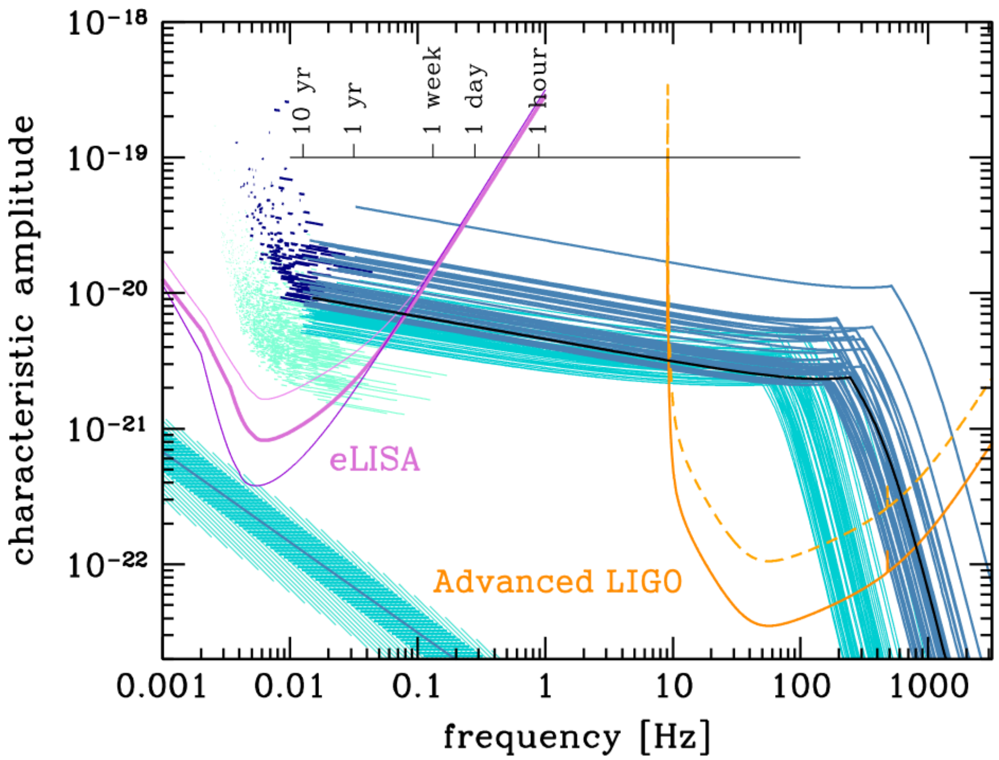
LISA



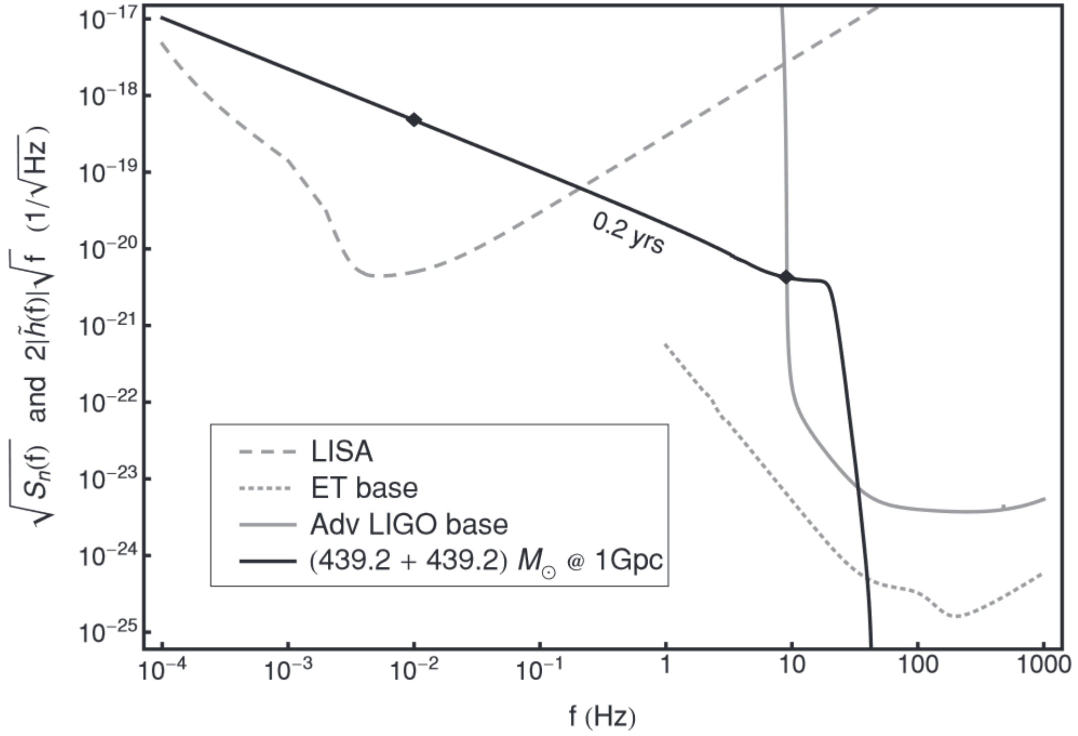
(https://www.aei.mpg.de/lisa)

Can we use next-gen ground-based detectors together with space-borne detector(s)?

- Early multiband concepts



Alberto Sesana (2016)
DOI:10.1103/PhysRevLett.116.231102



Pau Amaro-Seoane and Lucía Santamaría (2010)
DOI: 10.1088/0004-637X/722/2/1197

SOBHBs and IMBHBs can be multiband GW sources

2 / Difficulties in the LISA+3G Multiband Observation

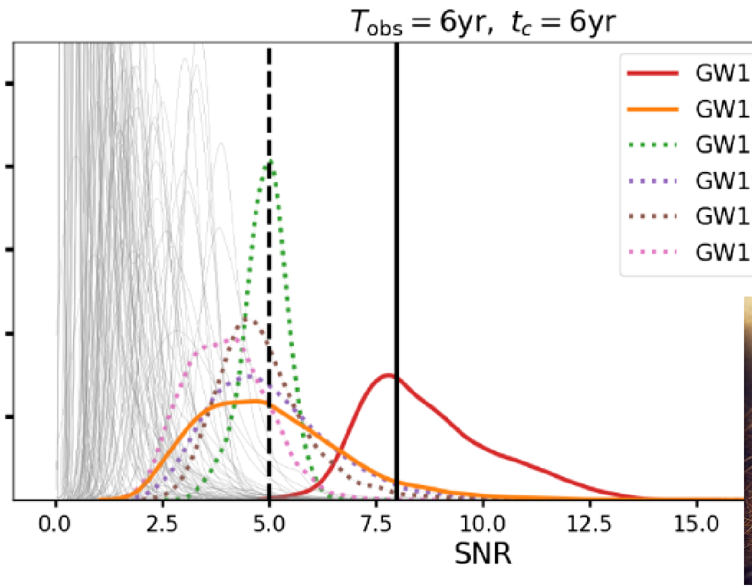
- Fisher Information Matrix

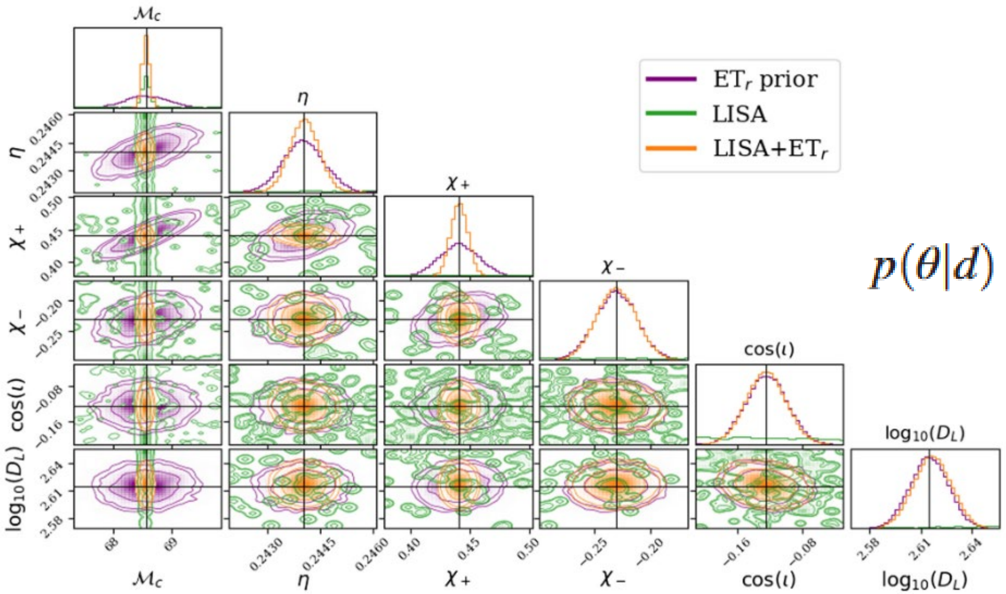
$$\Gamma^{(0)}_{\alpha\beta} = \langle \tilde{h}_\alpha, \tilde{h}_\beta \rangle \qquad \tilde{h}_\alpha = \partial \tilde{h}(f;\vec{\theta})/\partial\theta_\alpha \qquad \langle a, b\rangle = 2\int_{f_{\rm low}}^{f_{\rm high}} \frac{a(f)b^*(f) + a^*(f)b(f)}{S_h(f)}\,df$$

$$\Gamma_{\alpha\beta} = \Gamma^{\rm CE}_{\alpha\beta} + \Gamma^{\rm LISA}_{\alpha\beta}, \qquad C^{\alpha\beta} = (\Gamma^{-1})^{\alpha\beta}$$

- Bayesian Parameter Estimation (archival search)

Alexandre Toubiana, et al (2022)
DOI:10.1103/PhysRevD.106.104034





$$p(\theta|d) = \frac{p(d|\theta)p(\theta)}{p(d)}$$

Too many local maxima: Finding a needle in a haystack!

- Most of SOBHBs will sub-threshold.

Table 4 List of SOs and SIs that are degraded when a duty cycle $\mathcal{D} = 0.75$ is applied to the baseline LISA mission, defined as SciRD

Scenario	T4C	T4G5	T4G1	T5C	T6C	T6G5	T6G1
T_{elapsed}		4 yr		5 yr		6 yr	
$T_{\text{data}} = 0.75 \times T_{\text{elapsed}}$		3 yr		3.75 yr		4.5 yr	
Gaps	one	5 days	1 day	one	one	5 days	1 day
Galactic binaries (SO1 SI1.2) (§3)							
Black hole seeds (SO2 SI2.1) (§2)							
EM counterparts (SO2 SI2.3) (§2, §5)							
EMRIs (SO3 SI3.1) (§4)							
Multiband SOBHs (SO4 SI4.1) (§3)							
SOBH formation (SO4 SI4.2) (§3)							
Kerr tests (SO5 SI5.1&5.2) (§9)							
Tests of GR (SO5 SI5.3&5.4) (§8)							
Ultralight bosons (SO5 SI5.5) (§7)							
H_0 via standard sirens (SO6 SI6.1) (§6)							
Cosmological parameters (SO6 SI6.2) (6)							

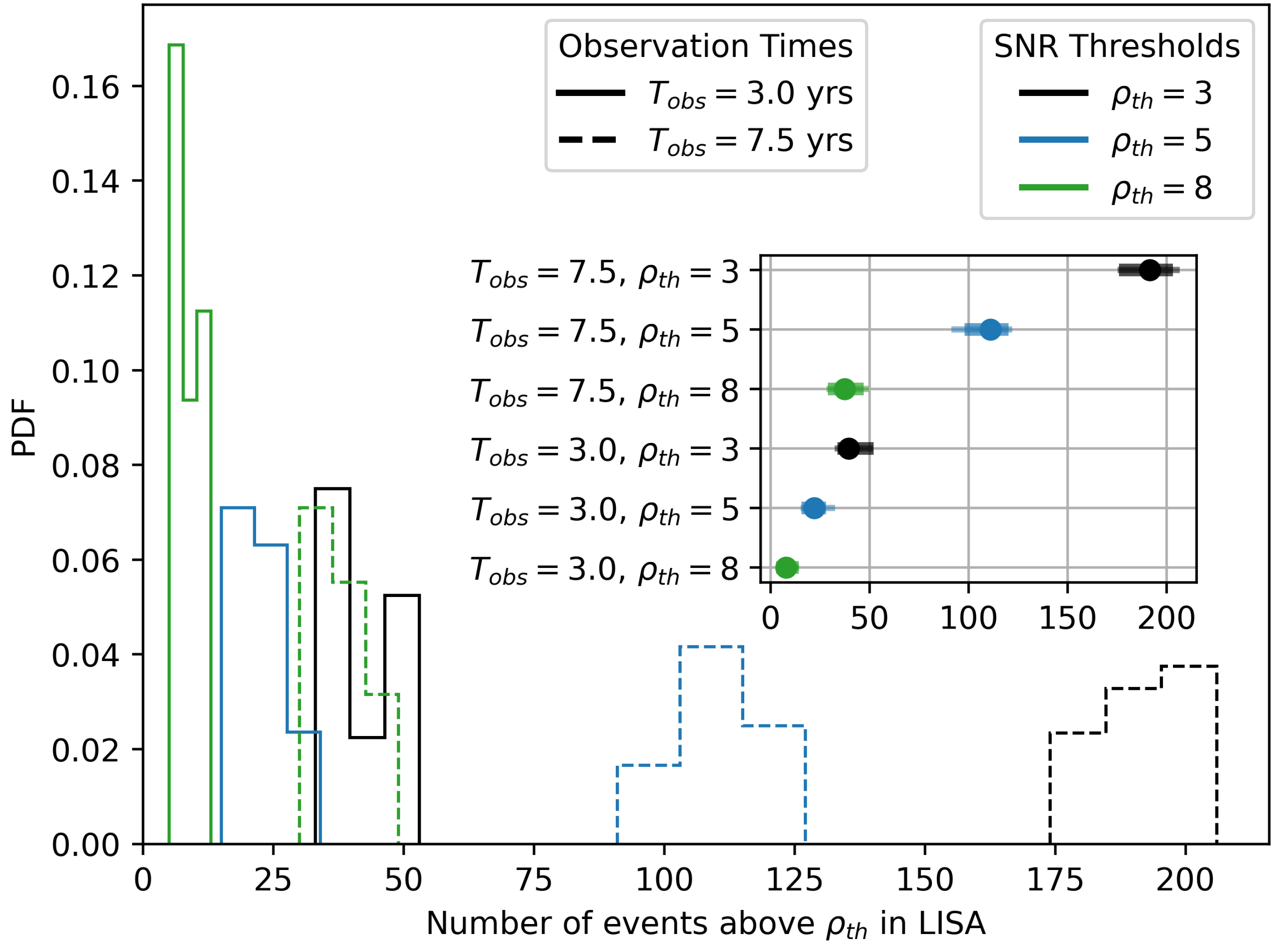
	sBHB type	definition	$\langle N \rangle$	90 % confidence	no sBHB (%)
SI 4.1	detected	$\mathrm{SNR} > 8$	4.9	0.4 – 9.8	2.2
	archival	$5 < \mathrm{SNR} < 8$ & $t_c < 15\,\mathrm{yr}$	5.6	0.8 – 10.0	1.4
SI 4.2	massive	$\mathrm{SNR} > 8$ & $m_1 > 50\,M_\odot$	1.3	0 – 3.6	34.1
SI 4.3	multiband	$\mathrm{SNR} > 8$ & $t_c < 15\,\mathrm{yr}$	1.5	0 – 3.8	26.7
		$\mathrm{SNR} > 8$ & $t_c < 4.5\,\mathrm{yr}$	0.4	0 – 1.4	67.7

Pau Amaro-Seoane. et al (2021)
DOI:10.1007/s10714-021-02889-x

LISA Definition Study Report - ESA-SCI-DIR-RP-002 (2024)
DOI: 10.48550/arXiv.2402.07571

2 / Difficulties in the LISA+3G Multiband Observation

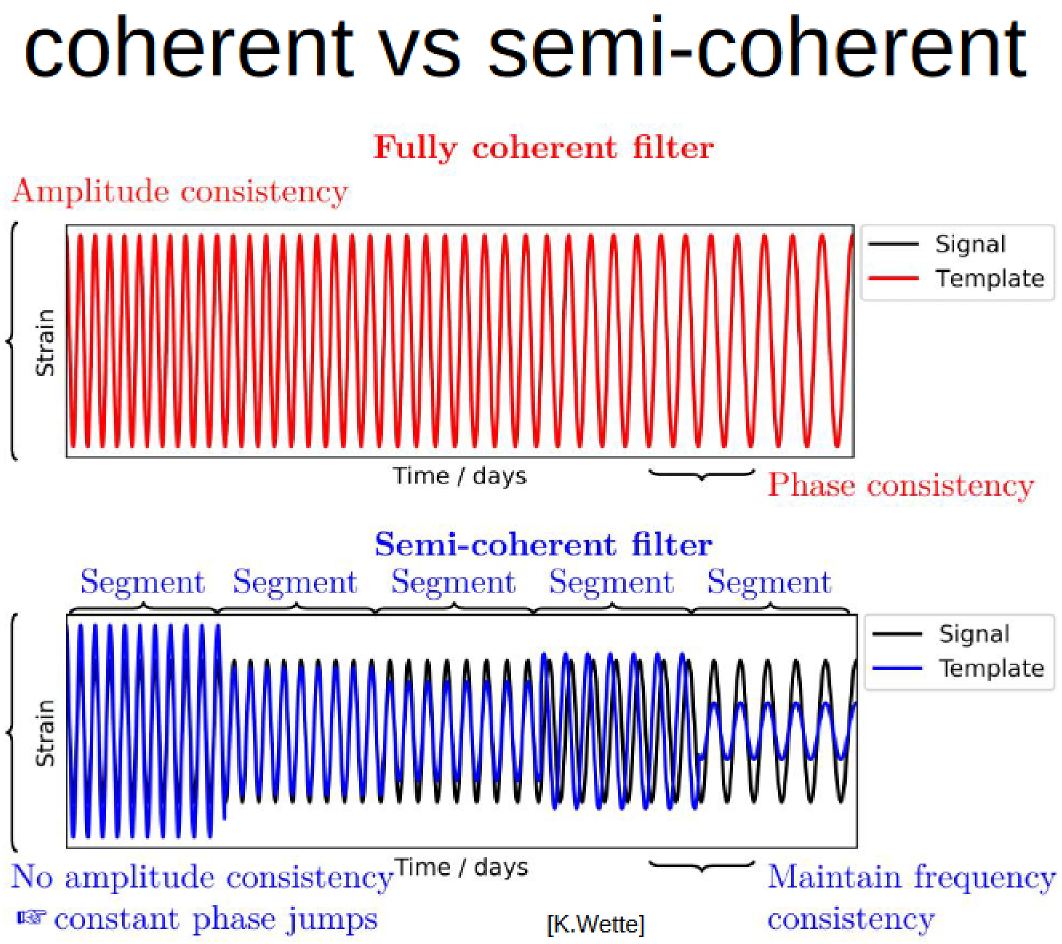
- Most of SOBHBs will sub-threshold.



Using the GWTC-3 population model, we generate several data sets for LISA+ET+2CE observations.

The left figure shows the event rate above SNR thresholds in LISA for different LISA mission durations, assuming a duty cycle of 0.75.

- Can we make use of those low-SNR signals?



Coherent filter is more sensetive than semi-coherent filter, which means it can detect lower-SNR signals.

Coherent multiband PE (our new method):

- Maintains amplitude/phase consistency, updating the LISA/3G waveforms consistently for each multiband likelihood call.

Semi-coherent multiband PE (3G posterior as LISA prior):

- Any inaccuracies in the 3G posterior or LISA prior will introduce an additional non-physical degree of freedom.

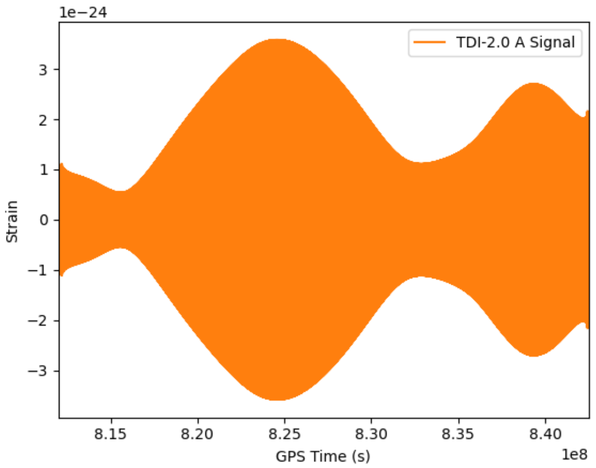
(check all the technical details in our upcoming paper)

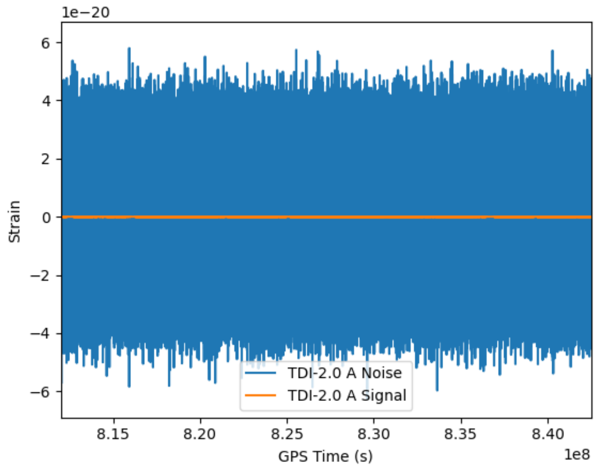
Coherent Multiband Parameter Estimation using PyCBC

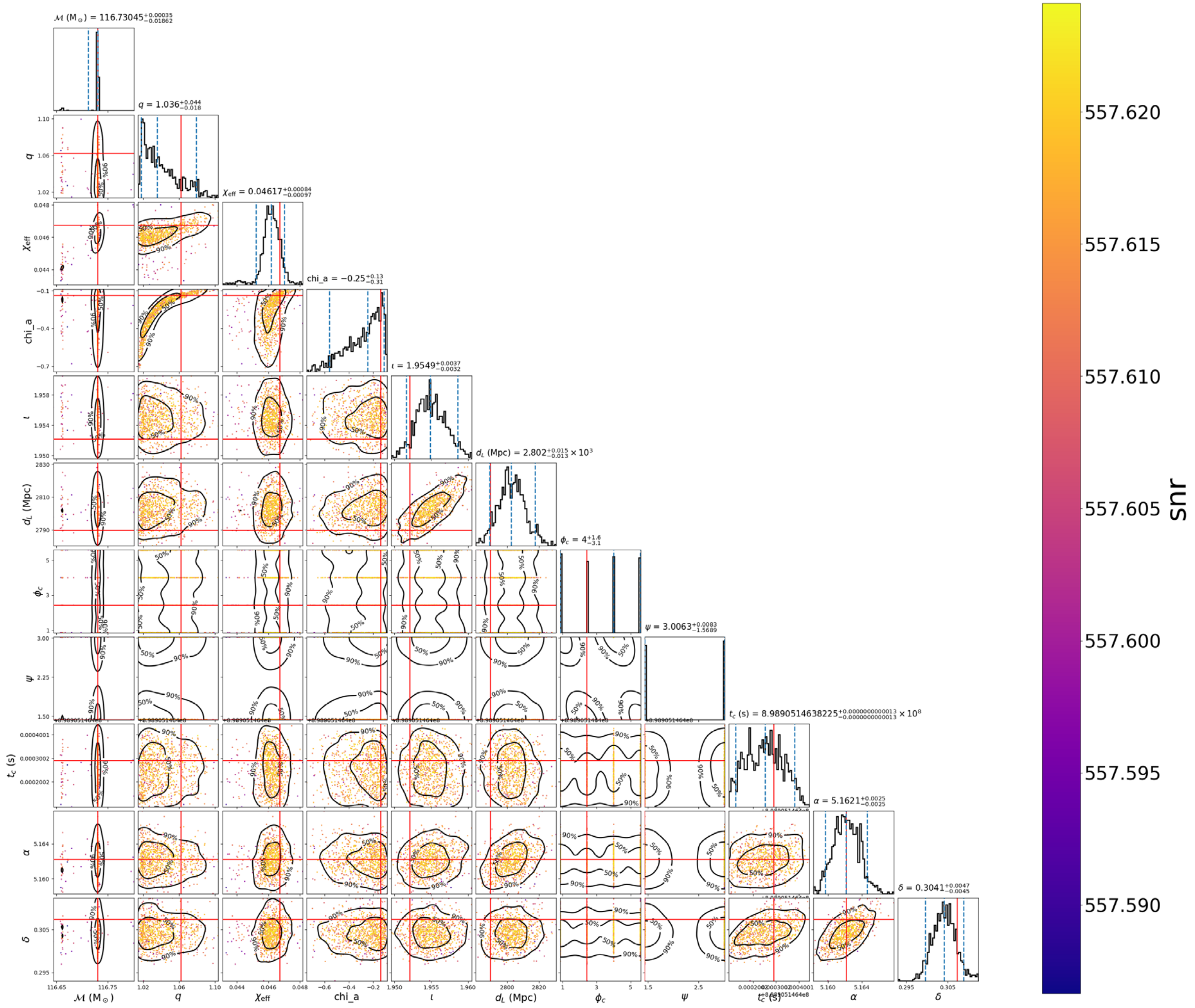
- Some preliminary results:

```
mass1 = 138.21330173038837
mass2 = 130.11023585510668
mchirp = 116.7306837343259
q = 1.0622784658103719
spin1z = 0.17949779887774292
spin2z = -0.09428955549731385
chi_eff = 0.046738155156461035
chi_a = -0.13818027324138493
distance = 2789.5913568879737
```

SNR in LISA: 3.07
SNR in 3G network: 558.47
SNR in LISA+3G network: 558.48

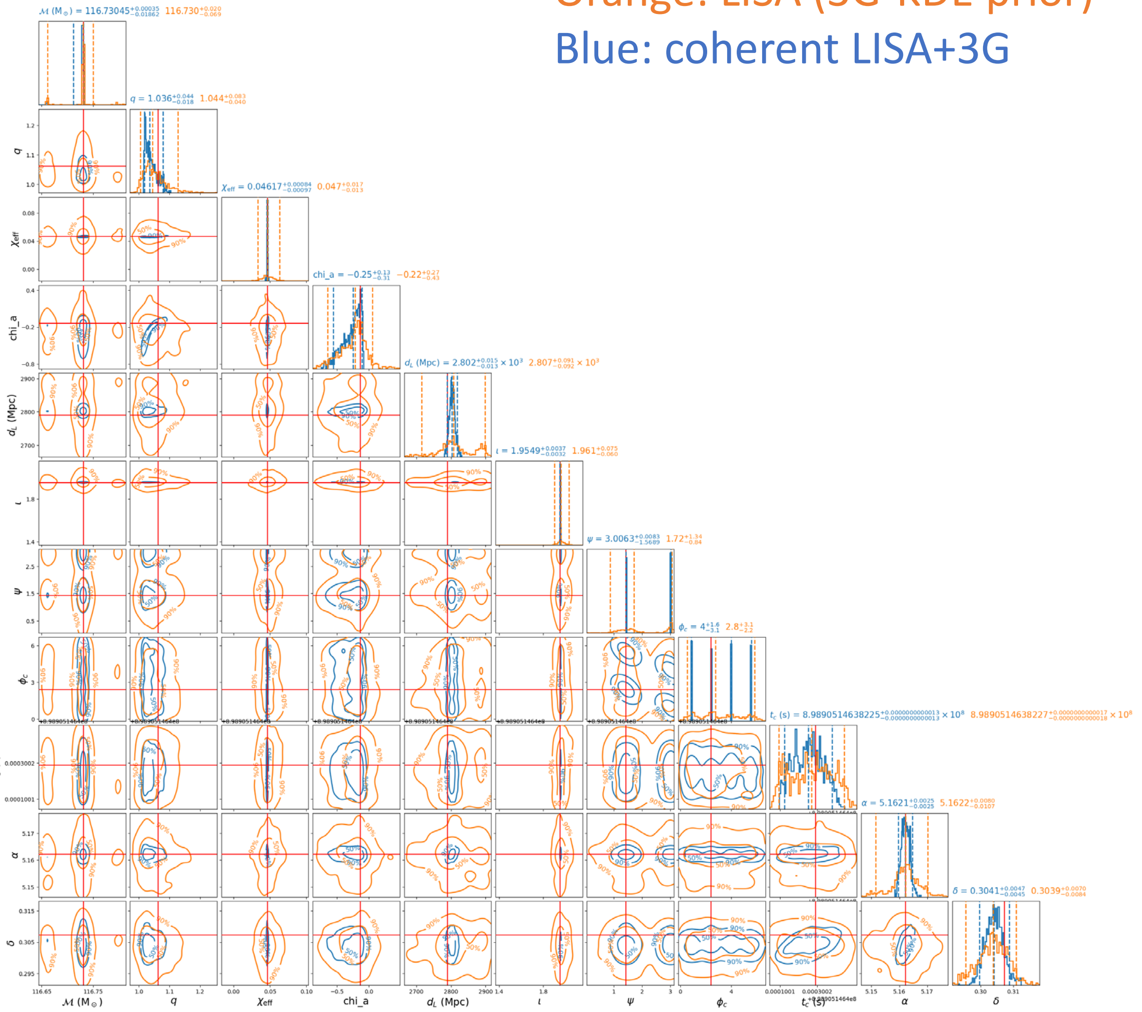




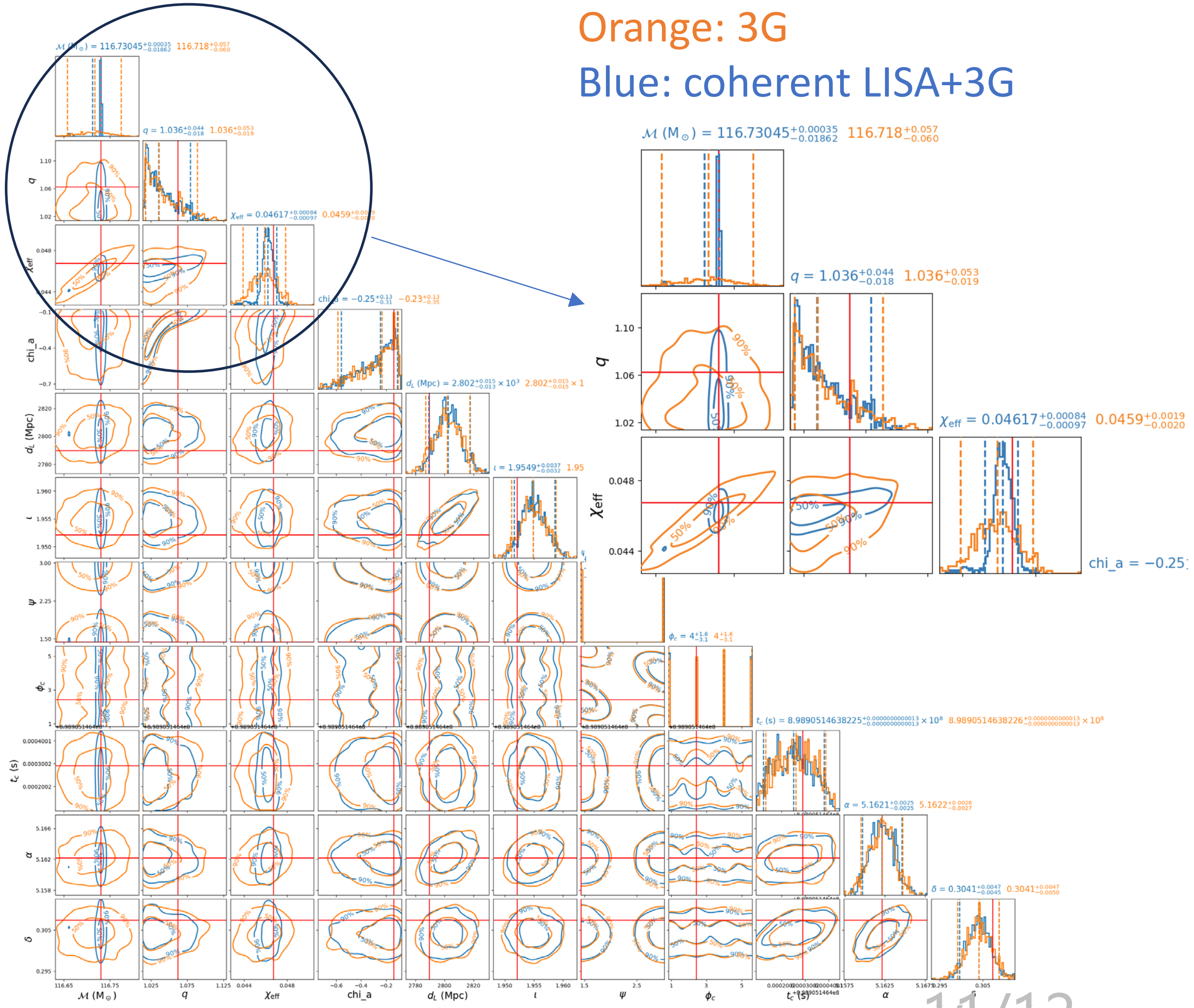


3 Coherent Multiband Parameter Estimation using PyCBC

Orange: LISA (3G-KDE prior)
Blue: coherent LISA+3G



Orange: 3G
Blue: coherent LISA+3G



Conclusions

1. We are extending PyCBC for LISA data analysis.
2. Difficulties in LISA+3G multiband observations:
   - Most of SOBHBs will have extremely low SNR in LISA band.
   - Too many local maxima: Finding a needle in a haystack!
3. Our new coherent multiband method can analyse events down to SNR~3. Double the number of useful events!

Stay tuned for our upcoming paper!