LISA+3G coherent multiband parameter estimation of BBHs using PyCBC

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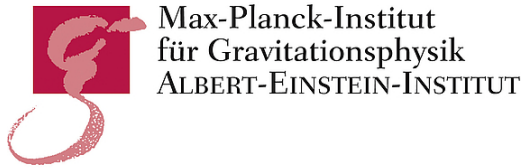
Collaborators: Alex Nitz, Ian Harry, Stas Babak, and Michael J. Williams

10 Years to LISA @ NASA JPL

03.04.2025

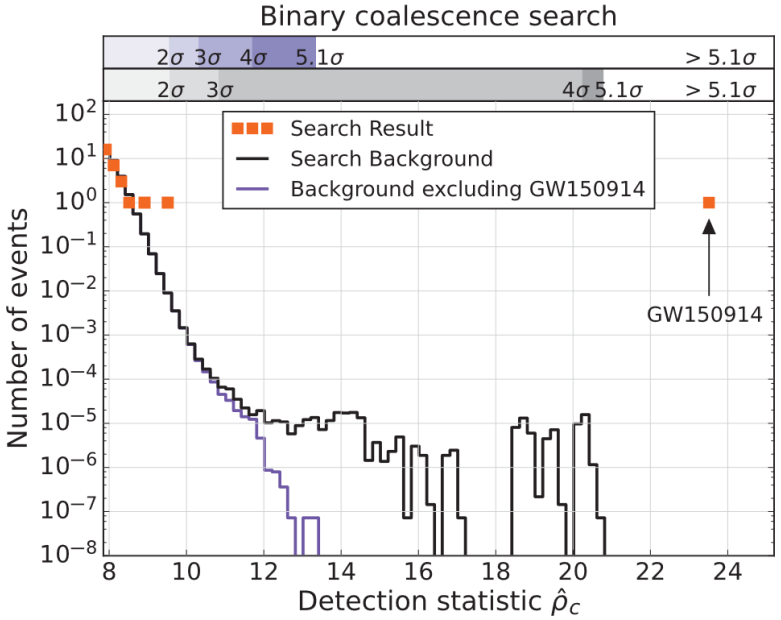


Outlines

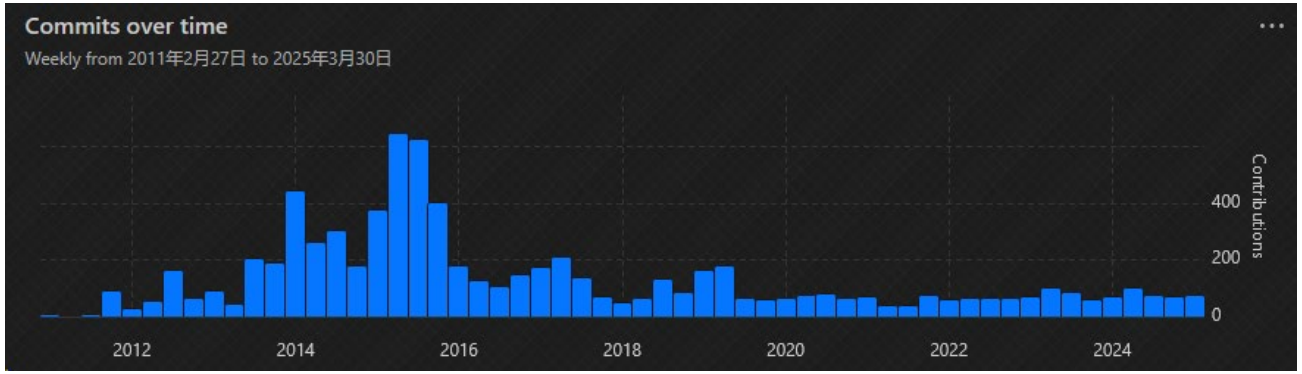
1. PyCBC: Past, Present, and Future
2. Difficulties in the LISA+3G Multiband Observation
3. Coherent Multiband Parameter Estimation using PyCBC
4. Conclusions

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 and PyCBC Inference to be used for LISA, TianQin, Taiji, and DECIGO



10.1103/PhysRevLett.116.061102
10.1103/PhysRevD.93.122003



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

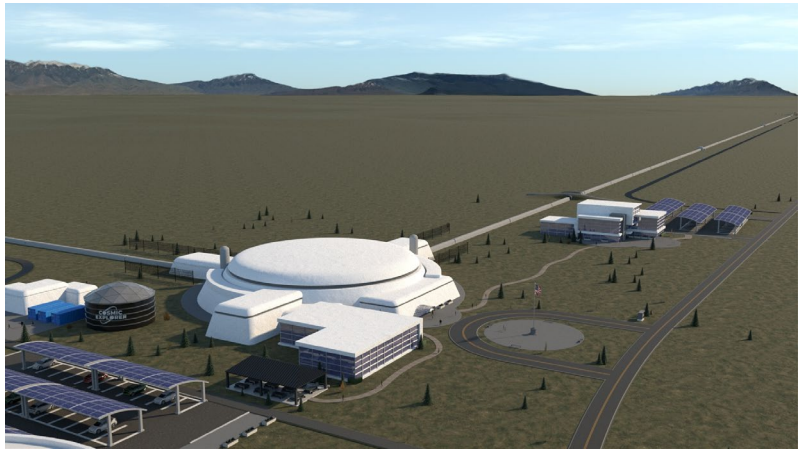
https://gracedb.ligo.org/superevents/S250331o/

Event Information	
Group	CBC
Pipeline	pycbc
Search	AllSky
Instruments	H1,L1,V1
Event Time	1427420106.438 (GPS time)
FAR (Hz)	3.168e-10
Submitted	2025-03-31 01:35:59 UTC

2 / Difficulties in the LISA+3G Multiband Observation

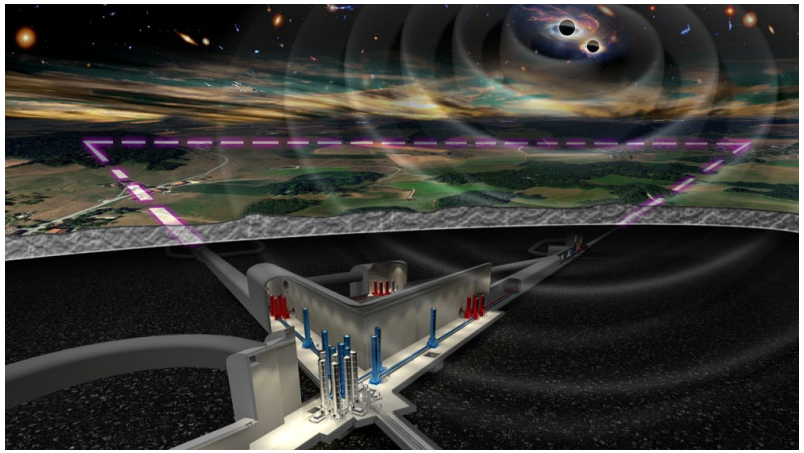
- GW detectors in the 2030s

Cosmic Explorer



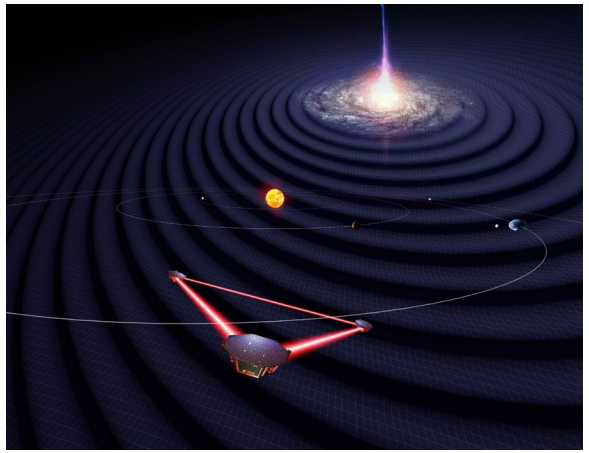
(https://cosmicexplorer.org)

Einstein Telescope



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

LISA

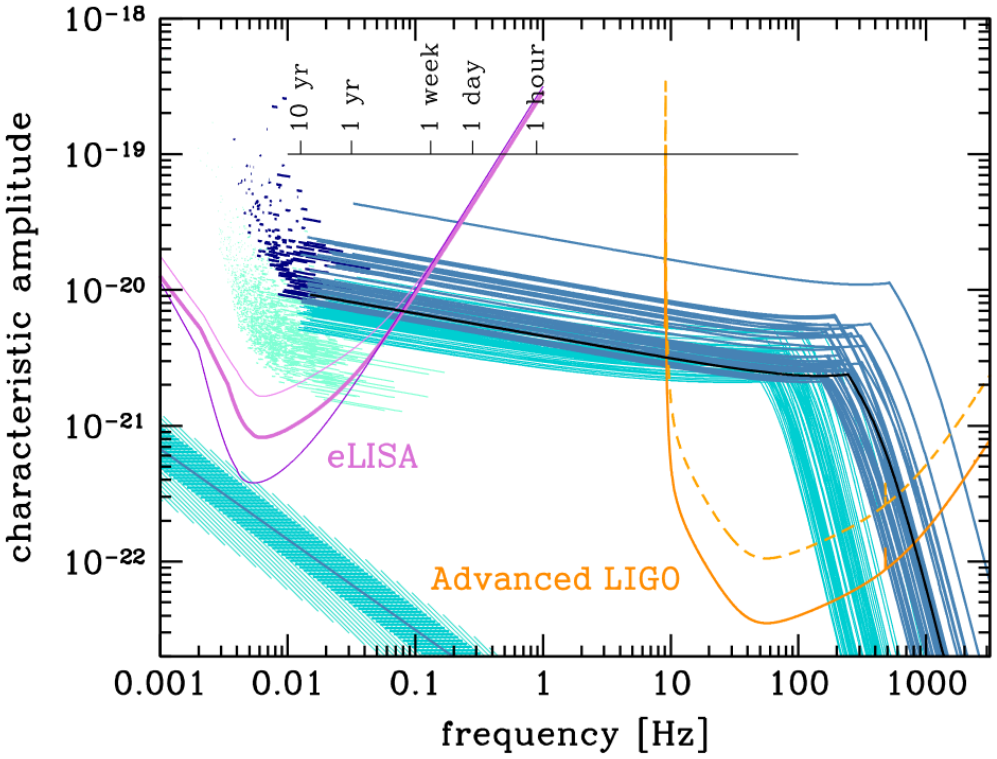


(https://www.aei.mpg.de/lisa)

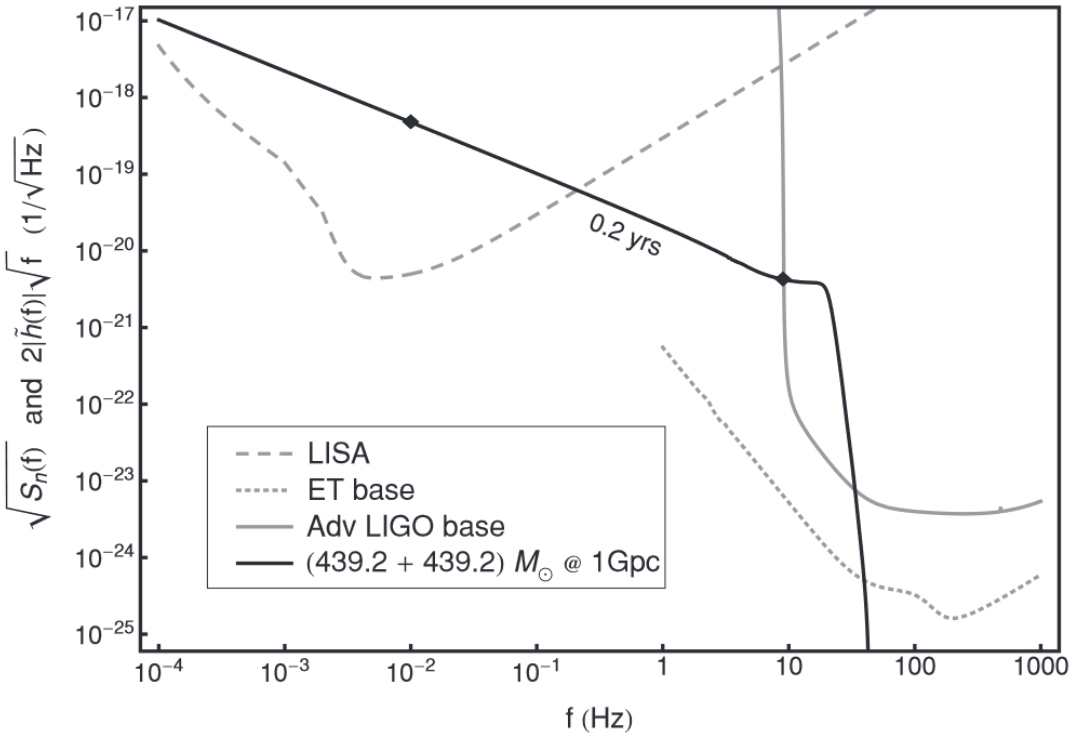
Can we use next-gen ground-based detectors together with space-borne detector(s)?

2 Difficulties in the LISA+3G Multiband Observation

- 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

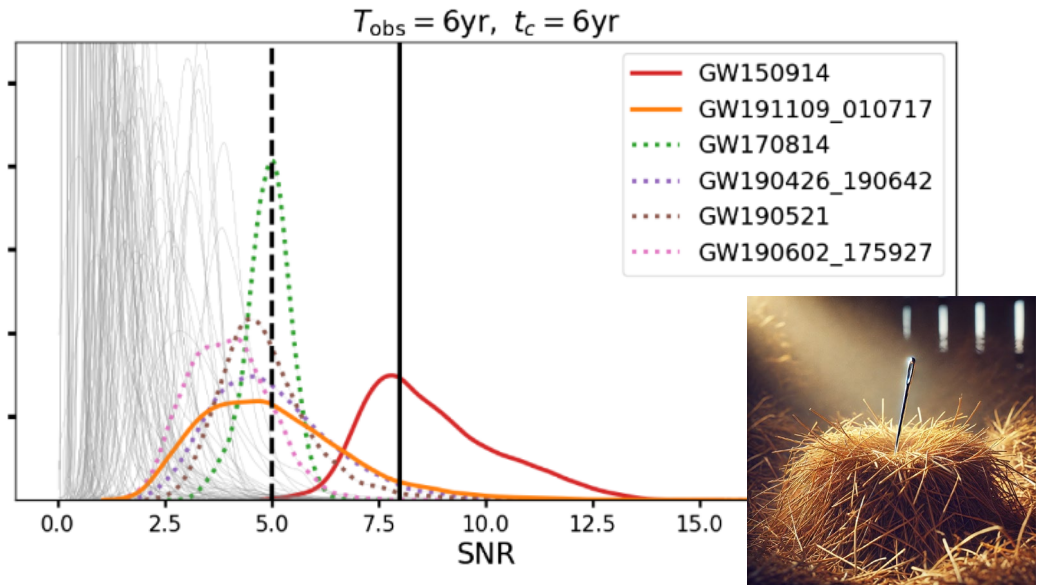
- Fisher Information Matrix

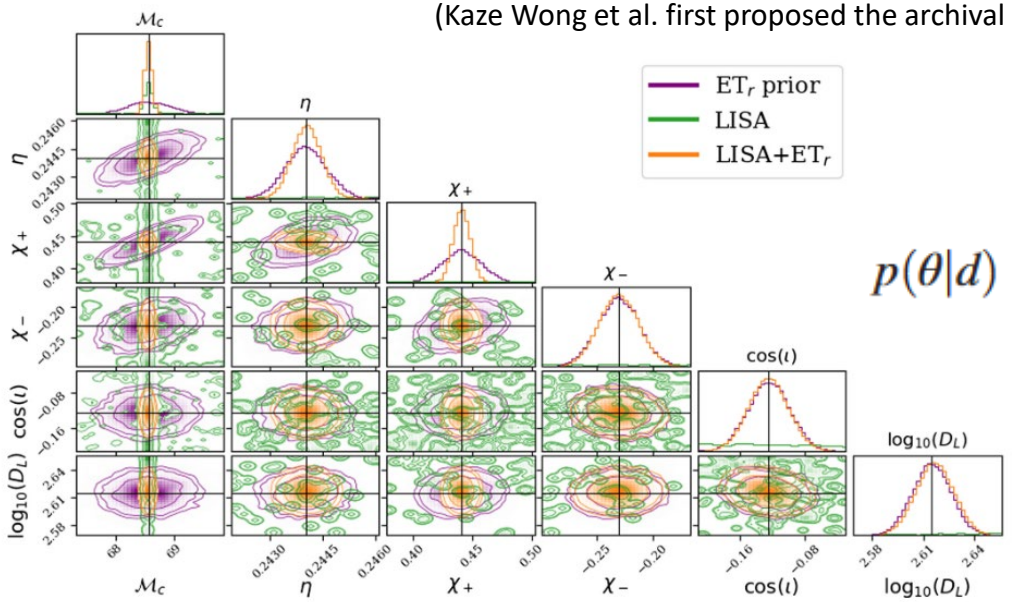
$$\Gamma^{(0)}_{\alpha\beta} = \langle \tilde{h}_\alpha, \tilde{h}_\beta \rangle \qquad \tilde{h}_\alpha = \partial \tilde{h}(f;\vec{\theta})/\partial\vec{\theta}_\alpha \qquad \langle a, b \rangle = 2\int_{f_{\rm low}}^{f_{\rm high}} \frac{a(f)b^*(f) + a^*(f)b(f)}{S_h(f)} df$$

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

- Bayesian Parameter Estimation (archival)

Alexandre Toubiana, et al (2022)
DOI:10.1103/PhysRevD.106.104034
(Kaze Wong et al. first proposed the archival search, but not PE)





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

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

2 / Difficulties in the LISA+3G Multiband Observation

- 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
$T_{\rm elapsed}$		4 yr		5 yr		6 yr	
$T_{\rm data} = 0.75 \times T_{\rm elapsed}$		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)							

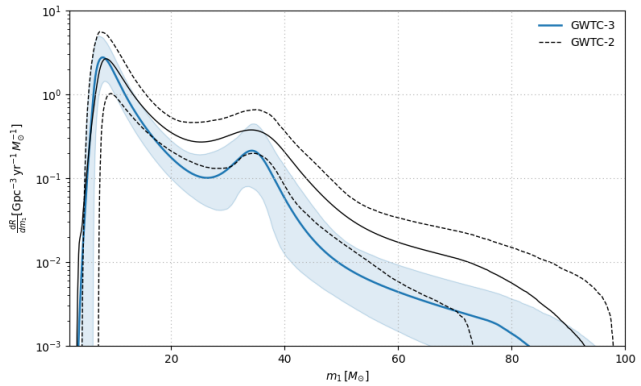
Pau Amaro-Seoane. et al (2021)
DOI:10.1007/s10714-021-02889-x

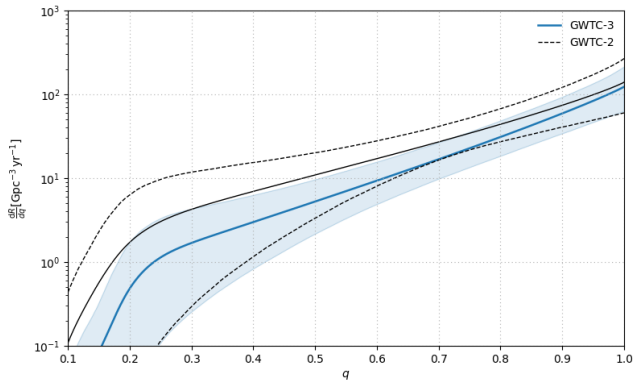
	sBHB type	definition	$\langle N \rangle$	90 % confidence	no sBHB (%)
SI 4.1	detected	SNR > 8	4.9	0.4 – 9.8	2.2
	archival	5 < SNR < 8 & t_c < 15 yr	5.6	0.8 – 10.0	1.4
SI 4.2	massive	SNR > 8 & $m_1 > 50\,M_\odot$	1.3	0 – 3.6	34.1
SI 4.3	multiband	SNR > 8 & t_c < 15 yr	1.5	0 – 3.8	26.7
		SNR > 8 & t_c 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

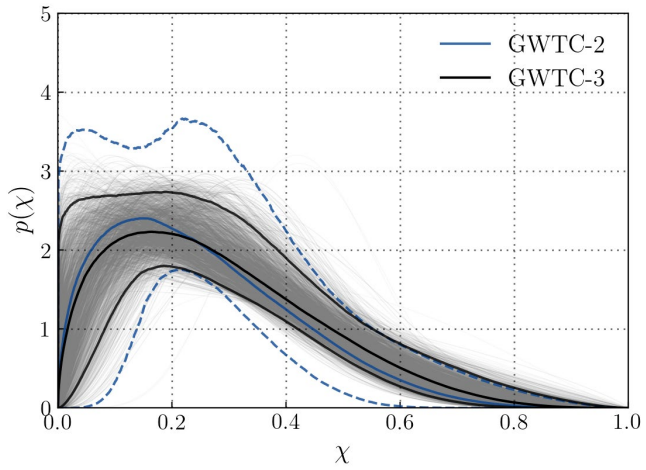
LISA Definition Study Report - ESA-SCI-DIR-RP-002 (2024)
DOI: 10.48550/arXiv.2402.07571

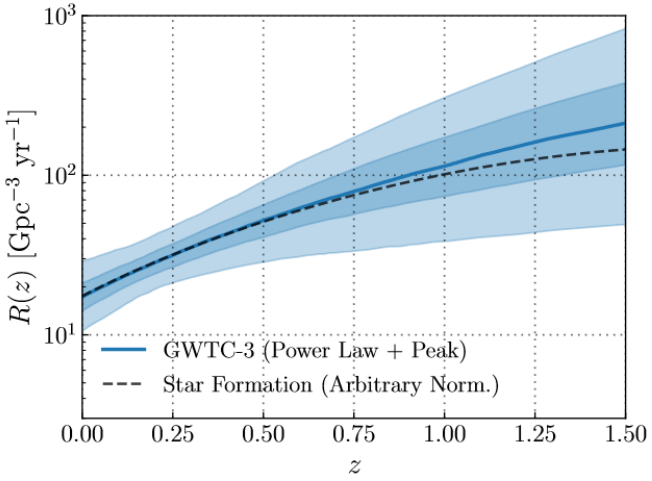
2 Difficulties in the LISA+3G Multiband Observation

- The Population Models: mass and spin distributions from GWTC-3









power-law+peak model: primary BH in BBH

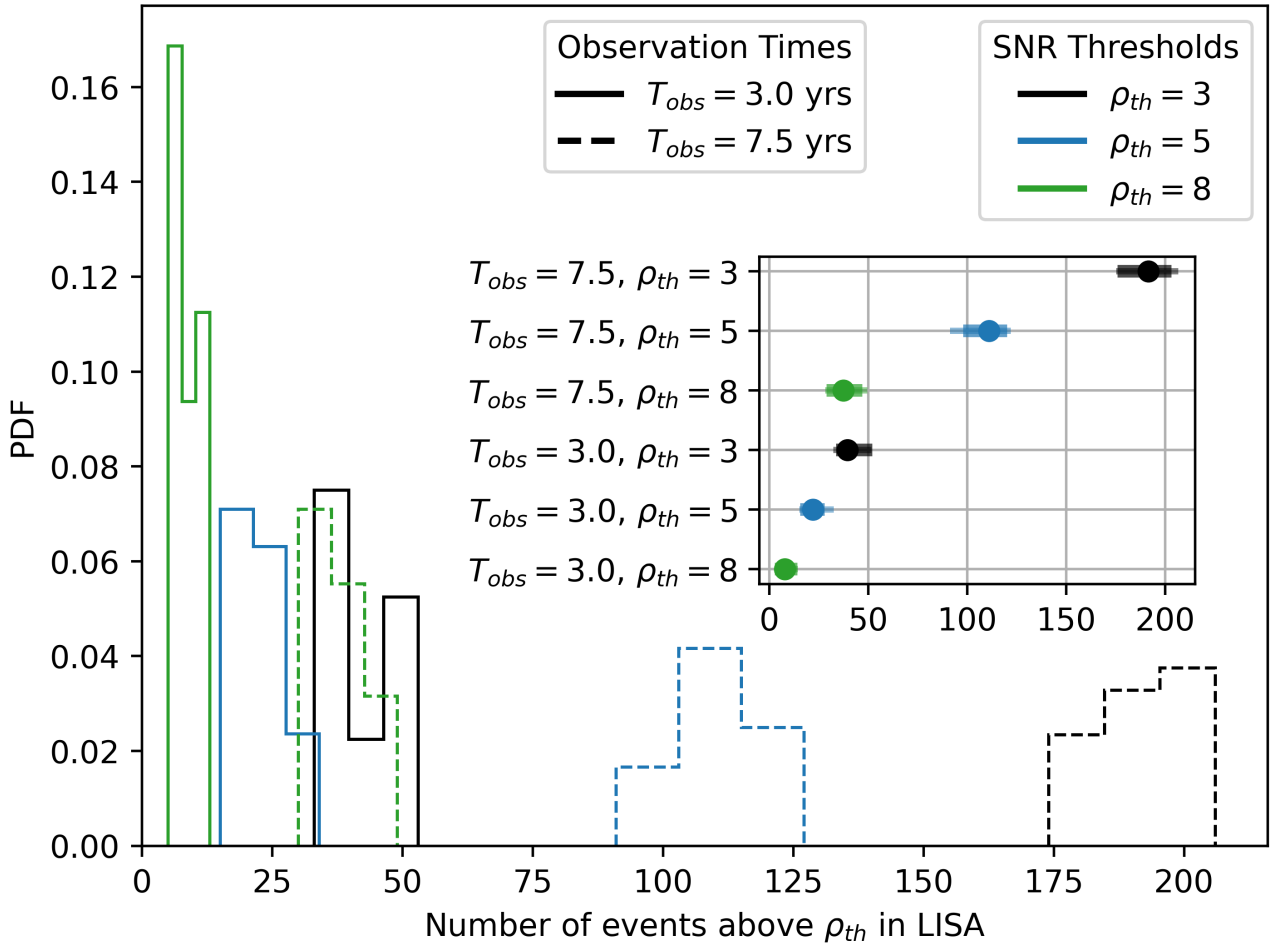
	median
BBH:	$22\ \mathrm{Gpc^{-3}yr^{-1}}$

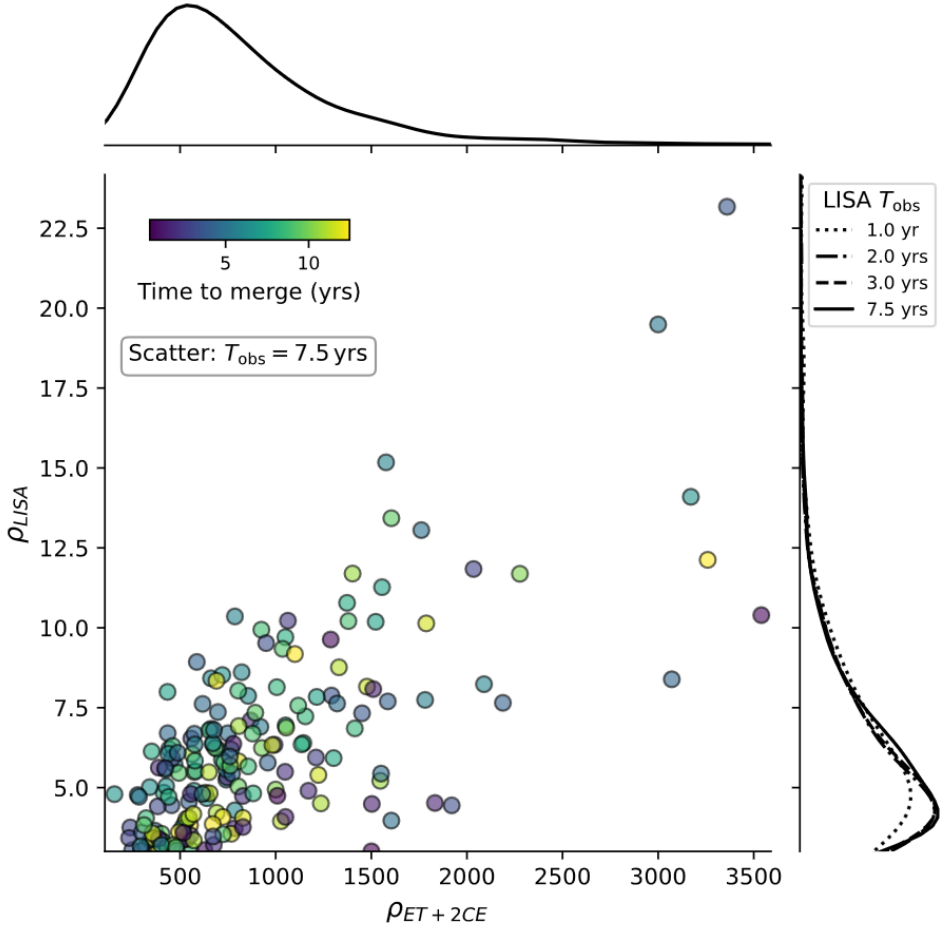
Using the GWTC-3 population model, we generate several data sets for LISA+ET+2CE observations for different LISA mission durations, assuming a LISA duty cycle of 0.75.

(DOI: 10.1103/PhysRevX.13.011048)

2/ Difficulties in the LISA+3G Multiband Observation

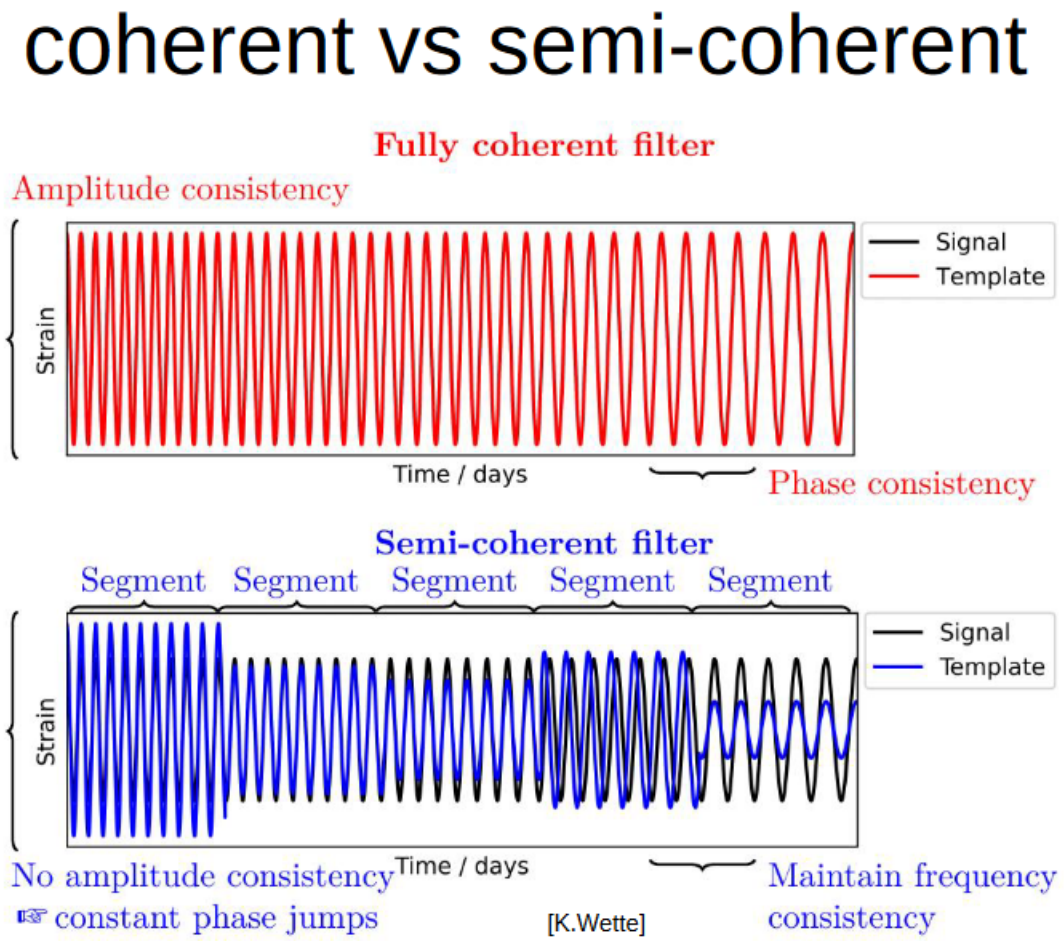
- Most of SOBHBs will sub-threshold.





3 / Coherent Multiband Parameter Estimation using PyCBC

- 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.

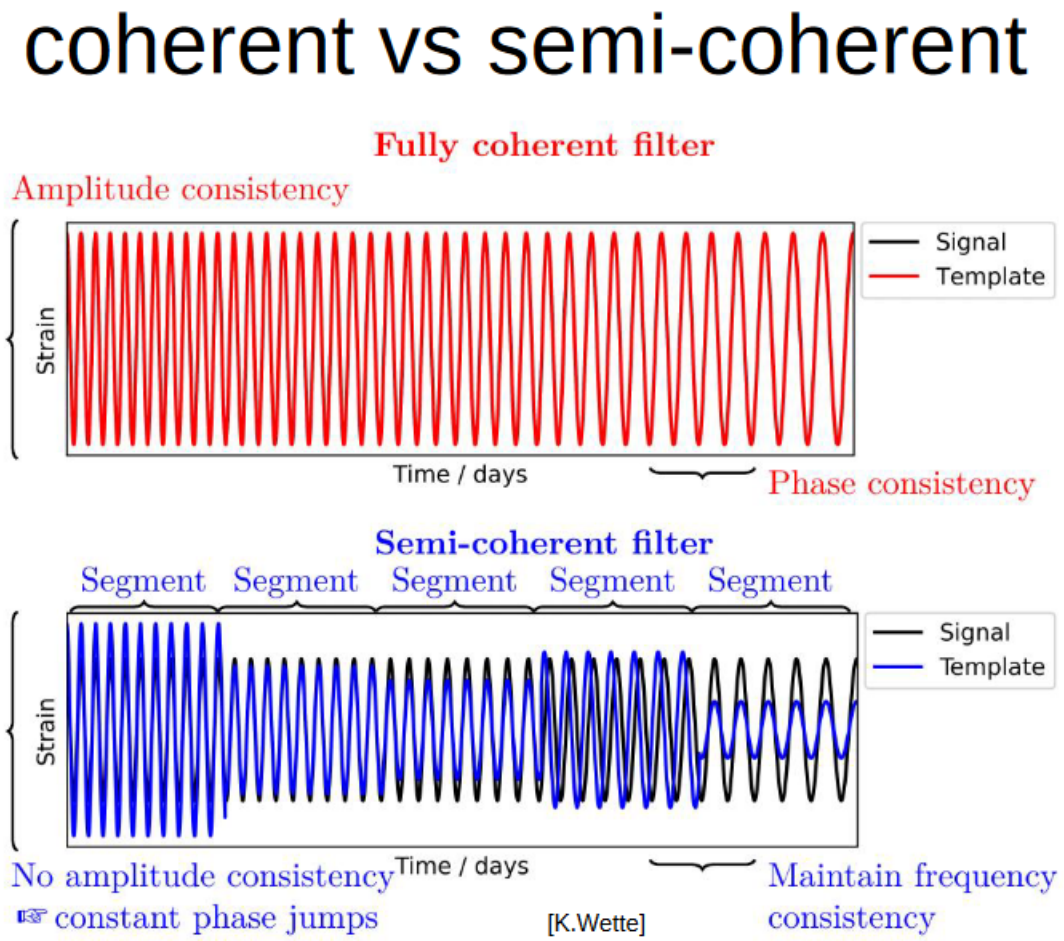
Semi-coherent multiband PE (3G posterior as LISA prior):

- 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)

3 / Coherent Multiband Parameter Estimation using PyCBC

- Can we combine the data from LISA and 3G coherently?



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

Coherent multiband PE:

1. (tc, sky position, psi) are frame-dependent: LISA/SSB frame -> GEO frame
2. amplitude/phase consistency: for each multiband likelihood call, update the LISA/3G waveforms consistently
3. make parameter space simpler: multiband marginalization using importance sampling

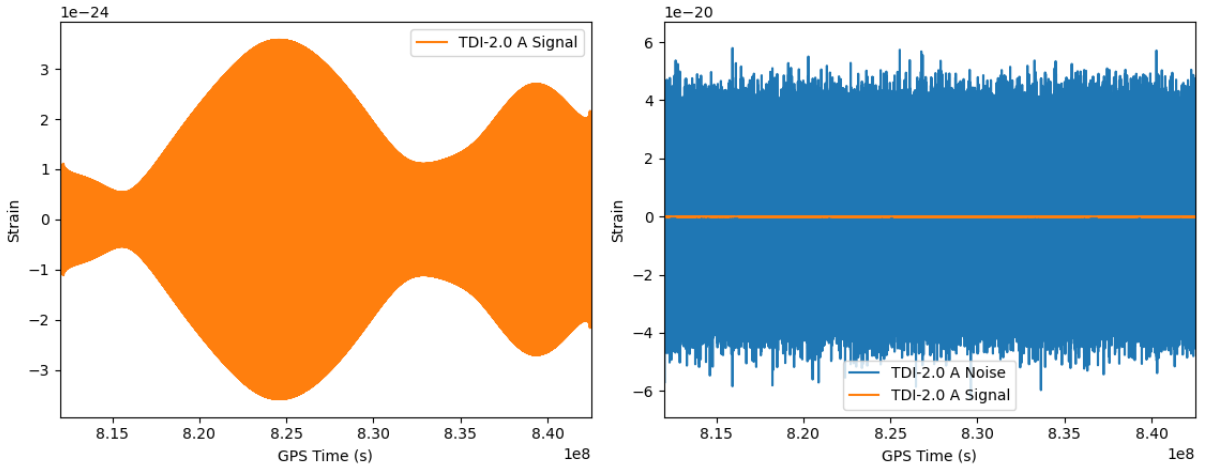
(check all the technical details in our upcoming paper)

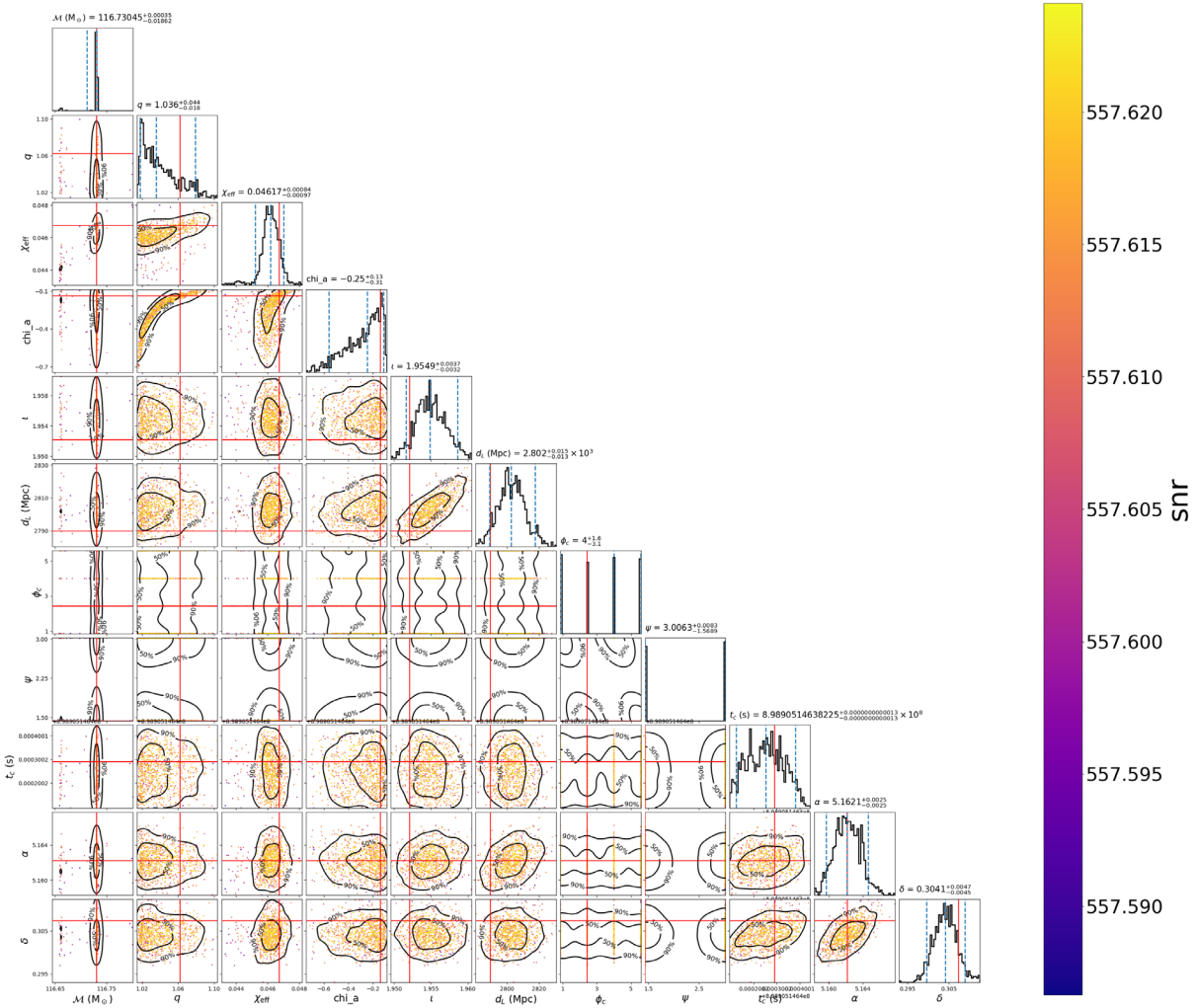
3 Coherent Multiband Parameter Estimation using PyCBC

- A low-SNR example:

```
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
```

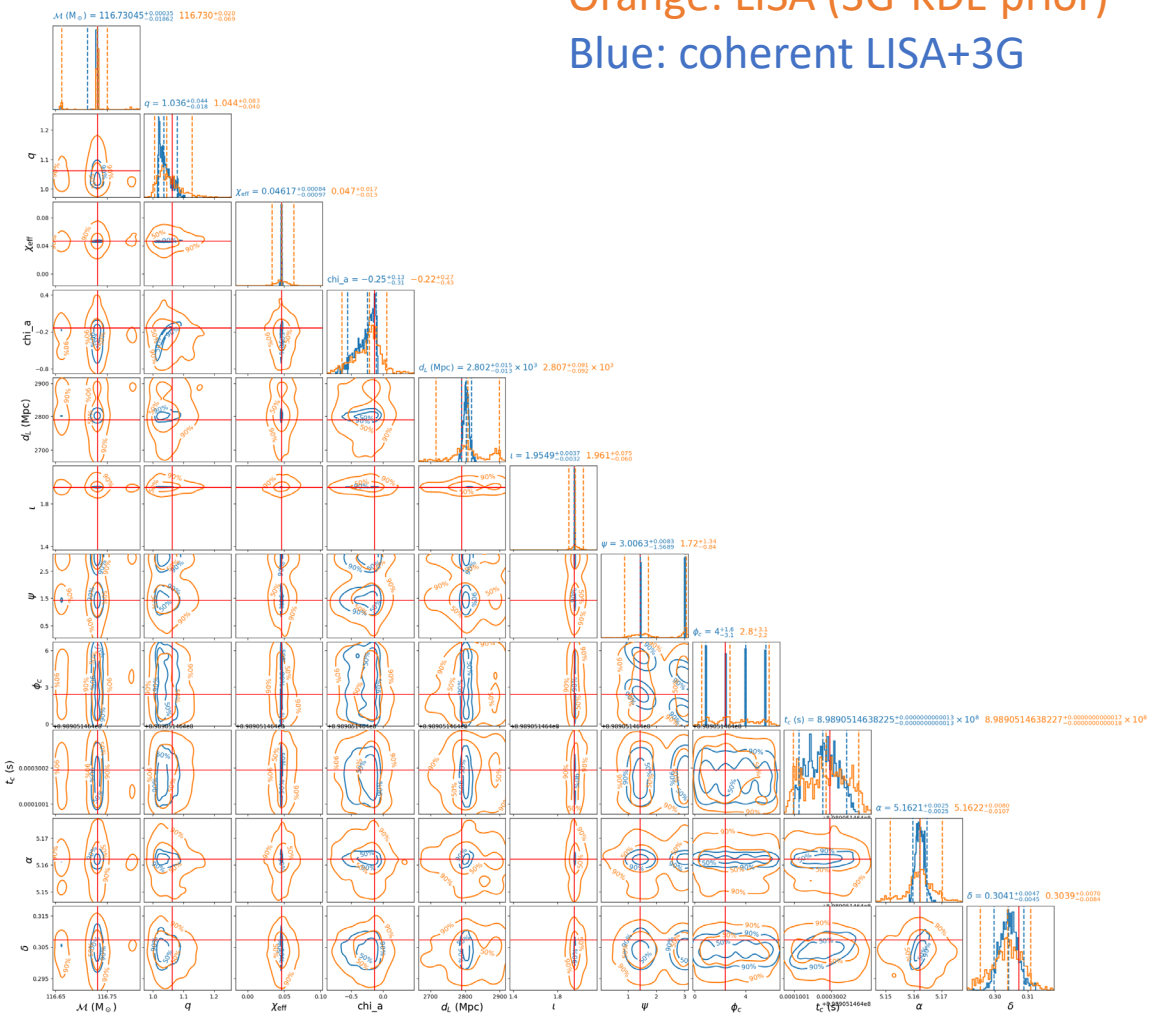
SNR in LISA: 3.07
SNR in 3G network: 558.47
SNR in LISA+3G network: 558.48



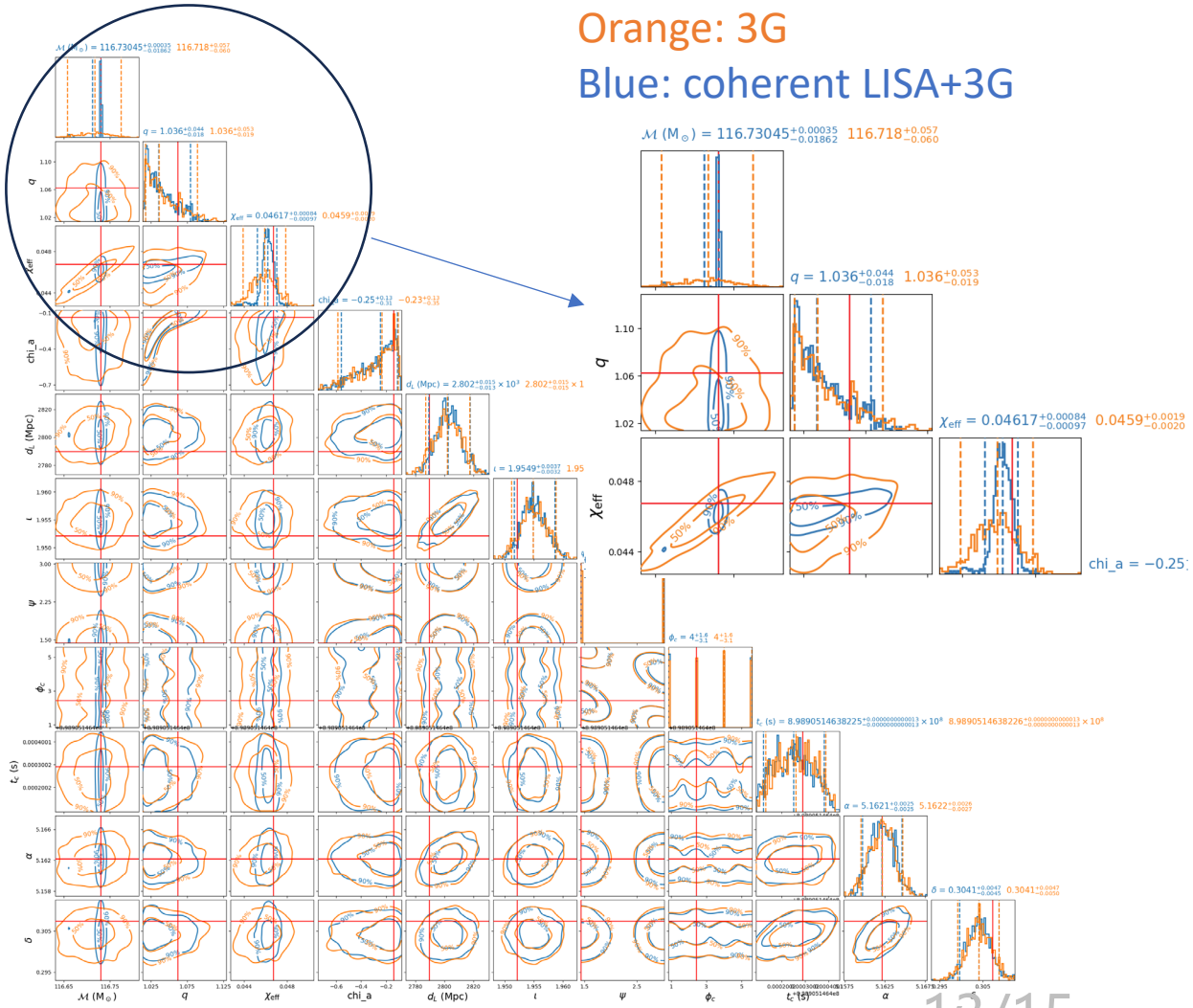


3 Coherent Multiband Parameter Estimation using PyCBC

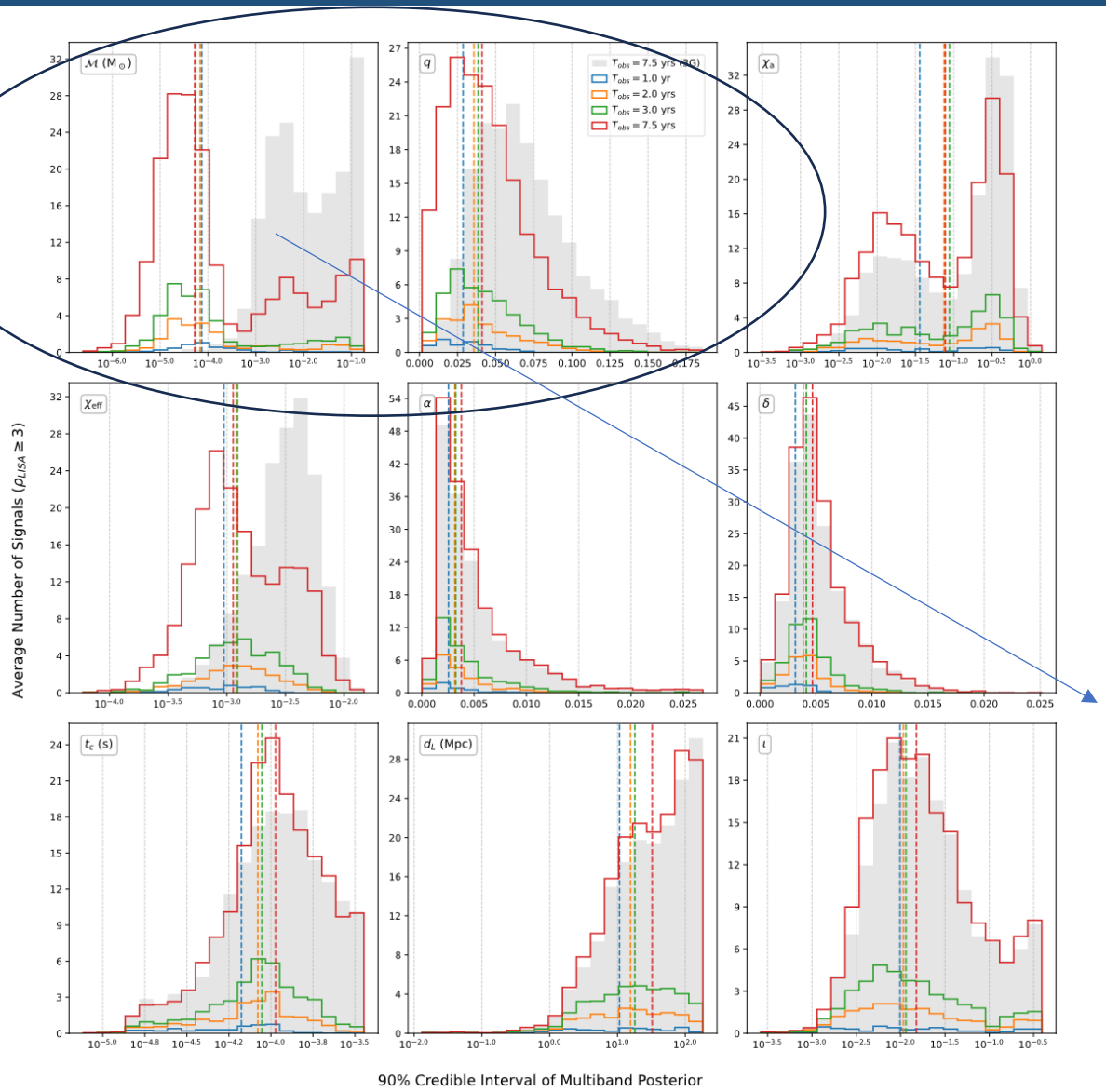
Orange: LISA (3G-KDE prior)
Blue: coherent LISA+3G



Orange: 3G
Blue: coherent LISA+3G

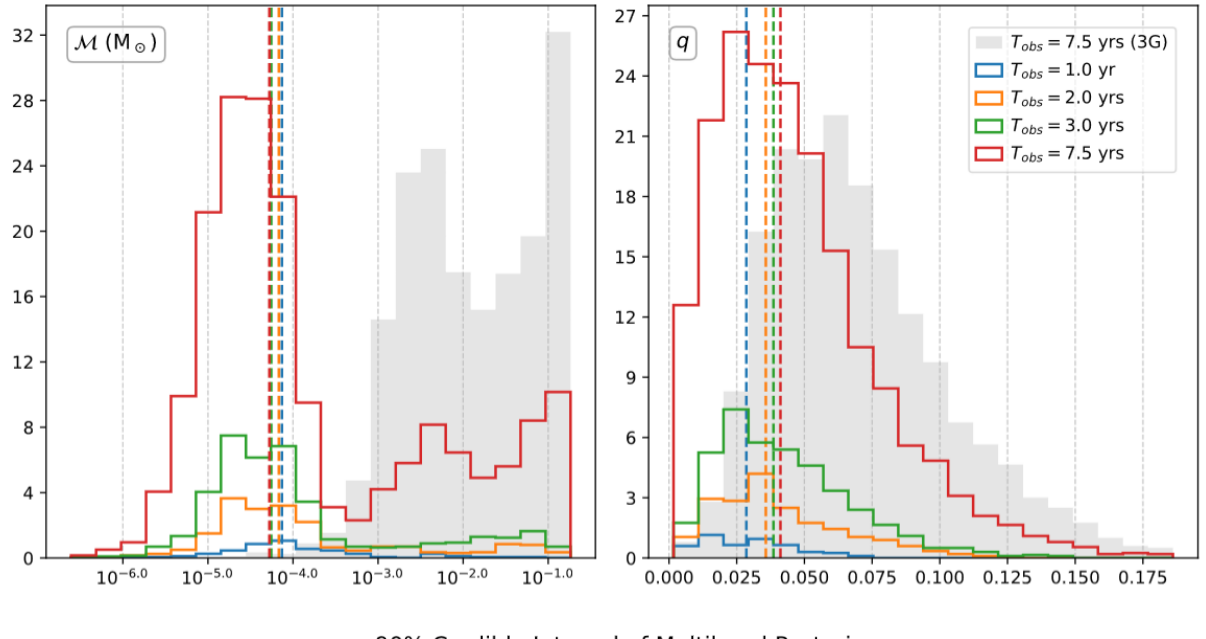


3 Coherent Multiband Parameter Estimation using PyCBC



The 1st multiband Bayesian parameter estimation on population-scale:

- Even if LISA observes for 1 year, the detector-frame chirp mass's 90% CI is still better than that of the golden events for 3G in 7.5 years of observation.



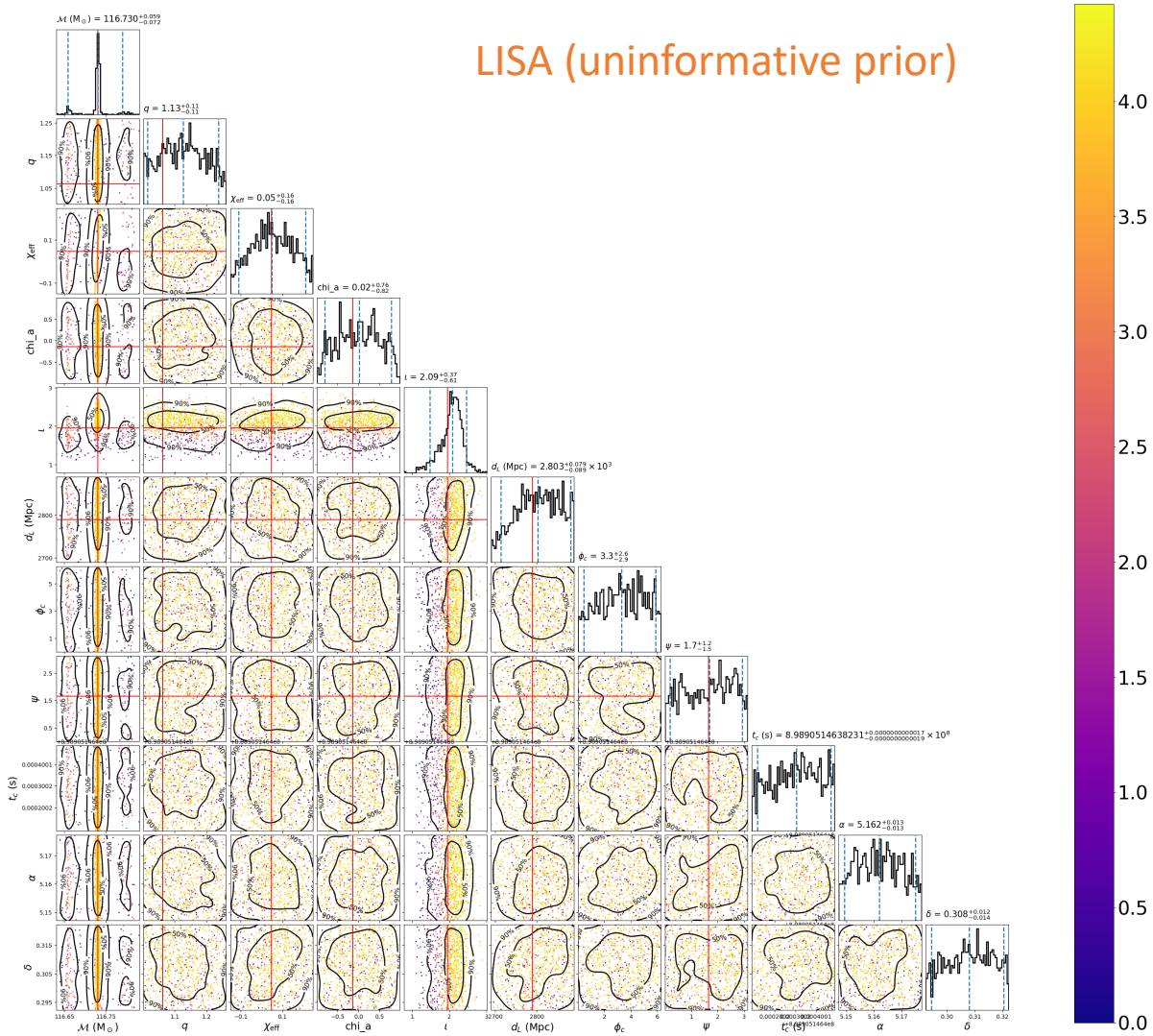
4 / Conclusions

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!
4. For the first time, we can run Bayesian multiband PE on population-scale.

Stay tuned for our paper this month!

5 / Backup

LISA (uninformative prior)



LISA (3G-KDE prior)