Calibration, Data Quality and Vetos: Now and the upcoming challenges

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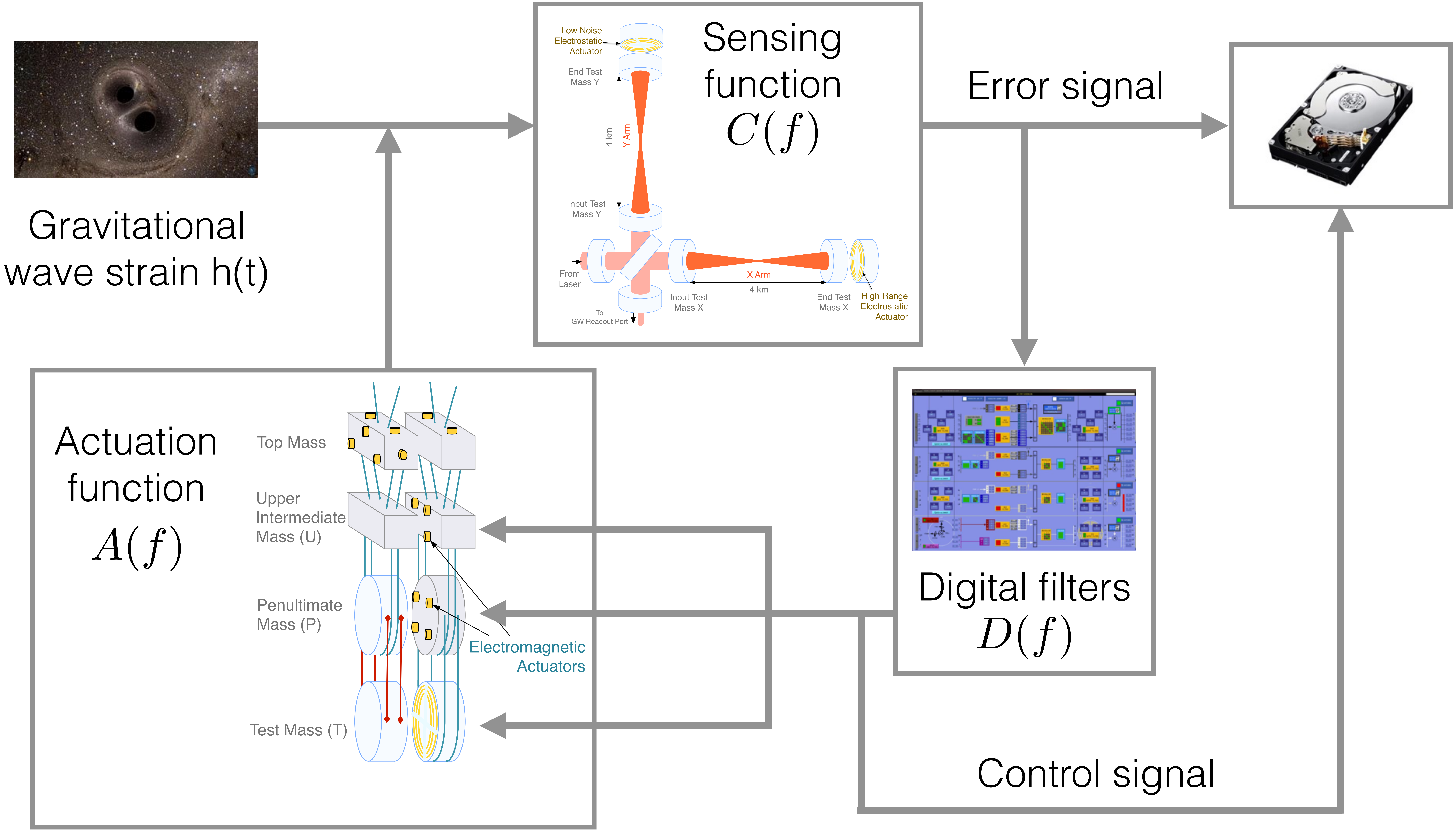
Thanks to...

- Jeff Kissel
- Maddie Wade
- Craig Cahillane
- Chris Biwer
- Ben Lackey
- Daniel Finstad
- and the LIGO calibration group...
- Jessica McIver
- Andrew Lundgren
- TJ Massinger
- Laura Nuttall
- and the LSC/Virgo DetChar group...

Calibration

- The goal is gravitational-wave physics and astronomy
- Calibration is the process by which we convert the detector output into a measured gravitational-wave strain that encodes the astrophysics
- The accuracy of the calibration and our knowledge of its uncertainty affects our ability to do precision astrophysics
- Problem is to get $L_{DARM} = L_x - L_y$ measured in meters from digitized photodetector signal in (arbitrary) counts



Gravitational wave strain h(t)
Low Noise Electrostatic Actuator
End Test Mass Y
4 km
Y Arm
Input Test Mass Y
From Laser
To GW Readout Port
Input Test Mass X
X Arm
4 km
End Test Mass X
High Range Electrostatic Actuator
Sensing function $C(f)$
Error signal
Actuation function $A(f)$
Top Mass
Upper Intermediate Mass (U)
Penultimate Mass (P)
Test Mass (T)
Electromagnetic Actuators
Digital filters $D(f)$
Control signal

In principle...

$$G(f) = C(f)D(f)A(f)$$

$$R^{-1}(f) = \frac{1 + G(f)}{C(f)}$$

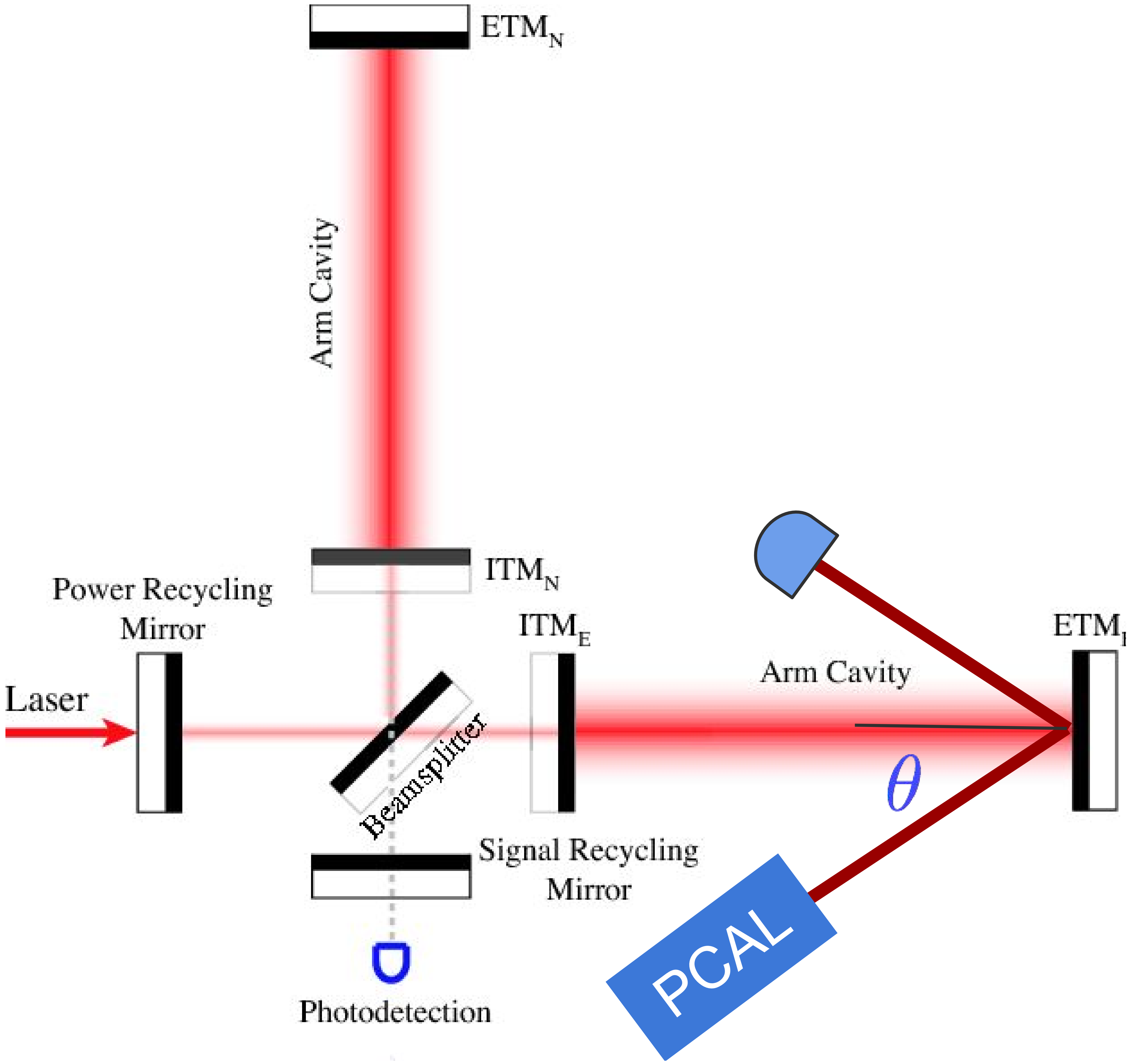
$$\tilde{h}(f) = \frac{1}{L}\ R^{-1}(f)\ d_{\mathrm{error}}(f)$$

Siemens et al. CQG **21** S1723 (2014)

Kissel's Seven Rules of Calibration

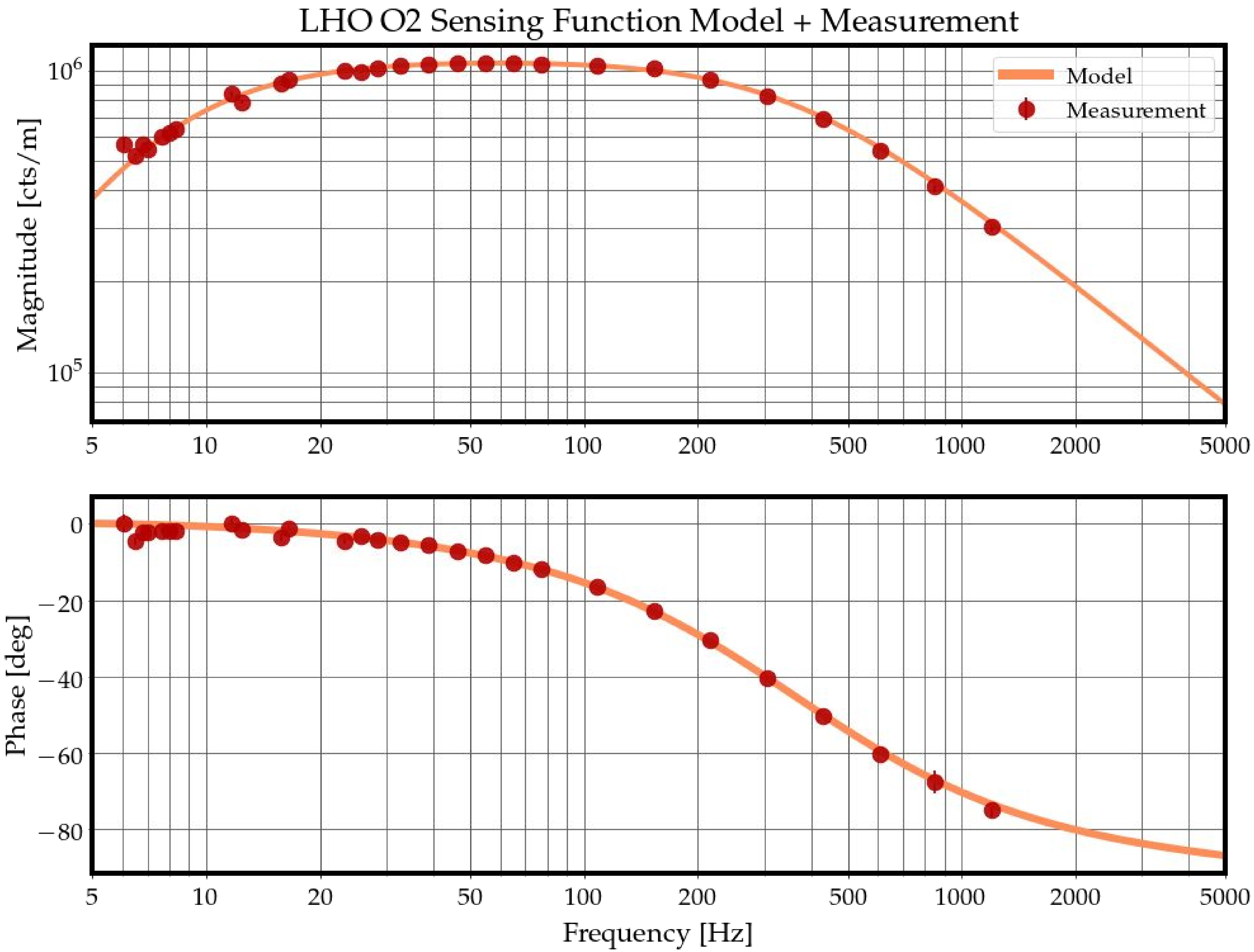
- Your detector response will be more complicated than you want it to be
- You will need to invert the response
- The response will be time dependent
- You will be fighting your awesome isolators trying to calibrate
- Your reference will not be perfect
- Your calibration will change between runs (and during runs)
- Achieving 1%/1 deg accuracy will be a bookkeeping nightmare

- LIGO calibration is performed using the photon calibrator laser
- Push on one test mass with very well calibrated 2W laser (~0.8%)
- Push on one mirror to simulate an incident gravitational-wave signal
- The photodetector readout allows us to convert from meters to counts



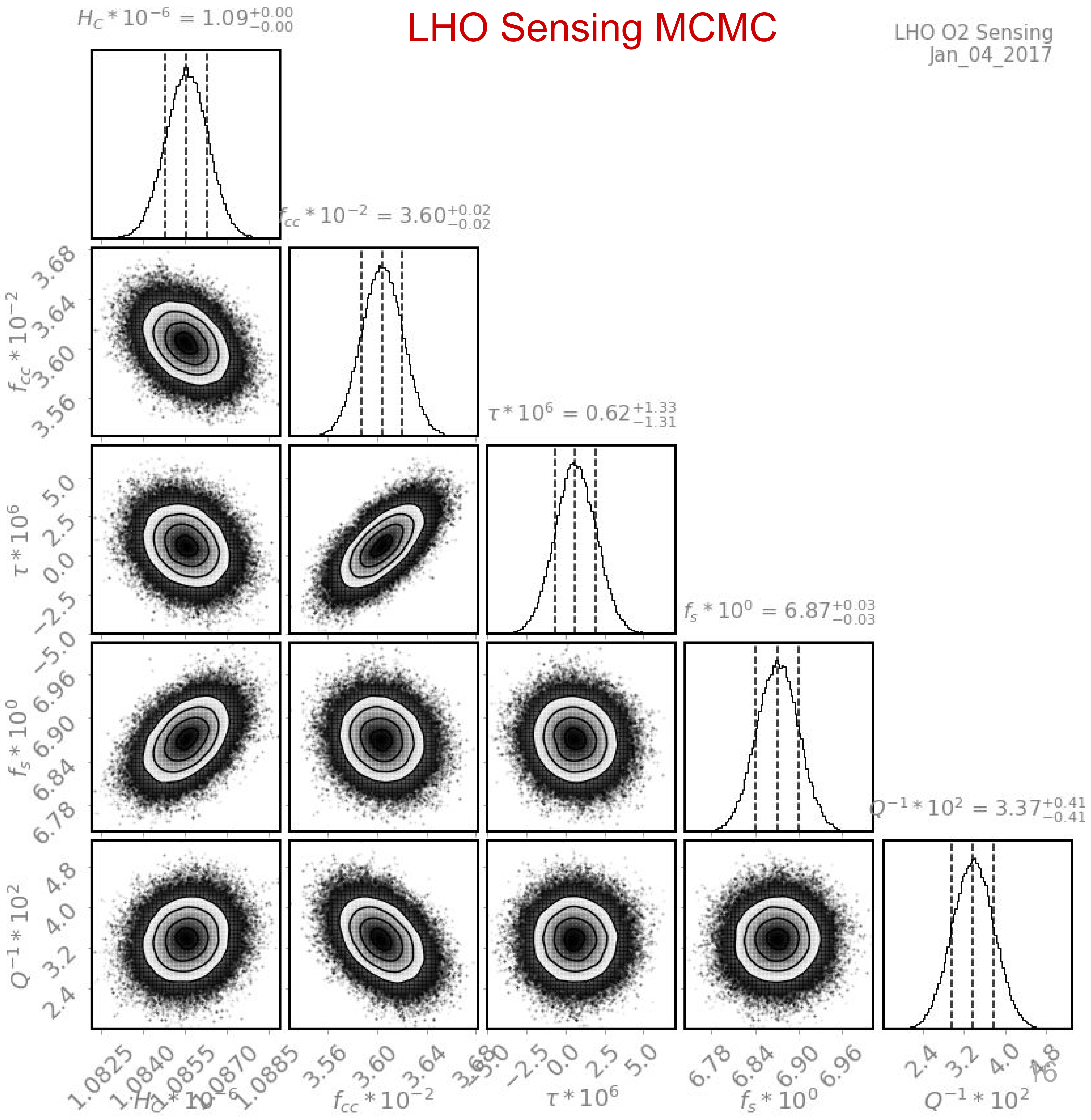
Karki et al. Review of Scientific Instruments **87**, 114503 (2016)

- Sensing function C(f) is well modeled
  - Buonanno and Chen (2001)
    Ward (2010)
    Hall (2017)
- Use Markov Chain Monte Carlo to fit model parameters to measurement
- Similar technique for actuation function A(f)



Cahillane et al. (in prep)

LHO Sensing MCMC



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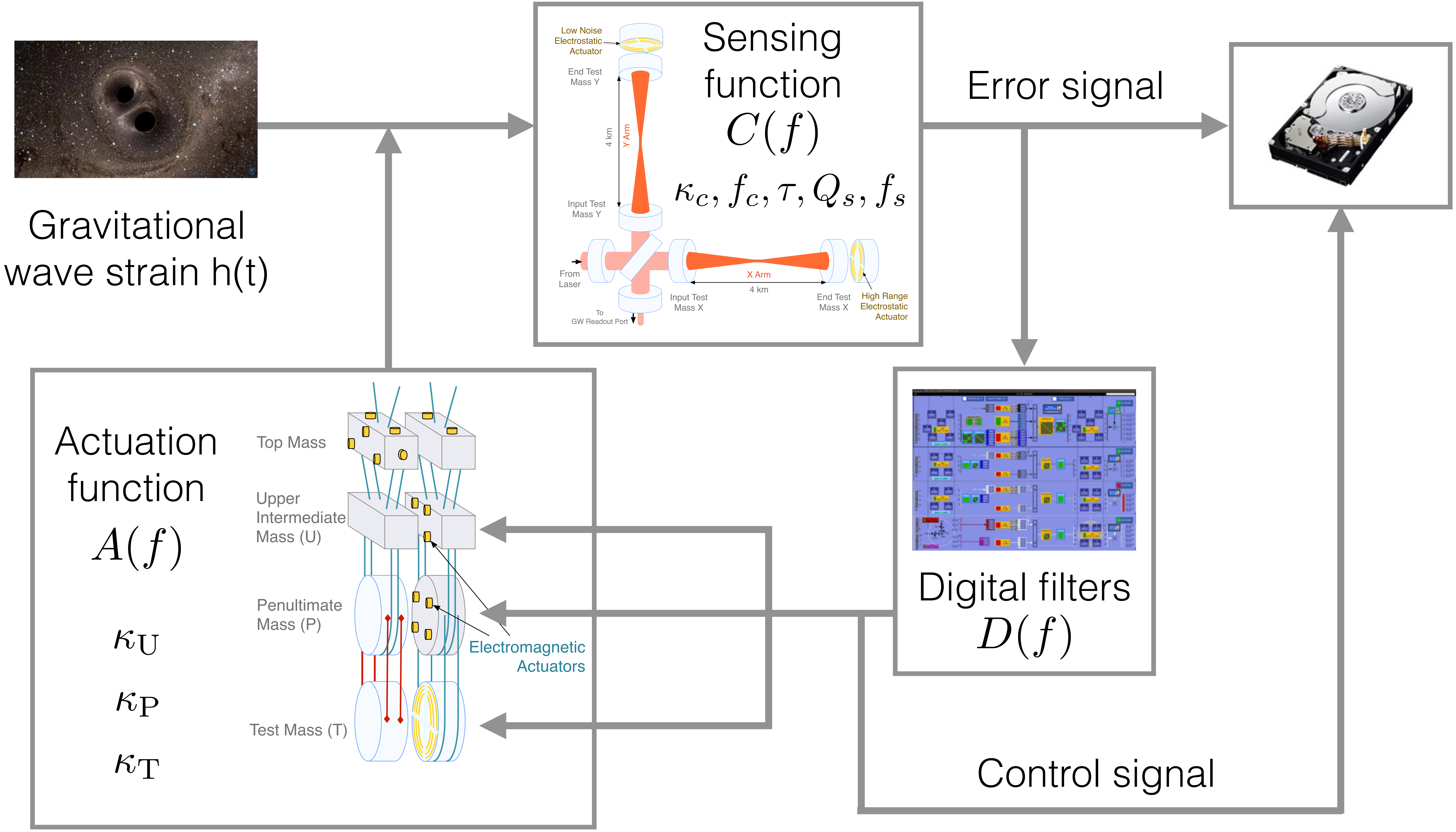

Gravitational wave strain h(t)
Sensing function
$C(f)$
$\kappa_C, f_C, \tau, Q_s, f_s$
Low Noise Electrostatic Actuator
End Test Mass Y
4 km
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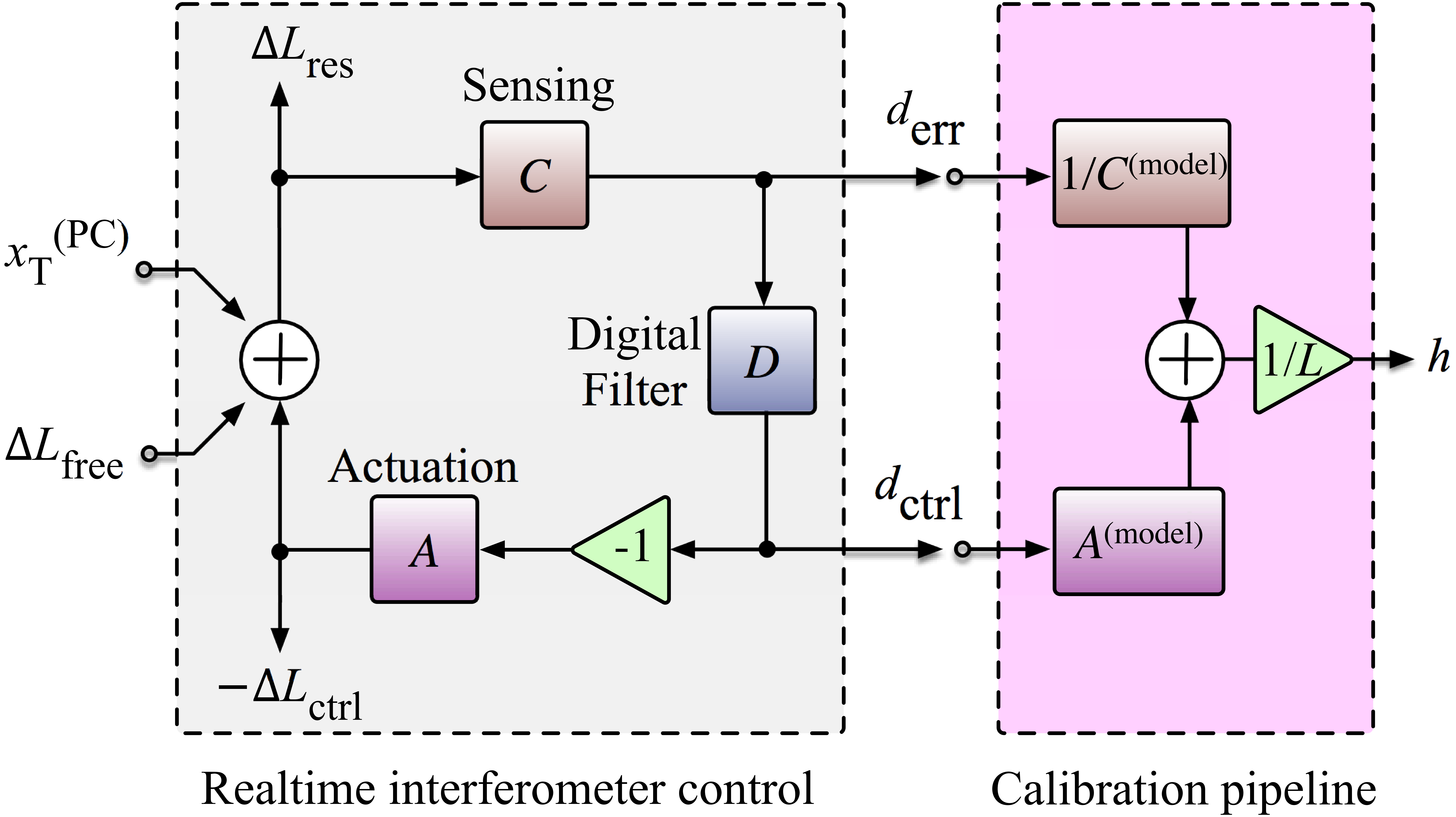
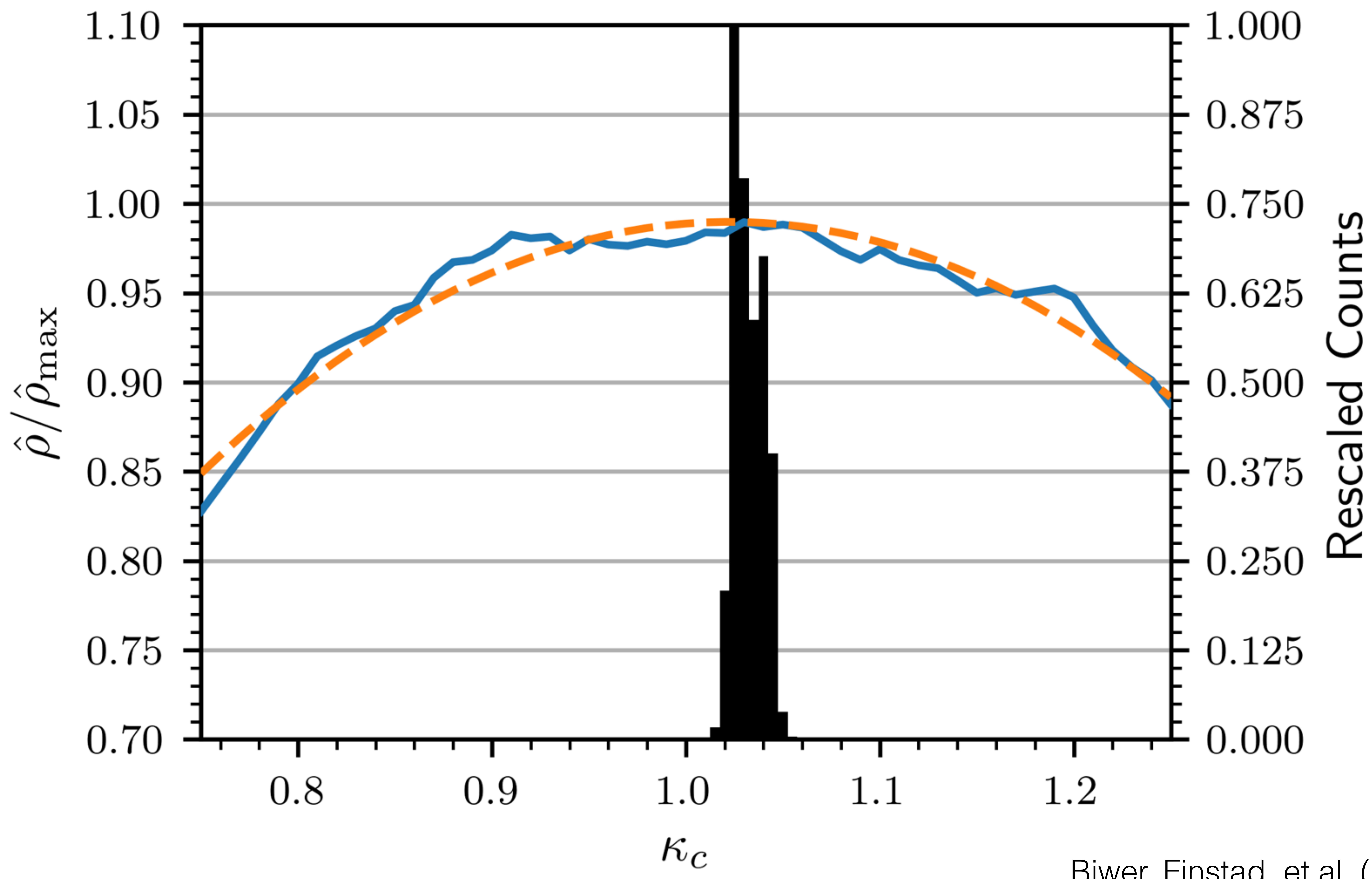
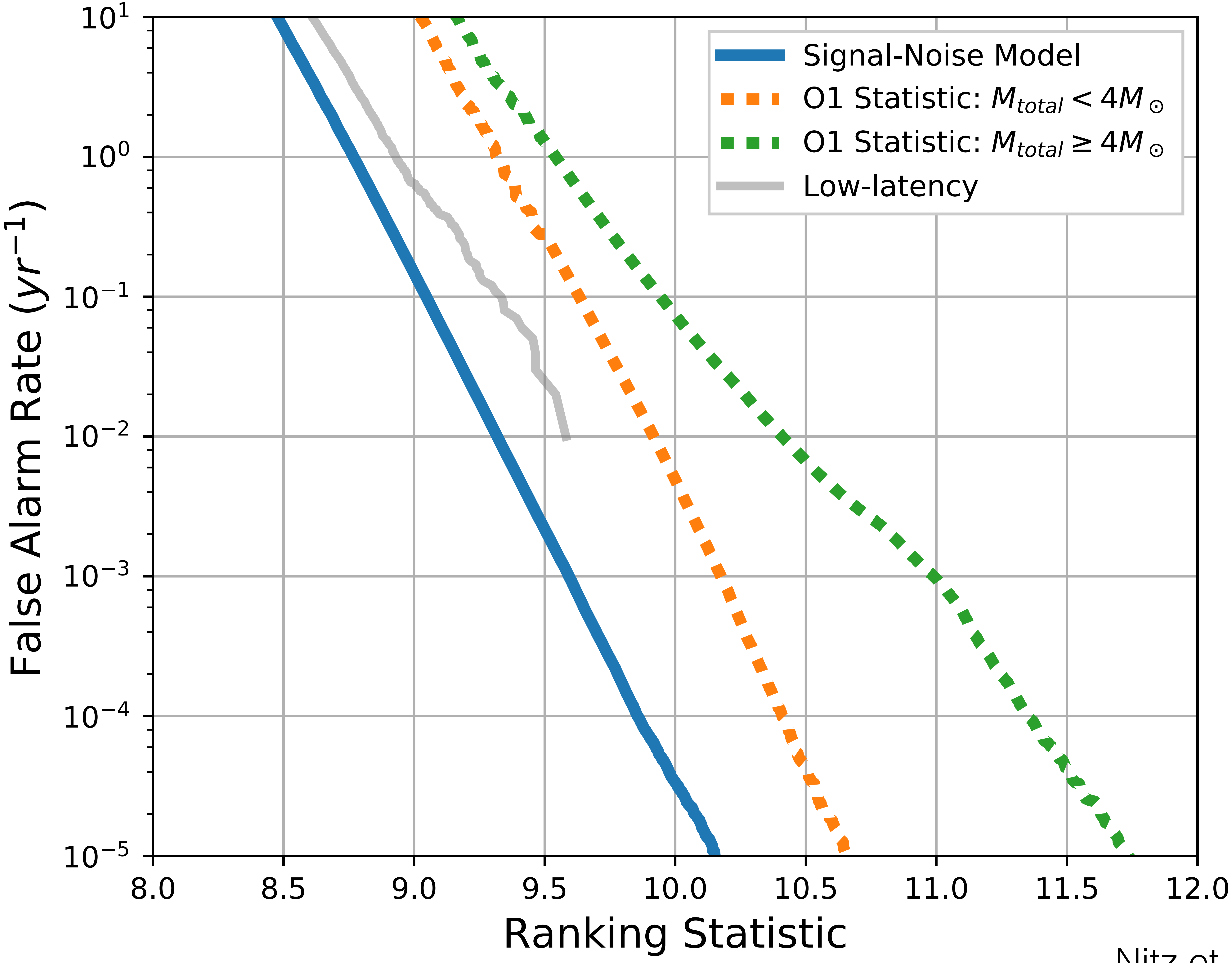


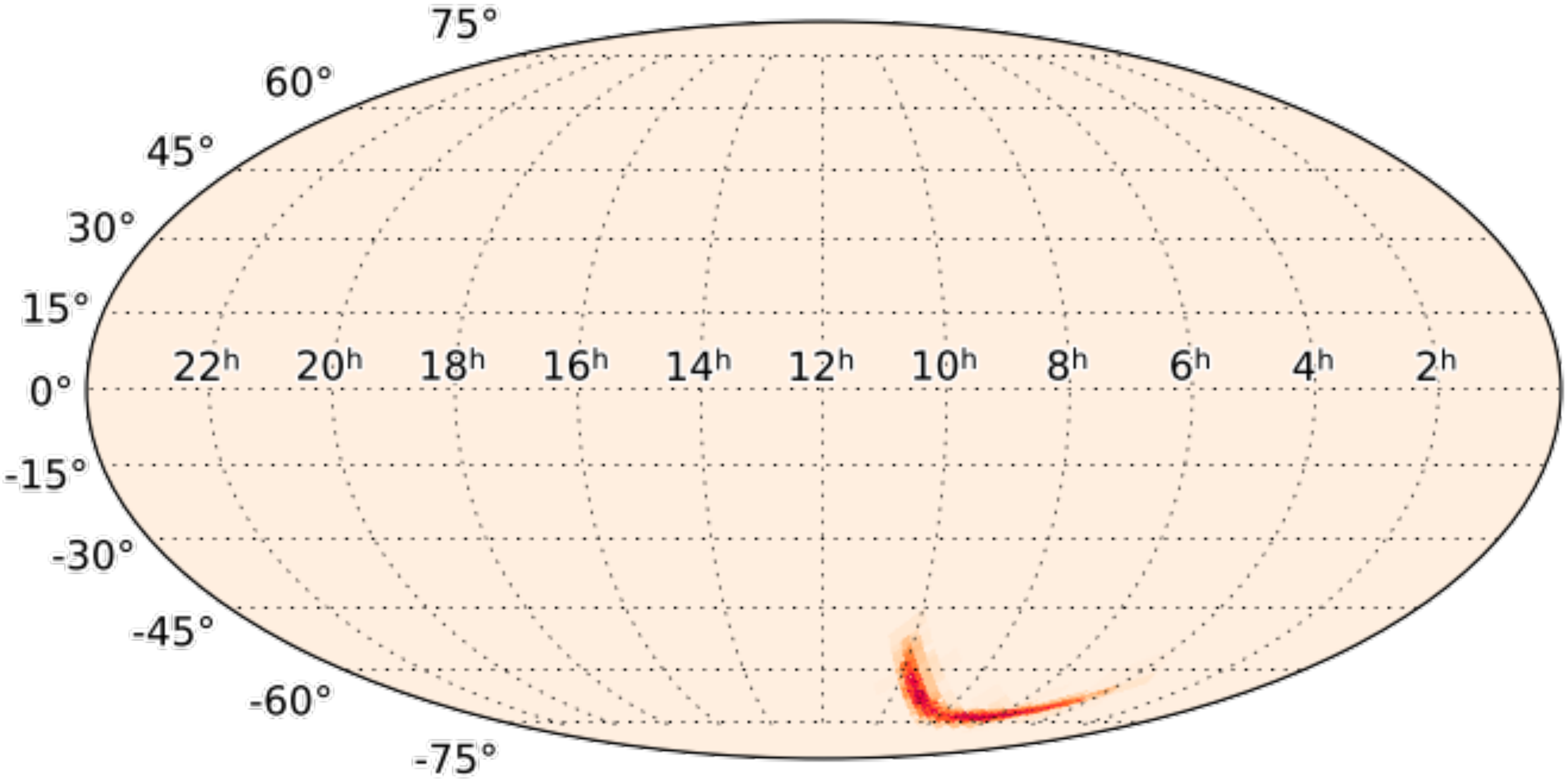
Abbott et al. PRD **95** 062003 (2017)



Biwer, Finstad, et al. (in prep)



Nitz et al. arXiv:1705.01513



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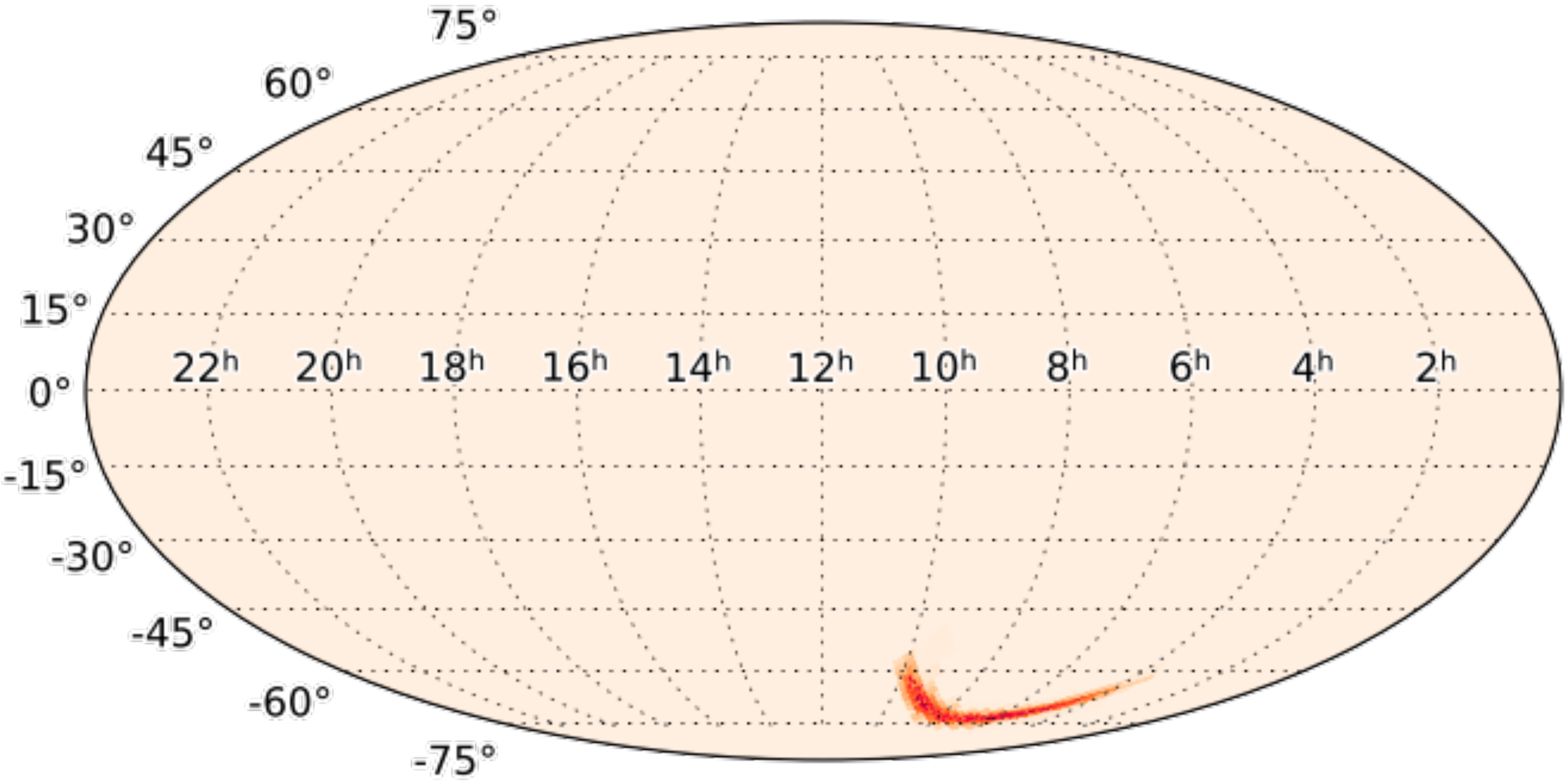

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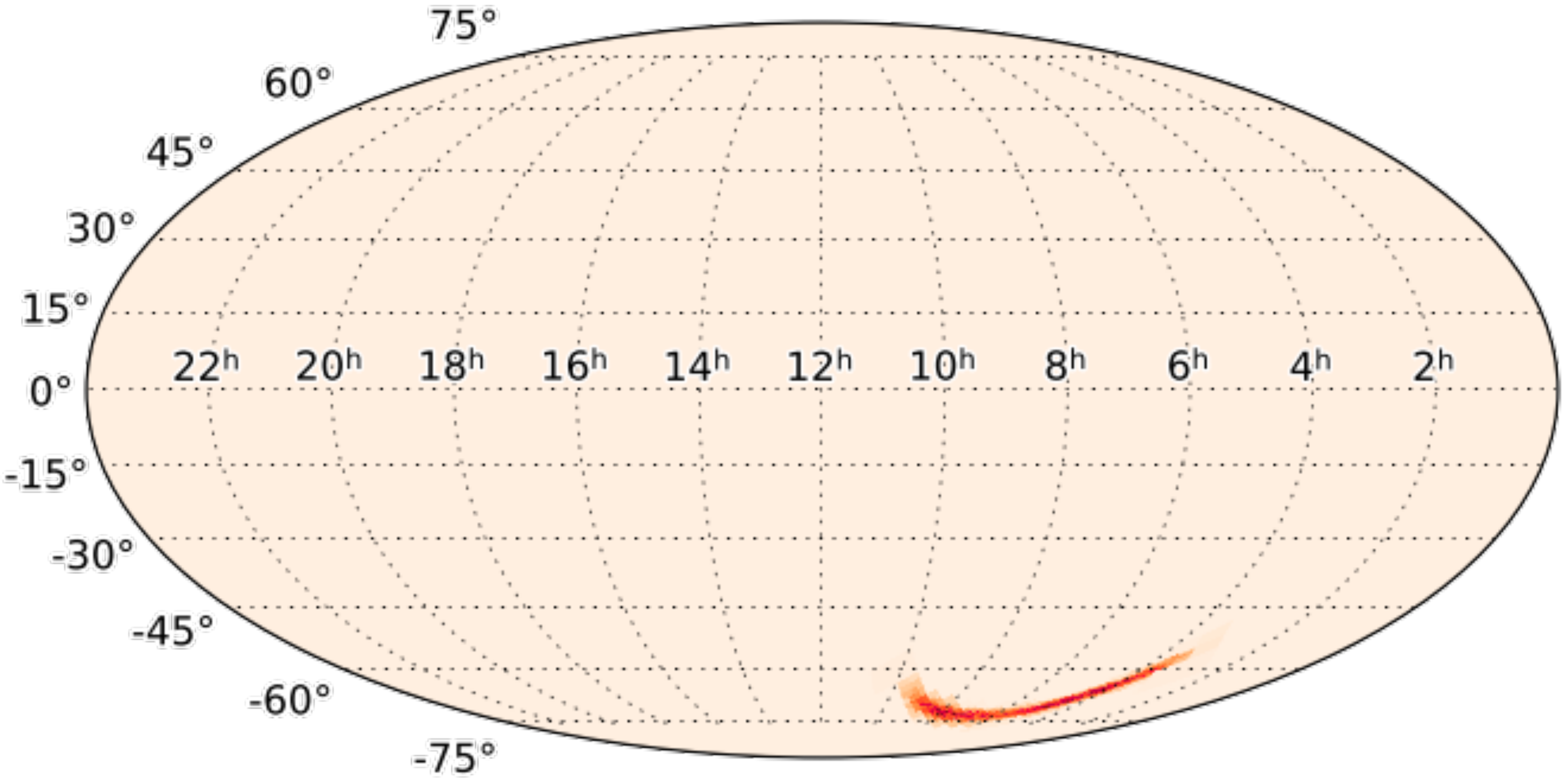

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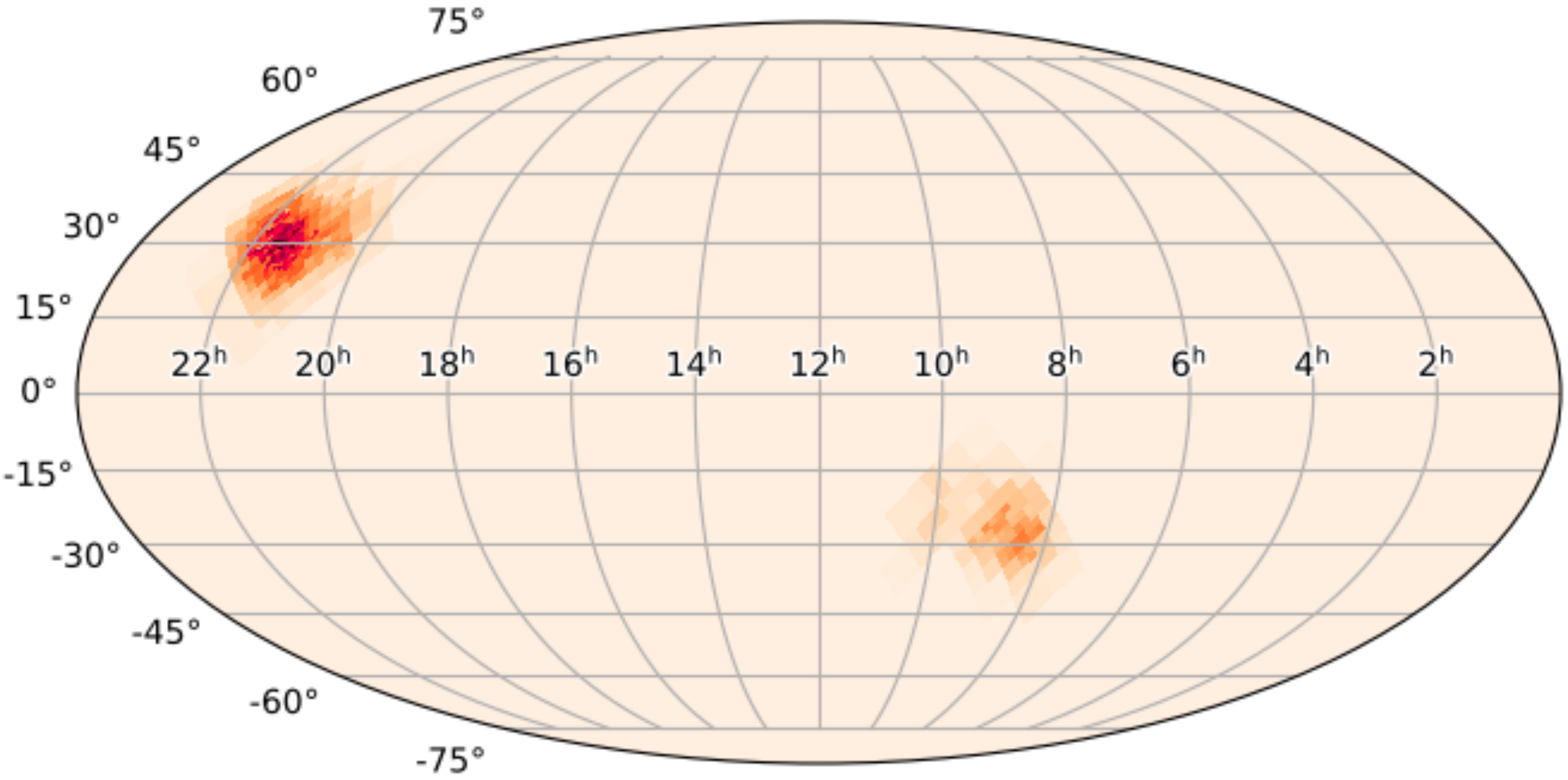
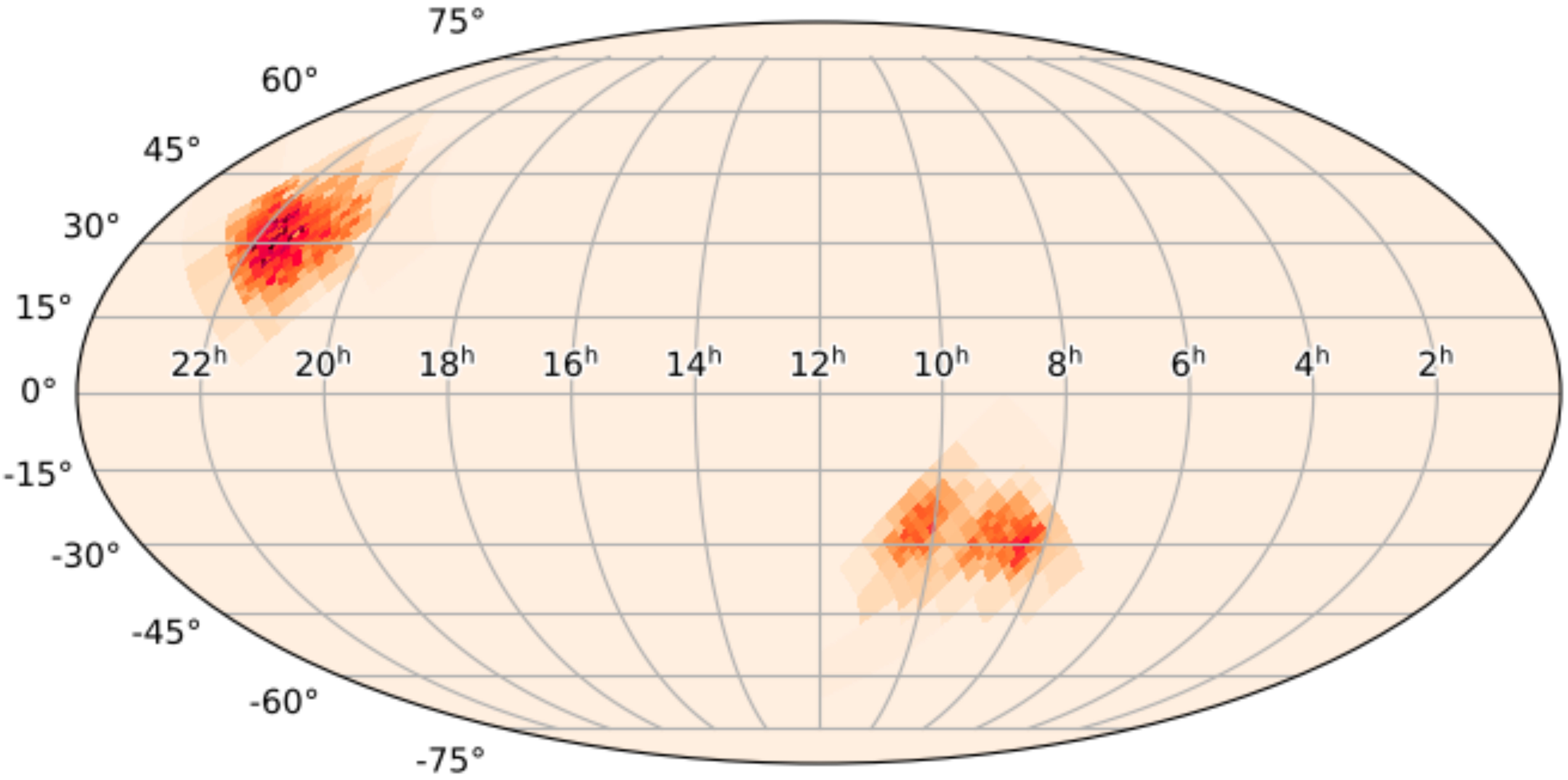


Preliminary



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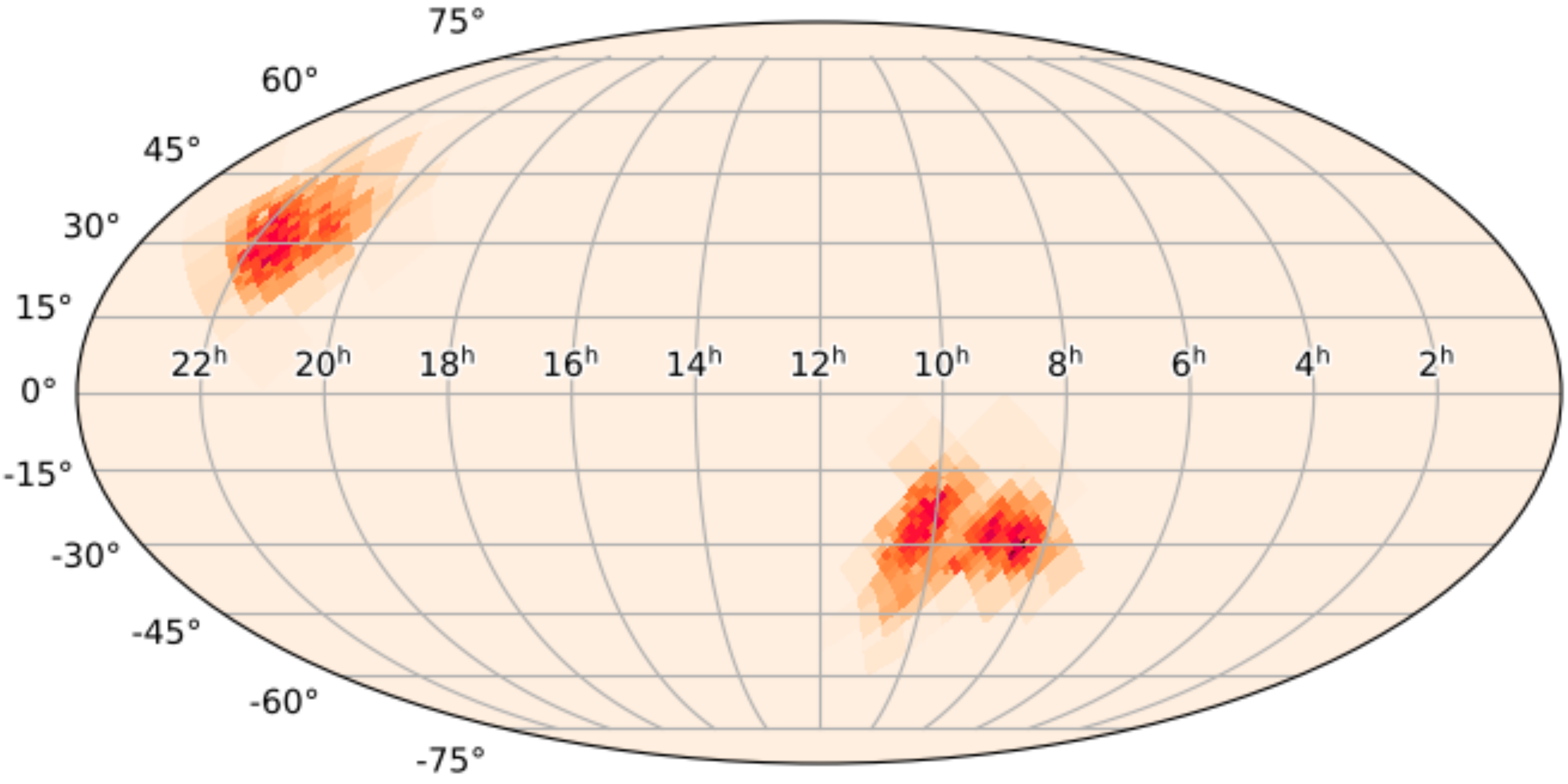

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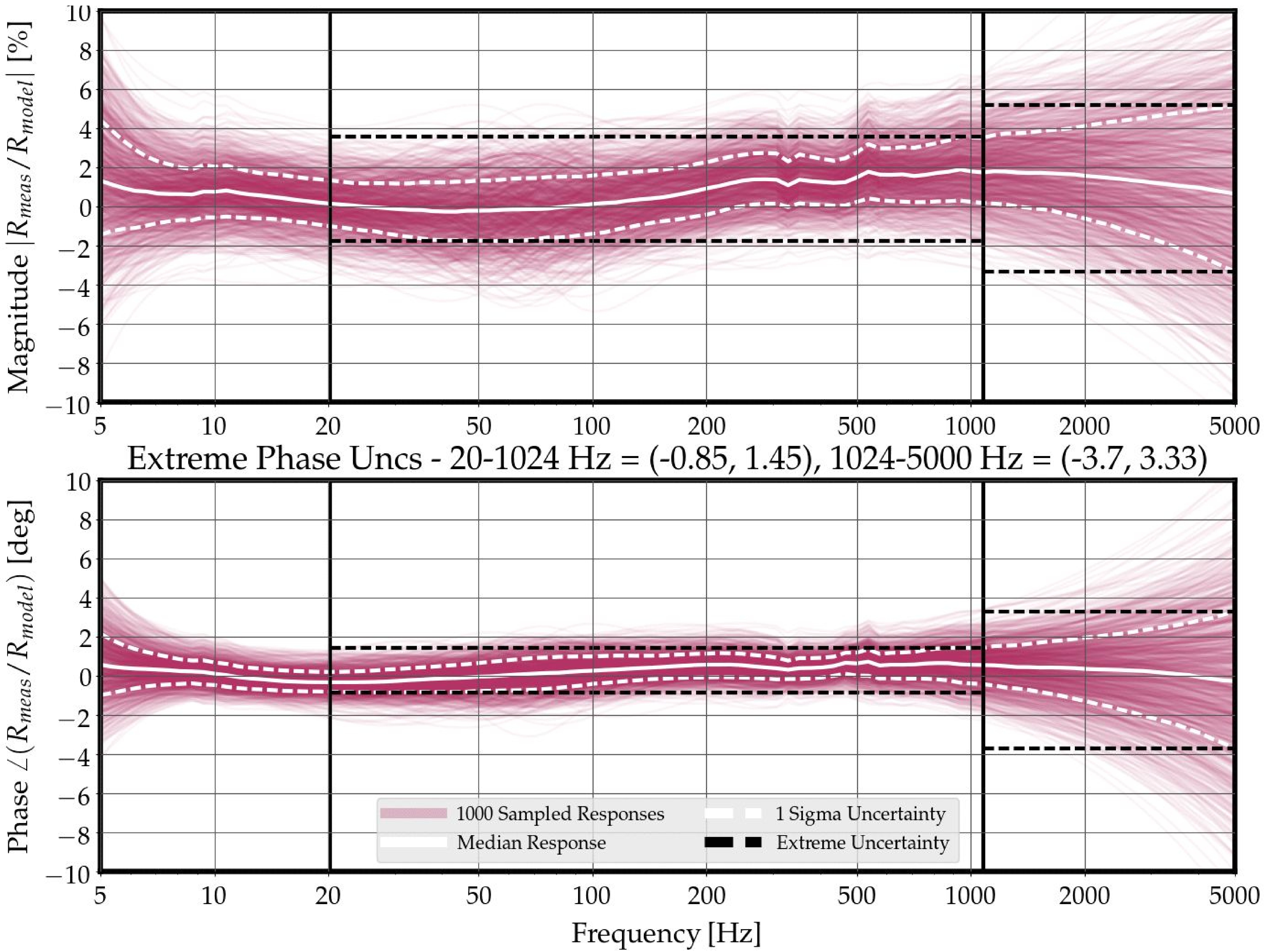
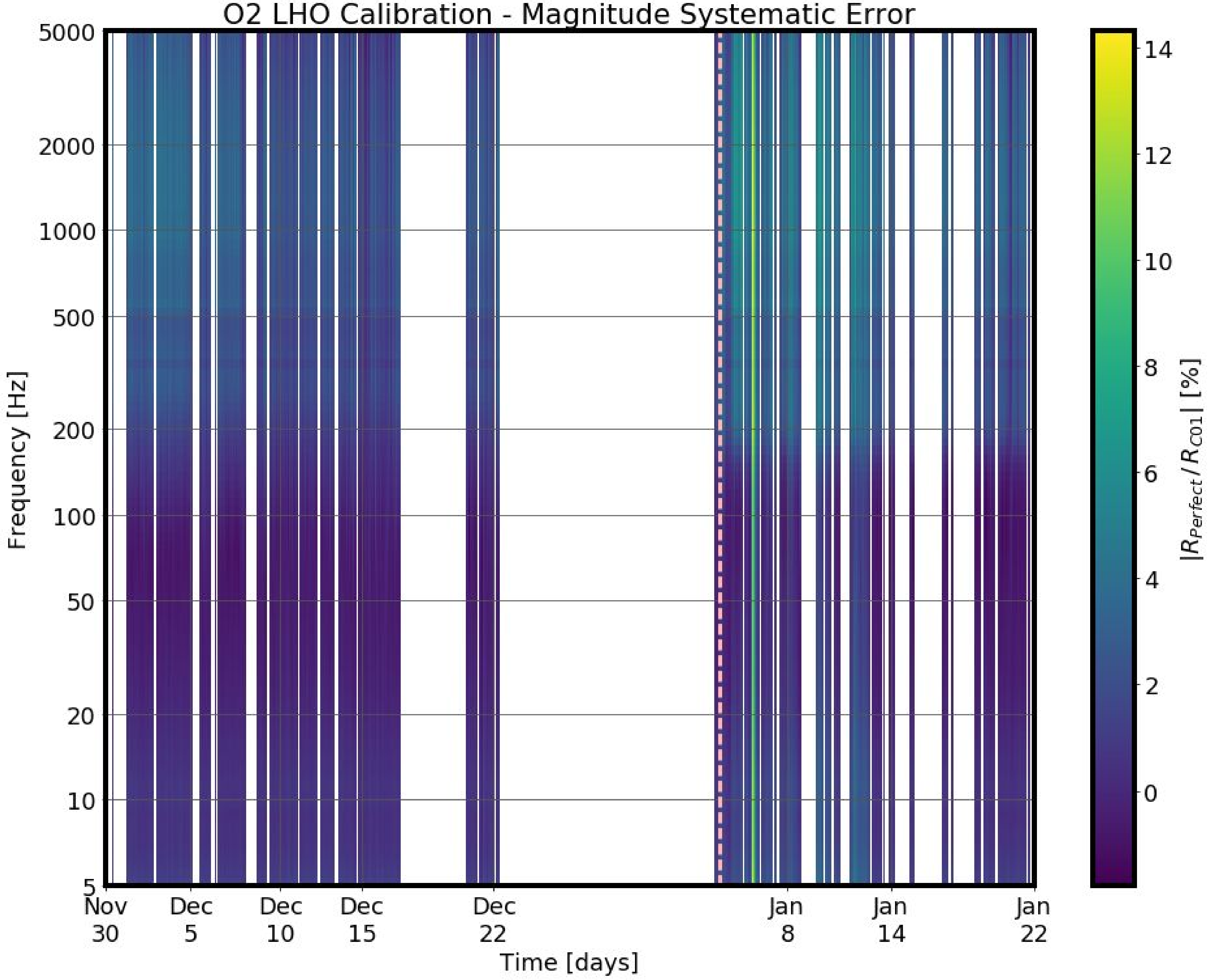
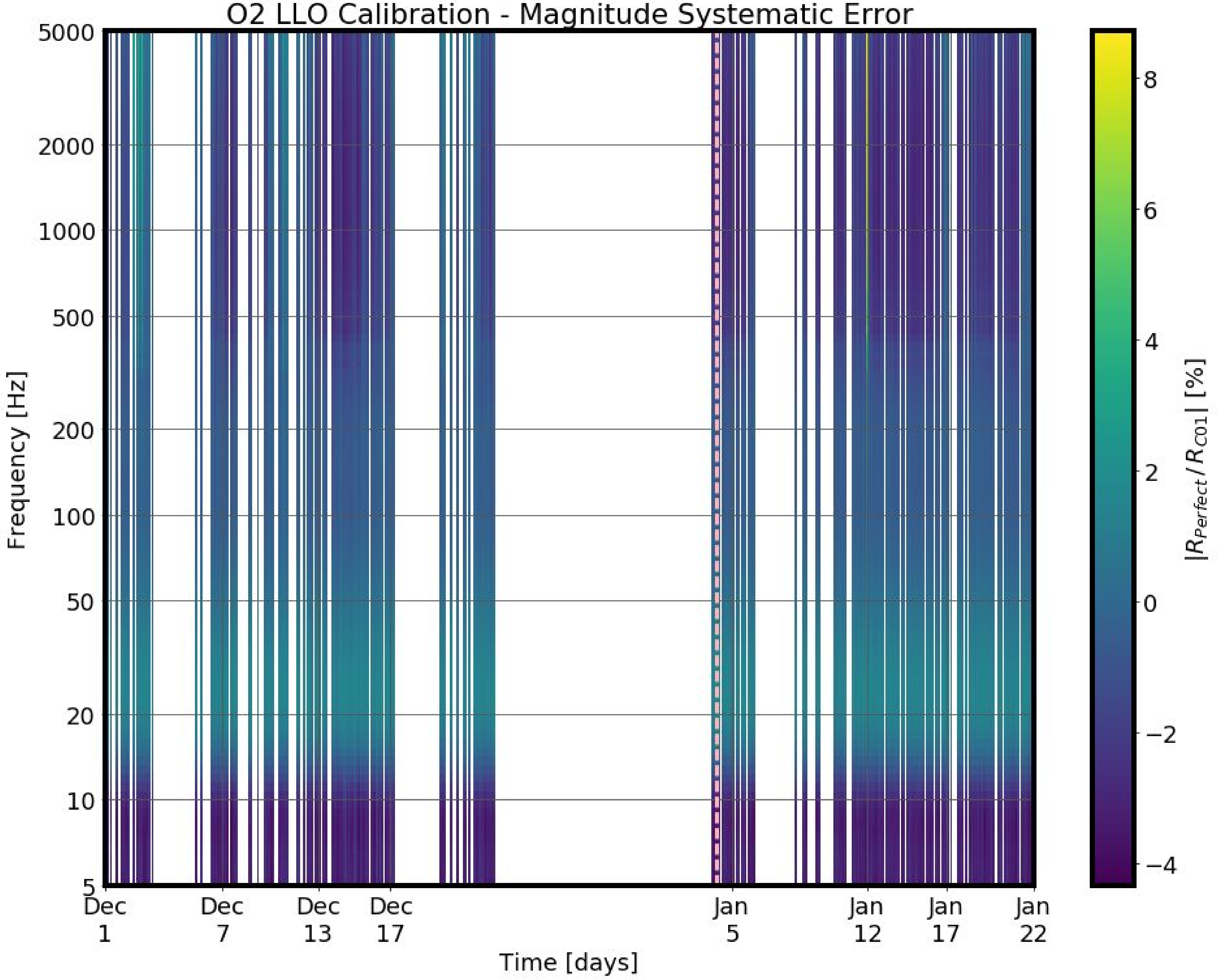


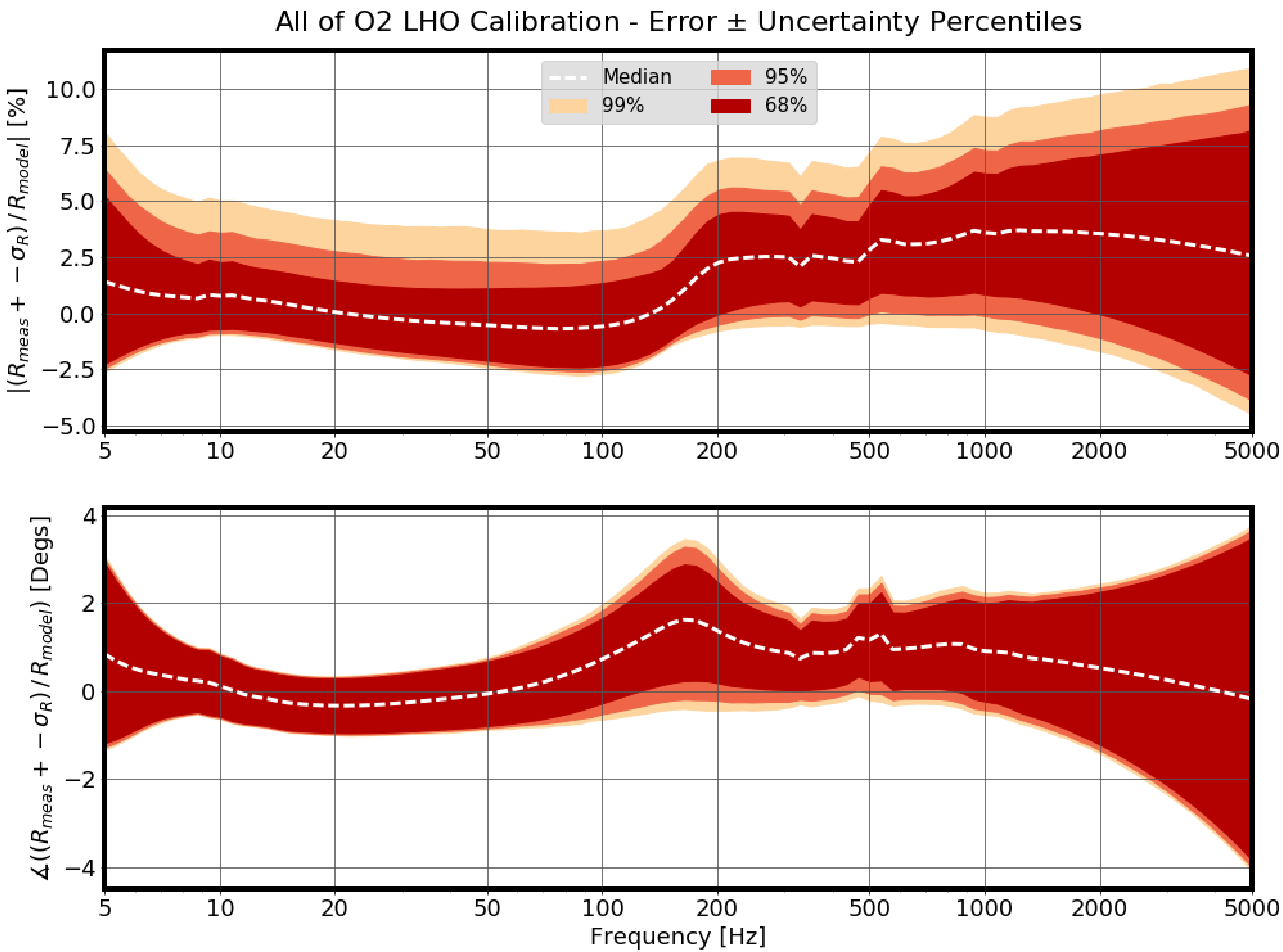
Cahillane et al. (in prep)





Both the calibration and its error very with time

Cahillane et al. (in prep)



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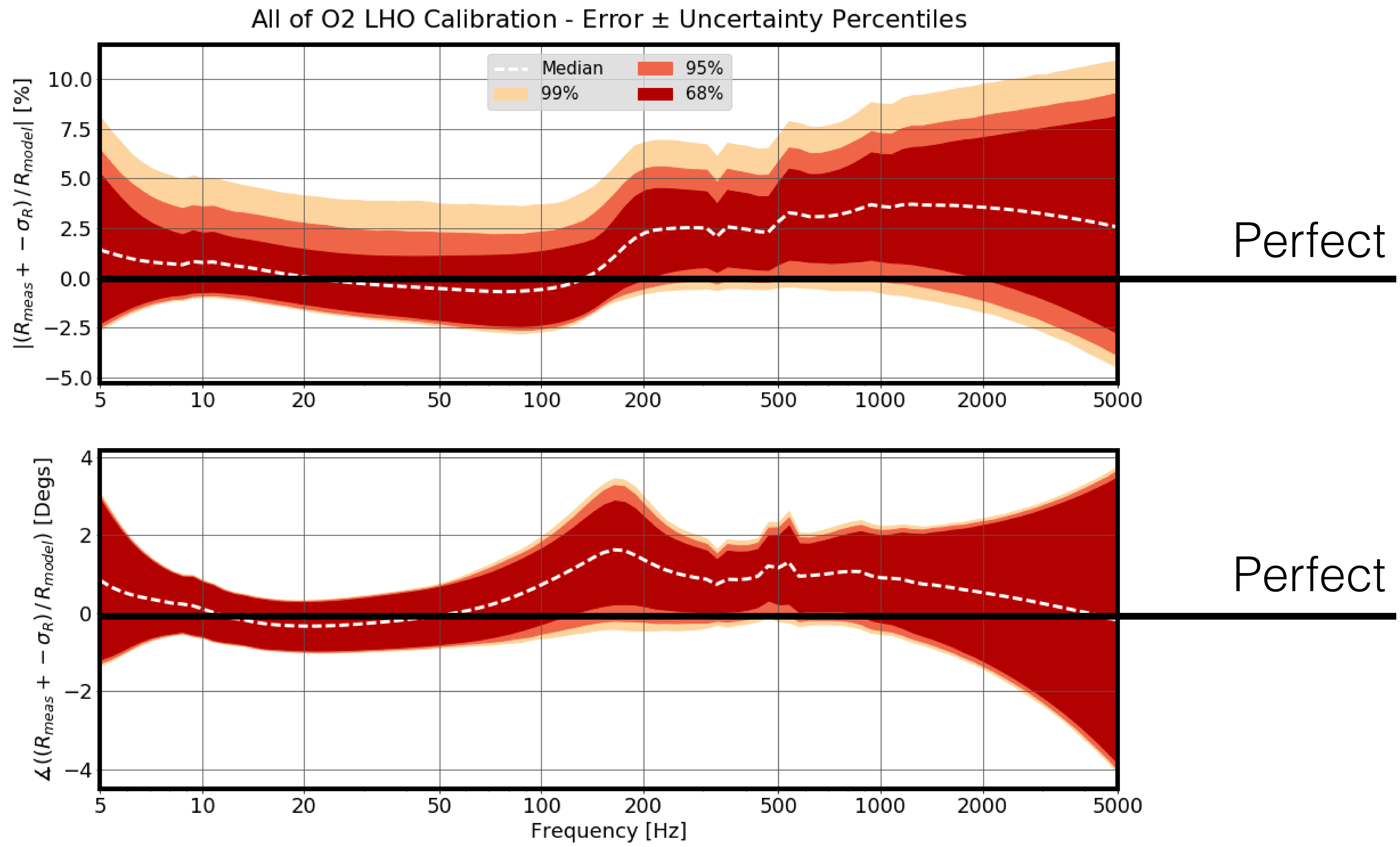

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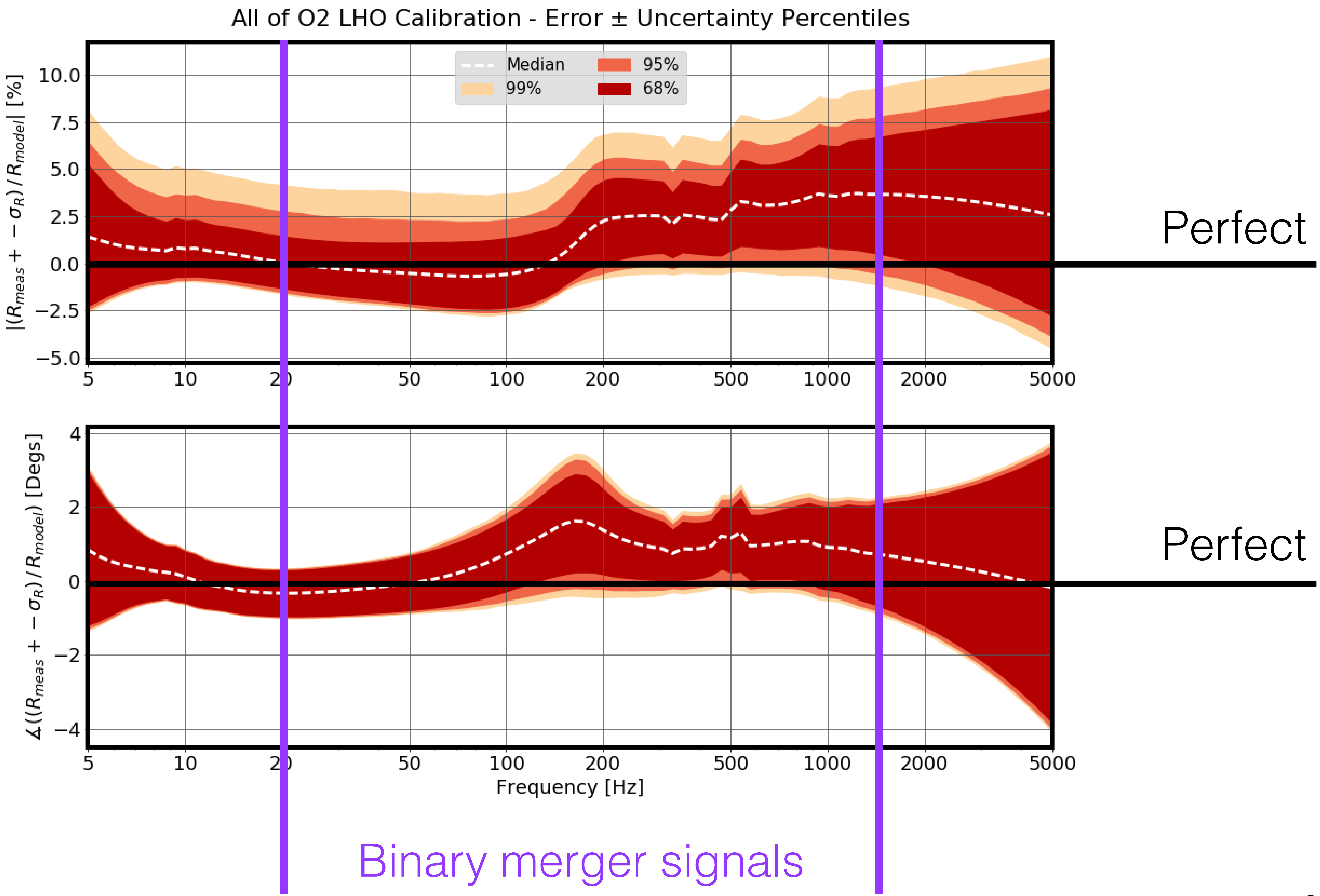

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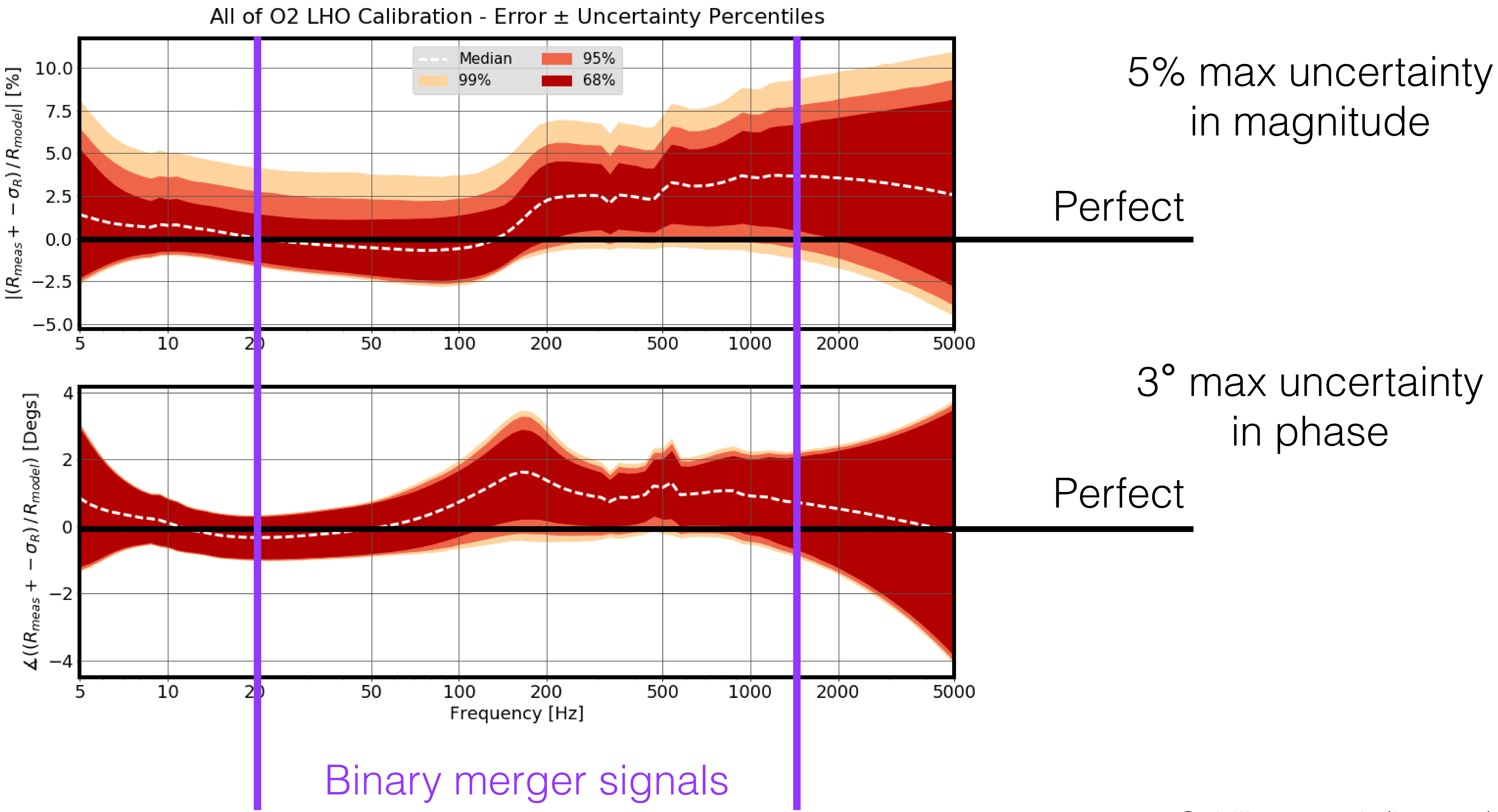
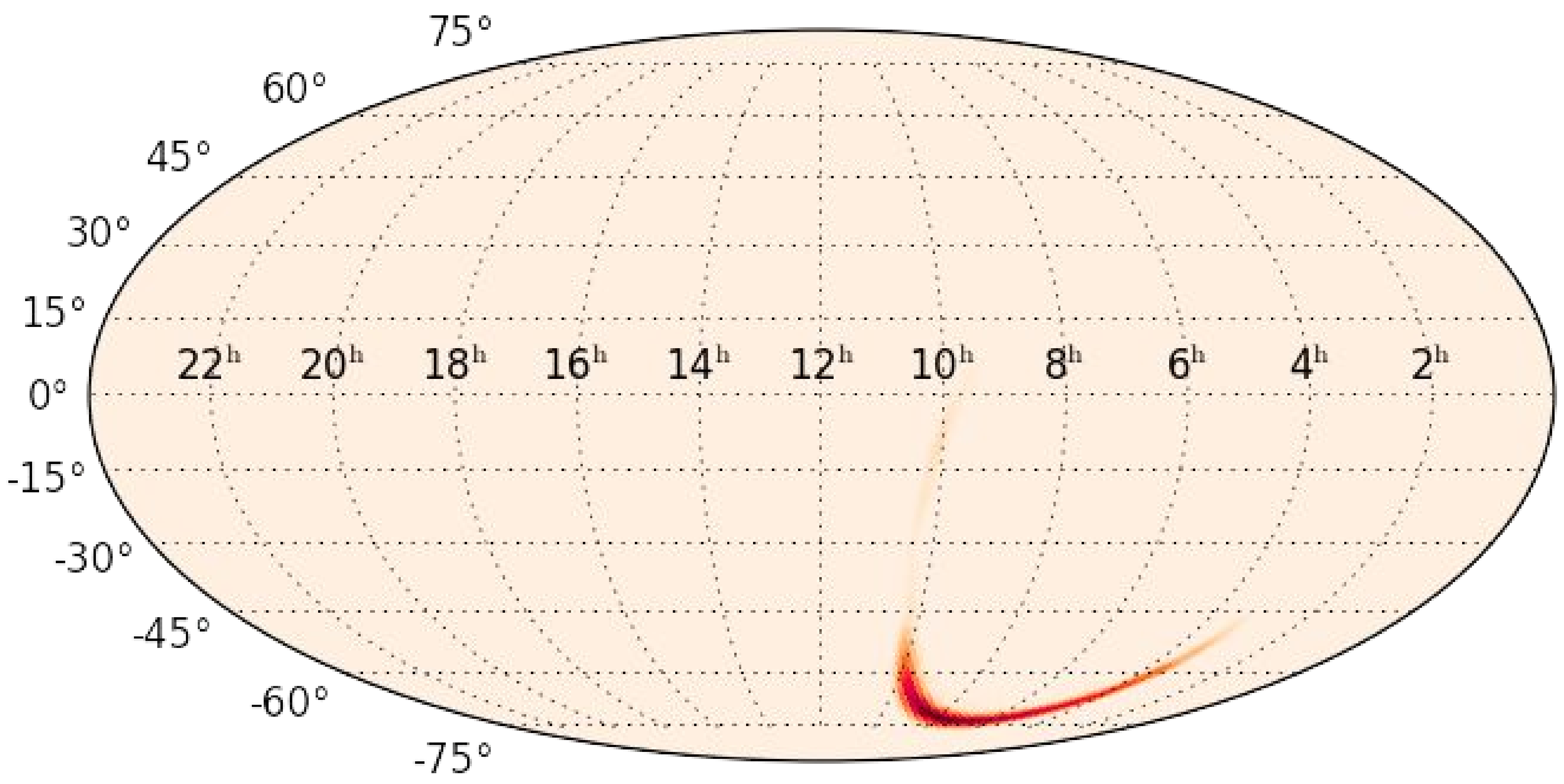
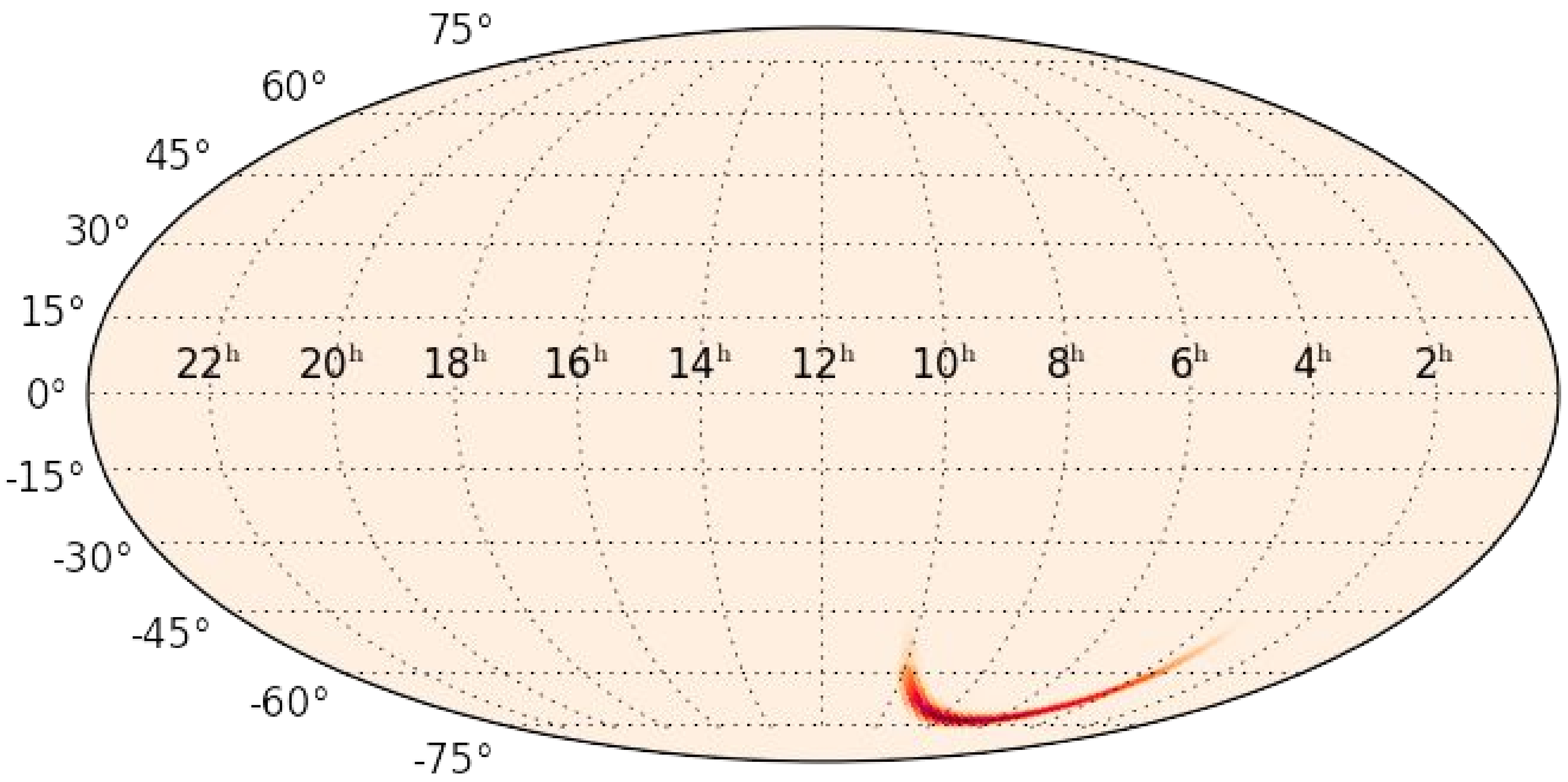


Cahillane et al. (in prep)

GW150914 90% sky area with
10% and 10 degrees uncertainty
231 square degrees



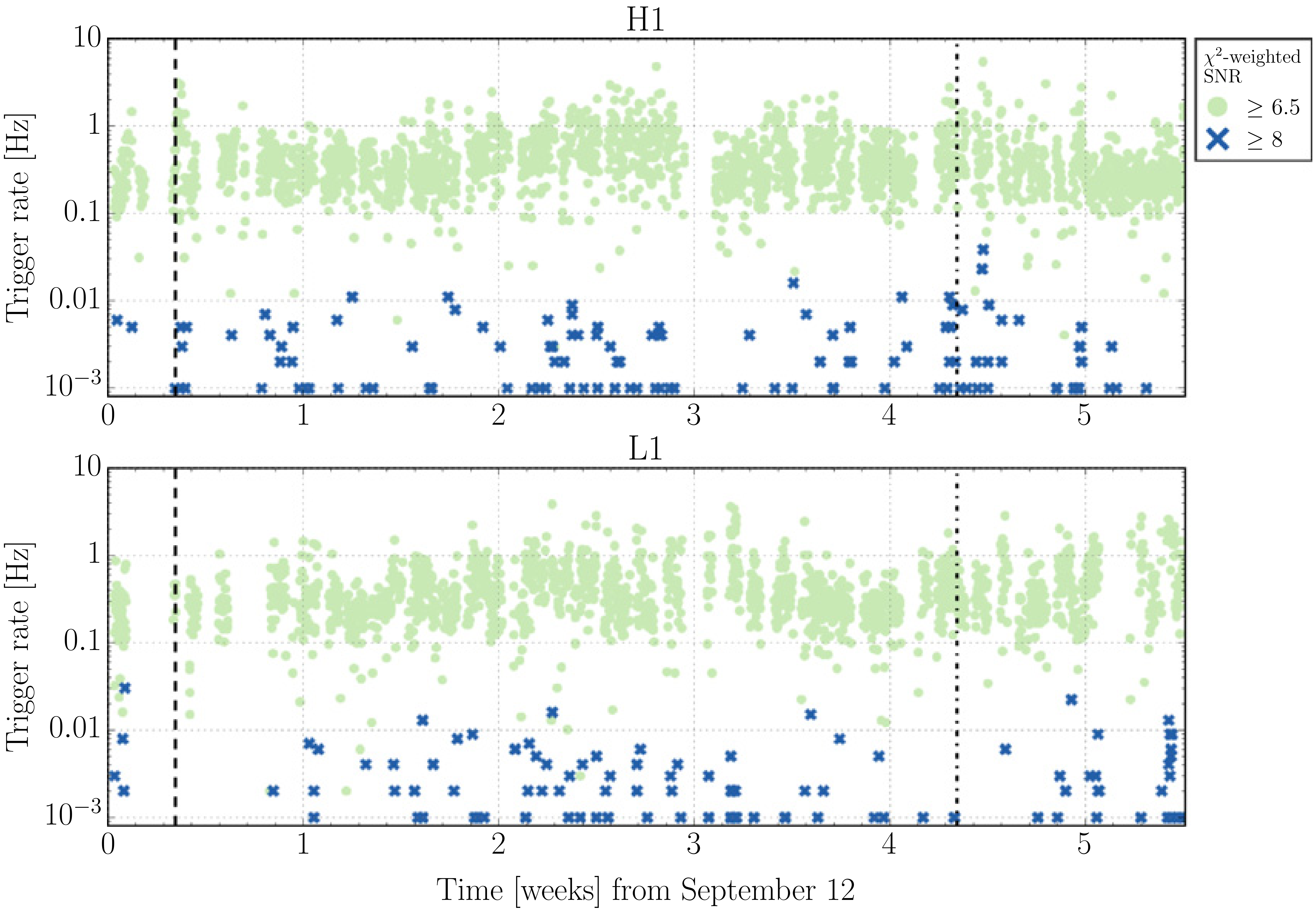
GW150914 90% sky area with
no calibration uncertainty
153 square degrees



Chris Berry

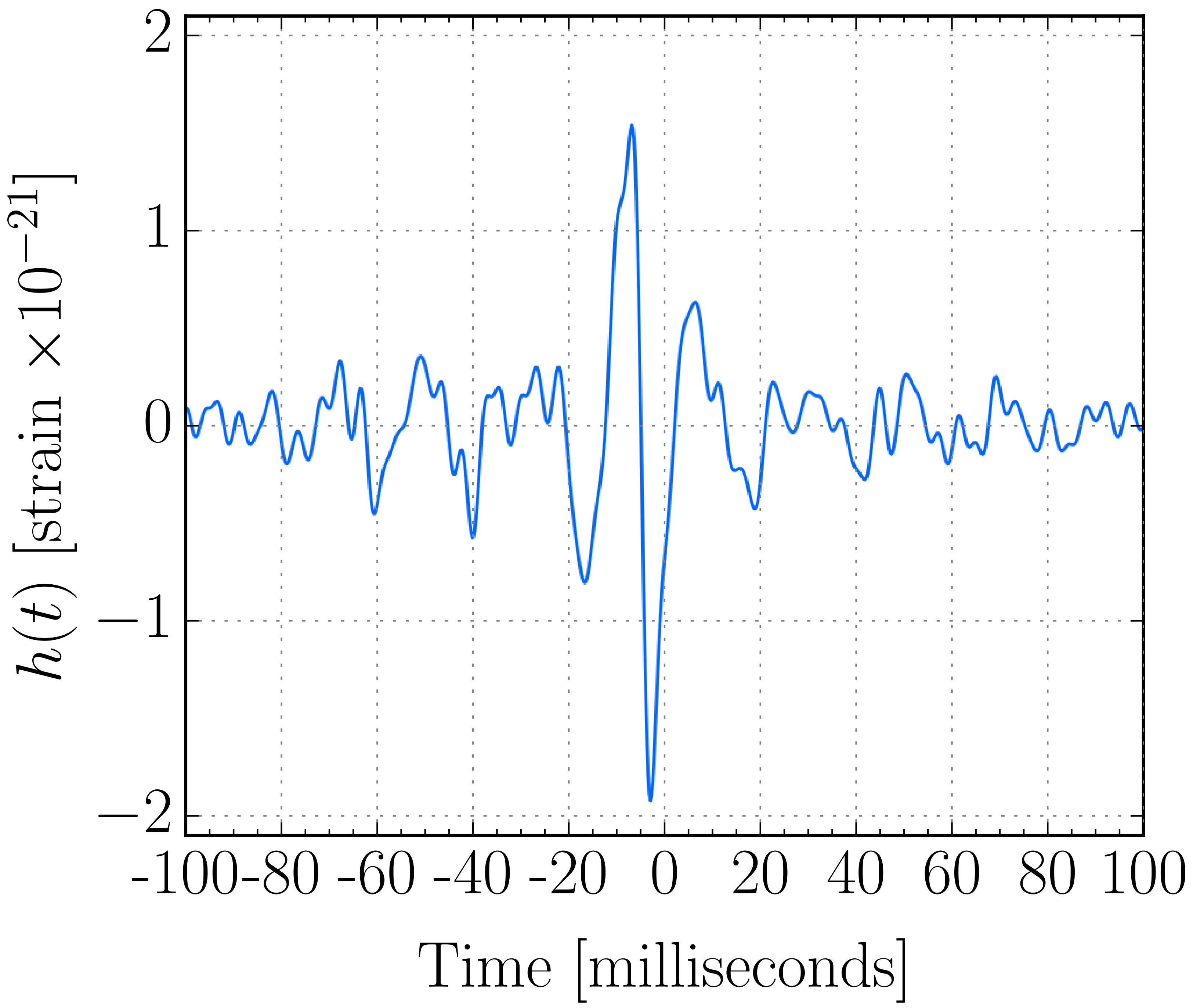
Detector Characterization

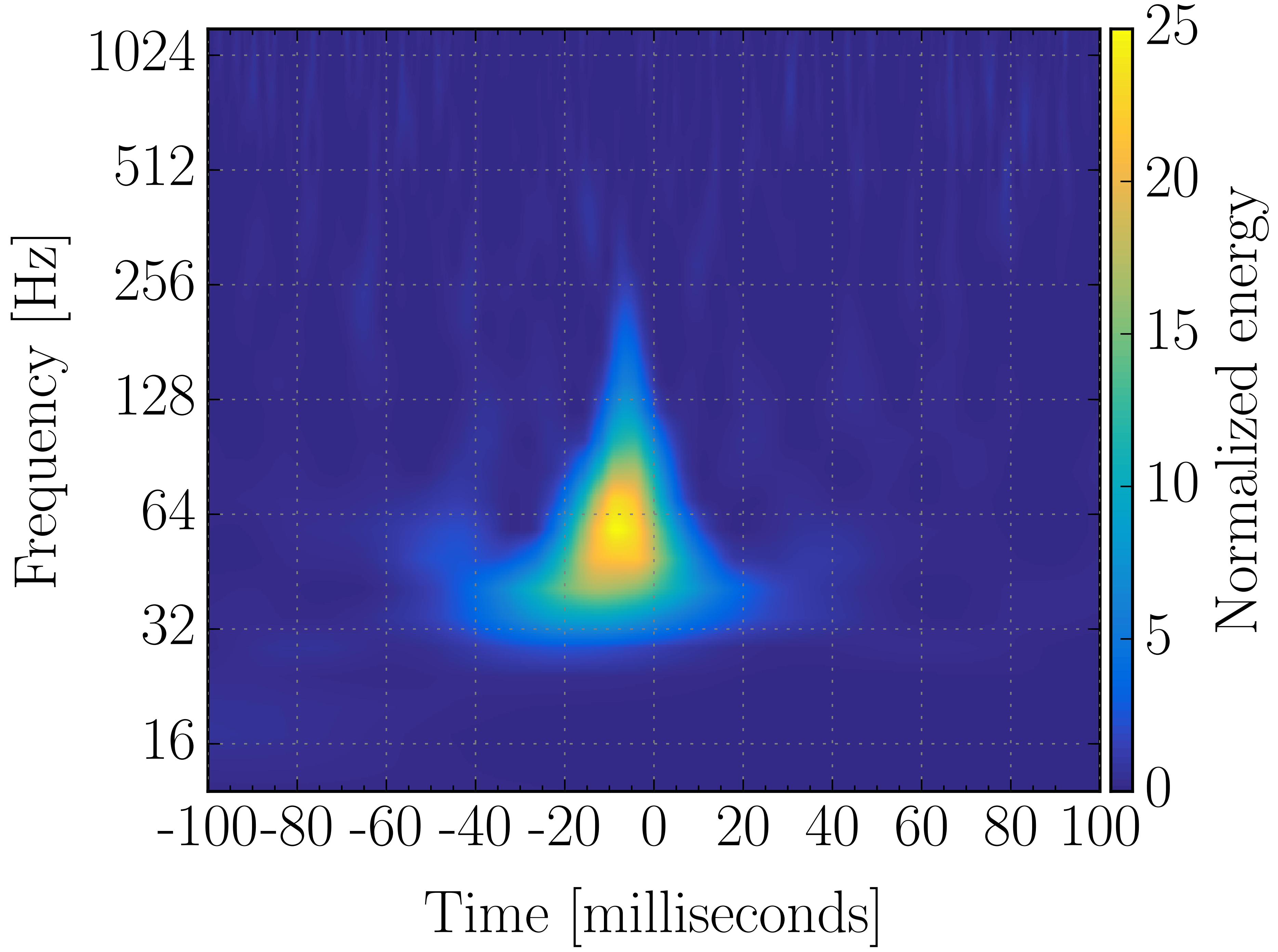
- Gravitational-wave detector noise contains a stationary Gaussian component, an non-stationary component, and transient noise
- DetChar is the process of identifying the sources of non-stationary and transient noise and (ideally) mitigating the problems in the detector, or removing them from the search (vetoing)
- Very time-dependent problem... needs constant work!



Abbott et at. CQG **33** 134001 (2016)

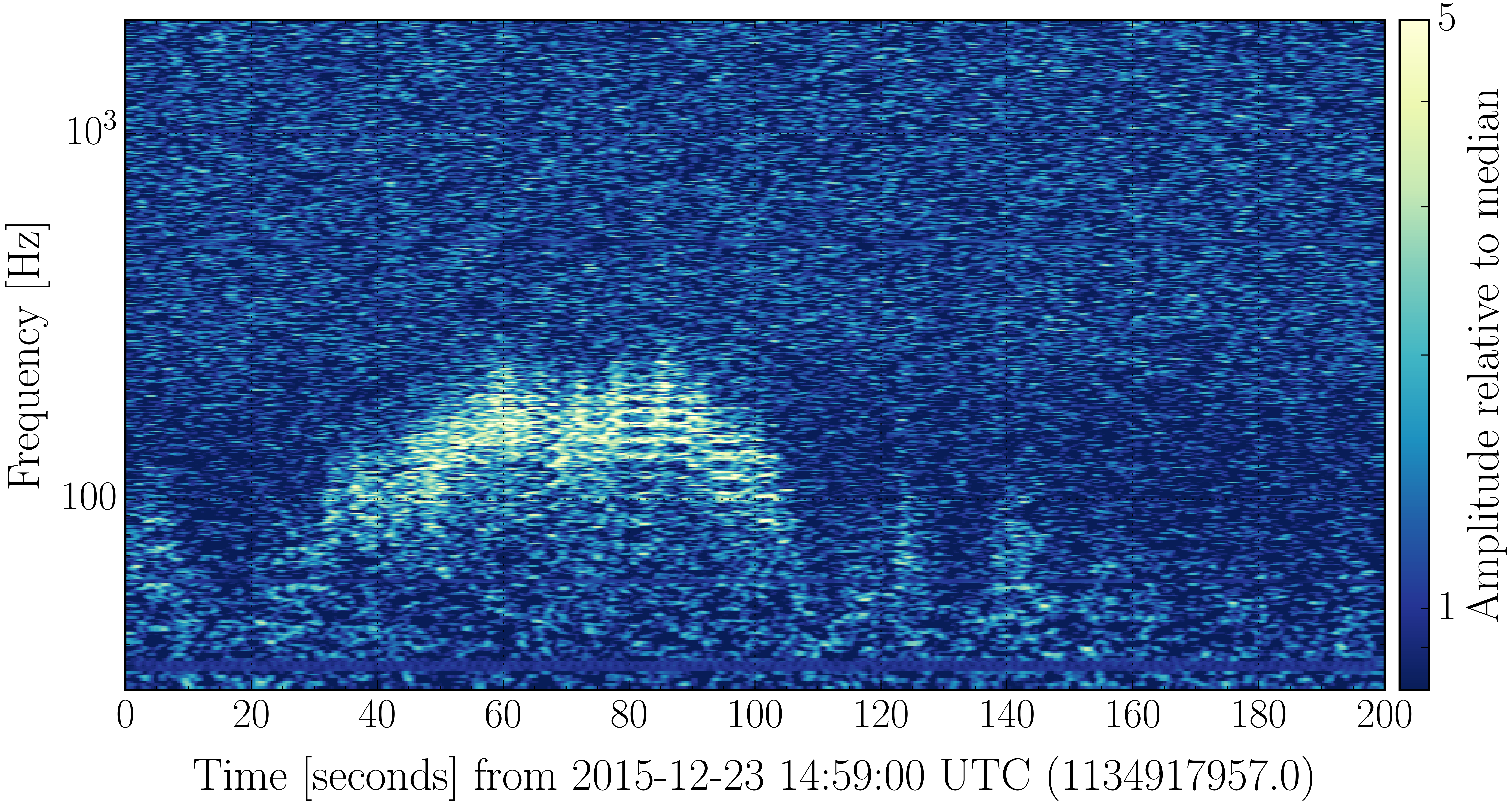
Blip Glitch





- Seen in both LIGO detectors with no known cause

60-200 Hz Mystery Noise

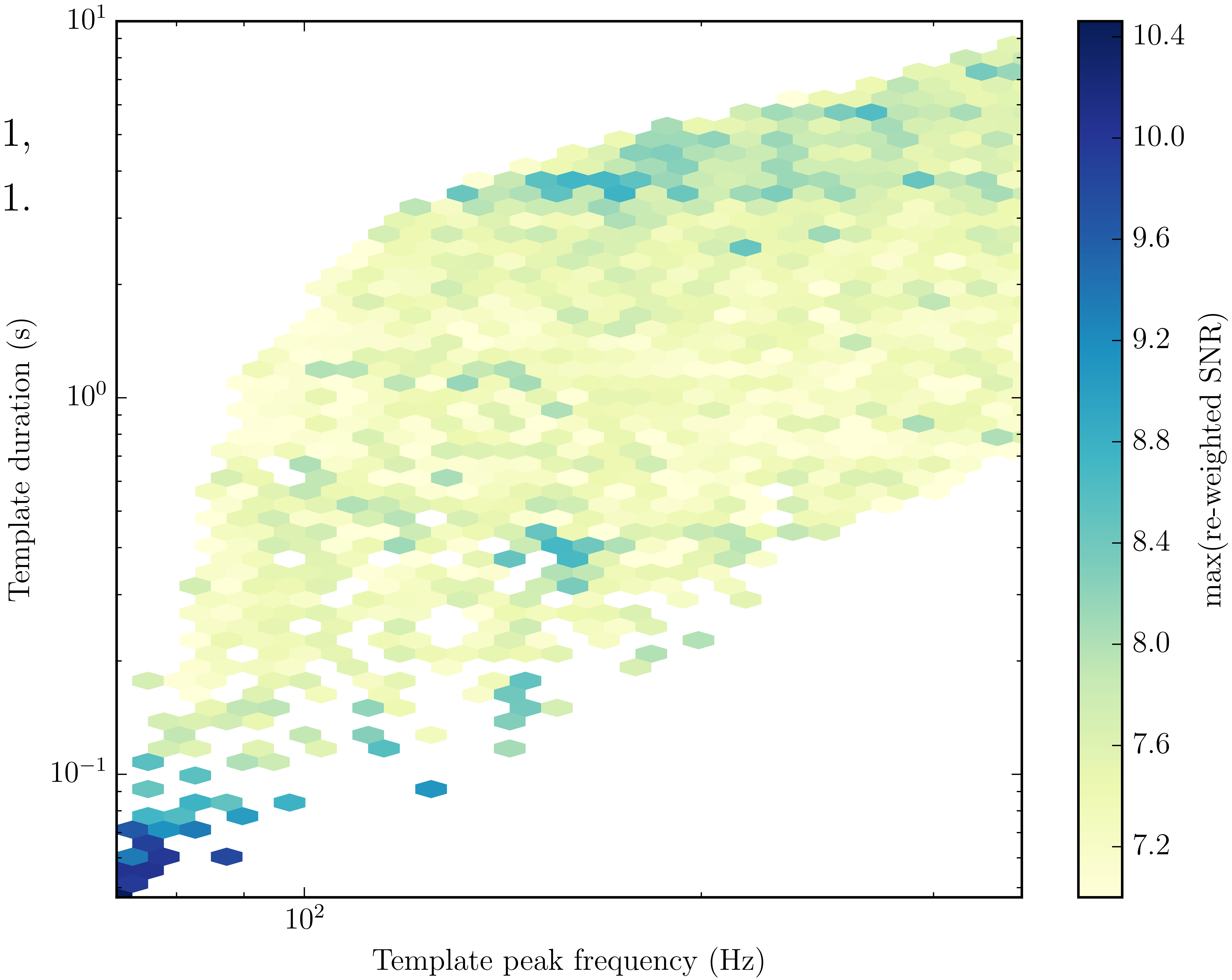


- Only in Livingston. Similar to scattered light, but is not scattering

$$\hat{\rho} = \begin{cases} \rho \Big/ [(1 + (\chi_r^2)^3)/2]^{\frac{1}{6}}, & \text{if } \chi_r^2 > 1, \\ \rho, & \text{if } \chi_r^2 \leq 1. \end{cases}$$

$$\chi^2 = p \sum_{l=1}^{p} \left(\frac{\rho^2}{p} - \rho_l^2 \right)^2$$

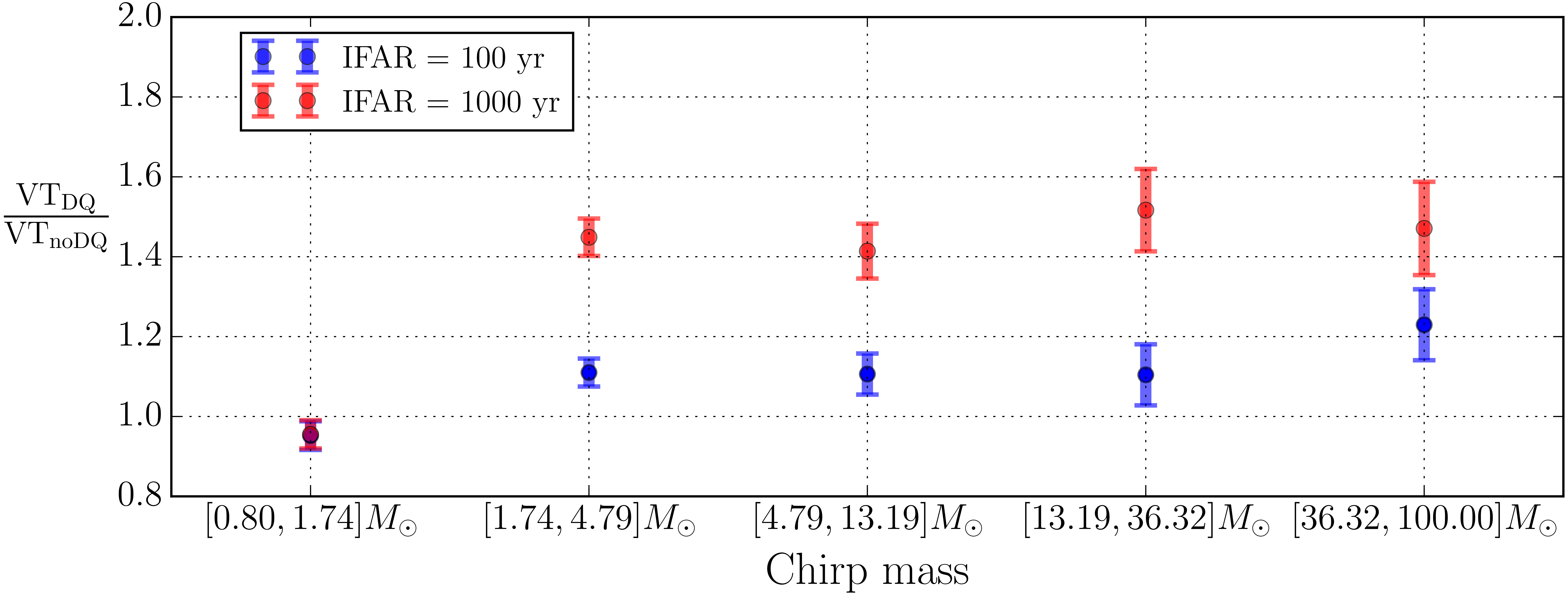
Usman et al Class. Quantum Grav. **33** 215004 (2016)



TJ Massinger (in prep)

- Repeat PyCBC search using data from the first observing run with and without data quality vetoes
- Both analyses use PyCBC's internal veto tools:
    - "gating" and chi-squared veto
- Measure change in sensitive volume using software injections

TJ Massinger (in prep)



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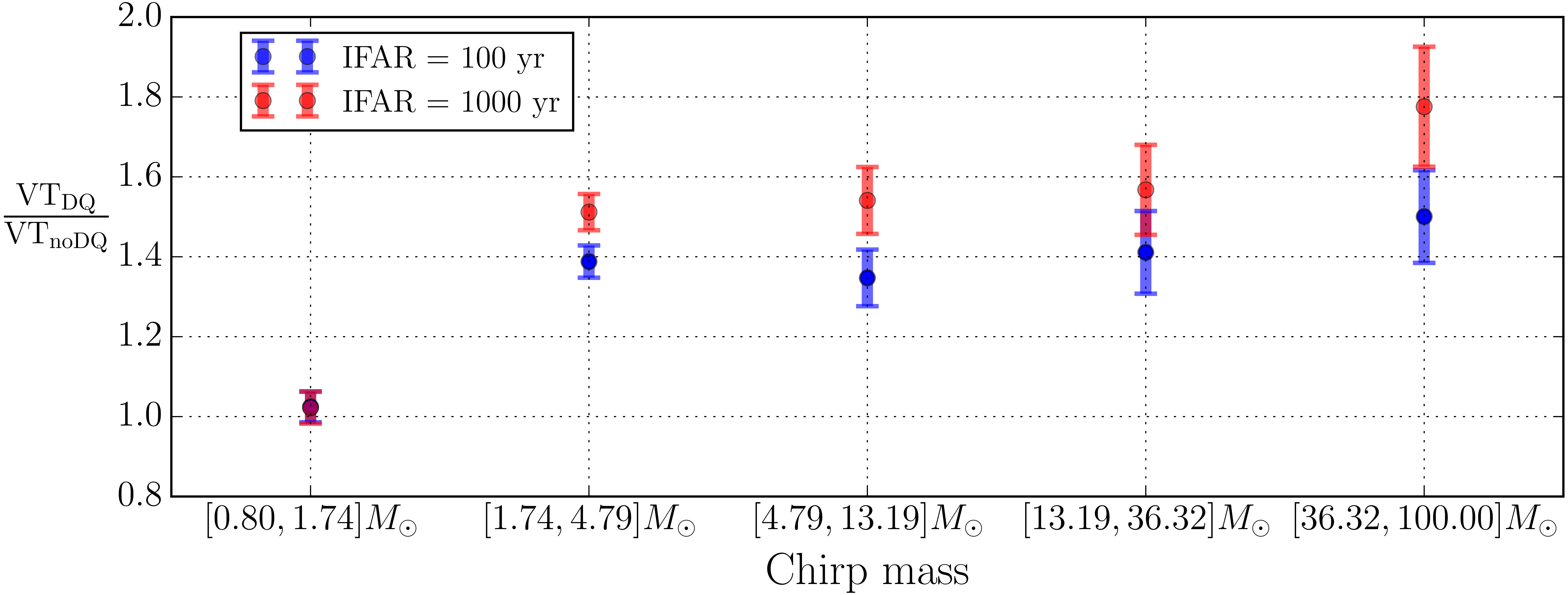

TJ Massinger (in prep)

Effect on False Alarm Rate

- GW150914 is so loud that it's FAR is insensitive to vetoes
- GW151226 has a FAR of less than 1 in 186,000 years with vetoes
- The significance of GW150914 is reduced to 1 in 770 years without applying data quality vetoes
- The significance of LVT151012 is also reduced by a factor of two, if vetoes are not used

TJ Massinger (in prep)

Conclusions 1

- Time to start planning for 3G calibration is now!
    - What are your astrophysical requirements on calibration?
- But don't forget about 2G detectors
    - Need assess effect of accuracy and uncertainty on astrophysics for the LIGO-Virgo network using real calibration models
    - Need to incorporate physical calibration models into parameter measurement (currently codes use spline models)

Conclusions 2

- DetChar and Vetoes can make a significant difference to search sensitivity and false alarm rate of detected signals
- Detector state is constantly changing: problems come and go
  - Needs sustained effort to keep on top of the issues
  - Ongoing work is needed to mitigate unknown noise sources in the detectors and generate vetoes for searches
  - Still need effort to add better signal-based vetoes to searches