

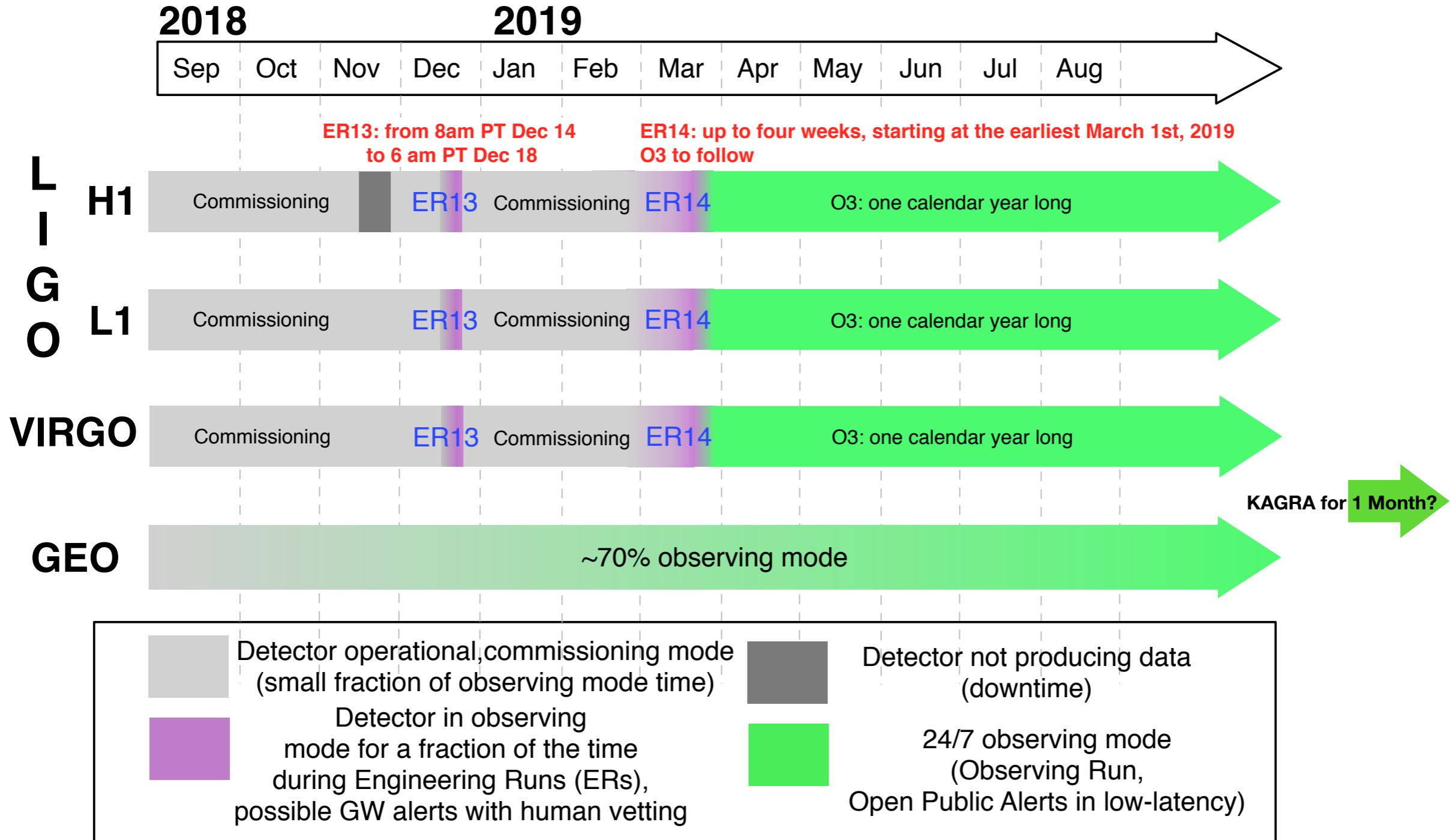
LIGO-Virgo Observing Status, Perspectives, and KGWG

Hyung Mok Lee
KASI
On behalf of KGWG

LIGO-VIRGO Joint Run Planning Committee

Working schedule for O3

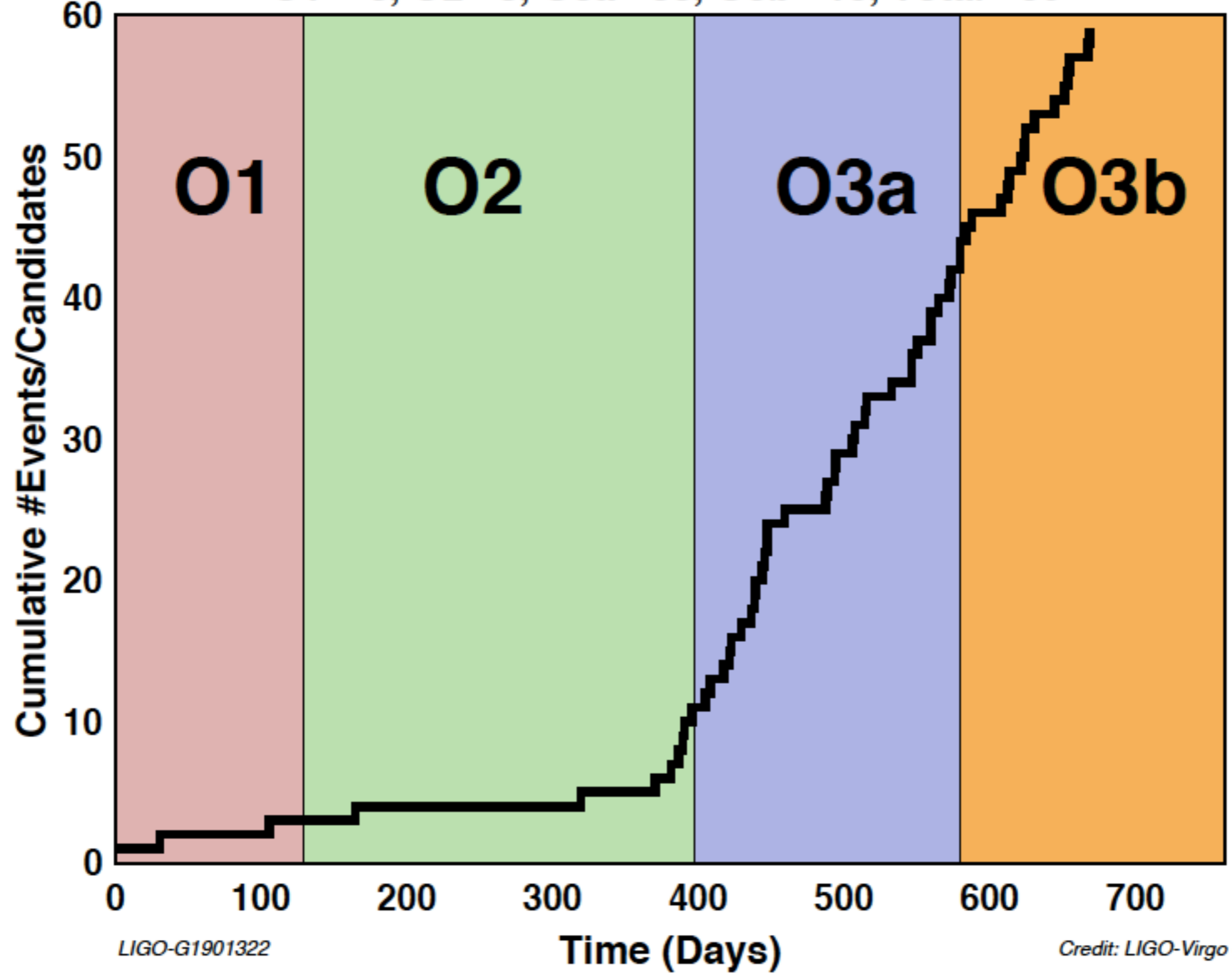
(Public document G1801056-v4, based on G1800889-v7)





Cumulative Count of Events and (non-retracted) Alerts

O1 = 3, O2 = 8, O3a = 33, O3b = 15, Total = 59



LIGO-G1901322

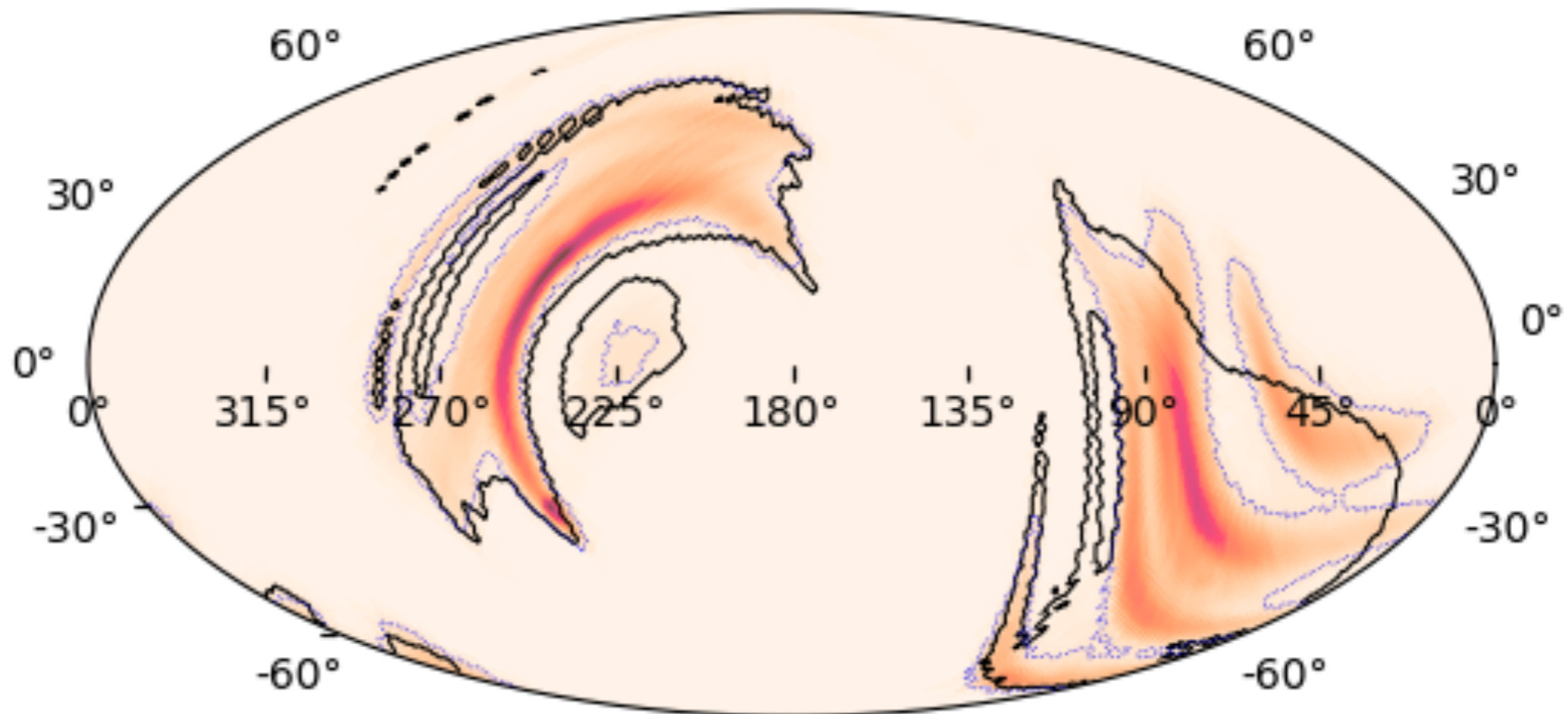
Credit: LIGO-Virgo Collaboration

As of January 29, 2020

GW 190425: another Binary Neutron Star merger (arXiv:2001.01761)

- Network status:
 - Hanford: Offline
 - Livingstone: Online, BNS Range: 135 Mpc, SNR=12.9
 - Virgo: Offline, BNS Range: 48 Mpc, SNR=2.5

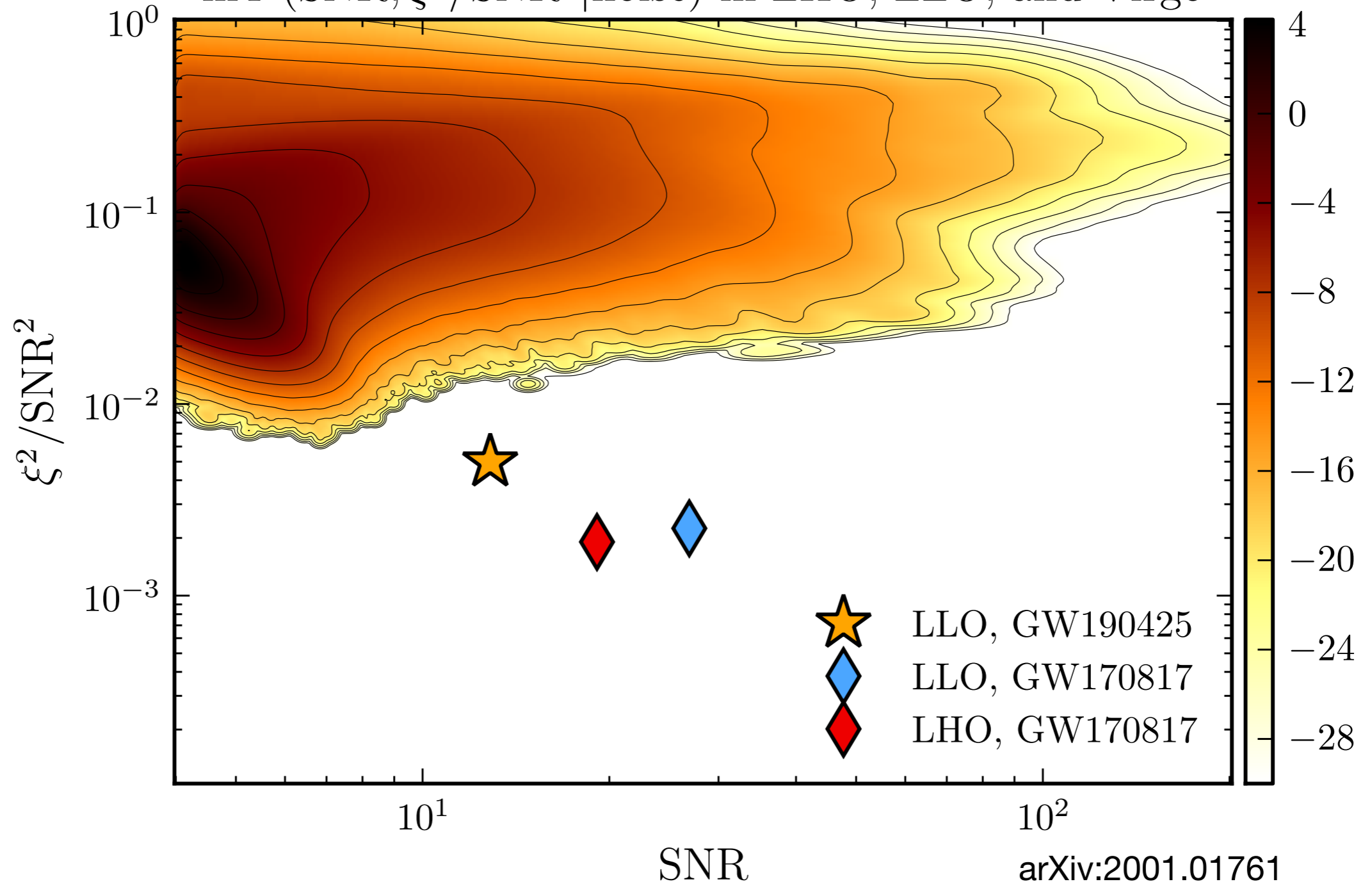
Sky localization



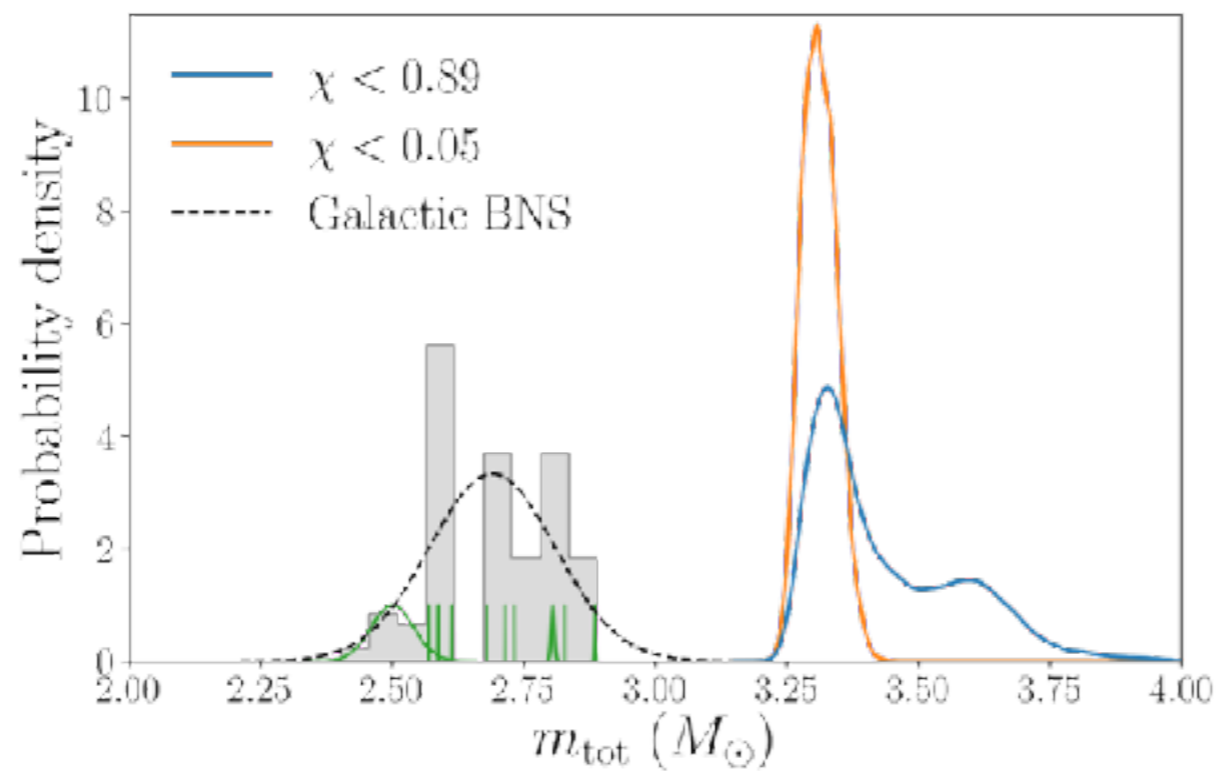
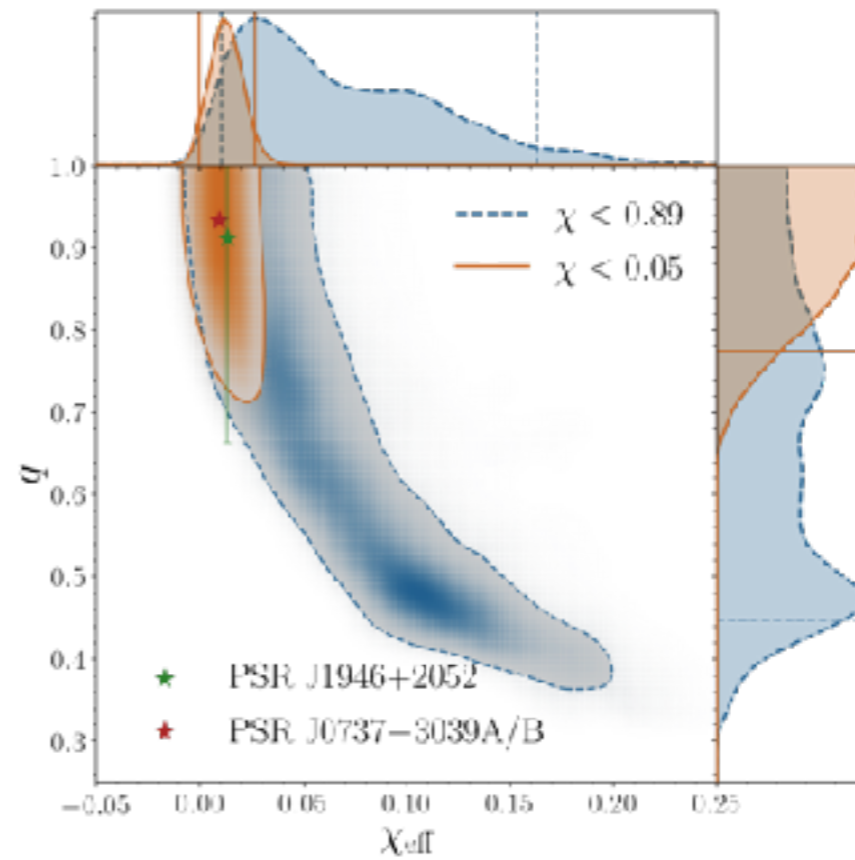
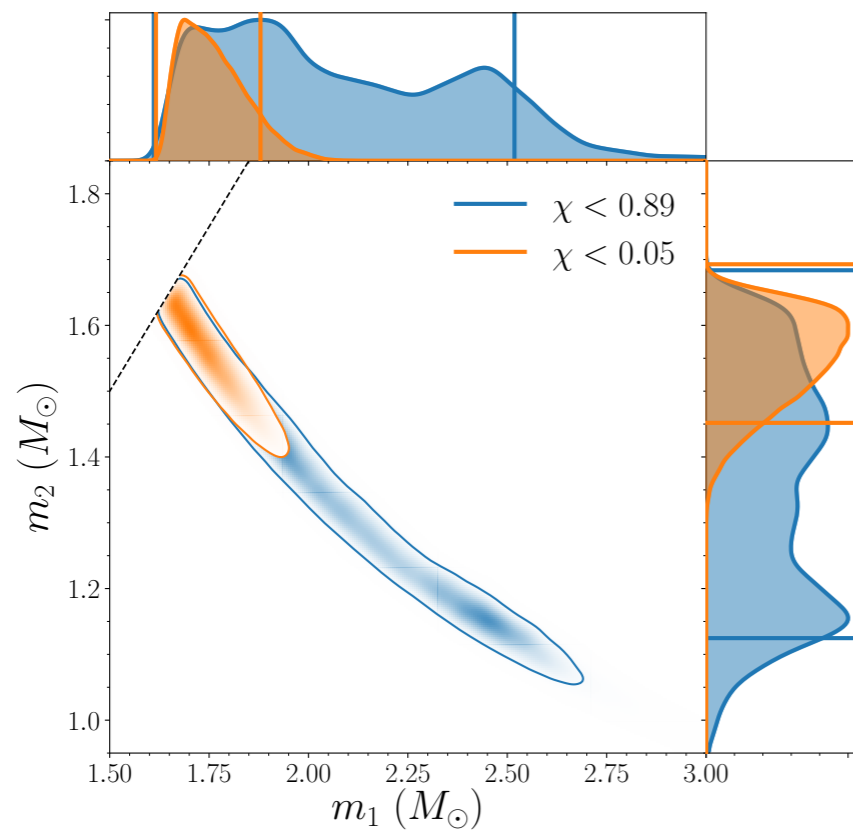
arXiv:2001.01761

Confidence

$\ln P(\text{SNR}, \xi^2/\text{SNR}^2 | \text{noise})$ in LHO, LLO, and Virgo

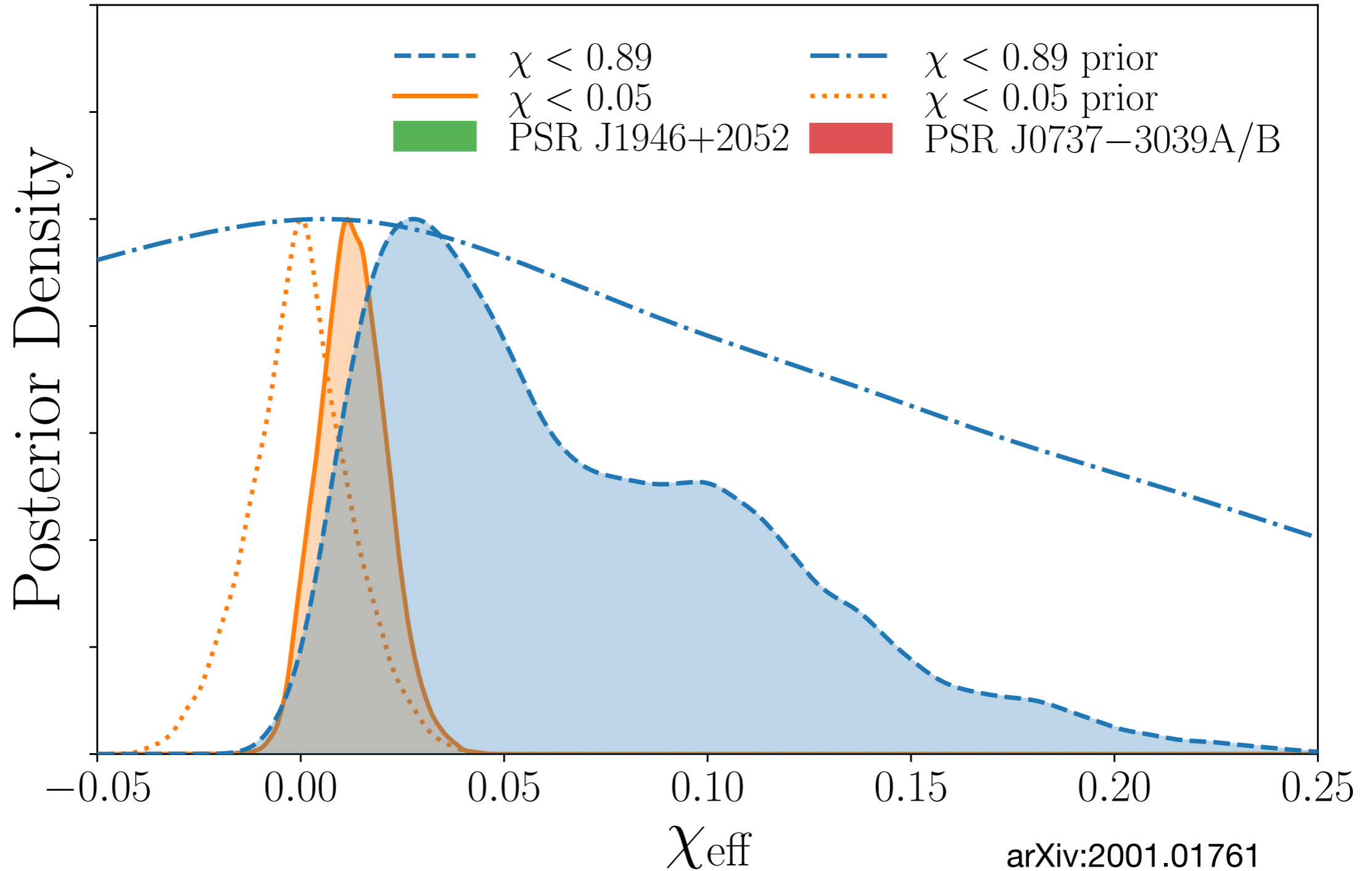


Masses

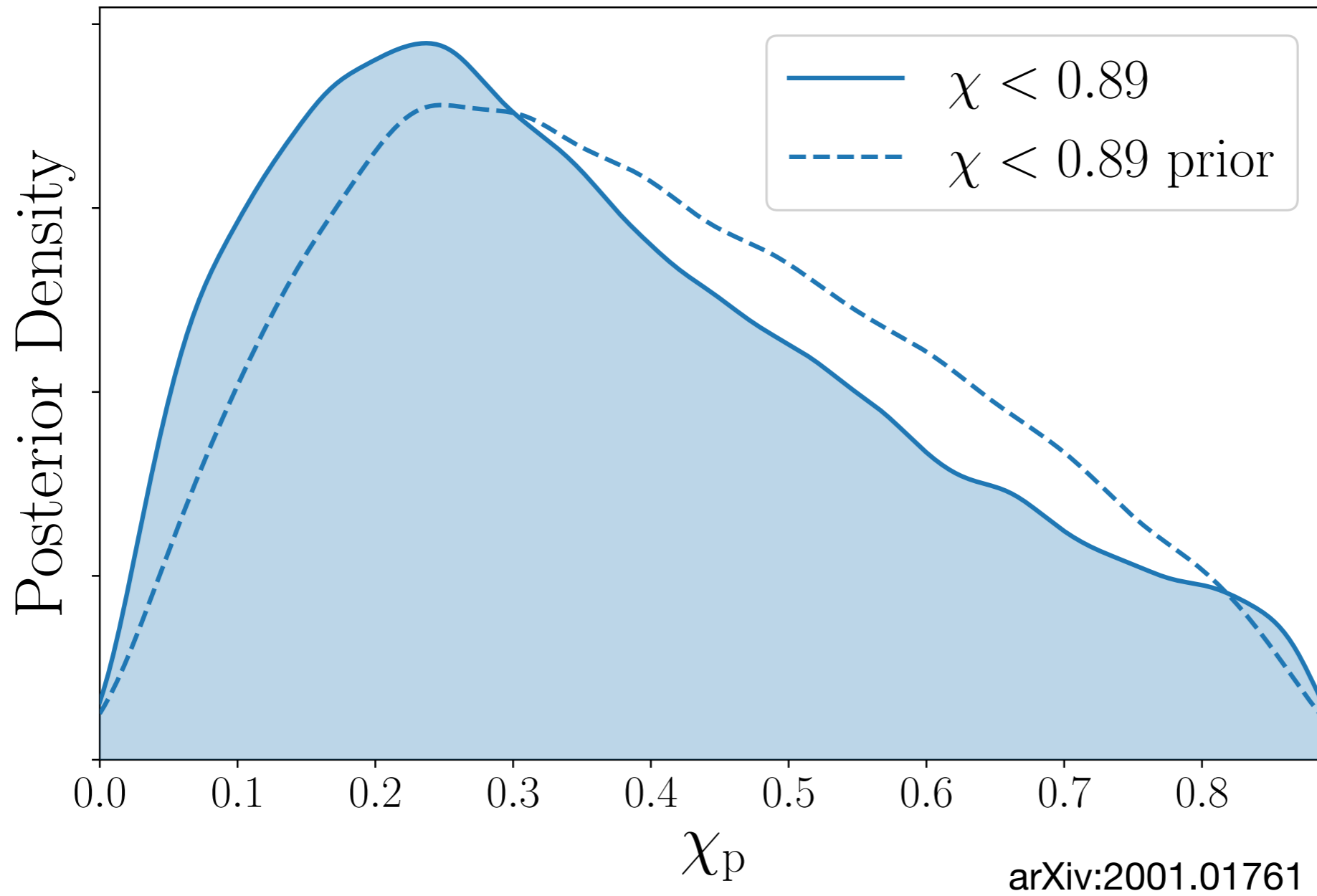


arXiv:2001.01761

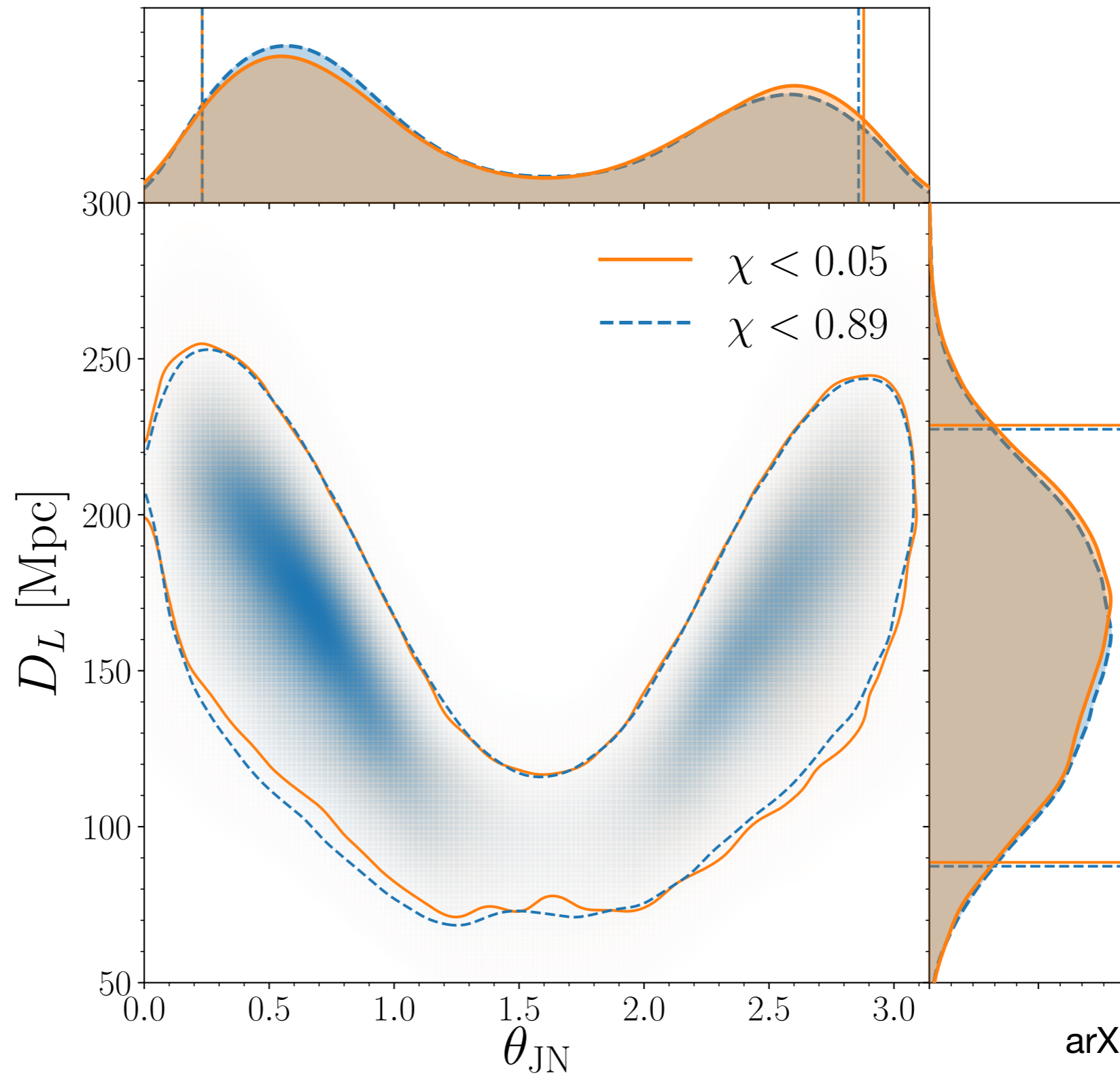
Effective Spin



Spin of the primary



Distance - Inclination

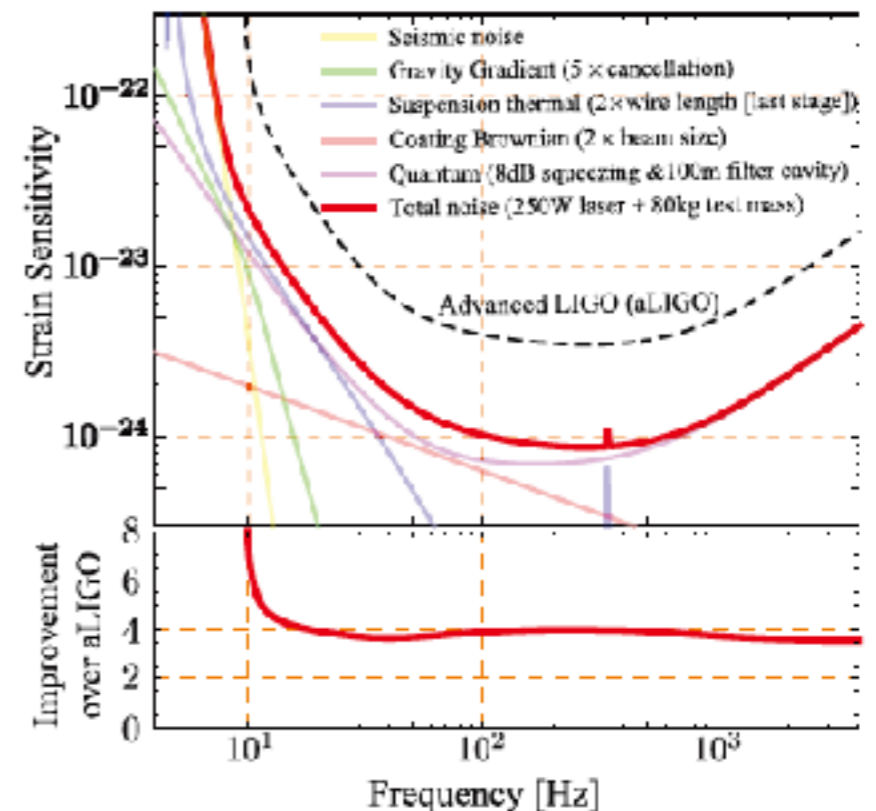
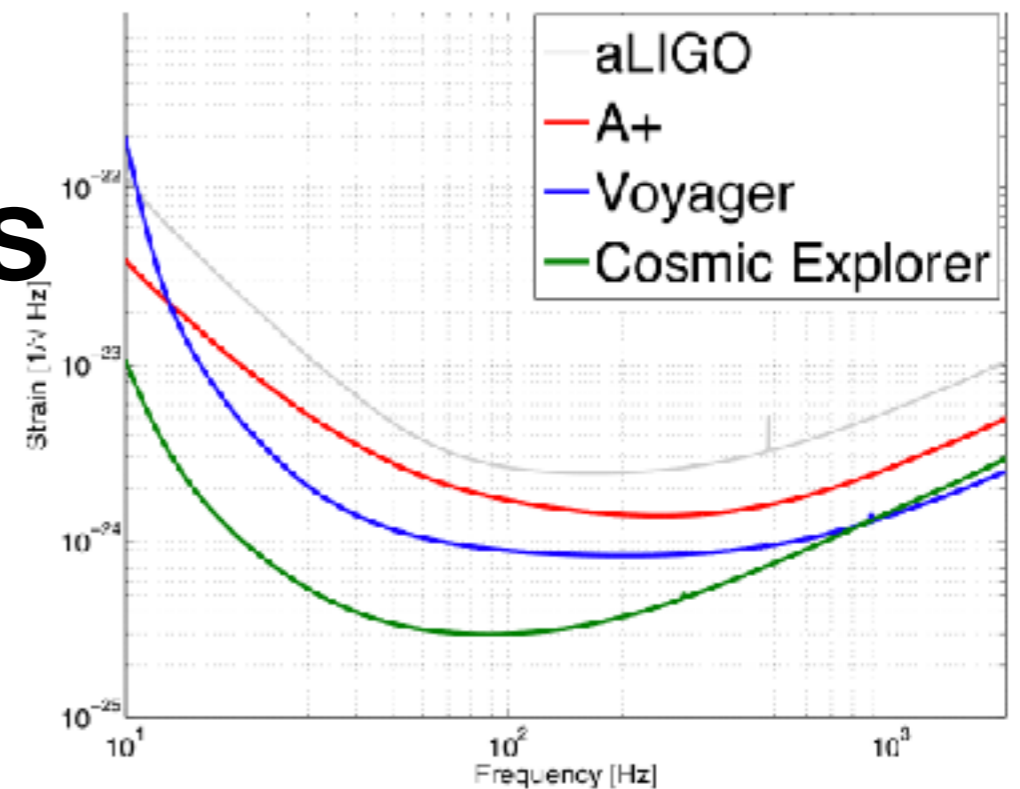


Outstanding Issues

- More BNS (or NSBH) with EM counterpart
 - A few candidates but no EM counterpart yet
- Black Hole in the mass gap above NS ($< 3 M_{\odot}$) but smaller than the lowest BH mass so far ($\sim 5 M_{\odot}$)
- Intermediate mass black holes ($m_1 + m_2 > 120 M_{\odot}$)
- Individual spin + Spin Alignment

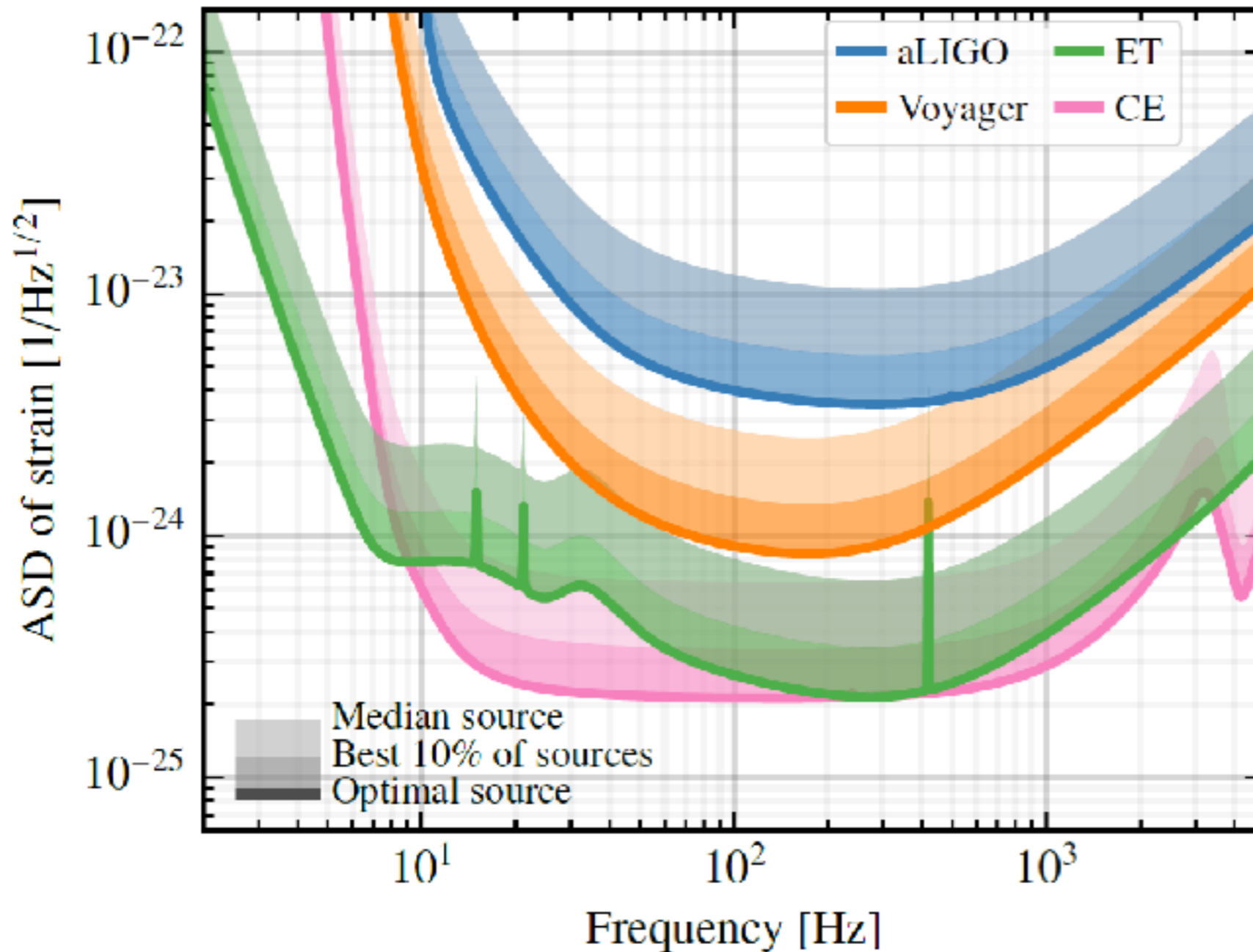
LIGO/Virgo Upgrades and near future detectors

- Accuracy of the sky localization could be improved by additional detectors and better sensitivity
- LIGO's upgrade plan
 - A+ (~50%)
 - Voyager (factor of 3)
 - **Cosmic Explorer (order of magnitude)**
- Additional Detectors
 - KAGRA (~2019), LIGO India (~2020)
 - **8 km detectors in Australia (and possibly in China)**
 - **Einstein Telescope**



Blair et al. 2015, Science China Physics, Mechanics, and Astronomy, 58, 5747

3G Ground based detectors



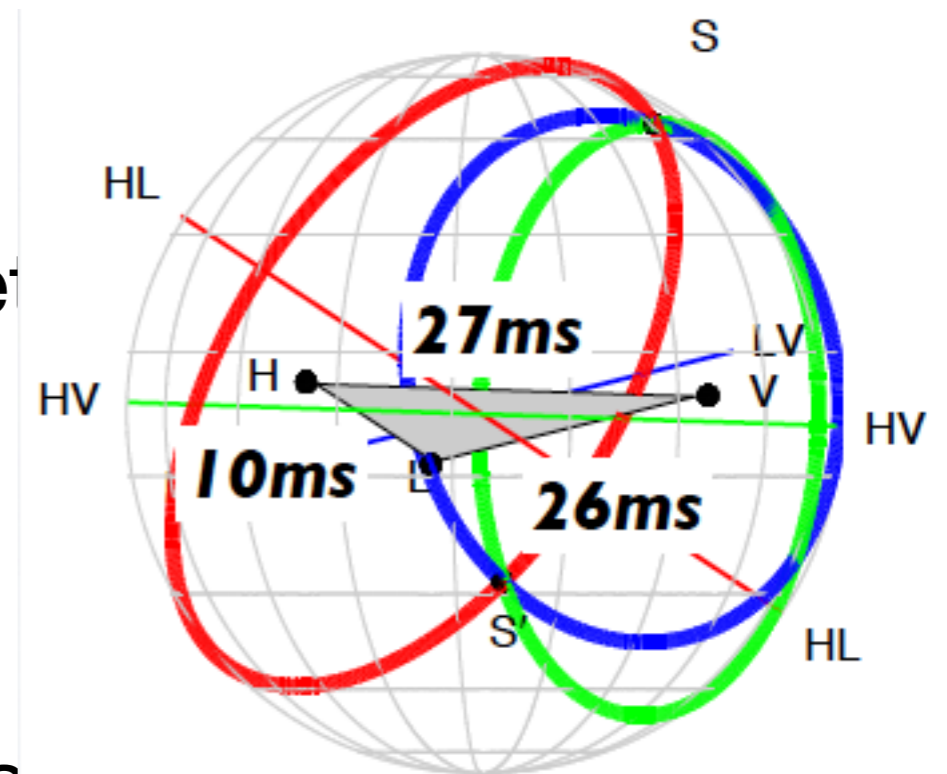
- Laser interferometers similar to LIGO/Virgo covers frequencies higher than 10 Hz (except for ET which will be located underground)

Sensitivity gain and localization

- Detection of more distant sources
- Higher signal-to-noise ratio means better resolution

$$\sin \theta d\theta = \frac{\sqrt{\sigma_1^2 + \sigma_2^2}}{\Delta t} \quad \sigma_t = \frac{1}{2\pi \rho \sigma_f}$$

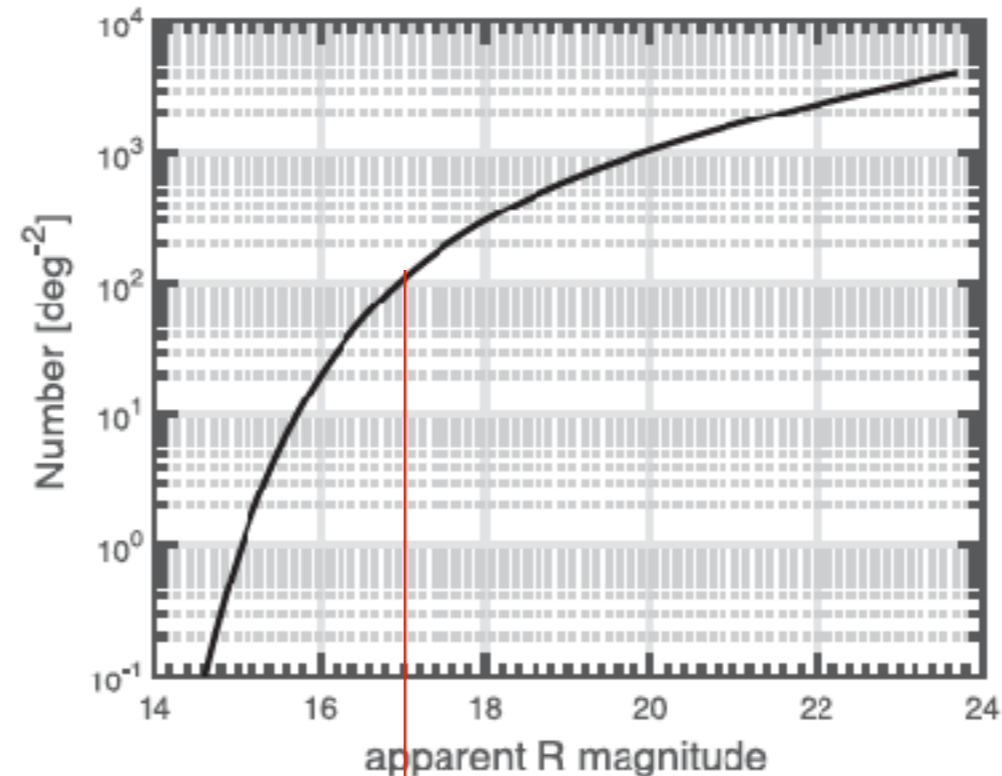
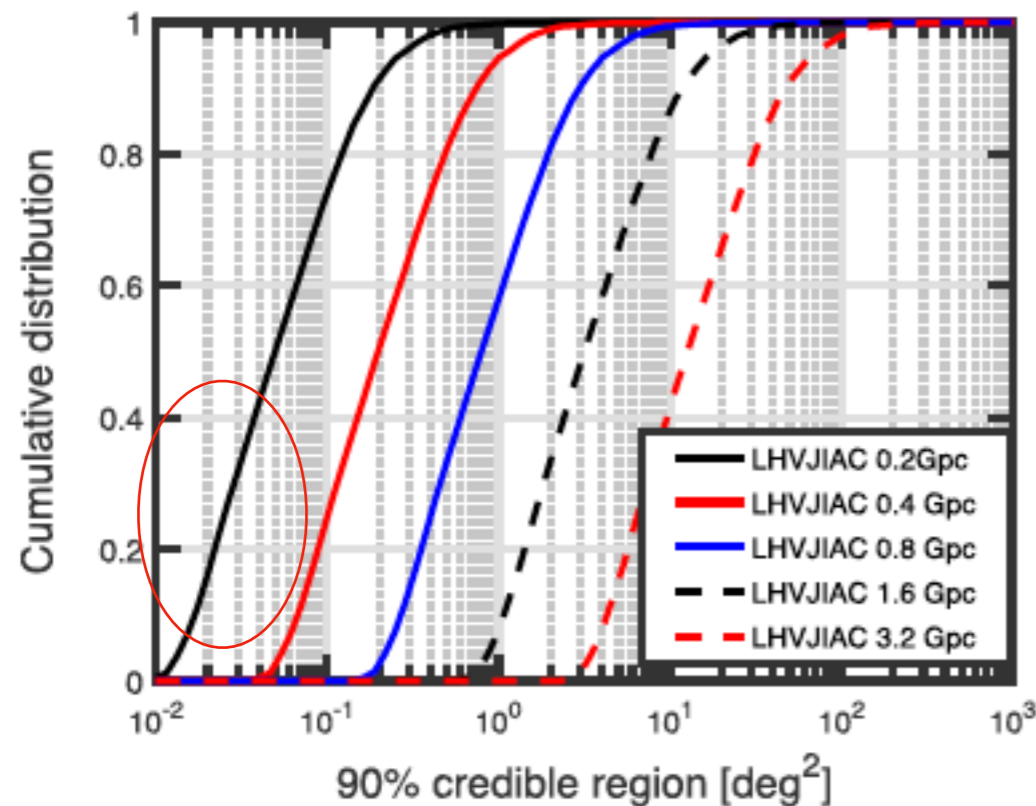
- $d\theta$: width of the ring, Δt : baseline, ρ : Signal-to-noise ratio, σ_f : effective bandwidth of the source, (~ 100 Hz for NS binaries, smaller for BH binaries)



Fairhurst 2011

Can BBH hosts be identified with GW alone?

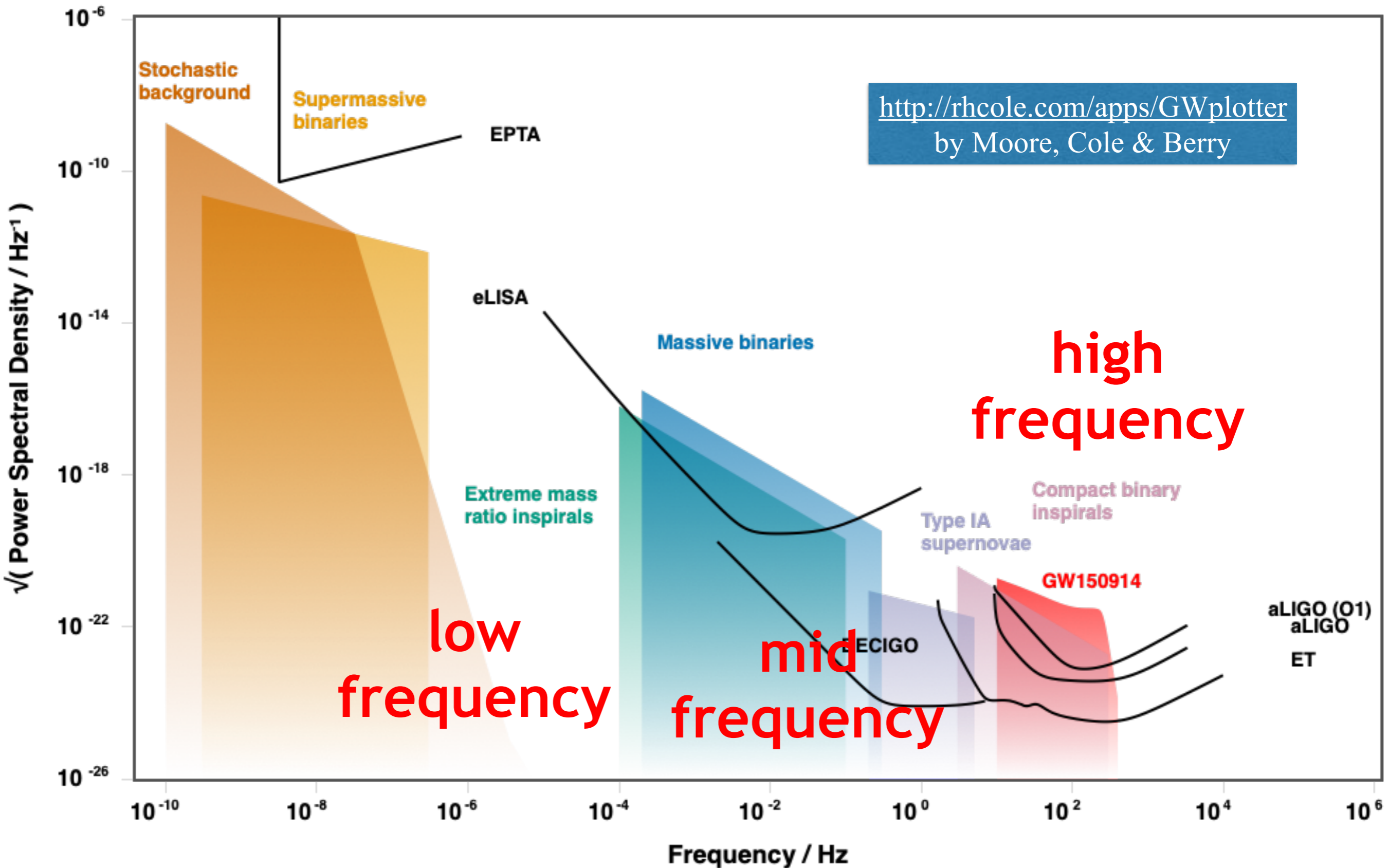
Howell,,, HML,,,et al. 2018



Milky Way Galaxy at 0.4 Gpc

- ~20% of the BBHs at 400 Mpc can be localized with 0.1 sq. deg.
- There could be 10-20 galaxies within the 0.1 sq. deg.

Gravitational Waves in Wide Spectral Range



Sources at different frequencies

- High-frequency
 - LIGO/Virgo
 - 30 - 1000 Hz
 - Stellar mass black holes, neutron stars
- Low Frequency
 - LISA: 0.01 mHz ~ 0.1 Hz
 - White dwarf binaries
 - Massive black holes ($10^6 M_{\text{sun}}$)
 - Pulsar timing array: nHz
 - Lower frequencies than LISA
 - Supermassive black holes (SMBH, $10^{8-9} M_{\text{sun}}$)
- Mid-Frequency
 - 0.01 - 1 Hz
 - Intermediate mass black holes (IMBH, $10^{3-4} M_{\text{sun}}$)
 - New concepts are being discussed

Proposed Future Detectors

(not a complete list!)

- Ground based
 - Einstein Telescope (ET)
 - Cosmic Explorer (CE)
 - Superconducting Omni-directional Gravitational Radiation Observatory (SOGRO)
 - Mid-band Atomic Gravitational-Wave Interferometric Sensor (MAGIS)
- Space based
 - eLISA (Europe/US)
 - Tianqin and Taiji (China)
 - DECIGO (Japan)

Sources involving massive black holes

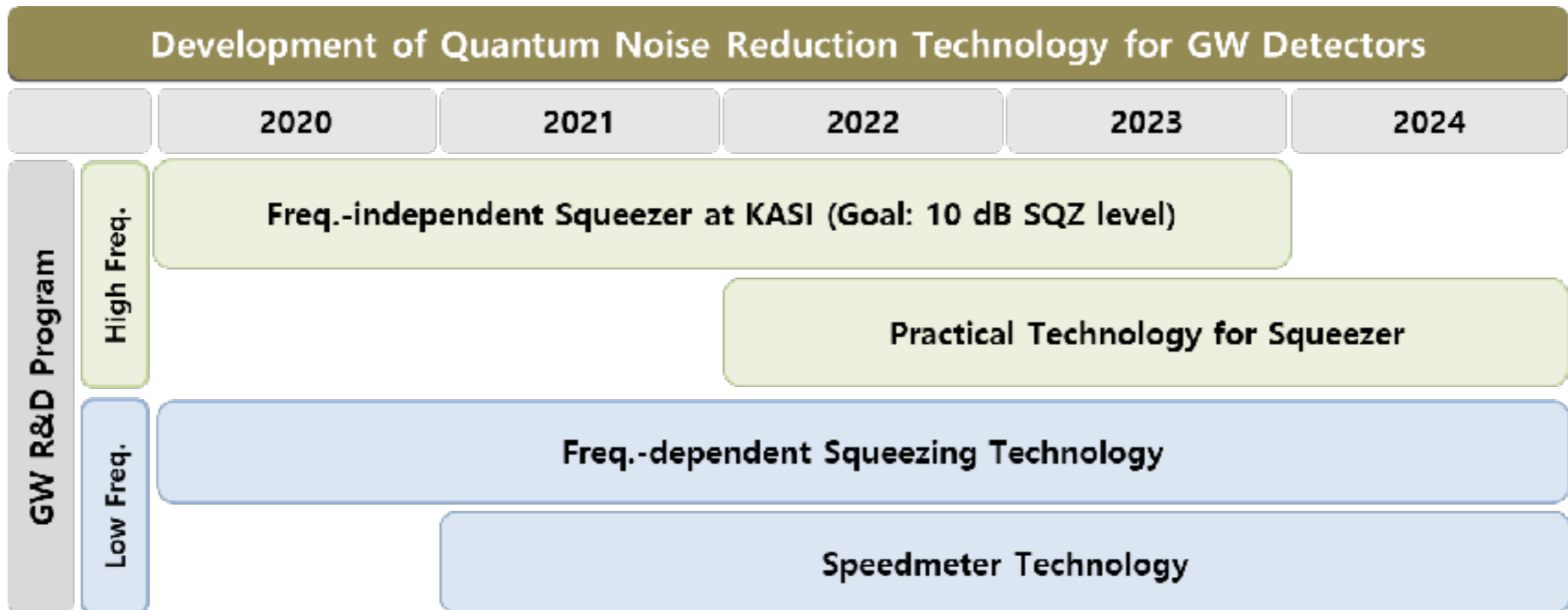
- Extreme mass ratio inspiral (EMRI)
 - $q = m_1/m_2$
 - $m_1 \sim 10^6 M_{\text{sun}}$ (massive black hole), $m_2 \sim 1-10 M_{\text{sun}}$ (NS, stellar mass BH) $\rightarrow q > 10^5$
 - Initially very eccentric, many cycles before being swallowed by the MBH
 - mHz GW, galactic nuclei
- Intermediate mass ratio inspiral (IMRI)
 - $m_1 \sim 10^{2-4} M_{\text{sun}}$ (Intermediate mass BH)
 - $q \sim 10^{2-4}$
 - mili to Deci Hz GW, Star Clusters
- Nearly circular binaries

**Development of Quantum
Noise Reduction at KASI
led by Sungho Lee**



GW R&D Program (from 2020)

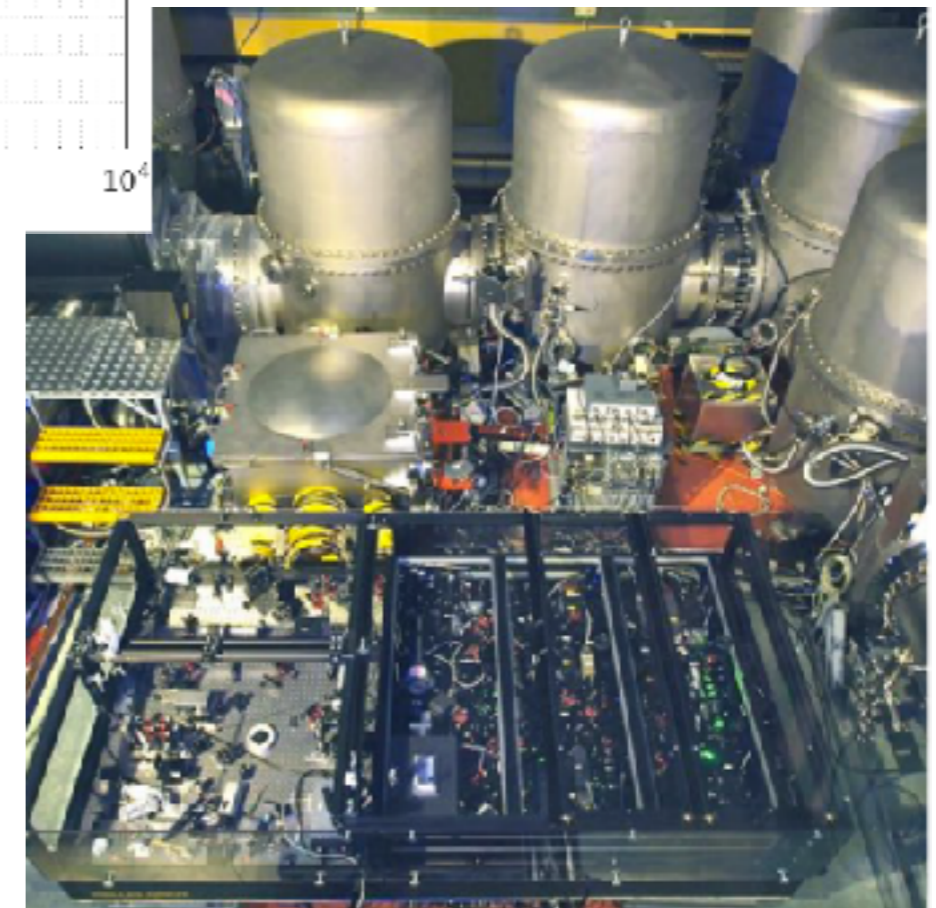
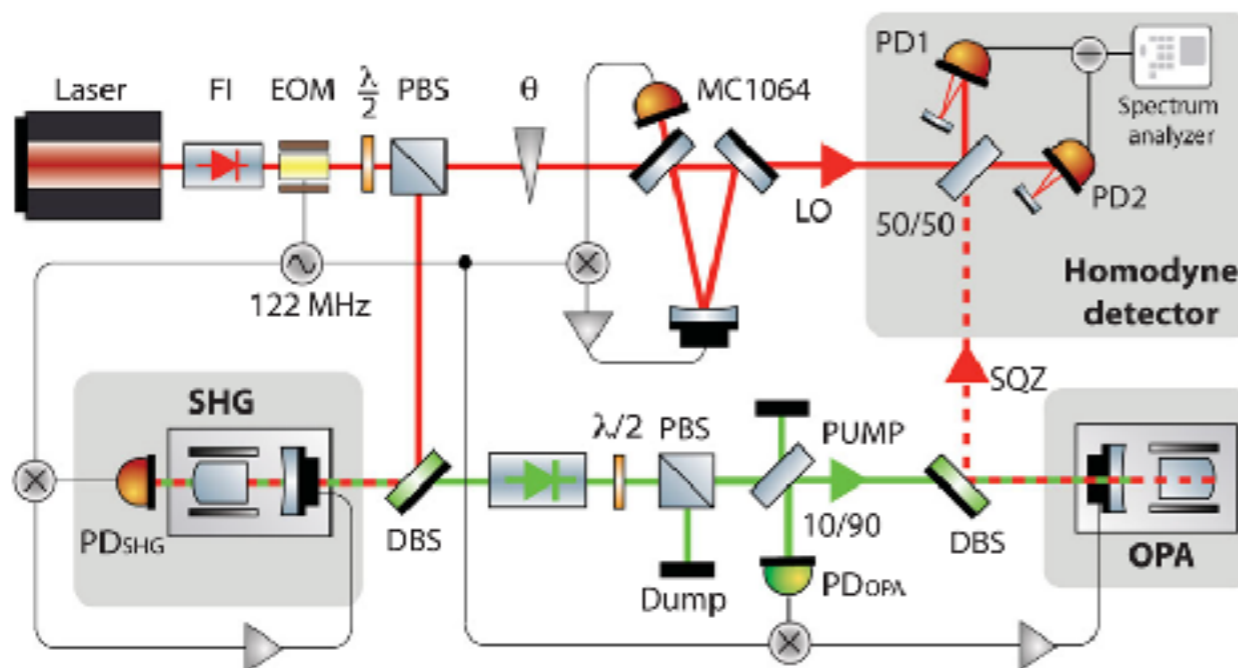
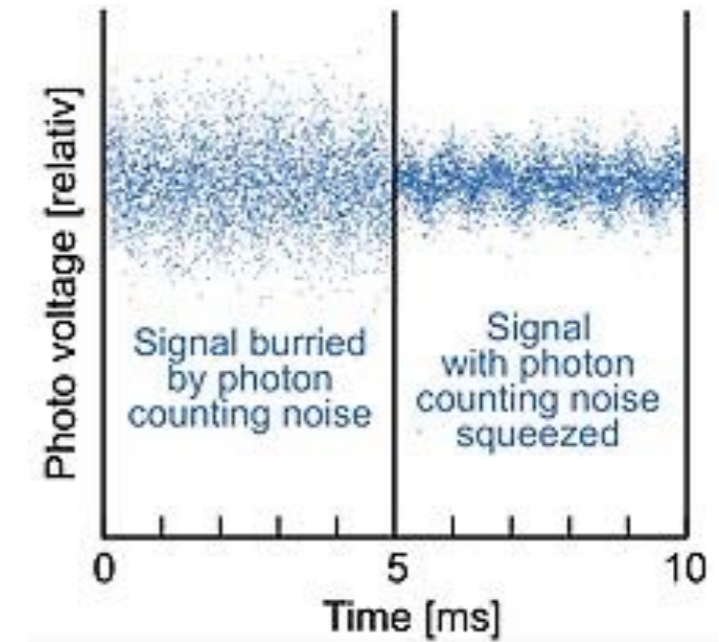
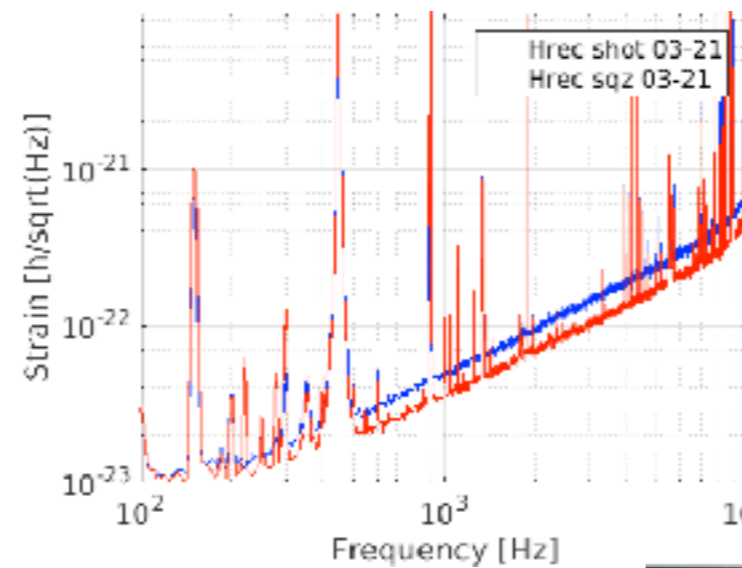
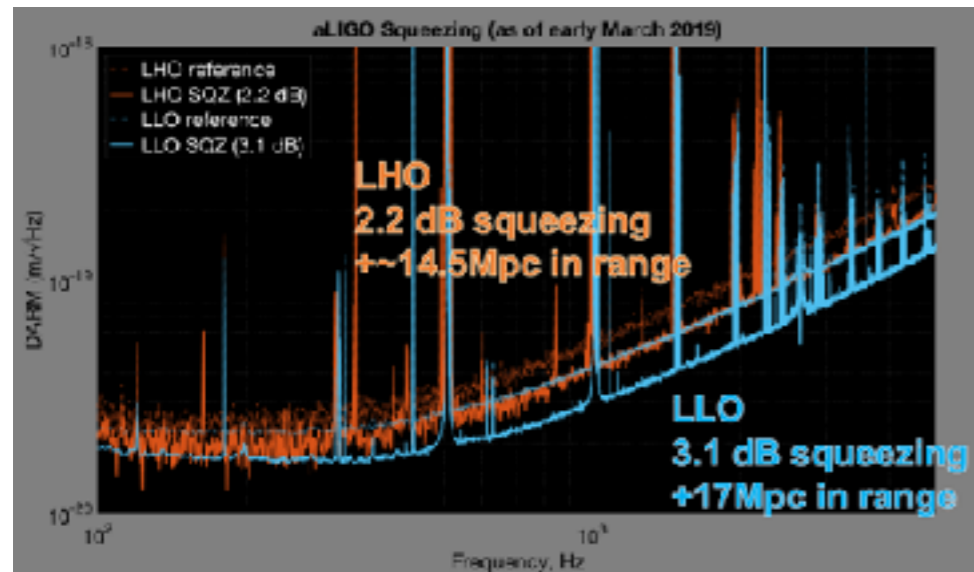
- ❖ Periods : 2020 - 2024 (5 years)
- ❖ Research Topics
 - **Crystal based Squeezer Technology**
 - Extending the pilot study carried out in 2019 together with Myungji U. Group
 - Practical technology improvement for squeezer
 - **Quantum noise reduction at lower frequencies**
 - Frequency dependent squeezing (by international collaborations)
 - Other technologies (Sagnac interferometer, non-demolition measurement)





Squeezer Technology Development

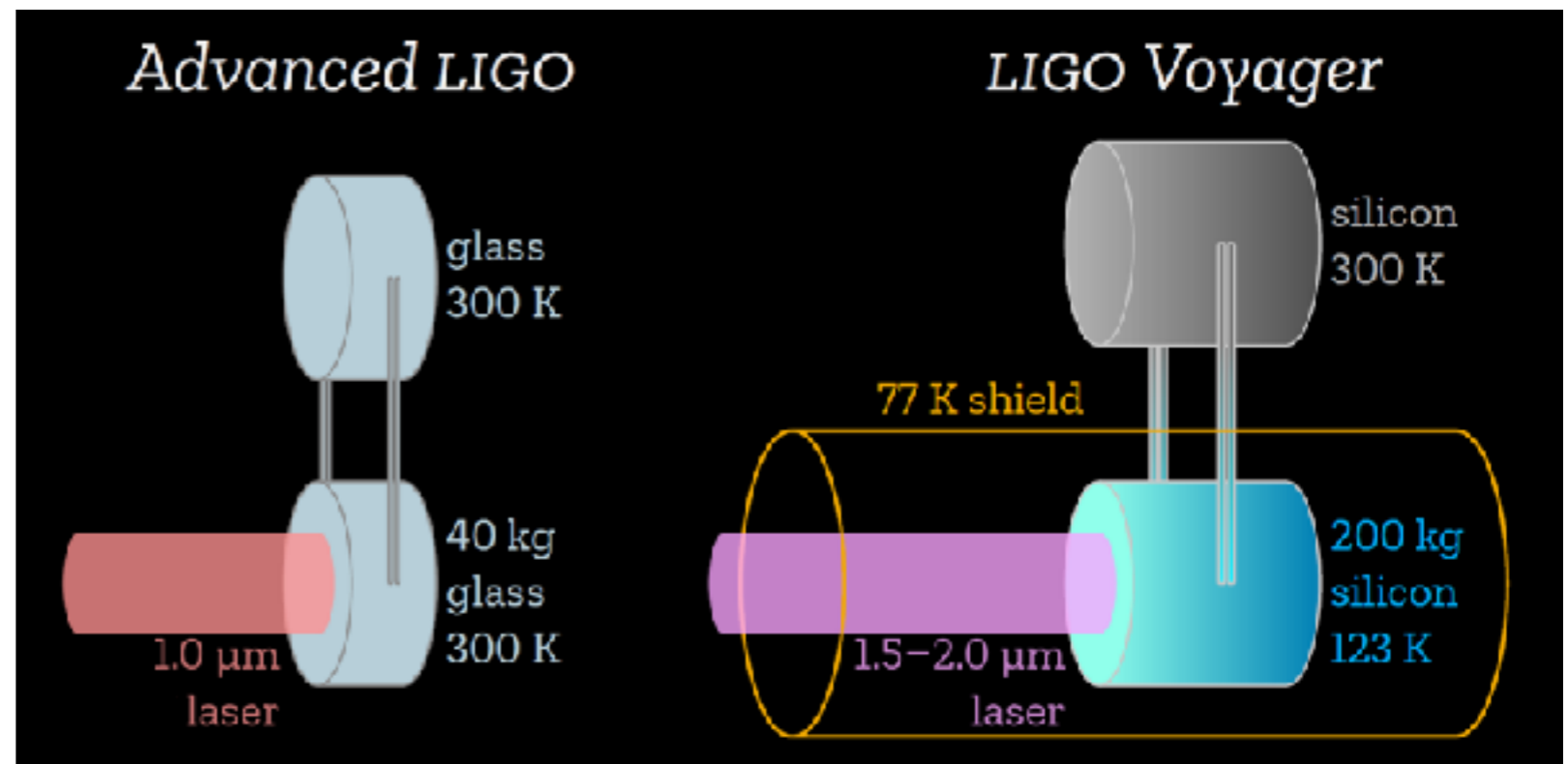
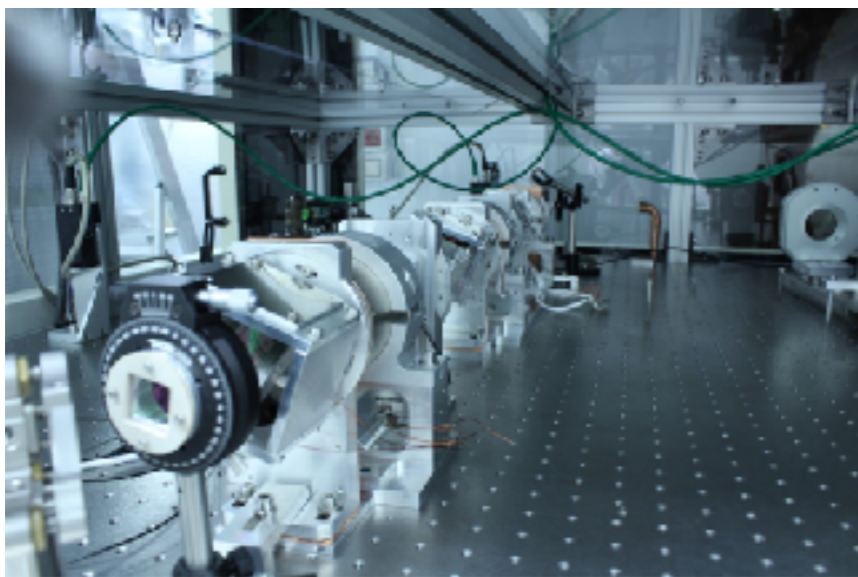
- ❖ Development of a freq.-independent squeezer at KASI
 - Goal: 10 dB SQZ level
 - Fundamental study for R&D capability at KASI
 - Basic testbed for related studies





Squeezer Technology Development

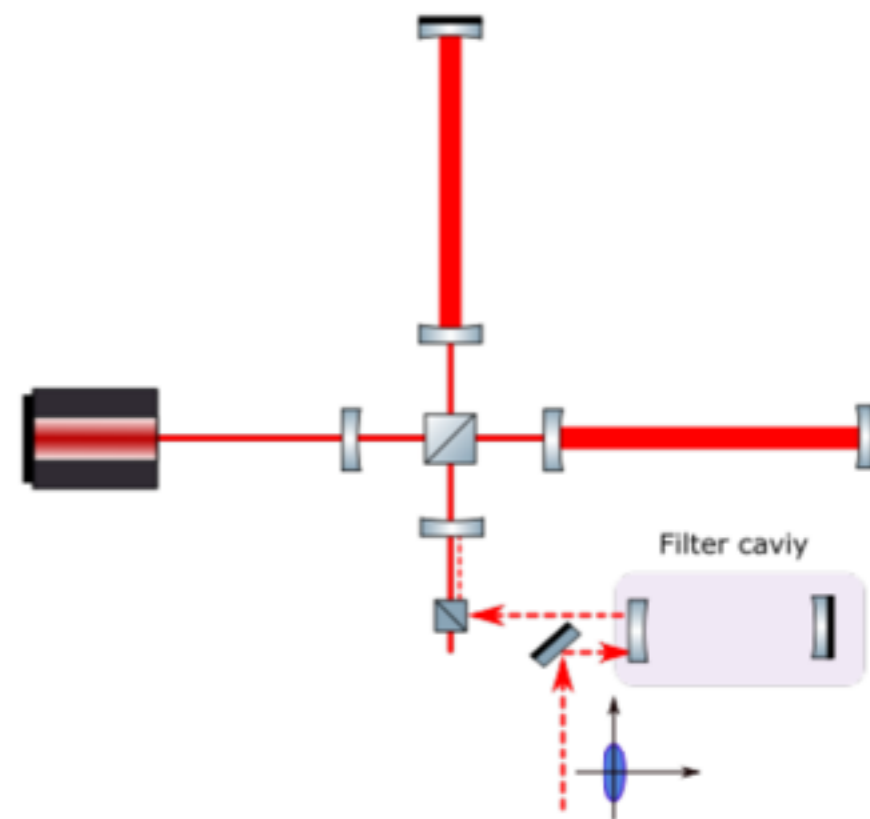
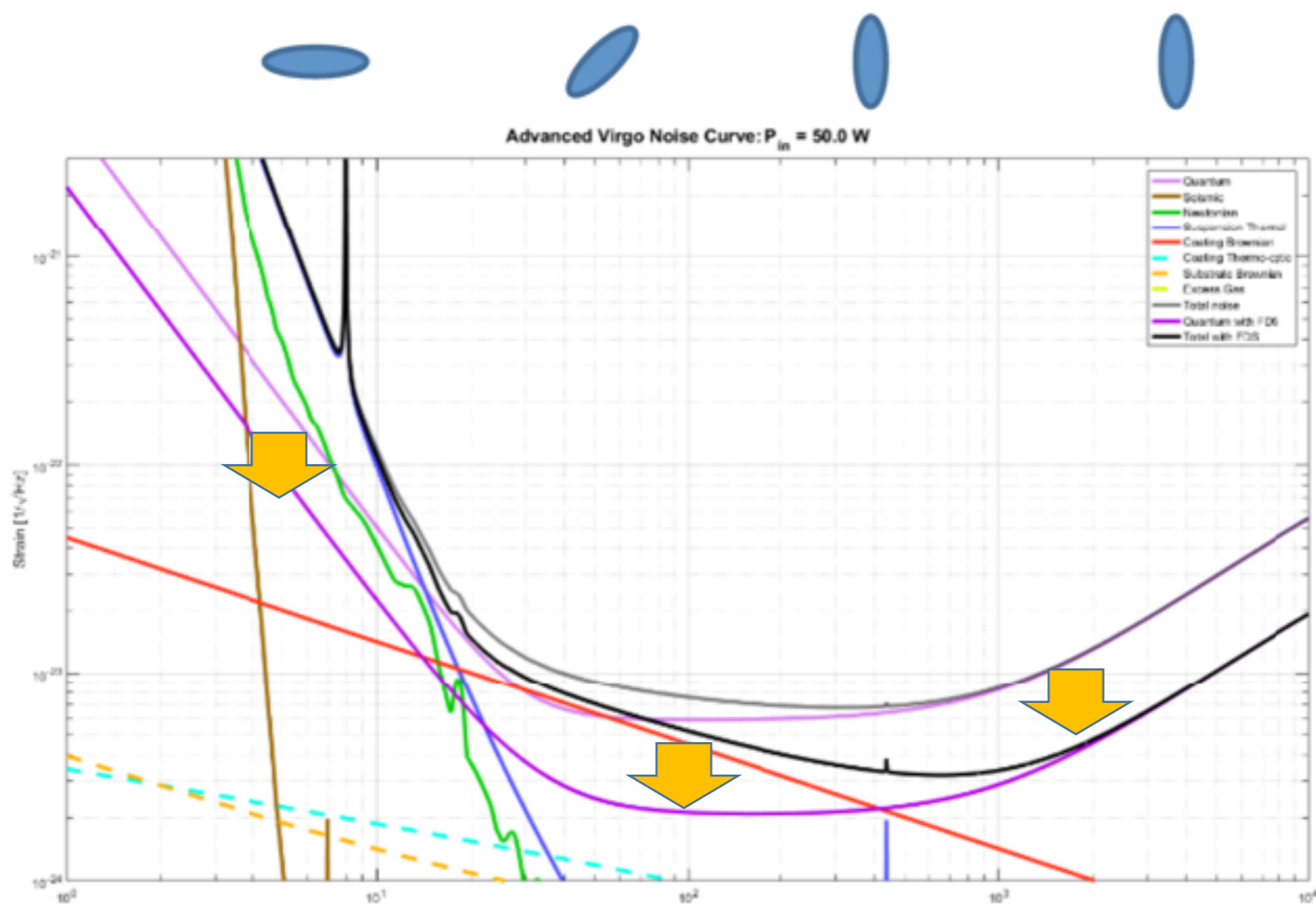
- ❖ Practical technology improvement for squeezer
 - Compact squeezer: to reduce optical loss by less number of components
 - Squeezer in vacuum: to reduce optical loss, phase error by interface, etc.
 - Longer wavelength squeezer (e.g. $1.5 \mu\text{m}$): for cryogenic GW detectors
 - Spatial mode-matching technology based on multi-mode squeezing
- Prototyping of one or more selected technology





Quantum Noise Reduction at Lower Freq.

- ❖ Frequency dependent squeezing using filter cavity
 - Collaboration with NAOJ and NTHU for KAGRA upgrade
 - Participation to TAMA 300 experiment from 2020
 - Contribution to development of the KAGRA filter cavity (~60 m) (cavity length control, optical fabrication, etc.)



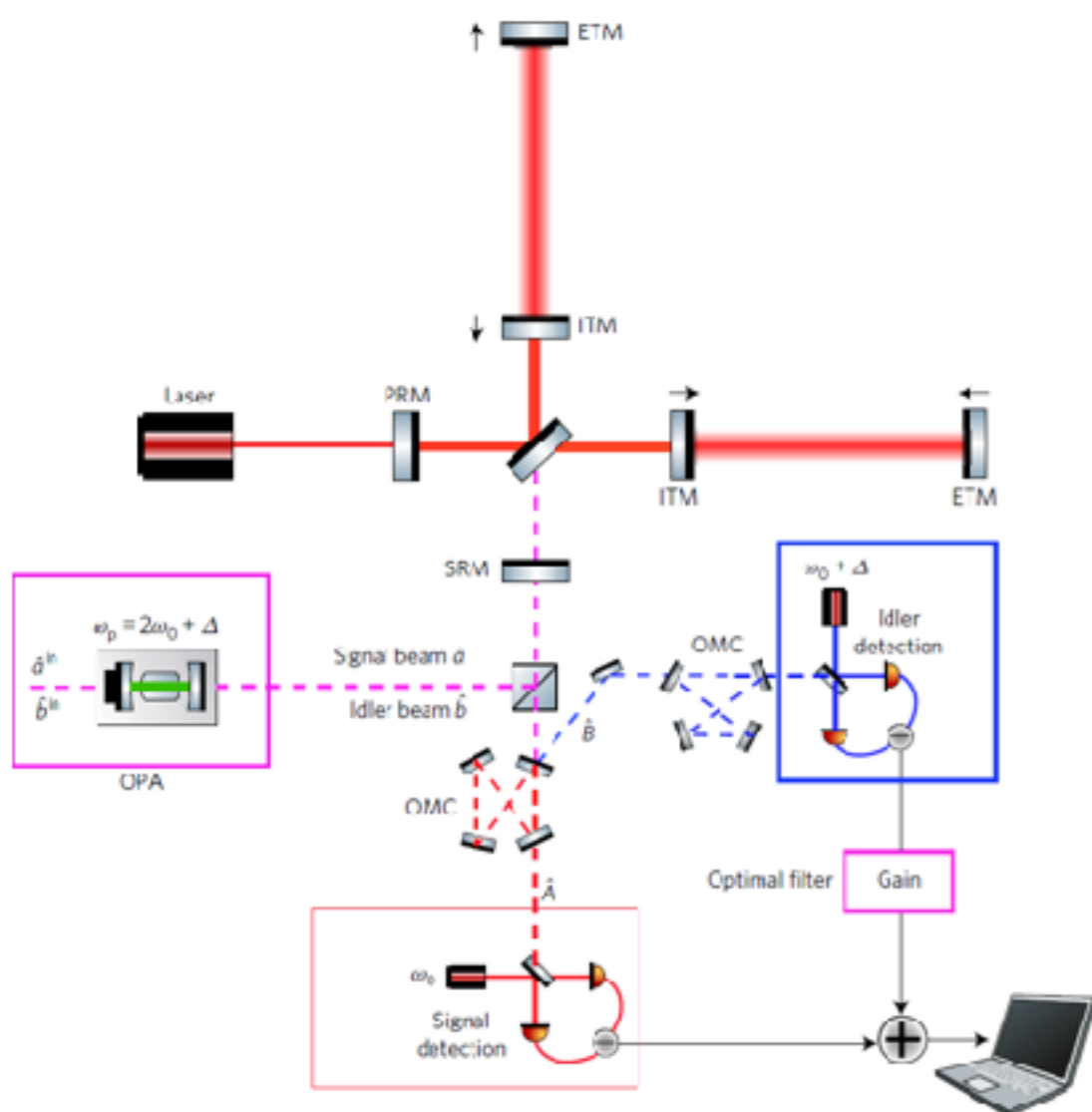
F. Sorrentino – QN reduction in AdV



Quantum Noise Reduction at Lower Freq.

❖ Development of EPR technology

- Participation to the Virgo/ET R&D
 - ① Table top demonstration
 - ② Implementation on a testbed interferometer
 - ③ Development for AdV+ and ET



Interferometer de-tuned for the idler

Interferometer working like a filter cavity for the idler















Idler freq.-dependent squeezed

Measurement of an idler fixed quadrature

Signal conditionally squeezed in a freq. dependent way



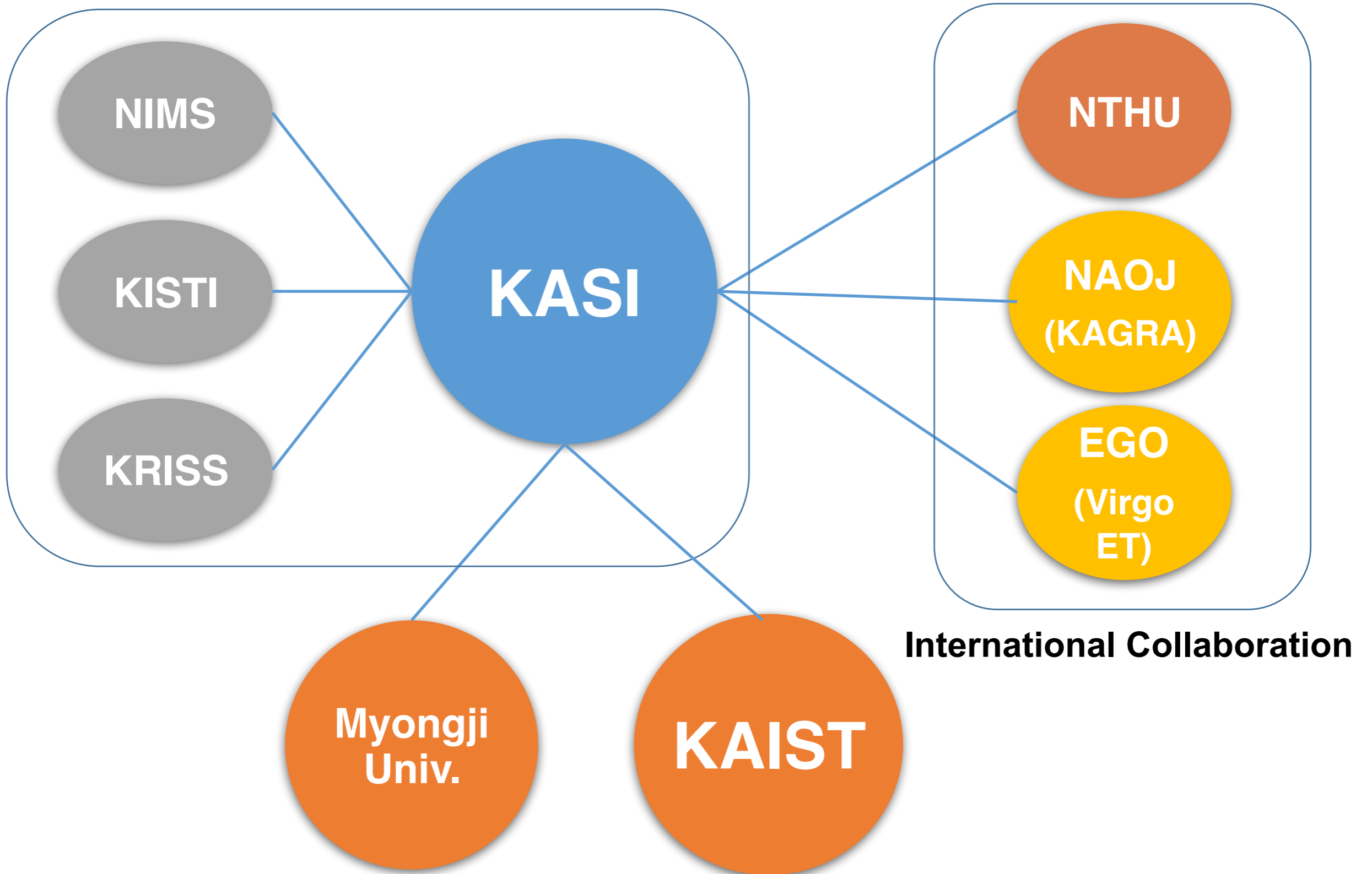
Squeezing R&D Team at KASI

						
Systems Engineering	Opto-Mechanics, Optical Fabrication	Optics, Metrology, Alignment	Control Electronics, Cryogenics	Opto-mechanics, Cryogenics	Opto-mechanics	Detector Electronics
						
Project Management, Optics	Project Management, Systems Engineering	Mechanics	Electronics, Software	Electronics, Systems	Optical Fabrication, Alignment	Electronics
+ Two PostDocs from March 2020						



Collaboration for Squeezing

MoU for GW Technology Development





Collaboration – KAIST



Prof. Young-Sik Ra
Dept. of Physics /
Optics Lab *Quantum*



(2018.11~present)



Ms. Geunhee Gwak
Graduate student



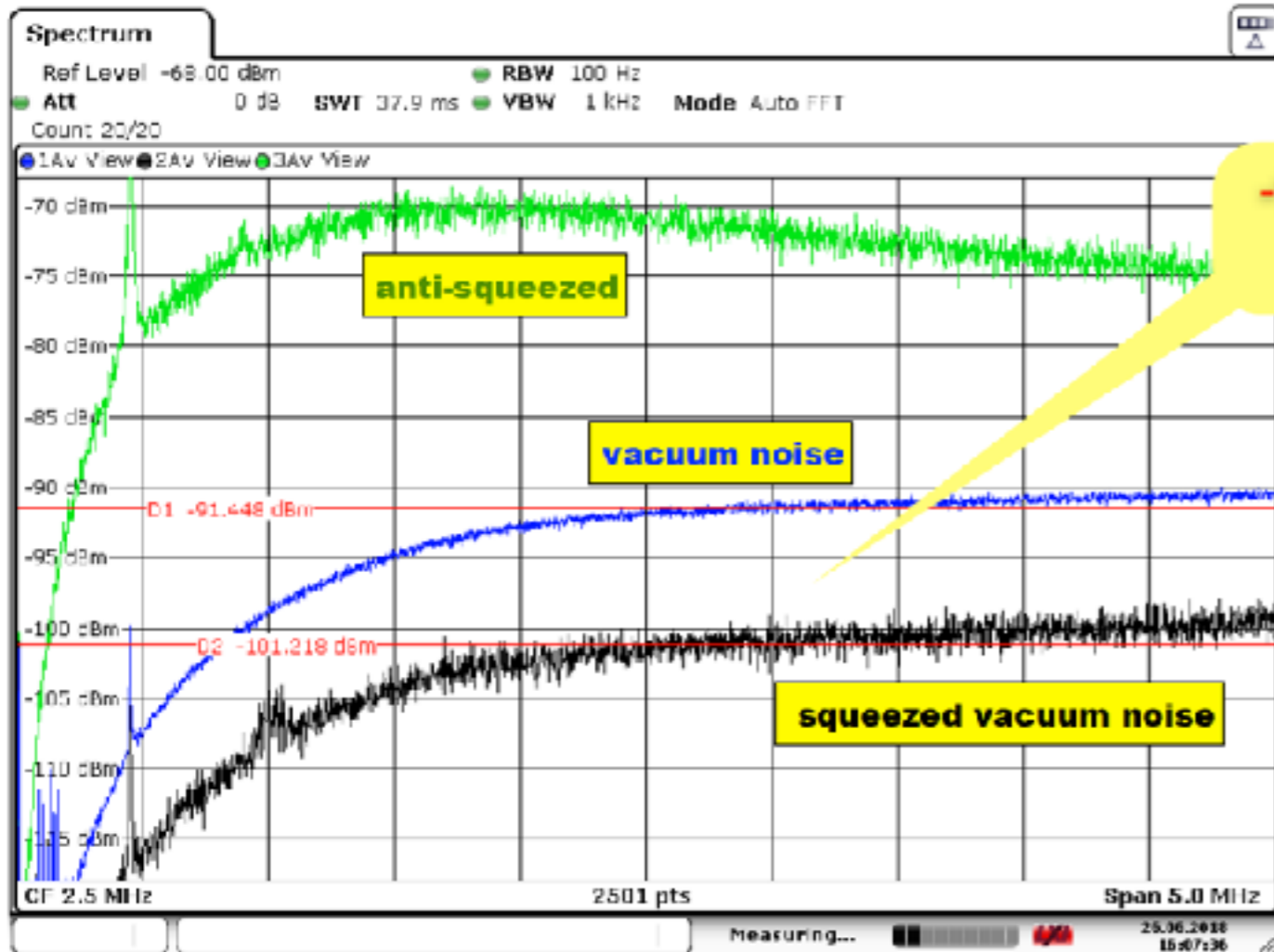
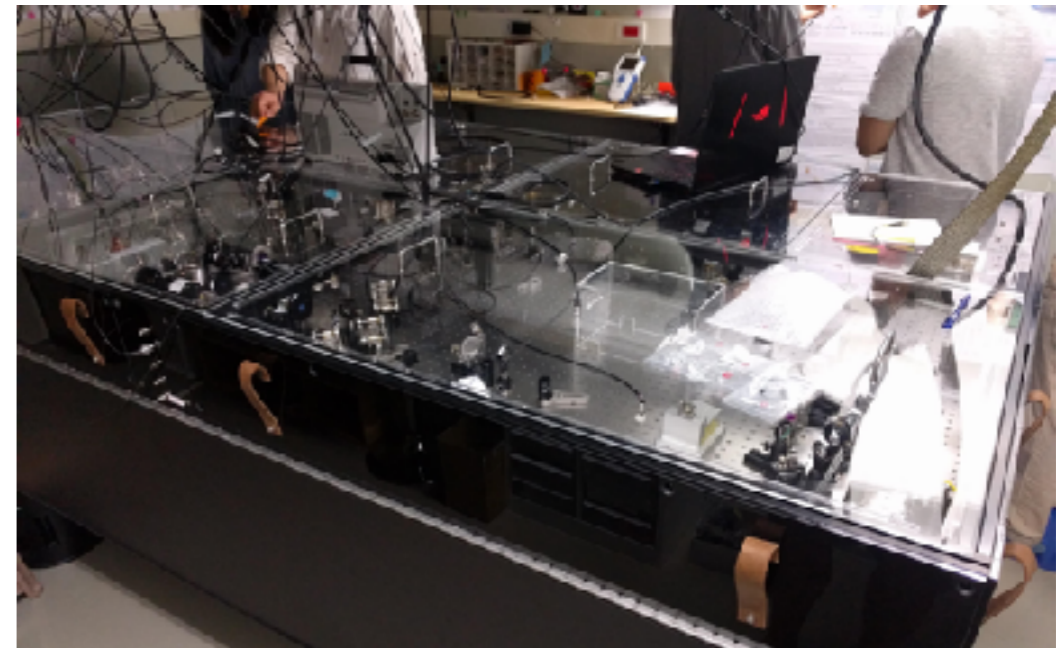
- **Generation and measurement of nonclassical light**
 - Single-photon source and multiple-photon entangled states
 - Multimode squeezed vacuum states
 - Multimode non-Gaussian states
- **Quantum interference**
 - Hong–Ou–Mandel interference
 - Multi-photon interference and its coherence properties
 - Decoherence in multi-photon interference
- **Quantum information processing**
 - Encoding quantum information on nonclassical light
 - Manipulating and exploiting quantum entanglement
 - Optical quantum computing



Collaboration – NTHU



Prof. Raykuang Lee
National Tsing Hwa Univ.



-10dB Squeezed vacuum between 1-5 MHz

Scan 10Hz ~ 5MHz
RBW=100 Hz

Squeezed at 3MHz
-9.76dB

Blue Line: 14.5mW Vacuum noise
Black Line: Squeezed signal
Green Line: Anti-squeezed signal



by Chien-Ming Wu (吳建明博士)

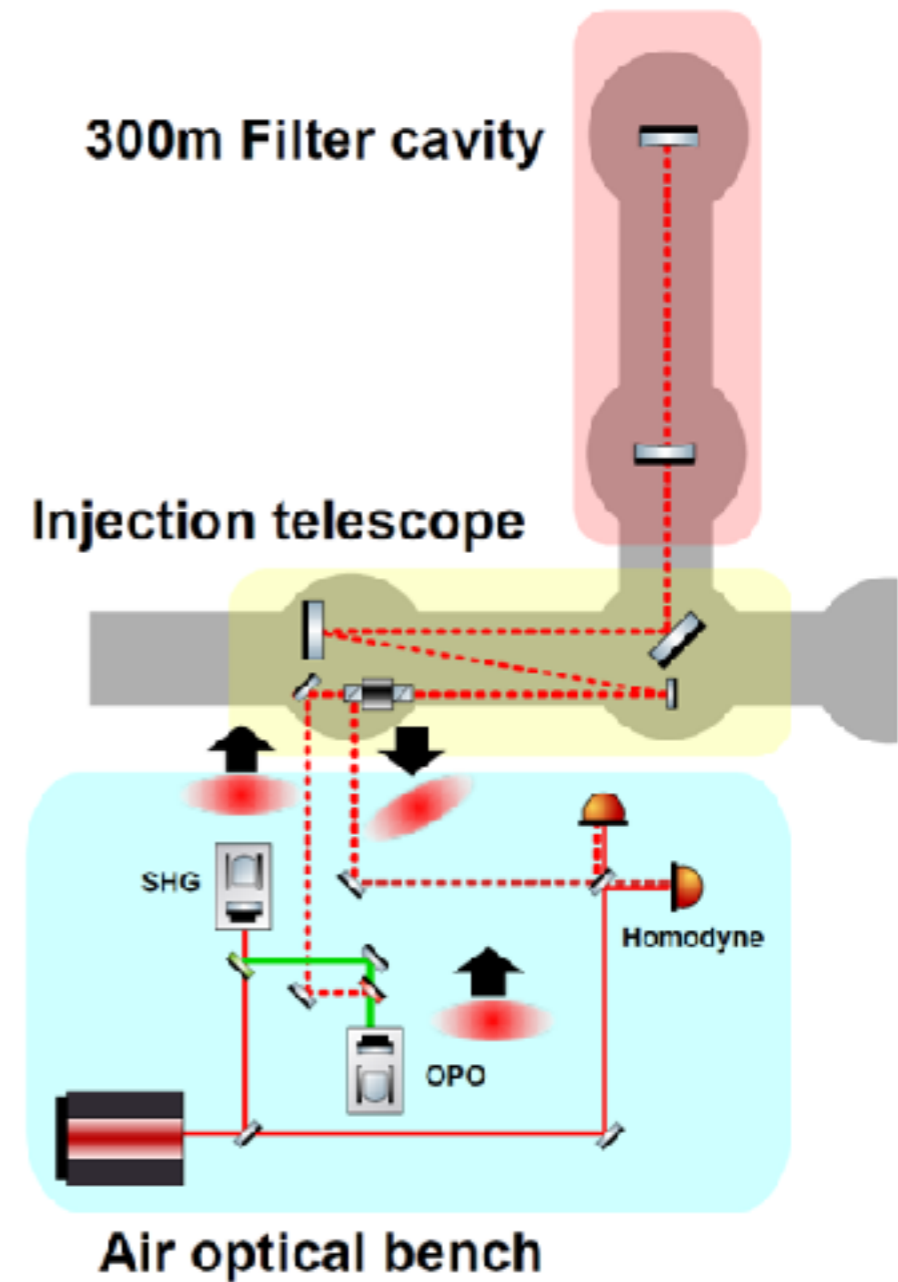
Date: June 26th, 2018



Collaboration – NAOJ (KAGRA)



*Prof. Matteo Leonardi
Natl. Astronomical Obs. of Japan*



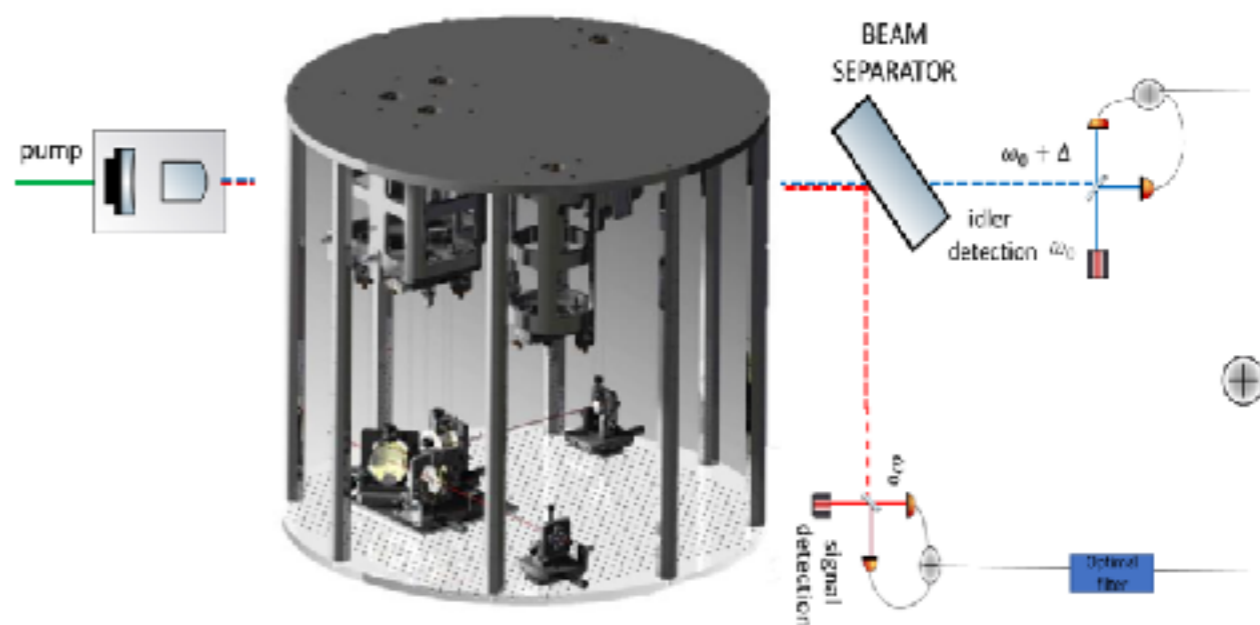
- Participation to TAMA 300 experiment from 2020
- Contribution to KAGRA filter cavity (60 m) (cavity length control, optical fabrication, etc.)



Collaboration – EGO (Virgo/ET)



Dr. Luca Naticchioni
INFN/EGO



- Experiments at EGO for EPR Squeezing
- Component R&D at KASI
 - Development of Alternative cavities
 - Automatic alignment algorithms
 - Vacuum squeezer technology

Summary

- O3 underway, to be completed by the end of April 2020
- Future ground-based laser interferometer detectors include
 - Improvement based on current infrastructure (up to factor of 3)
 - New infrastructure (more than an order of magnitude)
- In Korea, KASI is just launched a project for development of quantum noise reduction