Design of the LCGT interferometer observation band

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On behalf of LCGT BW
special working group

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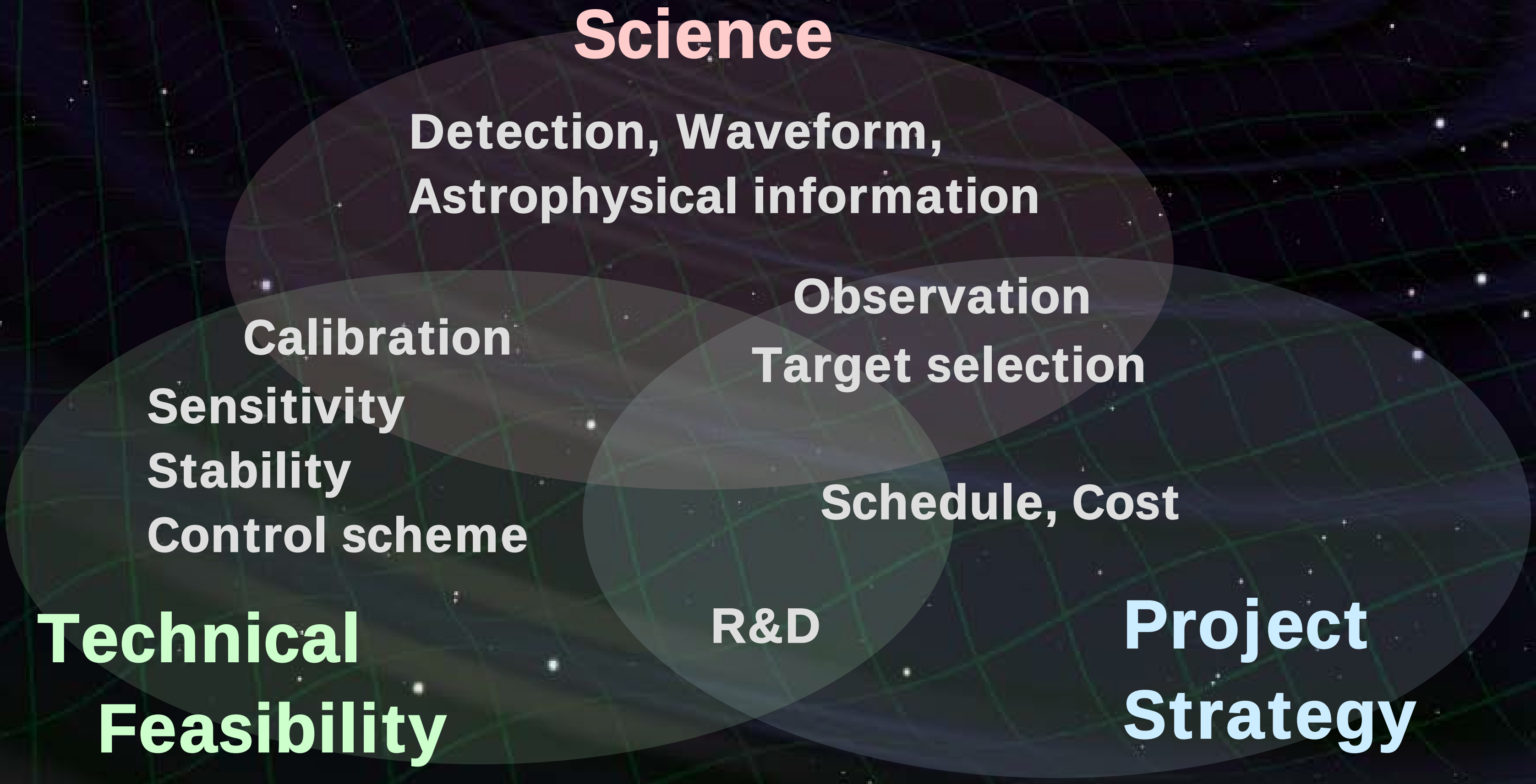
Abstract

Explain how
the observation band of
a LCGT interferometer
(and the optical configuration)
has been determined.

Scope

Interferometer observation band should be determined with investigations from various view point…

⇨ **Special working group**



Science

Detection, Waveform,
Astrophysical information

Observation
Target selection

Calibration
Sensitivity
Stability
Control scheme

Schedule, Cost

R&D

Technical Feasibility

Project Strategy

Outline

Introduction

Candidate configurations

Science outcomes

Technical Feasibility

Project Strategy

Conclusion

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Interferometer setup

Based on LCGT original designs

Arm length of 3km, Underground site of Kamioka

Cryogenic mirror and suspension

High-power RSE interferometer with cryogenic mirrors

Resonant-Sideband Extraction

Input carrier power : 75W

DC readout

Main IFO mirror

20K, 30kg (Φ250mm, t150mm)

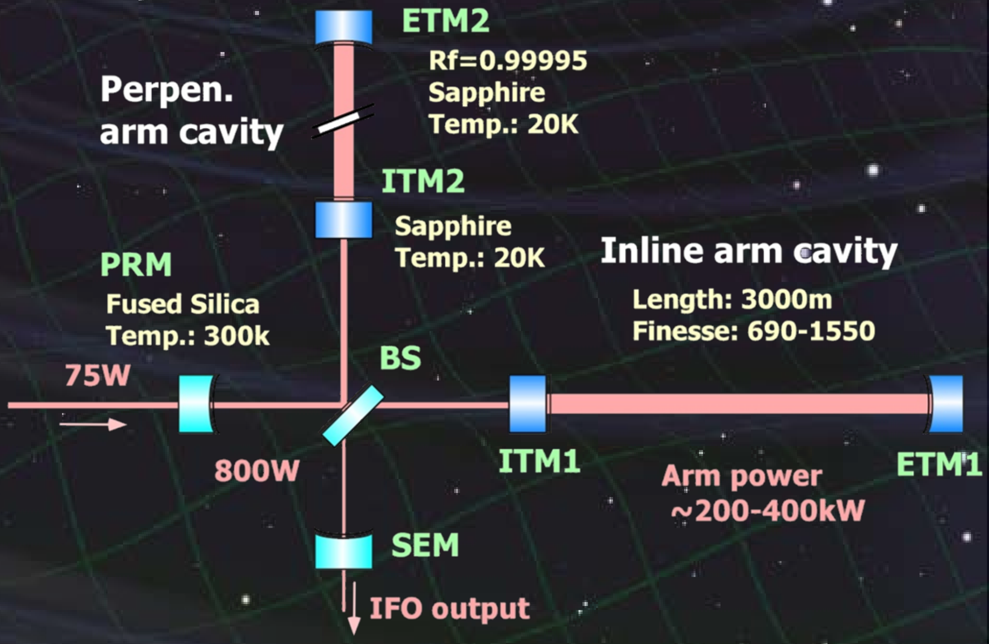
Mech. Loss : 10^{-8}

Opt. Absorption 20ppm/cm

Suspension

Sapphire fiber 16K

Mech. Loss : 2×10^{-8}



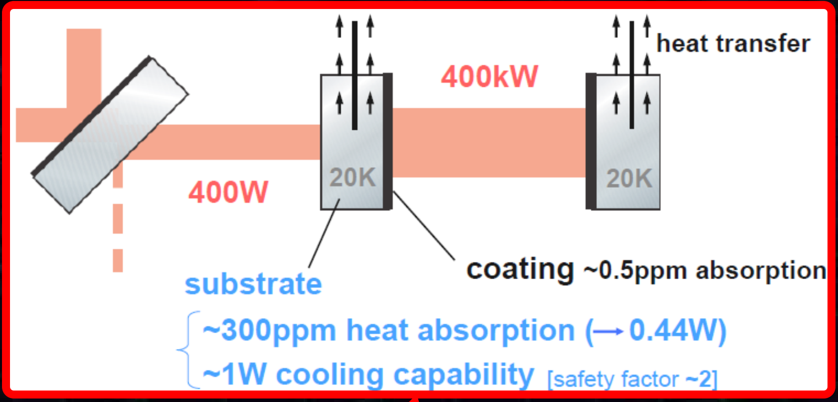
RSE and cryogenics

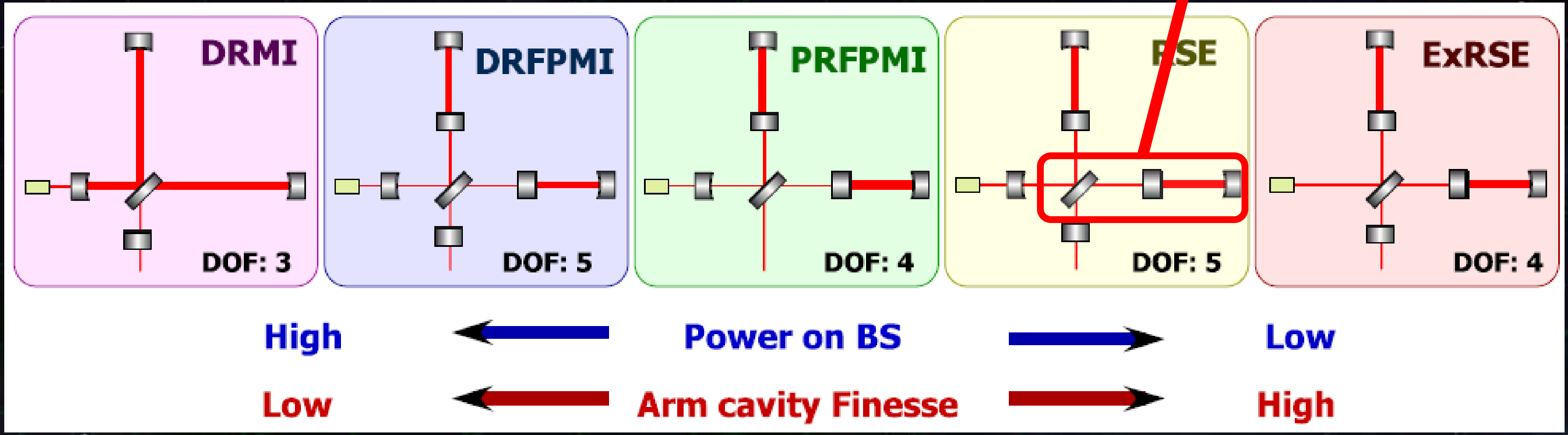
RSE

- High arm-cavity finesse
- moderate Power recycling gain
  - → Smaller optical loss and absorption in ITM substrate

⇨ high power and cryogenics

Figure: K.Somiya





Quantum and Classical noises

Quantum noise is dominant

→ **Optimization of RSE configuration** ⇨ **Tuning of obs. band**
DC readout

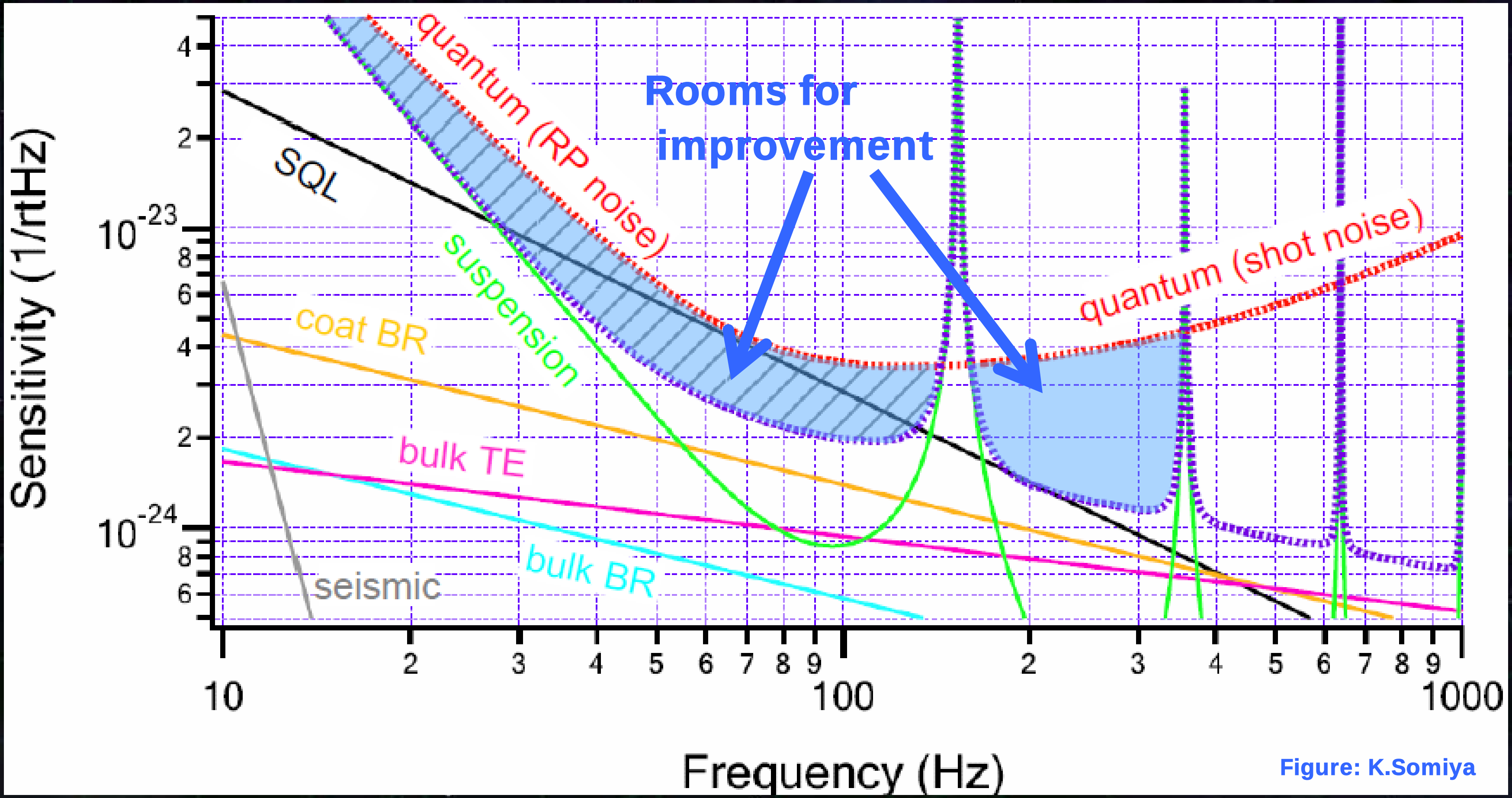


Figure: K.Somiya

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Tuning of observation band

Tune the resonance condition of Signal-Extraction Cavity ⇨ Enhance IFO response, Reduce quantum noise at certain frequency band

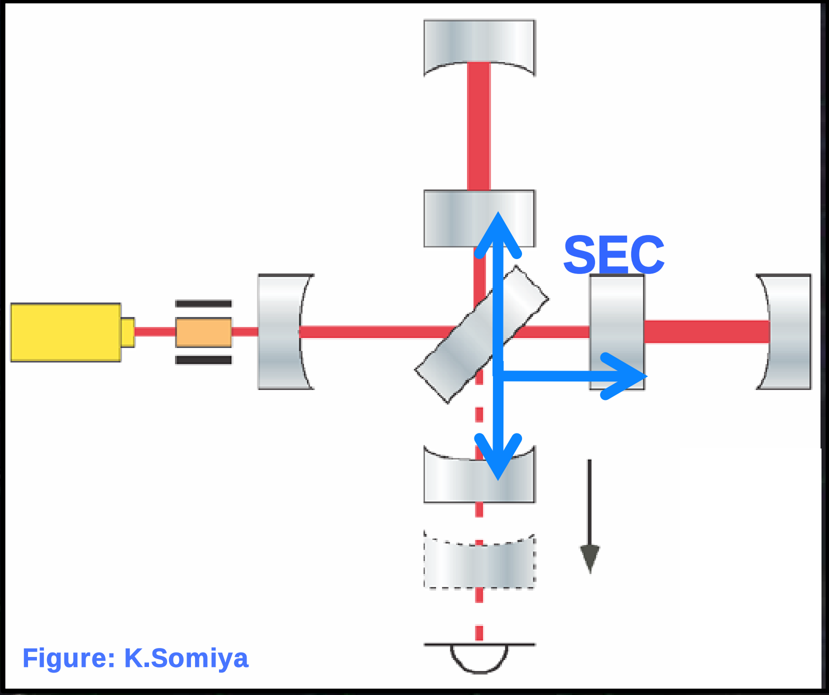

Figure: K.Somiya

Optimal reflectivity of mirrors are different in Broadband RSE (BRSE) and Detuned RSE (DRSE) configurations

Variable RSE (VRSE)
Change tuning without replacement of mirrors or changing in macroscopic position

Candidate configurations

4 candidate configurations

	Broadband	Detuned
Fixed	BRSE	DRSE
Variable	VRSE-B	VRSE-D

⇨

Optimize parameters for Neutron-star binary inspirals

(Primary target of LCGT)

Arm cavity finesse, SEC finesse

Detuning phase, DC readout phase

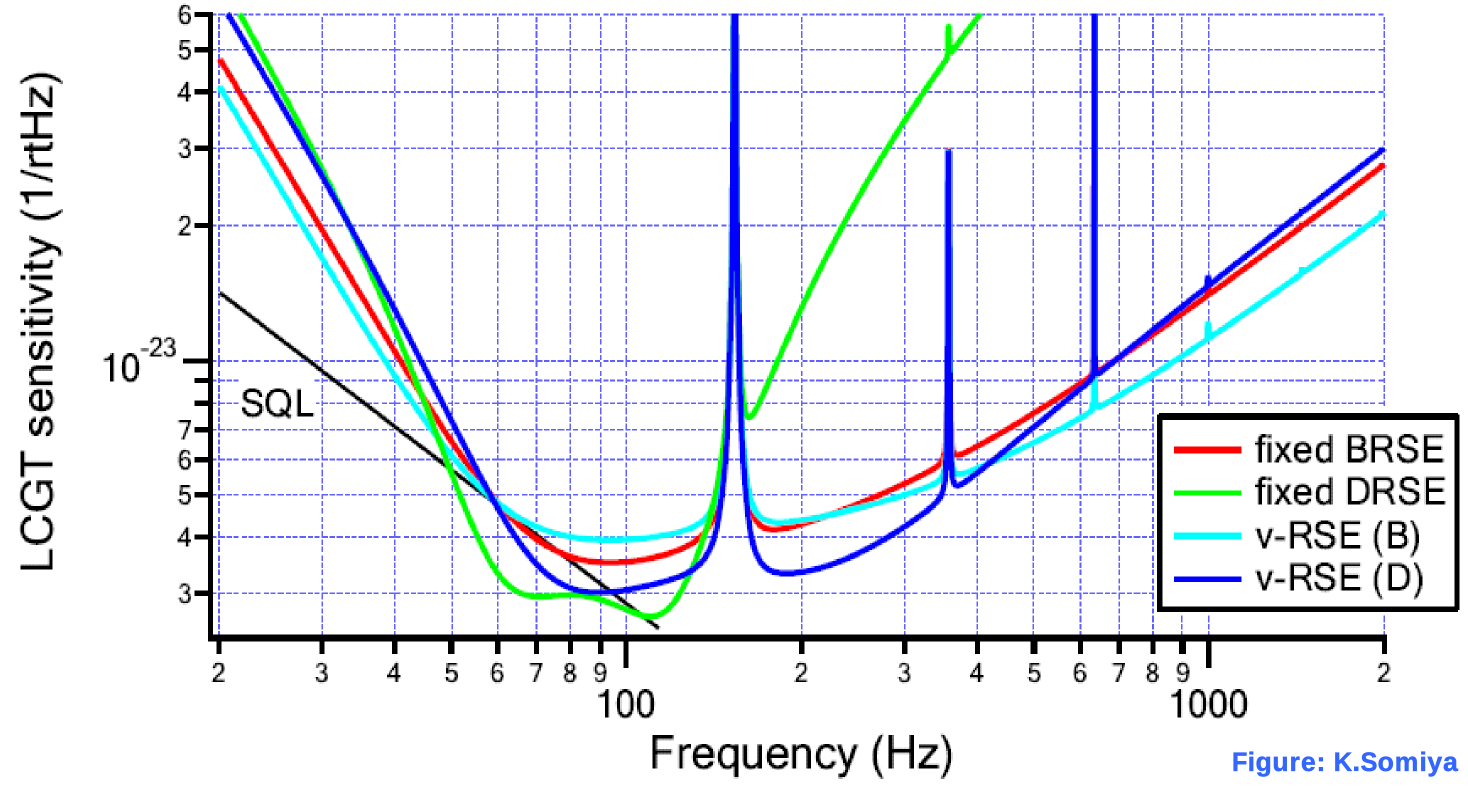

Figure: K.Somiya

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Neutron-star binaries

Primary purpose of LCGT : Detection of GW

→ **First target : Neutron-star binary inspirals**

Observable range :

estimated from sensitivity curve

Galaxy number density :

$$\rho = 1.2 \times 10^{-2} \quad [\mathrm{Mpc}^{-3}]$$

R. K. Kopparapu et.al.,
ApJ. 675 1459 (2008)

Event rate :

$$\mathcal{R} = 83.0^{+209.1}_{-66.1} [\mathrm{events/Myr}]$$

V. Kalogera et.al.,
ApJ, 601 L179 (2004)

	Observable range	Detection rate
BRSE	114 Mpc	5.4 yr^{-1}
VRSE-B	112 Mpc	5.2 yr^{-1}
VRSE-D	123 Mpc	6.9 yr^{-1}
DRSE	132 Mpc	8.2 yr^{-1}

(SNR 8, Sky averaged)

Detection probability

Detection probability in one-year observation

⇨ **Success probability of the LCGT project**

	IR	DP
BRSE	114 Mpc	99.6 %
VRSE-B	112 Mpc	99.4 %
VRSE-D	123 Mpc	99.9 %
DRSE	132 Mpc	99.9 %

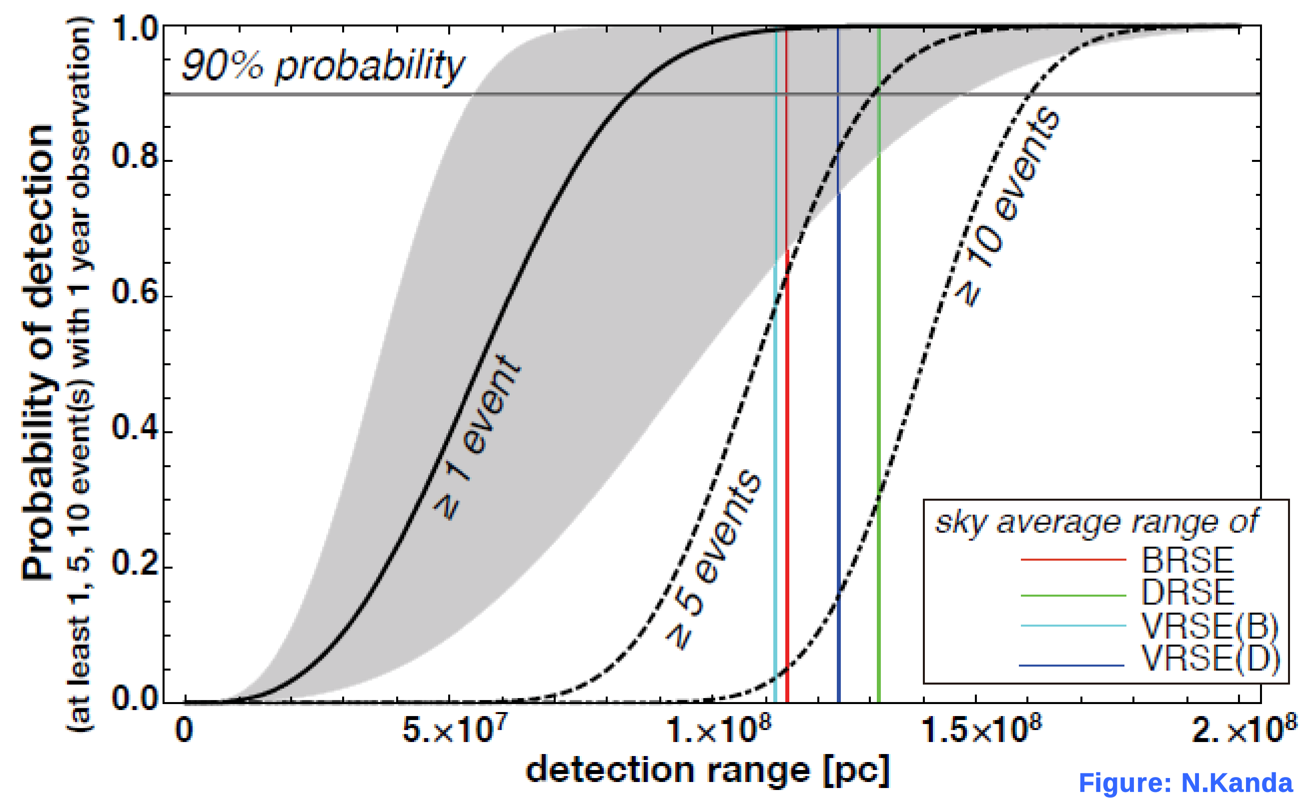


Figure: N.Kanda

Assume
Poisson distribution

Parameter Estimation

Errors in parameter estimation from observed waveform

	SNR	Arrival time	Mass parameters	
mass 1.4-1.4	ρ (@185Mpc)	δtc [msec]	δMc/Mc	δη/η
BRSE	14.0	0.24	$2.0x10^{-5}$	0.0042
DRSE	19.1	0.73	$5.2x10^{-5}$	0.010

By H.Tagoshi

⇨ **DRSE has better observable range,**
but poorer astrophysical information
(factor ~2 difference)

Other Targets

Binary black hole

- Obs. range : 570-670 Mpc

Black hole Quasi-Normal mode

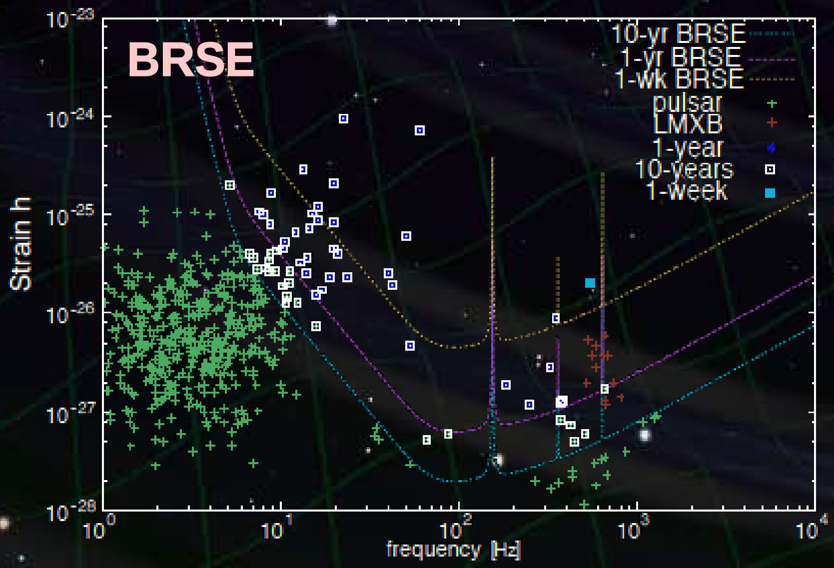
- Obs. range : 2-3 Gpc

Core-collapse supernova

- Galactic events are detectable
- Out of band for DRSE ?

Pulsars

- 25-38 pulsars within band
- Better sensitivity than spin-down upper limit
- Less targets for DRSE



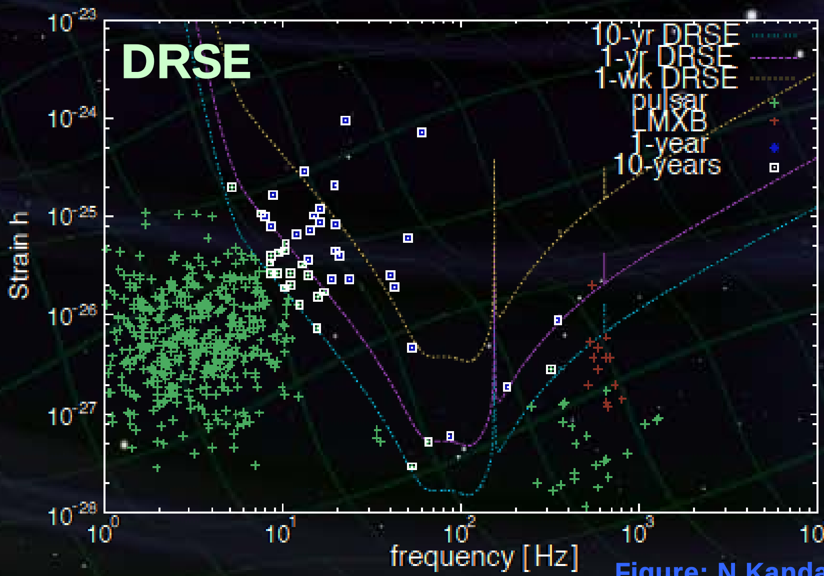


Figure: N.Kanda

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Technical feasibility

Mainly discuss the difference in technical difficulties
though there will be many common problems…

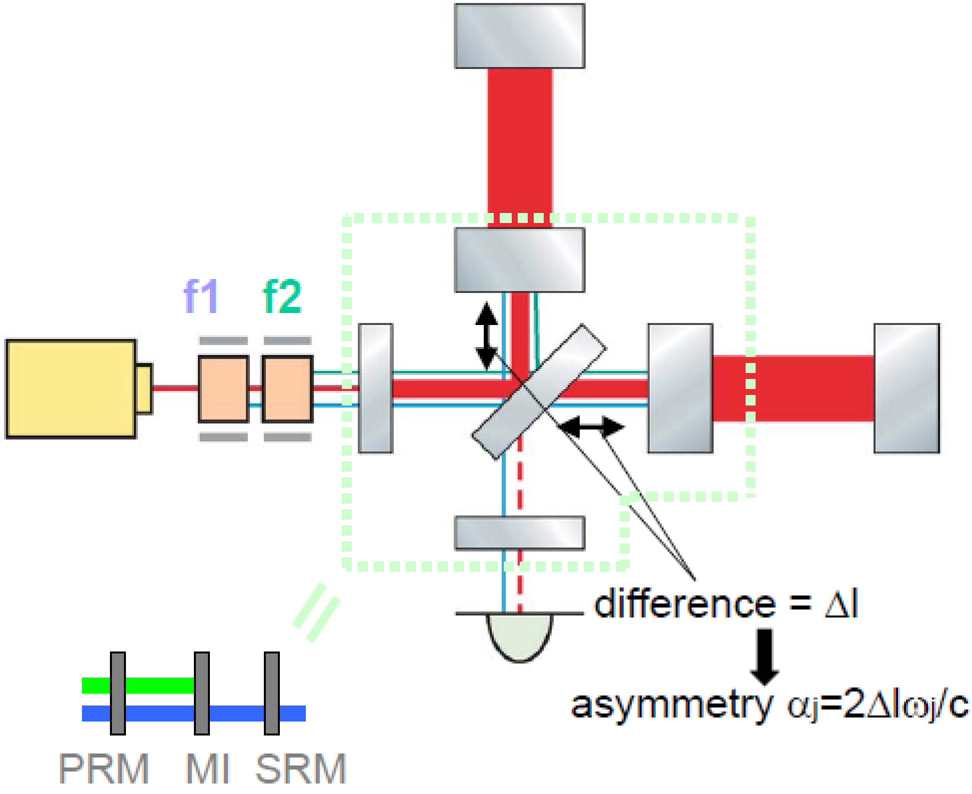
- **IFO Control** (Signal extraction and SNR, Coupling noise by control)
  →No critical difference, though each configuration
  has advantages and disadvantages
  VRSE : realized by additional offset to the error signal

- **Requirement for mirror**
  High arm-cavity finesse (1550) in BRSE, VRSE
  → lower optical loss is required (45ppm)
  Backup plan:
  Increase of input power, tuning of opt. Config.

⇨ **No critical difference**

Control scheme

5 length DoF should be controlled in RSE



- RF sidebands f1 and f2
  f1 resonates in PR-SRC
  f2 resonates in PRC
- Ctrl-signals are obtained by
  - beat of carrier and SB (single demod)
  - beat of f1 and f2 (double demod)
  - beat of carrier and carrier (DC)
- RC finesse depends on α_j

Figure: K.Somiya

Signals are extracted with RF sidebands at two freq.

SEM control and VRSE

VRSE is realized by adding
an offset in SEM control signal

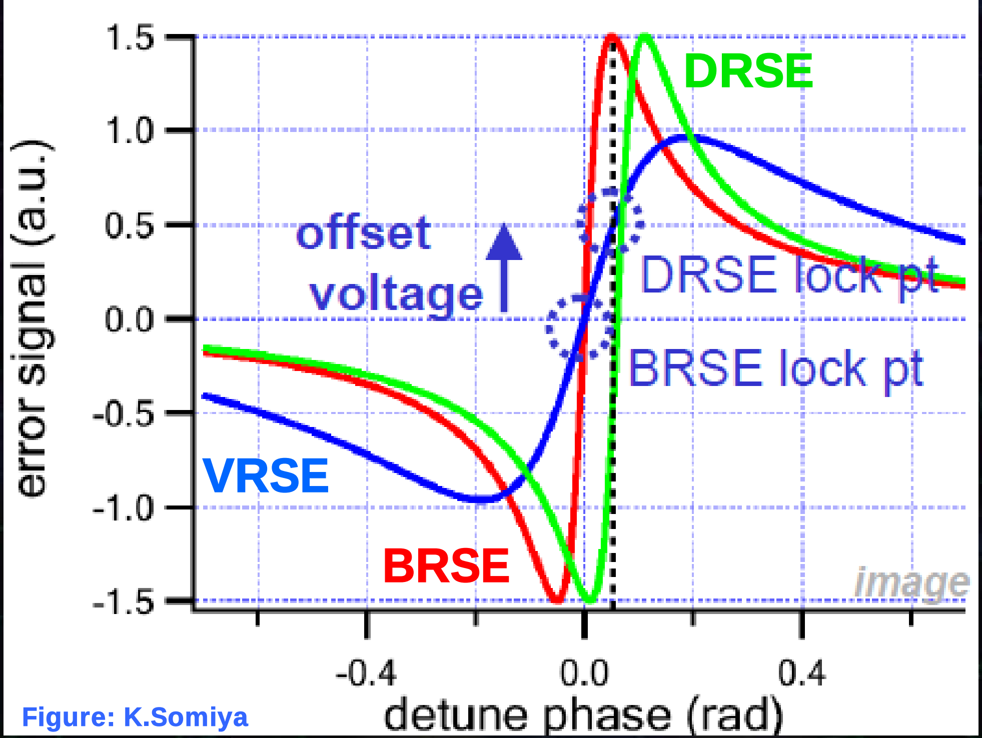
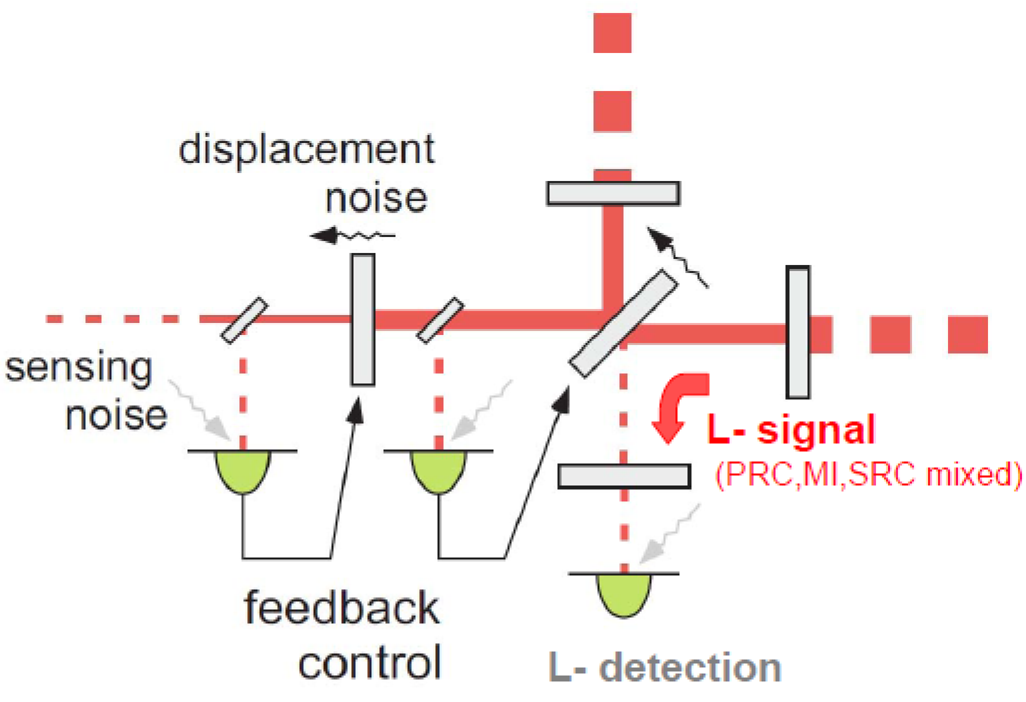


Figure: K.Somiya

Tradeoff between
signal strength and
control range

Signal strength
depends on the finesse
of SRC + SEC

Control loop noise



- Original mirror motion is suppressed by control
- Mirror is shaken by shot noise
- Mirror's motion appears at L- port as *loop noise*

Figure: K.Somiya

Control loop noise

Control loop noise in VRSE

Normal operation with VRSE-B, control offset for VRSE-D

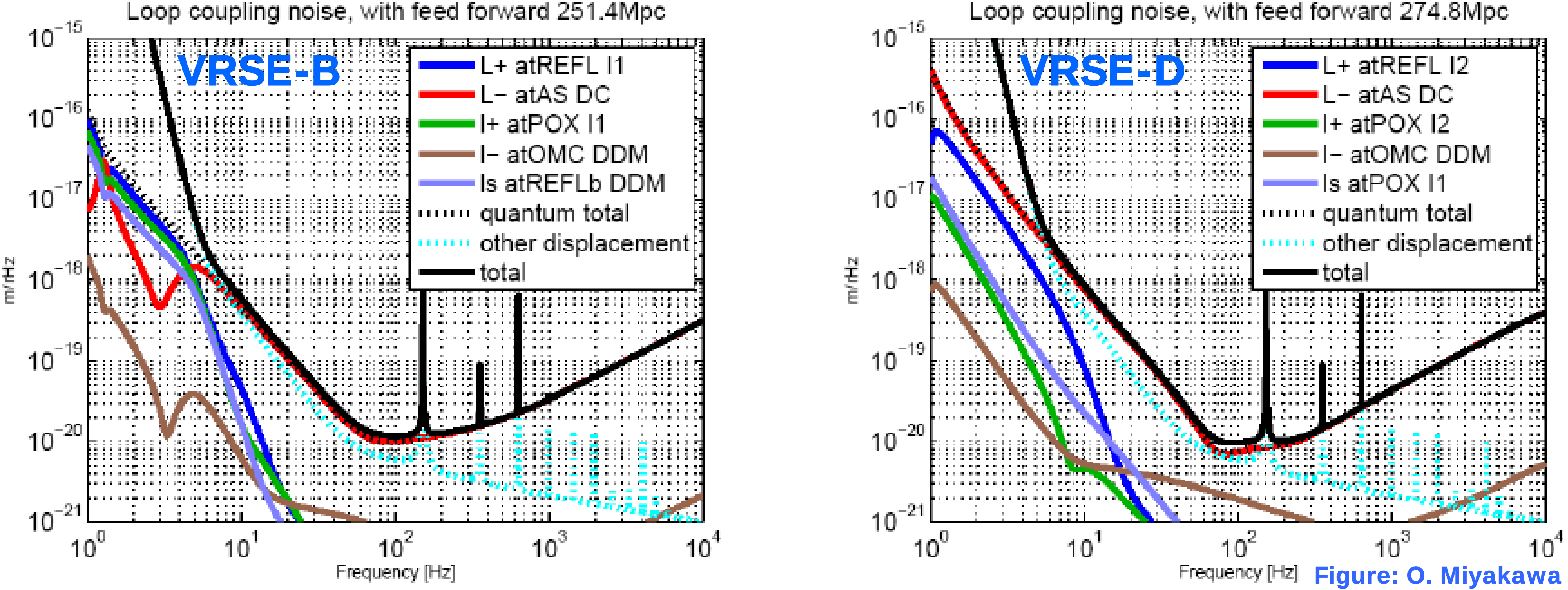


Figure: O. Miyakawa

⇨ **Contribution of I- and Is loop noise does not degrade the sensitivity.**

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Project Strategy

LCGT should contribute to the first detection

→ Earlier start of observation is desirable

Should consider the total time of

Commissioning term and

Observation time required for the first detection.

- Observation time for the first detection
  Two month difference at most
- Commissioning term
  Many uncertainties
  Difficult to predict in precision of month
  In the best guess from current experiences...
  → No critical difference.
- Cost, Risks, Room for future upgrades
  → No critical difference.

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Conclusion

1. LCGT should be
   Variable RSE configuration (VRSE).
2. In the first stage, it should be
   at the detuned operation point (VRSE-D).

In 4 candidate configurations, ...

- No critical difference in detection probabilities.
- No critical difference in technical feasibilities.

- DRSE is tuned for detection of BNS event,
  but has less capabilities for the other targets.
- VRSE-D is slightly better sensitivity for BNS than VRSE-B.
- We have an option to be VRSE-B after first few detections,
  for wider scientific outcomes.

Conclusion

Summary of LCGT interferometer parameters

optical/mechanical parameters

mass	30kg
dimension	ϕ12.5x15cm
susp fiber	ϕ1.8mmx40cm
coating	9/18
beam radius	3cm
opt loss	45ppm/mirror
ETM trans	5ppm
finesse	1550
power on BS	825W
SRM trans	15%
mass temp.	10K/20K

control parameters (tentative)

f1 (PR-SRC)	11.25MHz (AM)
f2 (PR)	45MHz (PM)
Δl	3.3m
PRC	73m
SRC	73m
ϕ for DRSE	87 deg
ζ for BRSE	122 deg
ζ for DRSE	135 deg

* f1/f2 are naively chosen; subject to change.

* f1 SB may better be a single SB

By K.Somiya

Acknowledgements

Special Working Group members

Coordinator: Seiji Kawamura (NAOJ)

Chair: Masaki Ando (Kyoto University)

Members: Nobuyuki Kanda (Osaka City University), Yoichi Aso (University of Tokyo), Kentaro Somiya (Caltech), Osamu Miyakawa (ICRR), Hideyuki Tagoshi (Osaka University), Daisuke Tatsumi (NAOJ), Hirotaka Takahashi (Nagaoka University of Technology), Kazuhiro Hayama (AEI), Kazuhiro Agatsuma (NAOJ), Koji Arai (Caltech), Kiwamu Izumi (NAOJ), Yuji Miyamoto (Osaka City University), Shinji Miyoki (ICRR), Shigenori Moriwaki (University of Tokyo), Shigeo Nagano (NICT), Noriaki Ohmae (University of Tokyo), Shuichi Sato (Hosei University), Toshikazu Suzuki (KEK), Ryutaro Takahashi (NAOJ), Takashi Uchiyama (ICRR), Hiroaki Yamamoto (Caltech), Kazuhiro Yamamoto (AEI)

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Stan Whitcomb (Chair), Stefan Ballmer, Hartmut Grote, Benoit Mours, Peter Shawhan

End

Scientific outcomes

Scientific outcomes		BRSE	VRSE-B	VRSE-D	DRSE	
Neutron-star binary						1.4Msolar neutron-star
Detection probability	[%]	99.6	99.4	99.9	99.9	At least one detection with one-year observation
Observation time required for the first event detection	[Month]	5.1	5.3	4.0	3.4	With 90% probability
Observable range	[Mpc]	114 (259)	112 (255)	123 (281)	132 (299)	SNR 8, sky average SNR 8, maximum direction
Detection rate	[/yr]	5.4	5.2	6.9	8.2	One-year observation
Parameter estimation		○	○	○	△	Factor of two difference
Error in arrival time	[msec]	0.254	0.220	0.255	1.08	200Mpc events
Fake reduction		○	○	○	△	
Black-hole binary						10Msolar black-hole inspirals
Observable range	[Mpc]	570	557	615	677	
Event rate	[/yr]	0.07-7				
Black-hole ringdown						
Observable range	[Gpc]	2.1	2.0	2.3	3	
Mass range	[Msolar]	110-910	115-760	100-490	100-450	Events within 1 Gpc distance
Supernova						
Observation possibility		○	○	○	△	
Event rate	[/yr]	0.01 - 0.05				Events in our Galaxy
Pulsar						With one-year observation
Number of observable pulsars		35	38	35	25	Reach spin-down upper limit
Crab upper limits	1e-27	8.5	8.5	8.3	5.9	60Hz
Vela upper limits	1e-27	6.9	6.0	9.3	1.0	22Hz
LMXB	1e-26	1.1	0.95	1.1	14	600Hz

LCGT BW special working group

Scope: To make recommendations on the interferometer optical configuration design of LCGT, and its observation band for gravitational waves.

Members: 22 members from LCGT collaborators

Reviewed by an external evaluation committee