km-scale Space Gravitational Wave Detector

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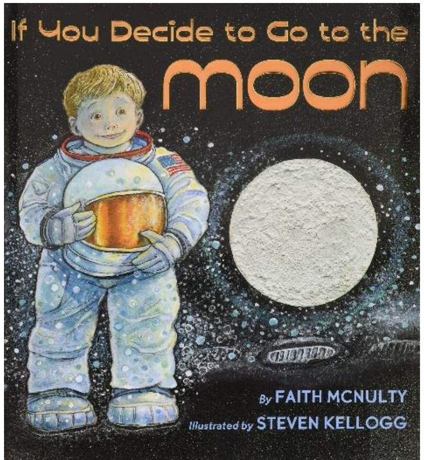
Science-Driven Approach
C-DECIGO
(10 kg, 10 km Fabry-Perot)

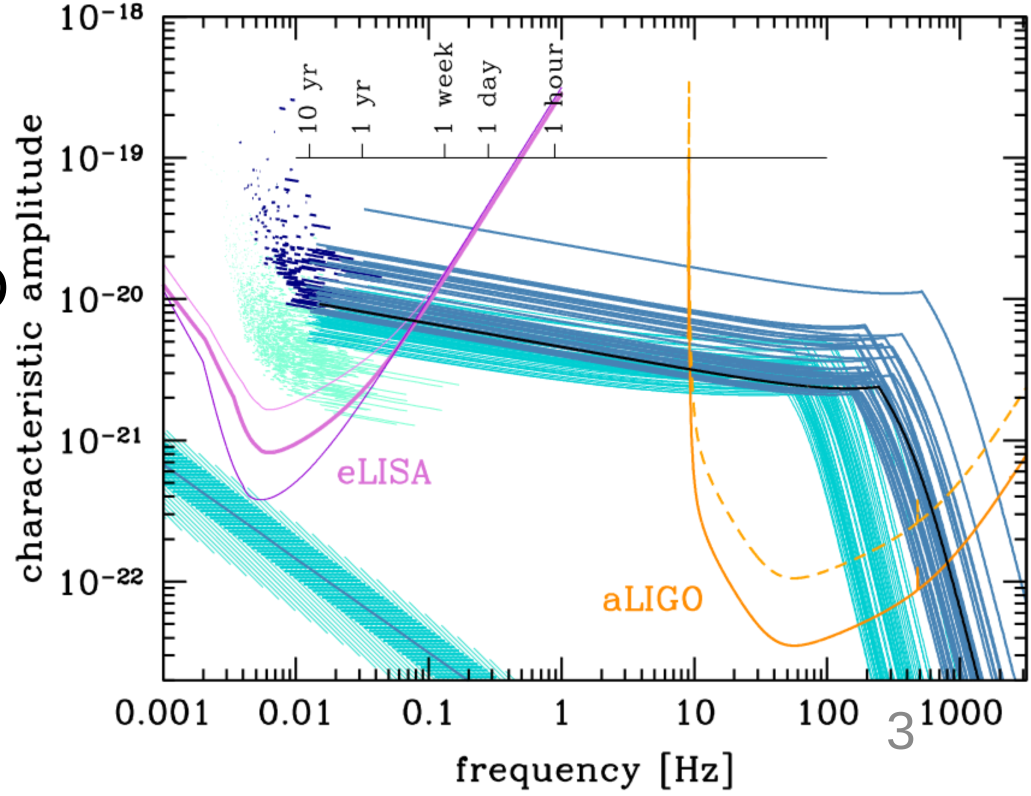
Motivations

- Demonstration of multiband gravitational wave detection
  - Detect BBHs and BNSs a few days before the merger
- IMBH search with unprecedented sensitivity

- km-scale space mission
- Demonstration of interferometry and formation flight for B-DECIGO and DECIGO



A. Sesana, Phys. Rev. Lett. 116, 231102 (2016)

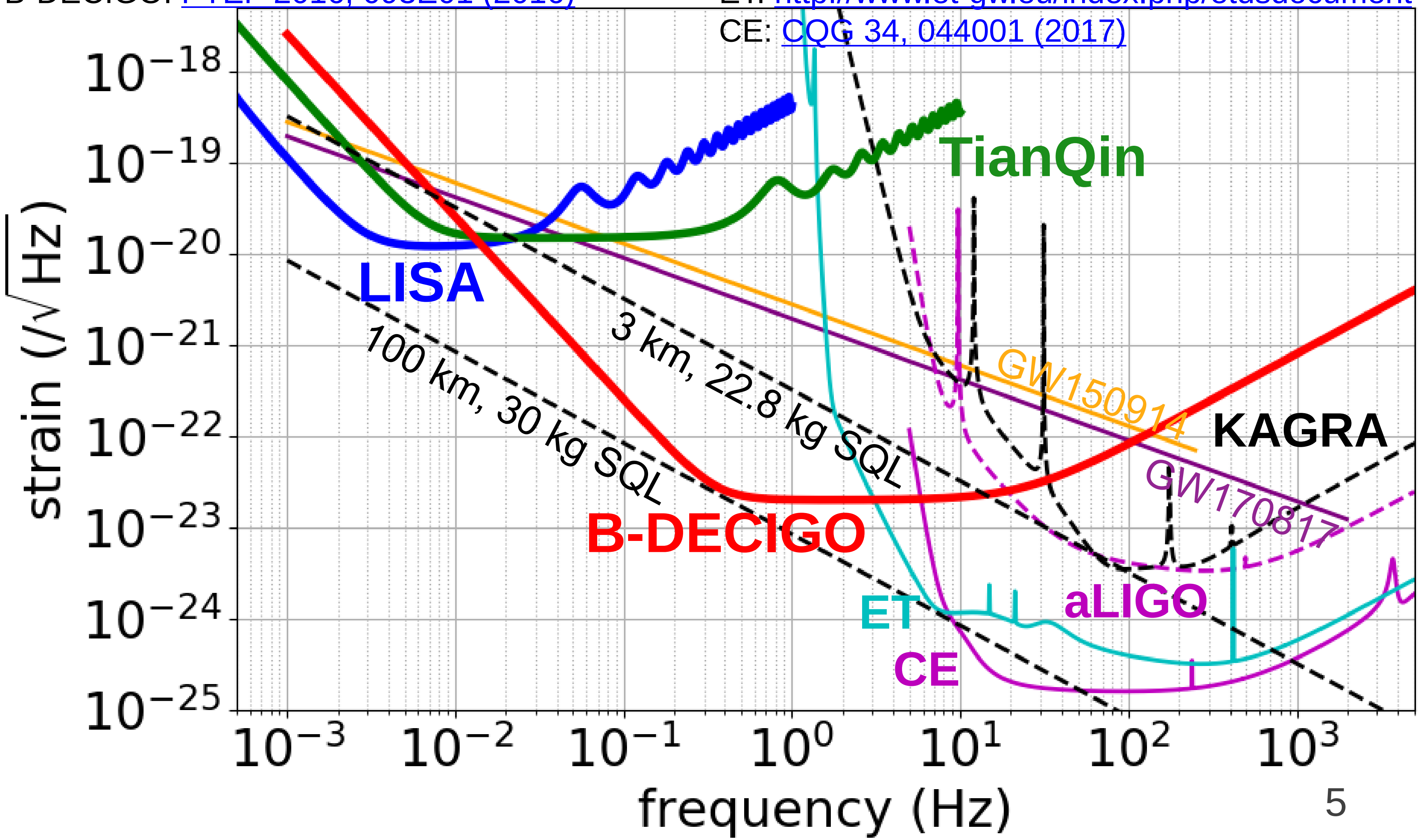


Existing Space GW Projects

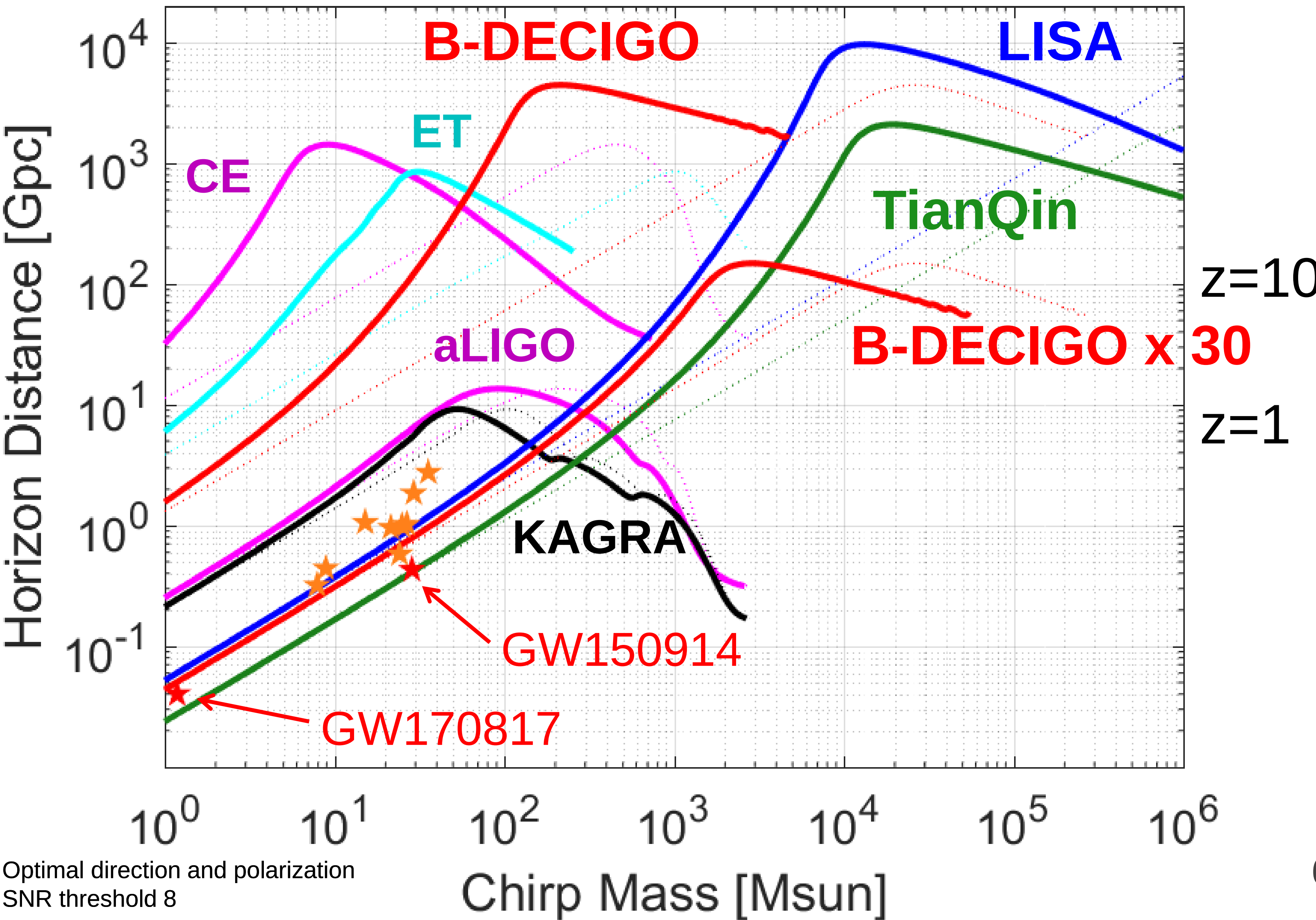
	LISA	TianQin	B-DECIGO
Arm length	2.5e6 km	1.7e5 km	100 km
Interferometry	Optical transponder	Optical transponder	Fabry-Pérot cavity
Laser frequency stabilization	Reference cavity, 1064 nm	Reference cavity, 1064 nm	Iodine, 515 nm
Orbit	Heliocentric	Geocentric, facing J0806.3+1527	Geocentric (TBD)
Flight configuration	Constellation flight	Constellation flight	Formation flight
Test mass	1.96 kg	2.45 kg	30 kg
Force noise req.	8e-15 N/rtHz Achieved PRL 120, 061101 (2018)	7e-15 N/rtHz CQG 33, 035010 (2016)	1e-16 N/rtHz

Sensitivity Comparison

LISA: https://perf-lisa.in2p3.fr/
TianQin: arXiv:1902.04423 (from Yi-Ming Hu)
B-DECIGO: PTEP 2016, 093E01 (2016)
KAGRA: PRD 97, 122003 (2018)
aLIGO: LIGO-T1800044
ET: http://www.et-gw.eu/index.php/etdsdocument
CE: CQG 34, 044001 (2017)

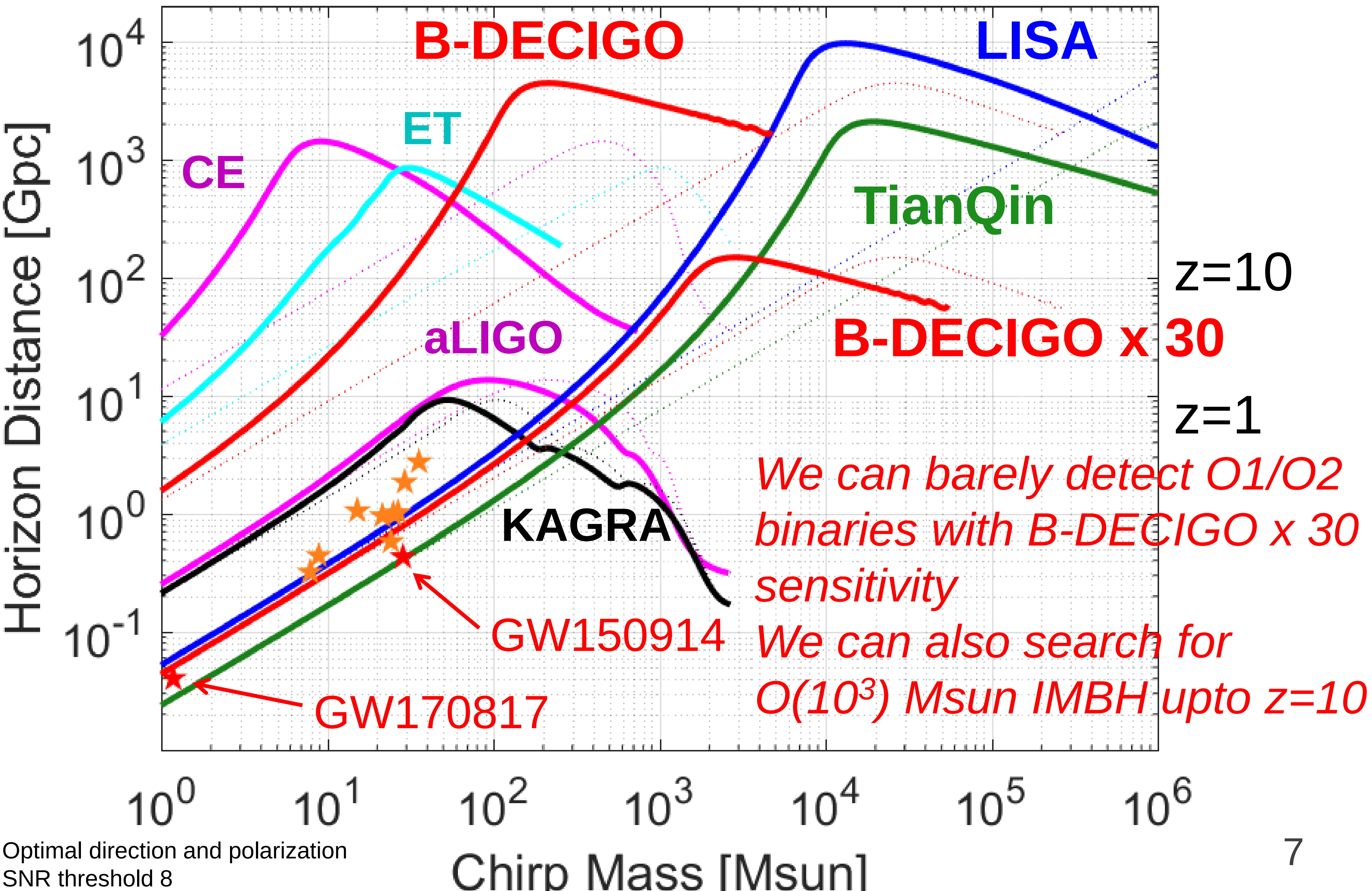


Horizon Distance



Optimal direction and polarization
SNR threshold 8

Horizon Distance



Optimal direction and polarization
SNR threshold 8

C-DECIGO

- Target sensitivity
  C-DECIGO
  = B-DECIGO x 30
  = DECIGO x 300

- For GW150914 and GW170817 like binaries, C-DECIGO can measure coalescence time to < ~150 sec a few days before the merger

Multiband gravitational-wave astronomy: Observing binary inspirals with a decihertz detector, B-DECIGO

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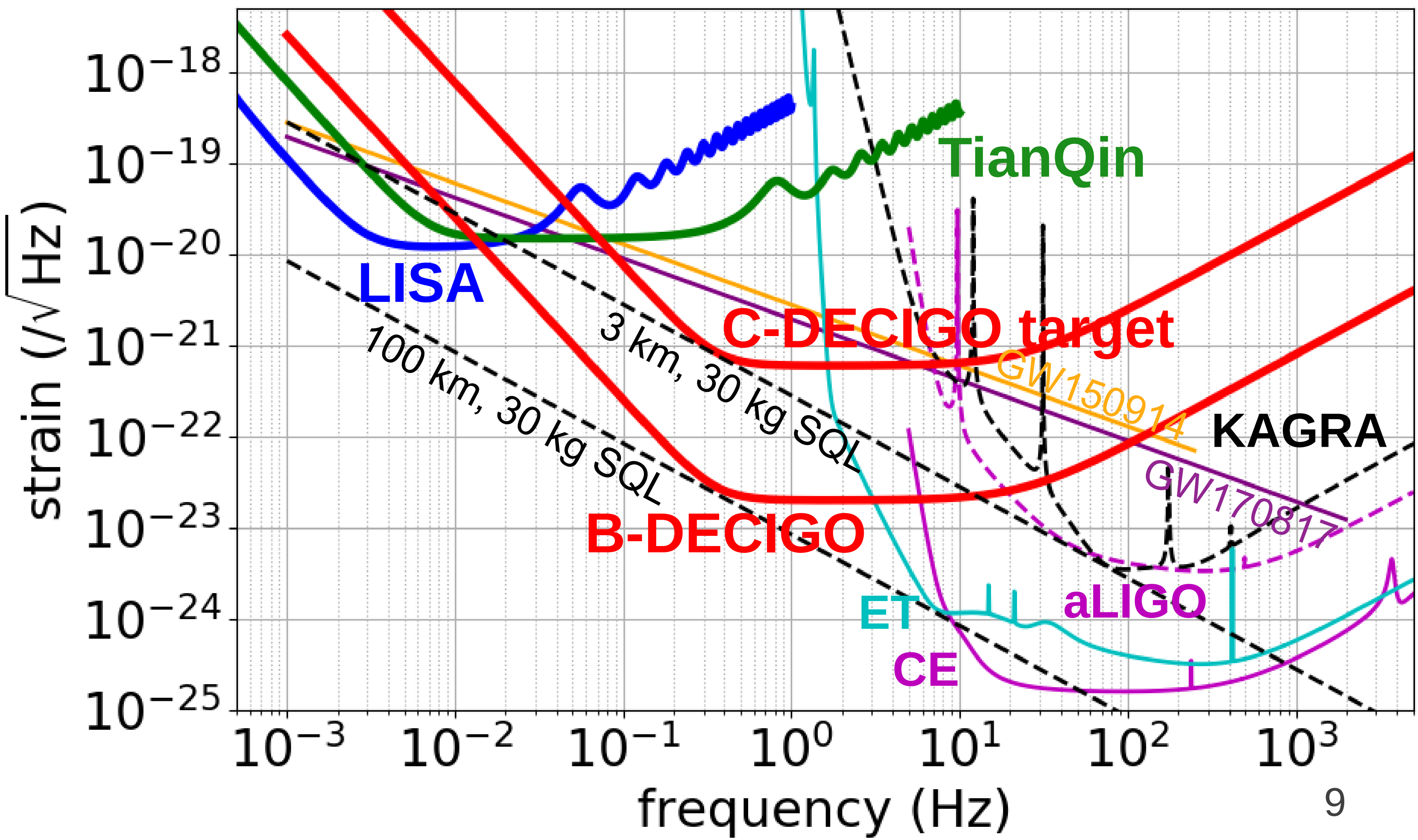
An evolving Japanese gravitational-wave (GW) mission in the decihertz band, B-DECIGO (DECihertz laser Interferometer Gravitational wave Observatory), will enable us to detect GW150914-like binary black holes, GW170817-like binary neutron stars, and intermediate-mass binary black holes out to cosmological distances. The B-DECIGO band slots in between the aLIGO–Virgo–KAGRA–IndIGO (hectohertz) and LISA (millihertz) bands for broader bandwidth; the sources described emit GWs for weeks to years across the multiple bands to accumulate high signal-to-noise ratios. This suggests the possibility that joint detection would greatly improve the parameter estimation of the binaries. We examine B-DECIGO's ability to measure binary parameters and assess to what extent multiband analysis could improve such measurement. Using non-precessing post-Newtonian waveforms with the Fisher matrix approach, we find for systems like GW150914 and GW170817 that B-DECIGO can measure the mass ratio to within $< 0.1\%$, the individual black-hole spins to within $< 10\%$, and the coalescence time to within < 5 s about a week before alerting aLIGO and electromagnetic facilities. Prior information from B-DECIGO for aLIGO can further reduce the uncertainty in the measurement of, e.g., certain neutron star tidally induced deformations by a factor of ~6, and potentially determine the spin-induced neutron star quadrupole moment. Joint LISA and B-DECIGO measurement will also be able to recover the masses and spins of intermediate-mass binary black holes at percent-level precision. However, there will be a large systematic bias in these results due to post-Newtonian approximation of exact GW signals.

S. Isoyama+, [PTEP 2018, 073E01 (2018)]

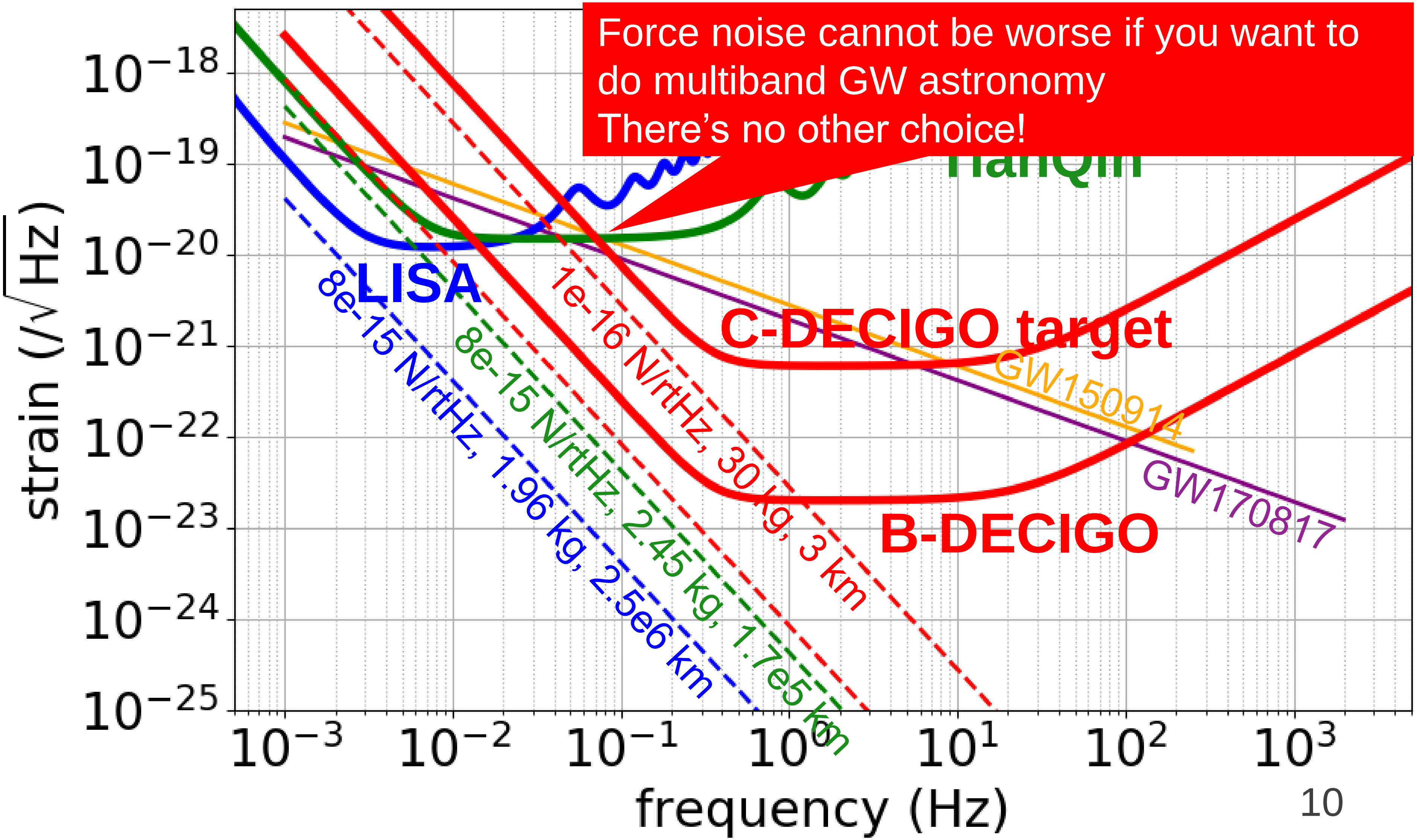
Sensitivity Target

- Requires $\sqrt{mL} > 3\sqrt{30}\,\sqrt{\mathrm{kg}\cdot\mathrm{km}}$ detector from SQL



Force Noise

- Requires 1e-16 N/rtHz for $mL = 90\,\mathrm{kg}\cdot\mathrm{km}$



Quantum Noise and Topology

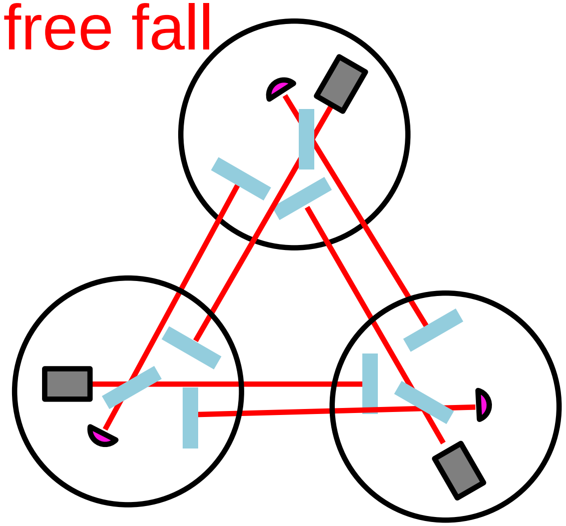
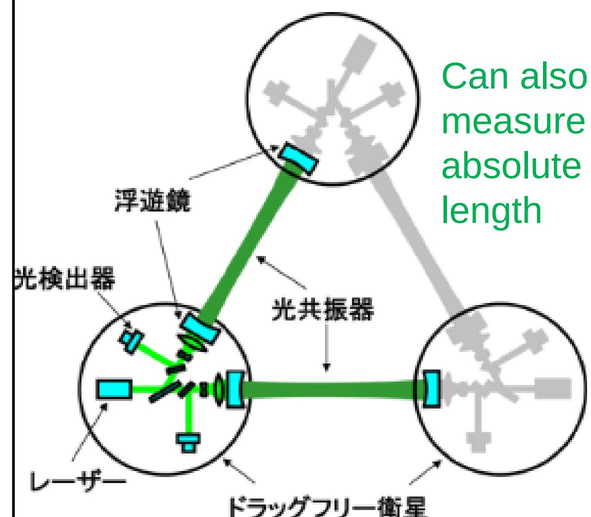
- Optical transponder (LISA/TianQin-style)
  Cannot dig the bucket unless you increase
  the size of the test mass
- Michelson interferometer
  - arm length: 30 km
  - mirror mass: 3 kg (diffraction loss is small enough)
  - input power: 3 W (arm should be long to reduce power)

  gives you C-DECIGO target
- Fabry-Perot interferometer (DECIGO-style)
  - arm length: 3 km
  - mirror mass: 30 kg
  - finesse: 300
  - input power: 0.01 W

  gives you C-DECIGO target (one example)

Michelson or Fabry-Perot

- Fabry-Perot seems reasonable choice

	Michelson	Fabry-Perot
Initial alignment	Same accuracy required	
Difficulties	Recombination	Cavity
3 satellites	BS have to be in free fall 	BS can be fixed  Can also measure absolute length
Arm length change	Possible (if mode mismatch is accepted)	Possible (if mode mismatch is accepted)

Mirror Mass and Arm Length

- Force noise requirement

$$h_{\mathrm{f}} = \frac{f}{m\omega^2 L} = \frac{1 \times 10^{-16}\,\mathrm{N}/\sqrt{\mathrm{Hz}}}{90\,\mathrm{kg}\cdot\mathrm{km}\,\omega^2}$$

- Radiation pressure noise

$$h_{\mathrm{rp}} = \frac{1}{m\omega^2 L}\frac{4\mathcal{F}}{\pi}\sqrt{\frac{16\pi\hbar P}{c\lambda}} = k_{\mathrm{safe}} h_{\mathrm{f}}$$

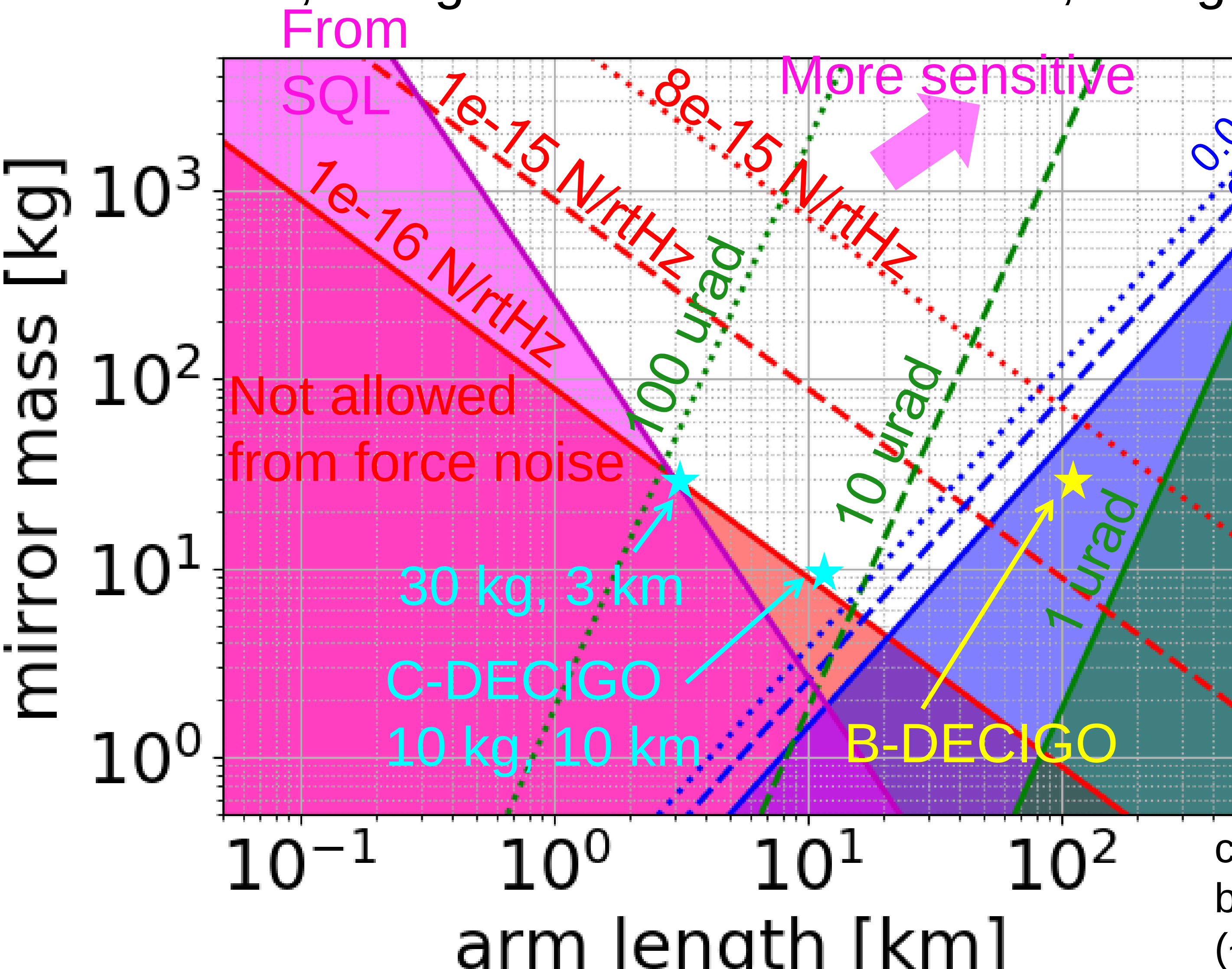
Say, this is 3

There's no point in reducing the finesse and input power if force noise is larger, in terms of sensitivity.

- If you fix requirement for f, requirement for mL is set
- If you fix P, finesse $\mathcal{F}$ is set
- Assuming g-factor g=0.3 and L, beam size is calculated
- This gives you the minimum mirror mass from diffraction loss (assume fused silica, aspect ratio t/d = 1)
- Also, if you fix initial alignment accuracy, minimum mirror diameter d is determined from d/L

Mirror Mass and Arm Length

- 10 km, 10 kg seems better than 3 km, 30 kg



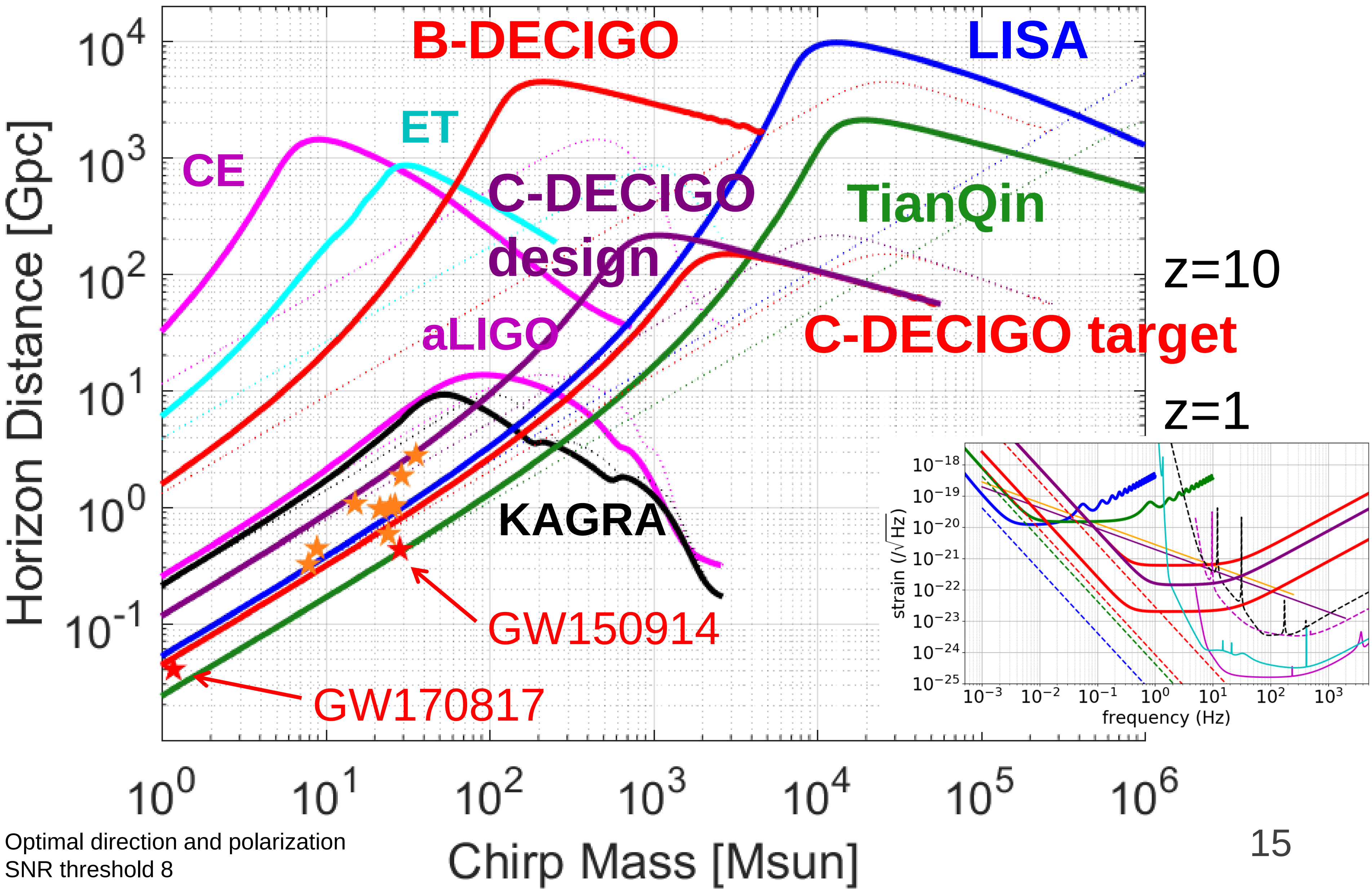
Not allowed from diffraction loss (depends much on aspect ratio)

cf. GRACE-FO launched May 2018 does 220 km FF

Not allowed from initial alignment

cf. star tracker can do better than 1 arcsec (~5 urad)

C-DECIGO Design



Optimal direction and polarization
SNR threshold 8

C-DECIGO Summary

- Multiband gravitational wave astronomy
  - Measure coalescence time of O1/O2 binaries within a few minutes, a few days before the merger
- IMBH search
  - O(10^3) Msun IMBH within the whole universe
  - Better than ET/CE and LISA
- C-DECIGO design parameters
  - Arm length: 10 km
    (Does this reduce the cost? Or increase the feasibility?)
  - Mirror mass: 10 kg
  - Force noise: $<$1e-16 N/rtHz (same as B-DECIGO)
  - finesse: 400
  - input power: 0.01 W (no high power amp necessary?)
- Better to do B-DECIGO if the cost is similar

Findings

- To do original science in 3G-LISA era,
  - Force noise < ~1e-16 N/rtHz
  - $mL > 90\,\mathrm{kg}\cdot\mathrm{km}$
  - $\sqrt{mL} > 3\sqrt{30}\,\sqrt{\mathrm{kg}}\cdot\mathrm{km}$

  are required
- Fabry-Perot seems more feasible
- Although beam size will be smaller for shorter arm length, it requires heavier mass to keep force noise requirement the same (~ a few kg is the minimum for the test mass)
- Longer arm length is better due to SQL but
  - initial alignment accuracy will be tougher
  - higher power laser will be necessary due to lower finesse (diffraction loss)

Engineering-Driven Approach
F-DECIGO
(2 kg, 10 km Fabry-Perot)

Motivations

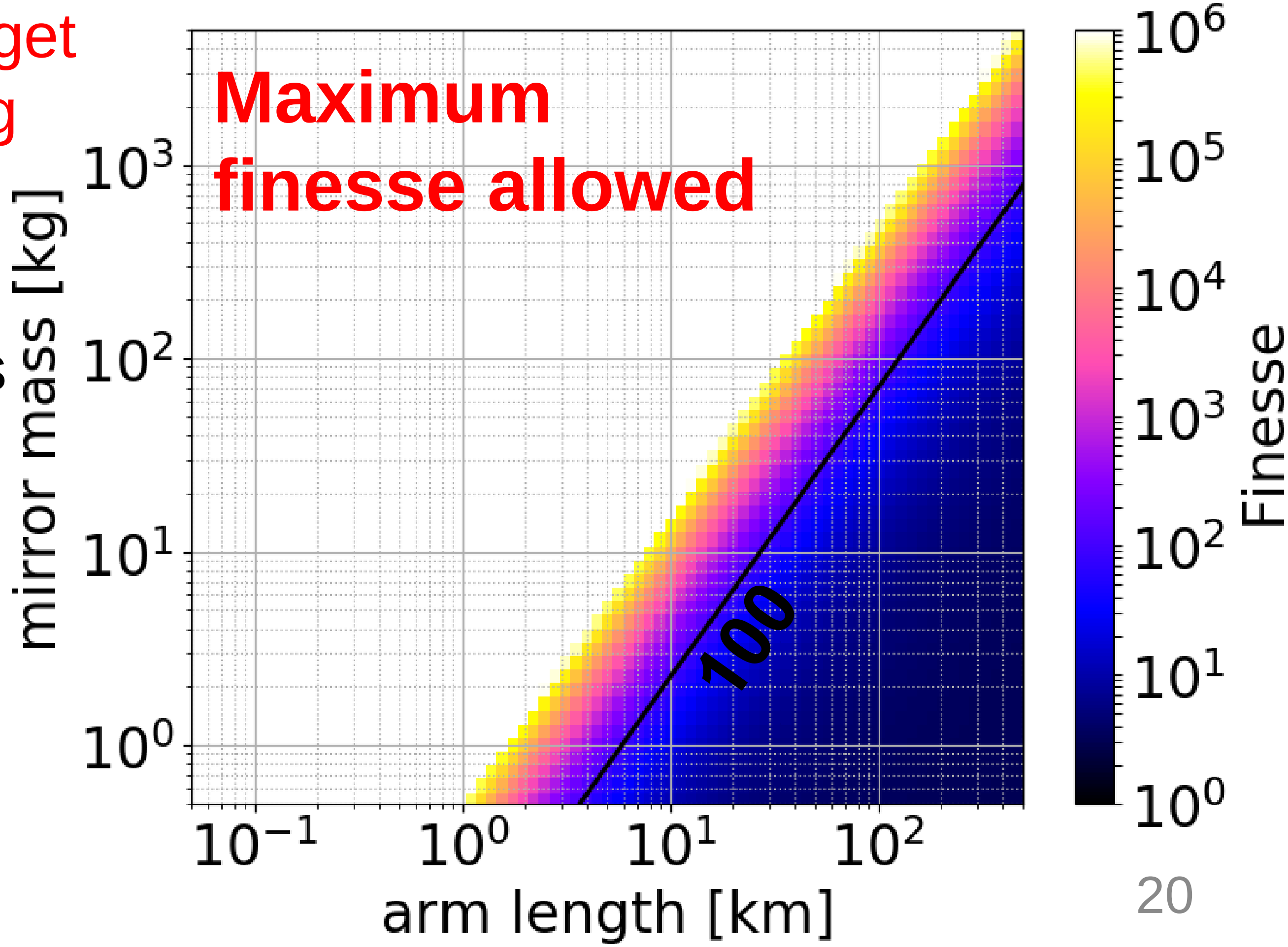
- Demonstration of formation flight
- Demonstration of laser interferometry between satellites

- Full success: technology demonstration (primary target)
- Extra success: IMBH search with unprecedented sensitivity
  - to realize this, we have to launch before LISA and TianQin (before ~2034)

- Launch within ~5-10 years
- Based on proven technologies
  - 2 kg mass (same mass with LISA/TianQin)
  - 8e-15 N/rtHz force noise (LISA-level)

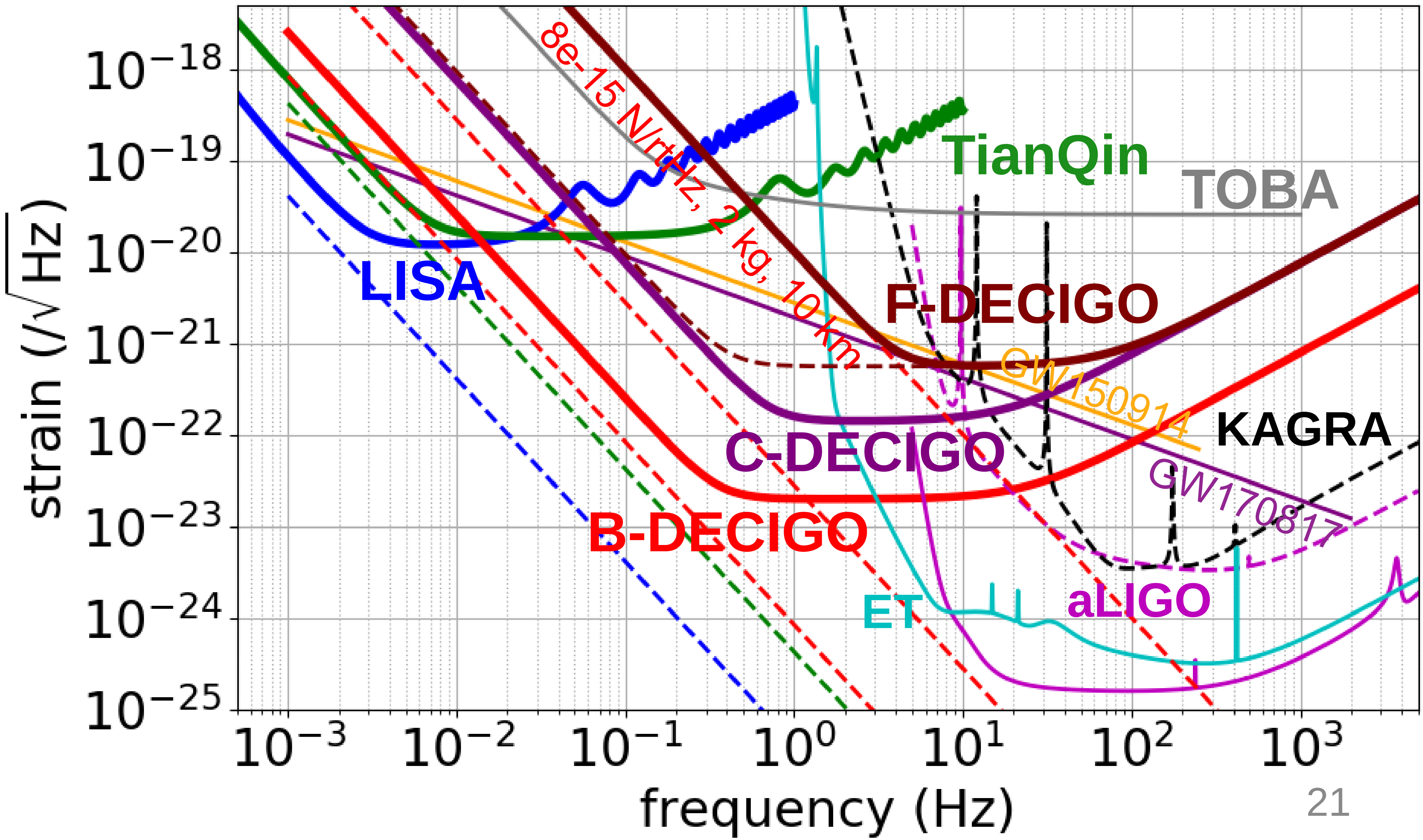
Force Noise and Finesse

- Larger force noise requires larger P and $\mathcal{F}$ to reach SQL
  - for example, for 8e-15 N/rtHz, P=0.01 W and F=3e4 are required and this finesse is not feasible with small test mass
- We should forget about reaching SQL
- 2 kg test mass 10 km arm Finesse 100 seems reasonable

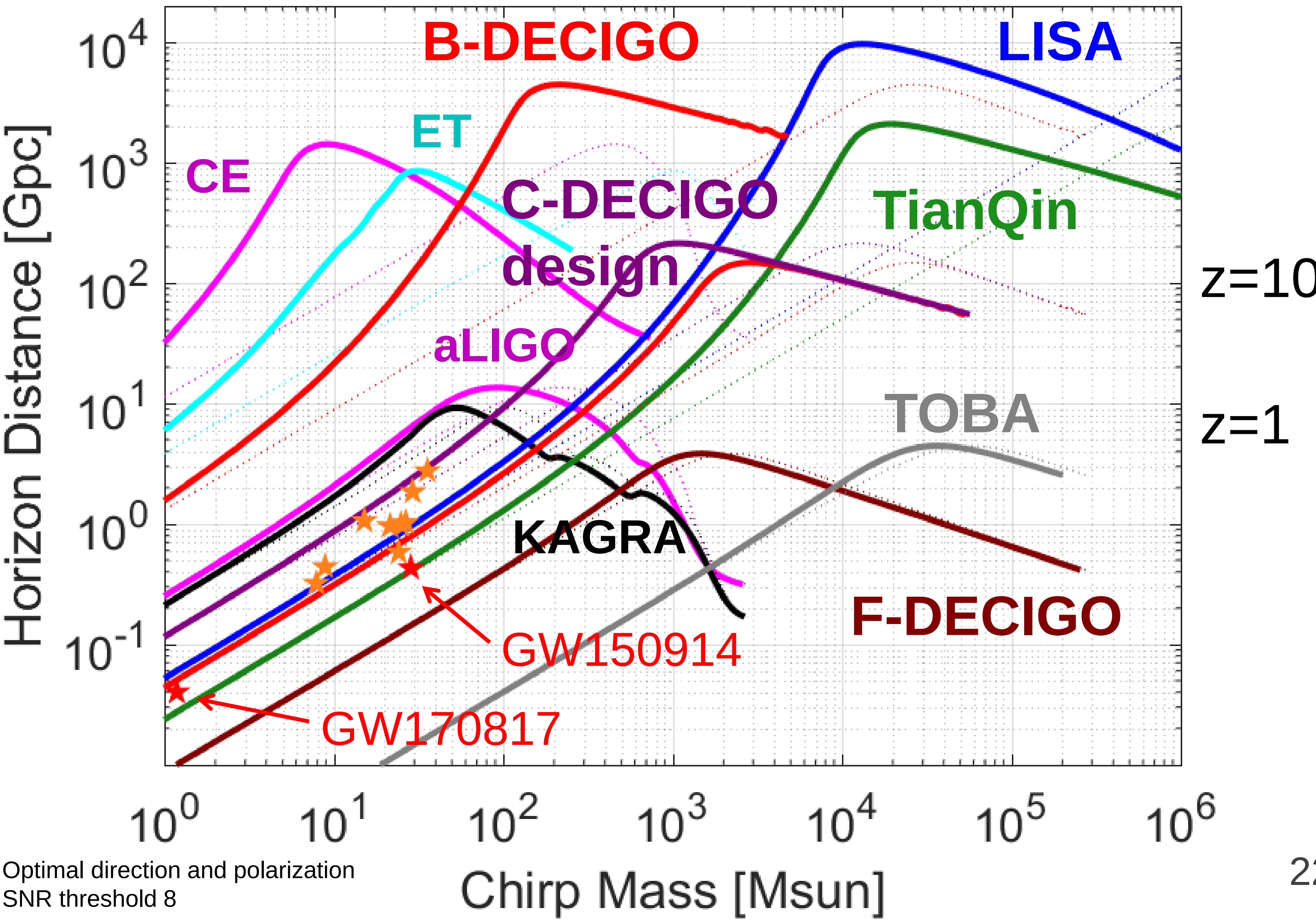


F-DECIGO Design

- Force noise limited sensitivity (could be used to evaluate force noise)



F-DECIGO Design



Optimal direction and polarization
SNR threshold 8

F-DECIGO Summary

- Demonstration of key technologies for DECIGO
  - formation flight
  - Fabry-Perot cavity between satellites
  - measure force noise in orbit
- IMBH search
  - O(10^3) Msun IMBH to ~3 Gpc (event rate to be calculated)
  - Should launch before LISA/TianQin and ET/CE (before ~2034)
- F-DECIGO design parameters
  - Arm length: 10 km
    (Does this reduce the cost? Or increase the feasibility?)
  - Mirror mass: 2 kg (same mass as LISA)
    Fused silica, 10cm dia. 10cm thick
  - Force noise: <8e-15 N/rtHz (same as LISA)
  - finesse: 100
  - input power: 0.01 W (no high power amp necessary?)

Questions

- Mirror density?
  - smaller the better to make the mirror large considering diffraction loss
  (SQL and force noise do not depend on the density)
  - so far fused silica (2.2e3 kg/m^3) is assumed
- Michelson?
  - alignment requirement is almost the same with FP
  (depends on FP cavity geometry, but independent on finesse)
  - FP alignment will be tougher if finesse is very high
  (input test mass transmission will be smaller)