

Detection Prospects of Core-Collapse Supernovae with Supernova-Optimized Third-Generation Gravitational-wave Detectors

Yuka Oshima (M1)
Dept. of Physics, Univ. of Tokyo

Today's paper



Kimio Club #00paper

- [arXiv:1906.00084](https://arxiv.org/abs/1906.00084)

Detection Prospects of Core-Collapse Supernovae with Supernova-Optimized Third-Generation Gravitational-wave Detectors

Varun Srivastava,¹ Stefan Ballmer,¹ Duncan A. Brown,¹ Chaitanya Afle,¹
Adam Burrows,² David Radice,^{2,3} and David Vartanyan²

¹*Department of Physics, Syracuse University, Syracuse, New York 13244, USA*

²*Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544*

³*Institute for Advanced Study, 1 Einstein Dr, Princeton NJ 08540*

(Dated: June 4, 2019)

We optimize the third-generation gravitational-wave detector to maximize the range to detect core-collapse supernovae. Based on three-dimensional simulations for core-collapse and the corresponding gravitational-wave waveform emitted, the corresponding detection range for these waveforms is limited to within our galaxy even in the era of third-generation detectors. The corresponding event rate is two per century. We find from the waveforms that to detect core-collapse supernovae with an event rate of one per year, the gravitational-wave detectors need a strain sensitivity of $3 \times 10^{-27} \text{ Hz}^{-1/2}$ in a frequency range from 100 Hz to 1500 Hz. We also explore detector configurations technologically beyond the scope of third-generation detectors. We find with these improvements, the event rate for gravitational-wave observations from CCSN is still low, but is improved to one in twenty years.

Summary

- GW waveforms from core-collapse supernovae are created by 3-dimensional simulations
- Optimized 3rd-generation detectors and hypothetical detectors are proposed for core-collapse supernovae

Detectors	Detection range	Event rate
Optimized 3rd-generation	Milky Way Galaxy (- 100 kpc)	one per 50 years
Hypothetical	Andromeda Galaxy (- 1 Mpc)	one per 20 years

- Detectors need a strain sensitivity of $3 \times 10^{-27} / \sqrt{\text{Hz}}$ from 100 Hz to 1500 Hz in order to detect core-collapse supernova one per 2 years

Contents

- Introduction



「わからないマーク」

- Create a reference GW waveform by 3D simulations

- Optimized 3rd-generation detectors

- ① Tuning for broadband

- ② Detuning for narrow-band

- ③ Tuning for narrow-band

- Hypothetical detectors

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Detections so far

- More than 10 BBHs and one BNS

	Event	m_1/M_\odot	m_2/M_\odot	\mathcal{M}/M_\odot	χ_{eff}	M_f/M_\odot	a_f	$E_{\text{rad}}/(M_\odot c^2)$	$\ell_{\text{peak}}/(\text{erg s}^{-1})$	d_L/Mpc	z	$\Delta\Omega/\text{deg}^2$
First detection	<u>GW150914</u>	$35.6^{+4.7}_{-3.1}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.7}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.4}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	440^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	182
	GW151012	$23.2^{+14.9}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.1}_{-1.2}$	$0.05^{+0.31}_{-0.20}$	$35.6^{+10.8}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.6^{+0.6}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1080^{+550}_{-490}	$0.21^{+0.09}_{-0.09}$	1523
	GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.5}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	450^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
	GW170104	$30.8^{+7.3}_{-5.6}$	$20.0^{+4.9}_{-4.6}$	$21.4^{+2.2}_{-1.8}$	$-0.04^{+0.17}_{-0.21}$	$48.9^{+5.1}_{-4.0}$	$0.66^{+0.08}_{-0.11}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-1.0} \times 10^{56}$	990^{+440}_{-430}	$0.20^{+0.08}_{-0.08}$	921
	GW170608	$11.0^{+5.5}_{-1.7}$	$7.6^{+1.4}_{-2.2}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.4}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	392
	GW170729	$50.2^{+16.2}_{-10.2}$	$34.0^{+9.1}_{-10.1}$	$35.4^{+6.5}_{-4.8}$	$0.37^{+0.21}_{-0.25}$	$79.5^{+14.7}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	2840^{+1400}_{-1360}	$0.49^{+0.19}_{-0.21}$	1041
	GW170809	$35.0^{+8.3}_{-5.9}$	$23.8^{+5.1}_{-5.2}$	$24.9^{+2.1}_{-1.7}$	$0.08^{+0.17}_{-0.17}$	$56.3^{+5.2}_{-3.8}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	1030^{+320}_{-390}	$0.20^{+0.05}_{-0.07}$	308
	GW170814	$30.6^{+5.6}_{-3.0}$	$25.2^{+2.8}_{-4.0}$	$24.1^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.12}$	$53.2^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	600^{+150}_{-220}	$0.12^{+0.03}_{-0.04}$	87
First BNS detection	<u>GW170817</u>	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+7}_{-15}	$0.01^{+0.00}_{-0.00}$	16
	GW170818	$35.4^{+7.5}_{-4.7}$	$26.7^{+4.3}_{-5.2}$	$26.5^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.4^{+4.9}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1060^{+420}_{-380}	$0.21^{+0.07}_{-0.07}$	39
	GW170823	$39.5^{+11.2}_{-6.7}$	$29.0^{+6.7}_{-7.8}$	$29.2^{+4.6}_{-3.6}$	$0.09^{+0.22}_{-0.26}$	$65.4^{+10.1}_{-7.4}$	$0.72^{+0.09}_{-0.12}$	$3.3^{+1.0}_{-0.9}$	$3.6^{+0.7}_{-1.1} \times 10^{56}$	1940^{+970}_{-900}	$0.35^{+0.15}_{-0.15}$	1666

[O1/O2 Catalog](#)

GW190412

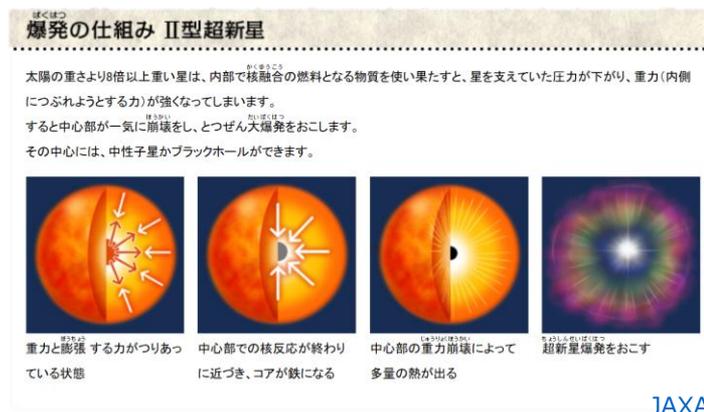
GW190425

...

- GWs from core-collapse supernova are yet to be observed

Core-collapse supernovae

- Core-collapse supernovae (CCSN)
= Type II supernovae
- Mass range: 8 – 60 M_{\odot}



- GW is generated deep in the star and emitted untouched by the outer envelope
→ GW has a lot of information about the interior of the star and the core-collapse process

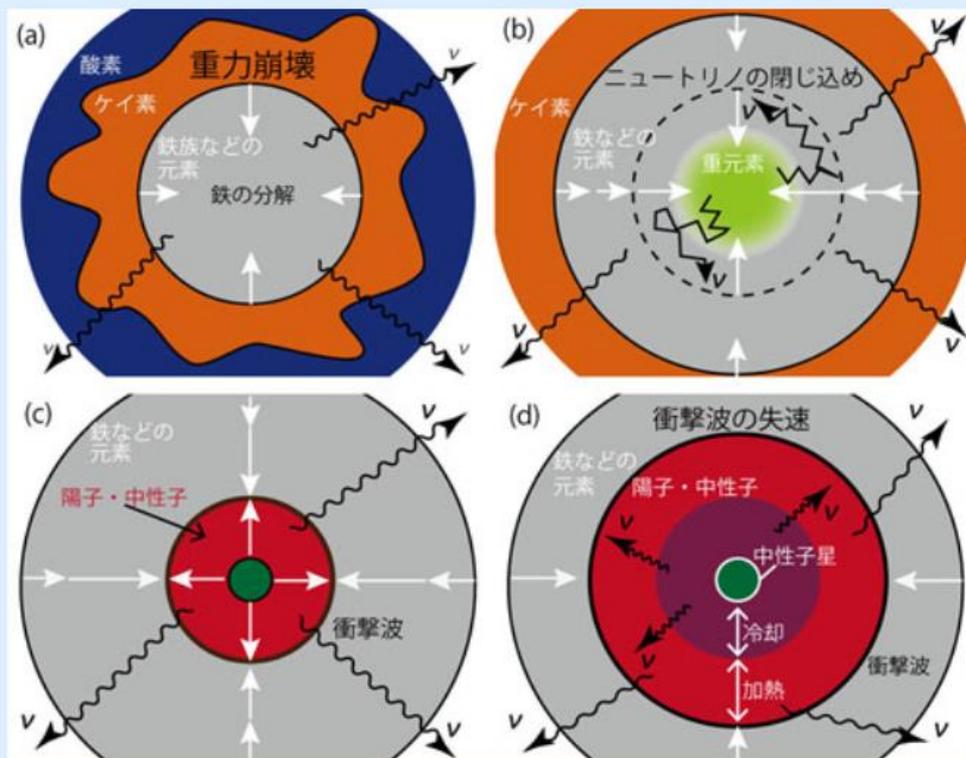
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Process of CCSN

Core-collapse

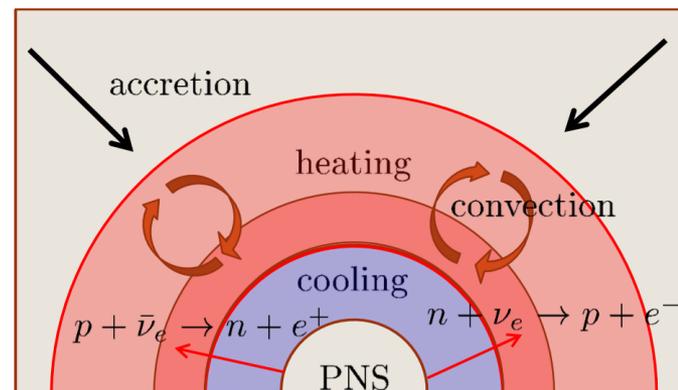
Neutrino trapping



Need to revival
shock wave

Key word:

Neutrino heating



ニュートリノ加熱によるSNシミュレーション

Core bounce Explosion

図2: 太陽質量星の重力崩壊の模式図

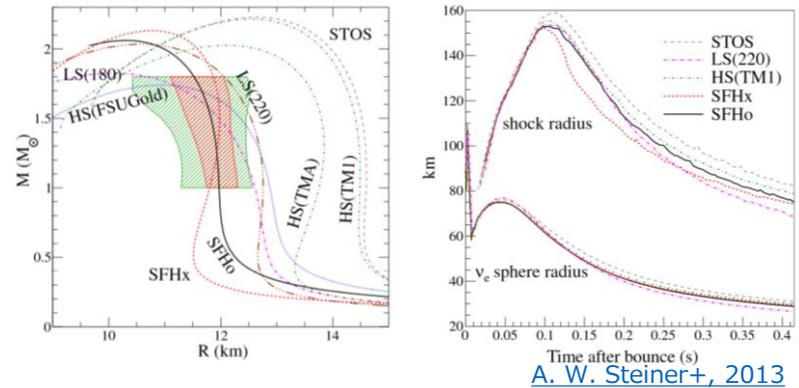
a、b、c、dの順に時間が経過し、中心密度が高くなる。「ν」はニュートリノを表す。

(クレジット:国立天文台)

NAOJ CfCA

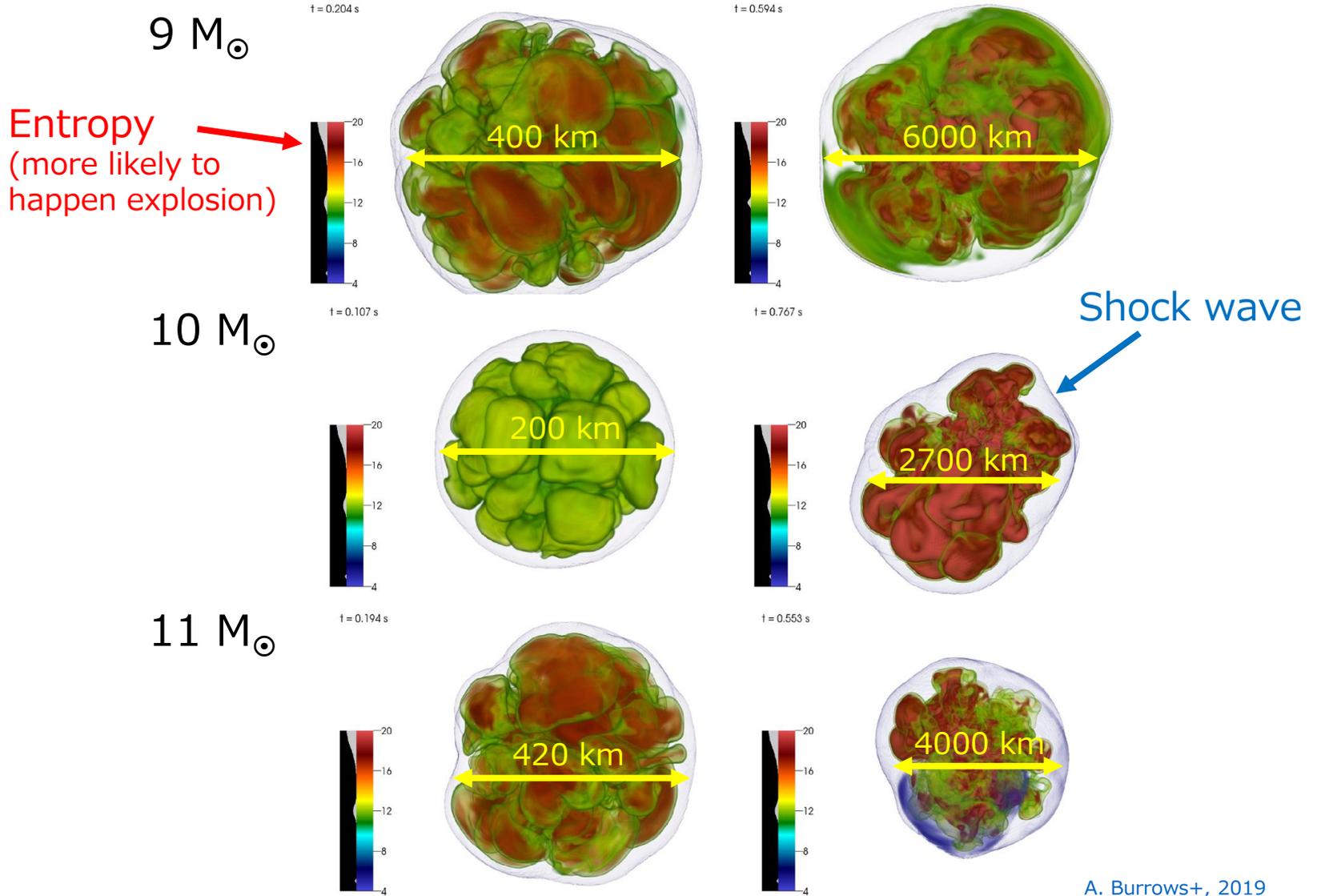
3D simulations setups

- Eulerian radiation-hydrodynamics code FORNAX
- All models have solar metallicity
- Add small velocity perturbation in 10 msec
- Stellar and nuclear matter: SFHo equation of state



- Neutrino transport:
a multi-dimensional moment method
- Gravity: the monopole approximation using an effective general-relativistic potential
- GW: the quadrupole approximation

CCSN by 3D simulations



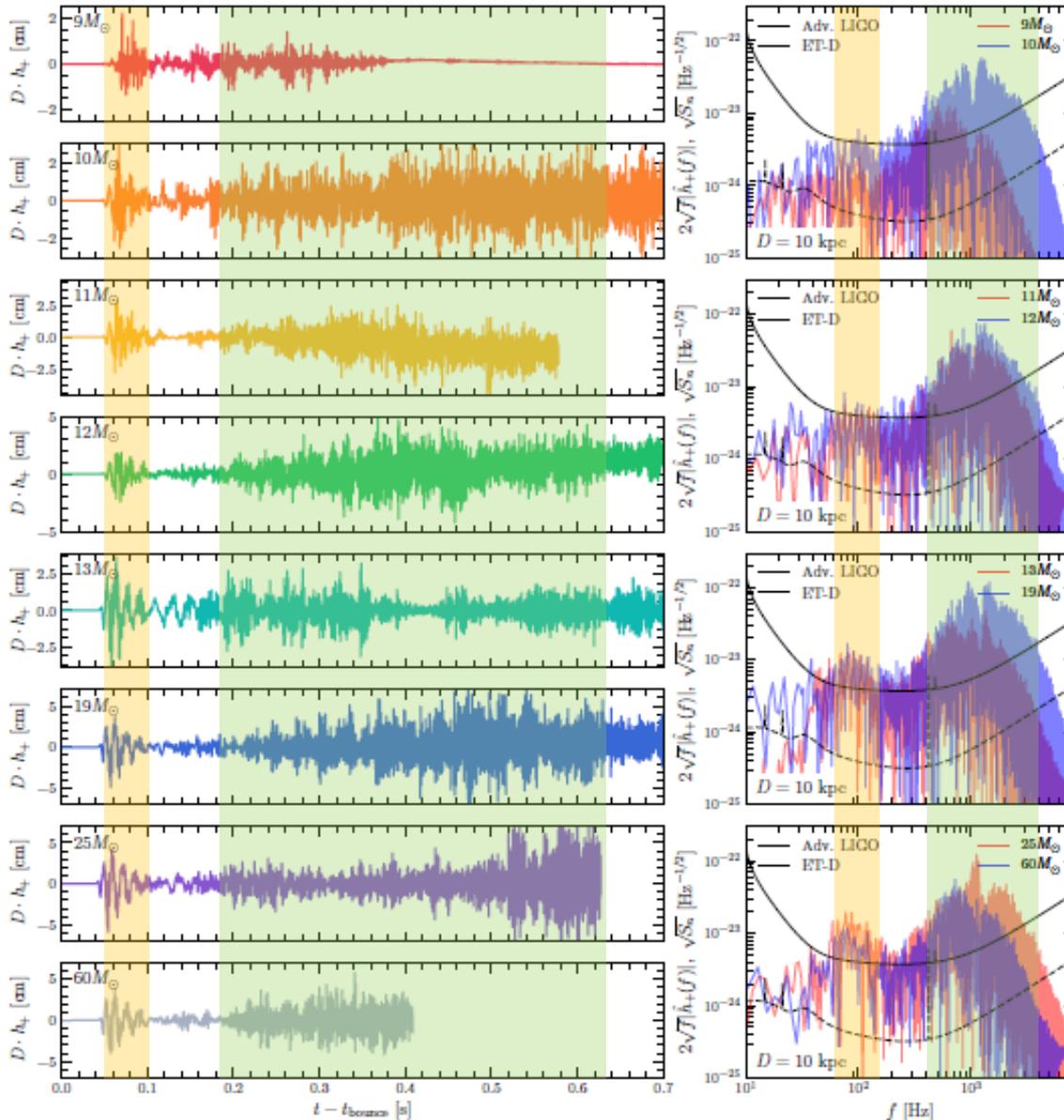
[A. Burrows+, 2019](#)

20 M_{\odot}

[Movie](#) by Max Planck Institutes

May 1st, 2020 @ Ando Lab Seminar

GW from CCSN by 3D simulations



about 100 Hz
Prompt convection

several hundred Hz
- a few kHz
Proto-neutron star
oscillations

2D simulations vs. 3D simulations

- distance to get an optimal SNR of 8

$$d_{opt} = \frac{\sigma}{\rho^*} = \frac{1}{\rho^*} \left[2 \int_{f_{low}}^{f_{high}} df \frac{\tilde{h}(f)\tilde{h}^*(f)}{S_h(f)} \right]^{\frac{1}{2}}$$

SNR = 8
10 Hz
Power spectral density

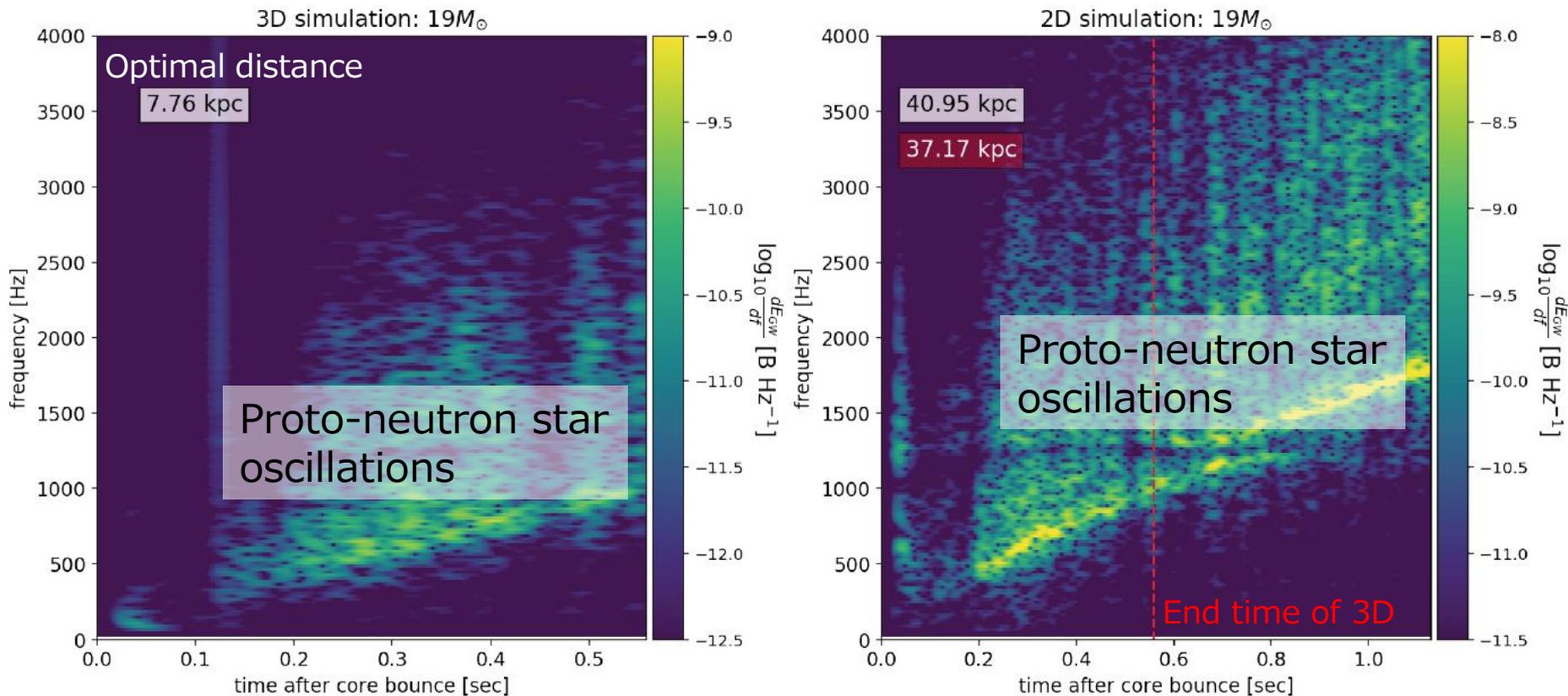
zero-age main sequence (零歳主系列) → ZAMS Mass

	Optimal distance (kpc)		
	3D	2D	2D truncated recalculate
$9M_{\odot}$	2.43	15.51	15.46
$11M_{\odot}$	5.87	31.96	26.68
$11M_{\odot}$ (w/o MB) ?	5.99	28.78	26.04
$19M_{\odot}$ (w/o MB)	7.75	40.61	37.18
$25M_{\odot}$	13.35	48.26	40.09
$60M_{\odot}$	9.63	48.79	36.30

< =

- 3D simulations have shorter time
→ Truncate 2D simulations to compare d_{opt}
- 2D waveforms are 4 times louder than 3D waveforms
→ use 3D waveforms

2D simulations vs. 3D simulations



- 3D simulations have shorter time
→ Truncate 2D simulations to compare d_{opt}
- 2D waveforms are 4 times louder than 3D waveforms
→ use 3D waveforms

Reference GW waveform

- Sum of sine-Gaussian signals

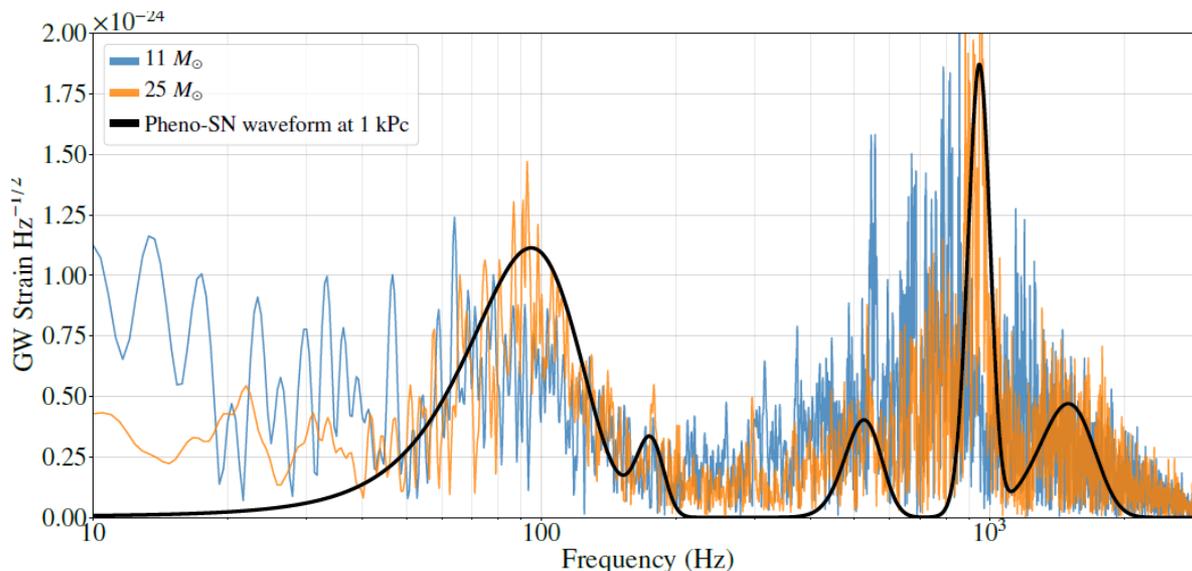
$$\tilde{s}(f) = \frac{h_o}{4\sqrt{\pi}} \frac{Q}{f_o} e^{-\frac{(f-f_o)^2 Q^2}{4f^2}}$$

- $f_0 = 95, 175, 525, 950, 1500$ Hz

Chosen by hand to avoid over-fitting

Emissions at high freq. are much lower in amplitude

→ an upper limit of 2 kHz



Reference GW waveform

- Sum of sine-Gaussian signals

$$\tilde{s}(f) = \frac{h_o}{4\sqrt{\pi}} \frac{Q}{f_o} e^{-\frac{(f-f_o)^2 Q^2}{4f^2}}$$

- 4 bins ... 10 Hz – 250 Hz, 250 Hz – 500 Hz, 500 Hz – 1 kHz, 1 kHz - 2 kHz
- Q and h_o are chosen to minimize the error in 4 bins

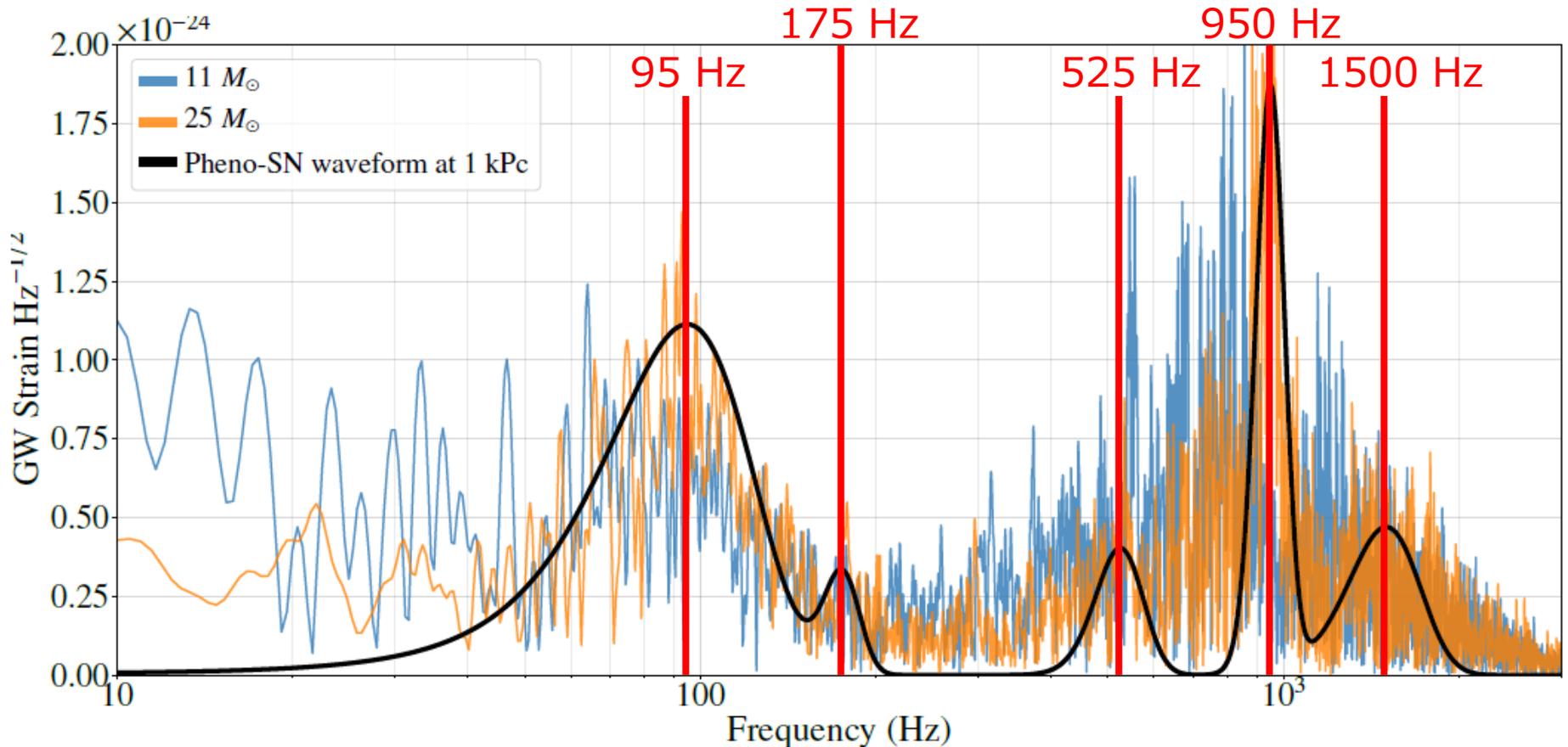
$$\Delta e = \sqrt{\frac{1}{N-1} \sum_i^N (\text{Model}_{flow}^{f_{high}} - \text{NR}_{flow}^{f_{high}})^2}$$

- The error in 1 kHz – 2 kHz is high (19%) because of an upper limit to 2 kHz

Reference GW waveform

- Sum of sine-Gaussian signals

$$\tilde{s}(f) = \frac{h_o}{4\sqrt{\pi}} \frac{Q}{f_o} e^{-\frac{(f-f_o)^2 Q^2}{4f^2}}$$



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Classification of GW detectors

- On the earth

1st-generation

... iLIGO, Virgo, GEO600, TAMA300

2nd-generation

... aLIGO, aVirgo, GEO600(@ high freq.),
CLIO, KAGRA

3rd-generation

... Einstein Telescope, Cosmic Explorer



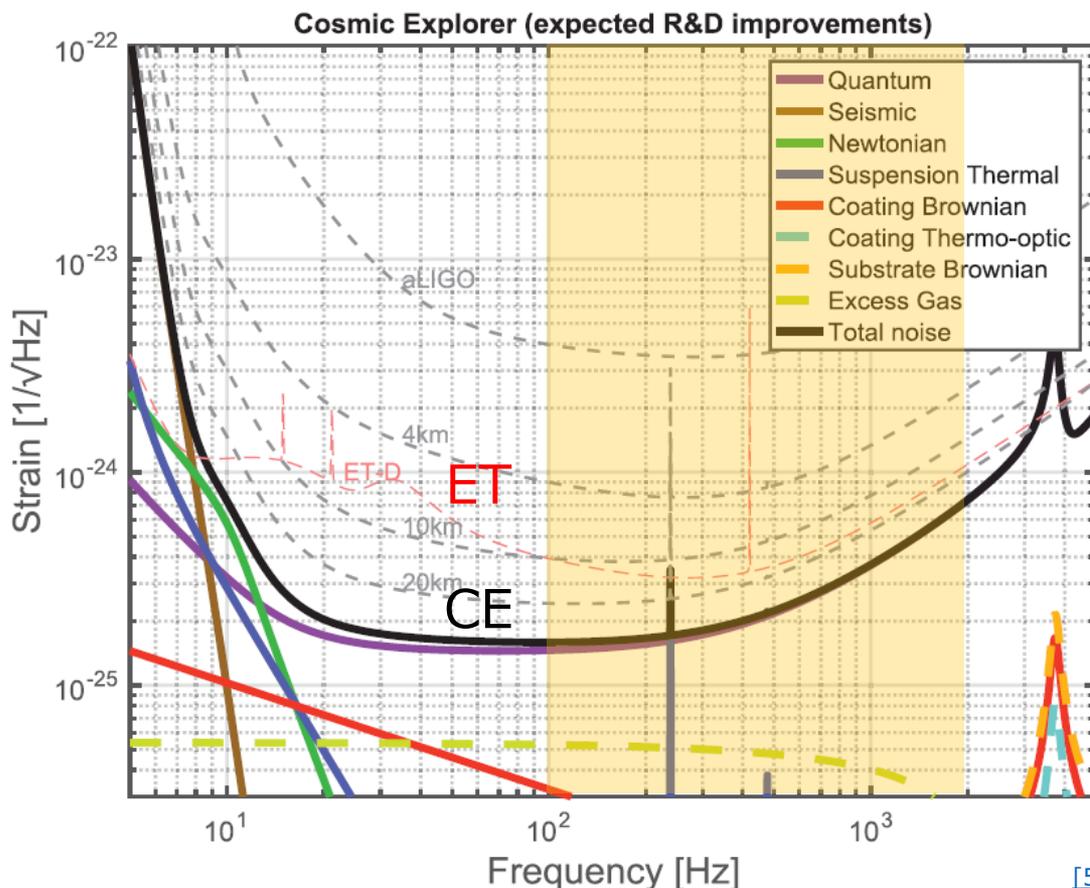
CCSN-optimized

- In the universe

... LISA, DECIGO

Cosmic Explorer

- Use a sensitivity of Cosmic Explorer as the starting point
- Cosmic Explorer has a better performance than Einstein Telescope at important freq. for CCSN



[51] B. P. Abbott+, 2016

Relationship between distance & rate

Distance: 30 kpc
Event rate: 1 per 50 years

Distance: 800 kpc
Event rate: 1 per 20 years

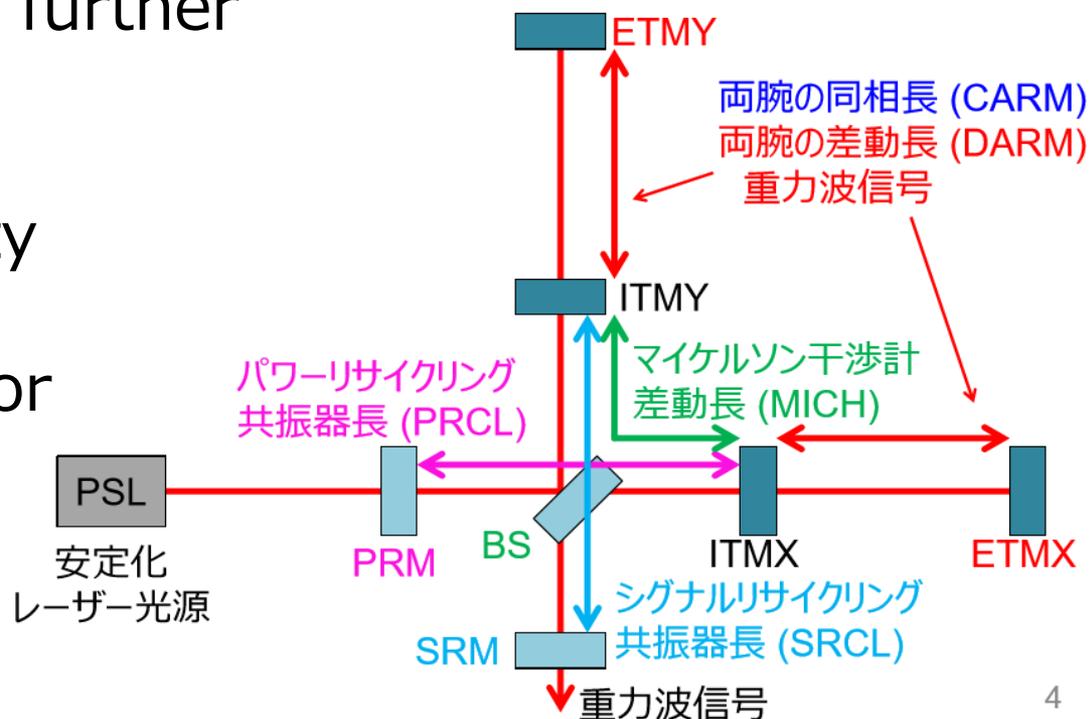
Here
(CE) →

Distance	Type-II CCSN rate (per century)
Milky way ($D < 30$ kpc)	0.6-2.5
M31 or Andromeda ($D = 770$ kpc)	0.2-0.83
M33 ($D = 840$ kpc)	0.62
Local Group ($D < 3$ Mpc)	9
Edge of Virgo Super-cluster ($D < 10$ Mpc)	47
Virgo-cluster ($D < 20$ Mpc)	210

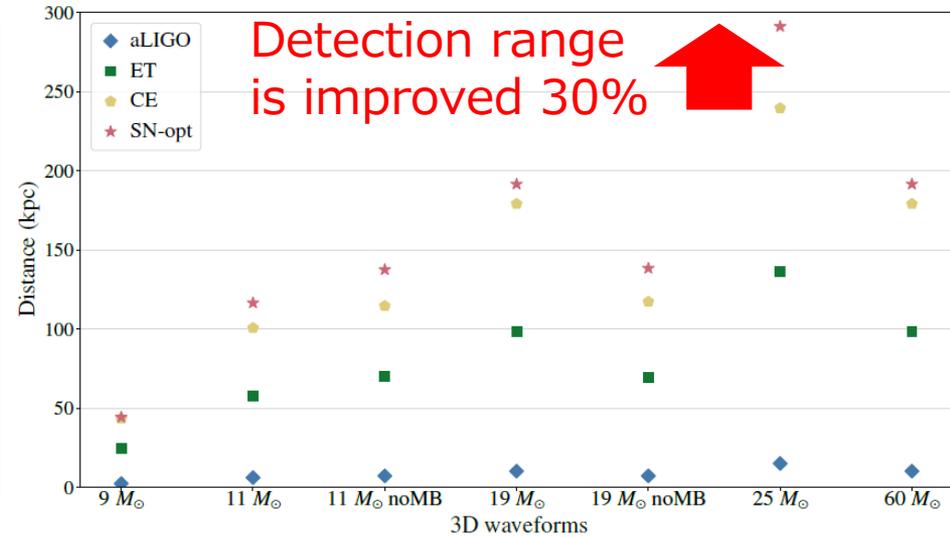
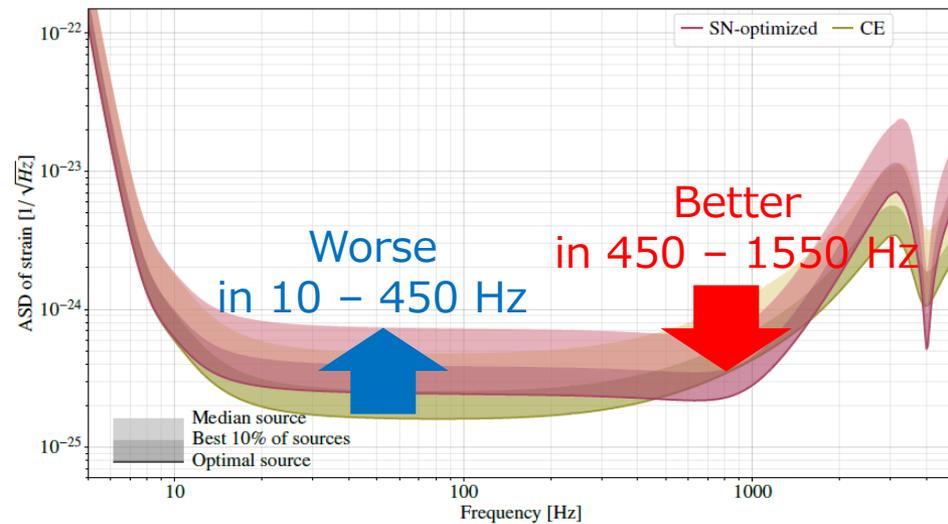
Our goal
Distance: 10 Mpc
Event rate: 1 per 2 years

① Tuning for broadband

- Reduce quantum noise, especially shot noise at high freq.
- Keep a sensitivity to compact binary stars
- L_{arm} : 40 km (f_{FSR} : 4 kHz)
(cannot increase any further because of f_{FSR})
- Signal recycling cavity
 L_{src} : 55 m \rightarrow 180 m
- Signal recycling mirror
 T_{srm} : 0.04 \rightarrow 0.015



① Tuning for broadband



① Tuning for broadband

- 30% improvement in detection range for CCSN
- 15% loss in detection range for BNS
- Extending range (75 kpc \rightarrow 90 kpc) does not add any new galaxies
- Event rate is still one per 50 years
- SNR from the source at a fixed distance is improved 25%

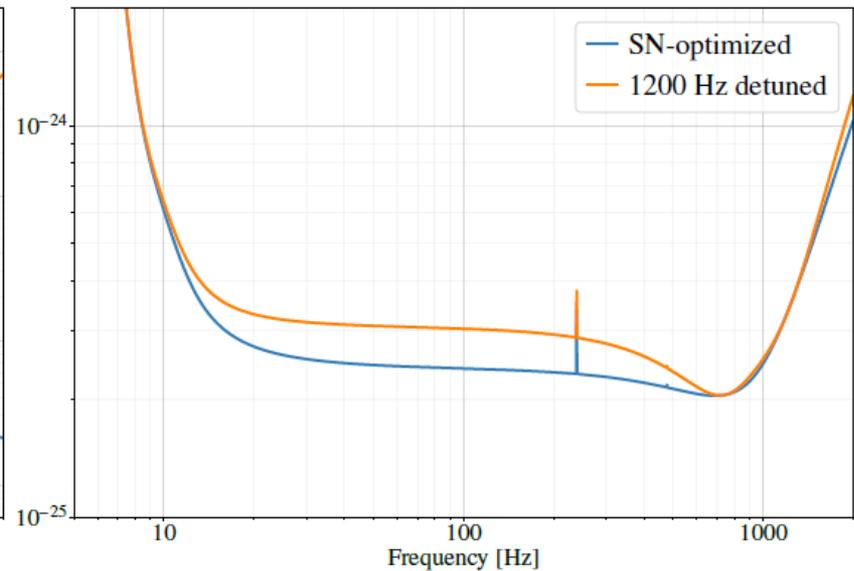
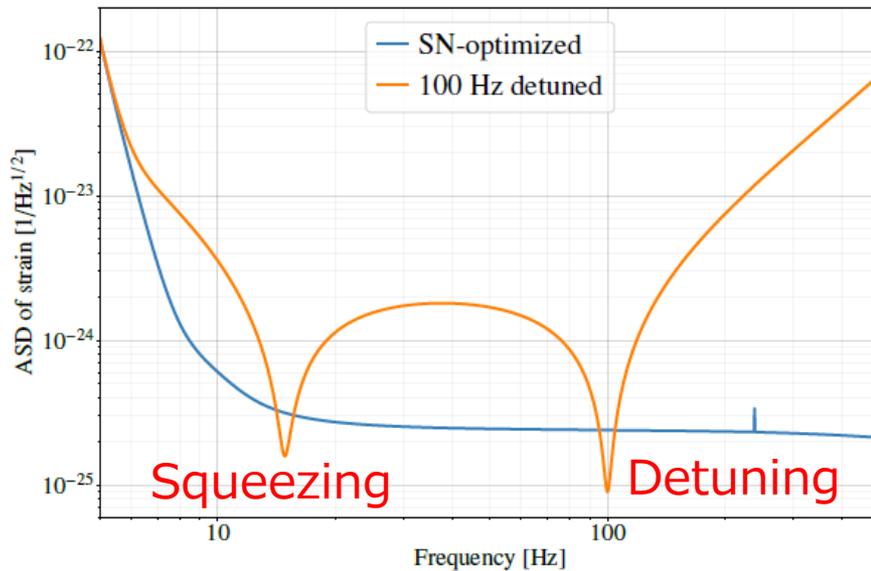
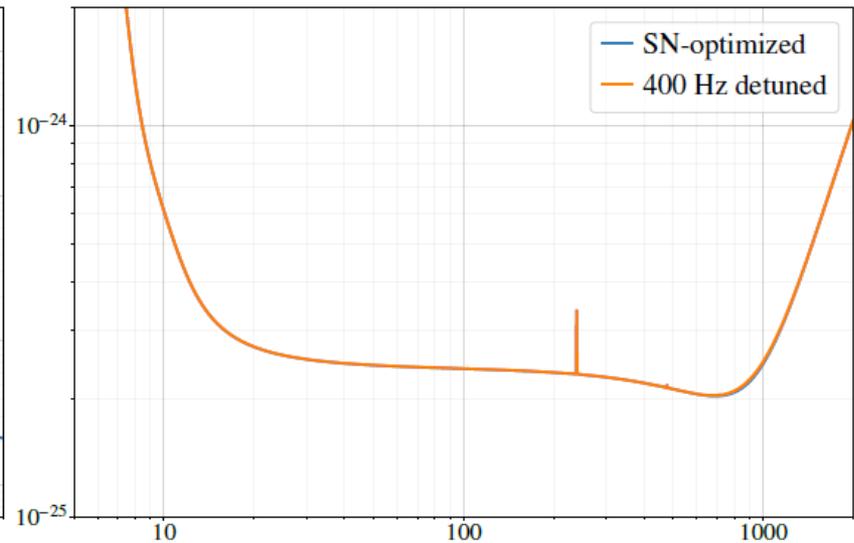
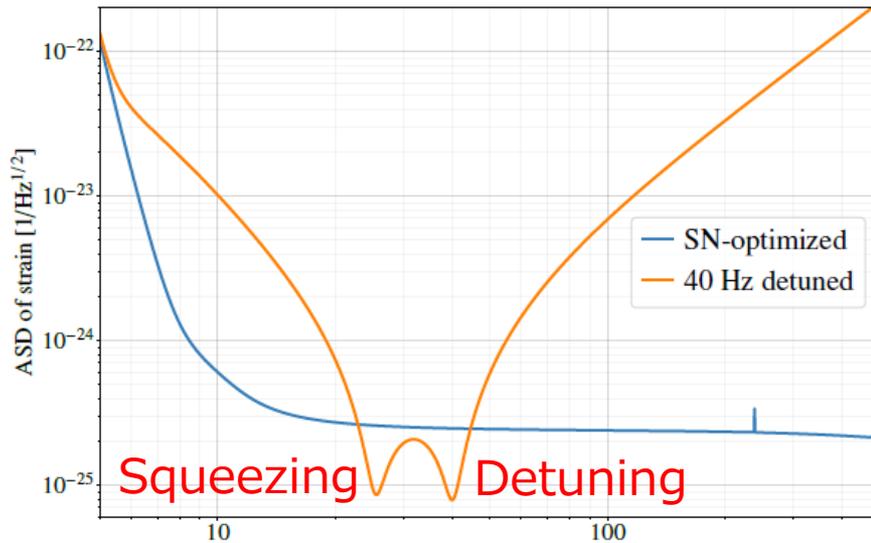
② Detuning for narrow-band

- A sensitivity can exceed standard quantum limit by detuning
- Detuning is achieved only below 400 Hz
- Freq. range below 400 Hz is not useful for CCSN

Relationship between squeezing and detuning

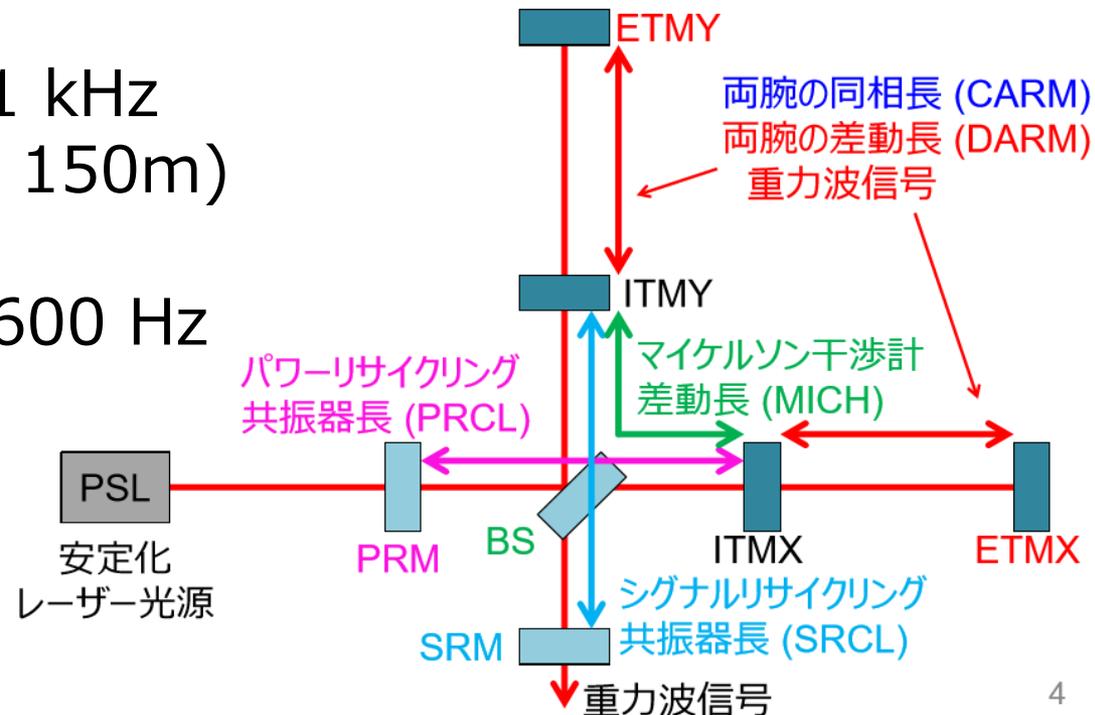
- 15 dB squeezing is achieved by changing the squeezing angle in accordance with the amount of detuning
- The amount of detuning: from $-\pi/5$ to $\pi/5$
- Squeezing angle: from $-\pi$ to π

② Detuning for narrow-band

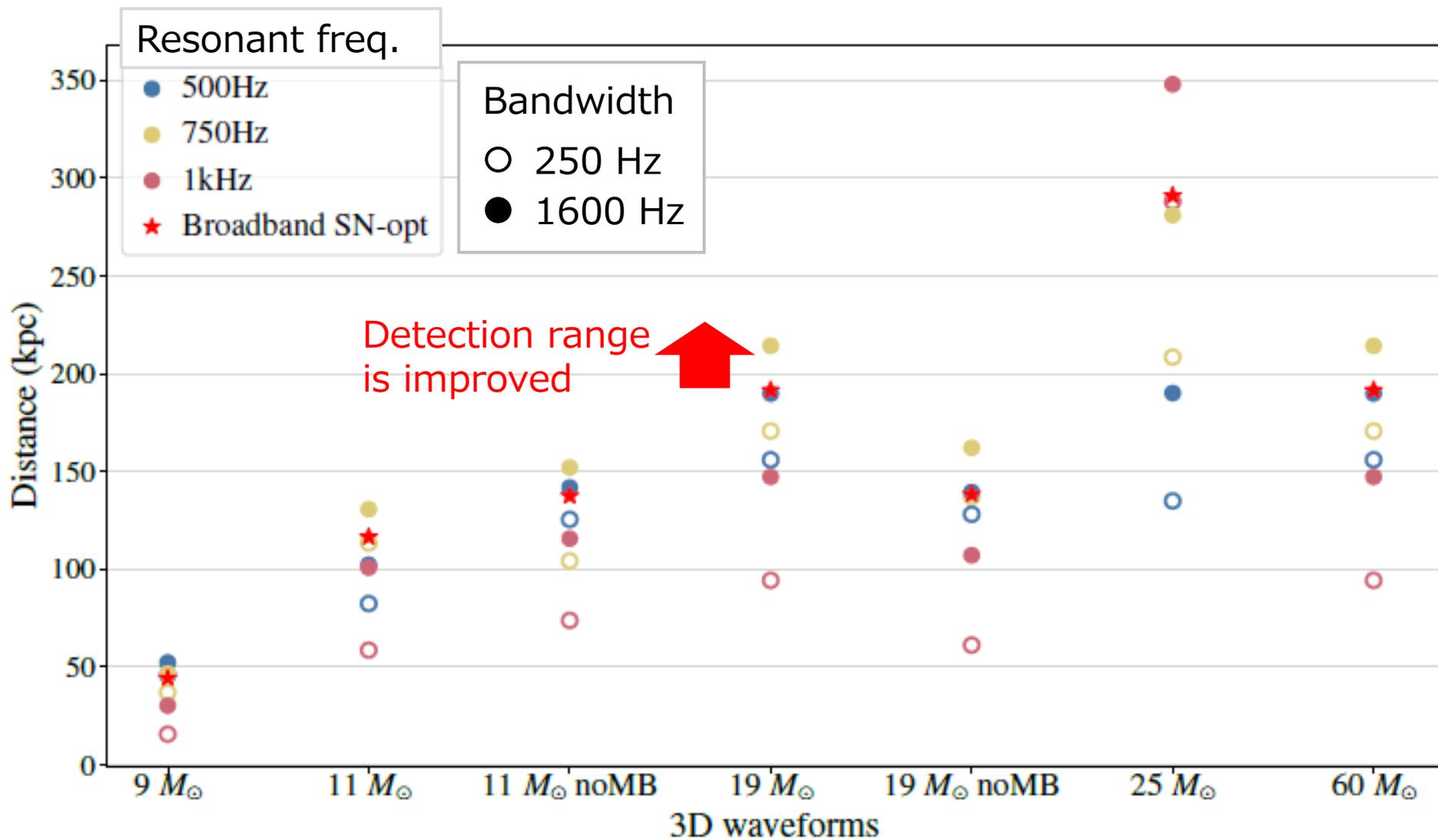


③ Tuning for narrow-band

- Narrow-band optimization without reference waveforms
- Coupling of the signal recycling cavity with the arms of the interferometer
- Resonant frequency:
500 Hz, 750 Hz, 1 kHz
(L_{src} : 750 m, 300 m, 150m)
- The bandwidth:
from 250 Hz to 1600 Hz



③ Tuning for narrow-band



③ Tuning for narrow-band

- Improvement in SNR with the 750 Hz narrow-band and 1600Hz bandwidth detector is about 10%
- Note that loss sensitivity below 400 Hz and above 1100 Hz
- BNS range gets worse about 20%

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Here
(Opt.)

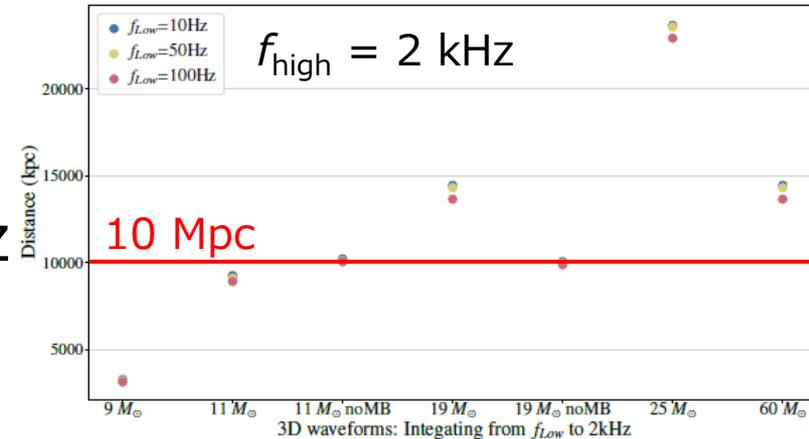
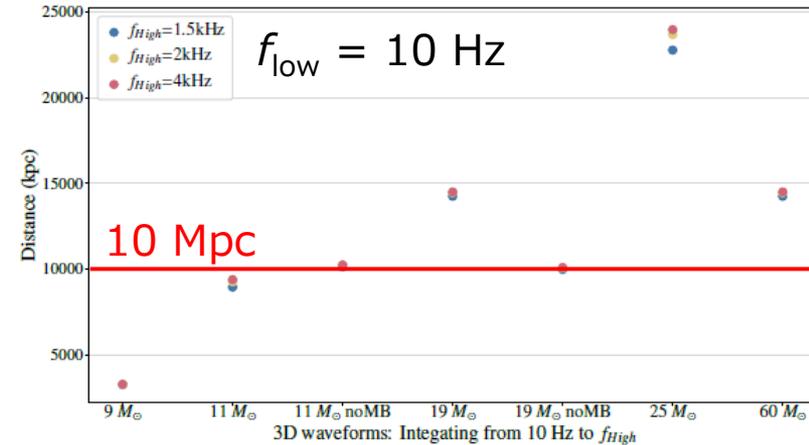
Our goal
Distance: 10 Mpc
Event rate: 1 per 2 years

Goal of hypothetical detectors

- Event rate: one per 2 years
- Range: order ~ 10 Mpc
- Fix f_{low} or f_{high} and change the other
- Calculate optimal distance

$$d_{\text{opt}} = \frac{\sigma}{\rho^*} = \frac{1}{\rho^*} \left[2 \int_{f_{\text{low}}}^{f_{\text{high}}} df \frac{\tilde{h}(f)\tilde{h}^*(f)}{S_h(f)} \right]^{\frac{1}{2}}$$

- Strain sensitivity: $3 \times 10^{-27} / \sqrt{\text{Hz}}$ from 100 Hz to 1500 Hz
- 100 times better than Cosmic Explorer



Design of hypothetical detectors

- A sensitivity of Cosmic Explorer is limited by quantum noise
- L_{arm} : 40 km (f_{FSR} : 4 kHz)
(cannot increase any further because of f_{FSR})
- Input laser power: 500 W
- Photon-detection efficiency: 1
(cf. 0.96 for Cosmic Explorer design)
- Optical and squeezing injection losses: 0

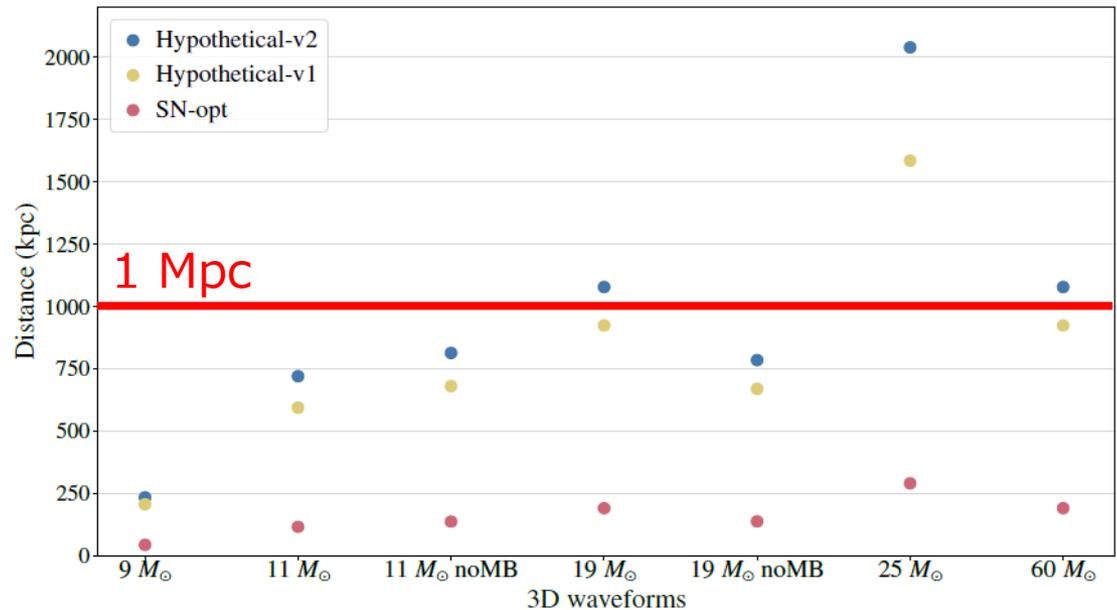
Design of hypothetical detectors

- Next limiting factors: coating thermal noise, residual gas noise
- Reduce them by an order of magnitude from Cosmic Explorer design
- Give up below 100 Hz because not important for CCSN
-  Reduce the masses of mirror to improve shot noise, at the cost of higher radiation pressure

Hypothetical detectors

- Sensitivity: $5 \times 10^{-26} / \sqrt{\text{Hz}}$
- Detection range: 1 Mpc (Andromeda Galaxy)
- Event rate: one per 20 years

- Not sufficient to a sensitivity of $3 \times 10^{-27} / \sqrt{\text{Hz}}$
- A long way to one per 2 years



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Here
(Hyp.)

Our goal
Distance: 10 Mpc
Event rate: 1 per 2 years

Designs of all detectors

Parameters	aLIGO	Cosmic Explorer-2	SN Optimized	Hypothetical-1	Hypothetical-2
Input Power	125W	220W	220W	500W	500W
SRM transmission	0.325	0.04	0.015	0.0030	0.0122
ITM transmission	0.014	0.014	0.014	0.0036	0.0269
PRM transmission	0.030	0.030	0.030	0.030	0.0011
L_{src}	55m	55m	175m	30m	260m
Finesse	446.25	447.52	447.52	1745.33	233.33
Power Recycling Factor	40.66	65.32	65.32	94.25	1300.09
Arm power	712.43 kW	2025.70 kW	2025.70 kW	26.06 MW	47.61 MW
Thermal load on ITM	0.386 W	1.150 W	1.150 W	13.094 W	24.180 W
Thermal load on BS	0.051 W	0.253 W	0.253 W	0.008 W	0.080 W
BNS range	173.00 Mpc	4.29 Gpc >	3.67 Gpc	5.32 Gpc	5.09 Gpc
BNS horizon	394.83 Mpc	11.05 Gpc	9.49 Gpc	12.97 Gpc	12.53 Gpc
BNS reach	246.06 Mpc	8.54 Gpc	6.90 Gpc	11.56 Gpc	10.80 Gpc
BBH range	1.61 Gpc	6.13 Gpc	6.10 Gpc	6.15 Gpc	6.09 Gpc
BBH horizon	3.81 Gpc	11.86 Gpc	11.85 Gpc	11.85 Gpc	11.70 Gpc
BBH reach	2.54 Gpc	11.73 Gpc	11.73 Gpc	11.72 Gpc	11.52 Gpc
Supernovae range	4.34 kpc	71.95 kpc <	94.24 kpc	540.53 kpc	716.03 kpc
Supernovae horizon	9.84 kpc	163.08 kpc	213.61 kpc	1225.22 kpc	1623.06 kpc
Supernovae reach	6.10 kpc	101.04 kpc	132.35 kpc	759.15 kpc	1005.65 kpc
Stochastic Omega	2.36e-09	1.82e-13	2.77e-13	1.1e-13	2.58e-13

Milky way
One per 50 years

Andromeda
One per 20 years

Summary

- GW waveforms from core-collapse supernovae are created by 3-dimensional simulations
- Optimized 3rd-generation detectors and hypothetical detectors are proposed for core-collapse supernovae

Detectors	Detection range	Event rate
Optimized 3rd-generation	Milky Way Galaxy (- 100 kpc)	one per 50 years
Hypothetical	Andromeda Galaxy (- 1 Mpc)	one per 20 years

- Detectors need a strain sensitivity of $3 \times 10^{-27} / \sqrt{\text{Hz}}$ from 100 Hz to 1500 Hz in order to detect core-collapse supernova one per 2 years

Extra Slides

Betelgeuse

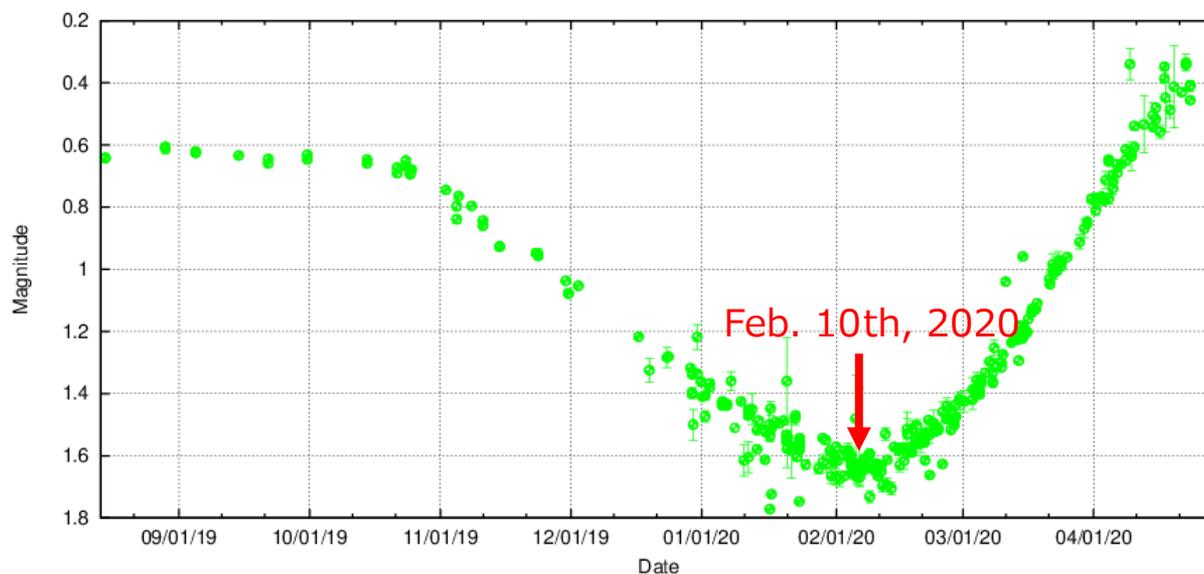


[ESO](#)

- Distance: 200 pc
- If SN happens, GW will be observable with 2nd generation detectors

Light curve of Betelgeuse (V-band)

AAVSO DATA FOR BETELGEUSE - WWW.AAVSO.ORG

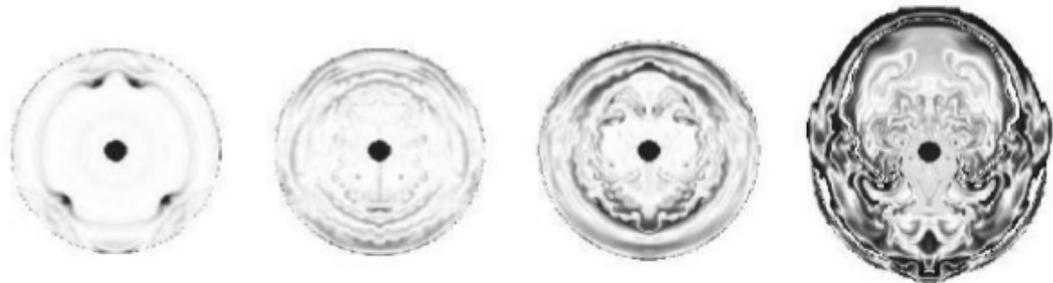
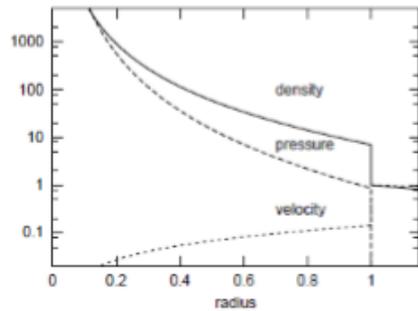


[AAVSO: Light Curve Generator](#)

SASI

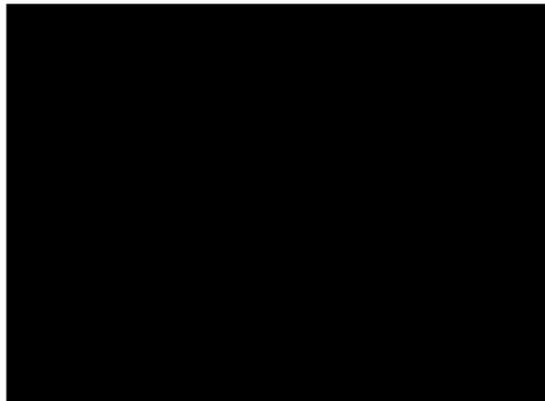
定在降着衝撃波不安定性

SASI(Standing accretion-shock Instability)



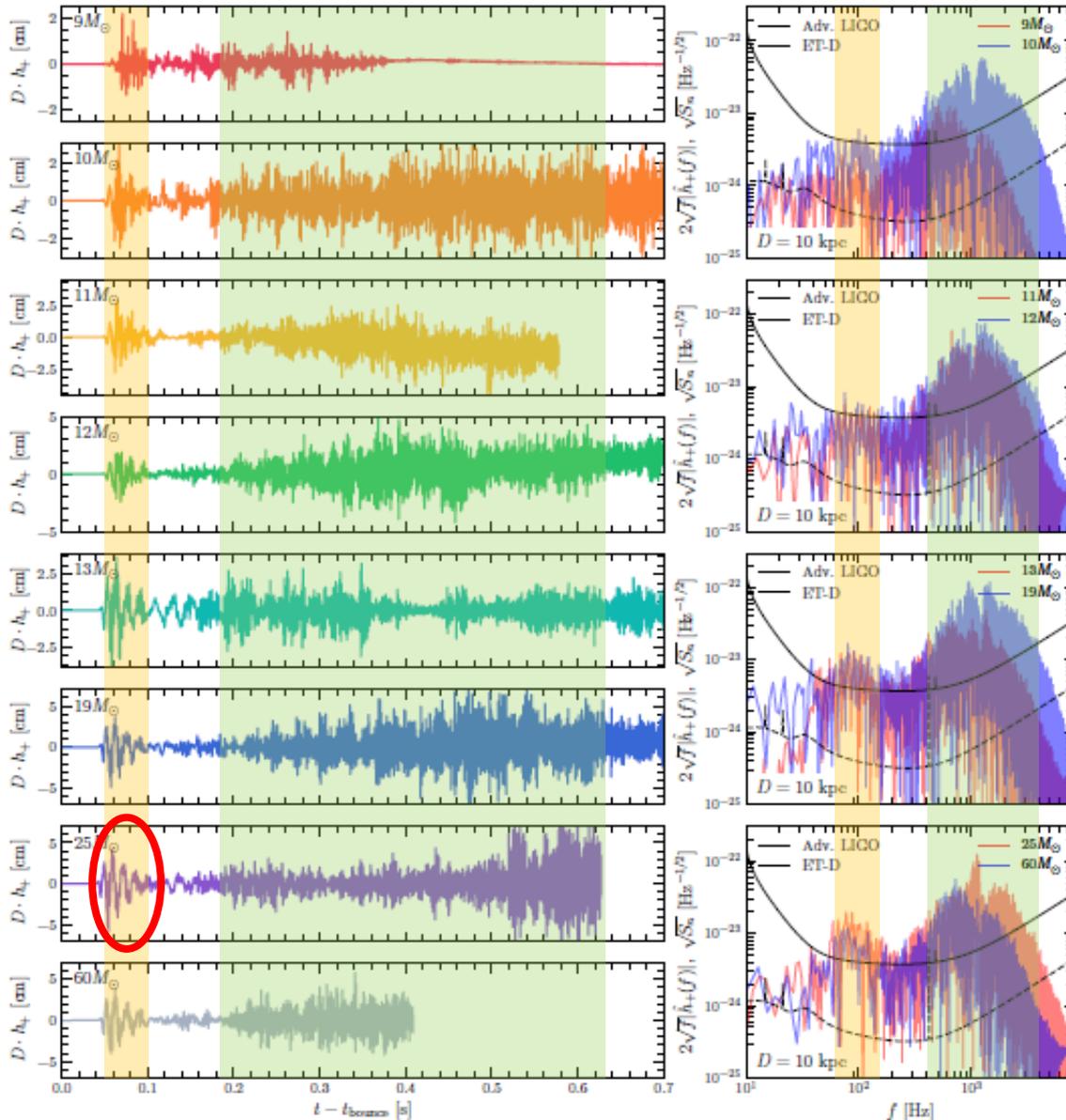
Blondin 2003

SASI: 衝撃波は球状の形状を保てない不安定性。

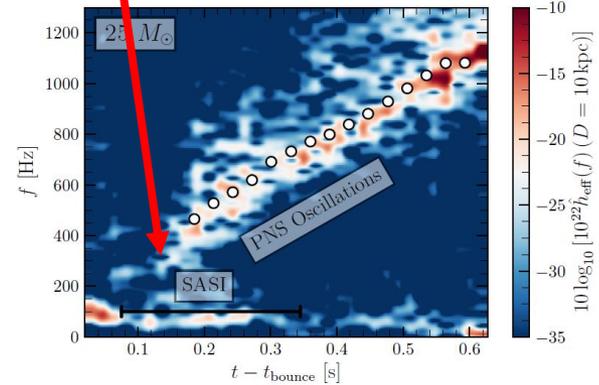


<http://irfu.cea.fr/Projets/SN2NS/outreach.html>

GW from CCSN by 3D simulations



Only $25 M_{\odot}$
 SASI (standing accretion shock instability)
 定在降着衝擊波不安定性



[19] D. Radice+, 2018

Hypothetical detectors

