Detection of Gravitational Waves from Core-Collapse Supernovae

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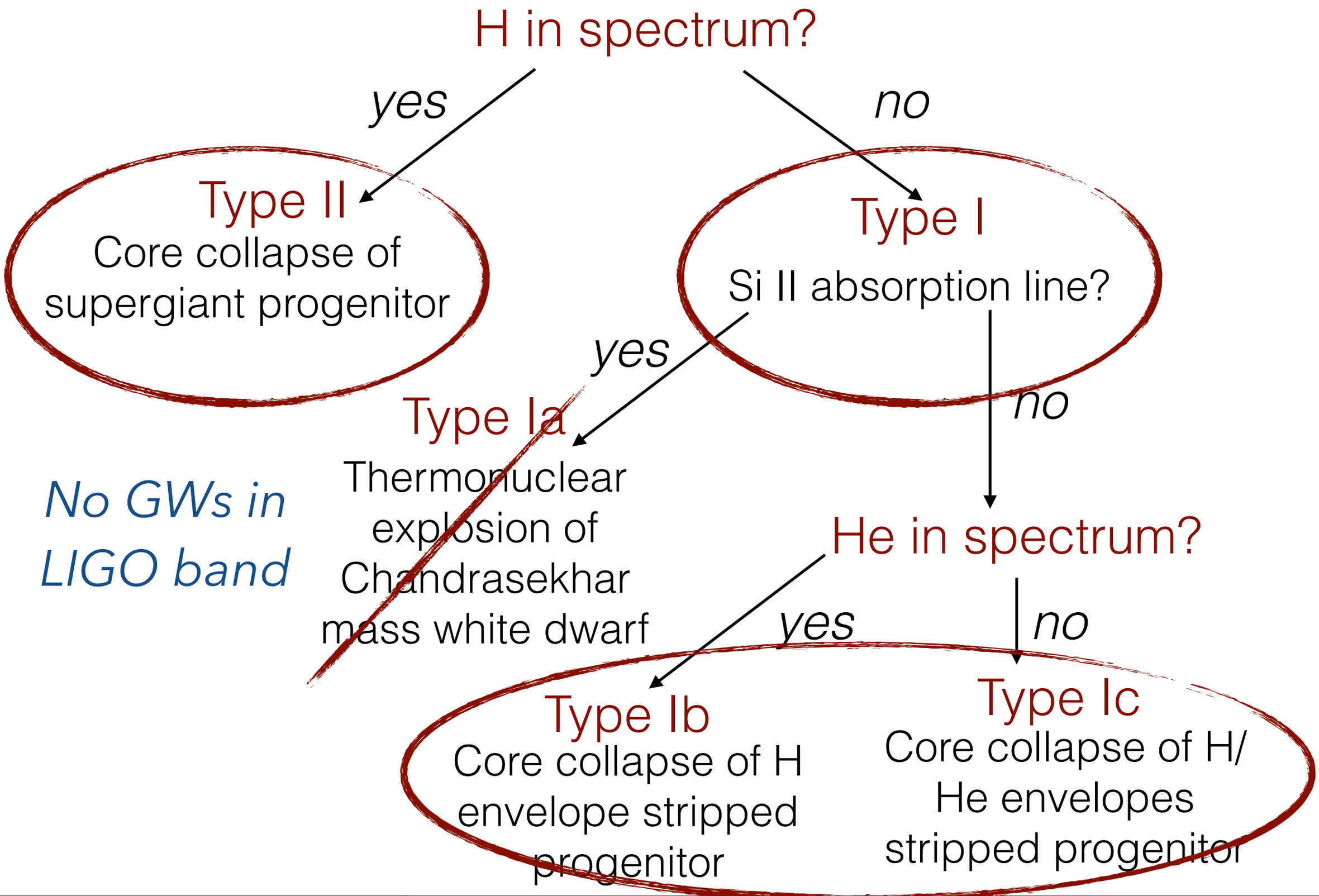
ERAU

Breaking down SN Classification



Intuitive Parameterization of SNe

Type II

Red supergiant progenitor
Stellar radius ~ (500-1000) $R_\odot$
Shock breakout time ~ [5, 50]h

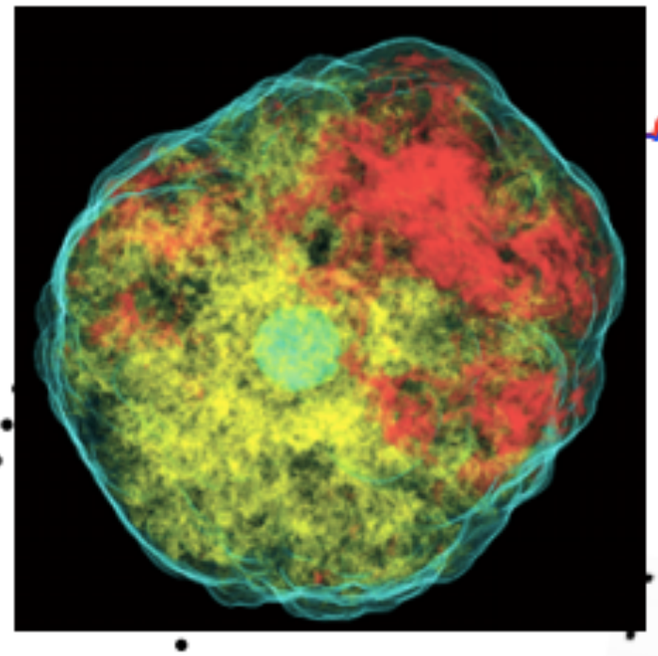
Type Ibc → Ib - mass transfer in binary & Ic - extreme stellar winds (CSM)

Stripped envelope progenitor - no H (no He for Type Ic Sne)
Stellar radius ~ (5-10) $R_\odot$
Shock breakout time ~ [1, 35]s

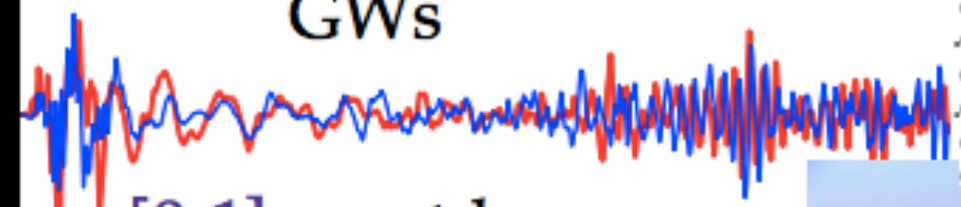
	Radius	Optical Emission Timescale	Length of peak luminosity
Wolf-Rayet	~10^{11} cm (5-10 $R_\odot$)	3 seconds	10 - 20 seconds
Blue Supergiant	~ 3 x 10^{12} cm (25-50 $R_\odot$)	100 seconds	15 minutes
Red Supergiant	~ 3 x 10^{13} cm (500-1000 $R_\odot$)	15 minutes	2 - 3 hours

CCSNe Observation

From the supernova central engine



GWs

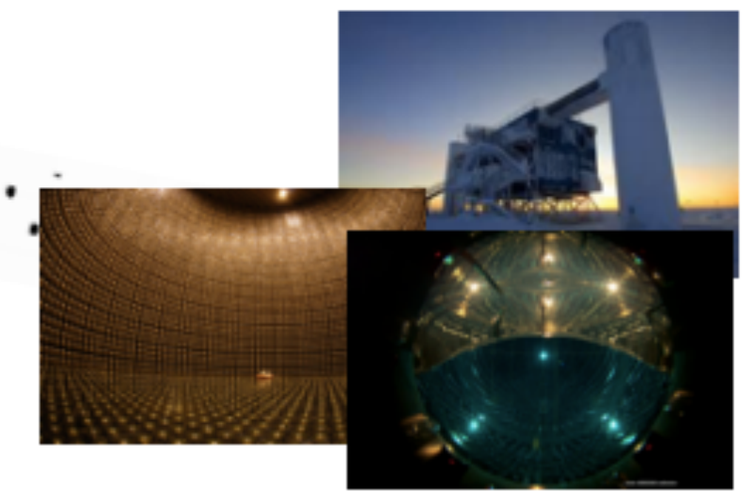


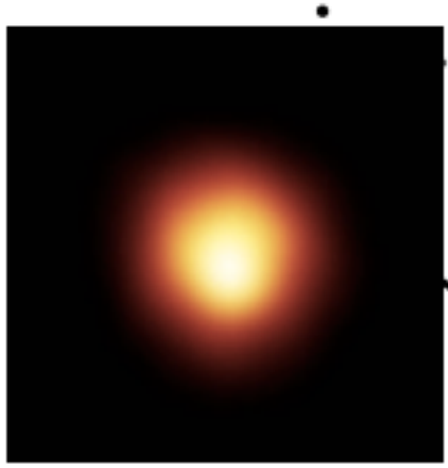
[0-1]s post-bounce

LIGO

Neutrinos (ν)

[few ms,10s] post-bounce





Explosion reaches surface few s-days post-bounce

EM from surface

Formal MOU!

ASAS-SN

Can last years post-bounce

Understanding the Physical Landscape of CCSNe

Slowly Rotating

- Prompt convection
- Neutrino-driven convection & SASI
- PNS convection

Rapidly Rotating

- Bounce/ringdown of millisecond PNS
- low T/|W| instabilities

Understanding the Physical Landscape of CCSNe

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- *Slowly rotating progenitor ~ 99% of expected CCSNe*

Understanding the Physical Landscape of CCSNe

Slowly Rotating

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Rapidly Rotating

- Bounce/ringdown of millisecond PNS
- low T/|W| instabilities

- *Rapidly rotating progenitor ~ 1% of expected CCSNe*
- *Rotation profile is parameterized by central angular velocity and a differential rotation*

Holistic Perspective

Emission Process	Duration [ms]	Spectrum [Hz]	*h* @ 1 Mpc	E_{GW} [$M_\odot c^2$]
Rotating Collapse & Bounce	~10	~400 - 900	~5×10^{-24} - 2×10^{-22}	~2×10^{-11} - 1×10^{-7}
Dynamical Shear	10 - ≳ 100	~700 - 1000	~ few $\times10^{-23}$	10^{-7} (change in time/100ms)
Bar Mode	10 - ≳ 100	~1000 - 2000	~ few $\times10^{-23}$ - $\times10^{-21}$	10^{-7} - 10^{-2} (change in time/100ms)
Prompt Convection	10 - 30	~50 - 1000	~ $\times10^{-25}$ - $\times10^{-23}$	10^{-12} - 10^{-9}
v-driven Convection/ SASI	100 - 500	~100 - 1000	~ $\times10^{-25}$ - $\times10^{-23}$	10^{-12} - 10^{-9} (change in time/100ms)
Convection in PNS	≳ 1000	~600 - 1000	~ $\times10^{-25}$ - $\times10^{-23}$	10^{-8} (change in time/100ms)
BH Formation	≲ 1 - 2	~600 - 4000	~ $\times10^{-23}$ - $\times10^{-22}$	~10^{-8} - 10^{-7}
Aspherical Outflows	≳ 100 - 1000	~ 20	~ $\times10^{-23}$ - $\times10^{-22}$	≲ 10^{-11}
Accretion Disk Instabilities	≳ 1000	~100 - 1000	~ $\times10^{-22}$ - $\times10^{-19}$	~10^{-5} - 10^{-1}

Please refer to work & talks given by Yakunin & Mezzacappa!

The Search for GWs from CCSNe

Detection of CCSNe limited to Milky Way (neutrino-driven convection) and LMC (rotating core-collapse).

Nearby CCSNe

Model	Milky Way HLV 2019 $d^{50\%}$ [kpc]	LMC HLV 2019 $d^{50\%}$ [kpc]
Convection & SASI (3D: müller, ott; 2D: yak)	2.4 - 5.5 ~	2.5 - 7.2 ✗
Bounce & ringdown of proto-NS (2D: dim)	17 - 38 ✔	18 - 50 ~
Non-axisymmetric rotational instabilities (3D: sch)	78 - 98 ✔	90 - 120 ✔

Distant CCSNe

	M31 (61m) HLV 2019 $d^{50\%}$ [Mpc]	M31 (51h) HLV 2019 $d^{50\%}$ [Mpc]	M82 (24h1m) HLV 2019 $d^{50\%}$ [Mpc]	M82 (74h) HLV 2019 $d^{50\%}$ [Mpc]
Long-lasting bar mode instability (longbar)	2.3 - 25 ✔	1.2 - 14 ✔	1.0 - 9.7 ~	0.7 - 8.3 ~
Accretion disk fragmentation (piro)	2.4 - 35 ✔	1.6 - 22 ✔	1.3 - 16 ~	1.3 - 15 ~

past results are shown with algorithms that *haven't undergone O2 improvement*

[4] Gossan et al. 2016

The Search for GWs from CCSNe

- GW emission from core-collapse detectable out to ~100kpc
- Extreme post-core-collapse GW emission models detectable out to ~10-15 Mpc

[3] Gill et al. 2017

aLIGO CCSNe Detection Distance

Waveform	cWB Distance (Mpc) @ 50% hrss	FC Distance (Mpc)	GRB Distance (Mpc)
LB1	0.732	5	5
LB2	2.252	5	5
LB3	0.191	5	5
LB4	3.292	5	5
LB5	11.511	15	15
Piro1	0.891	5	5
Piro2	4.409	15	15
Piro3	2.445	5	5
Piro4	12.569	15	15

3G CCSNe Detection Distance

Waveform	cWB Distance (Mpc) @ 50% hrss	FC Distance (Mpc)	GRB Distance (Mpc)
Muller1-N20-2	0.38	1	5
Muller1-L15-3	0.47	1	1
Muller1-W15-4	0.99	N/A	1
Yak1	0.002	0.5	0.1
Yak2	0.001	0.5	0.5
Yak3	0.002	0.1	0.1
Yak4	0.004	0.5	0.5

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Introducing a collective CCSNe population methodology!

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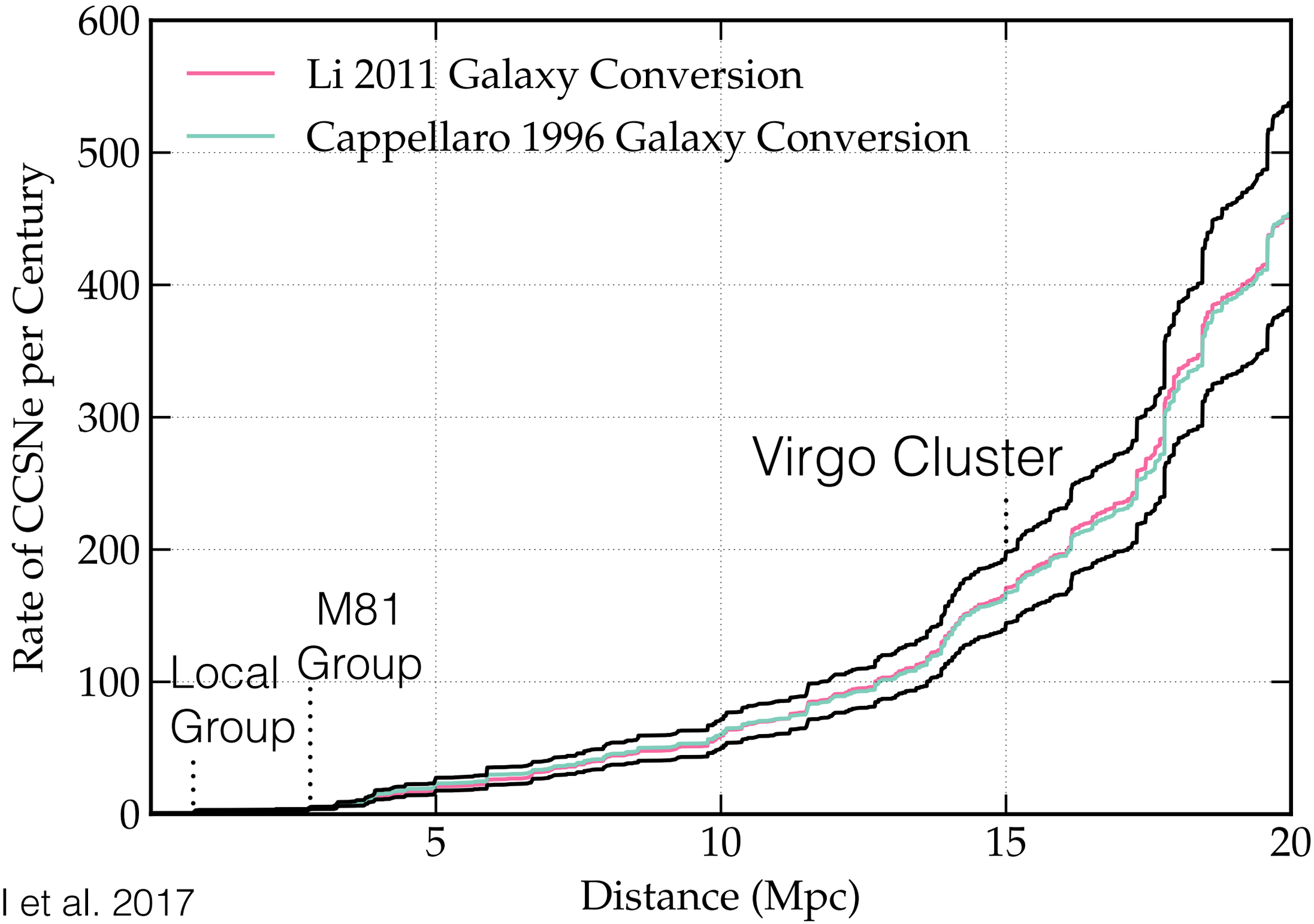
CCSNe Rate within 20 Mpc



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The Search for GWs from CCSNe

Externally-triggered Searches

- Galactic or Large Magellanic Cloud SN will have coincident neutrino signal from SuperKamiokande, LVD, Borexino
- Distant galaxy SN (e.g. M31, M82) will have coincident EM signal from e.g. ASAS-SN - dependent on progenitor star radius, shock velocity, and observation cadence).

The Search for GWs from CCSNe

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LSC-Virgo Outlook?

no deterministic waveform models for GW emission from core collapse = conduct searches over astrophysically motivated time period where we expect to find GW - neutrino or EM observations.

The Search for GWs from CCSNe

Externally-triggered Searches

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Talk covering "Science Goals: Algorithmic Developments within LVC-SN Group" will expand on the LSC-Virgo outlook flavor!

no deterministic waveform models for GW emission from core collapse = conduct searches over astrophysically motivated time period where we expect to find GW - neutrino or EM observations.