Gravitational Waves from Fallback Accretion and Black Hole Formation in Long GRBs

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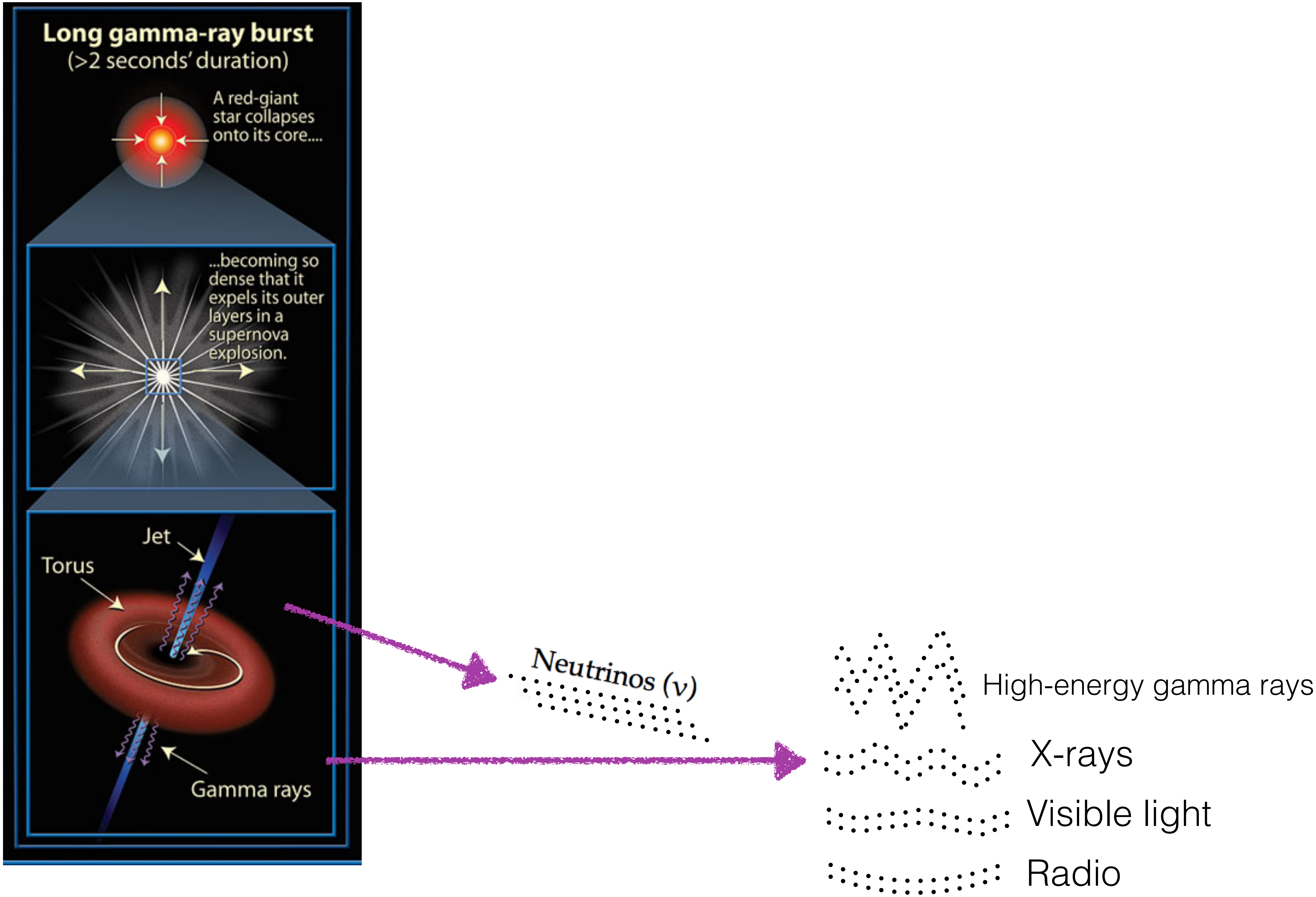
Motivation

- Detectability prospects with current and future generation GW detectors for both Ott *et al.* (2011) and Piro & Thrane (2012) collapsar waveforms
  - cWB and X-pipeline
- Introduction of **Gill & Gossan (2016) phenomenological gravitational waveform**
- Proposal of a radio search focusing on broad-line type Ic SNe in low metallicity environments within 20 Mpc

Observing Core-Collapse Supernovae & LGRBs



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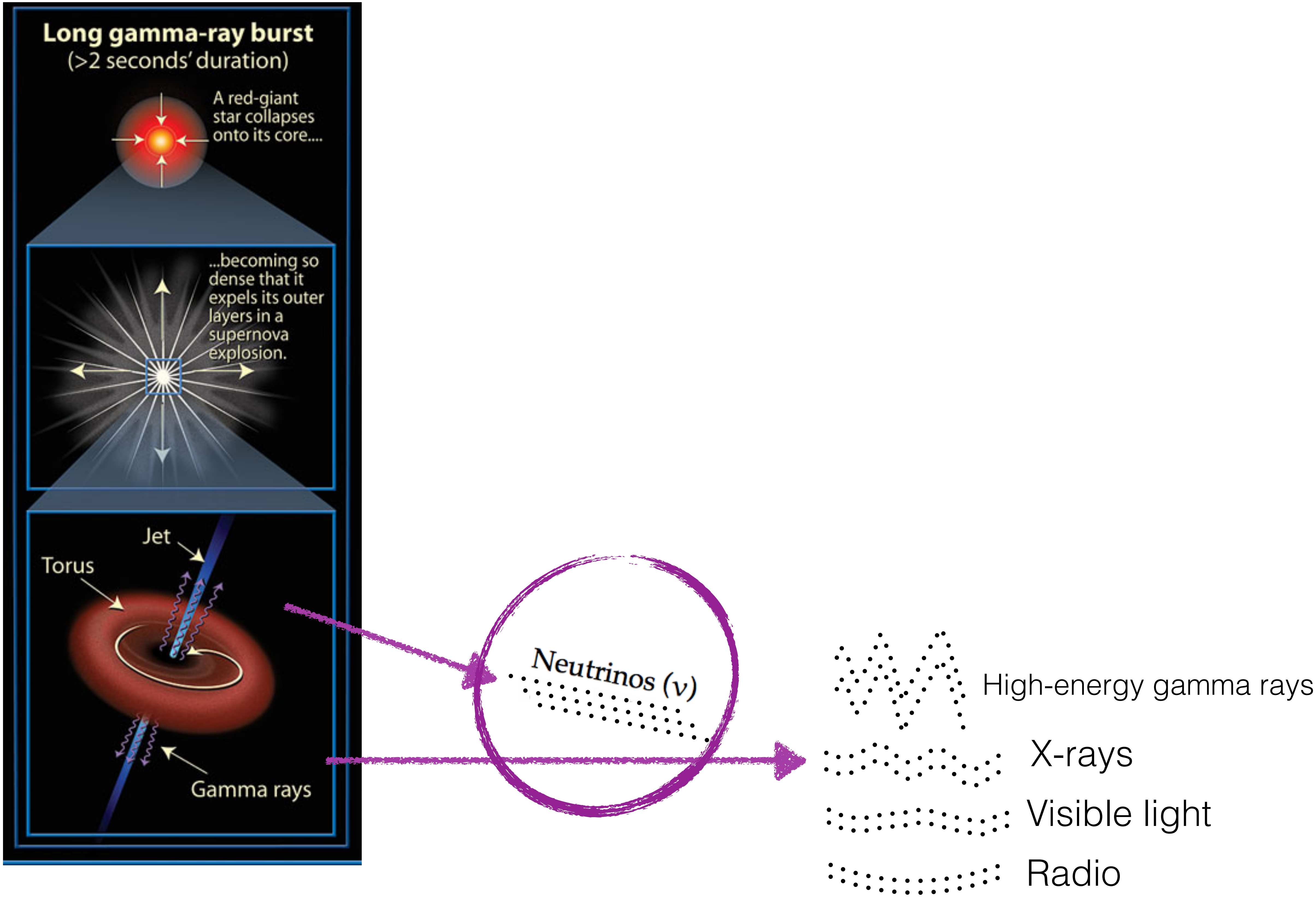

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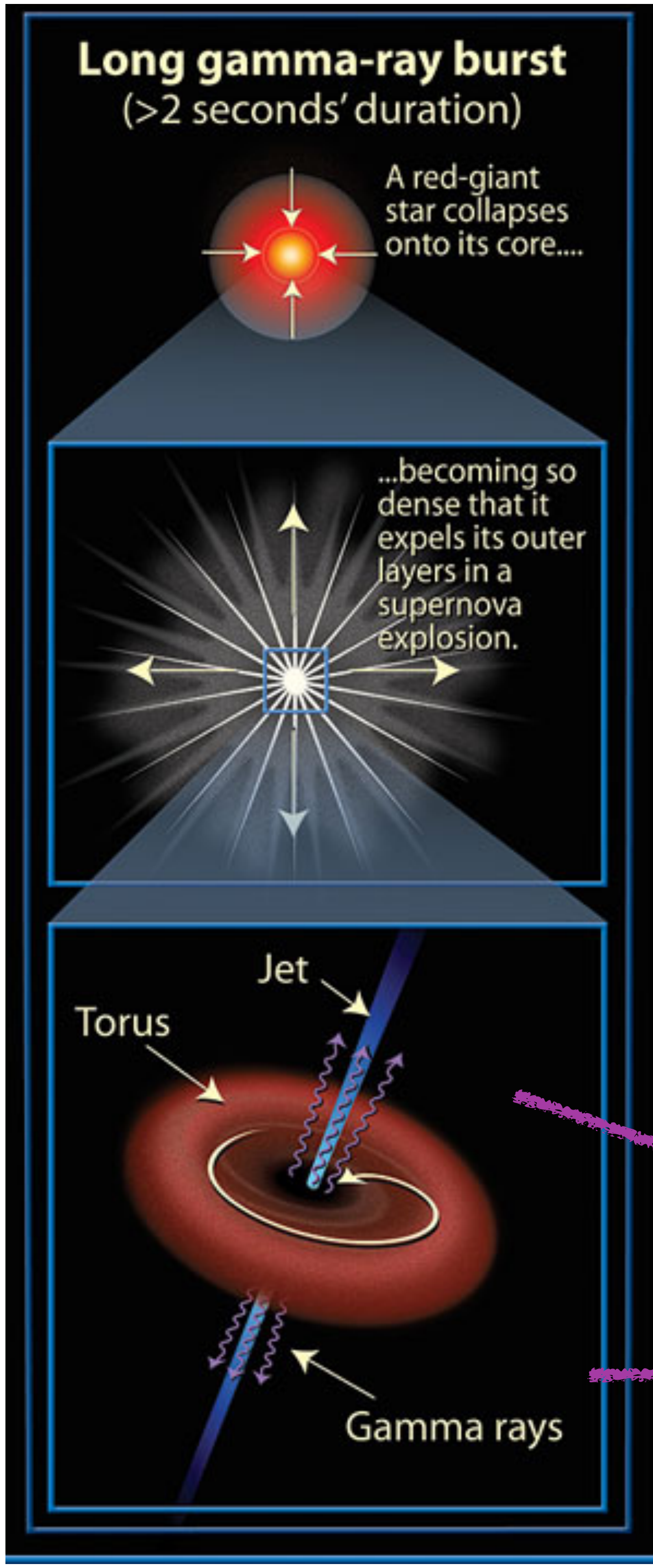

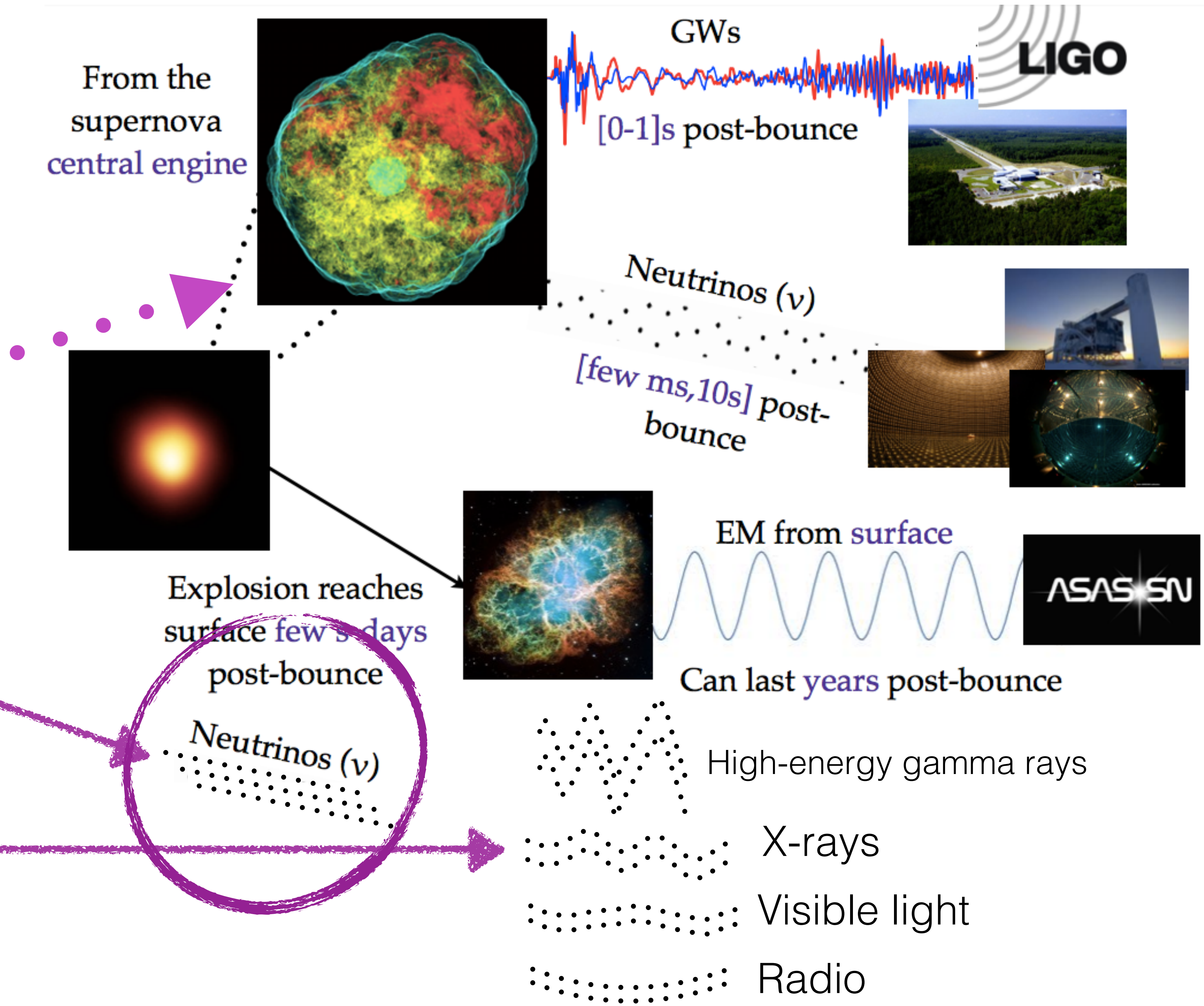

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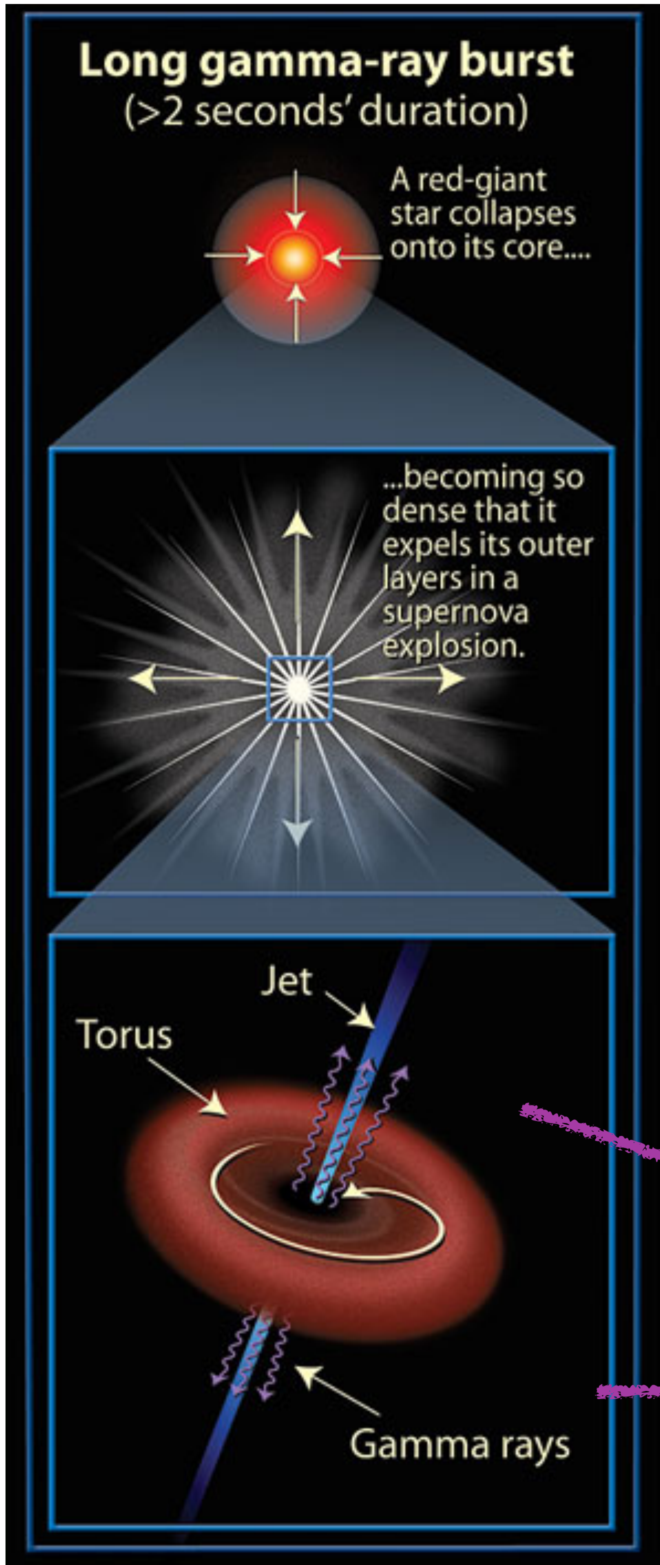

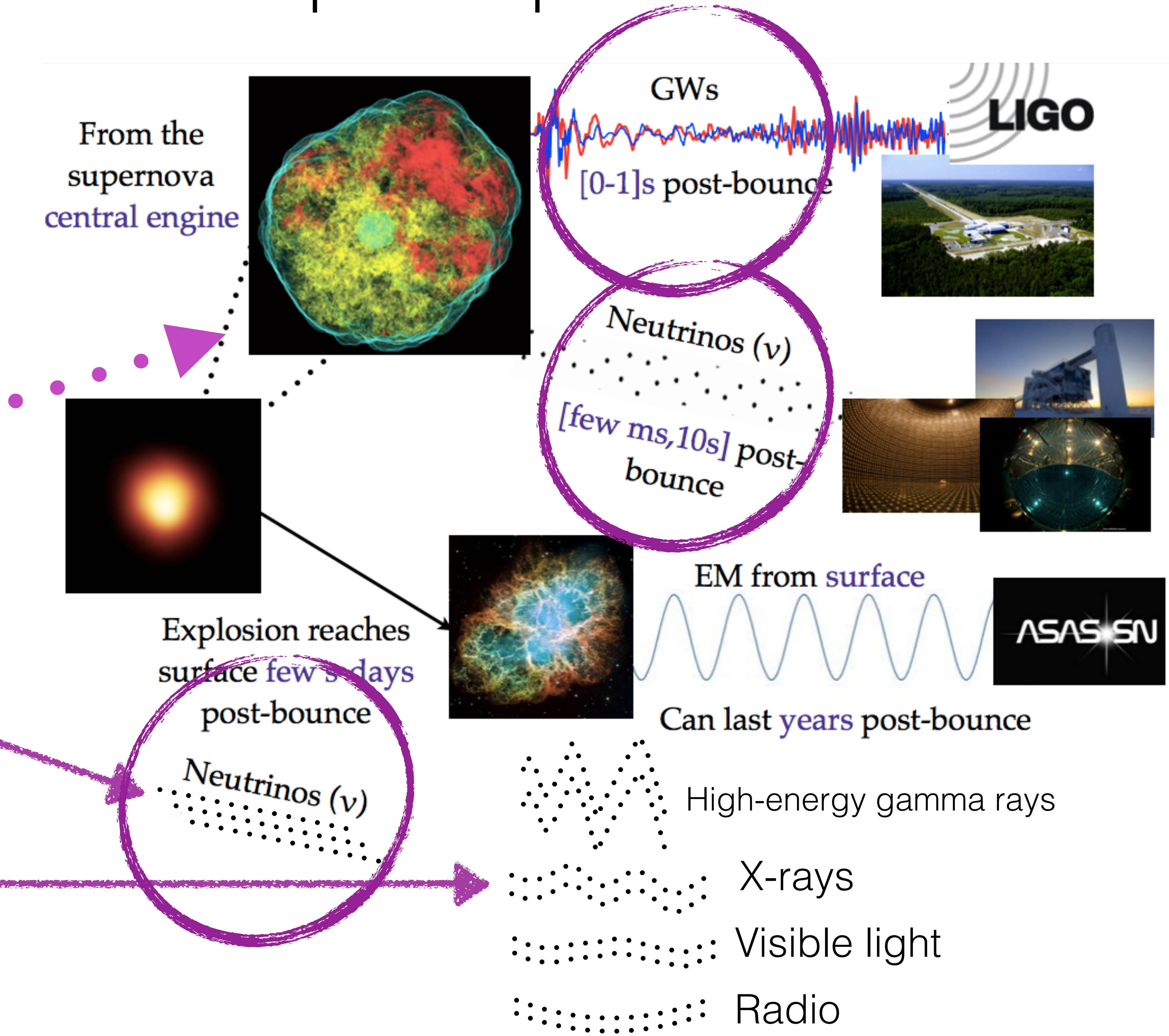

Long Gamma-Ray Bursts (LGRBs)

> 2 seconds duration

Spectroscopically confirmed GRB-SN:

- GRB 980425 / SN 1998bw: z = 0.0085
- GRB 030329 / SN 2003dh: z = 0.1687
- GRB 031203 / SN 2003lw: z = 0.1055
- GRB 060218 / SN 2006aj: z = 0.0335

confirmed GRB-SN connection as a special class of Type Ic-BL SNe

Smooth & featureless spectra

GRB peak spectra energy correlated w/ SN max luminosity

Red bump = interpreted as emergence of SN light curve

Zeh et. al (2004) = all LGRBs are associated with Type Ic-BL SNe

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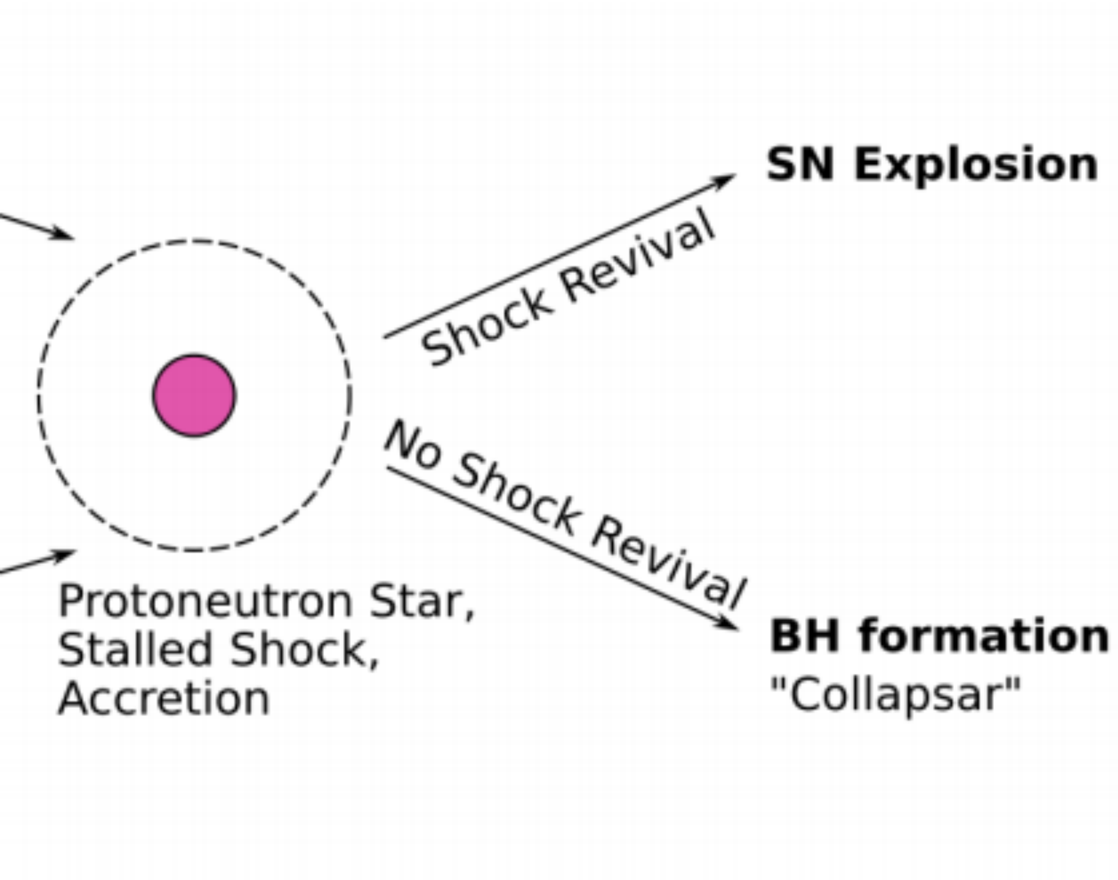
The LGRB-CCSNe Connection



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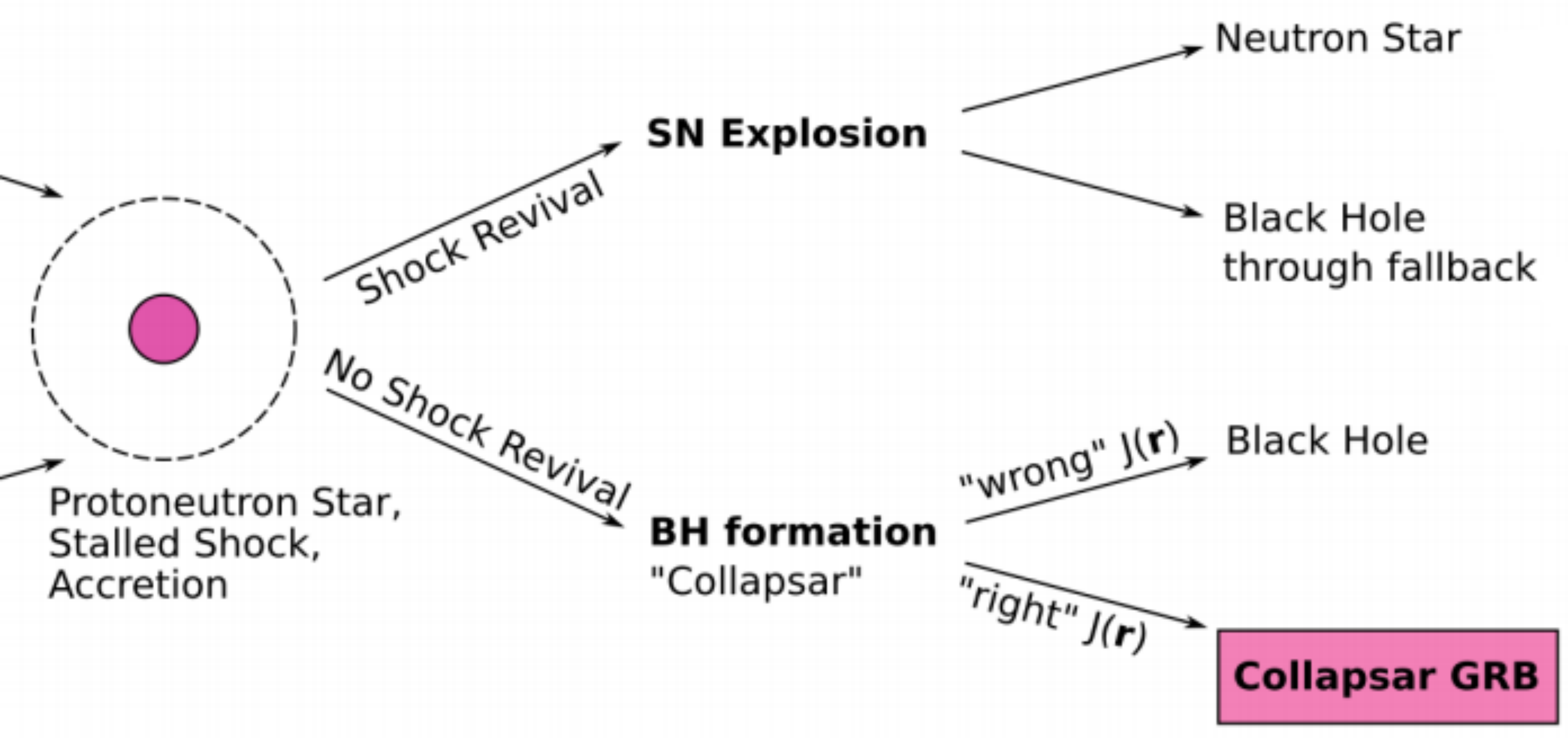

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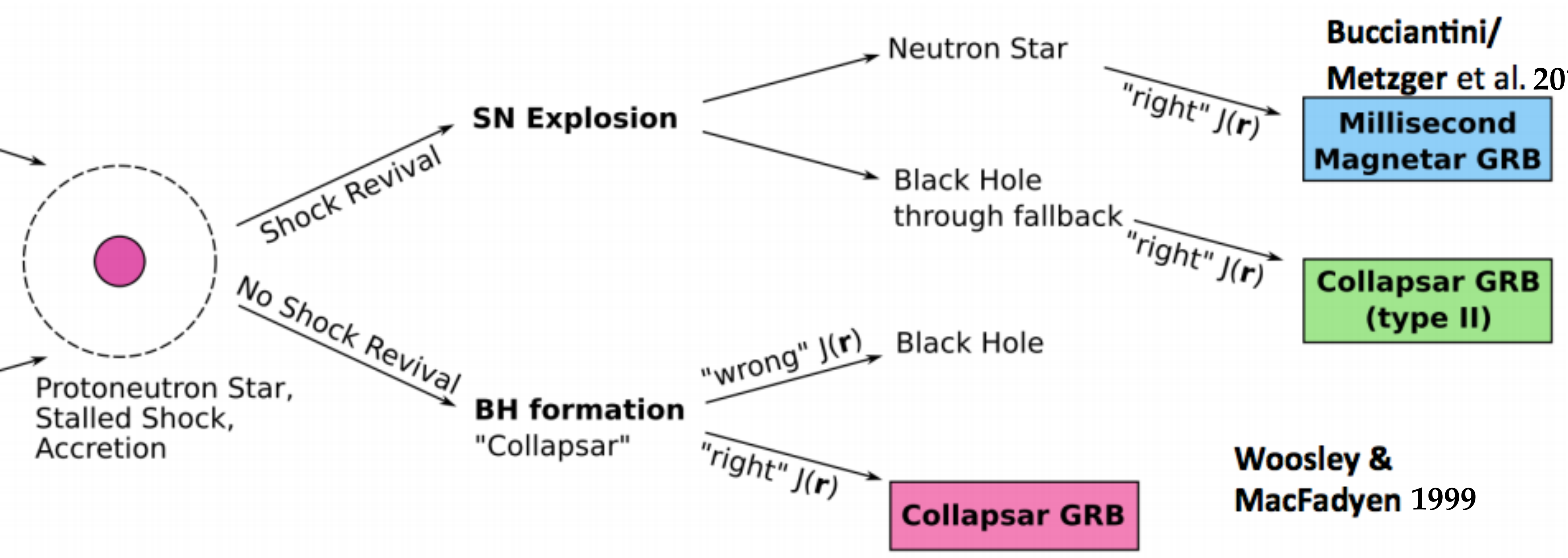

Bucciantini/ Metzger et al. 2012

Woosley & MacFadyen 1999

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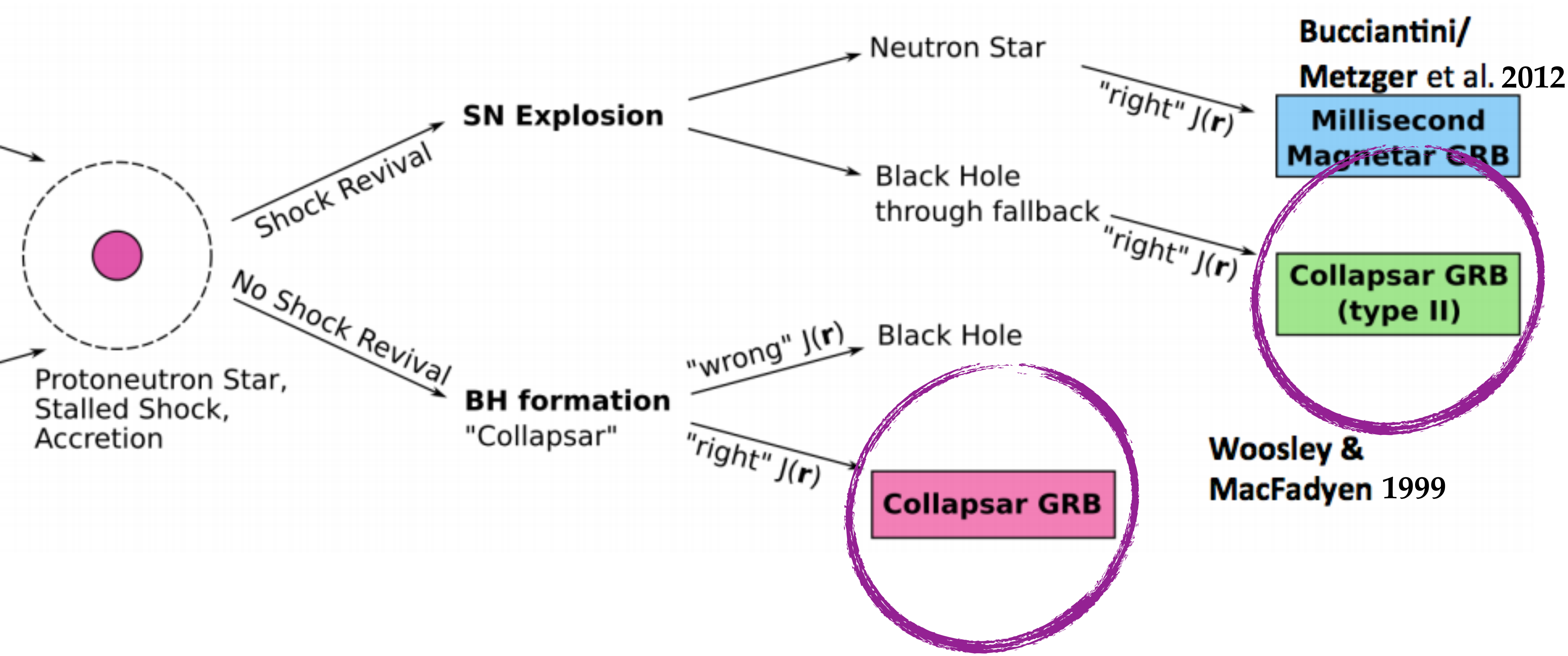

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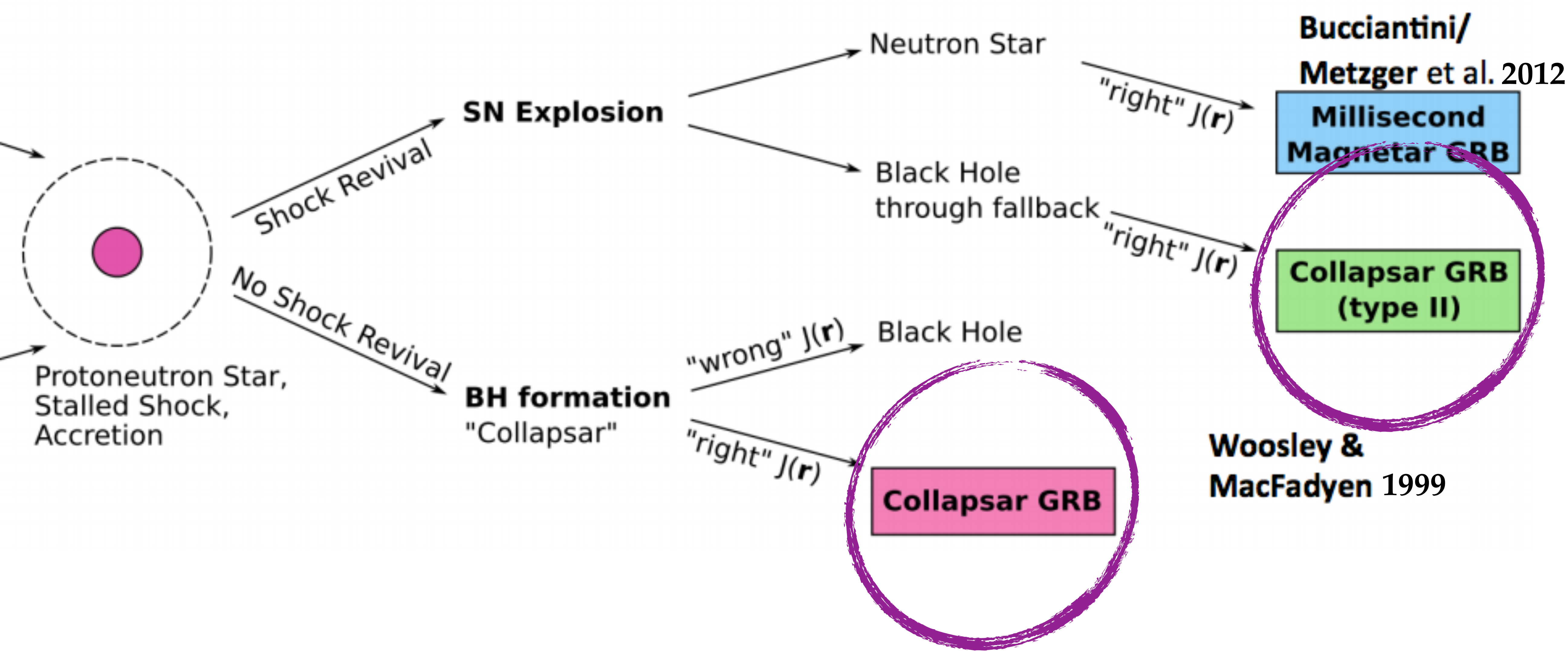
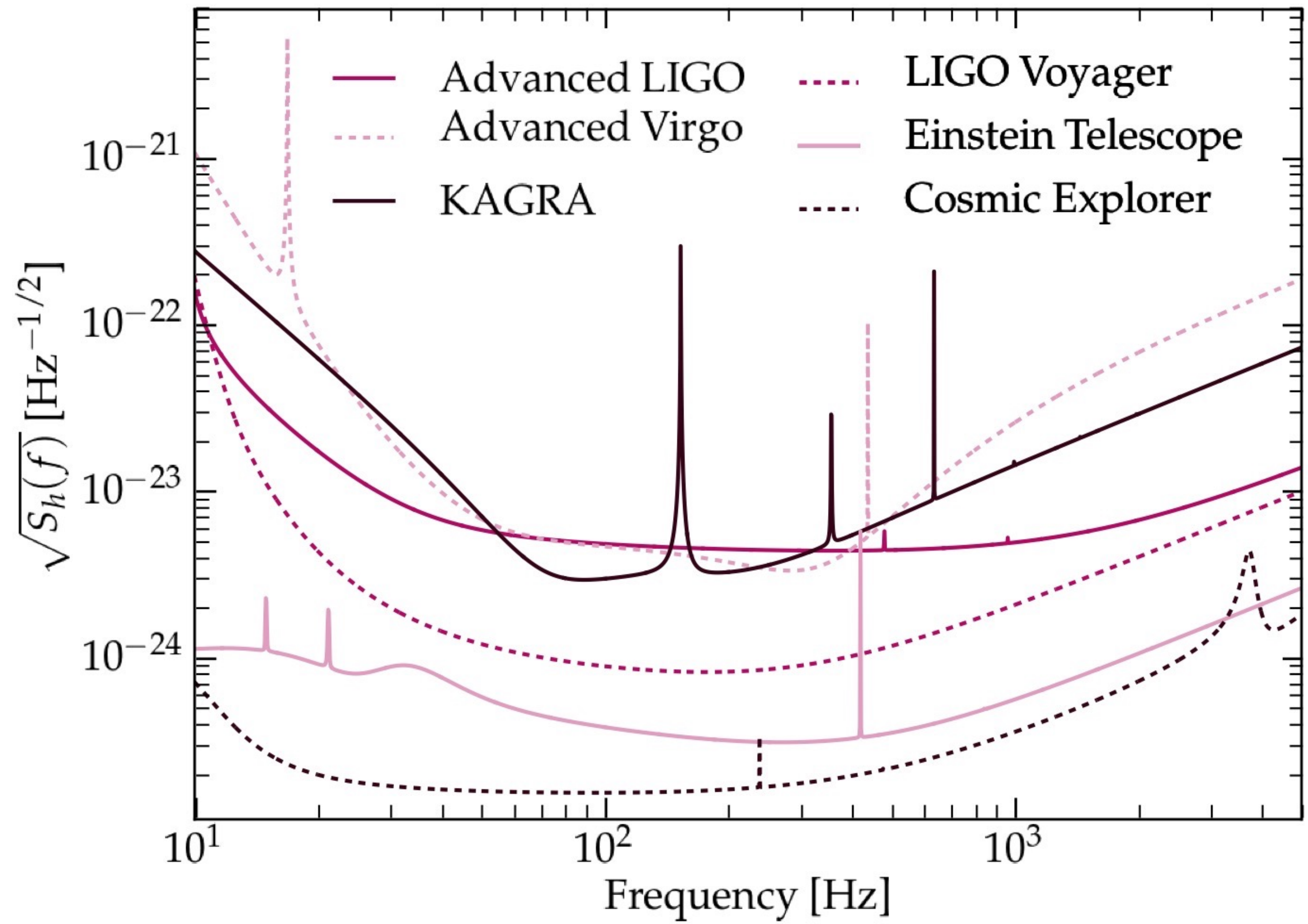


Collapsar progenitors need to satisfy 2 requirements:

- core-collapse produces a BH either promptly or shortly thereafter
- sufficient angular momentum must exist in order to form a disk outside the BH

Sensitivity of Current and Next Generation GW Detectors



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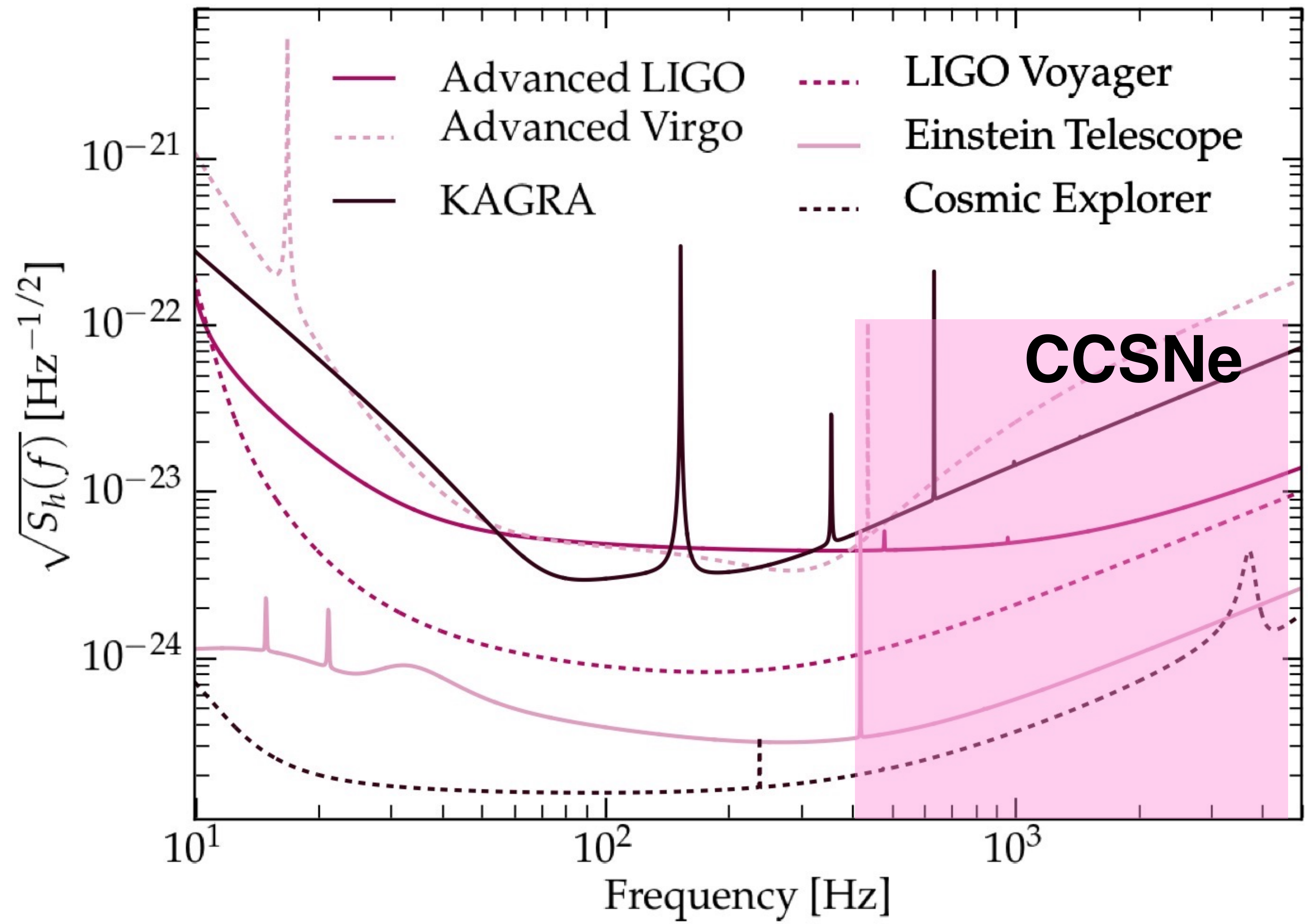

O11 Collapsar Waveforms

- u75 - 3D numerical simulations of a $75M_{\odot}$, 10^{-4} solar metallicity model with compact core that favors early BH formation
  - u75a - initial angular velocity of 1 rad s^{-1}
  - u75b - initial angular velocity of 1.5 rad s^{-1}
  - u75c - initial angular velocity of 2 rad s^{-1}

Ott *et al.* (2011)

O11 Collapsar Waveforms

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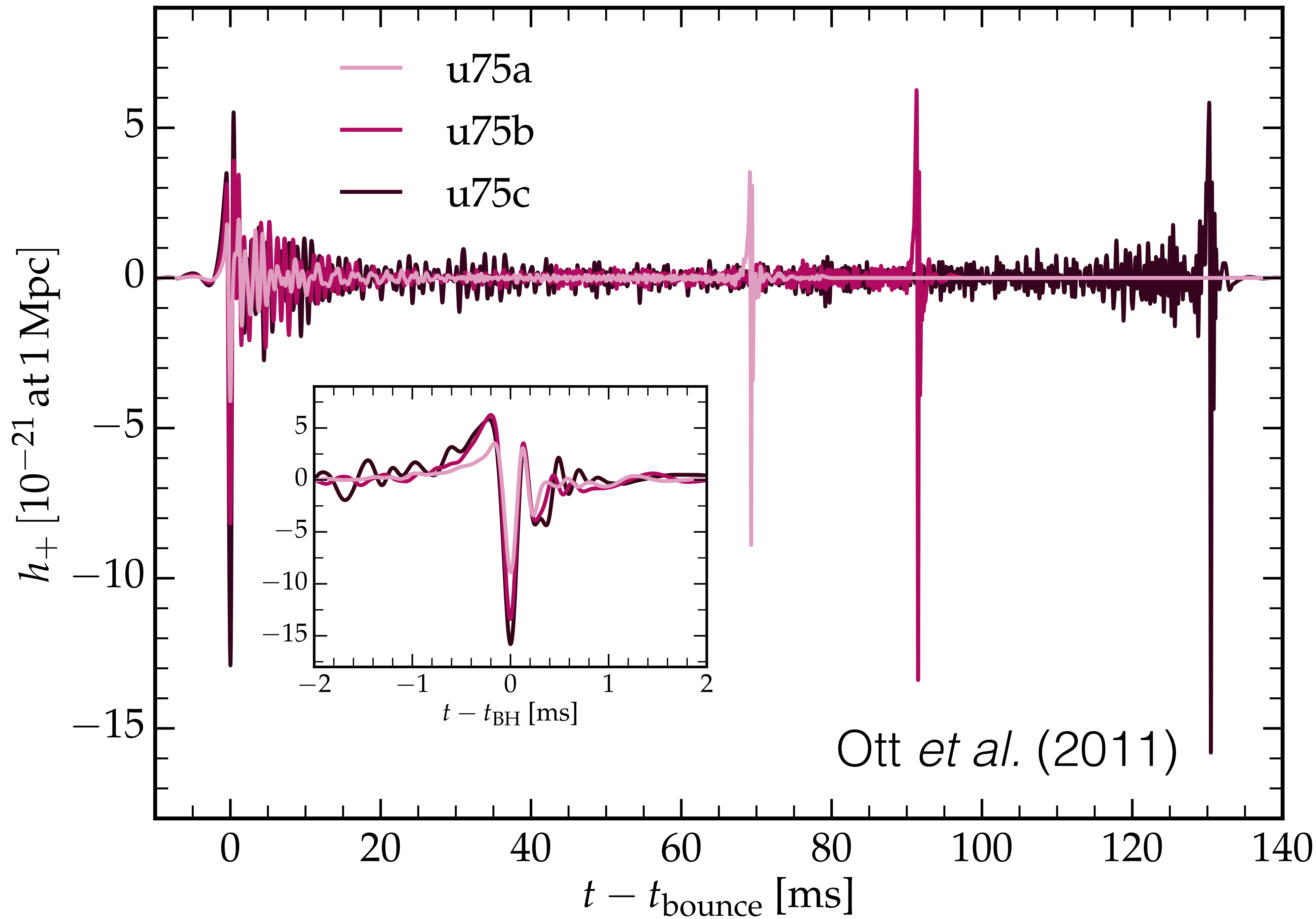
Ott *et al.* (2011)

Significant GW emission is associated with BH formation

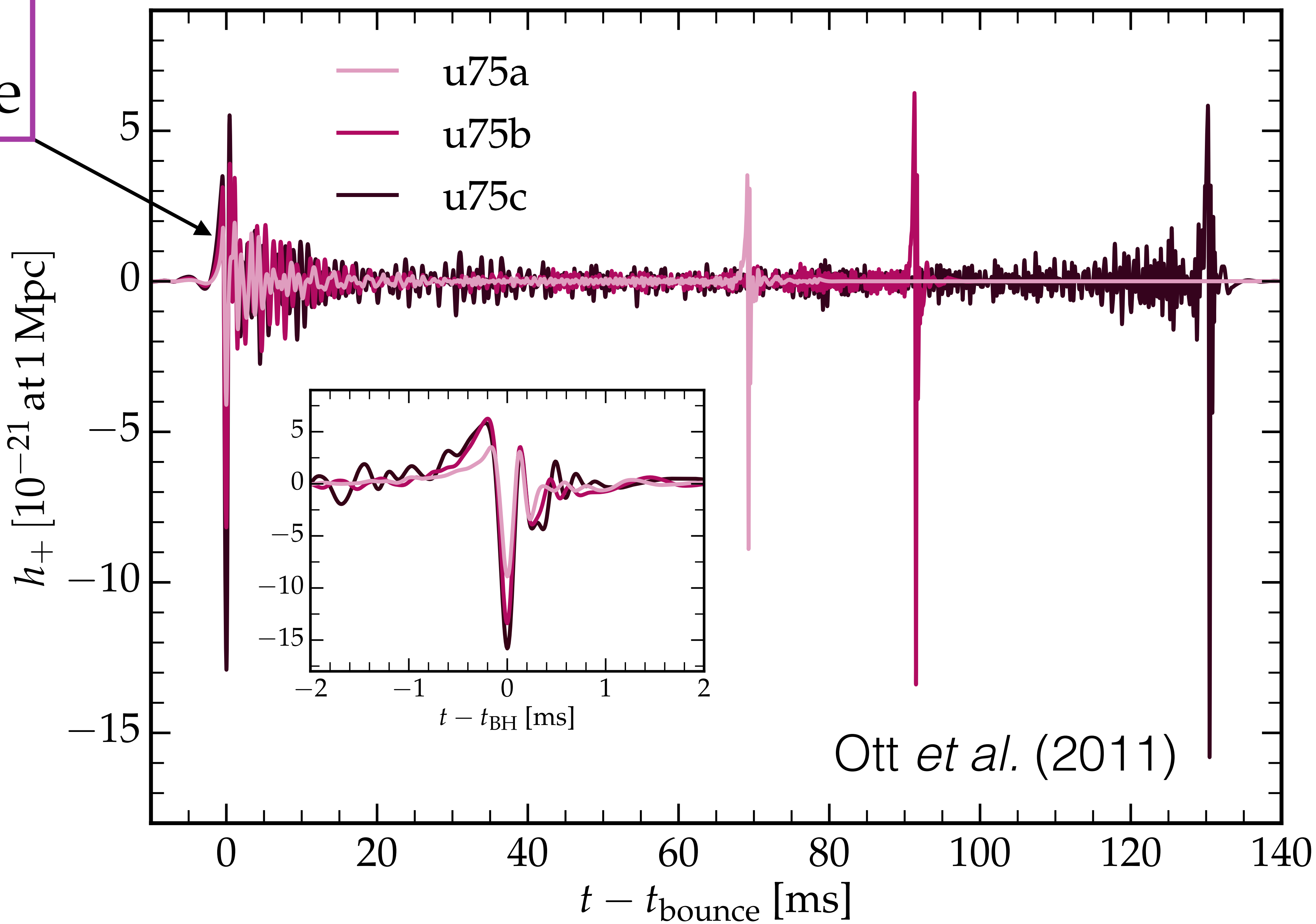
viability of u75 depends on the GRB progenitor & if the mass transfer to a binary companion has removed the H/He envelopes

O11 Collapsar Waveforms



O11 Collapsar Waveforms

Core bounce



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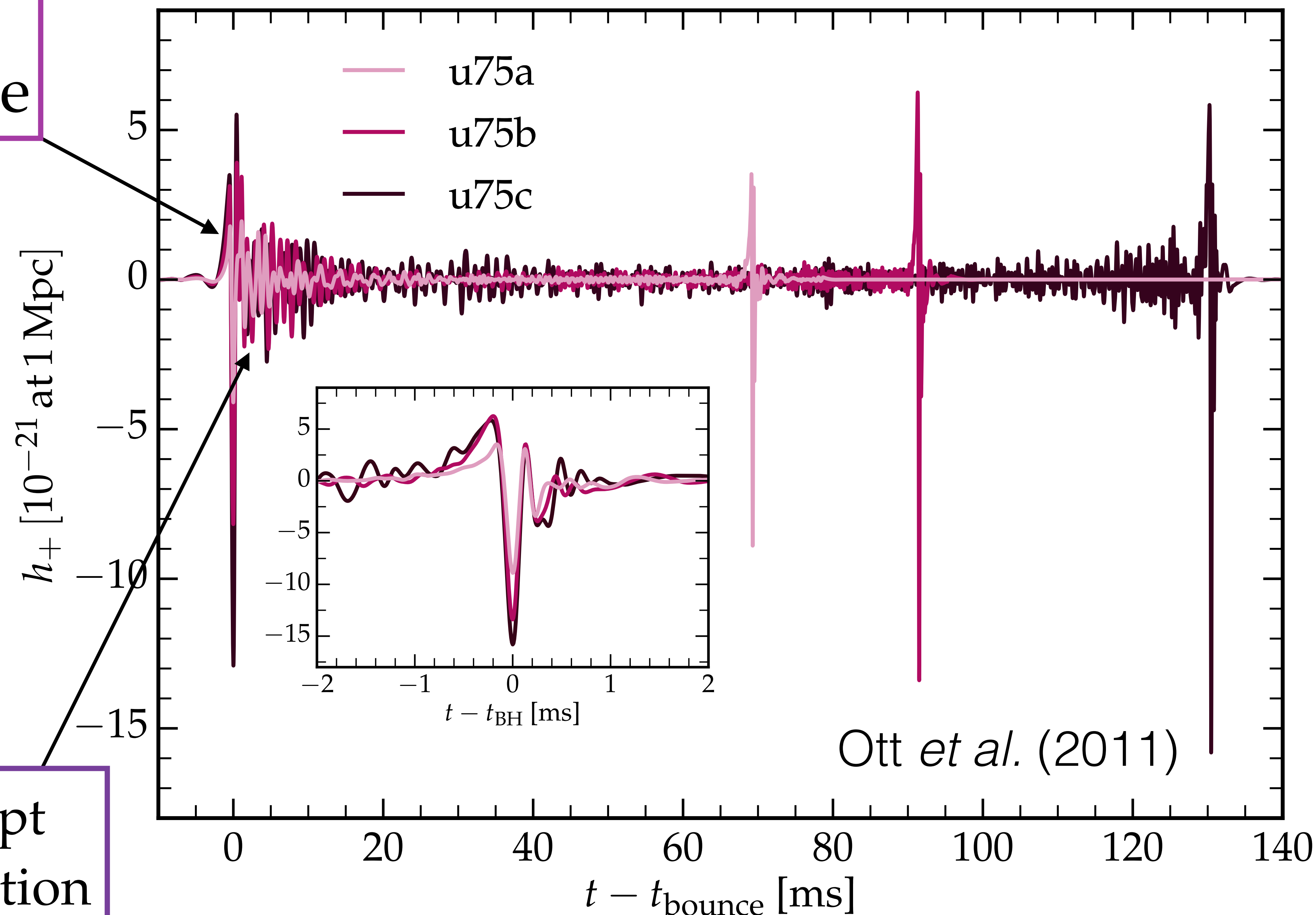
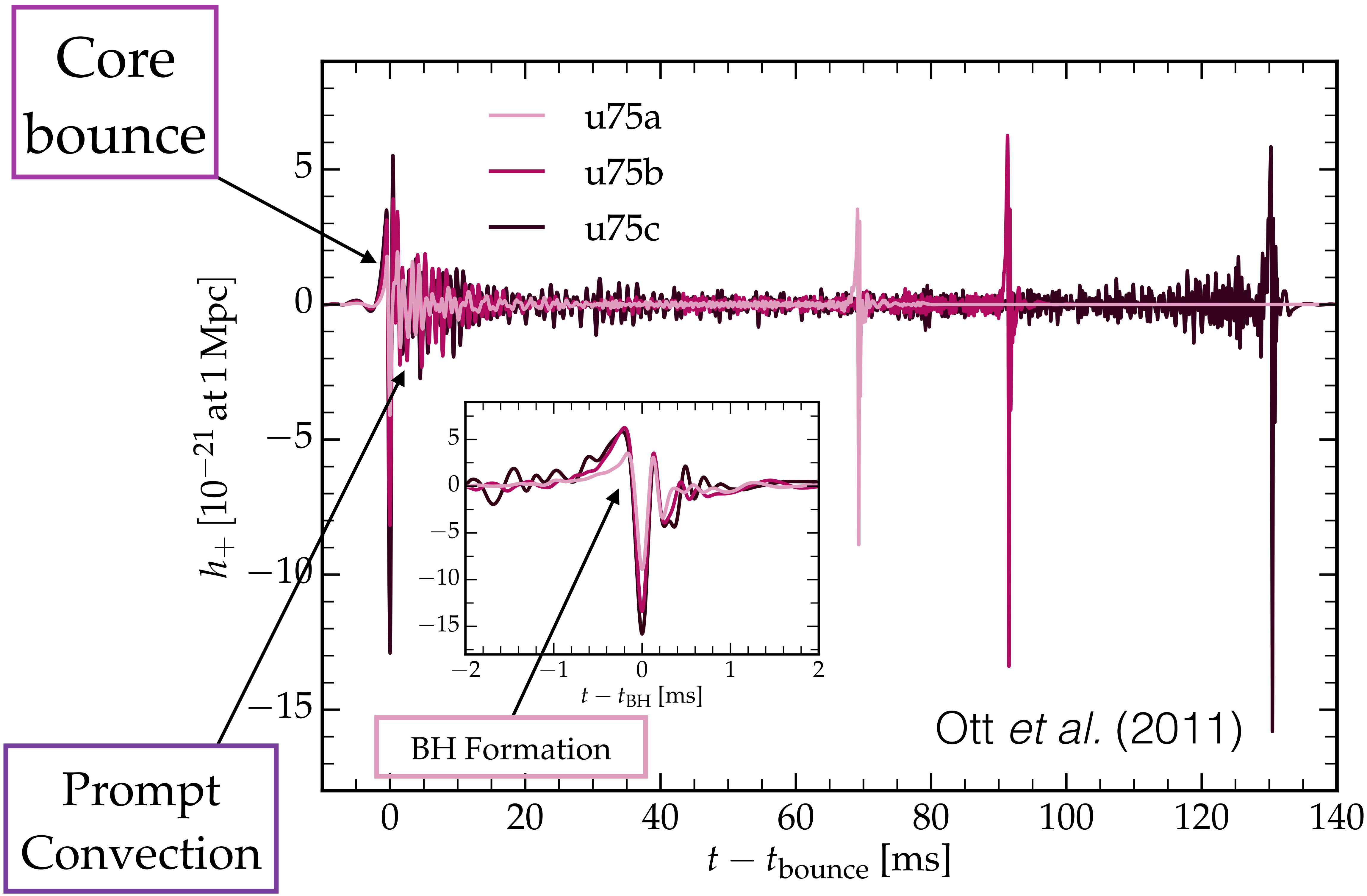


Prompt Convection

O11 Collapsar Waveforms



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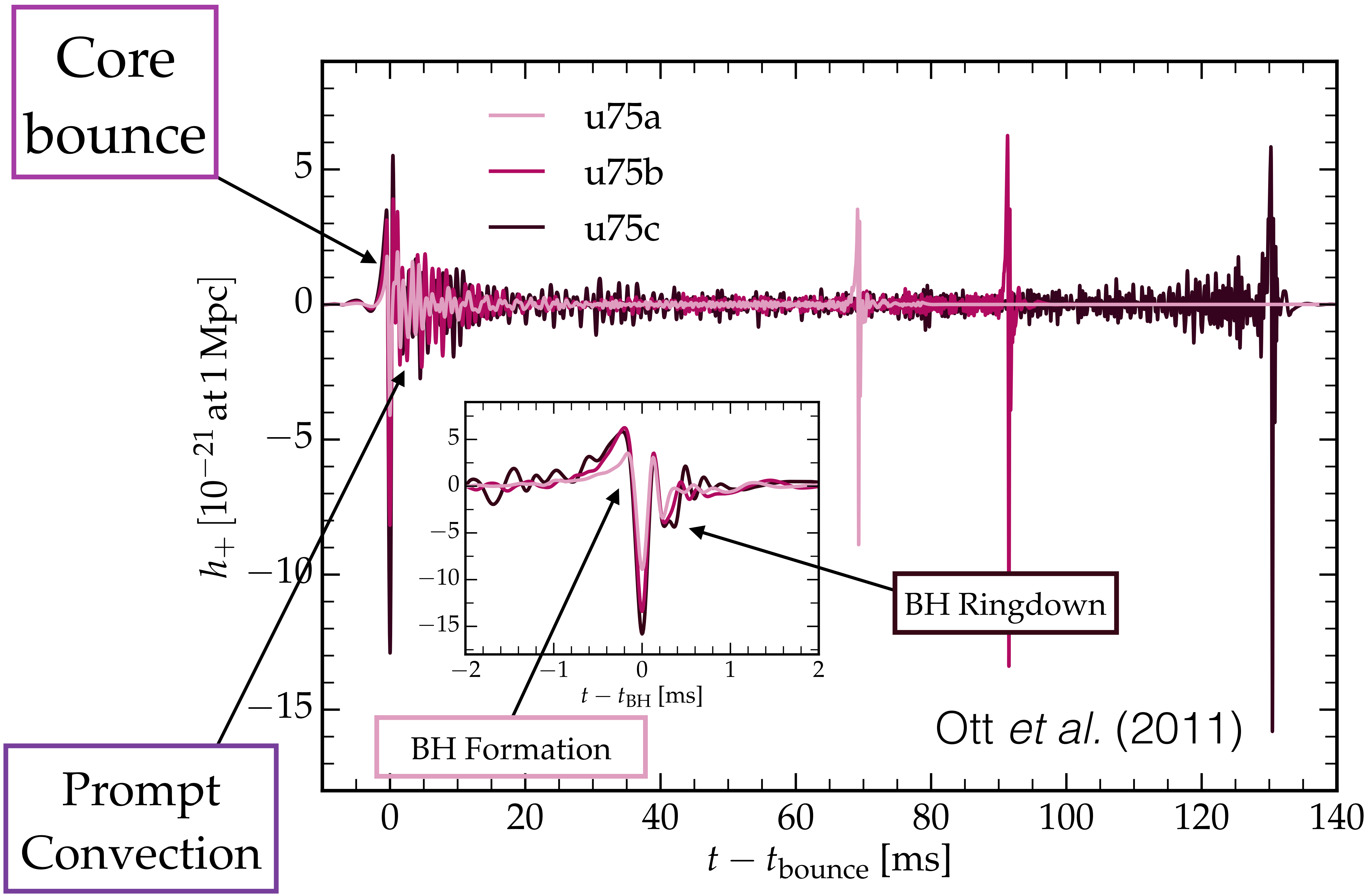
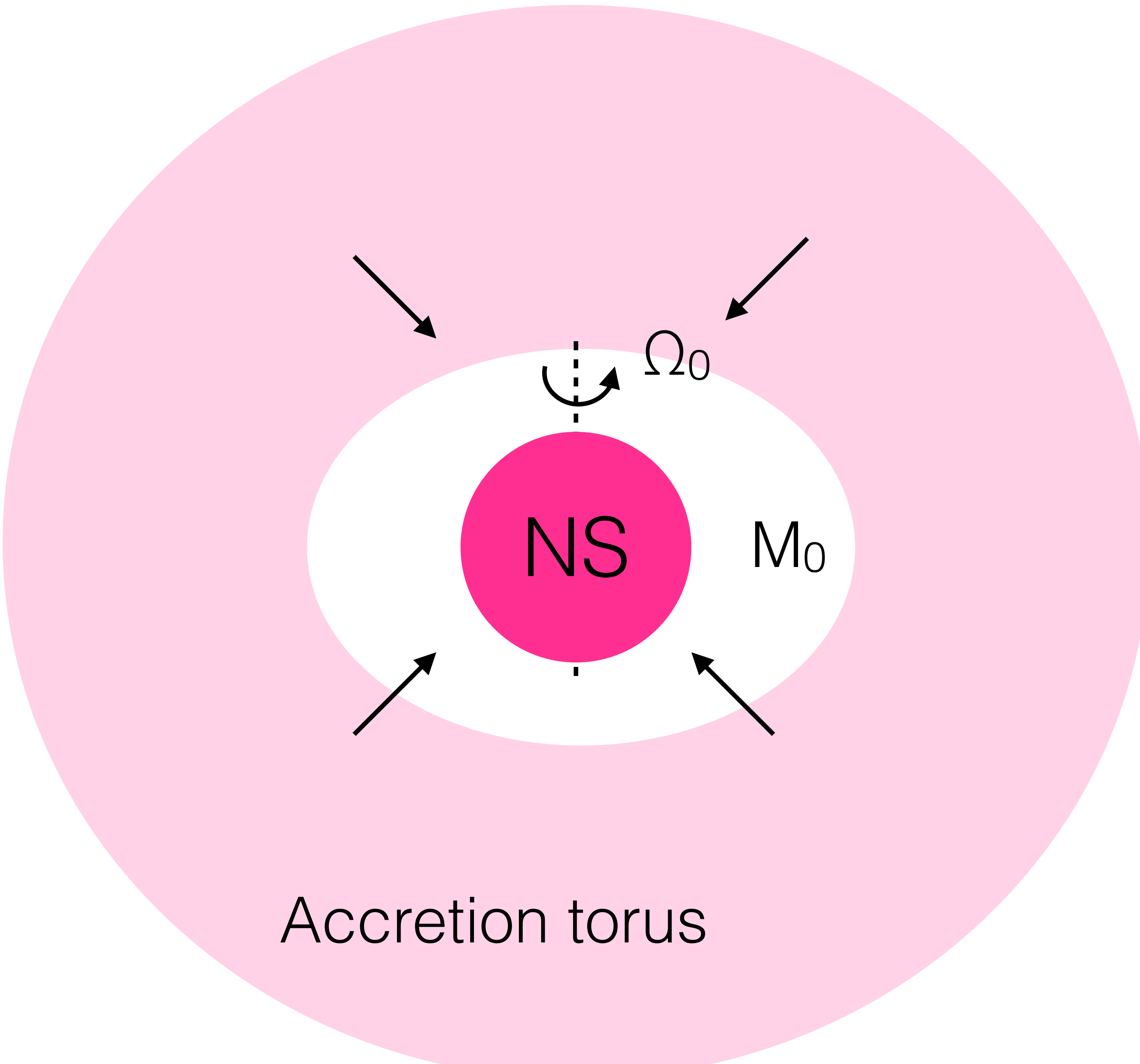


O11 Optimal SNR @ 1 Mpc

Waveforms	aLIGO	AdVirgo	KAGRA	Voyager	Einstein Telescope	Cosmic Explorer
u75a	0.4	0.2	0.2	1.1	3.8	6.2
u75b	0.7	0.4	0.4	2.1	7.2	11.7
u75c	0.9	0.5	0.5	3	9.9	16.2

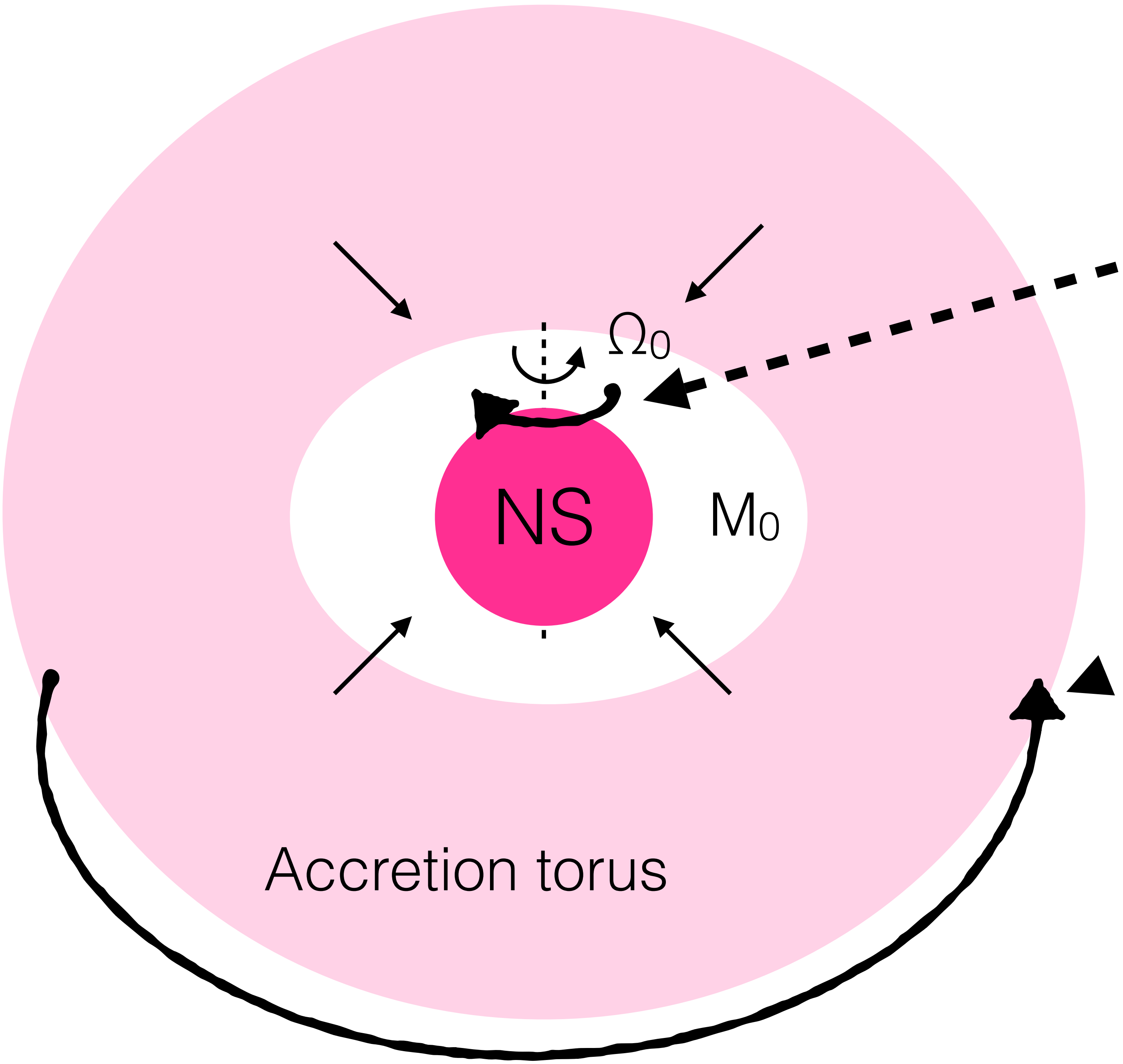
PT12 Collapsar Waveforms



- Fallback accretion spins up NS from conservation of angular momentum

Piro & Thrane (2012)

PT12 Collapsar Waveforms



$\beta > \beta_c$

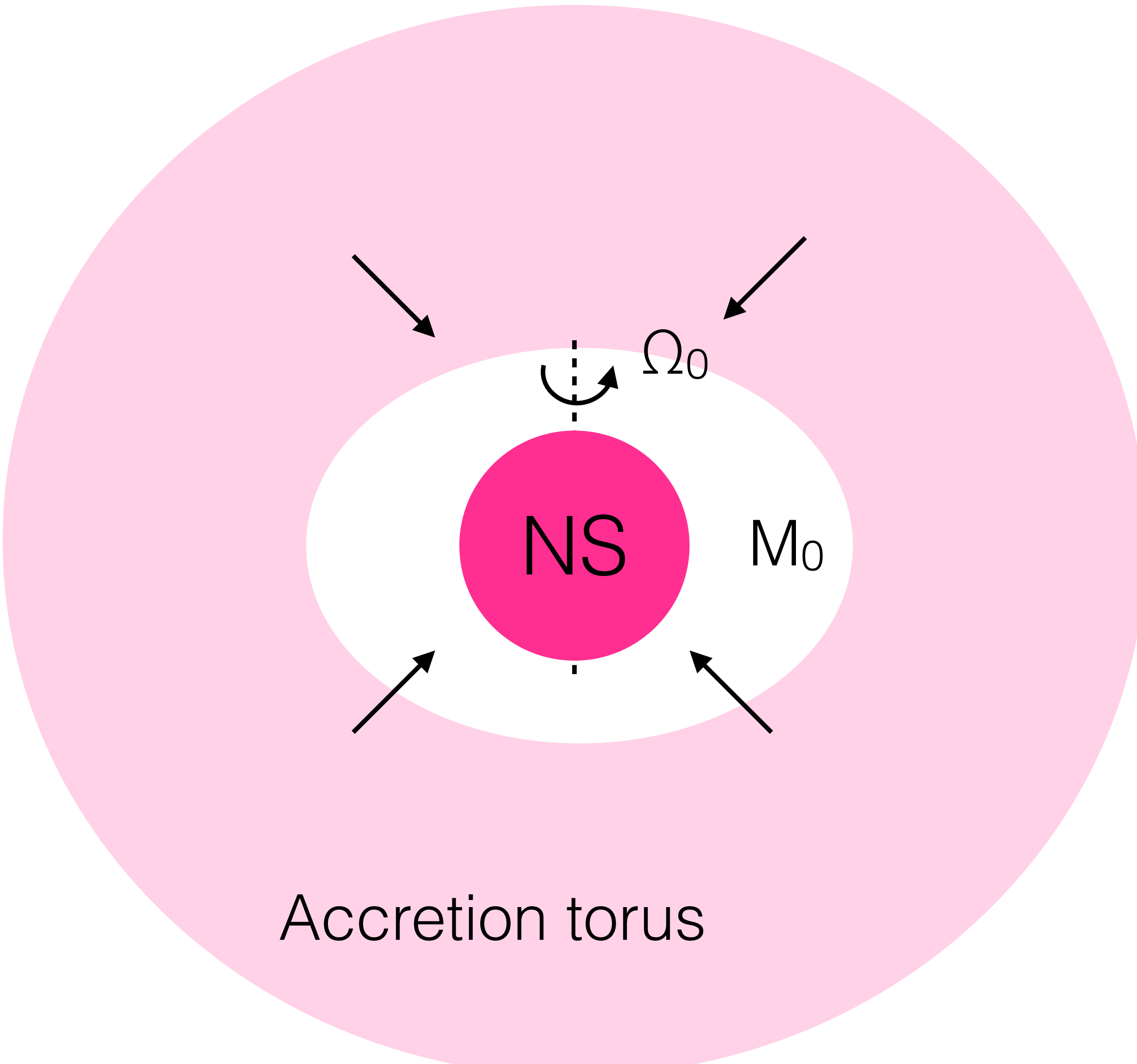
star is torqued down

$\beta < \beta_c$

spun up by accretion

Piro & Thrane (2012)

PT12 Collapsar Waveforms



- Fallback accretion spins up NS from conservation of angular momentum
- Spin parameter reaches a critical value, β_c

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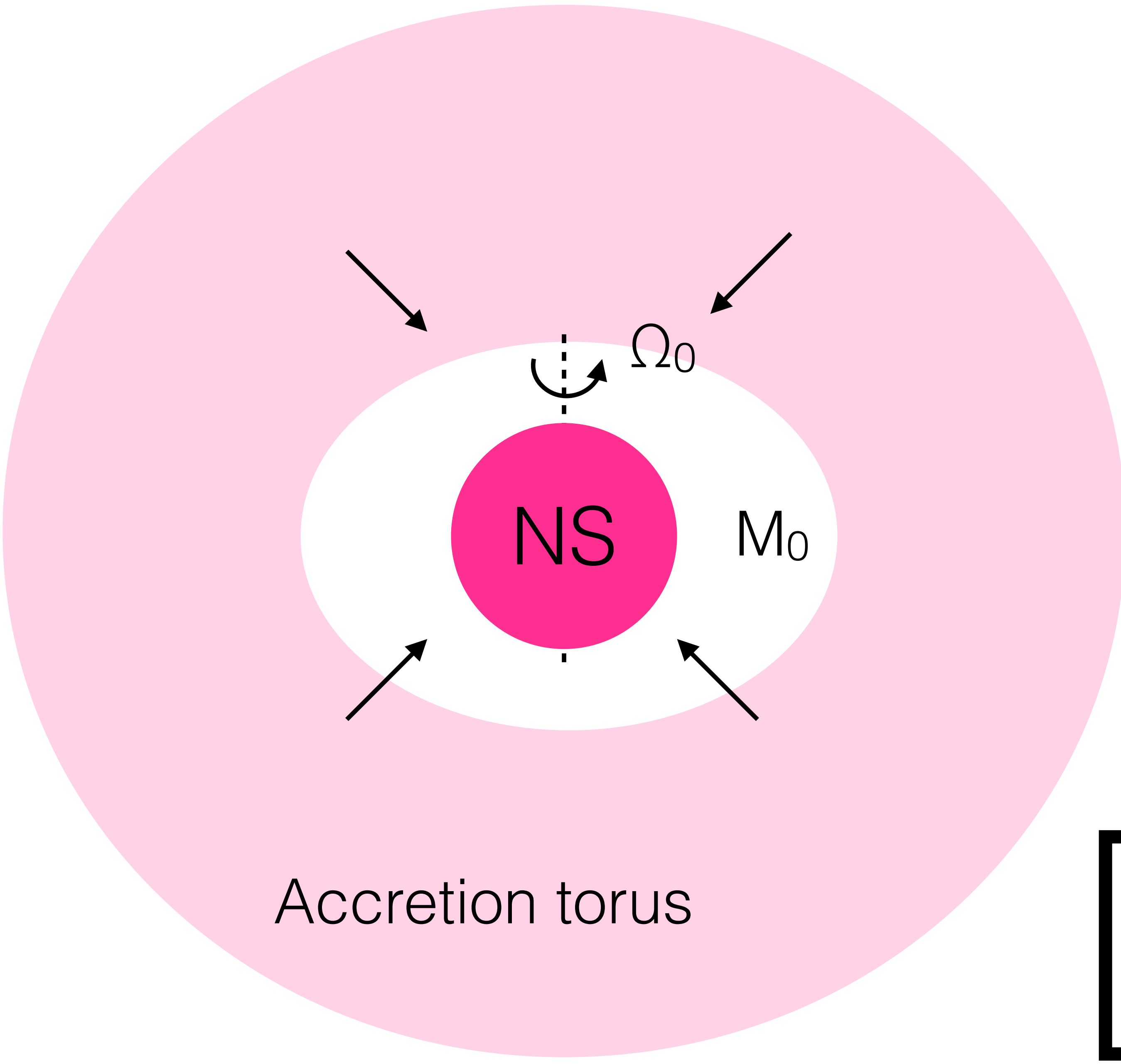


- Fallback accretion spins up NS from conservation of angular momentum
- Spin parameter reaches a critical value, β_c
- Above β_c, non-axisymmetric instabilities occur

30 - 3000 s of high frequency = GW production until the NS becomes sufficiently massive to collapse into a BH

Piro & Thrane (2012)

PT12 Collapsar Waveforms

Waveforms	Radius (km)	η	M_{max}	$t_{initial}$	t_{final}	duration
PT12a	12	0.1	2	489.5 s	748.3 s	258.8 s
PT12b	12	1	2	89.3 s	118.3 s	29.3 s
PT12c	12	5	2	29.3 s	37.7 s	8.4 s
PT12d	14.5	0.1	2.2	480.9 s	1176.9 s	696 s
PT12e	14.5	1	2.2	88.2 s	149.6 s	61.4 s
PT12f	14.5	5	2.2	28.9 s	45.9 s	17 s

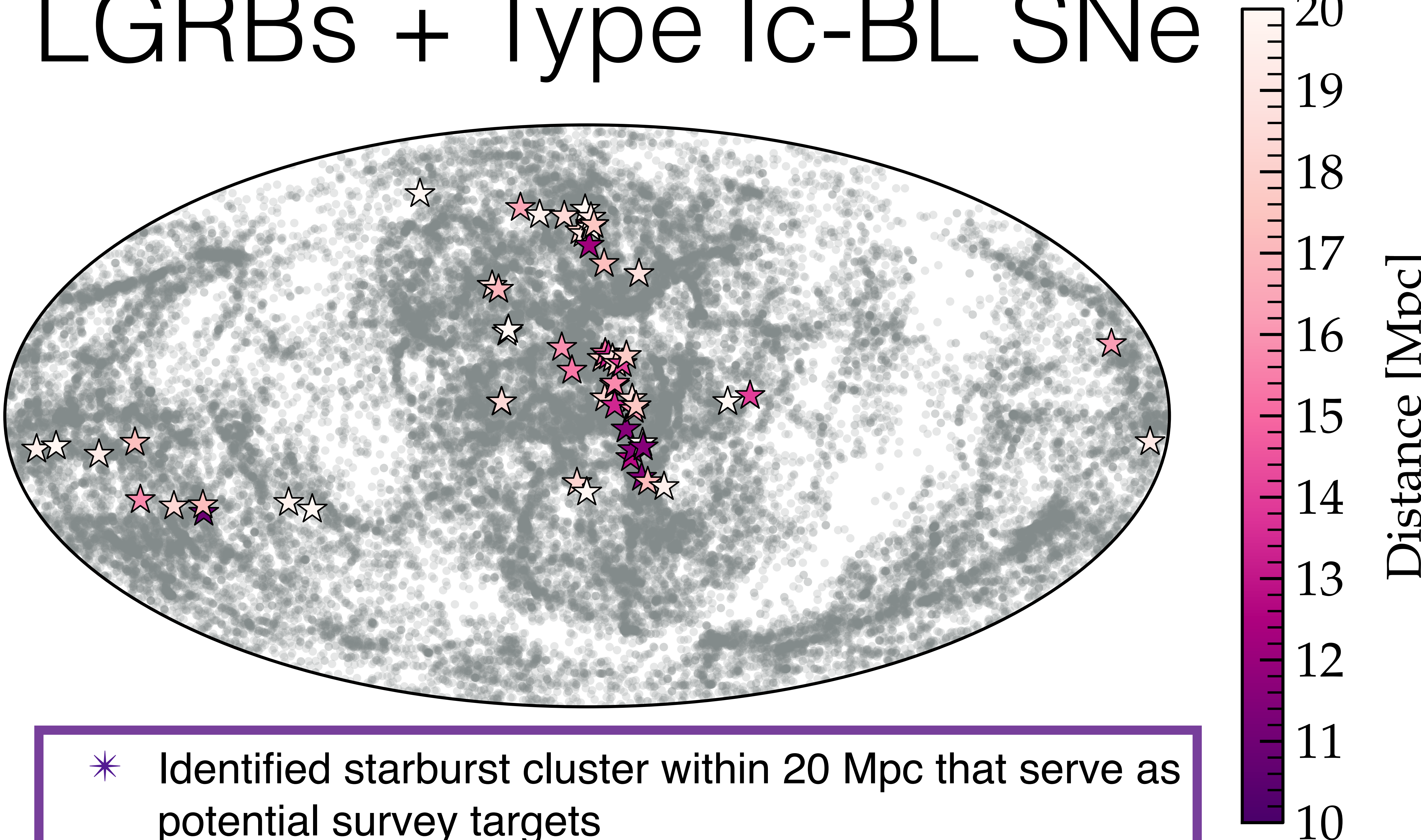
PT12 h_{rss} @ 1 Mpc

Waveforms	h_{rss}
PT12a	3.6540E-22
PT12b	3.6547E-22
PT12c	3.6556E-22
PT12d	6.4001E-22
PT12e	6.4010E-22
PT12f	6.4020E-22

Proposed Radio Search for LGRBs + Type Ic-BL SNe

- Radio search focusing on constraining the upper limit of the rate of Type Ic-BL SNe through the detection of LGRBs in starburst clusters within 20 Mpc
- Roughly 90 targets will be included in order to determine at least 90% chance of detecting an off-axis LGRB event
  - Conduct observations at lower frequencies (1.4 GHz) in order to further understand the rapidly evolving radio SN
- Recent advances in nearby CCSNe search capabilities (i.e. ZTF) provide possibility of finding an off-axis LGRB within 10 yrs

Proposed Radio Search for LGRBs + Type Ic-BL SNe



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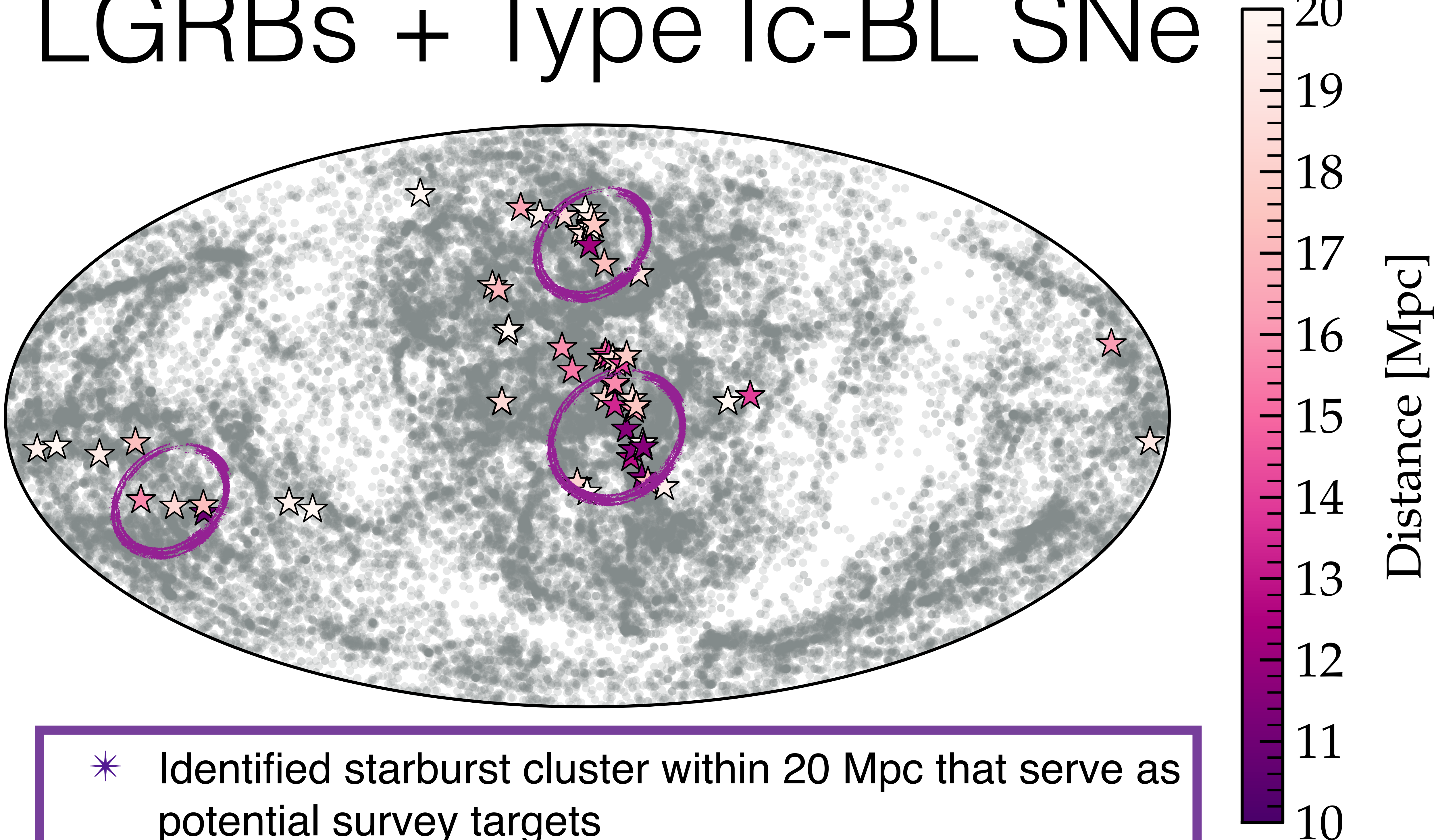

- ✳ Identified starburst cluster within 20 Mpc that serve as potential survey targets

Future Directions

- Finish running detectability prospects for GWs from fallback accretion by running cWB and X-pipeline search across the relevant parameter space with simulated noise for both advanced and 3rd generation detectors
- Implement realistic EoS: derive radius from mass evolution for finite temperature EoS
  - distinguishable at an effective distance (20 Mpc or less) that would produce equivalent waveform amplitude
- **Aiming for paper submission to ApJ in November 2016**

DCC link to paper draft: https://dcc.ligo.org/P1600252-x0

EXTRA SLIDES

Physics of Piro & Thrane+12 (PT12) collapsar waveforms

Issues

- As NS spins up → more oblate
  - changes the radius at equator → effects specific Ω of accreted material & potential energy of the configuration
- If the shape of the spun up NS becomes more bar-like, this may inhibit accretion
- Internal circulation patterns caused by secular instabilities may produce significant GW power at lower frequencies - isn't accounted for
- Values above 10^{-5} of the quadrupole moment exceed the max strain that a neutron crust can support - physics that is simply not included