Determining the angular momentum distribution of massive evolved stars from gravitational wave observations

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Abstract

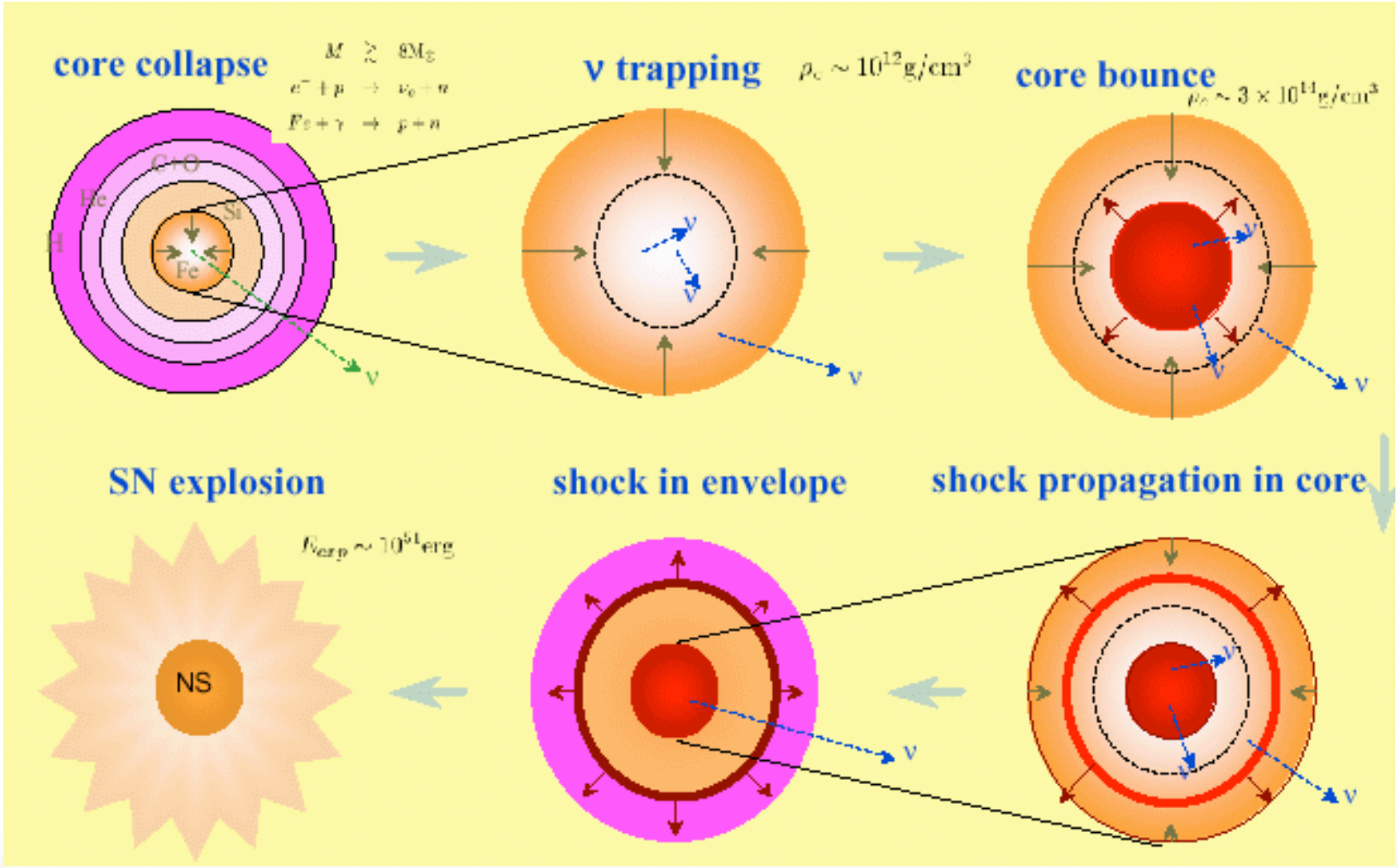
From recent two-dimensional hydrodynamic simulations of the rotational collapse of a supernova core in axisymmetry by Kotake et al(*)., It is found that, in the gravitational wave signal, the sign of the peak with the second largest absolute amplitude is negative for models with strong differential rotation in the core, and positive for the others. Although the simulations are limited to two-dimensions, this effect is expected to be a robust prediction. Therefore if we can detect the signs of the second peaks, we will obtain information about the angular momentum distribution of evolved massive stars.

In addition, the absolute amplitudes of the second peak are within the detection limit of initial LIGO for a source at a distance of 10 kpc.

We use simulations to study the capability of initial/advanced detector networks for the detection and resolution of sign of the second peak.

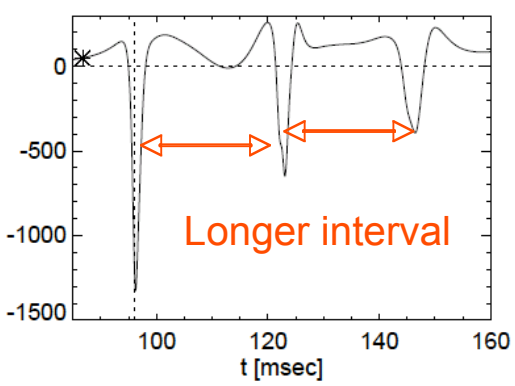
*K.Kotake,S.Yamada,K.Sato PRD68 044023(2003)

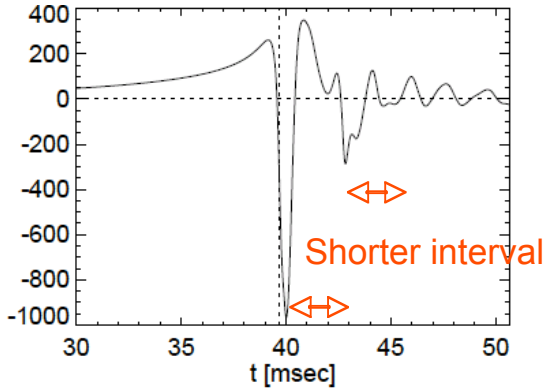
Standard scenario of supernova core collapse

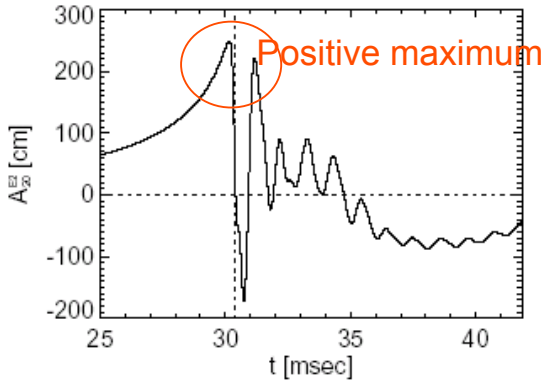


Gravitational waves from supernovae

Probe to understand innermost part of an evolved star







- EOS

  Stiff ----------> Soft

- Rotation
  - speed

    Rapid ----------> Slow
  - differential rotation

    Strong ----------> Weak

Models of core collapse

Calculate waveforms of 12 types
by changing

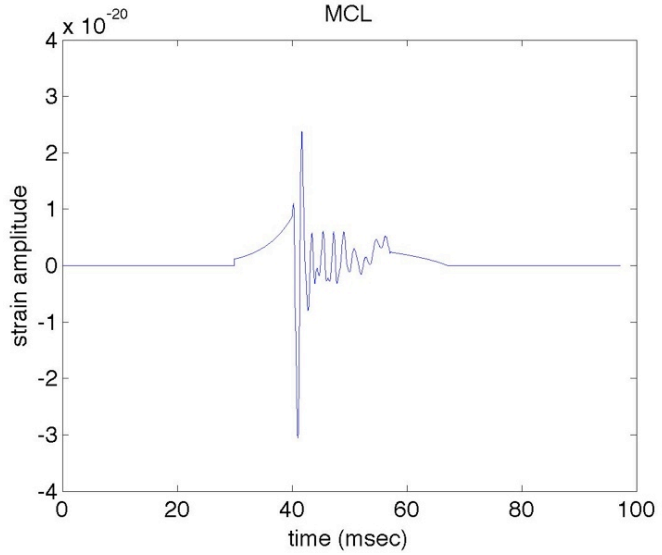
- Total angular moment

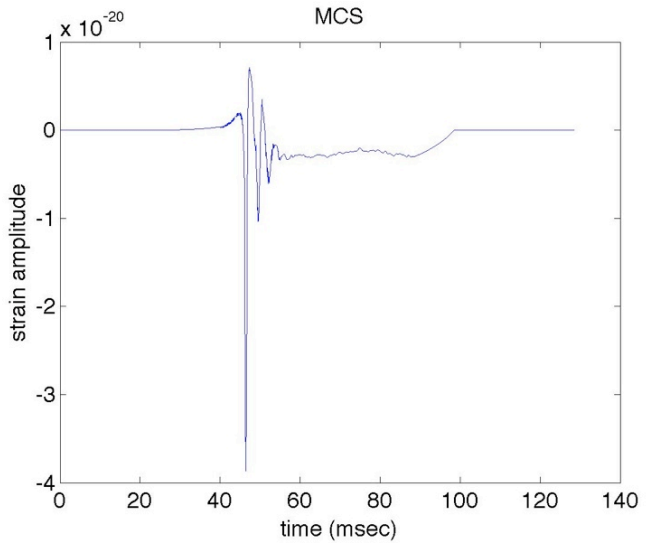
  S(slow), M(moderate), R(rapid)

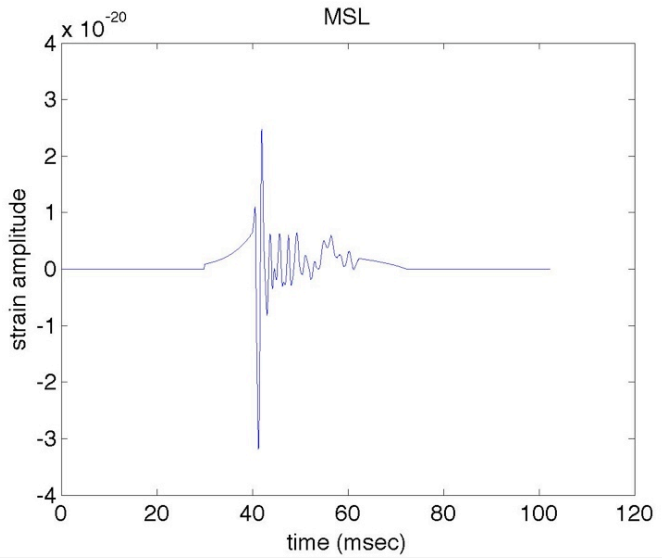
- Rotation law
  - Shell-type rotation (S)
  - Cylindrical rotation (C)
- Degree of differential rotation

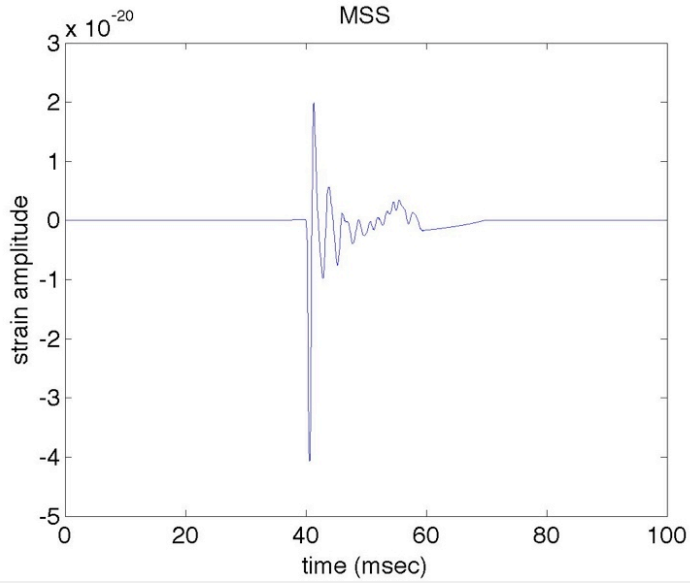
  S(long), S(short)

Gravitational waveforms





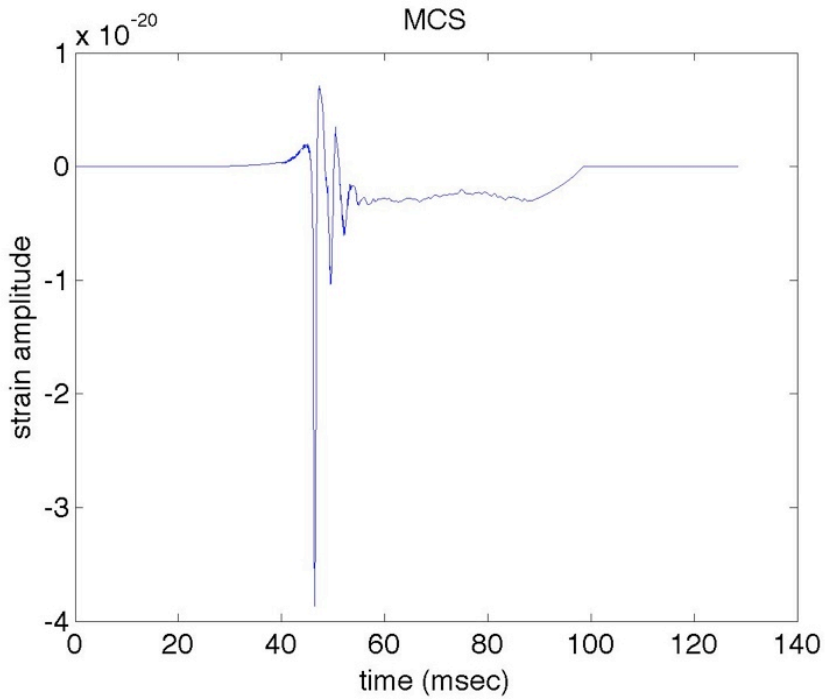


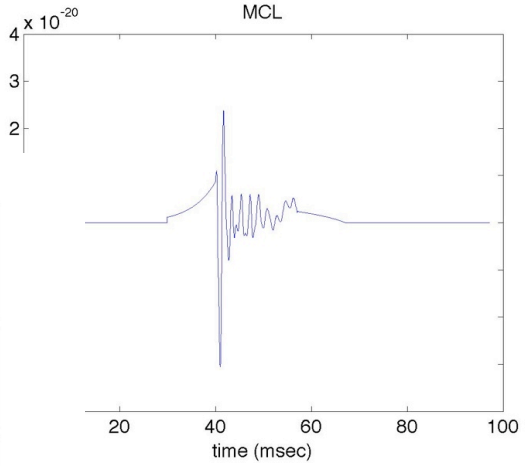


Sign of the second peak

"-" sign for types for o cylindrical law
o strong differential rotation

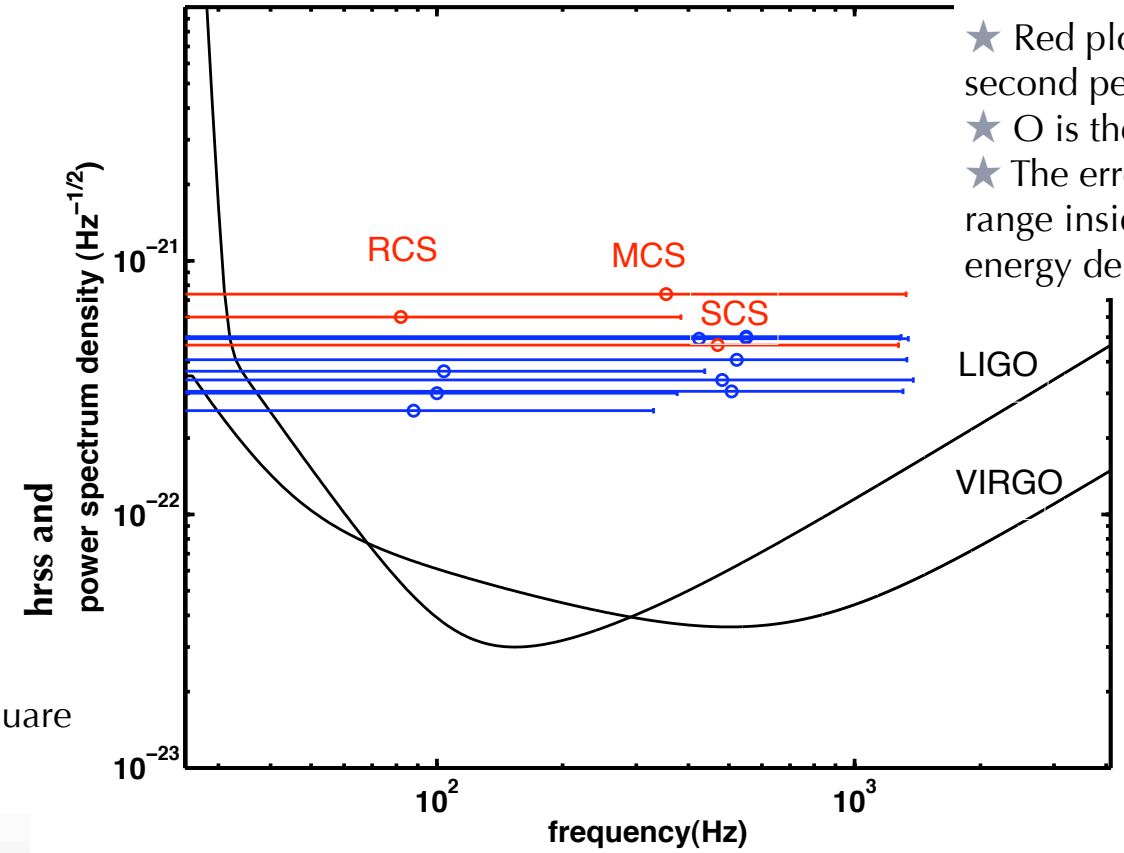
Model	$h_{second}(10^{-20})$
MCL	1.20
MCS	-0.79
MSL	1.23
MSS	0.98
RCL	0.25
RCS	-0.49
RSL	0.32
RSS	0.20
SCL	0.75
SCS	-0.57
SSL	0.82
SSS	0.94





Detectability

- The signals are located at a distance of 10 kpc from the earth.
- All types of signals are within LIGO/VIRGO sensitivity
- But is it possible to detect the sign of the second peaks ?



★ Red plots are the signals with the "-" second peak
★ O is the center frequency
★ The error bar marks the frequency range inside which 50 % of the spectrum energy density

hrss:
root sum square

Simulation of the detection of the sign

- Analysis pipeline:
  - RIDGE -- Fully coherent network analysis

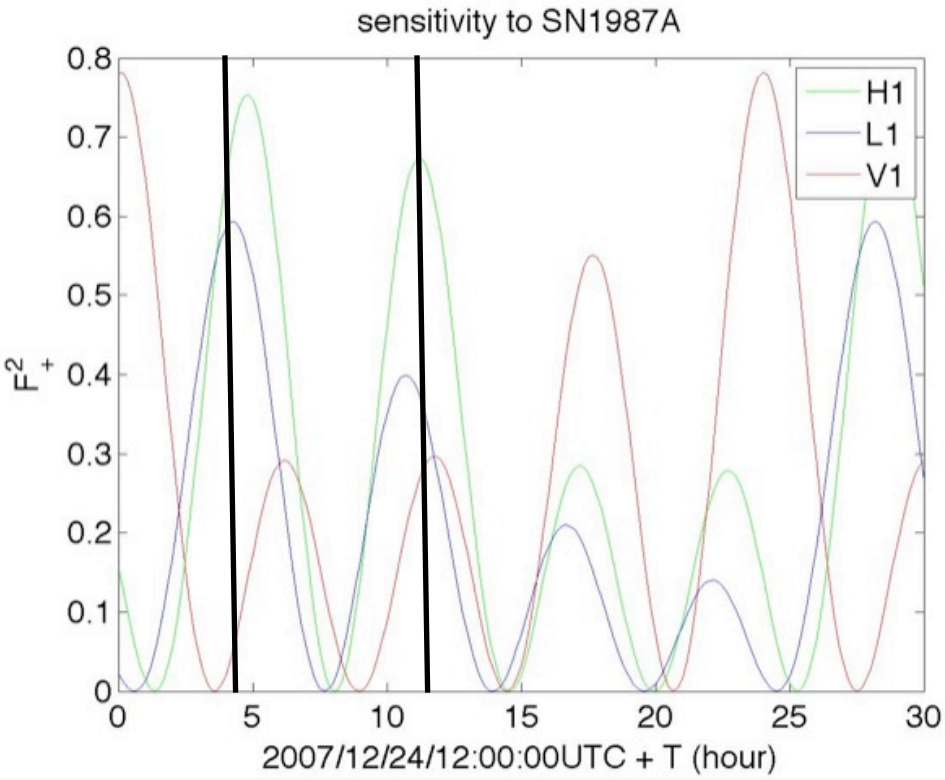
Hayama et al. CQG 24 2007

- Simulation
  - One polarization waveform.
  - Signals are located at the direction to SN1987A,Galactic center
  - Simulated data is whiten Gaussian data, the locations of detectors are the same as LIGO Hanford/Livingston, VIRGO
  - 200 trials
- Evaluation
  - Calculate the detection probability for the “-” sign of the type MCS,RCS, SCS waveforms by changing signal-to-noise

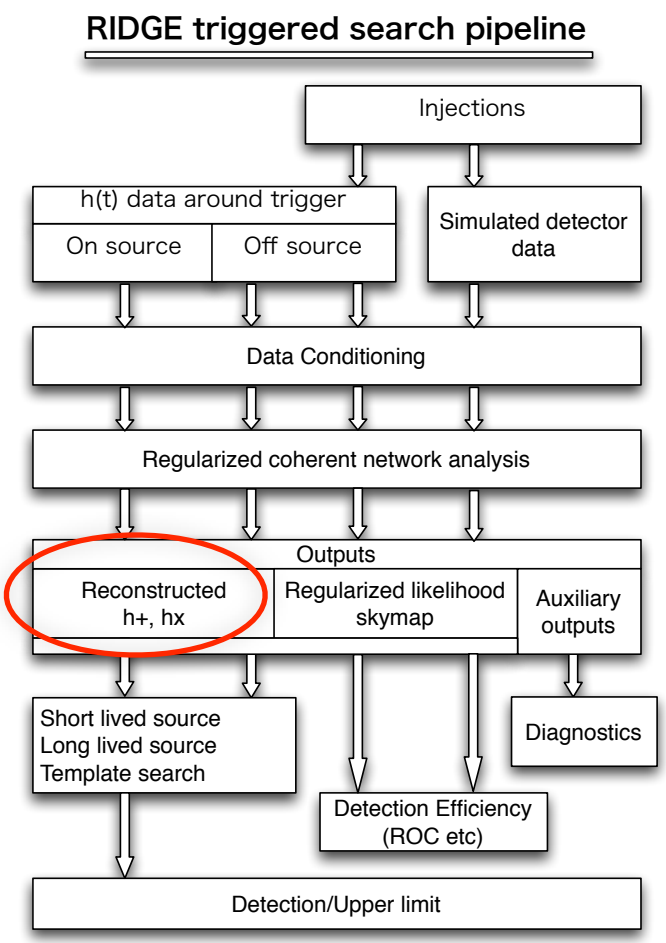
Interferometric gravitational wave detector network

Detector response

- Detector response of LIGO, VIRGO for the direction to SN1987A since 12 hours before this Christmas
- We use simulated data around Christmas and 8hours before Christmas

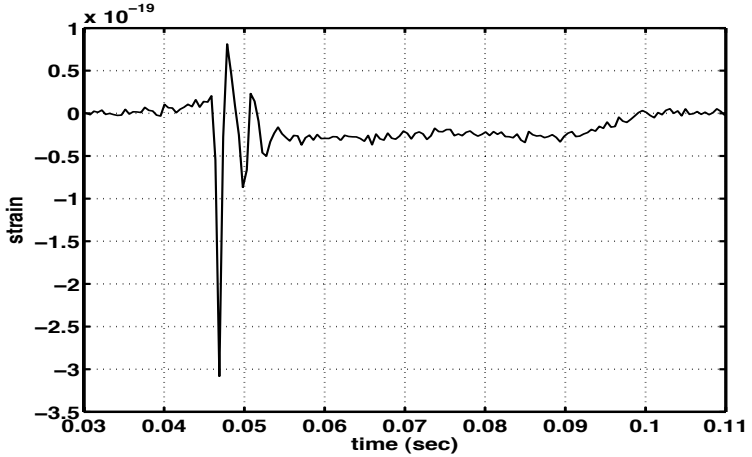


Reconstruction of GW waveform



- In principle, the detection of GW is an inverse problem.
- By Moore-Penrose inversion, both polarization waveforms are reconstructed.

Reconstructed waveform

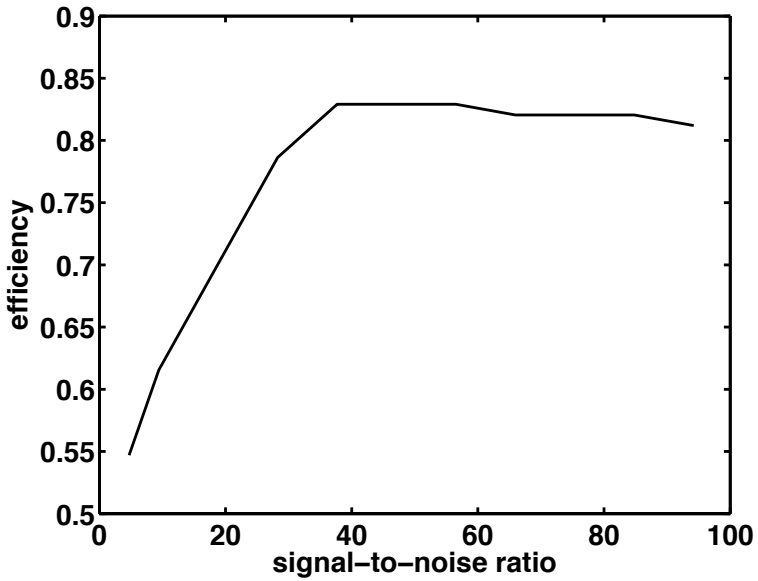


Estimated amplitude:
3rd peak: 8.11×10^{-20}
2nd peak: -8.67×10^{-20}

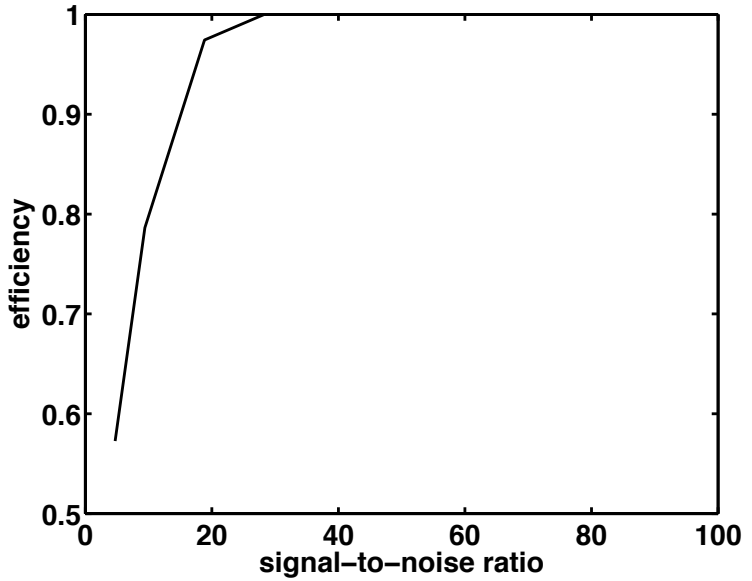
Detection efficiency (SN1987A)

- When Christmas, the "-" sign of signals with SNR=20 or larger is detectable with > 95%
- When 8 hours before Christmas, the "-" sign of signals with SNR=40 or larger is detectable with > 80%

8 hours before Christmas



Christmas

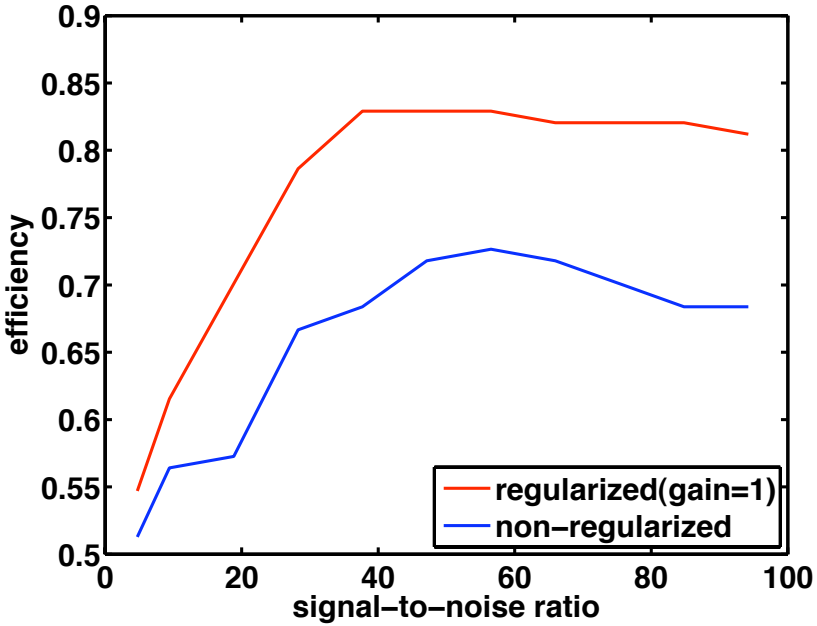


SNR is averaged over detectors

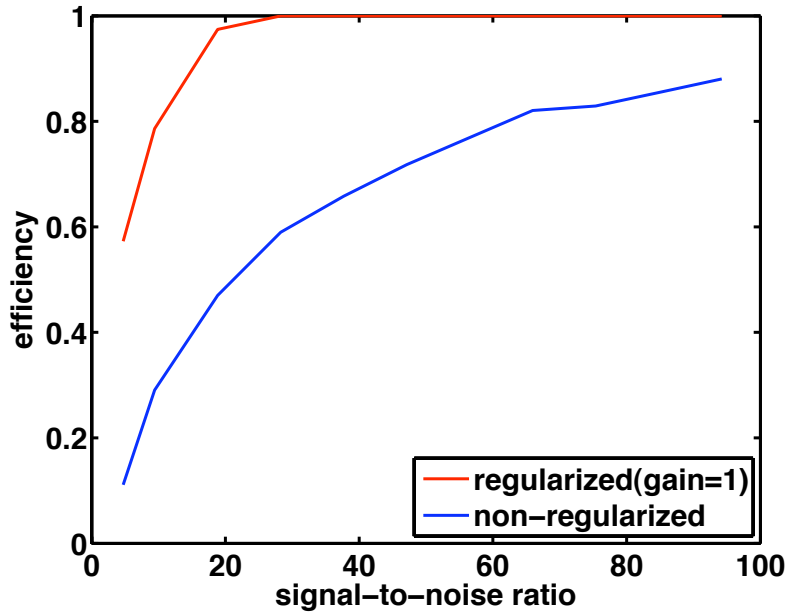
Notice : effect of regularization

- Regularization of coherent network analysis is quite effective for the detection of the sign

8 hours before Christmas



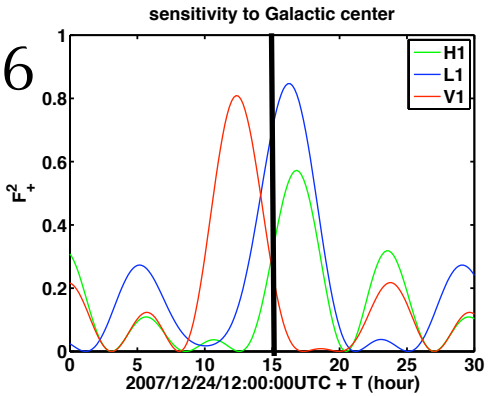
Christmas



Detection efficiency (Galactic center)

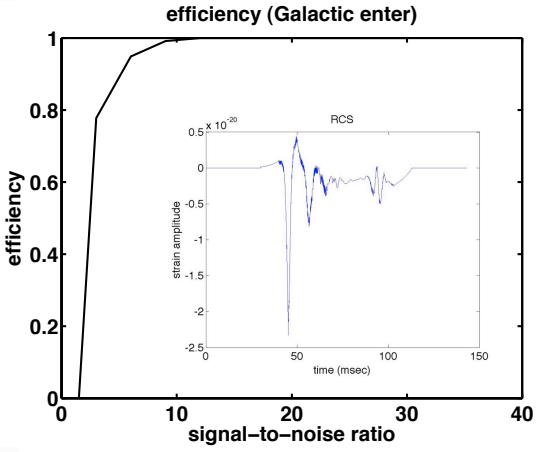
3 hours after Christmas,
efficiency > 90% for MCS,RCS with SNR > 6

Antenna pattern

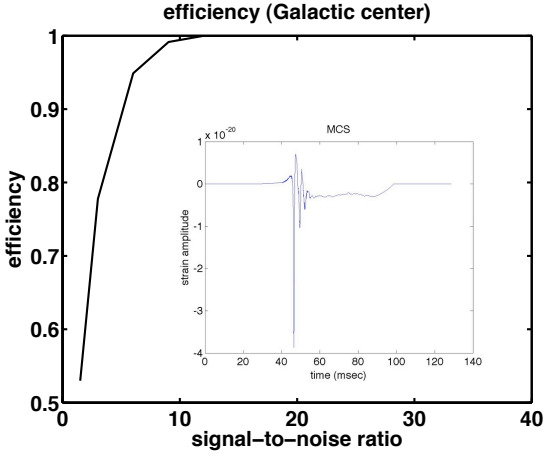


Interesting issue:
As for SCS, 3rd peak is estimated larger than 2nd peak. misestimate for the base-line after 2nd peak?

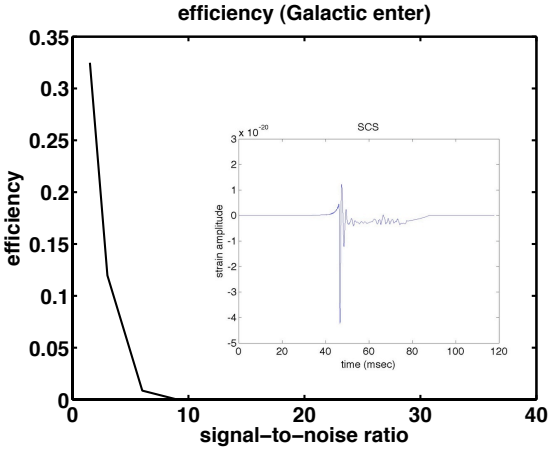
RCS



MCS



SCS



Summary

- Second peak of a gravitational wave from supernova provides information about an angular momentum distribution of a massive evolved star
- We demonstrate the detection of the sign of the second peak
- When Supernovae appear 3 hours after Christmas, the second peak can be detectable with efficiency > 90% of SNR>6 for MCS, RCS
- Essential to regularized coherent network analysis
- Issue:
  - As for type SCS signal, 3rd peak is estimated larger than 2nd peak.