Multimessenger Search for Gravitational Waves from Core-Collapse Supernovae

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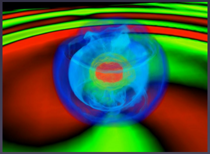
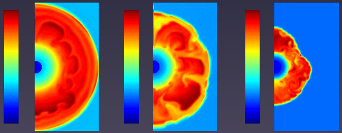
Core-Collapse Supernovae

- **How to produce a SN explosion**
  If iron core is sufficiently massive → unstable
  Collapse – compression to nuclear densities – EoS stiffens – bounce
  Shock wave, loss of E_{kin}, it must be revived to produce SN explosion
  Shock breakout happens long after CC (1 min to 1 day)
- **Precise CCSNe explosion mechanism is uncertain**
  Variety of proposed mechanisms (neutrino, MHD, acoustic)
  → relativistic dynamics in the core, hidden from EM view
- There has never been a targeted search for GW from CCSNe





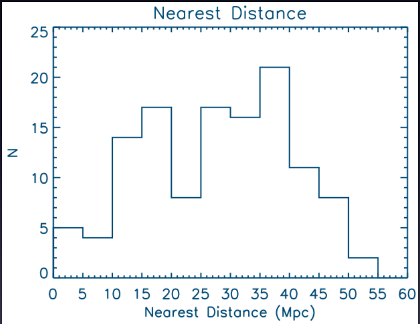
A GW Search for Core-Collapse Supernovae

Motivation

- EM radiation from star surface | A GW signal will allow us to see CC
- iLIGO epoch, 129 CCSNe

  9 were nearby (< 10 Mpc)

  5 at < 5 Mpc



- 10% CCSNe discovered within 1 week of explosion
- 60% between 1 week and 1 month

Shock breakout constraints:

- 8 CCSNe events have well-constrained explosion times to a period of few days
- **Targeted search:** more sensitive because it constrains sky location & time

Well-constrained SNe

Name	Type	Distance (Mpc)	t_{SBO}	LIGO Operation
2006bp	II	$\sim$18	2006 04 07.9 $\pm$ 0.4 days	S5
2007gr	Ib/c	$\sim$8	2007 08 12.5 $\pm$ 2.5 days	S5
2008D	Ib/c	$\sim$30	2008 01 09 $\pm$ 6 seconds	Between S5 & A5
2008ax	IIb	$\sim$8	2008 03 03 $\pm$ 0.15 days	A5
2008ij	IIp	$\sim$20	2008 12 17.5 $\pm$ 1.5 days	A5
2009K	II/IIb	$\sim$40	2009 01 12.5 $\pm$ 1.5 days	A5
2009bb	Ic	$\sim$40	2009 03 20 $\pm$ 1 day	A5
2009dq	IIb	$\sim$18	2009 04 14 $\pm$ 4 days	A5

Table 1: Well-constrained supernovae and their properties.

SN2008D constrained by X-ray flash. Shock breakout constrained to a few seconds. LIGO was off. GEO was taking data at 75% duty cycle

SN waveform catalog: Numerical Simulations

A handful of groups have computed GWs from CCSNe simulations

Rotational core collapse and bounce:

- Dimmelmeier et al. 2008

Convection / SASI*:

- Burrows et al. 2007
- Kotake et al. 2009 3D
- Marek et al. 2009
- Murphy et al. 2009
- Ott 2009
- Yakunin et al. 2010

MHD convection:

- Scheidegger et al. 2010 3D

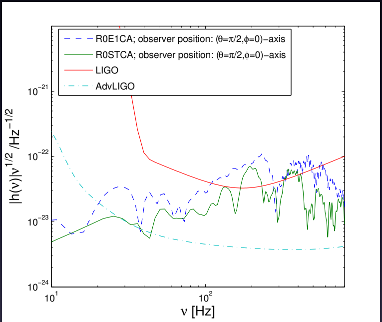
PNS core pulsations:

- Ott et al. 2006

Collapsar model:

- Ott et al. 2010

Scheidegger et al. 2010



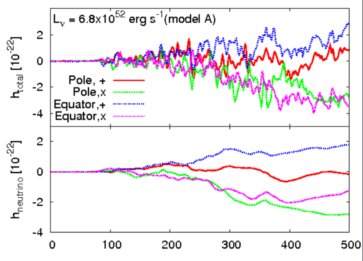
Different models and large parameter space

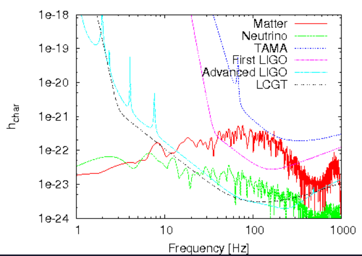
- Equations of state
- Rotation rates and profiles
- Axisymmetric vs. full 3D simulations
- Neutrino transport; electron capture...

* Standing accretion shock instability

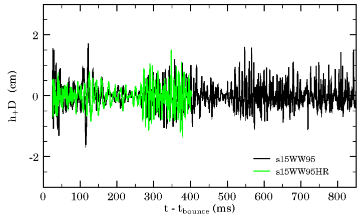
Numerical Simulations: Examples

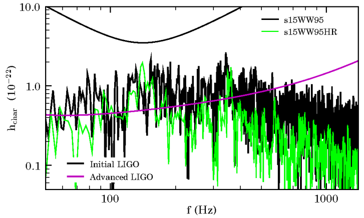
Kotake et al. 2009





Ott 2009





SN waveform catalog: Extreme Models (I)

Long-lived bar model [Fryer et al. 2002, worked out in Ott 2010, LIGO-T1000553]

- GWs from bar mode instabilities $\rightarrow$ spinning cylinder
- Astrophysically meaningful bar parameters:

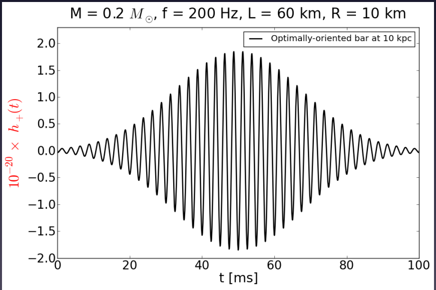
  Canonical protoneutron star (PNS) mass $M = 1.5 M_\odot \times \epsilon$, $\epsilon = 0.1 - 1$

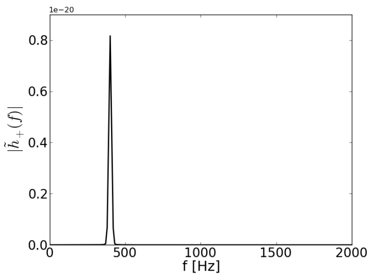
  Only $L > R$ makes sense. $L = 20\,\mathrm{km} - 60\,\mathrm{km}$

  $R = 5\,\mathrm{km} - 20\,\mathrm{km}$. Ratios of L/R of $\gtrsim 1$

  Spin frequency f above 200 Hz, below 1000 Hz.

  Note that f will decrease as spin energy is lost to GWs.





SN waveform catalog: Extreme Models (II)

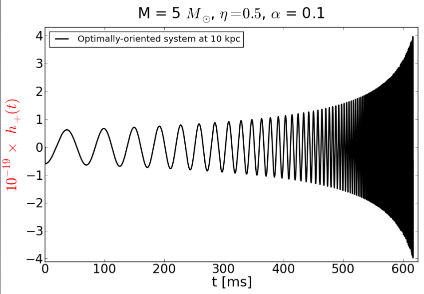
Fragmentation of collapsar disks [Piro et al. 2007, worked out by LS]

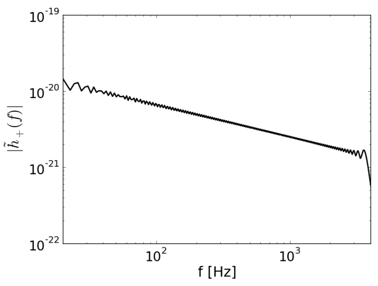
- Central stellar-mass BH surrounded by Keplerian accretion disk
- Under certain circumstances, gravitational instability leads to fragmentation
- The fragment migrates inward on the viscous timescale until GW emission takes over
- Astrophysically meaningful parameters:

  Mass of the BH $M_{\rm BH} = 3 - 10 M_\odot$ but maybe as high as $20 M_\odot$

  Viscosity $\alpha \approx 0.1$, Disk geometry $\eta = H/r \approx 0.3 - 0.6$

  Mass of the bound fragment $M_{\rm f} \approx 0.2\,(\eta/0.5)^2\, M_{\rm BH}/3$ $(0.2 - 1 M_\odot)$





CCSNe Search Strategy

- Data to analize: November 2005 until October 2010
- X-Pipeline: library of Matlab-based algorithms for GW burst searches

Mature general purpose burst pipeline – modify to effectively handle week-long onsource regions

+ Determine and parameterize the CCSNe set for use in the search
(Understand distances, onsource regions)

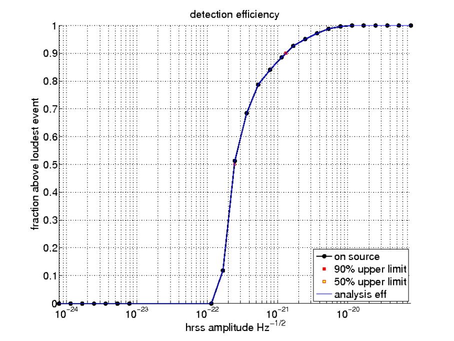
+ Prepare library of model waveforms
Estimate model-dependent loudest-event upper limits

+ Analyze onsource data & find loudest event

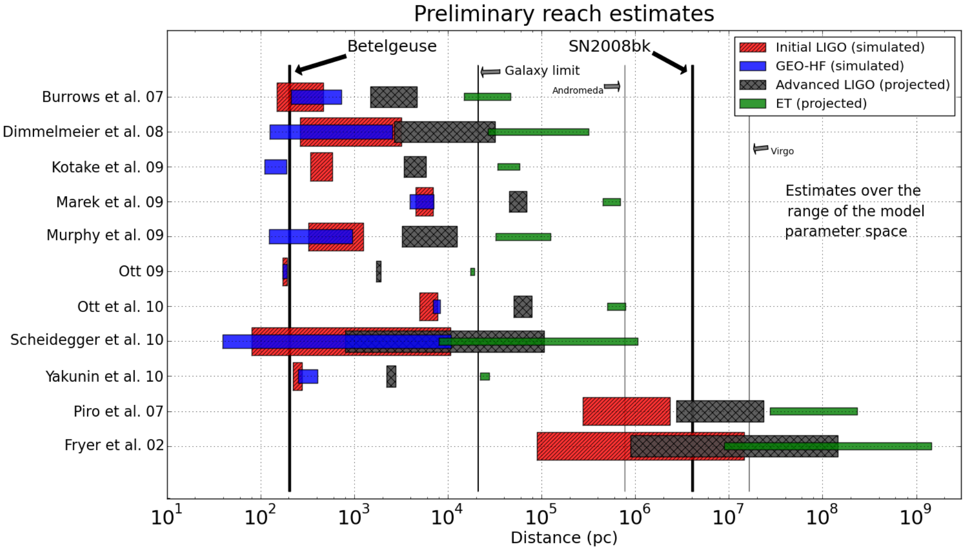
+ Assign statistical significance to
loudest event using background data

+ Set upper limit by comparing loudest event
to model waveforms injected into the background

+ Test search in data without a SN event ("closed box")
+ Open the boxes



Preliminary Reach Estimates on Simulated Data



Final Remarks

- First GW search targeted to CCSNe is happening now
  A GW signal will reveal information about the core collapse
- Plan: to complete the search by early 2012
- Initial LIGO epoch: possibility of constraining **extreme** models for extragalactic SNe
- GEO-HF and Advanced LIGO epochs: maybe Galactic SNe with **conservative** models
- We look forward to the Advanced LIGO era, with more sensitivity to GWs (1000x volume) and more precise SN shock-breakout times from upcoming quick-cadence optical sky survey telescopes!