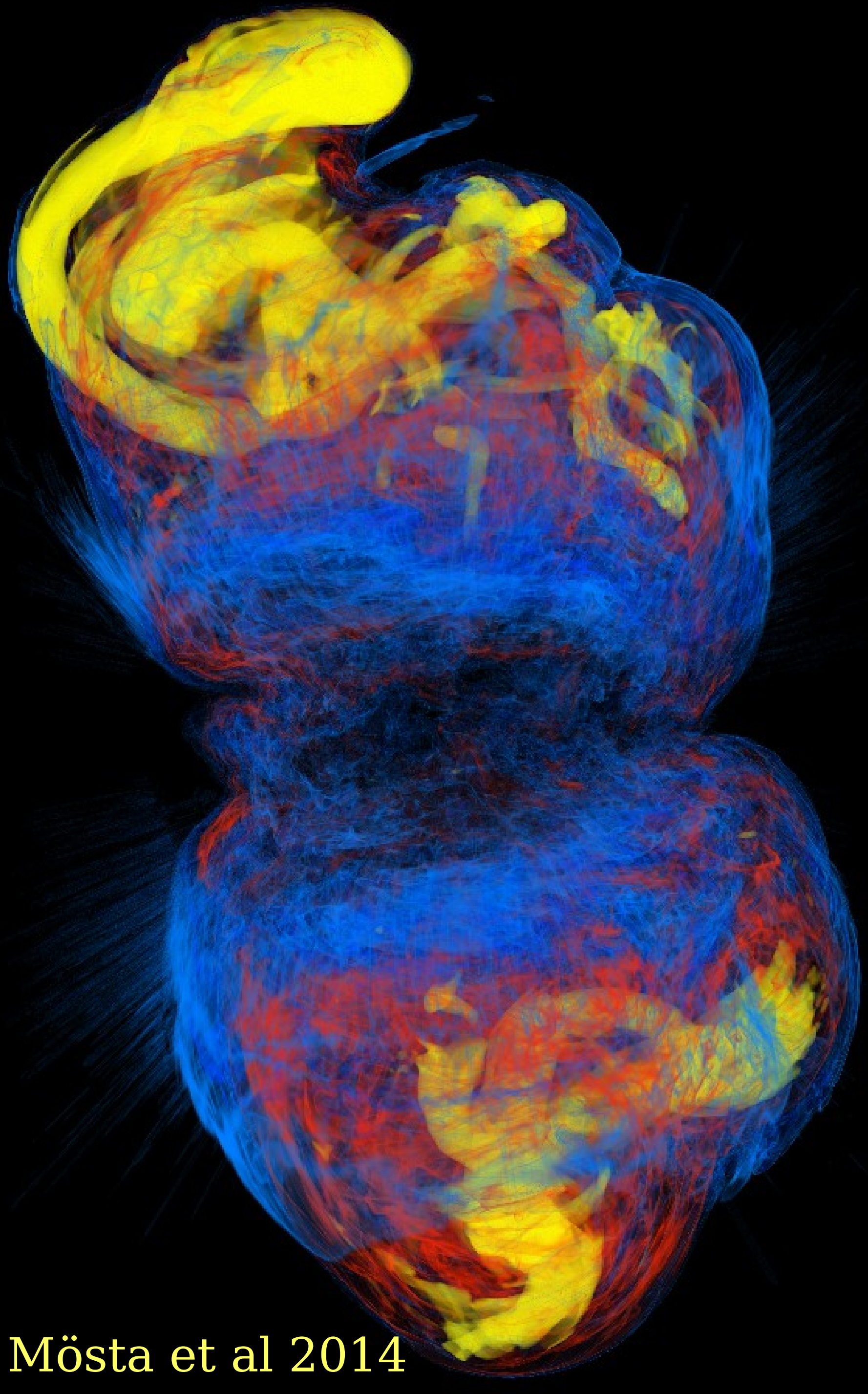


Mösta et al 2014

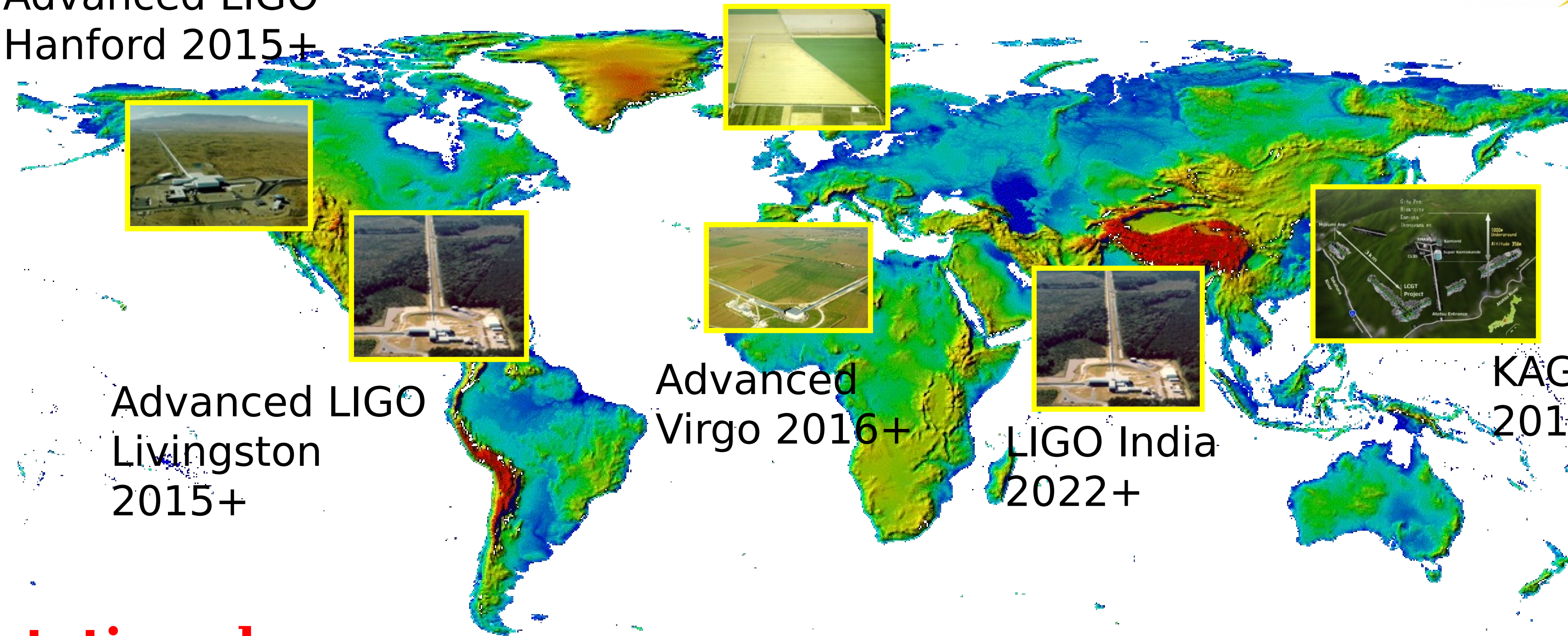
Core-Collapse Supernova Science with Advanced LIGO and Virgo

Fifty-One Erg
Raleigh, 06/01/2015

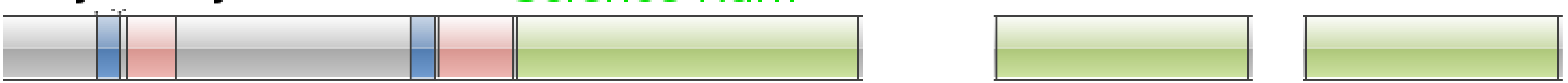
Marek Szczepańczyk

LIGO Scientific Collaboration
and Virgo Collaboration

The Advanced GW Detector Network



Tentative plan (LIGO white paper)



Gravitational Waves (GW)

Emission:

- **Accelerated aspherical (quadrupolar) mass-energy motions.**
- **Quadrupole approximation:**

$$h_{jk}^{TT}(t,\vec{x}) = \left[\frac{2}{c^4}\frac{G}{|\vec{x}|}\ddot{I}_{jk}(t-\frac{|\vec{x}|}{c})\right]^{TT}$$

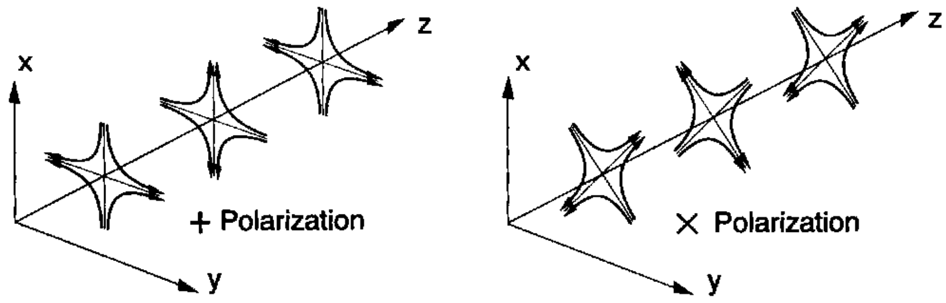
$$\frac{G}{c^4} \approx 10^{-49}\,\mathrm{s}^2\,\mathrm{g}^{-1}\,\mathrm{cm}^{-1}$$

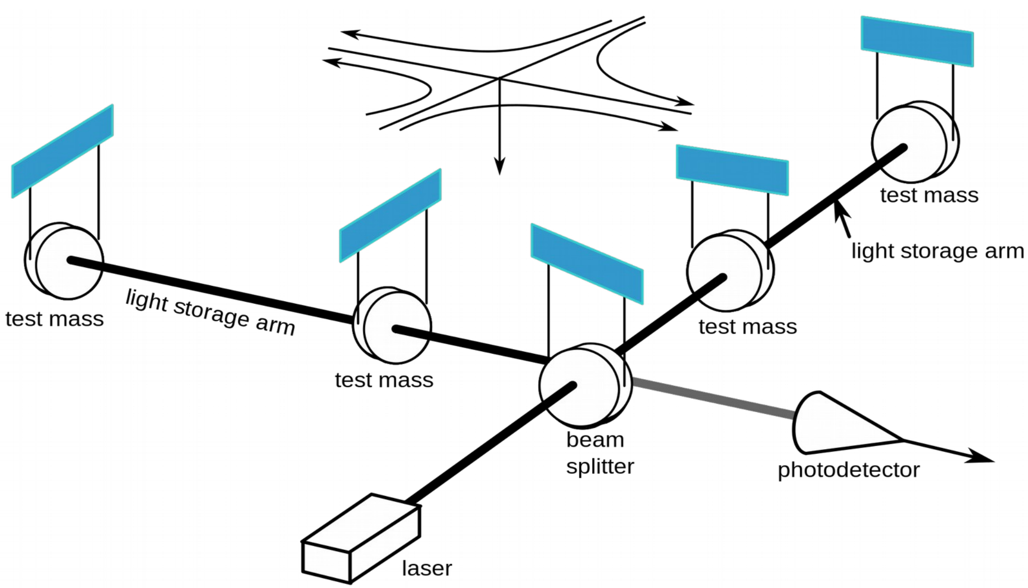
$$10\,\mathrm{kpc} \approx 3 \times 10^{22}\,\mathrm{cm}$$

Must measure fractional displacement of 10^{-22}

Detection:

Stretching and squeezing the space-time





Gravitational Waves from Core Collapse Supernovae

Recent reviews: Ott 09, Kotake 11, Fryer & New 11

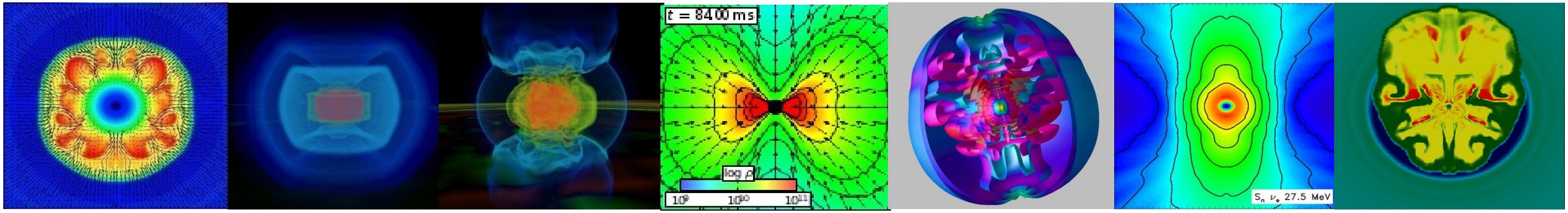
Need: $$h_{jk}^{TT}(t,\vec{x}) = \left[\frac{2}{c^4}\frac{G}{|\vec{x}|}\ddot{I}_{jk}\left(t-\frac{|\vec{x}|}{c}\right)\right]^{TT}$$

Candidate emission processes:

- Turbulent convection
- Rotating collapse & bounce
- 3D MHD/HD instabilities
- Aspherical mass-energy outflows

And also:

- Black Hole formation
- Pulsation of protoneutron star
- Anisotropic neutrino emission
- Magnetic stresses
- ...



First GW optically triggered SN search

Leads: Gossan, Ott, Stuver, Sutton, Szczepanczyk, Zanolin

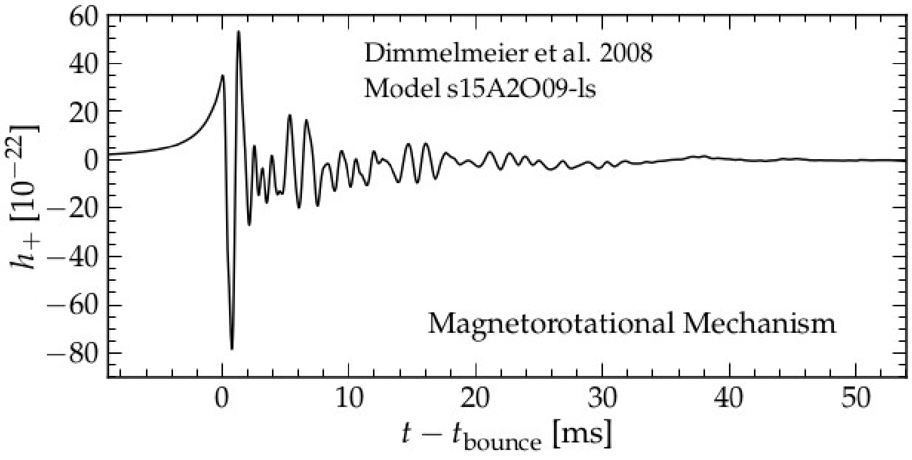
Goals

- Find GW from a supernova or establish upper limits sensitivity for GWs from CCSN in A5/S5/S6 runs (Astro Watch and Science Runs).
- Use optical triggers for nearby (~4-10 Mpc) CCSNe, based on the detector livetime and on-source window (estimated time range for GW search) considerations

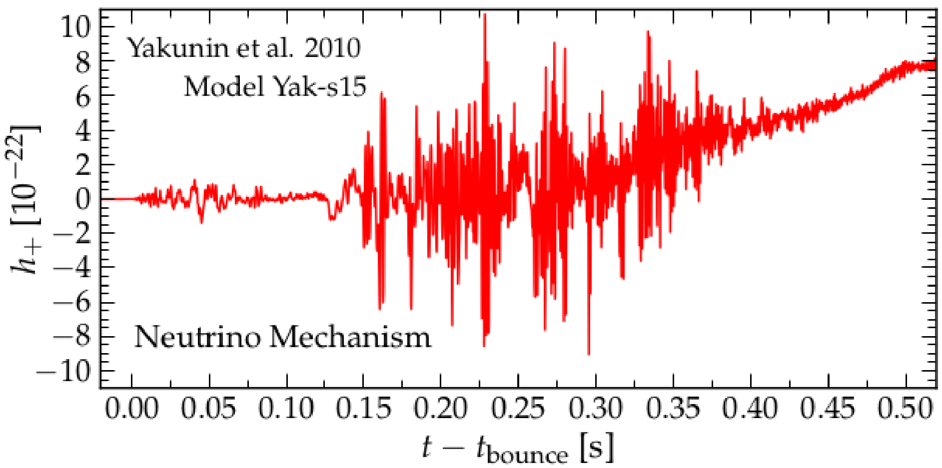
SN	Type	Host Galaxy	Distance [Mpc]	t_1	t_2	Δt [days]	LIGO/Virgo run	Detectors
2011dh	IIb	M51	8.40 ± 0.70	2011 May 30.37	2011 May 31.89	1.52	S6E/VSR3	G1,V1
2008bk	IIP	NGC 7793	$3.53\ {+0.41}\ {-0.29}$	2008 Mar 13.50	2008 Mar 25.14	12.64	A5	G1,H2
2008ax	IIb	NGC 4490	$9.64\ {+1.38}\ {-1.21}$	2008 Mar 2.19	2008 Mar 3.45	1.26	A5	G1,H2
2007gr	Ic	NGC 1058	10.55 ± 1.95	2007 Aug 10.39	2007 Aug 15.51	5.12	S5/VSR1	H1,H2,L1,V1

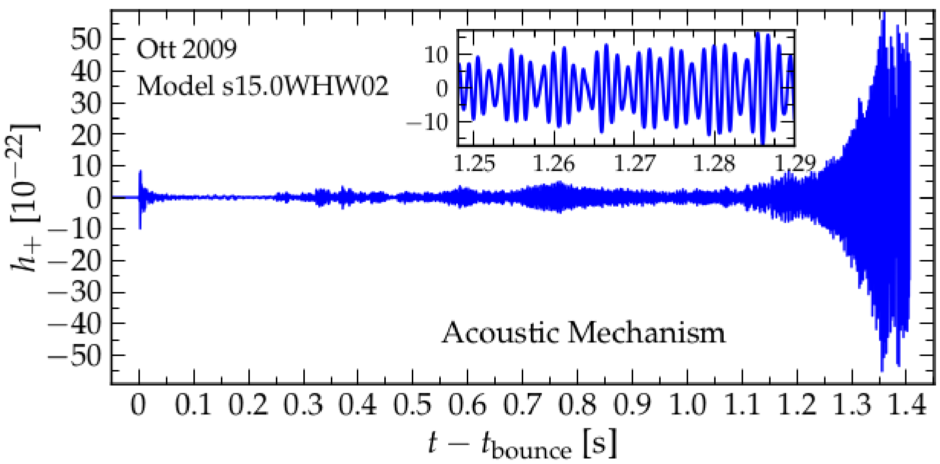
First GW optically triggered SN search
Numerical waveforms

Leads: Gossan, Ott, Stuver, Sutton, Szczepanczyk, Zanolin



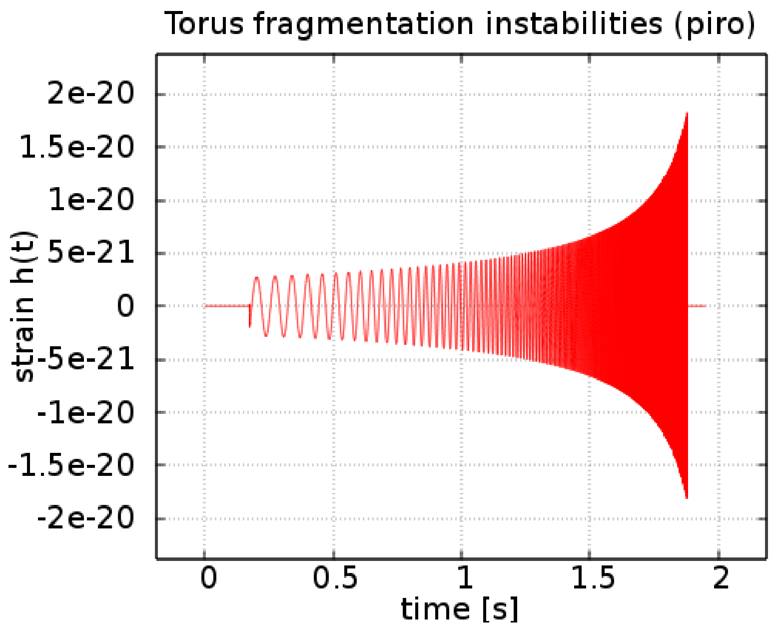
- **Magnetorotational** mechanism (Dimmelmeier+08, Scheidegger+10): rotating core collapse and bounce, rotational instabilities
- **Neutrino** mechanism (Yakunin+10, Muller+12, Ott+13): convection and Standing Accretion Shock Instabilities
- **Acoustic** mechanism (Ott+09): protoneutron star pulsation

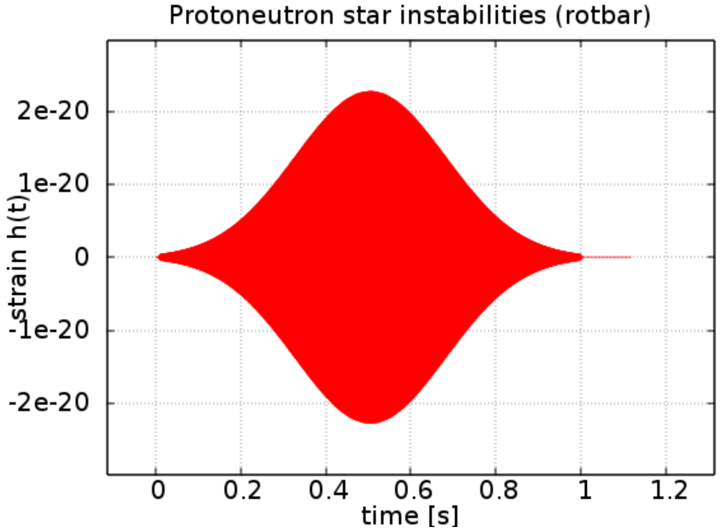




First GW optically triggered SN search
Analytical waveforms

Leads: Gossan, Ott, Stuver, Sutton, Szczepanczyk, Zanolin





Semianalytic models

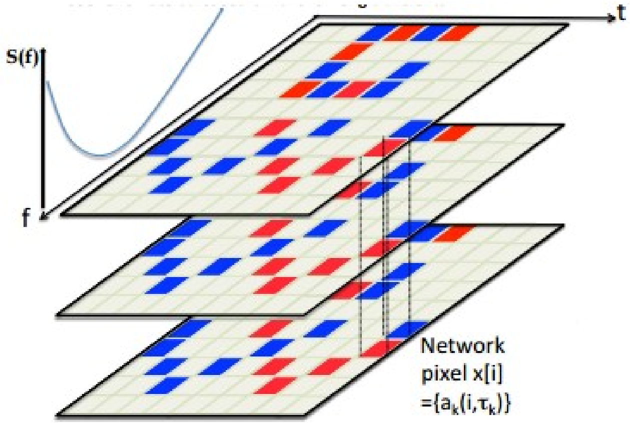
(extreme emission models)

- Torus fragmentation instabilities (Piro & Pfahl 2007)
- Long lasting rotational instabilities of the protoneutron star (Ott 2010, ref)

Sine Gaussians

First GW optically triggered SN search Analysis Strategy

Leads: Gossan, Ott, Stuver, Sutton, Szczepanczyk, Zanolin



Coherent analysis - combining data from each detector into unique list and creating list of trigger.

CWB (Klimenko+05) and X-pipelines (Sutton+10)

- Identifies burst **candidate events** by tiling the data in time and frequency via a wavelet transform.
- Extracts significant events using **likelihood statistic** maximized over all potential sky positions (cWB) or over specific location (X-pipeline).
- Analysis of the **background** and producing **efficiency curves** based on the injected signals.

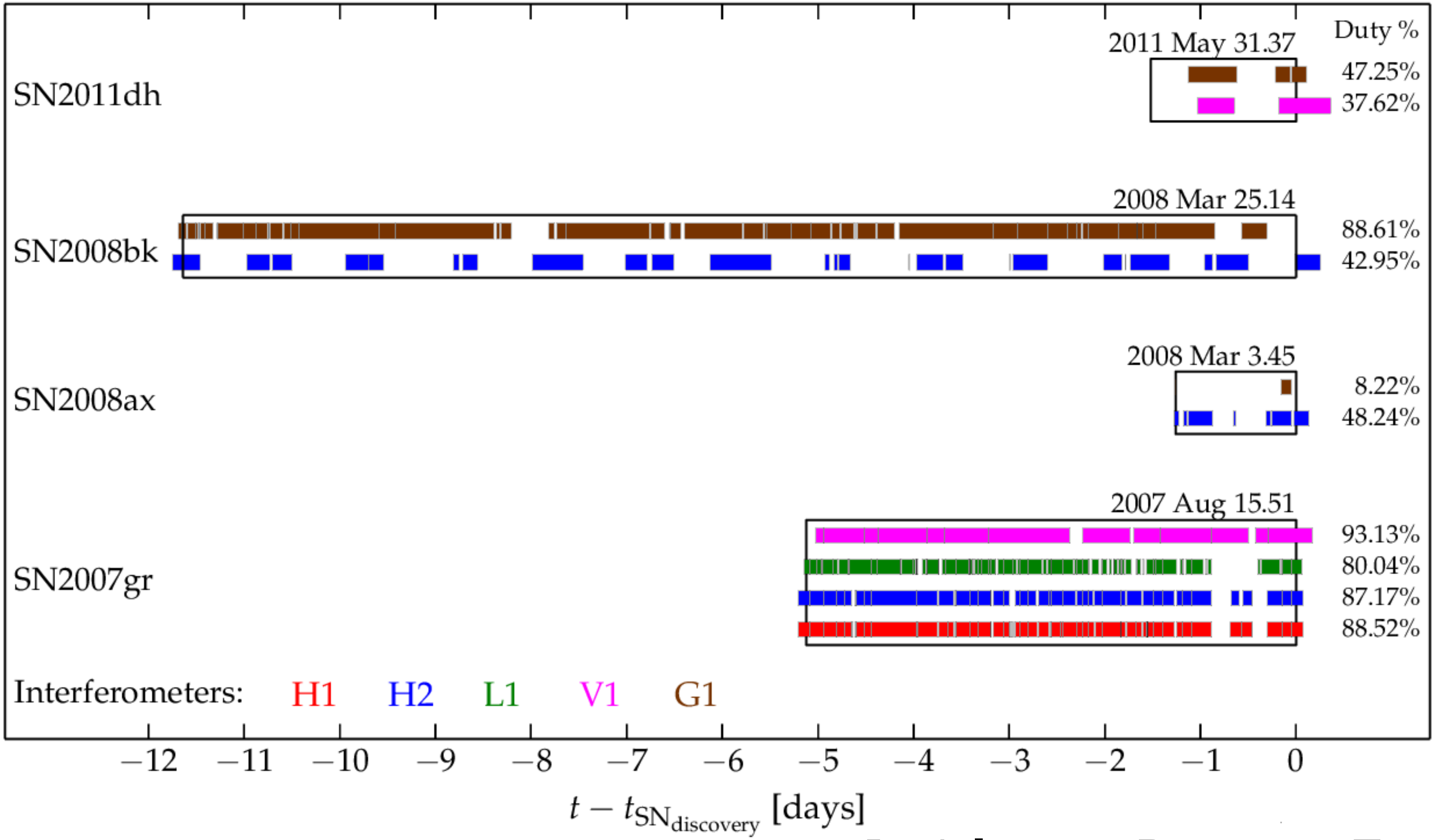
Coherent WaveBurst
a joint LSC-Virgo project

Loudest Event Limits

- Find the **most energetic event**.
- Produce the detection efficiency vs signal strength and distance.

First GW optically triggered SN search

Leads: Gossan, Ott, Stuver, Sutton, Szczepanczyk, Zanolin



SN2008ax/bk are not used for detection statements, high False Alarm Rate

No detection candidate!

Preparing Upper Limit Statements

In Advance Detector Era the detection sensitivity will increase thanks to:

a) better detector sensitivity

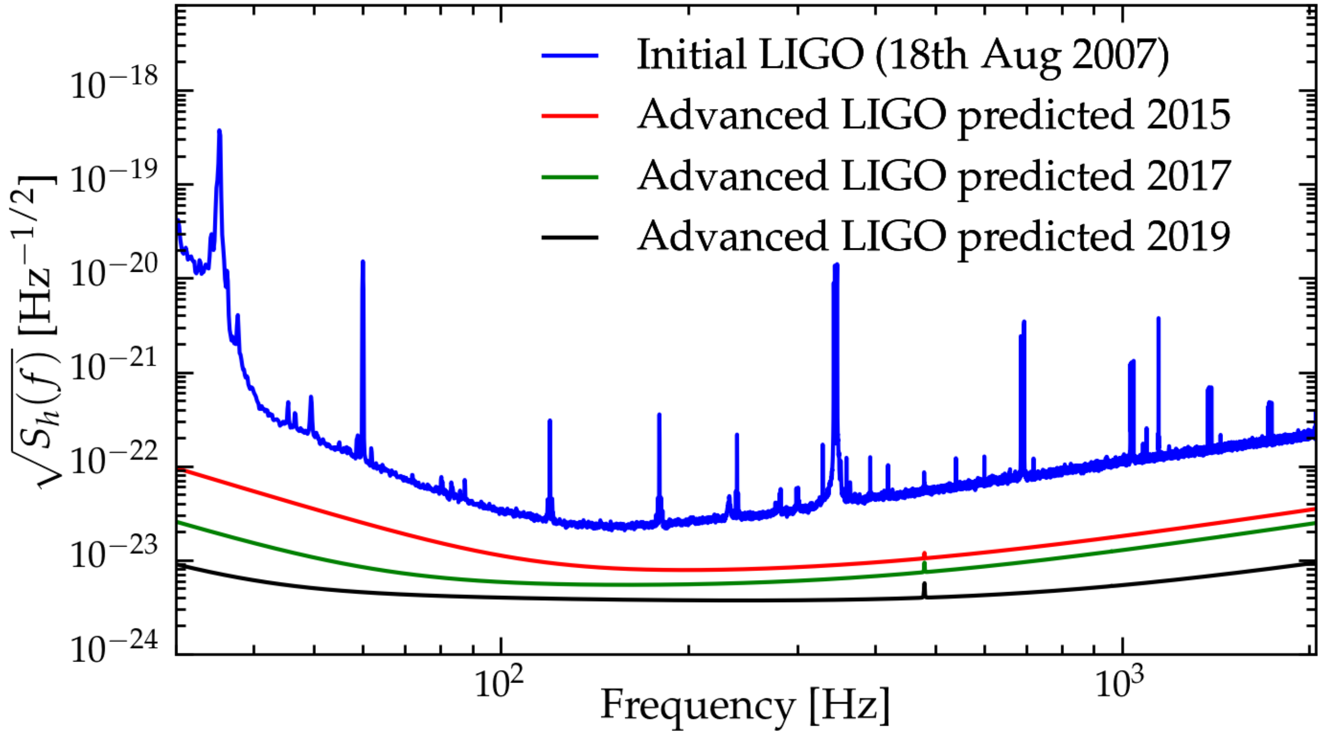
b) improved algorithms

SN search method paper

Gossan et al (in preparation)

Scope:

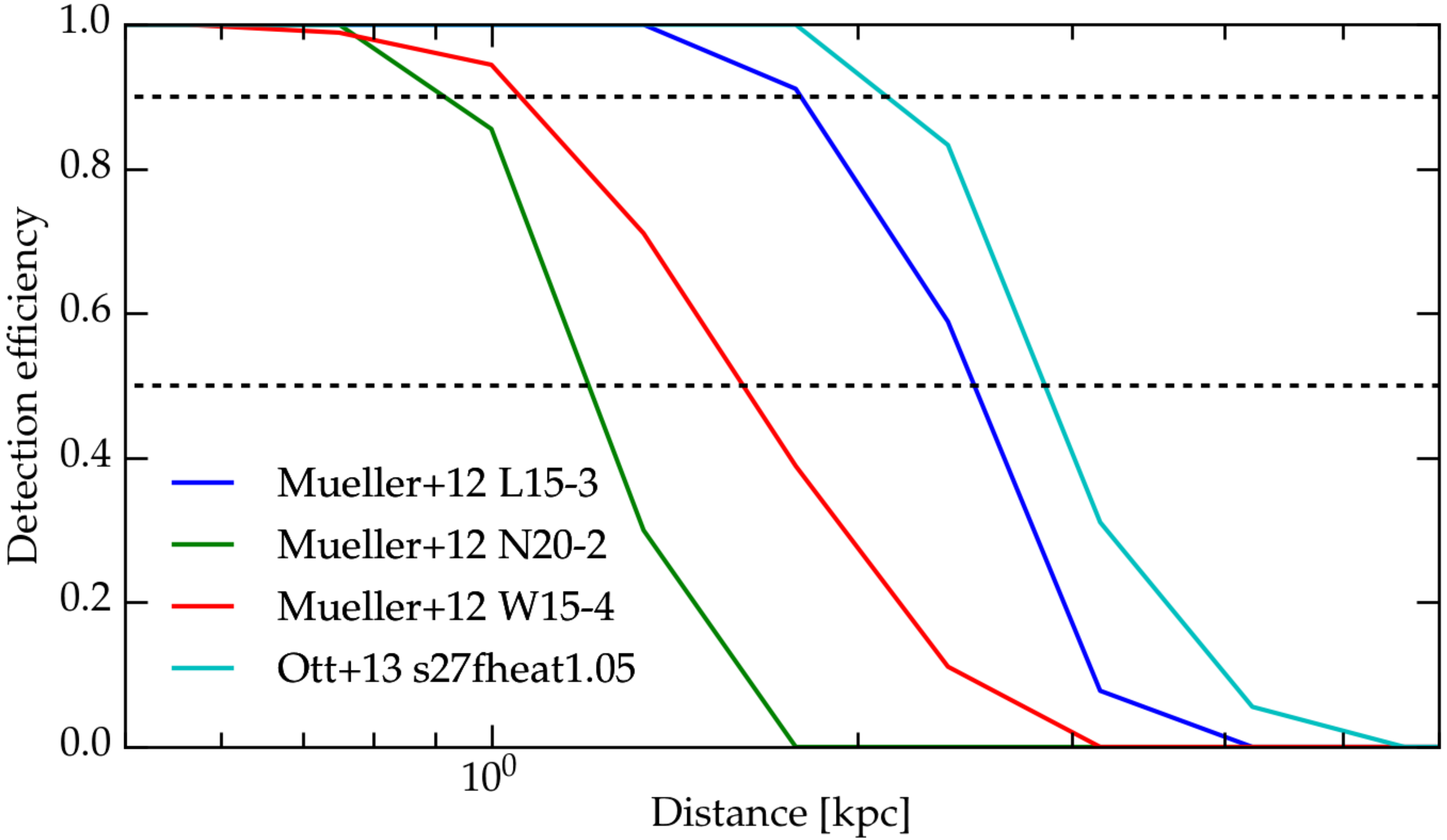
- Describe and test methods. Use recolored open S5 (Initial LIGO) data for **sensitivity studies** (recolored -> simulated LIGO noise).
- **Recolor** data for sensitivity estimates for early/interm./designed aLIGO, adVirgo noise.
- Consider multiple hypothetical **on-source** windows (1min to 100h) and **locations**: galactic center, LMC, M31, NGC 6822, M82.



SN search method paper, expected sensitivity

Gossan et al (in preparation)

PRELIMINARY study of neutrino mechanism waveforms



Supernova Model Evidence Extractor

Gossan et al (in preparation)

Assumption:

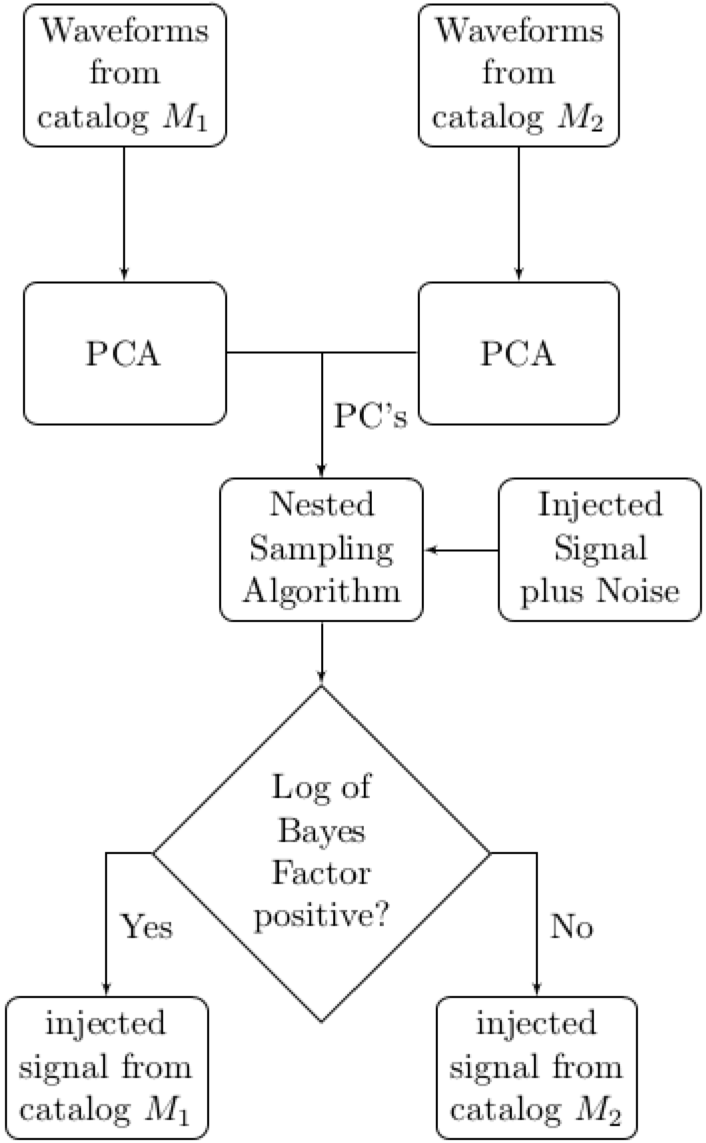
Gravitational wave signals have certain **distinct structures** in their time series or power spectra that can be reliably used to identify the explosion mechanism.

Approach:

- Bayesian Model Selection.
- Principal Component Analysis (PCA) + nested sampling.
- SMEE2G: Multiple detectors, arbitrary sky location, recolored noise.

SMEE1G: Logue+12

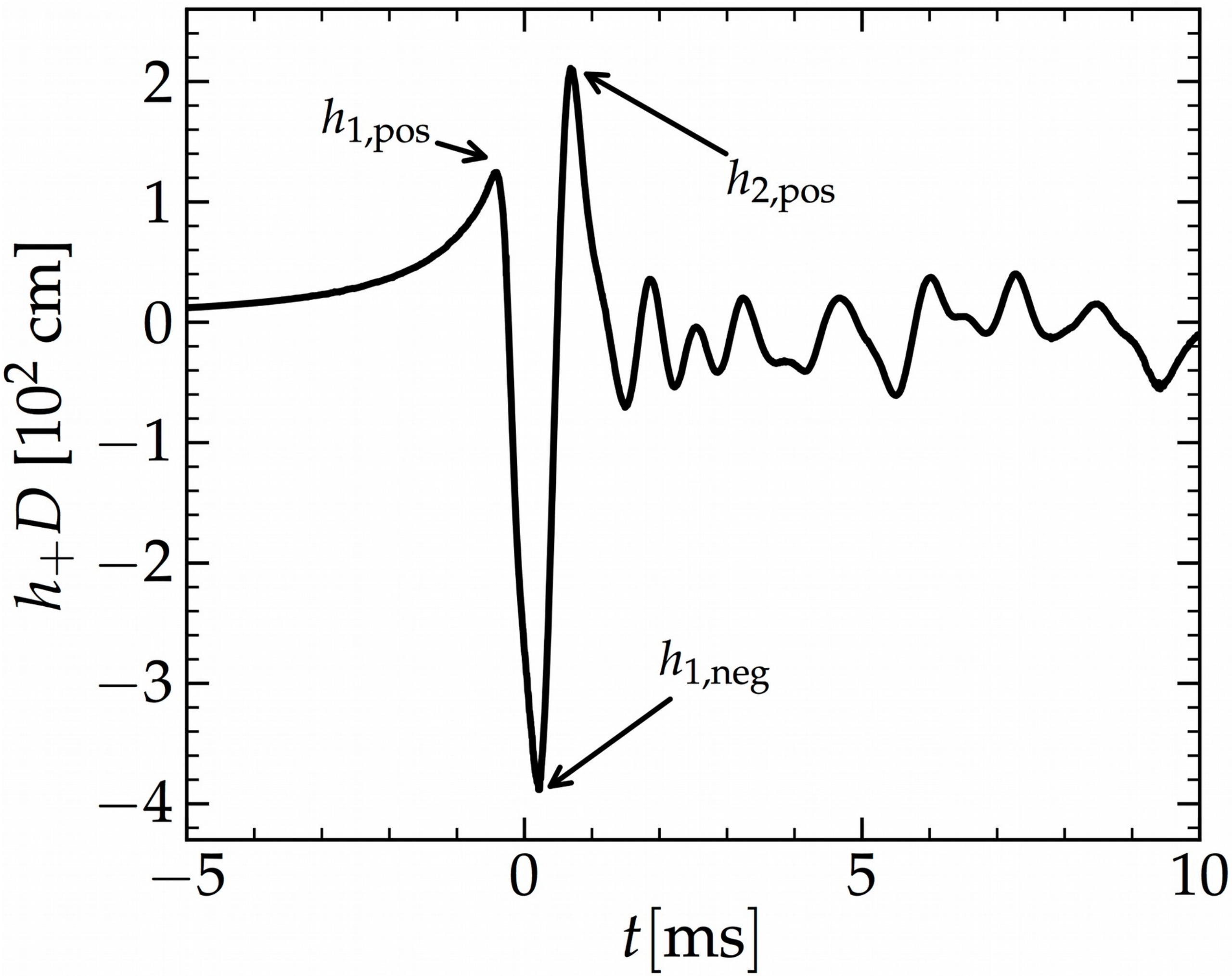
- Single detector, simulated aLIGO noise
- Magnetororational mechanism D<~10 kpc
- Neutrino&acoustic mechanisms , D<~2 kpc



Measuring Core Angular Momentum

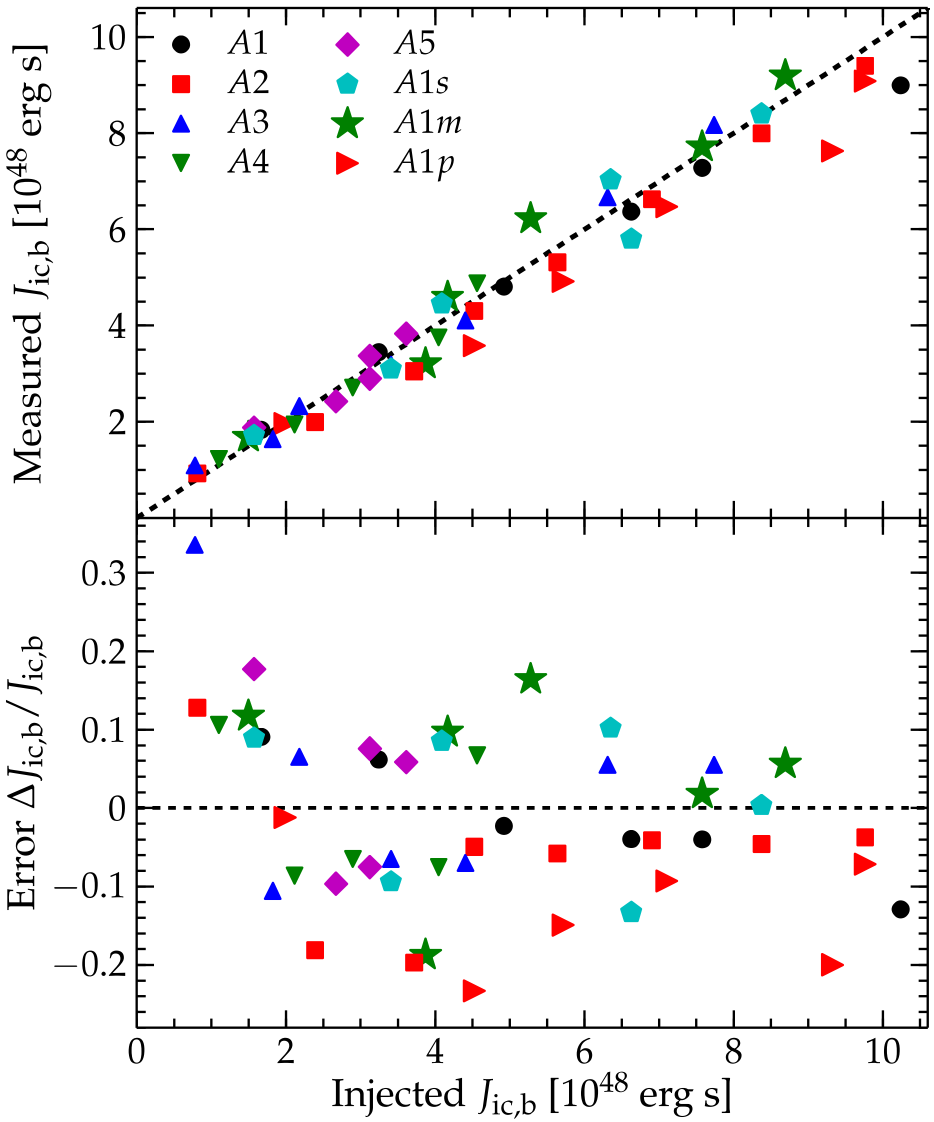
Abdikamalov, Gossan, DeMaio, Ott 2014, PRD

GWs from Rotating Collapse & Bounce



Measuring Core Angular Momentum

Abdikamalov, Gossan, DeMaio, Ott 2014, PRD



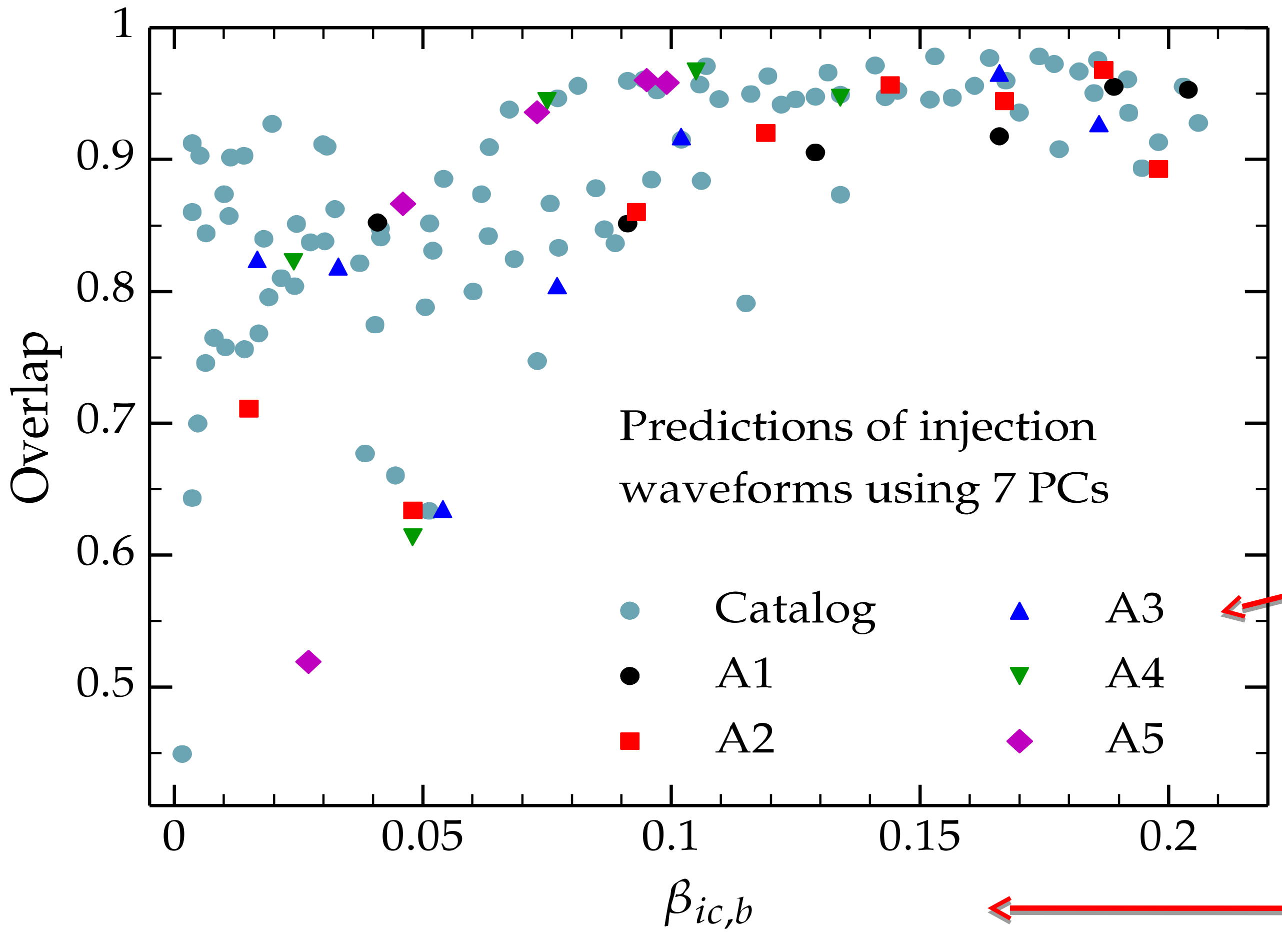
- Matched-filtering analysis; assumes signal known
- Can measure inner core angular momentum with < 30% error for CCSN at 10 kpc (assuming Gaussian noise and optimal source-detector orientation)

Mulivariate Regression Analysis of GW from Rotating Core Collapse

Engels, Frey & Ott +14, PRD

Challenge: must connect efficient **principal component** (PC) basis with **physical parameters** (e.g. core spin rate, differential rotation).

Details: http://www.stellarcollapse.org/ccsnmultivar



Abdikamalov+2014 waveforms

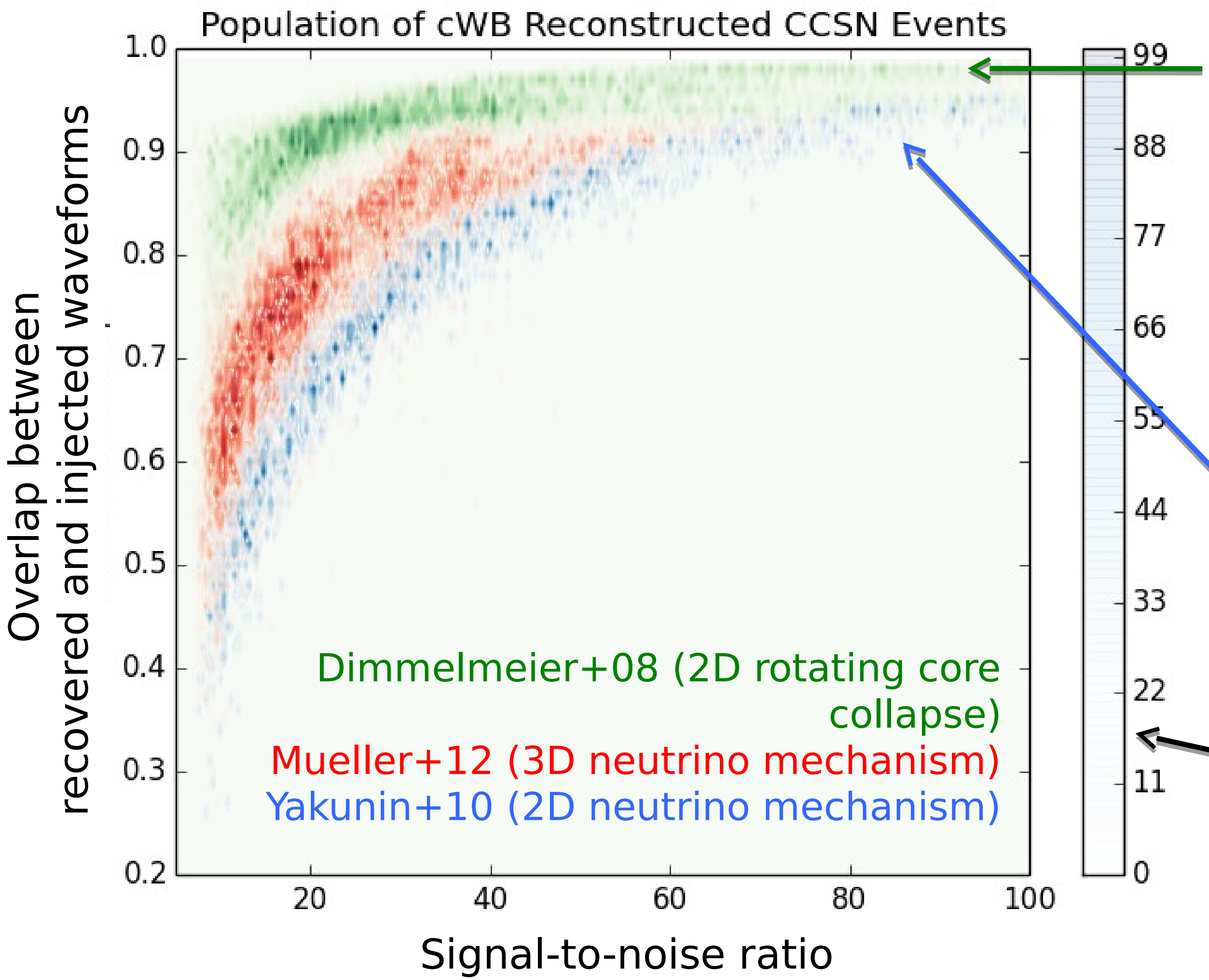
Parameter in rotational law:

$$\Omega(r) = \Omega_c \left[1 + (\frac{r}{A})^2\right]^{-1}$$

"rotation rate" (T/|W|)

Direct comparison of cWB2G CCSN reconstruction heatmaps

McIver+14 (Dissertation)



Dimmelmeiers+08 waveforms, most like a simple wavelet, are the easiest to reconstruct.

Yakunin+10 performance surpasses average Mueller+12 performance at high SNRs.

Heatmap color scale shows the number of discrete events with that overlap and SNR per bin.

SNEWS alerts

SNEWS - SuperNova Early Warning System

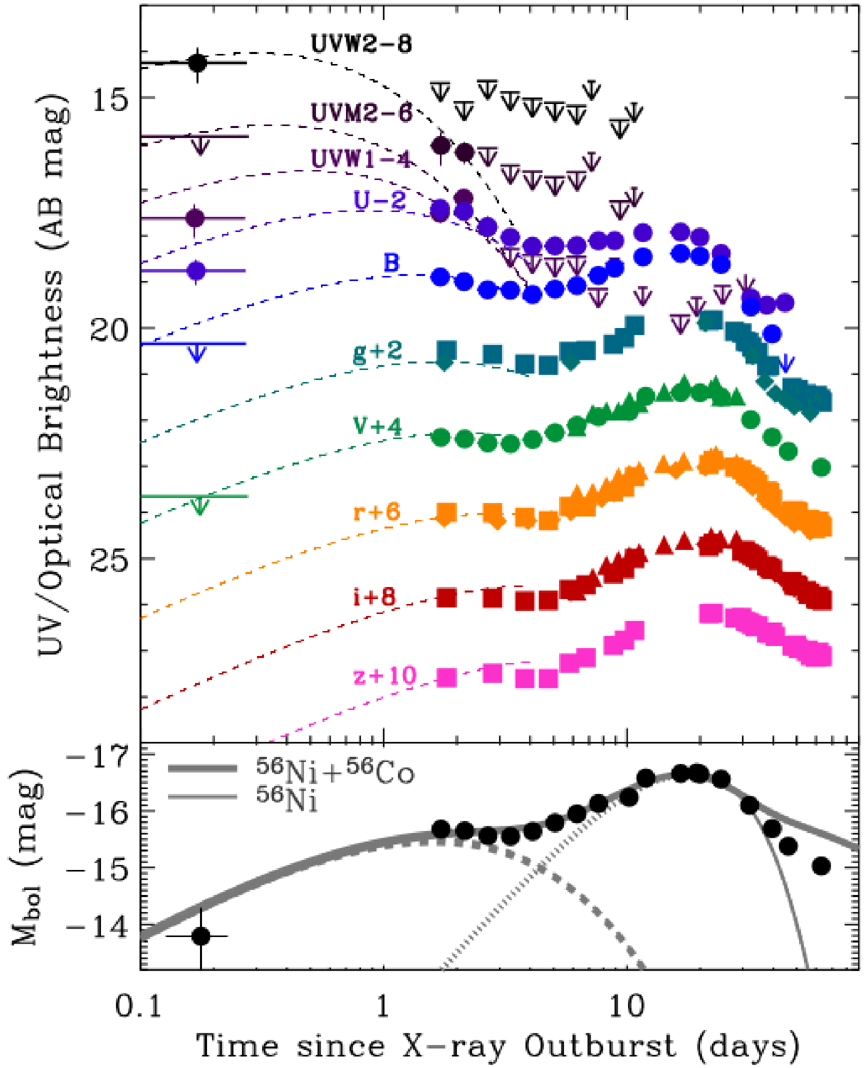
- Alerts based on neutrino bursts
- SNEWS description: Antonili+04 and http://snews.bnl.gov/
- Preliminary results after 3-4h.

Different scenarios for detection:

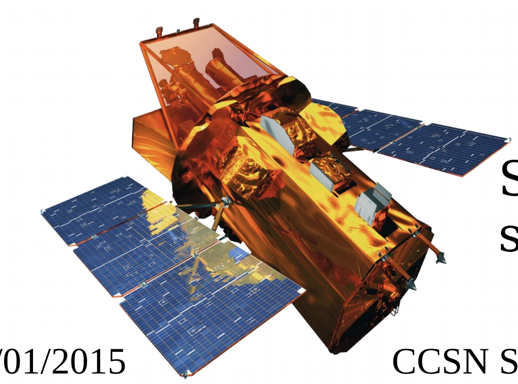
1. Initial alert has no or poor sky location information.
2. Follow-up alert has very good sky position to small/zero error.
3. The alert comes with only one detector on.
4. Seedless Clustering with two detectors and good sky localization.

Increasing supernova triggers

- More SN triggers gives better **Detection**, **Upper Limit**, **Model Exclusion** statements, need SNe up to 10 Mpc (model exclusion range is larger than detection range).
- We need better estimation of on-source window for the search.
- Soderberg+08, X-ray transient precedes optical/UV supernova light curves.
- We need to estimate how many potential SNe we can find with a dedicated SWIFT survey.
- Monitor galaxies in the local universe for X and UV transients related to CCSN.



Soderberg et al +08, Nature



SWIFT satellite

Conclusions

- The search and method paper in preparation.
- No GW candidate.
- Several projects with Parameter Estimation and Wave Reconstruction.
- Need more nearby supernovae for Model Exclusion and Upper Limits studies.
- Waiting for awesome science.