Detection of Gravitational Waves from Supernovae: CCSN Data Analysis Effort of the LVC Burst Group

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Brownsville and Edinburg, TX

Amaldi 12, Pasadena CA
July 13 2017

Group structure and members

Chair: Marek Szczepanczyk
Members: Adam Zadrozny, Carissa Cirelli, Claudio Casentini, Erik Katsavounidis, Filipe da Silva, Jade Powell, Jasmine Gill, Jess McIver, Kai Staats, Kellie Ault, Marco Cavaglia, Michele Zanolin, Oscar Valdez, Pablo Cerda-Duran, Sarah Gossan, Satzhan Sitmukhambetov, Scott Coughlin, Sergio Gaudio, Soma Mukherjee, Sophia Schwalbe, Teerth Gill, Vincent Roma, Wenhui Wang

Group web page:
https://wiki.ligo.org/Bursts/SupernovaWorkingGroup

Regular weekly telecons

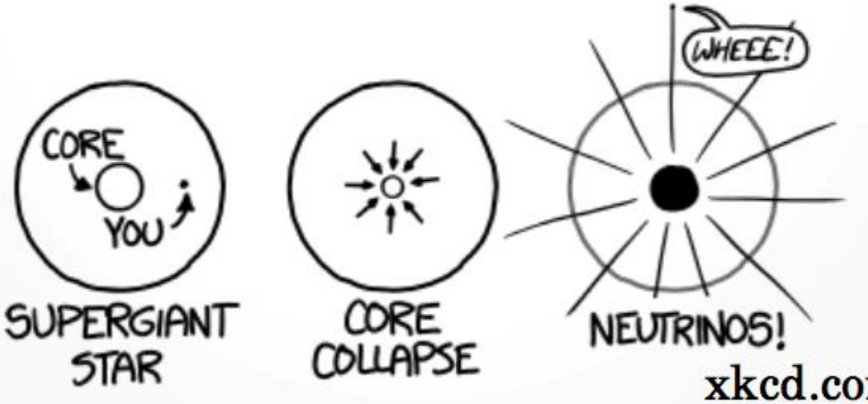
Outline

1. CCSN explosion mechanism
2. What do we learn?
3. CCSN rates and example waveforms
4. Working group projects
5. Methods of searches
6. Models and available waveforms
7. Pipelines
8. Future notes: 3G detectors

In a nutshell …

- Energy available ~ 3×10^{46}J

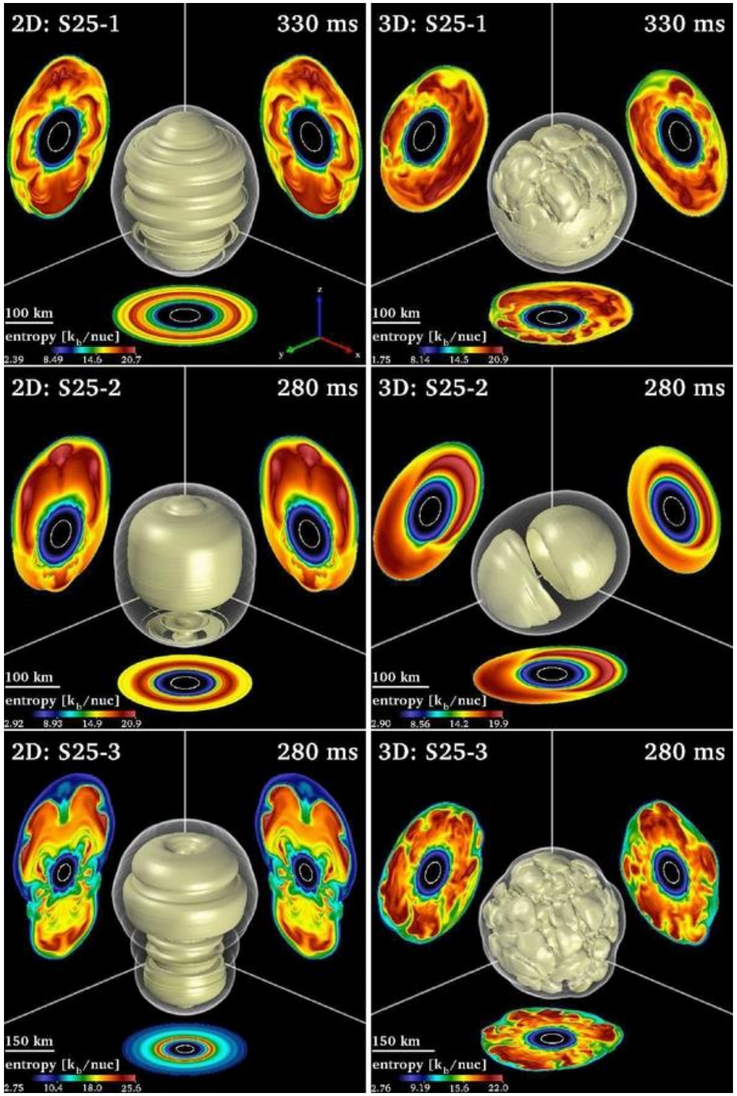
  Energy observed ~ 3-10 $\times 10^{44}$J
- Where does that energy go?
  - Electron capture: $p + e^- \rightarrow n + \nu_e$
  - 99% of explosion energy escapes with neutrinos!



xkcd.com

Explosion Mechanisms

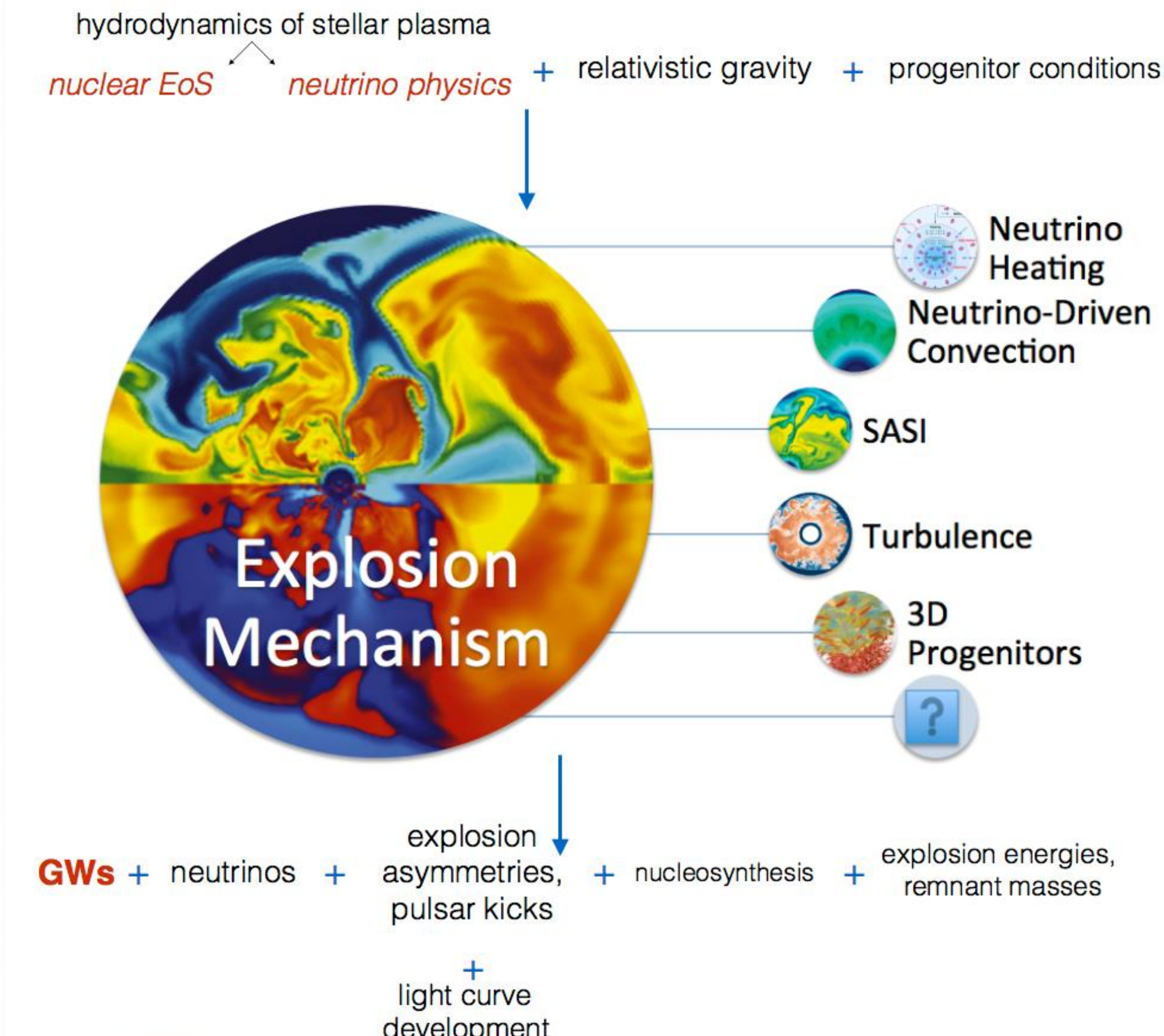
- Direct hydrodynamic mechanism
- Neutrino driven wind mechanism ~1D low mass progenitors
- 2D convection neutrino driven (Spherical Accretion Shock Instability *SASI* – shock instability)
- Neutrino driven jet/wind mechanism – Rapidly rotating accretion induced collapse of white dwarfs
- MHD/Rapid rotation – Hypernovae?
- Acoustic power/core oscillation mechanism
- 3D convection – neutrino driven mechanism



Burrows, Dolence, et. al.
file:///C:/Users/zbj903/Documents/SupernovaMechanisms.pdf

https://www.bing.com/images/search?view=detailV2&ccid=Mz8pZSCN&id=52AE4A81CD9EB98279EE9B14590DF850E30CE908&thid=OIP.Mz8pZSCN3t1b6fnsjin5FwDIEs&q=sasi+supernova&simid=607999871293852260&selectedIndex=10&qpvt=sasi+supernova&ajaxhist=0

What do we learn from CCSN



cred: A. Mezzacappa

What can we learn from CCSN GW signatures?

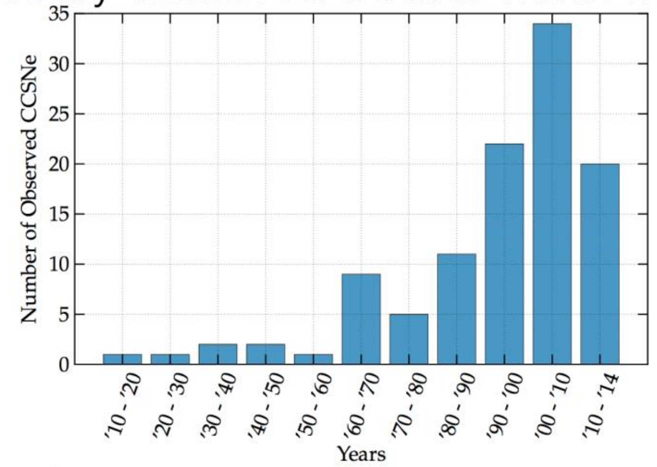
Find explosion mechanism

* Nuclear Equation of State,
* evolution of ProtoNeutron Star,
* asymmetry of explosion
* Set *upper limits on energy emitted by supernova*
* Measure angular momentum and rotational rate of ProtoNeutron Star
* Spot formation of Black Hole at its birth

CCSN Rates and example waveform

- CCSN Rate
  - ~ 1 SN/s in Universe
  - ~ 1 SN/day discovered
  - ~ 4 SN/year up to 20Mpc
  - ~ 2 SN/century (?) in Milky Way
- ~ 20% of all SN are thermonuclear, Type Ia
  - ~ 80% of all SN are CCSN
- Optically observed supernovae <~25Mpc during O1-O2: SN 2015as, SN 2016B, SN 2016C, SN 2016X, SN 2017aym

Optically Observed CCSNe within 20 Mpc



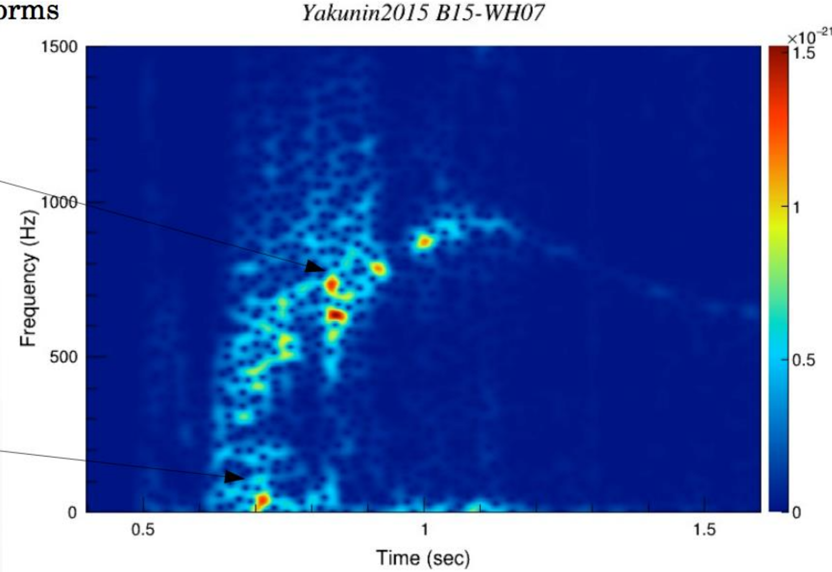
the calculation of the intrinsic CCSN rate within 20 Mpc was initiated at the "Multi-Messenger Observations and Studies of CCSNe" workshop at Urbino, Italy (G1500881)

K. Gill, MIT, 2017

- Broadband and long duration signal
- Strong high frequency component
- Non deterministic waveforms

Increasing with time peak frequency due to PNS g-mode oscillation

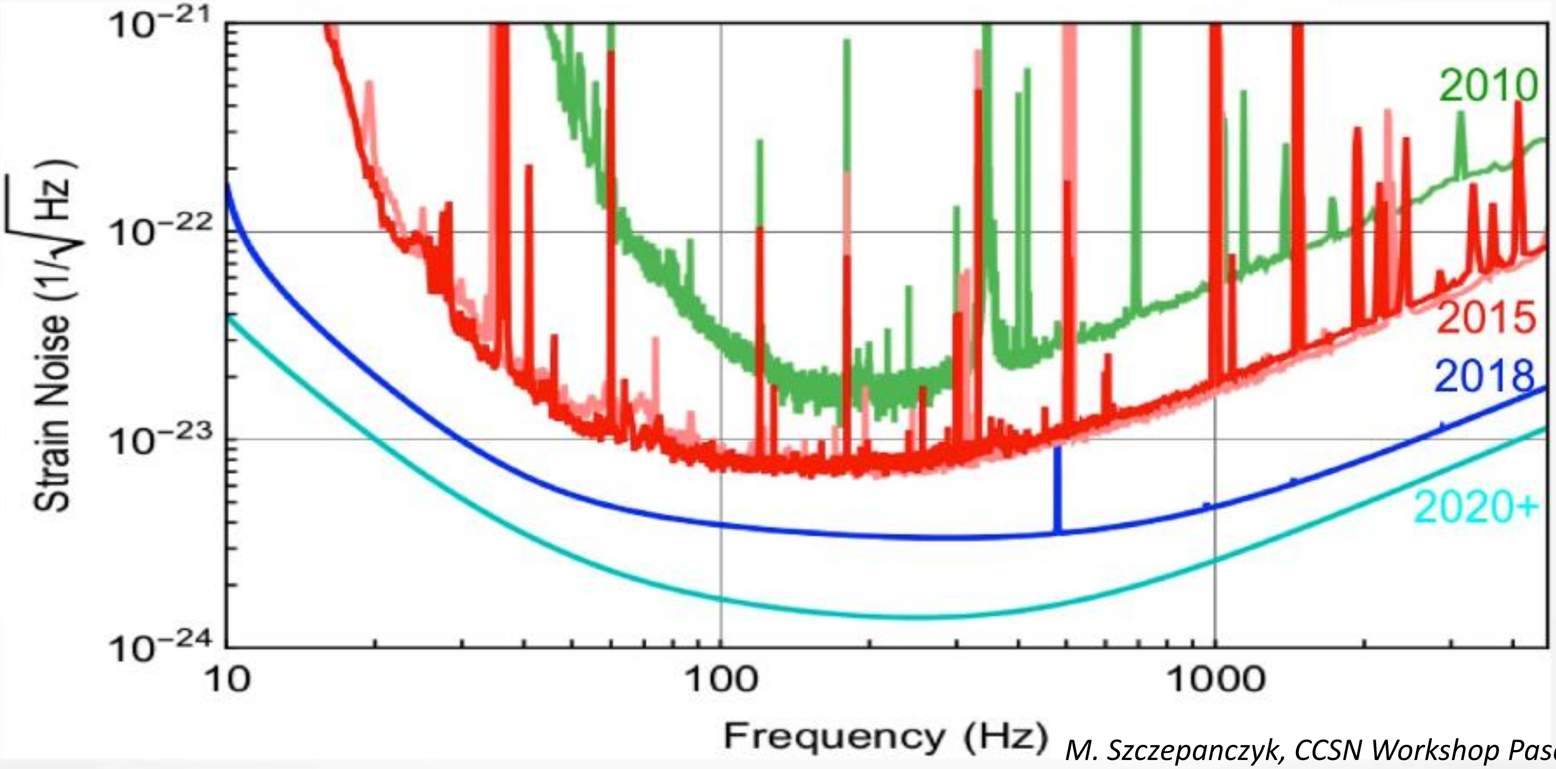
Low frequency sloshing mode instability, SASI



M. Szczepanczyk, CCSN Workshop Pasadena, 2017

Detector Sensitivity Evolution

- We already obtain a gain of a factor 4 around 500 Hz
- We hope to reach to a factor 10 @ 500 Hz in total at design sensitivity



M. Szczepanczyk, CCSN Workshop Pasadena, 2017

Current projects

- O1/O2 GW SN search
- SN Rate <20Mpc
- HRNR filter
- Distributional Tests
- Low Energy Neutrino Triggered search
- BayesWave follow up
- SMEE on real noise triggers
- On-Source/Off-Source Window
- SN Hardware Injections
- SNEWS alerts
- SN waveform reconstruction comparison
- Impact of HF environmental noise on SMEE classification
- SN science case for 3G detectors
- SN simulations and waveforms
- Approximations for GW detectors in HF
- Search for disappearing red giants
- Exploring Machine Learning
- SN waveforms matched filtering

- SN Detector characterization
- Single detector case

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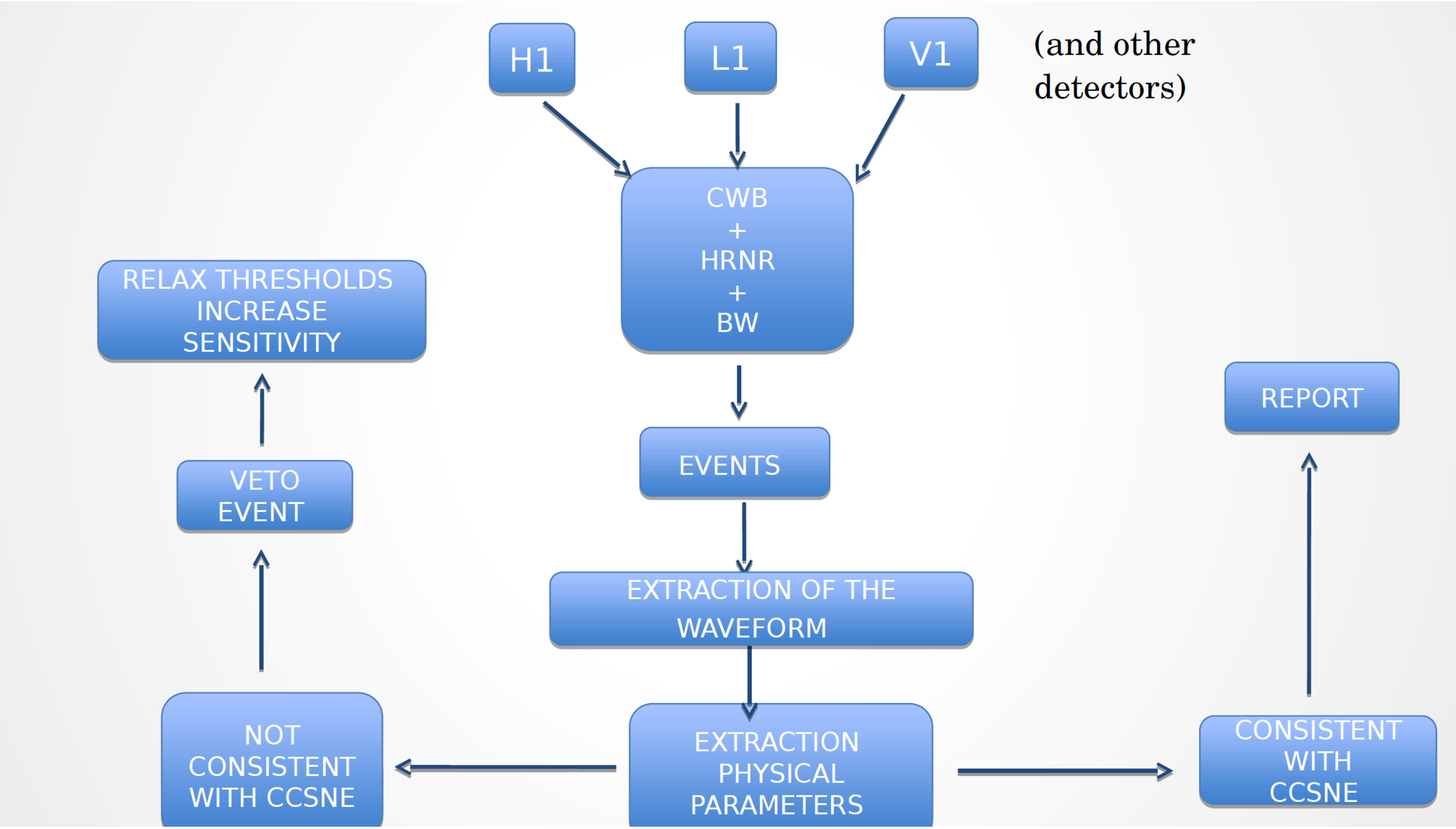
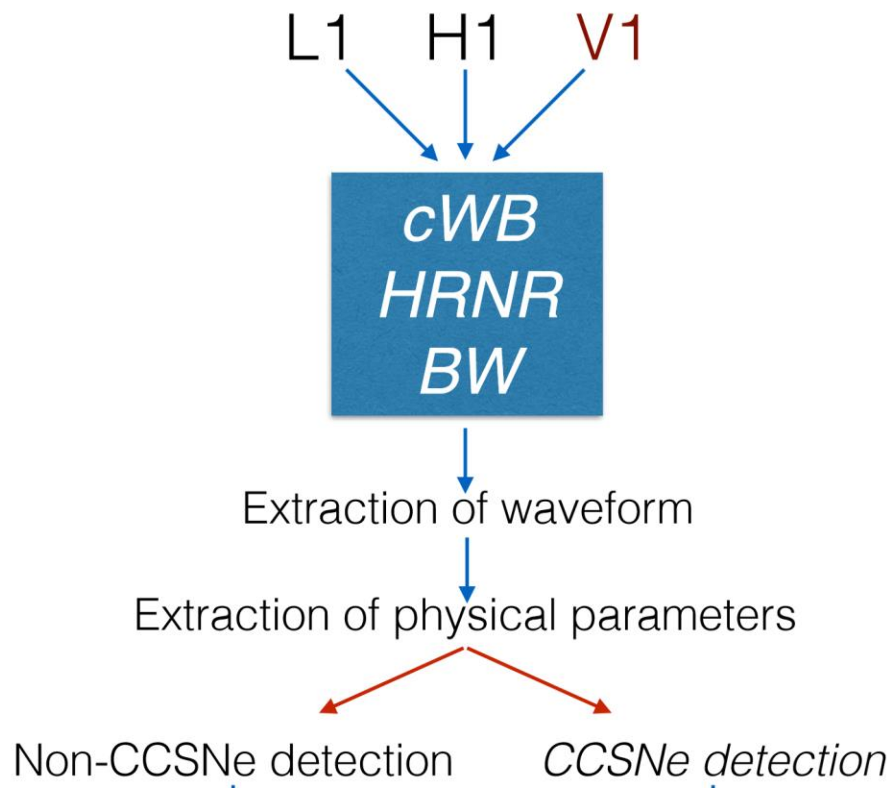
Detection and Parameter Estimation



M. Szczepanczyk, NRmGW Workshop, Valencia2017

Outlook of Current Searches



- *Coherent WaveBurst (cWB)*
- *Supernova Model Evidence Extractor (SMEE)*
- *BayesWave (BW)*
- *Two-Step De-noising (TSD) Filter*

Also,

- *Single IFO*
- *Matched Filtering*

K. Gill et. al., CCSN Workshop Pasadena, 2017

- ***Coherent WaveBurst (cWB)***
- *Supernova Model Evidence Extractor (SMEE)*
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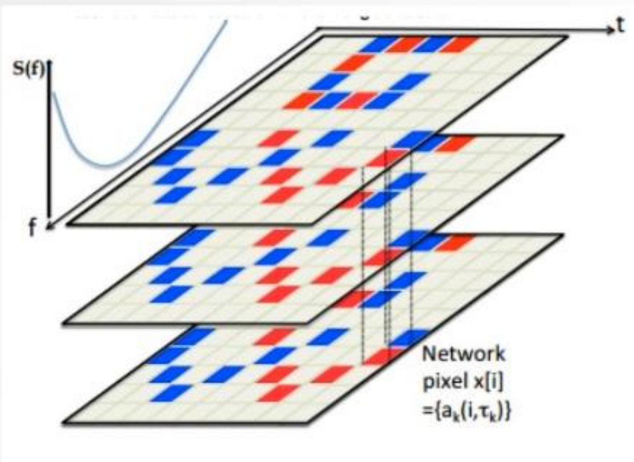
Coherent analysis - combines data from the detector network into a unique list of "triggers"

K. Gill et. al., CCSN Workshop Pasadena, 2017

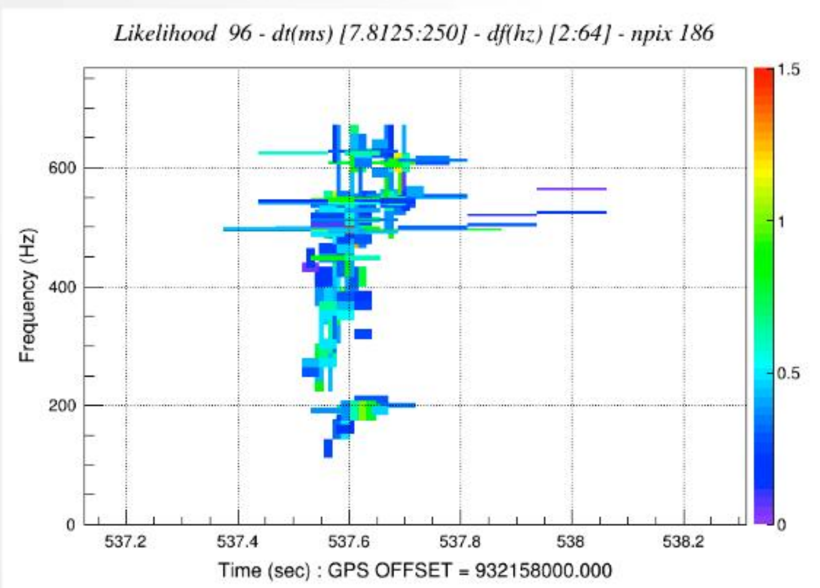
Burst Searches: Excess Power Method
(Coherent Wave Burst: *Klimenko et. al.* 2005)



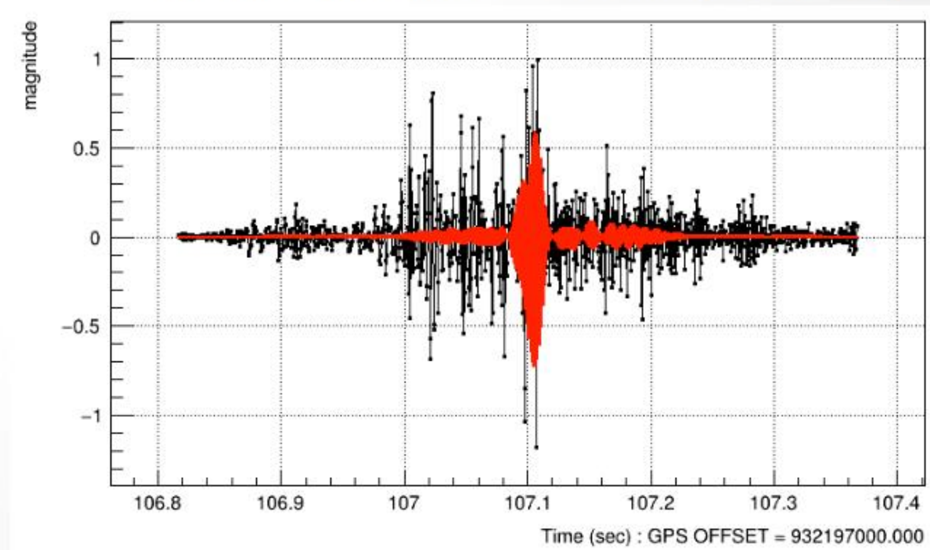
x(t) — Wavelet Transform →

- Time-Frequency decomposition
- Cluster selection, based on black pixel probability
- Constrained Likelihood

— Inverse Wavelet Transform → h(t)



Injected (black) vs reconstructed (red)



Methodology for assessing statistical significance of GW trigger associated with SN: Bayes Wave

Goal for LVC-SN Searches: reduction of the false alarm rate produced by cWB in order to improve the ROC curve for GW detection

Procedure

1) cWB outputs a *'ranking statistic'* that is used to *separate the background noise from the injected triggers*
2) All surviving triggers that are above the nominal value of the ranking statistic are then *post-processed through BW*
3) BW initially produces results using a scatterplot that differentiates between *glitches, noise, and signals* present in the data
4) This secondary classification is applied to the cWB ROC curve in hopes of *improving the false alarm rate - and essentially the detection efficiency of each waveform family*

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- *Coherent WaveBurst (cWB)*
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reconstruct the signal waveform using basis functions from the GW detector output & estimate appropriate parameters of the waveform (such as central time and frequency, signal duration and bandwidth)

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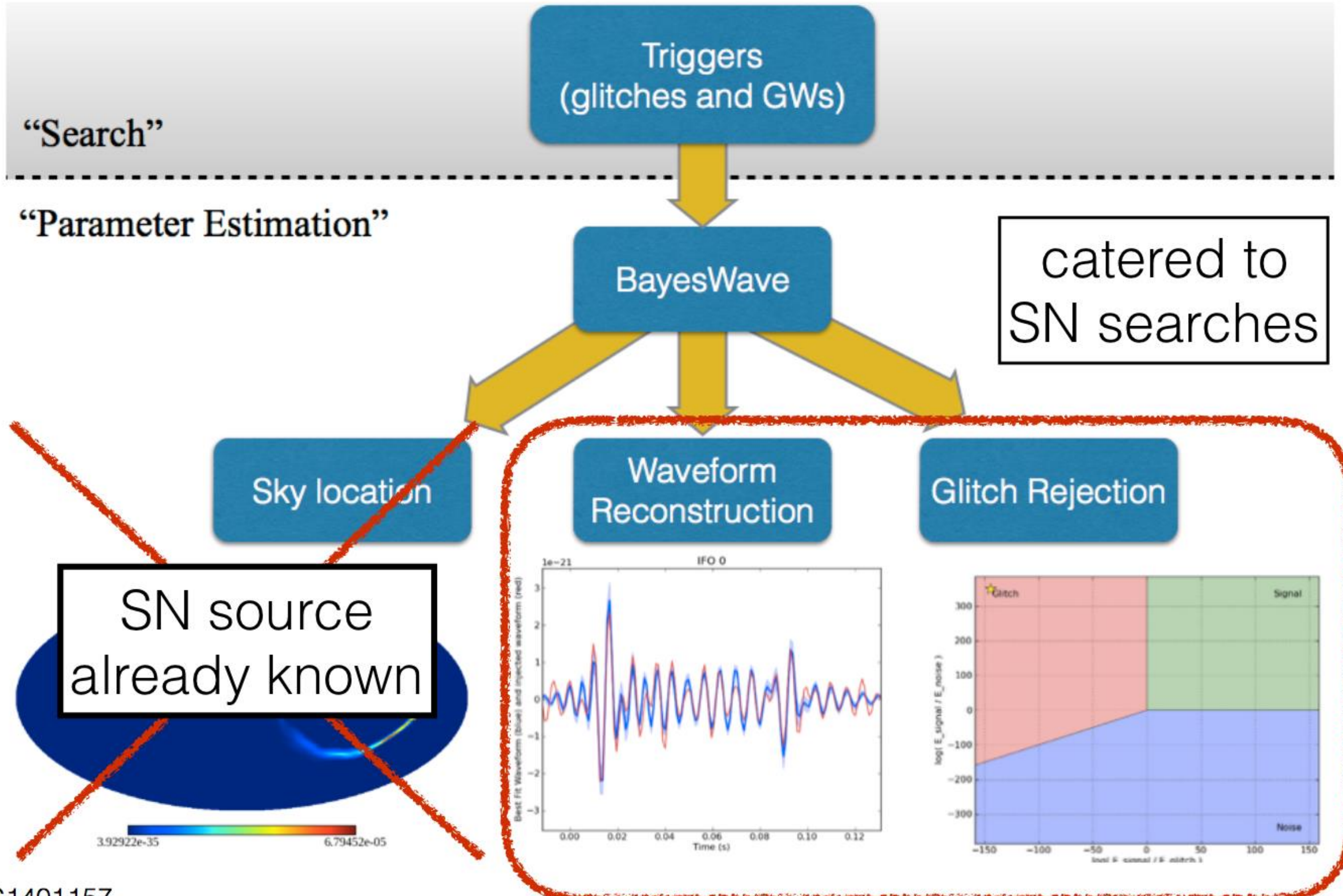
BayesWave Breakdown



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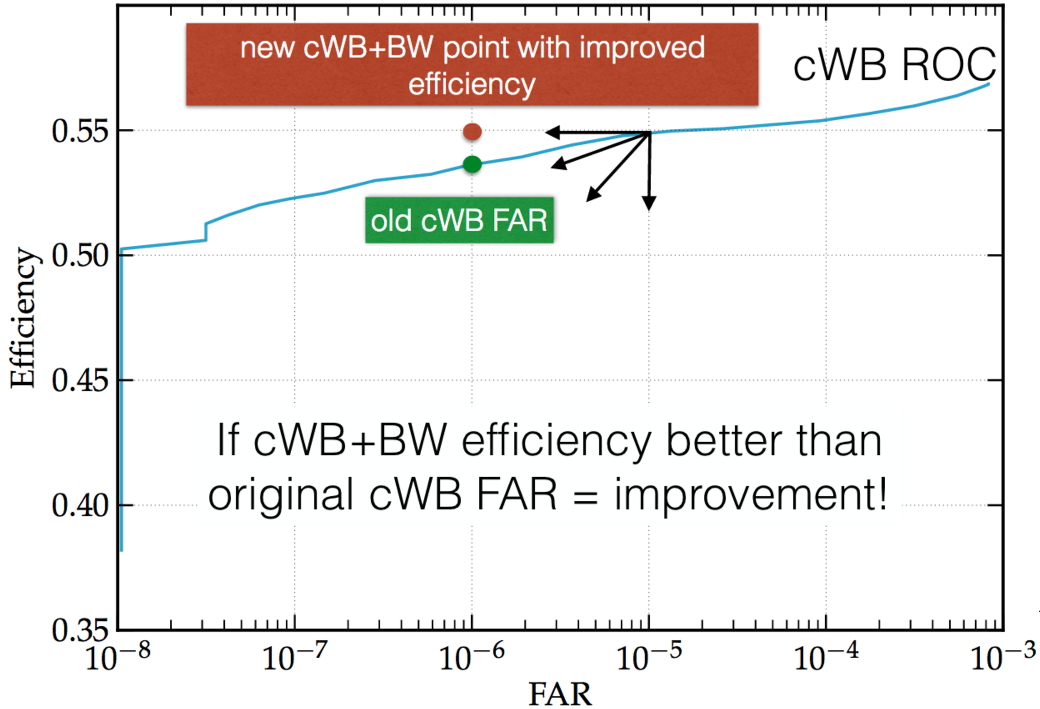
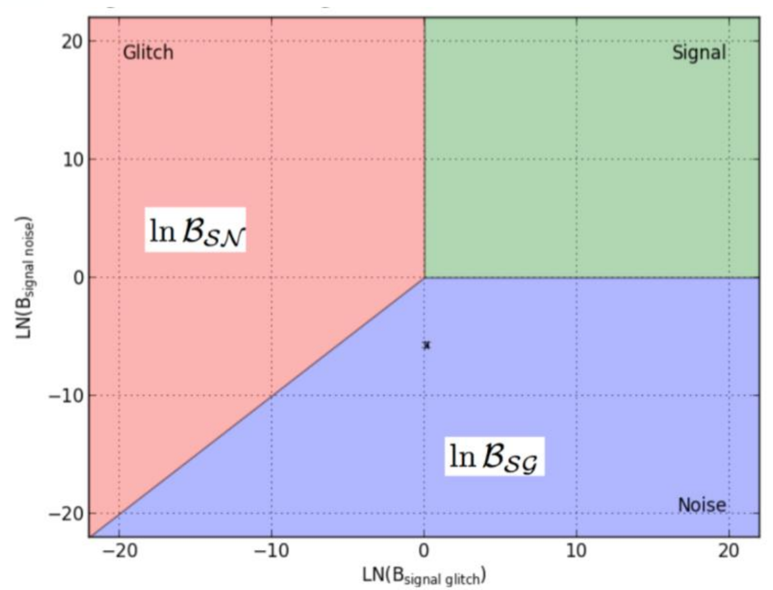
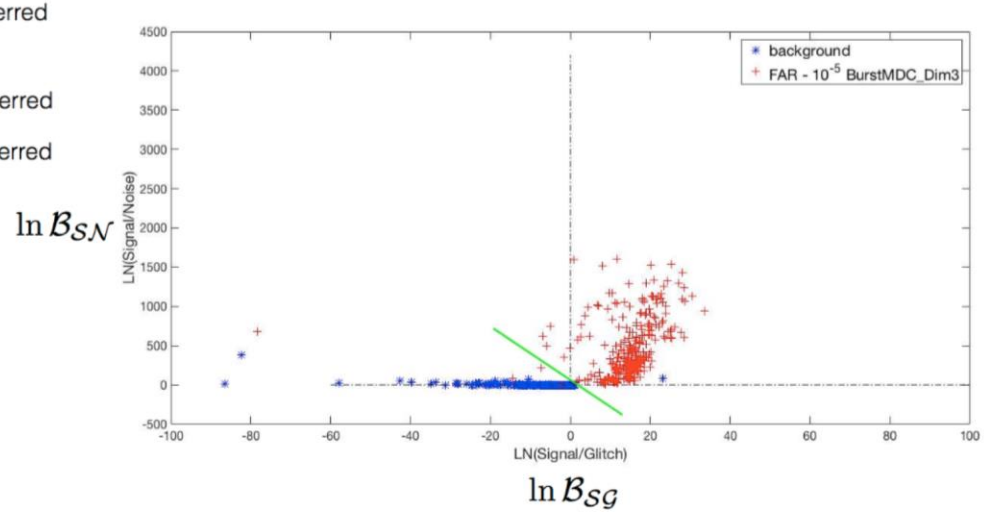




The ratio of evidences gives the **Bayes factor**

Signal-to-glitch Bayes factor: $\ln \mathcal{B}_{\mathcal{SG}} > 0 \implies$ Signal model is preferred
$\ln \mathcal{B}_{\mathcal{SG}} < 0 \implies$ Glitch model is preferred

Signal-to-noise Bayes factor: $\ln \mathcal{B}_{\mathcal{SN}} > 0 \implies$ Signal model is preferred
$\ln \mathcal{B}_{\mathcal{SN}} < 0 \implies$ Noise model is preferred



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Waveforms Used

Rotating Core-Collapse

Scheidegger+10

sch1: R1E1CA_L_thetaX.XXX_phiX.XXX
sch2: R3E1AC_L_thetaX.XXX_phiX.XXX
sch3: R4E1FC_L_thetaX.XXX_phiX.XXX

Dimmelmeier+08

dim1: signal_s15a2o05_ls
dim2: signal_s15a2o09_ls
dim3: signal_s15a3o15_ls

Neutrino-driven Explosion

Mueller+12

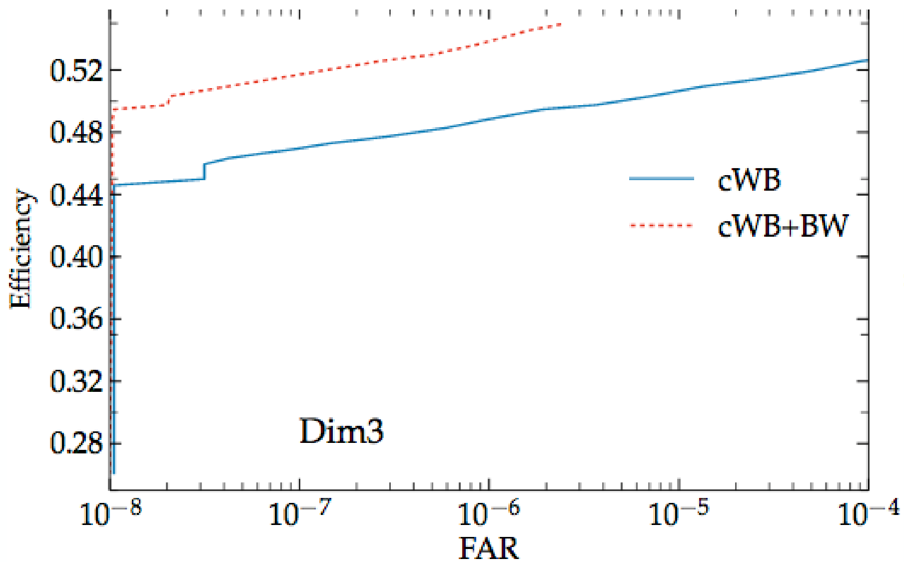
mul1: L153_thetaX.XXX_phiX.XXX
mul2: N202_thetaX.XXX_phiX.XXX
mul3: W154_thetaX.XXX_phiX.XXX

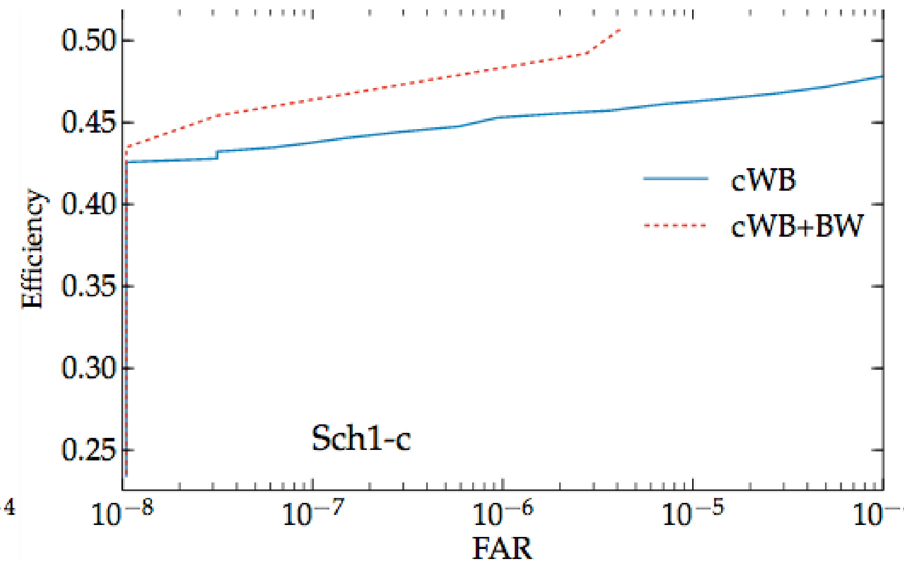
Ott+13

ott1: s27fheat1p05_thetaX.XXX_phiX.XXX

Yakunin+15

yak1: B12WH07
yak2: B15WH07
yak3: B20WH07
yak4: B25WH07





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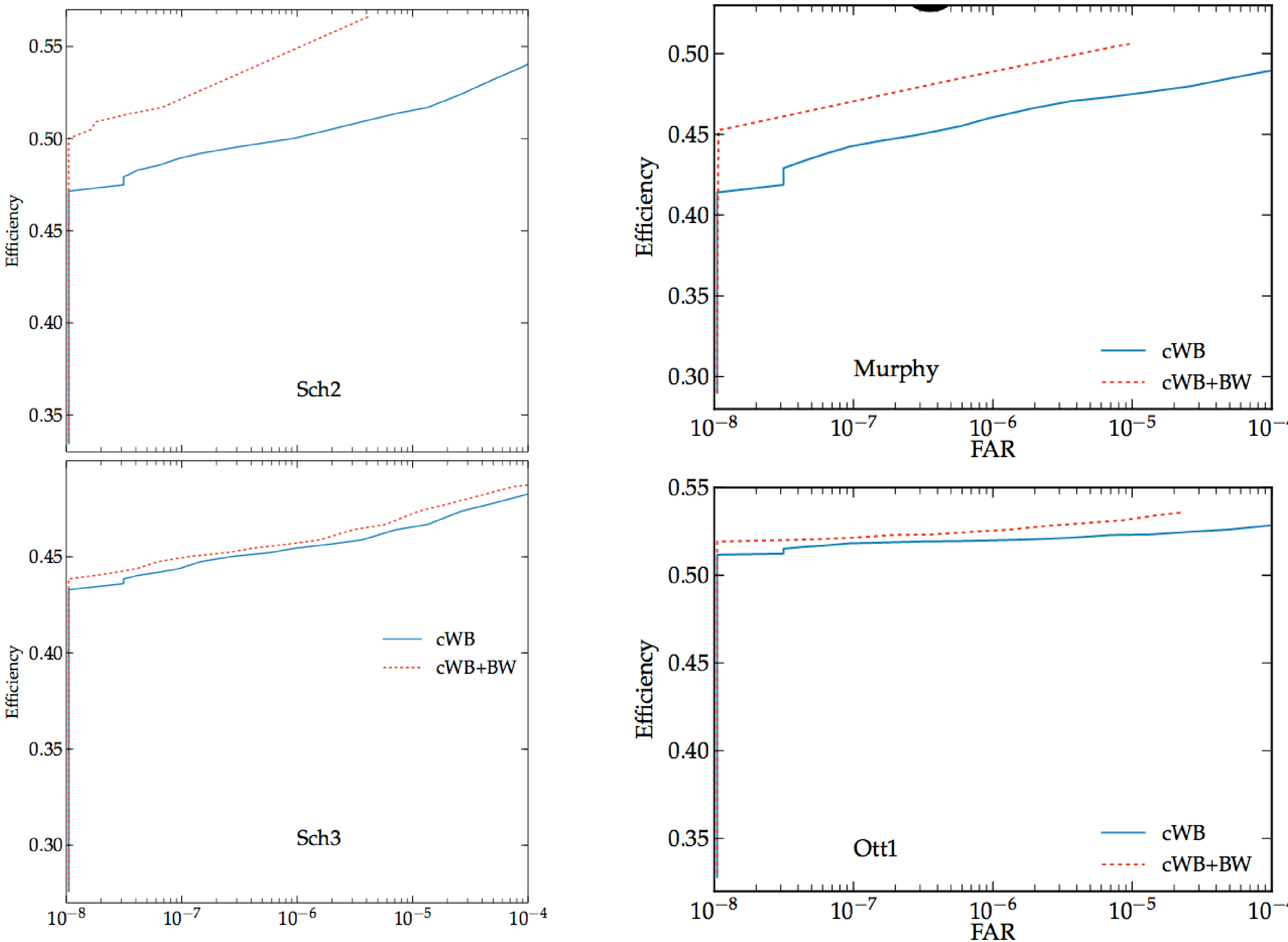

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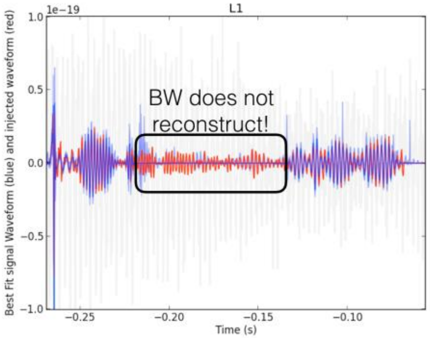
cWB+BW ROC Improvement

Waveform	FAR	cWB+BW
sch1-wf12	10^{-6}	**13.184% increase**
sch2	10^{-6}	**10.243% increase**
sch3	10^{-6}	**1.1643% increase**
dim1	10^{-6}	**4.522% increase**
dim2	10^{-6}	**3.062% increase**
dim3	10^{-6}	**10.434% increase**
murphy	10^{-6}	**12.412% increase**
ott1	10^{-6}	**1.193% increase**



Current CCSNe-focused BW Testing

List of Priors to be modified:

- Sky Location **(Done)**
- Glitch SNR **(currently being tested with Tyson)**
- Signal SNR **(Done)**
- Number of wavelets **(currently being tested)**
- Waveform Type **(Done)**
- Clustering **(currently being tested)**

The quest to maximize the estimation of appropriate parameters of the waveforms of interest

Priors	IMBH	Rapidly Rotating CCSNe
Sky Location (θ, ϕ)	Uniformly Distributed (All-Sky)	Specific to direction of CCSN
Glitch SNR	$p(\mathrm{SNR}) = \frac{\mathrm{SNR}}{\mathrm{SNR}_*^2} e^{-\mathrm{SNR}/\mathrm{SNR}_*^2}$	$p(\mathrm{SNR}) = \frac{\mathrm{SNR}}{\mathrm{a}} e^{-\mathrm{SNR}/\mathrm{b}}$
Wavelets	Ns [1, 100]; Ng [1, 100]*Nd	Adjust to number of wavelets needed to reconstruct CCSN waveform
Waveform Type	[10, 500] $M_\odot$ 0.4 s	s15a3o15 55 ms

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- *Coherent WaveBurst (cWB)*
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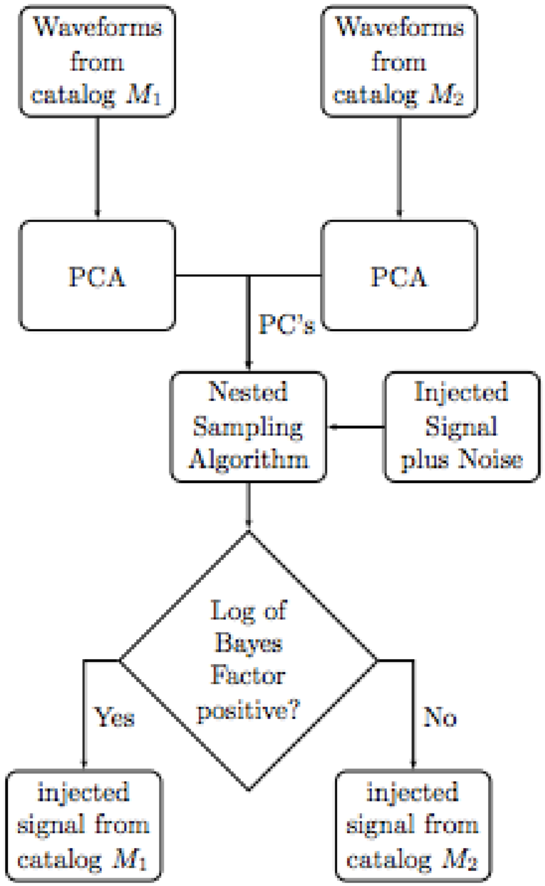
determines the explosion mechanism of a CCSN GW detection using Principal Component Analysis (PCA)



- Logue, Ott, Heng, Kalmus, Scargill (2012) arXiv:1202.3256
  - One detector study Gaussian noise
- Powell, Gossan, Logue, Heng (2016) arXiv:1610.05573
  - Three detectors, non-Gaussian non-stationary noise
- Powell, Heng (In prep)
  - Distinguishing CCSNe from other astrophysical and noise gravitational-wave transients.

[1] Jade Powell

Inferring Core-Collapse Supernova Physics with Gravitational Waves
Authors: J. Logue, C. D. Ott, I. S. Heng, P. Kalmus, J. Scargill
arXiv:1202.3256 [gr-qc]

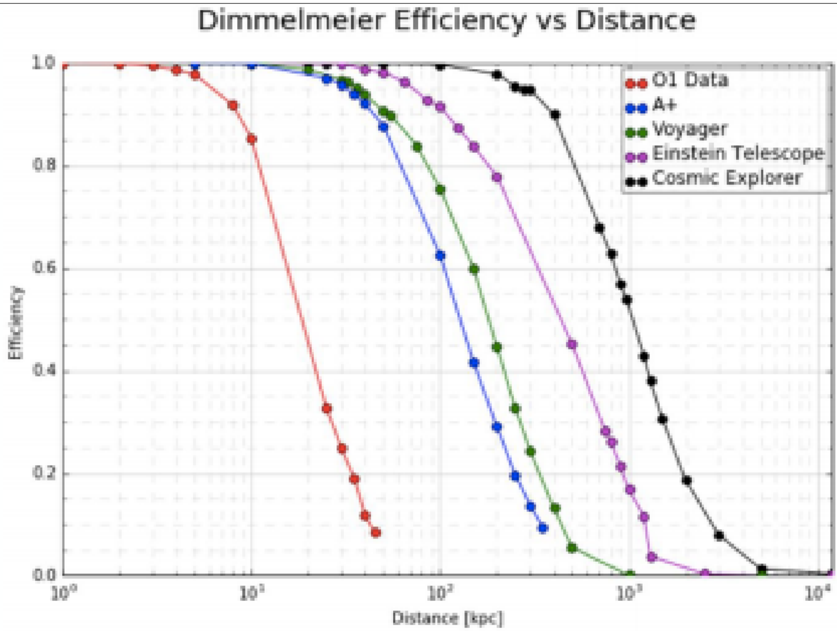
Inferring the core-collapse supernova explosion mechanism with gravitational waves
Authors: Jade Powell, Sarah E. Gossan, Joshua Logue, Ik Siong Heng
Phys. Rev. D 94, 123012 (2016)

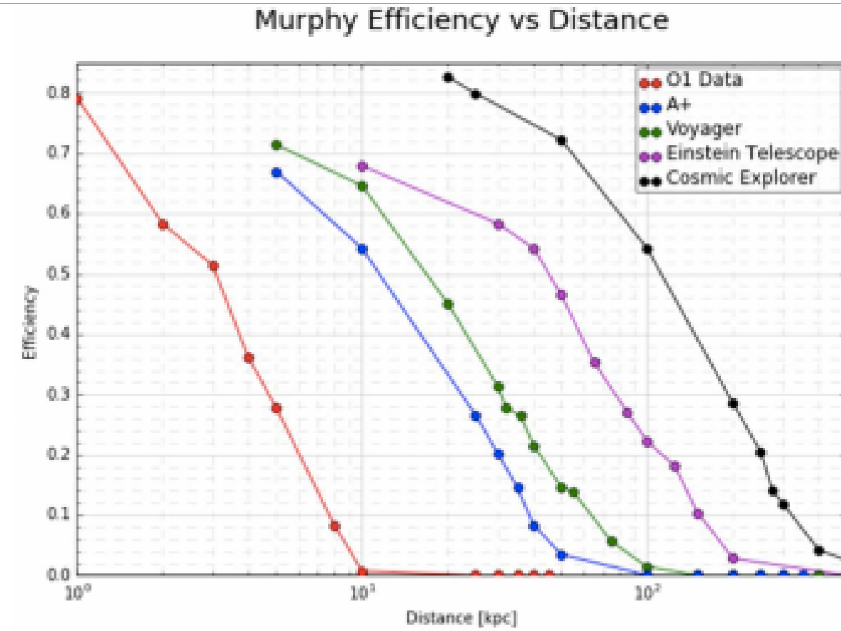
To test SMEE's CCSN waveform classification performance in future detectors 3 days of O1 data were recolored to each detector's estimated sensitivity curve

Two sets of principal components: Dimmelmeier and Murphy

Each waveform injected at *10 different times over a 24 hour period* to explore entire antenna pattern. 1440 total injections.

Injected 16 waveforms from the Murphy catalog (neutrino mechanism) and 128 waveforms from the Dimmelmeier





Magnetorotational Maximum Distances

A+: ~ 325 kpc
Voyager: ~ 450 kpc
Einstein Telescope: ~ 1200 kpc
Cosmic Explorer: > 2500 kpc

Neutrino Maximum Distances

A+: ~ 32 kpc
Voyager: ~ 51 kpc
Einstein Telescope: ~ 115 kpc
Cosmic Explorer: ~ 240 kpc

S. Gossan, CCSN Workshop, Pasadena, 2017
Figure credits: Jade Powell, Vincent Romo

- *Coherent WaveBurst (cWB)*
- *Supernova Model Evidence Extractor (SMEE)*
- *BayesWave (BW)*
- ***Two-Step De-noising (TSD) Filter***

calculating an estimator of the signal spectral density from the noisy observations s.t. the expectation value of the distortion between the true signal and its estimate is minimized before it enters the search pipeline

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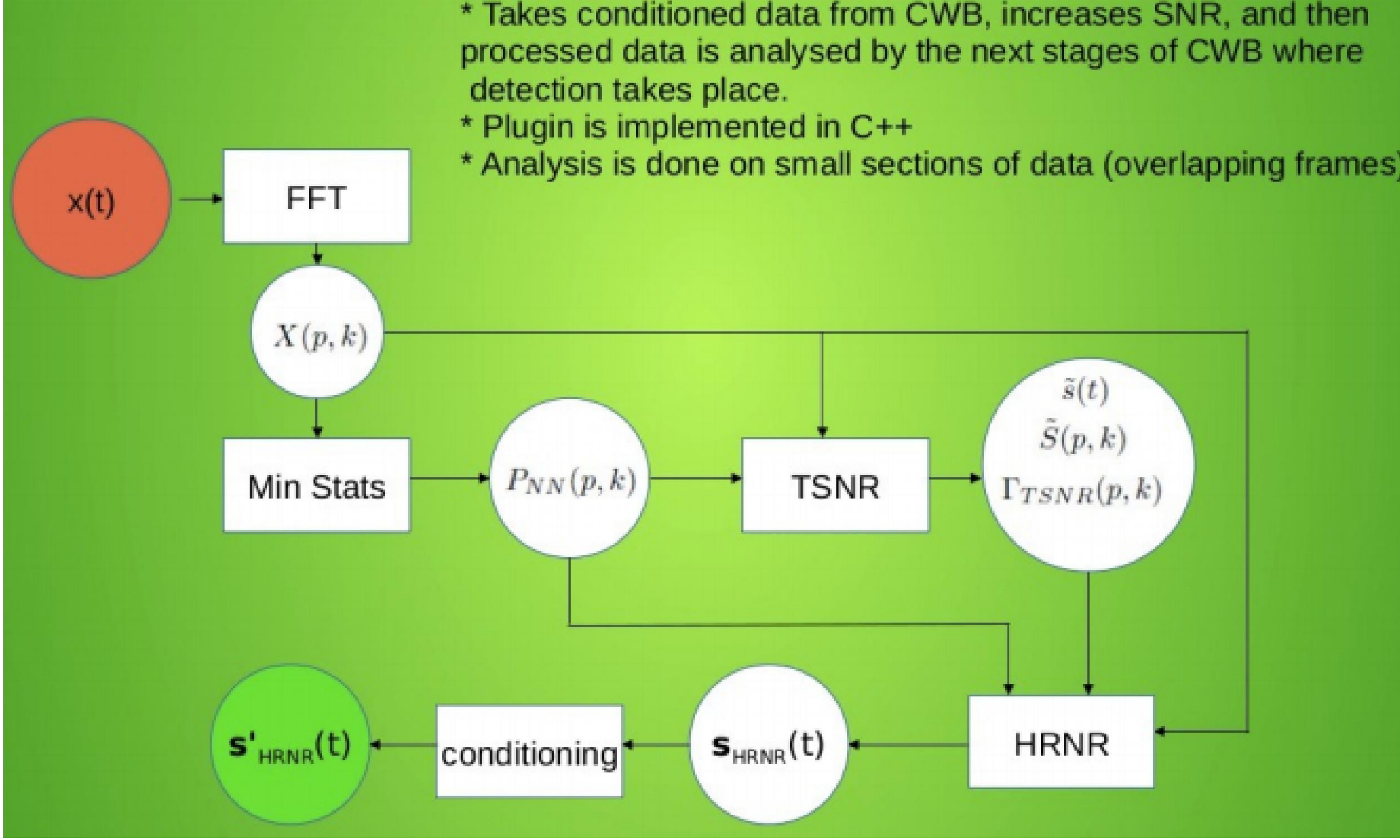


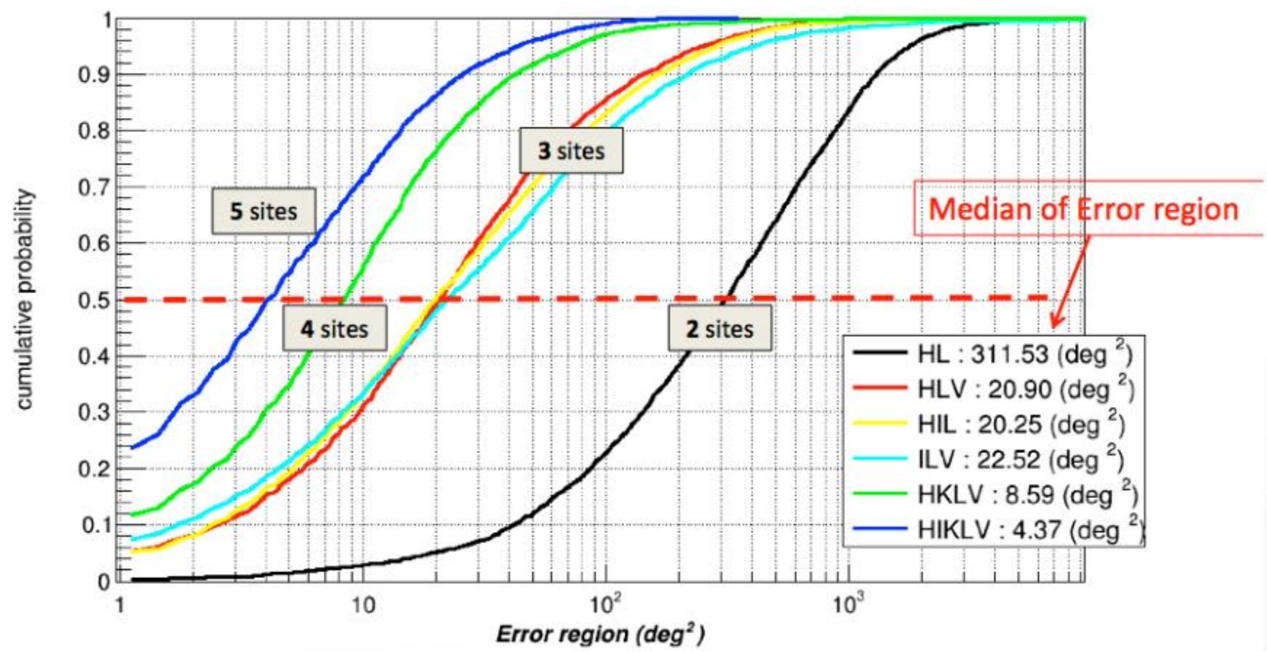
Slide: O. Valdez

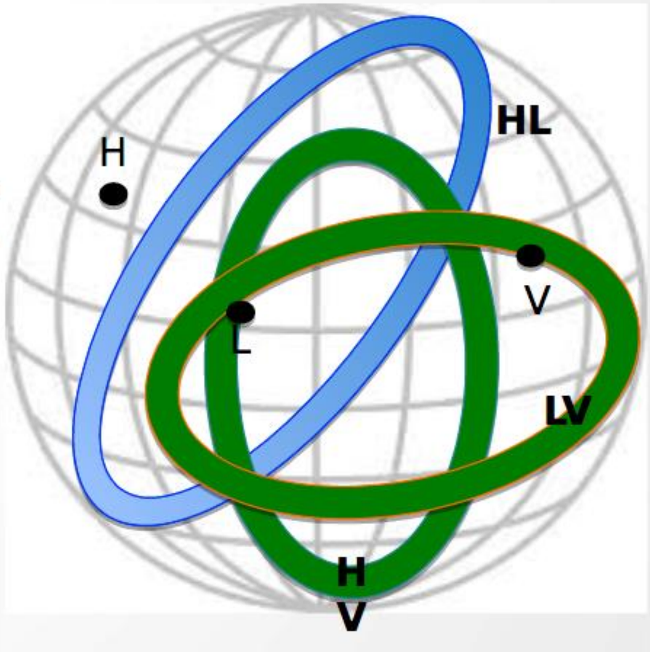
Emission type	Identifier	FAR [Hz]	Eff cWB	Eff cWB+TSD	Eff increment
Magnetorotationally driven explosion	dim1	1.0e-6	33.7%	41.7%	8.0%
		1.0e-5	34.4%	42.4%	8.0%
		1.0e-4	35.3%	43.0%	7.7%
	dim2	1.0e-6	45.4%	50.7%	5.3%
		1.0e-5	45.9%	51.2%	5.3%
		1.0e-4	46.1%	51.7%	5.6%
	dim3	1.0e-6	63.1%	71.6%	8.5%
		1.0e-5	63.4%	72.1%	8.8%
		1.0e-4	63.9%	72.1%	8.2%
Neutrino driven explosion	murpy	1.0e-6	42.0%	46.0%	9.5%
		1.0e-5	46.5%	52.5%	12.9%
		1.0e-4	53.5%	60.0%	12.1%
	ott	1.0e-6	41.1%	46.7%	5.6%
		1.0e-5	41.6%	46.9%	5.3%
		1.0e-4	42.4%	47.5%	5.0%

Results from: Mukherjee, Valdez et. Al. 2017

Triggered Burst Searches

- On-source window – period that we think contains GW, derived from optical or neutrino observations. Timescales:
  - Neutrino triggered search, seconds to minutes
  - Optically triggered search, hours to few days
- Sky location – usage of skymask
- Distance – used currently to constrain the models





M. Szczepanczyk, CCSN Workshop Pasadena, 2017

Can we claim a Supernova detection with one interferometer?

Sergio Gaudio, Marek Szczepanczyk, Kai Staats, Sergey Klimenko,
Gabriele Vedovato, Marco Cavaglia, Michele Zanolin

Material available at https://wiki.ligo.org/Bursts/SNcwbSDCtests

Motivation and method

We could have only one detector on line when we have the next galactic Supernova:

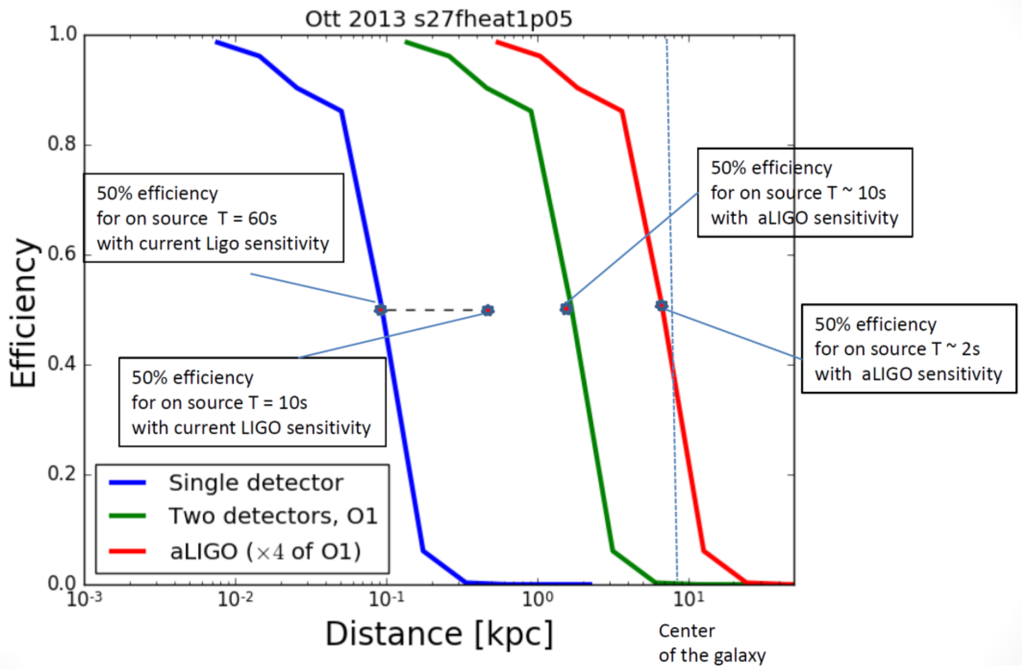
In O1, we had ~40%, single IFO collecting the data

coherent Wave Burst (cWB) single interferometer approach: perform a two-interferometer search where one data set is the exact copy of the other (it is a trick, but a legal one since we can still produce bona-fide Receiver operating curves).

In the standard two interferometers analysis the background events are derived with time lags. In the single interferometer case the background comes from the zero lag analysis with off source data, because statistical properties of the zero lag noise events are expected to be different than those from time lags.

https://na01.safelinks.protection.outlook.com/?url=https:%2F%2Femvogil-3.mit.edu%2F~kats%2Fsn2017%2Ftalk_SN_Ligo_workshop_3172017_f.pdf&data=02%7C01%7Csoma.mukherjee%40utrgv.edu%7C3ba8468459754d665ac708d4c8284668%7C990436a687df491c91249afa91f88827%7C0%7C1%7C636353522806147279&sdata=Qm0vVZQlTz6SUBDBGjjD24q1CYaGSHzMWkEvU0W1%2BEk%3D&reserved=0

Calculated in the case of FAP = 0.0027: preliminary result



- even for the most energetic realistic emission model (among the representative pool currently adopted for O1/O2), a galactic center detection with a 3σ confidence is out of reach for the single IFO case with the current implementation of cWB.

- next steps of this work:
  1) test benefits of including physical features of the SN GWs in the search algorithm;
  2) develop single IFO specific data quality flags;
  3) explore Machine Learning (ML)

https://na01.safelinks.protection.outlook.com/?url=https:%2F%2Femvogil-3.mit.edu%2F~kats%2Fsn2017%2Ftalk_SN_Ligo_workshop_3172017_f.pdf&data=02%7C01%7Csoma.mukherjee%40utrgv.edu%7C3ba8468459754d665ac708d4c8284668%7C990436a687df491c91249afa91f88827%7C0%7C1%7C636353522806147279&sdata=Qm0vVZQlTz6SUBDBGjjD24q1CYaGSHzMWkEvU0W1%2BEk%3D&reserved=0

Comparison of performance of matched filter and excess power toy models on Supernova waveforms

The University of Texas Rio Grande Valley
EMBRY-RIDDLE Aeronautical University PRESCOTT, ARIZONA

Satzhan Sitmukhambetov, Soma Mukherjee, Marek Szczepanczyk, and Michele Zanolin

Department of Physics and Astronomy at The University of Texas at Rio Grande Valley, One West University Boulevard, Brownsville, Texas, 78520

LIGO VIRGO

Abstract

In this poster, we compare the receiver operating curves and efficiency curves for toy model implementations of matched filtering and excess power detection approaches, in the case of Core Collapse Supernovae waveforms and publicly released LIGO data. We also address the degradation of the performance with the template mismatch to be expected from the stochastic nature of the SN signals and the foreseeable small pool of templates available in the nearby future. The implications for possible future usages of Matched filtering in Supernova searches as well as improvements of existing burst methodologies are discussed.

Method

The toy models of matched filter and excess power are Matlab codes. Toy model of matched filter consists of cross-correlation in time domain between LIGO data stream with injections and waveform templates. Cross-correlation defined as such: $A(k) = |\sum_{j=1}^{L} a(j+k) * w(j)|$ (cross correlation output), where 'L', 'w', and 'a' are length of the waveform template, normalized waveform template, and whitened data stream from L1 or H1 (Livingstone and Hanford interferometers). Whole analysis has been done purely in time domain with 4096 sampling frequency. Similar idea has been used for toy model of excess power: $B(k) = |\sum_{i=k}^{k+D} L1(i) * H1(i)|$ (excess power output), where L1 and H1 are data streams with simultaneous injections and 'D' is duration window for correlating two detectors. Waveforms were used are short duration Sine Gaussian and Yakunin 2015 waveforms.

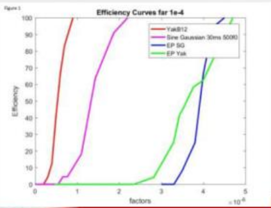
Procedure

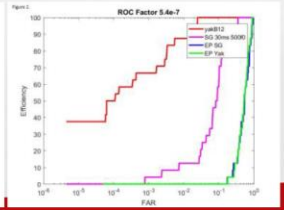
Test statistic is first applied to data without injections to estimate noise distribution, which is used to calculate false alarm rates (FARs) for different thresholds. Next, set of waveform factors are chosen and for each factor we: inject waveforms with selected factor into data stream, applying test statistic, and for fixed FAR we calculate how many injections pass that threshold. This in turn should give us an estimate on how efficient method at finding injections of selected factors and we produce efficiency curve plot. Same procedure is applied for different methods, which in this presentation are toy model of excess power and matched filter. The fixed FAR for efficiency curves is relative to the noise distribution for the selected methods, so that it becomes

Another approach at comparing methods is to calculate receiver operating characteristic (ROC) curves. The idea is instead of fixing FAR is to fix injection factor and to check how each method manages to detect it. For different FARs efficiency is calculated and produced at the plot.

Discussion

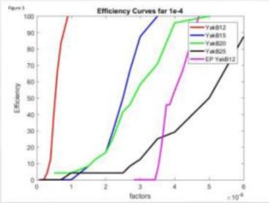
In this section, we will discuss plots obtained by implementing toy models of matched filter and excess power. We have used data from S6 about 4 min. The data is later resampled to 4096Hz, band passed between 40 to 2048Hz, and whitened. About 0.55s of YakuninB12 waveform is taken, resampled to 4096Hz, and normalized. 30ms normalized Sine Gaussian is produced with central frequency 500Hz and width 10. These two waveforms are used for the analysis in the plots on figure 1 and 2.

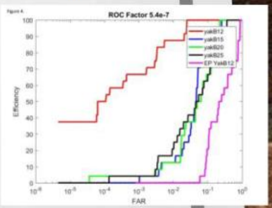




For the figure 1. If we look at the 50% efficiencies and check factors we obtain 5.3333e-07, 1.3310e-06, 3.9200e-06, 3.6033e-06 injection factors, from left to right respectively. The first two curves are produced by matched filter and next two by excess power. It can be seen from this plot that detection efficiency for YakuninB12 is higher than for Sine Gaussian with matched filter. However, the main reason for such difference can be length of waveform template and not the features of the template. On the figure 2, we can see rather dramatic difference if we look at 50% efficiencies: we get 8.1733e-05, 0.0859, 0.5432, 0.5226 FARs. For relatively low factor 5.4e-7 It can be said that excess power does not detect any injection. Rather suspicious difference of order of 3 (10^3), can be observed in the increase for the YakuninB12

On figure 3. we can see efficiency curves for matched filter by using Yakunin waveform templates with different progenitor masses as correlation templates. The actual injection we were looking for is YakuninB12. As it can be seen the more massive difference the worse the correlation – worse detection efficiency. However, the difference in masses is very big, where for actual matched filtering bank progenitor masses can be chosen with an extremely low difference. On figure 4, we observe ROC for the same procedure, but ROC is done for the very low injection factor. Apart from noticing that noise starts to dominate for the excess power method, very little is observed.





Conclusion

This toy model test indicates that for realistic CCSNe waveforms matched filtering can improve the range of detection almost by one order of magnitude at a fixed FAR. However, a mismatch between the template and the actual waveform can make the performance worse than the excess power. The next step is to check the degradation of the fitting factor between different waveforms of the same progenitor by randomizing the source orientation in 3-D models (which should be available in the next months).

Acknoledgements

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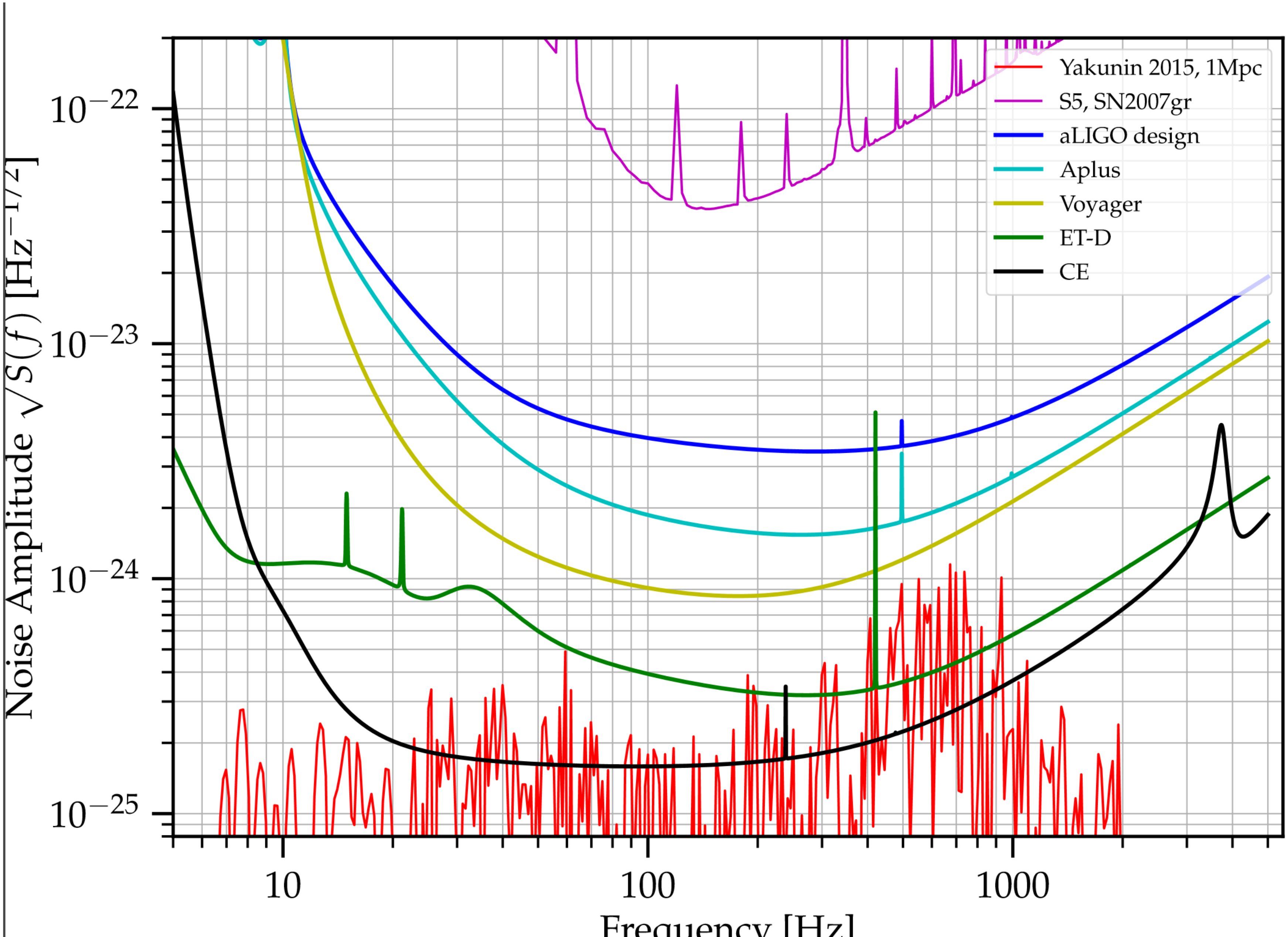
References

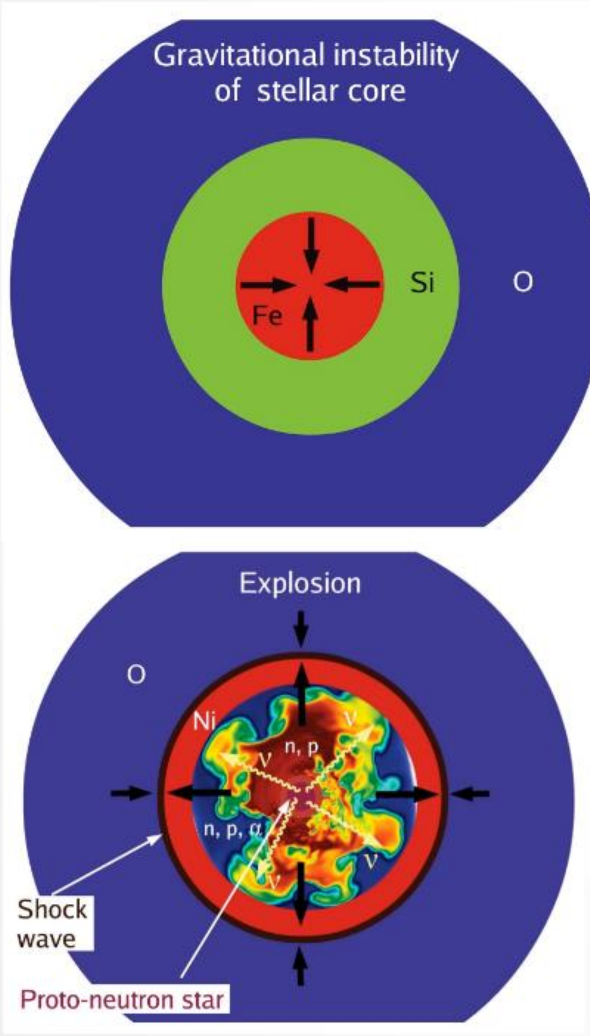
1. Yakunin et al. (2015) *Gravitational Wave Signatures of Ab Initio Two-Dimensional Core Collapse Supernova Explosion Models for 12-25 Solar Masses Stars.*



Credit: M. Szczepanczyk

Additional Material

Core Collapse Supernova Mechanism



Janka+12

- Burning of the star:
  H → He → … → Fe
- Before collapse: Fe core of size 1000-2000km

  After collapse: "nucleus" core of size 20-30km
- Energy available ~ 300B (1Bethe = 0.15 $M_{Sun}c^2$)

  Energy observed ~ 3-10B
- 99% of explosion energy escapes with neutrinos!

M. Szczepanczyk, CCSN Workshop Pasadena, 2017

Mechanisms of Explosion

- Direct Hydrodynamic Mechanism: always fails
- Neutrino-Driven Wind Mechanism, ~1D; Low-mass progenitors
- 2D Convection Neutrino-driven (circa 1995-2009)
  ("SASI" not a mechanism, but a shock instability)
- Neutrino-Driven Jet/Wind Mechanism, Rapidly rotating AIC of White Dwarf
- MHD/Rapid Rotation - "Hypernovae"?
- Acoustic Power/Core-oscillation Mechanism? (Aborted if neutrino mechanism works earlier; Weinberg & Quataert ?)
- 3D "Convection" Neutrino-driven Mechanism

Important Ingredients/Physics

- Progenitor Models (and initial perturbations?)
- Multi-D Hydrodynamics (3D)
- Multi-D Neutrino Transport (multi-D) (most challenging aspect)
- Instabilities - Neutrino-Driven Convection (+ SASI?)
- Neutrino Processes - Cross sections, emissivities, etc. (at high densities?)
- General Relativity (May & White; Schwartz; Bruenn et al.; Mueller et al.; Kotake et al.)
- Rotation!