CCSNe Algorithmic Developments for the Advanced LIGO Observation Era

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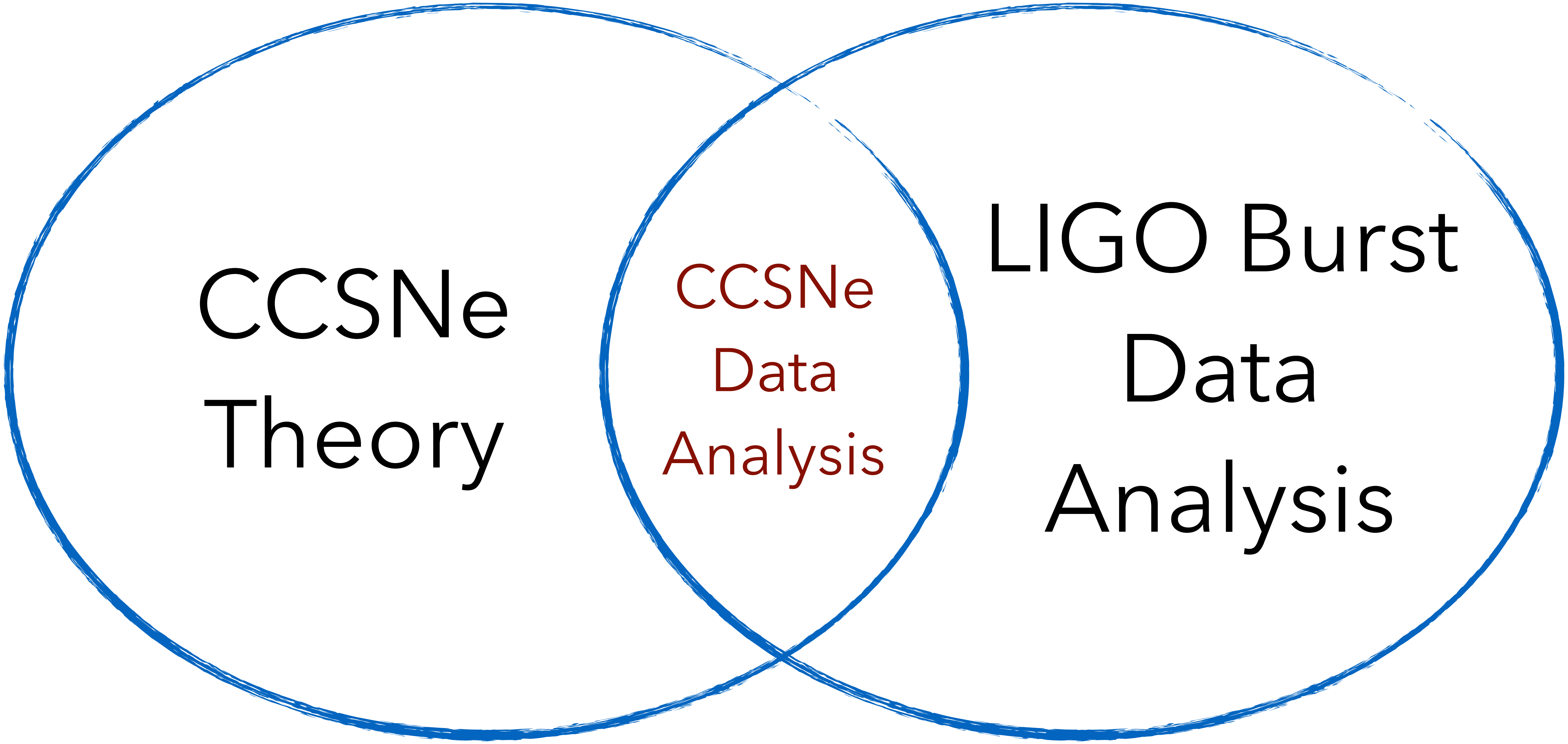
Internal/External Collaboration



O1/O2 Search Pool of Waveforms

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

O1/O2 Search Pool of Waveforms

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

Outlook of Current Searches

L1 H1 V1

cWB
HRNR
BW

Extraction of waveform

Extraction of physical parameters

Non-CCSNe detection

Veto event

Relax pipeline thresholds to increase sensitivity

CCSNe detection

Report & perform follow-up

Outlook of Current Searches

L1 H1 V1

Set priors in pipelines based on robust features present in waveform families
(slowly rotating/RR/non-rotating)

cWB
HRNR
BW

Tune the pipelines to the waveforms that explore the parameter space of the progenitors.

Extraction of waveform

Extraction of physical parameters

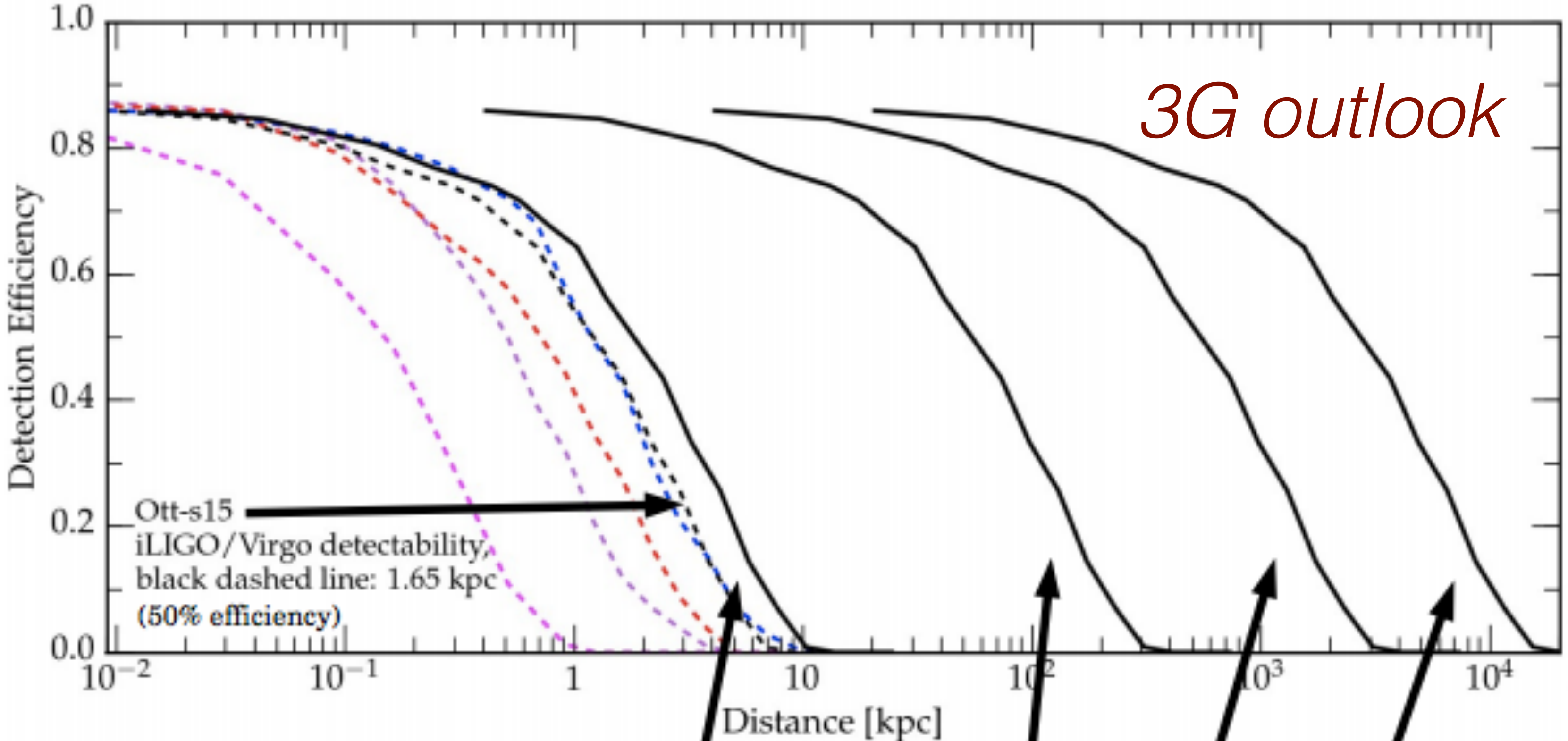
Non-CCSNe detection | *CCSNe detection*

Veto event | *Report & perform follow-up*

Relax pipeline thresholds to increase sensitivity

Outlook of Current and Future Searches

From iLIGO/Virgo SN search, PRD 94, 102001 (2016):



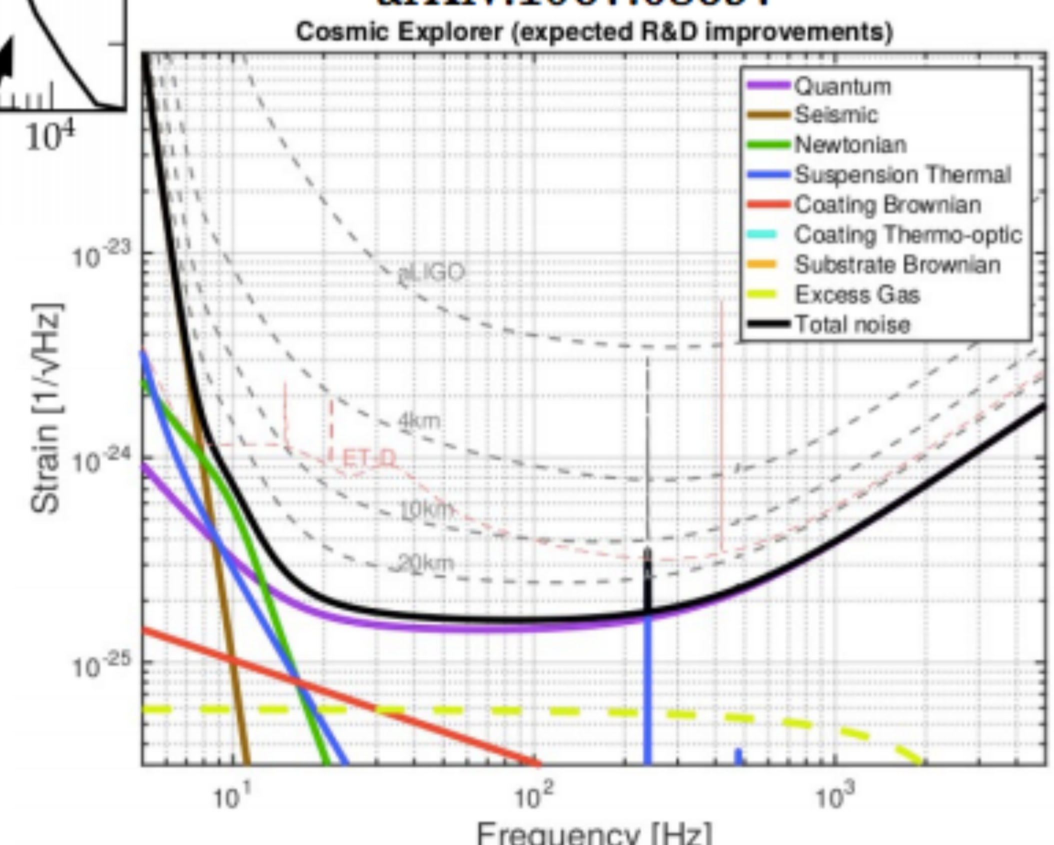
Improvements:

- x1.5 (algorithm + BW+ denoising)
- x30 (advanced LIGO design sensitivity)
- x10 (vanilla 3rd generation improvement)
- x5 counting techniques and distributional methods

Can we achieve sensitivity to reach 1SN/year rate?

1SN/year → ~13Mpc
4SN/year → ~20Mpc

arXiv:1067.08697



For more details, please refer to 3G panel-specific slides!

Current Internal LVC Algorithms used for SN Searches

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

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Coherent analysis - combines data from the detector network into a unique list of "triggers"

(will be covered by Sergey & Marek)

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determines the explosion mechanism of a CCSN GW detection using Principal Component Analysis (PCA)

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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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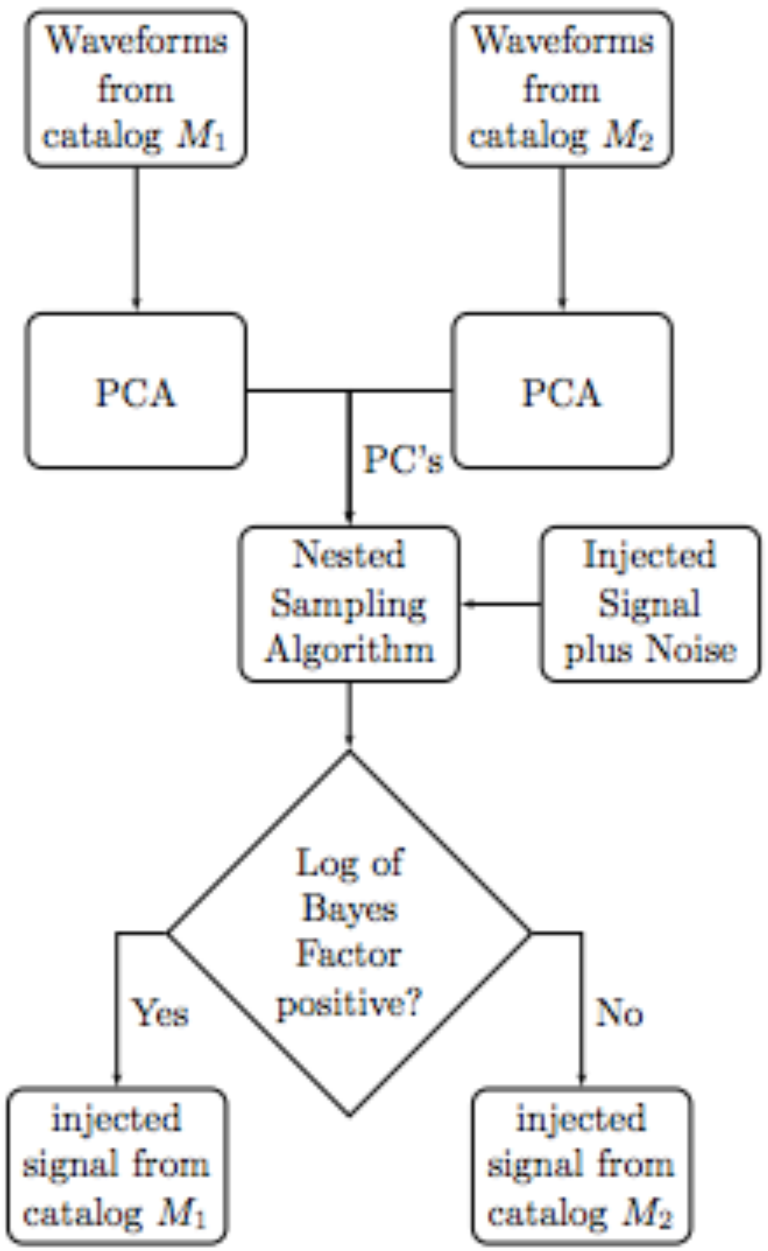
- ***Two-Step De-noising (TSD) Filter***

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

Supernova Model Evidence Extractor (SMEE)



- 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

Supernova Model Evidence Extractor (SMEE)

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

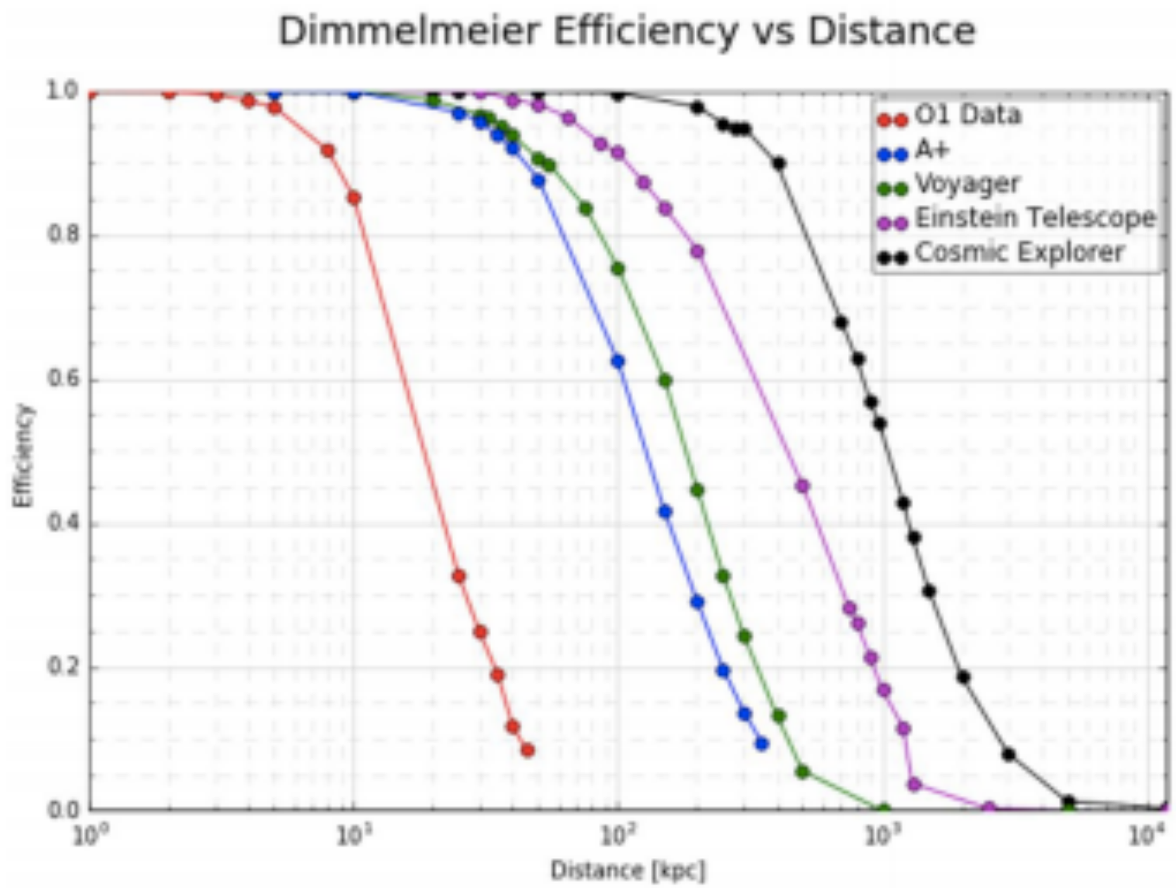
Two sets of principal components: Dimmelmeier and Murphy

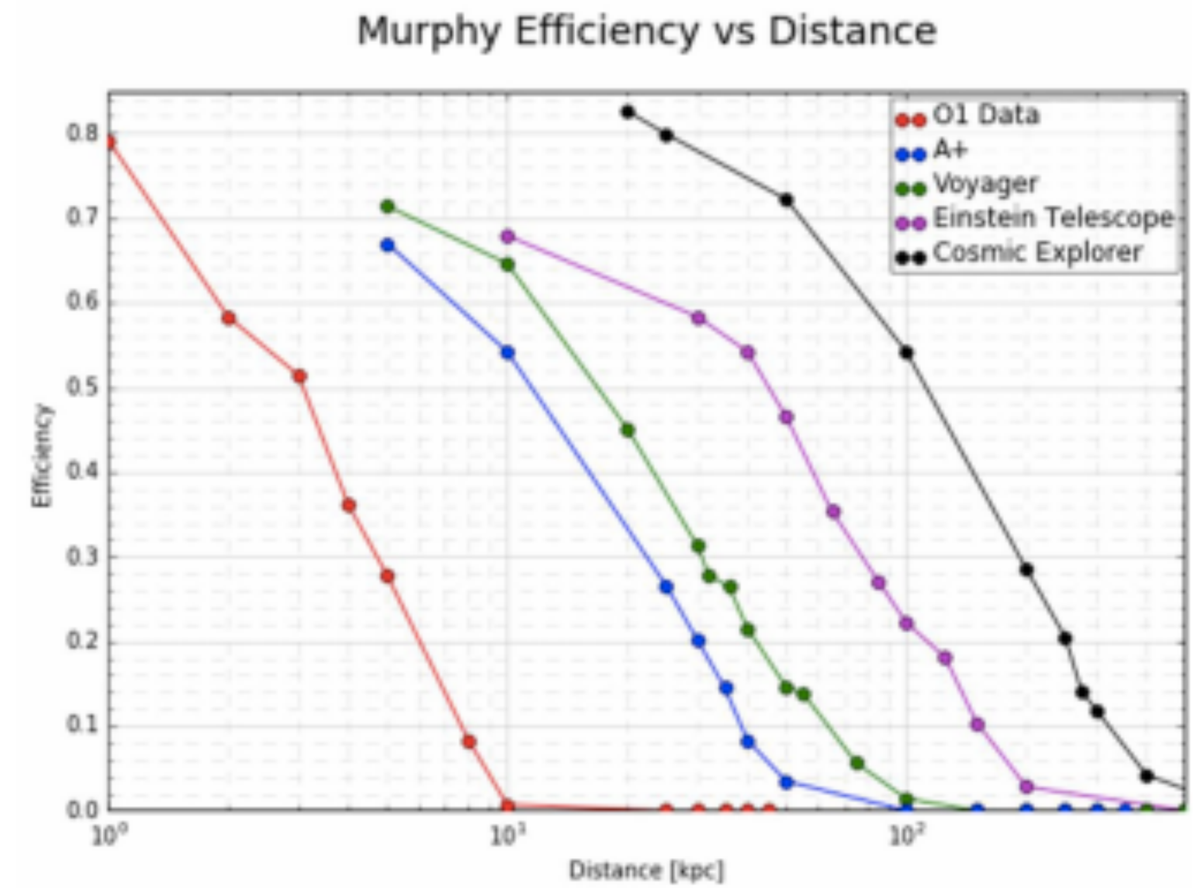
Each waveform injected at *10 different times over a 24 hour period* to explore entire antenna pattern. 1440 total injections.

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

[2] Vincent Roma

Supernova Model Evidence Extractor (SMEE)





Magnetorotational Maximum Distances

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

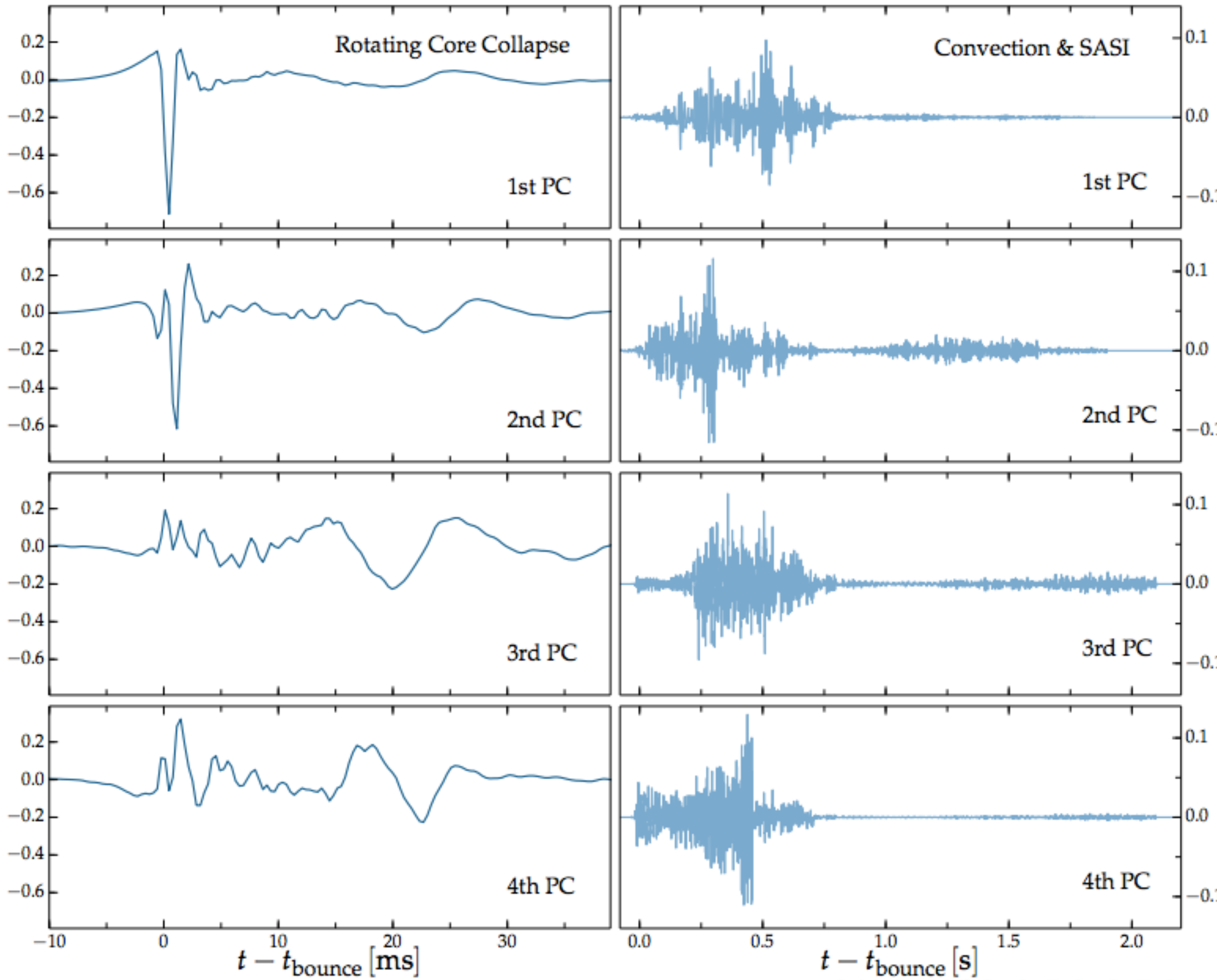
Neutrino Maximum Distances

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

[2] Vincent Roma

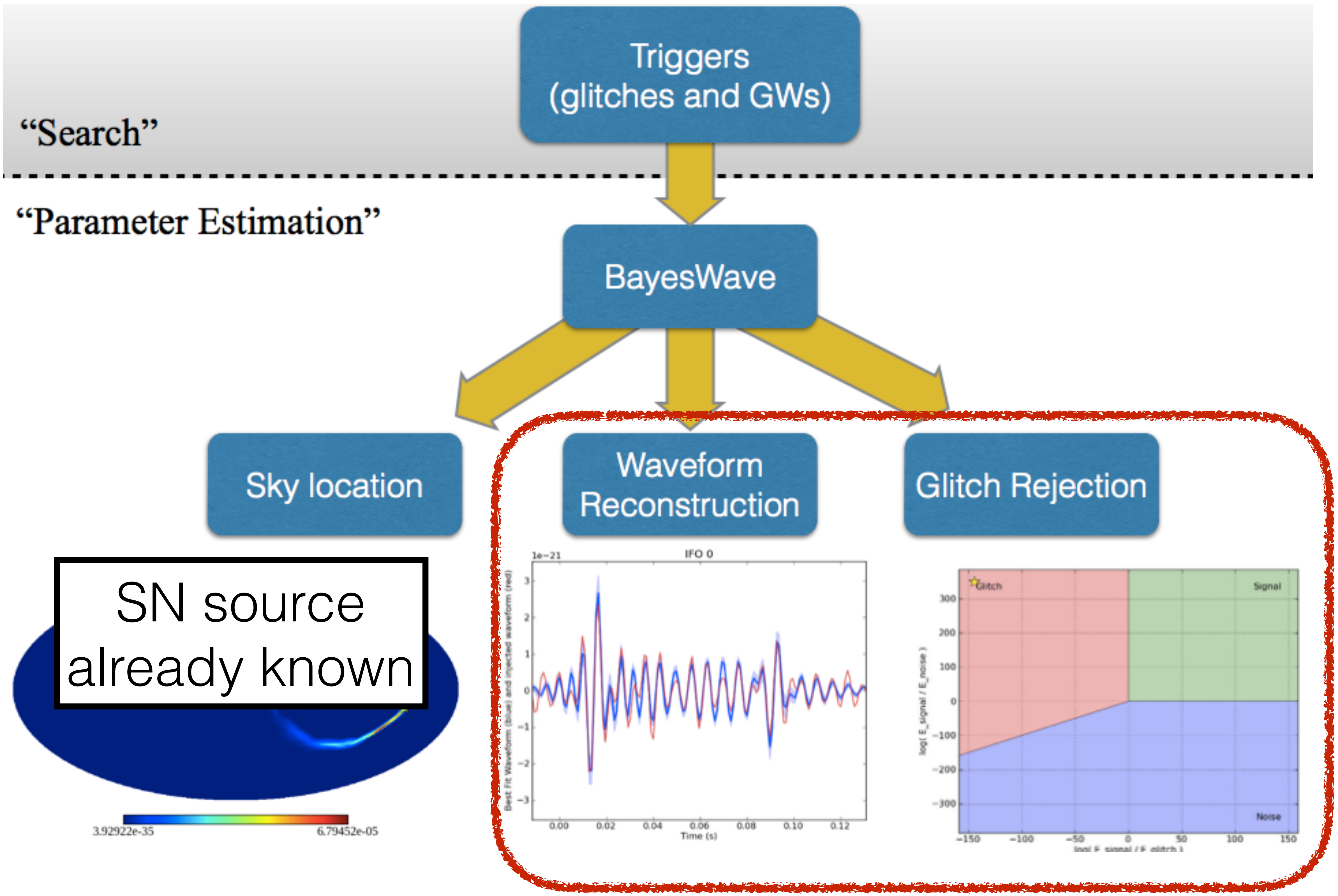
Supernova Model Evidence Extractor (SMEE)

Examples of some Principal Components...



[1] Jade Powell

BayesWave Breakdown



BW “Priors” Tailored to SN Searches

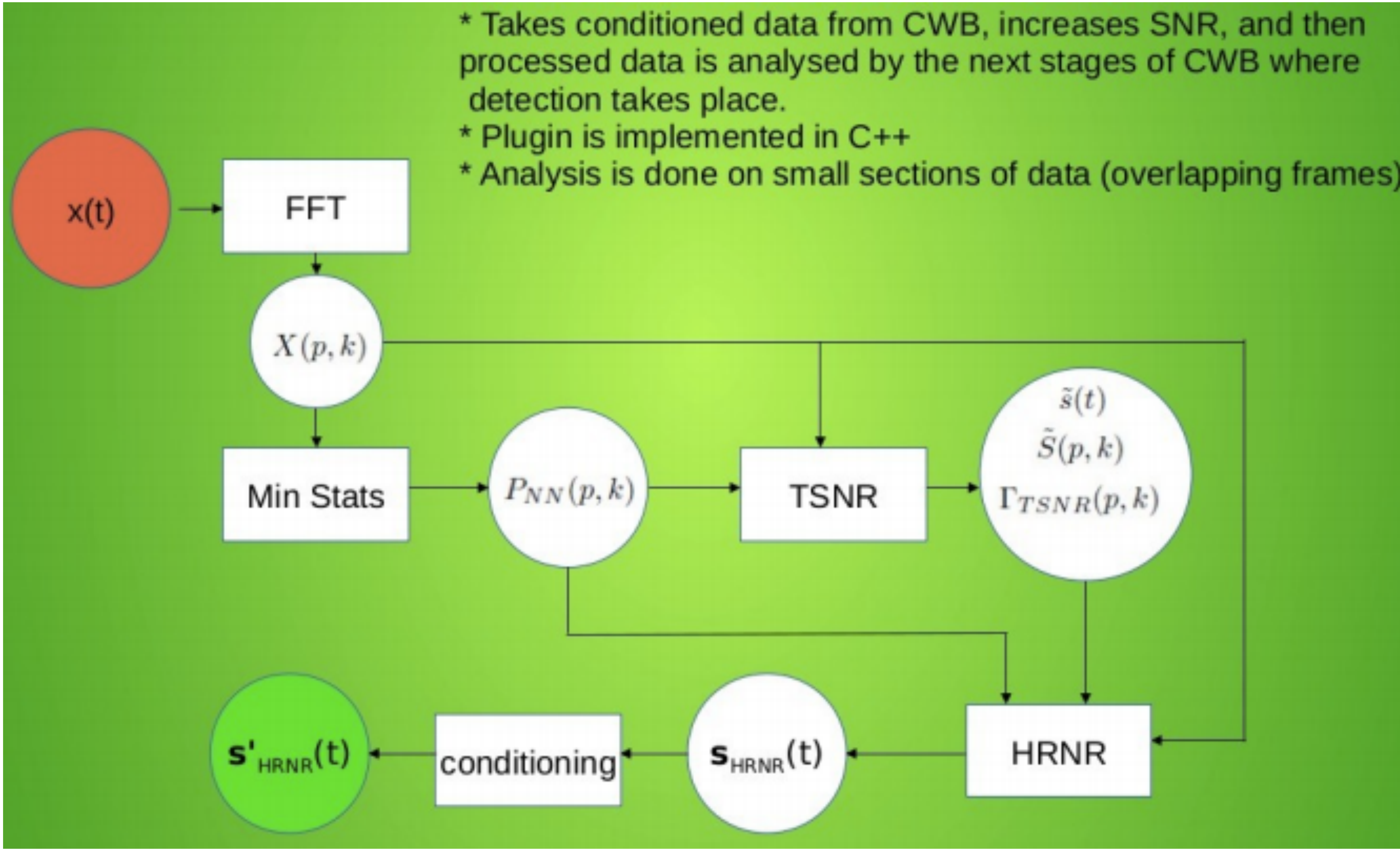
List of Priors to be modified:

- Sky Location **(Done)**
- Glitch SNR **(currently being tested)**
- 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	$\mathrm{p(SNR)} = \frac{\mathrm{SNR}}{\mathrm{SNR}_*^2} e^{-\mathrm{SNR}/\mathrm{SNR}_*^2}$	$\mathrm{p(SNR)} = \frac{\mathrm{SNR}}{\mathrm{a}} e^{-\mathrm{SNR}/\mathrm{b}}$
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

TSD



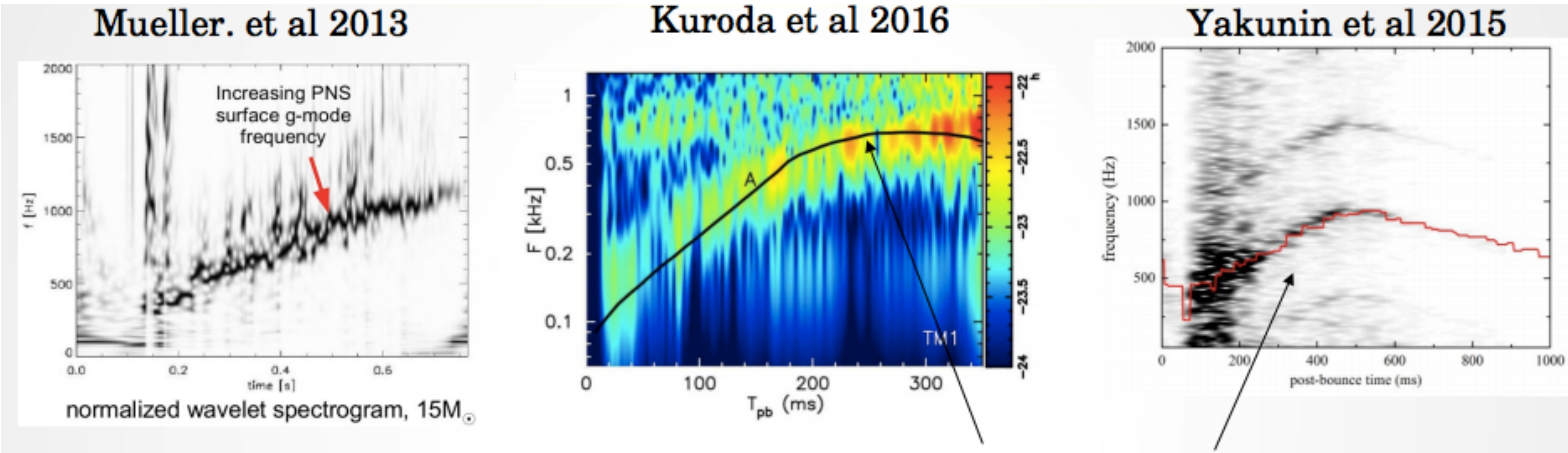
Please direct TSD specific questions to Soma!

TSD

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%

Please direct TSD specific questions to Soma!

An example where the bridge between SN theory and data-analysis is needed….



Growing "Ring up" Trend

Understanding: The frequency ramp up (high frequency linear g-modes) is robustly present in the most numerical simulations available on the "CCSNe market"

Exploring: Using a special tuning we can double the visible volume - should an optimized tuning be introduced just for the slowly rotating models (given their theoretical expected rate of occurrence to average around 99%)?

Questions to Address

Our understanding: only one group has exploding models in 3-D with first principle (approximated) physics included with common progenitor properties (i.e, another model explodes with a star at unusual density in the outskirt).

- *Large spikes in 2-D models* seem to be related to *unusually large funnels that do not happen in 3-D* & tend to develop around the θ=0 axis (of the reference frame)?

- Are the *rapidly rotating waveforms short and linearly polarized* or do they also *have a turbulent phase* similar to the *slowly rotating scenario* progenitors?

- What is the *exact weight* the LVC should give to phenomenological models?

- How can we catch more serious issues, i.e. the *non-linear low frequency g-mode bug* that produced the acoustic mechanism mode (now discarded but that made the initial LIGO SN result paper)?

Sketching out Future Steps

- Provide *waveforms*
- Provide consensus on *robust features*
- Feedback on *how realistic are different models* (including phenomenological models)
- Promote *cross correlation and checks of the results* among theory groups
- Promote systematic *exploration of the parameter span of progenitors*

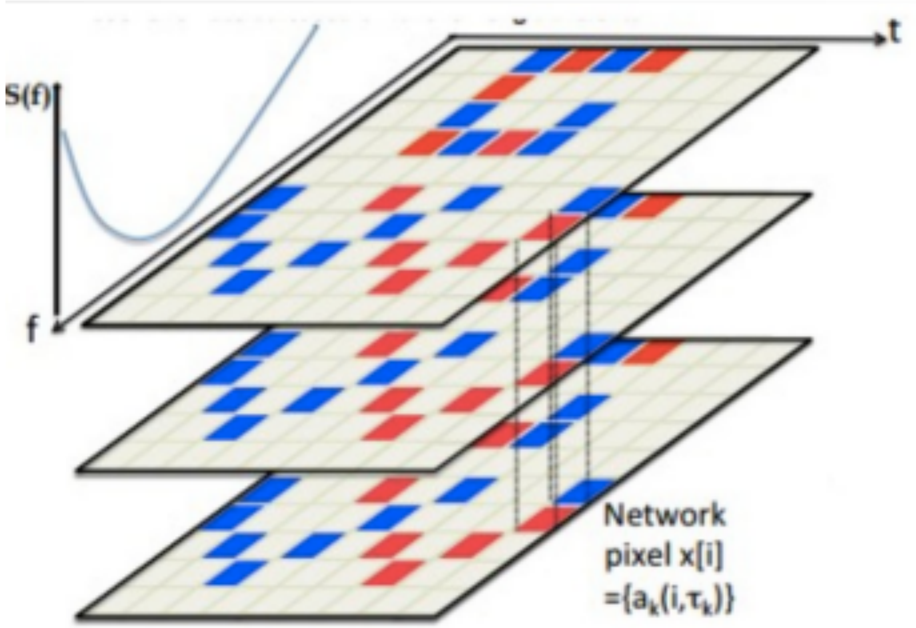
Extra Slides

Coherent WaveBurst

Coherent analysis - combines data from the detector network into a unique list of "triggers"

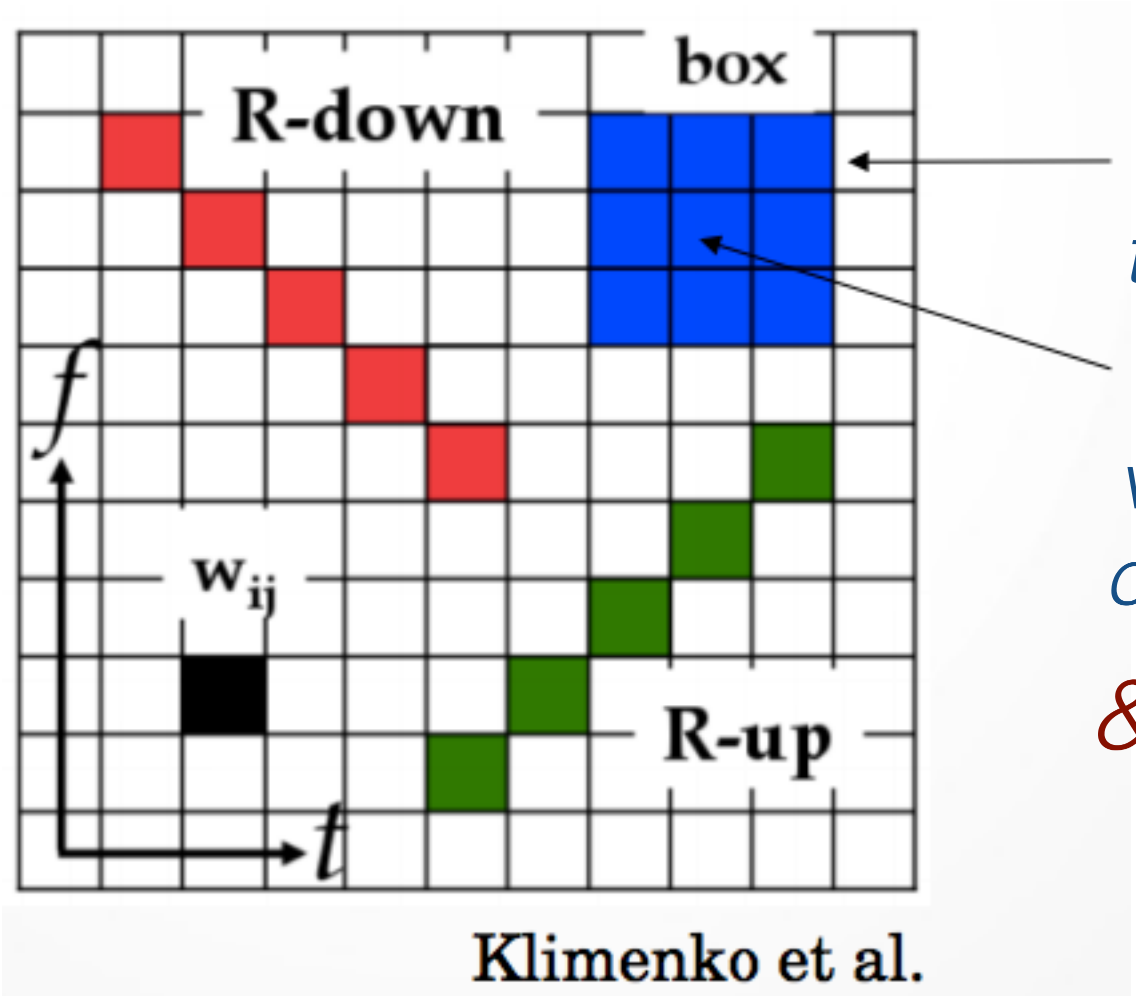
- Identifies burst candidate events by tiling data in a time-frequency plane via wavelet transformation
- Extracts significant events using a likelihood statistic
- With the analysis of the background and features extracted from the injected signals, efficiency curves are produced

Multilayer decomposition of GW data →



Coherent WaveBurst

Expansion on the wavelet packet ideology: *construction from generic T-F patterns using the superposition of basis wavelets*



summation of the energy of total # of pixels

calculated value in the central pixel

& repeat for entire T-F map…

Multilayer decomposition of GW data →