Core-Collapse Supernova Searches: how we search, searches conducted and challenges

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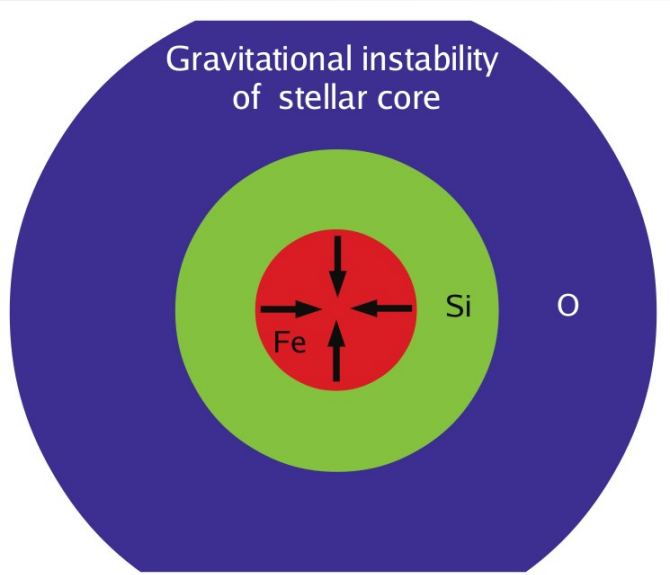
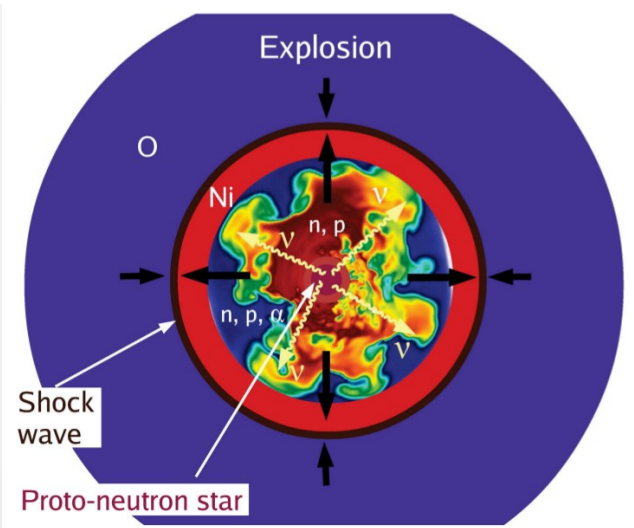
SN Workshop
Pasadena, 2017.04.17-18

Core-Collapse Supernova (CCSN)





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!

CCSN Rate

- CCSN Rate

  ~ 1 SN/s in Universe

  ~ 1 SN/day discovered

  ~ 4 SN/year up to 20Mpc

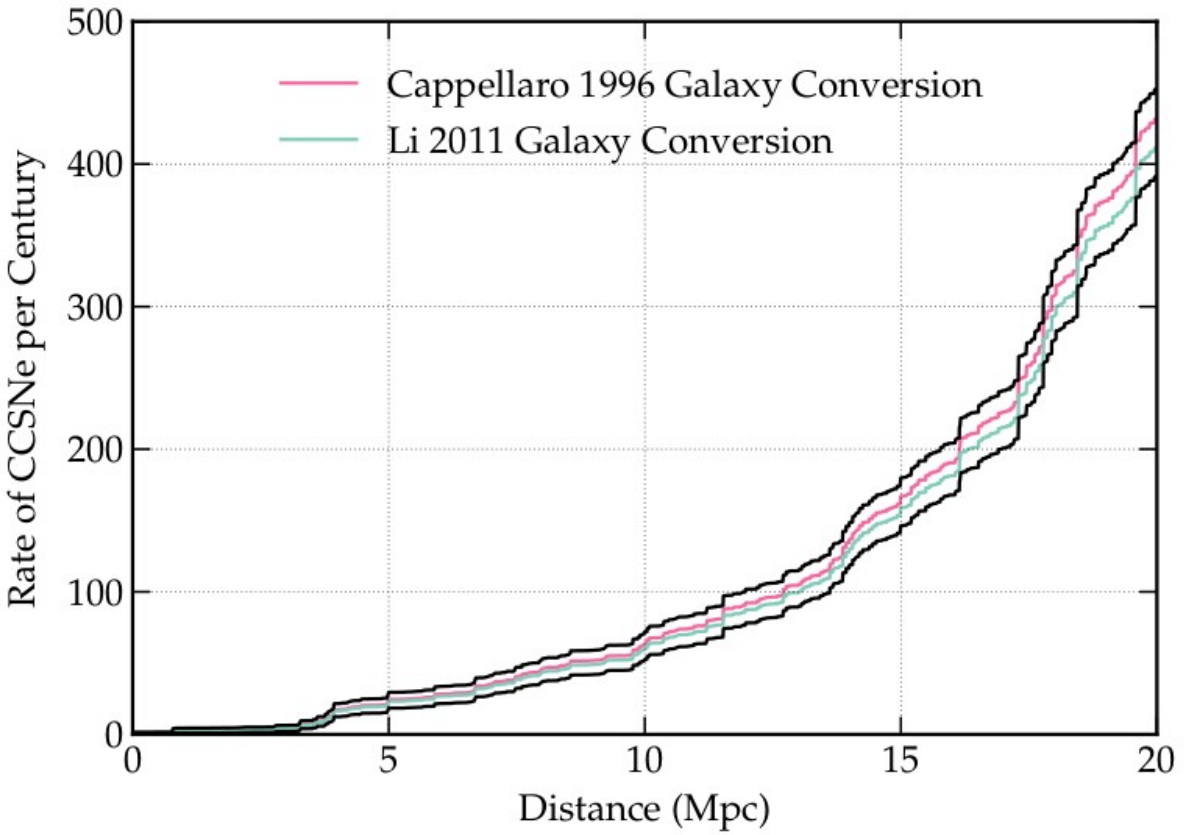
  ~ 2 SN/century (?) in Milky Way

- ~ 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



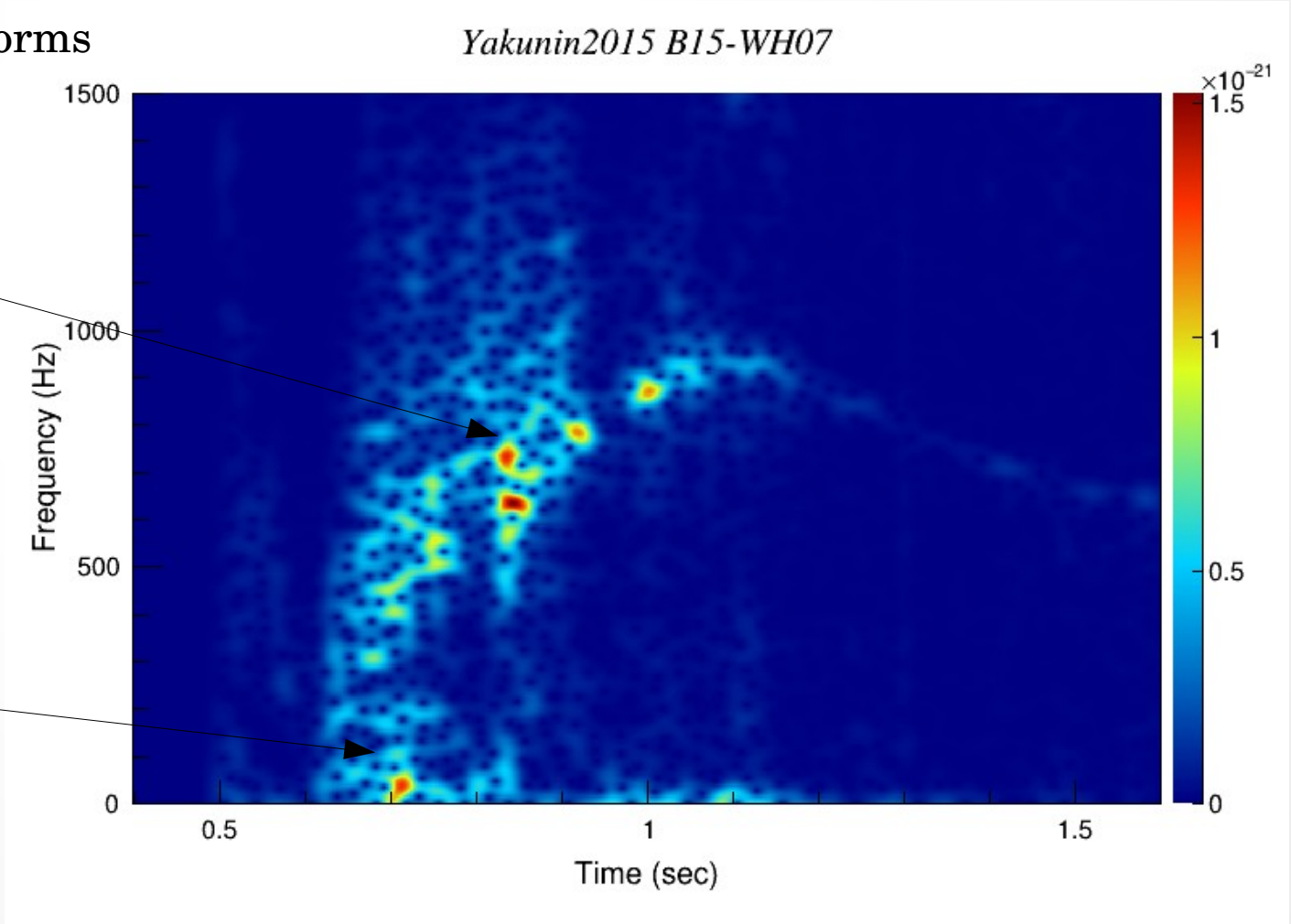
Gill et al 2017 (in preparation), see also the poster

CCSN waveform example of neutrino driven explosion

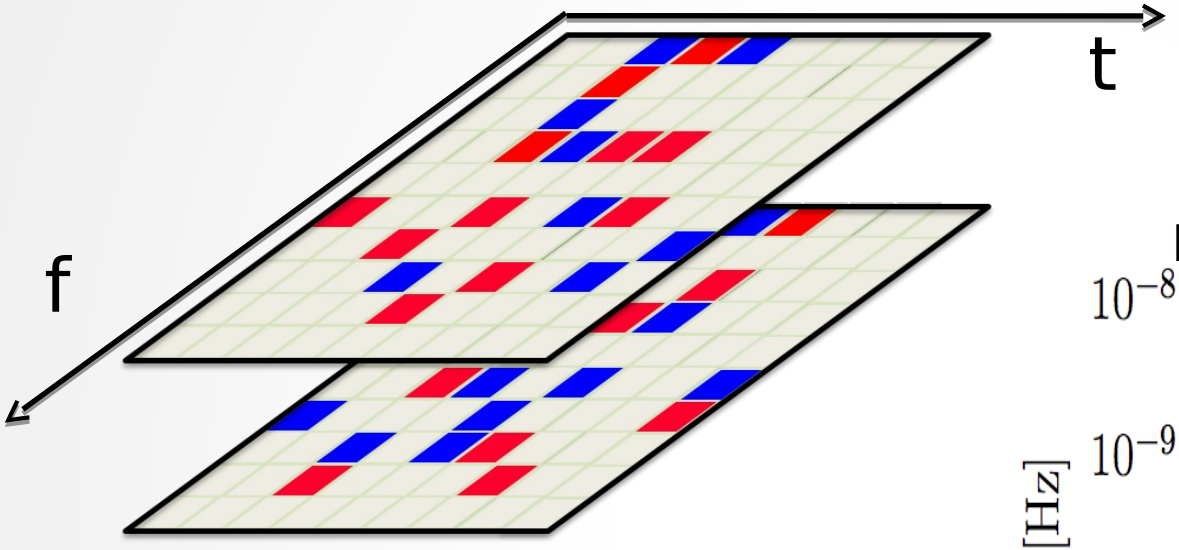
- Broadband and long duration signal
- Strong high frequency component
- Non deterministic waveforms

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

Low frequency sloshing mode instability, SASI

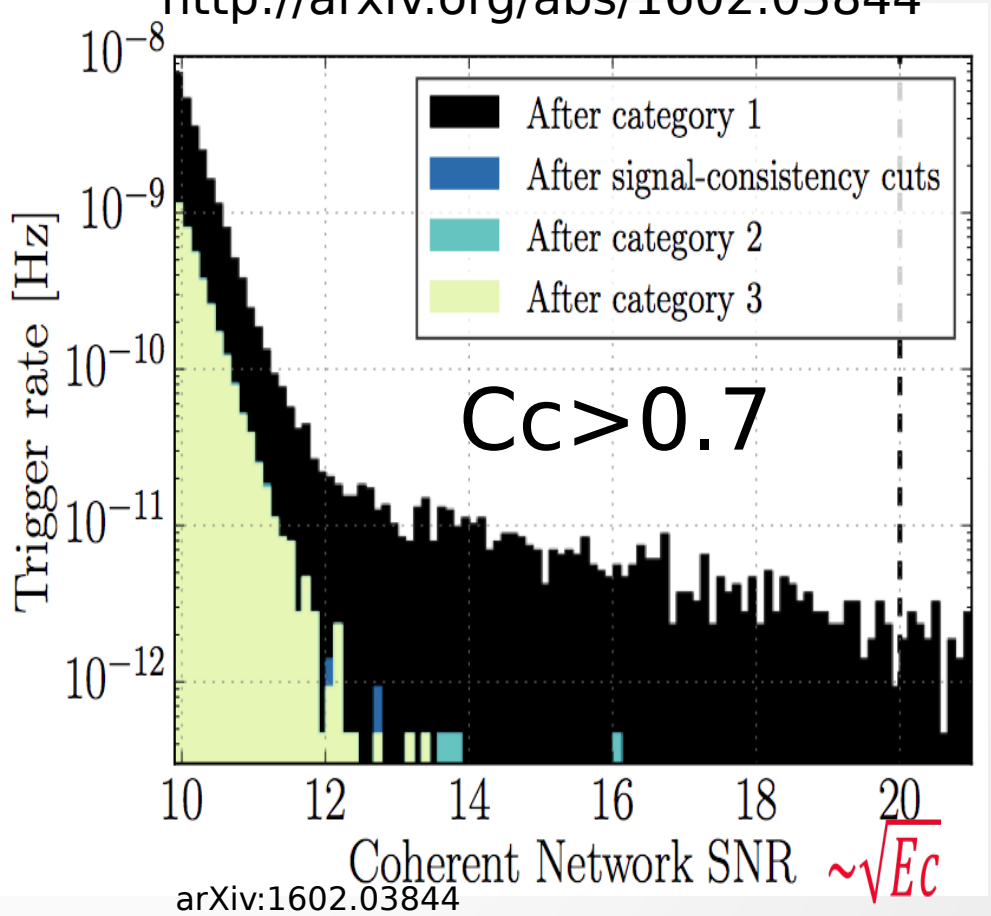


Bursts searches



$$c_c = E_c/(|E_c| + E_n)$$

http://arxiv.org/abs/1602.03844

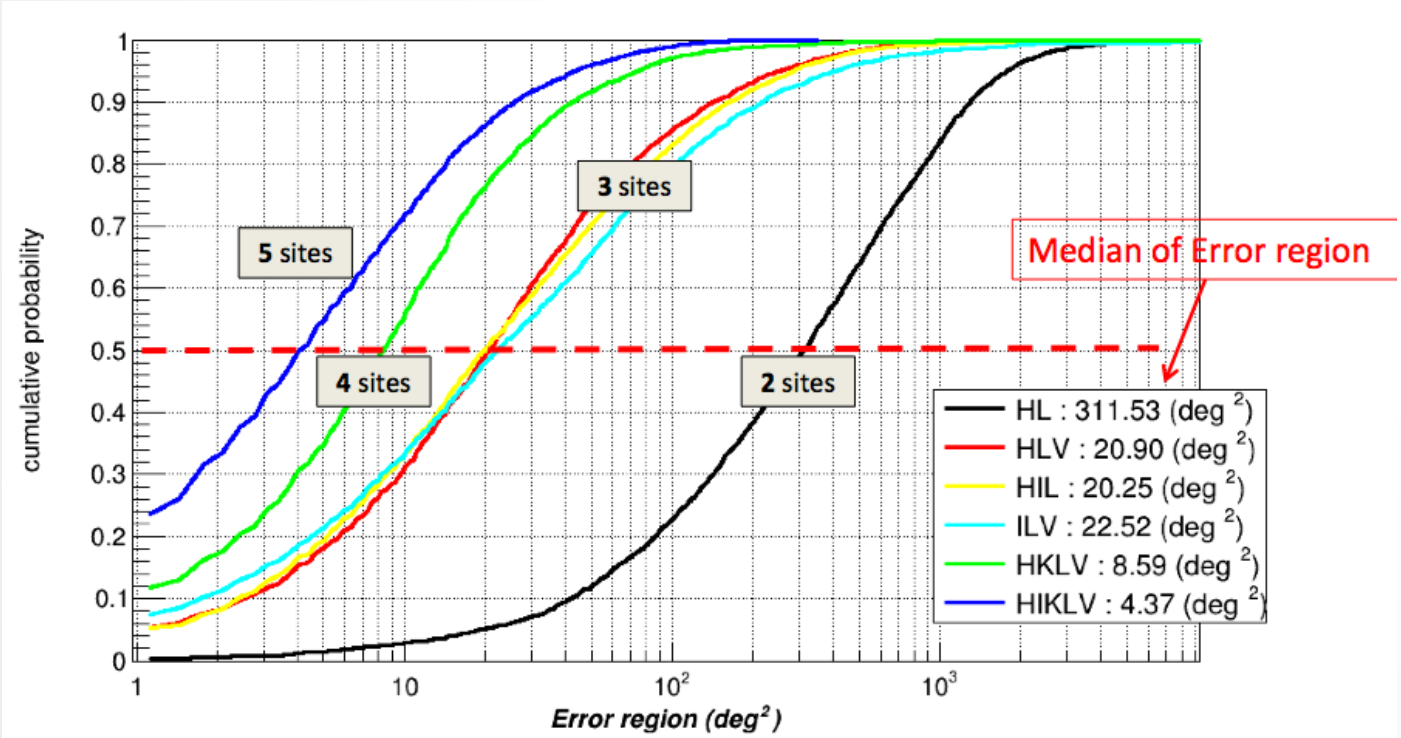


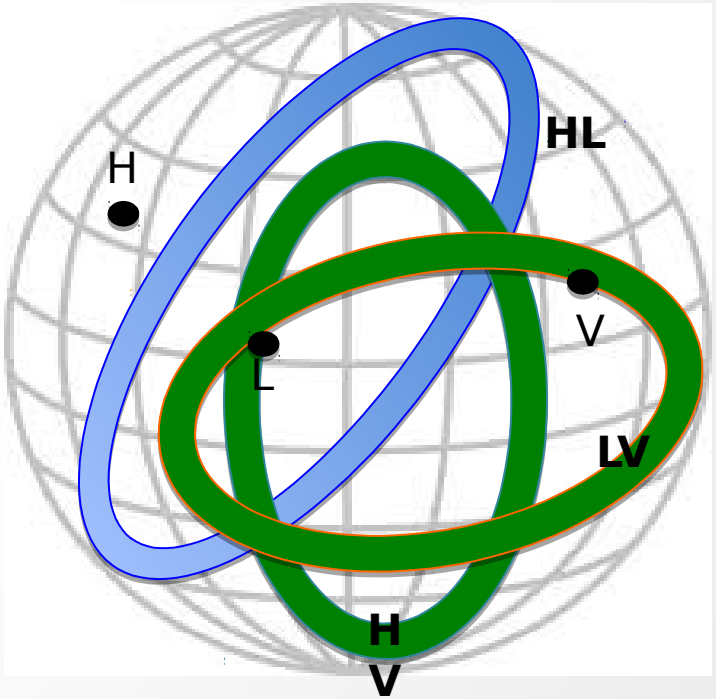
arXiv:1602.03844

- Look for excess power TF patterns consistent in different detectors
- Ec – coherent energy (>0 for signal)
- En – residual energy after reconstructed signal is subtracted

CCSN Triggered Searches

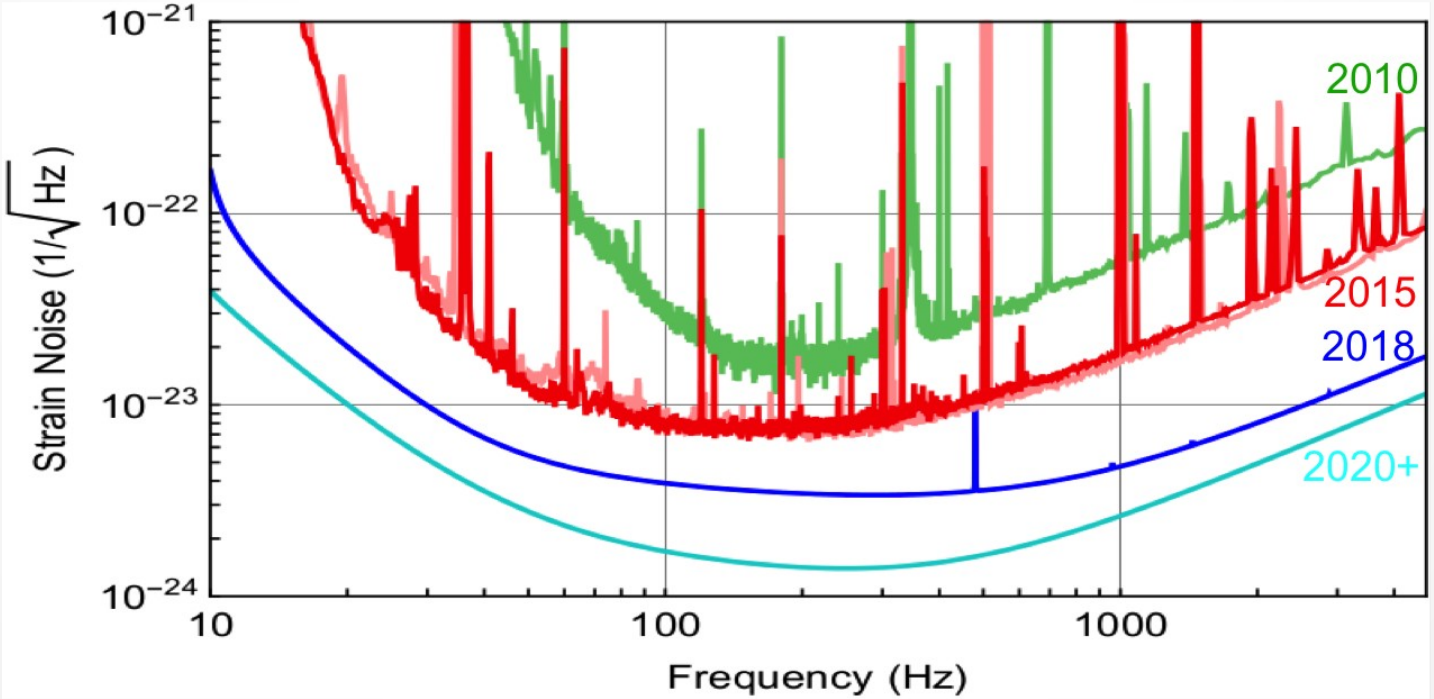
- On-source window – period that we think contains GW, derived from optical or neutrino observations. Timescales:
  - Neutrino triggered search, seconds to minutes
  - Optically triggered search, hours to few days
- Sky location – usage of skymask
- Distance – used currently to constrain the models





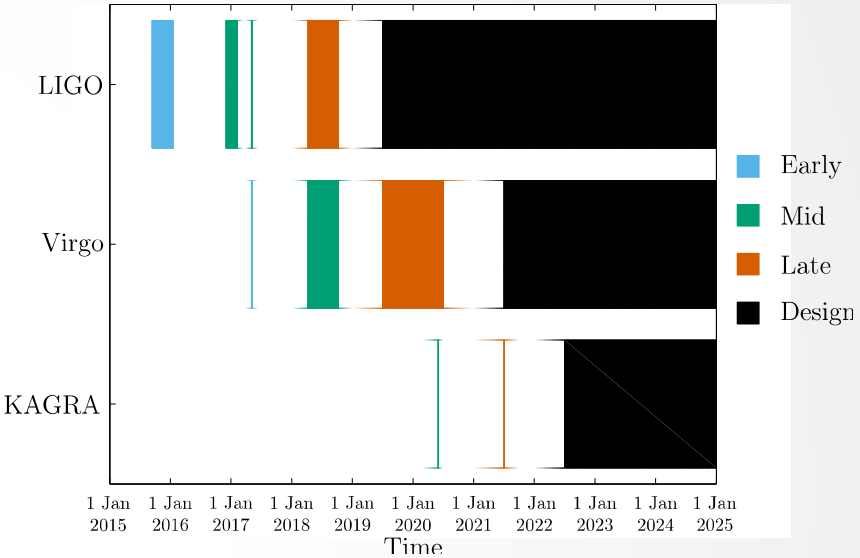
Evolution of sensitivity in the advanced detectors

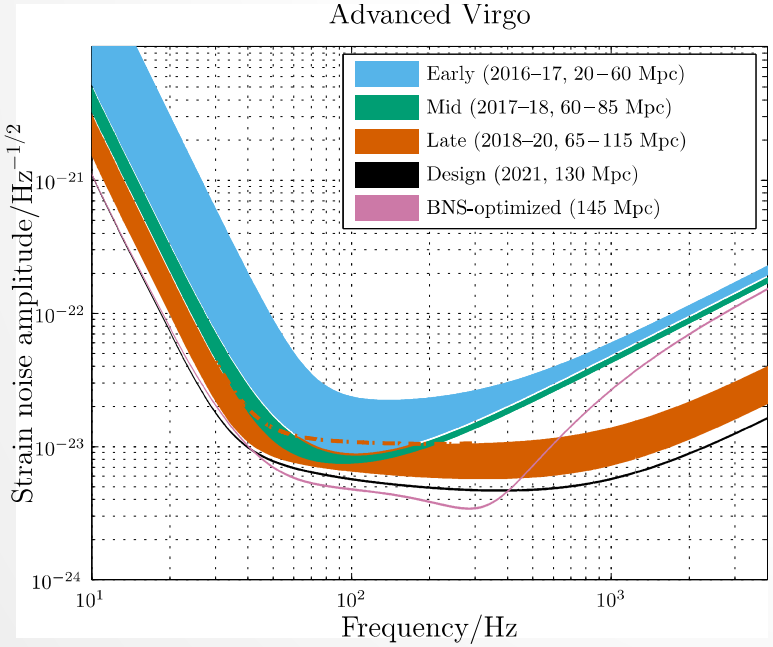
- We already obtain a gain of a factor 4 around 500 Hz
- We hope to reach to a factor 10 @ 500 Hz in total at design sensitivity

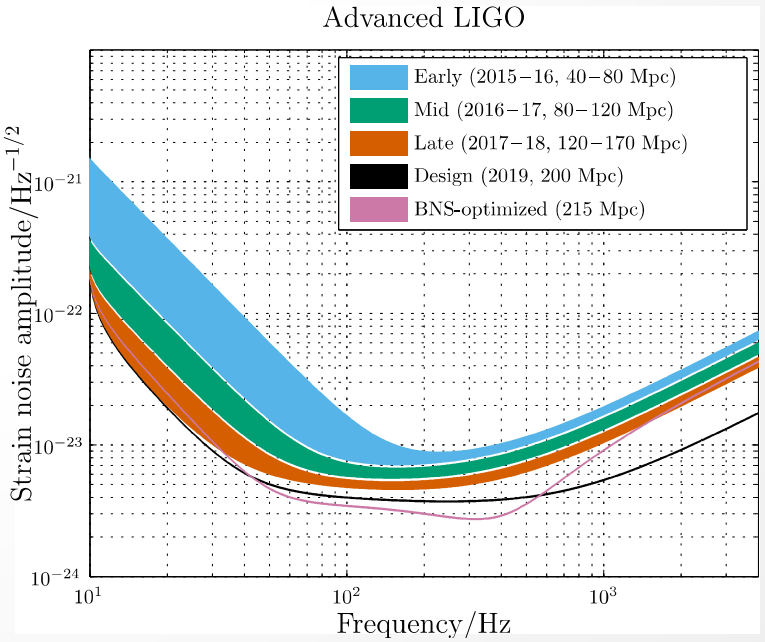


Possible scenario

- Sensitivity will improve with commissioning time
- New detectors will join the network in the next years:
  - Virgo we hope in the next months
  - KAGRA at beginning of the next decade
  - LIGO-India few years later







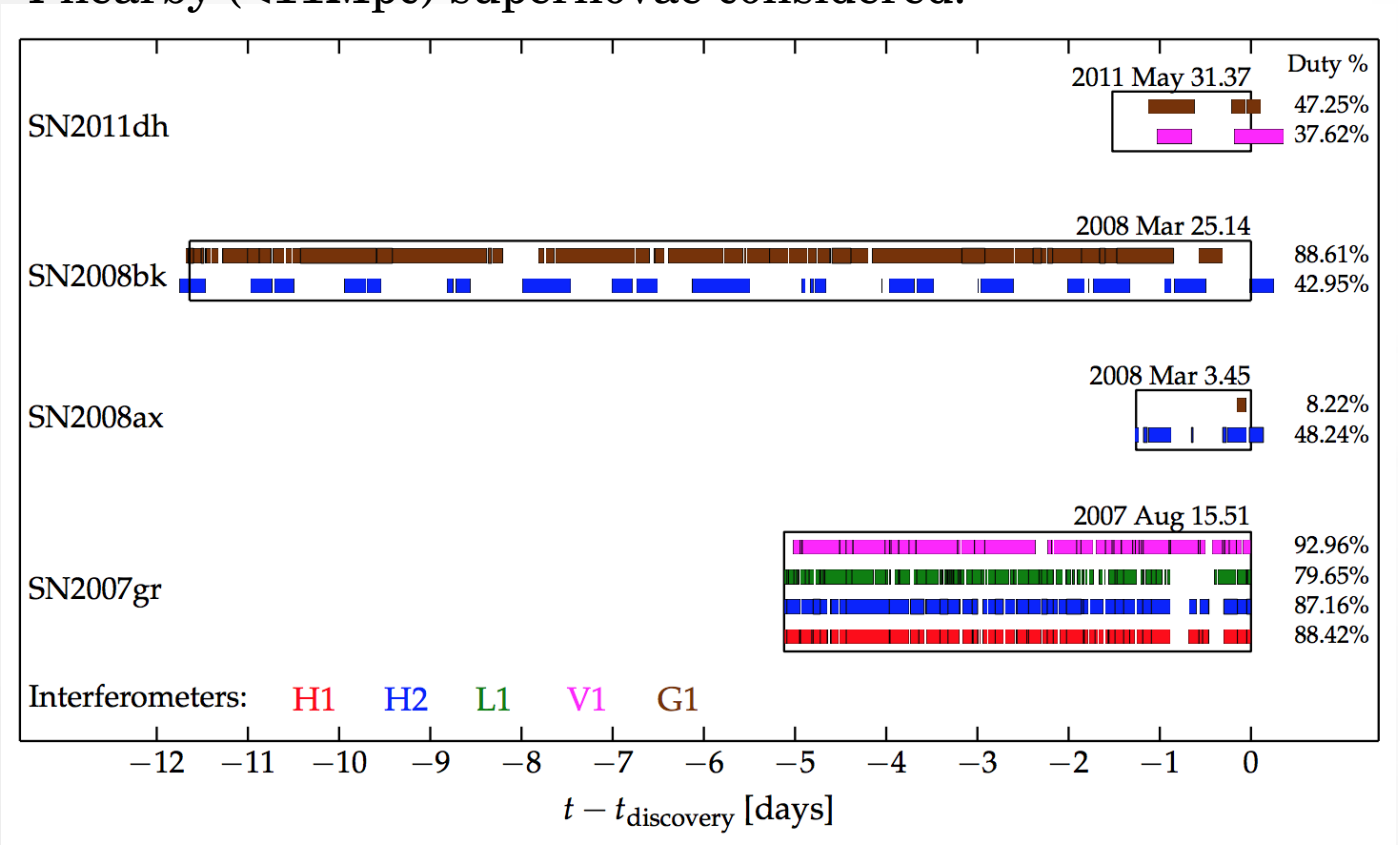
A First Targeted Search for Gravitational-Wave Bursts from Core-Collapse Supernovae in Data of First-Generation Laser Interferometer Detectors

PRD 94, 102001 (2016) (arXiv: 1605.01785)

Some of the SN Search challenges:

- search for non deterministic and weak waveforms,
- small SN rate in nearby universe (1-2 per century in Milky Way),
- a need for coincident data between detectors.

4 nearby (<11Mpc) supernovae considered.



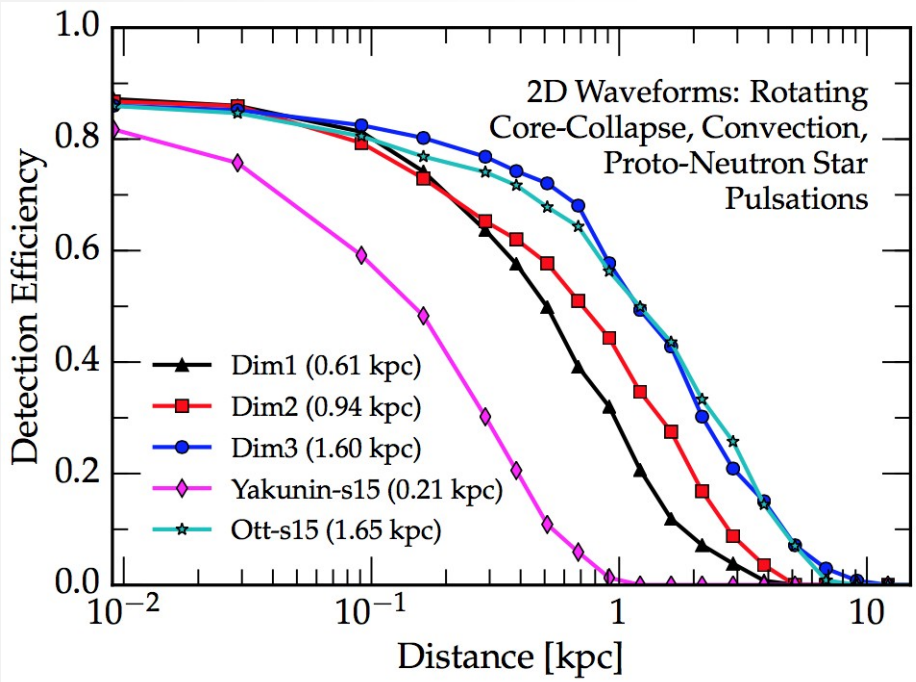
Only SN 2007gr and SN 2011dh were used for detection statements.

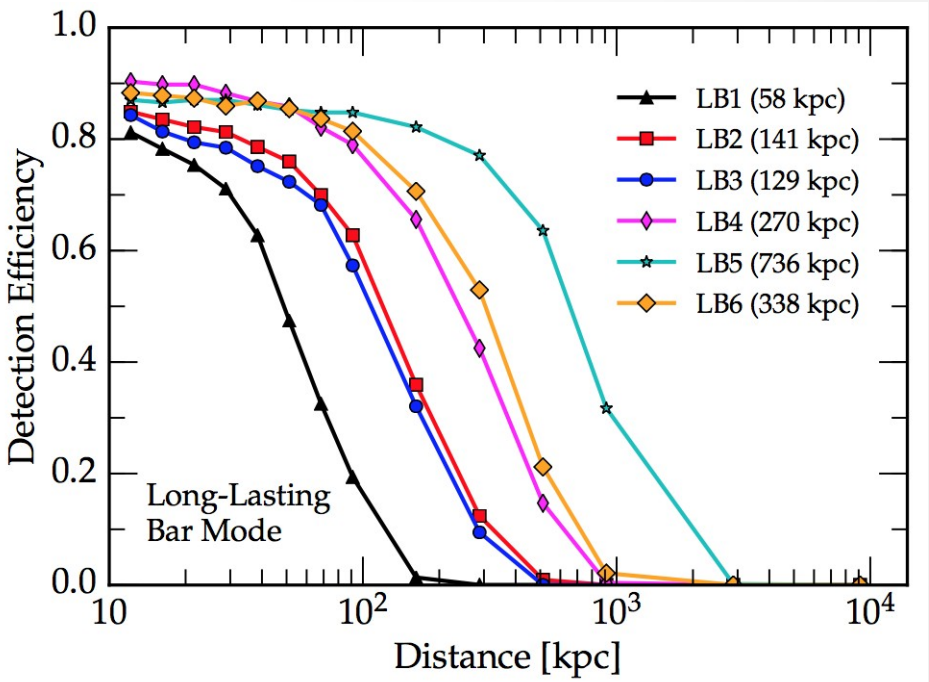
SN 2008ax/bk were excluded from detection statements because of high False Alarm Rate

A First Targeted Search for Gravitational-Wave Bursts from Core-Collapse Supernovae in Data of First-Generation Laser Interferometer Detectors

PRD 94, 102001 (2016) (arXiv: 1605.01785)

- Search Methodology described with challenges specific to SN search.
- Results: detection efficiency, upper limits and model exclusion statements.
- No gravitational wave candidate.



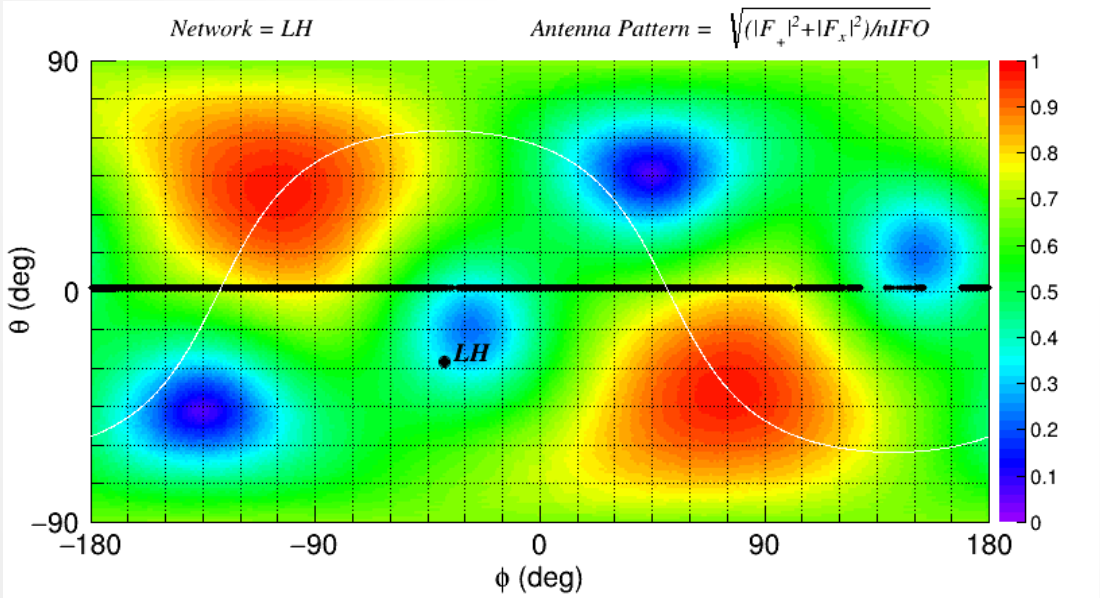


The following SN search paper for O1-O2 data is planned to be finished in spring 2018.

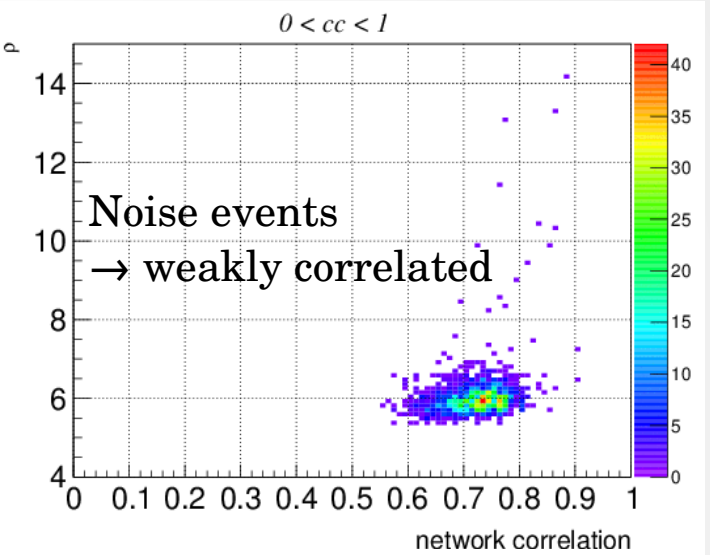
Backup slides

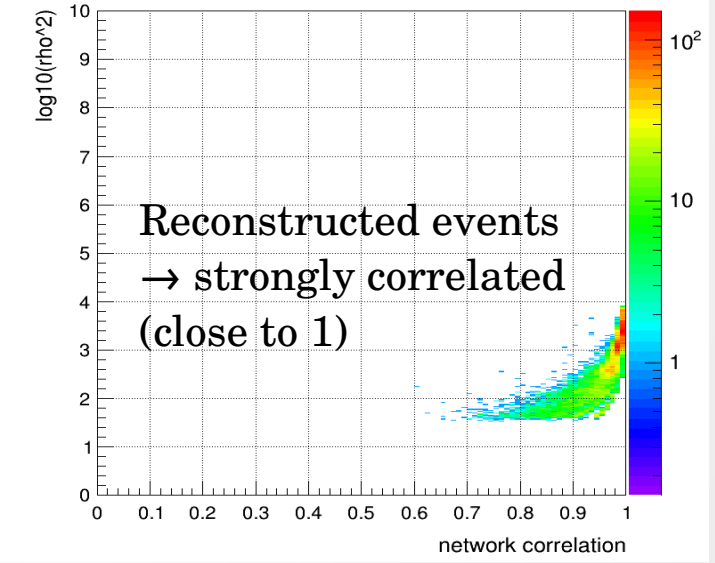
Eliminating noise events increases statistical detection significance and the sensitivity

- Antenna pattern constraints (regulators)
  - $F_+^2+F_x^2$ small
  - $F_x << F_+$
- Instrumental vetoes
- Skymask – circular, ring skymask
- Selection cuts (bandwith, duration etc.)
- Pairing cWB with other pipelines (e.g. BayesWave, SMEE)



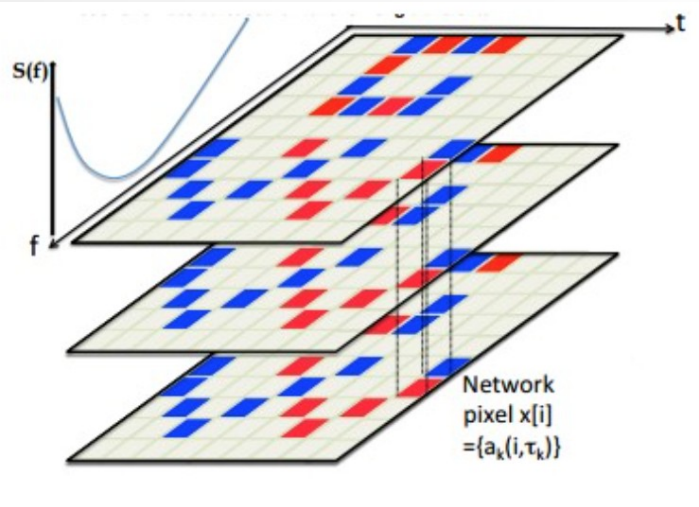
Correlation coefficient





Improving search, coherent WaveBurst (cWB)

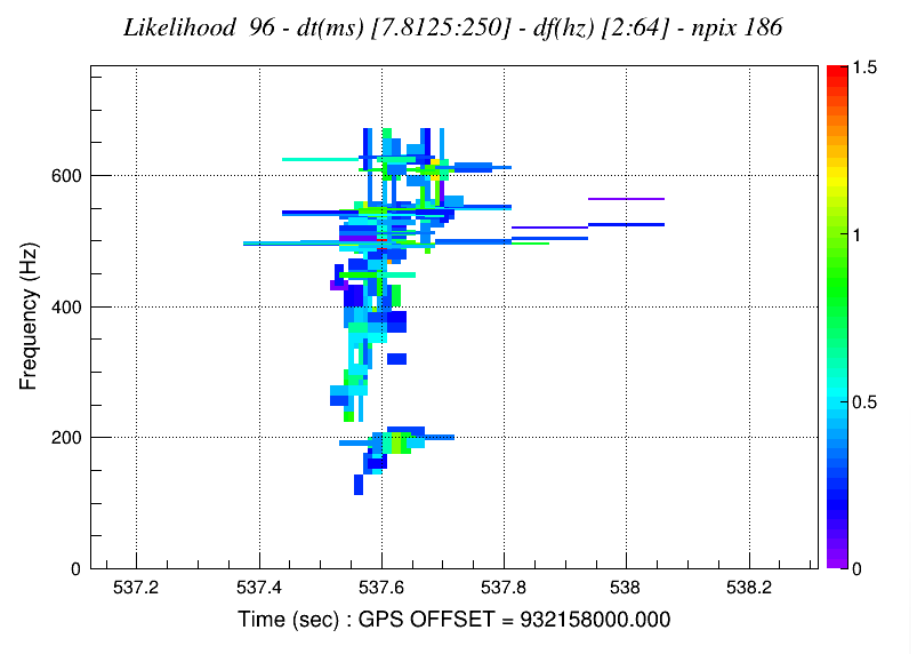
PRD 93, 042004 (2016), (arXiv:1511.05999)



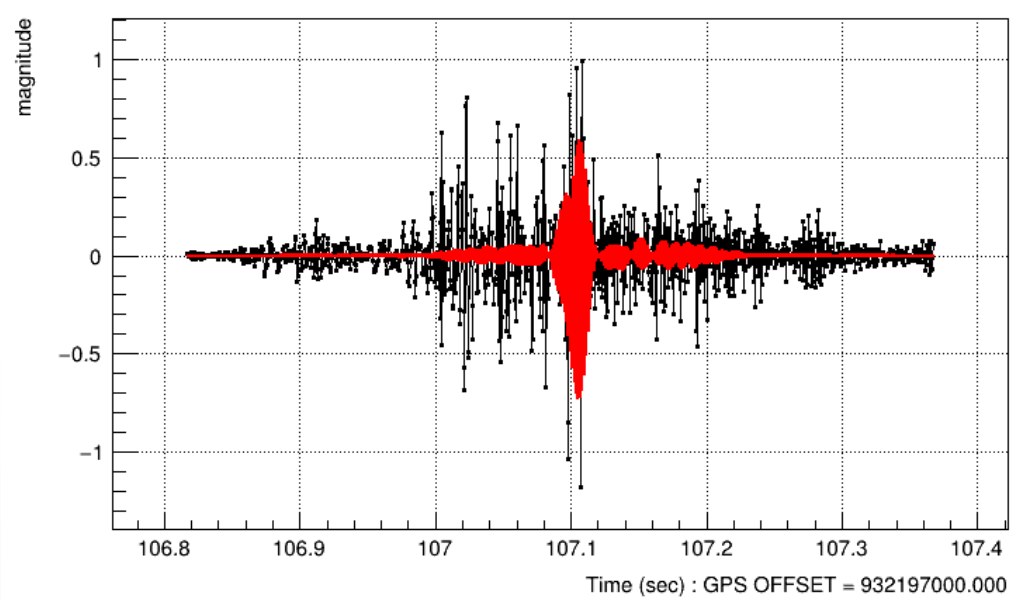
x(t) $\xrightarrow[\text{Transform}]{\text{Wavelet}}$

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

$\xrightarrow[\text{Transform}]{\text{Inverse Wavelet}}$ h(t)



Injected (black) vs reconstructed (red)



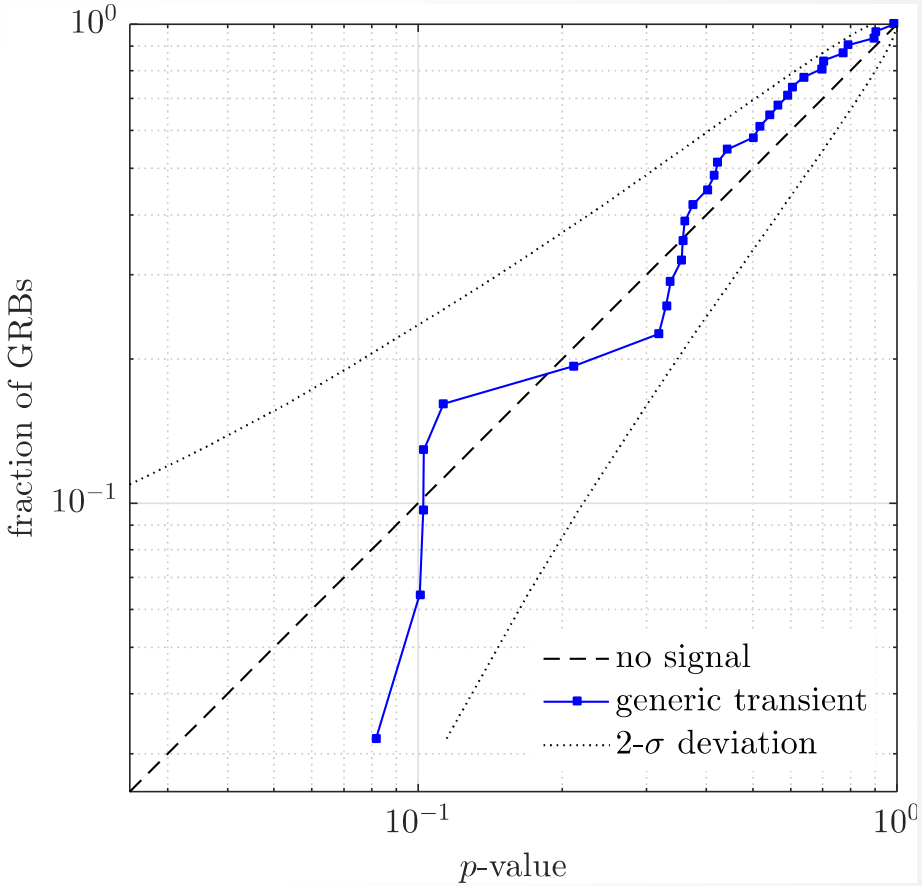
An other external triggered search : gamma-ray bursts

GRB as GW emitter

- As you all know GRB are very good candidate for GW emission:
  - short GRB with coalescence system (NSNS or NSBH)
  - Long GRB with supernovae/hypernovae models
- We use different search pipeline:
  - Short GRB : template based analysis and coherent excess power analysis
  - Long GRB: use only coherent excess power analysis
- Depending of the method we choose different time window (can scan different scenari):
  - Template based [-5s, 1s]
  - Coherent excess power [-600s, 60s (or T90 if larger)]

Method used

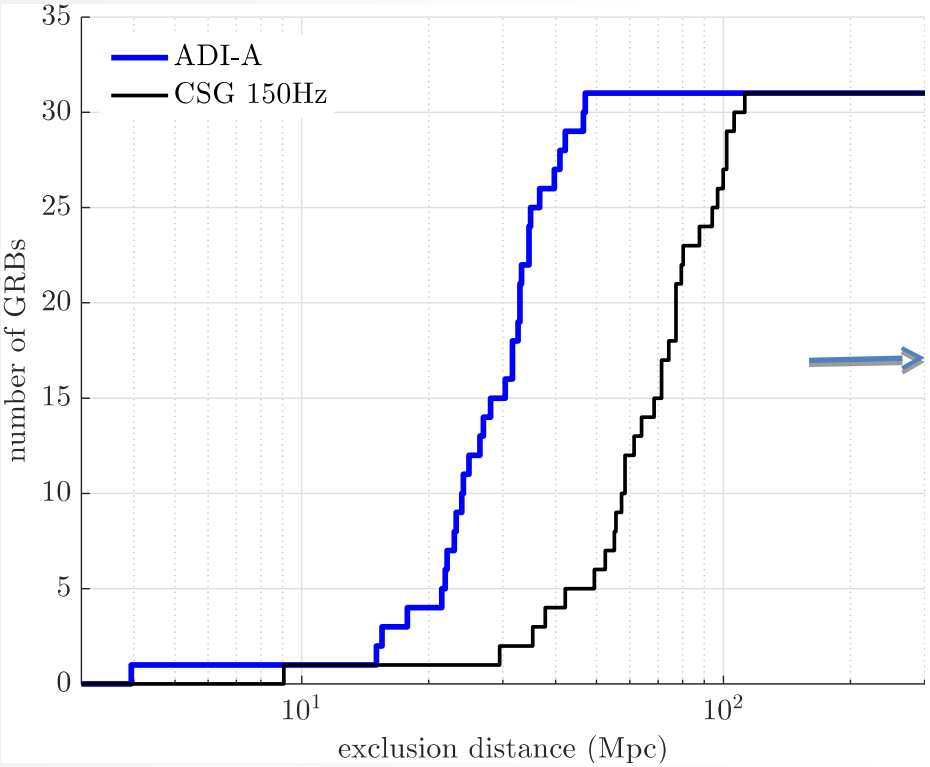
- Perform analysis for each GRB independently
  - Injections with different waveforms
  - Compute maximum detectable distance with the analysis based on the injections done
- Look for loudest event after data quality cuts applied and compute its false alarm probability (FAP)
- We can then check also if the distribution of FAP for all loudest events is compatible with a null result (binomial distribution)
- You need more than 10-20 events to be meaningful

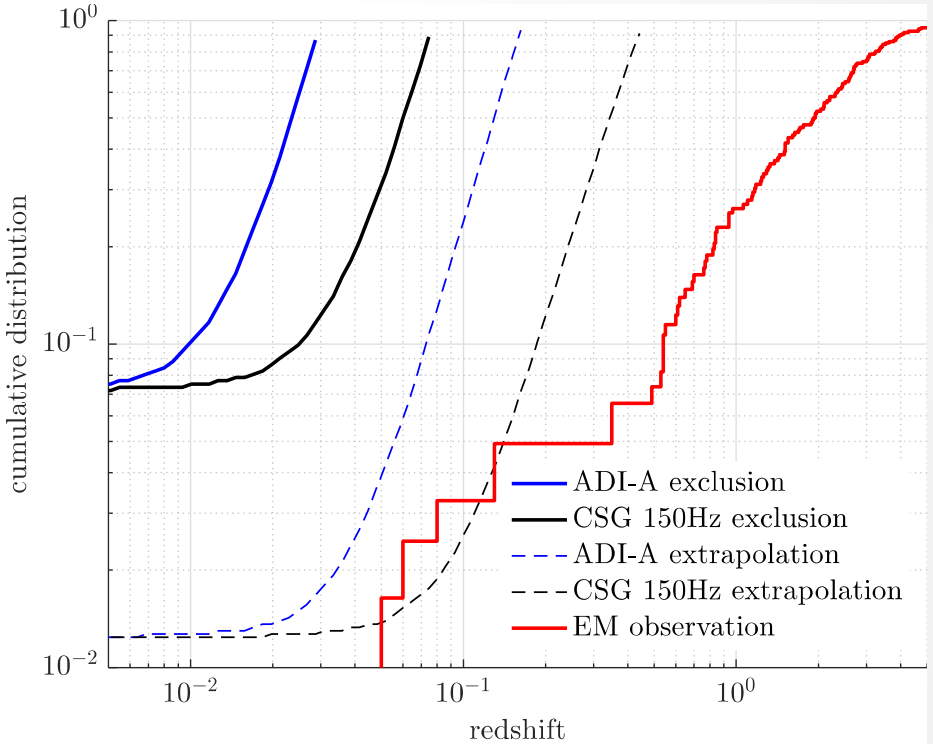


Binomial distribution of FAP for loudest event on 31 long GRBs analyzed during the O1 run

Final results

- Finally we can perform exclusion distance based on the different GRBs estimation

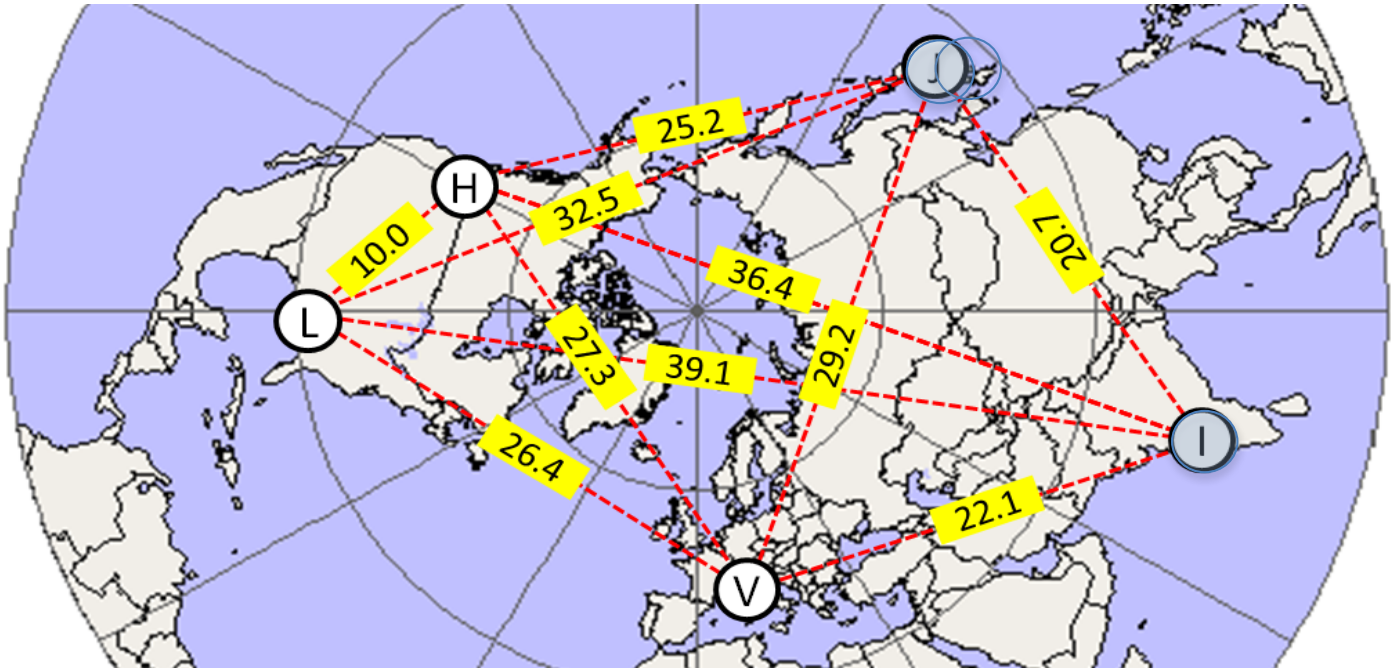




Exclusion distance based on the analysis of 31 long GRBs during the O1 run

Sergey Klimenko, University of Florida

aLIGO (H,L),
aVirgo(V),
KAGRA(J)
GEO HF(G)
LIGO-India (I)



- What we can learn from the burst search?
- How can we improve SN searches? Network?
- What specifically should we measure to characterize SN source?

Network Response

$$\vec{\xi}[i] = [\vec{f}_+^T[i], \vec{f}_\times^T[i]] \begin{bmatrix} h_+[i] \\ h_\times[i] \end{bmatrix} = f[i] \cdot \mathrm{h[i]}$$

- **Noise scaled network antenna patterns**
  - **in general time-frequency dependent**
  - **calculated for each TF data sample i characterized by noise PSD estimator S[i]**

$$\vec{f}_+[i] = \frac{F_{1+}(\theta,\phi,\psi)}{\sqrt{S_1[i]}}, \ldots, \frac{F_{K+}(\theta,\phi,\psi)}{\sqrt{S_K[i]}} = |f_+|\vec{e}_+$$

$$\vec{f}_\times[i] = \frac{F_{1\times}(\theta,\phi,\psi)}{\sqrt{S_1[i]}}, \ldots, \frac{F_{K\times}(\theta,\phi,\psi)}{\sqrt{S_K[i]}} = |f_\times|\vec{e}_\times$$

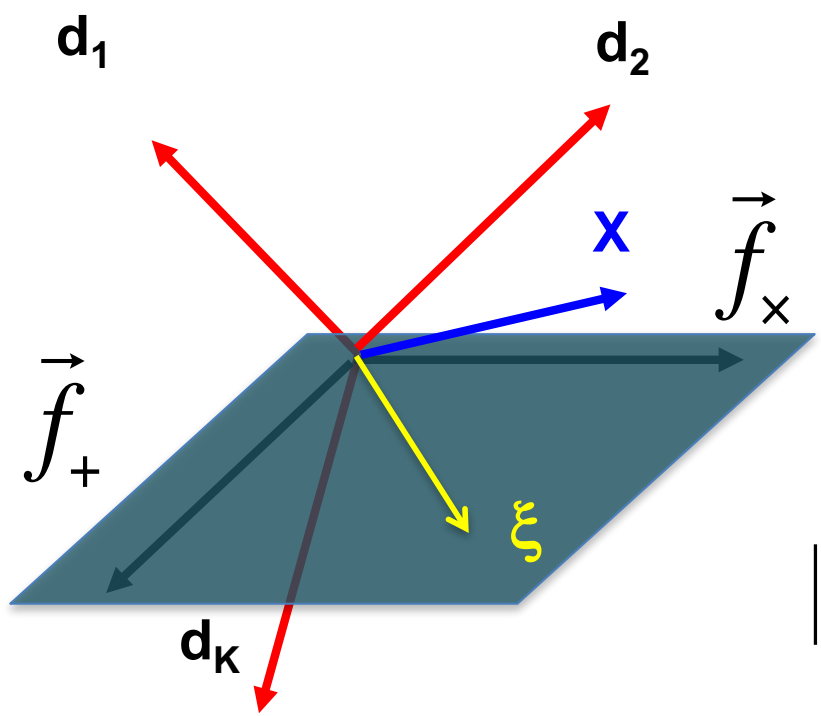
- **Dominant polarization wave frame:**

$$\vec{f}_+(\psi) \cdot \vec{f}_\times(\psi) = 0 \qquad |\vec{f}_+(\psi)| \geq |\vec{f}_\times(\psi)|$$

Klimenko et al, PRD 72, 122002 (2005)

Network Plane

- **Vectors** $\vec{f}_+, \vec{f}_\times$ **define network plane in the space {d_1,d_2,..d_K}**
- **GW response** $\vec{\xi} = (\xi_1, \ldots, \xi_K)$ **is always in the network plane**
- **Noisy response X can be outside of the network plane**

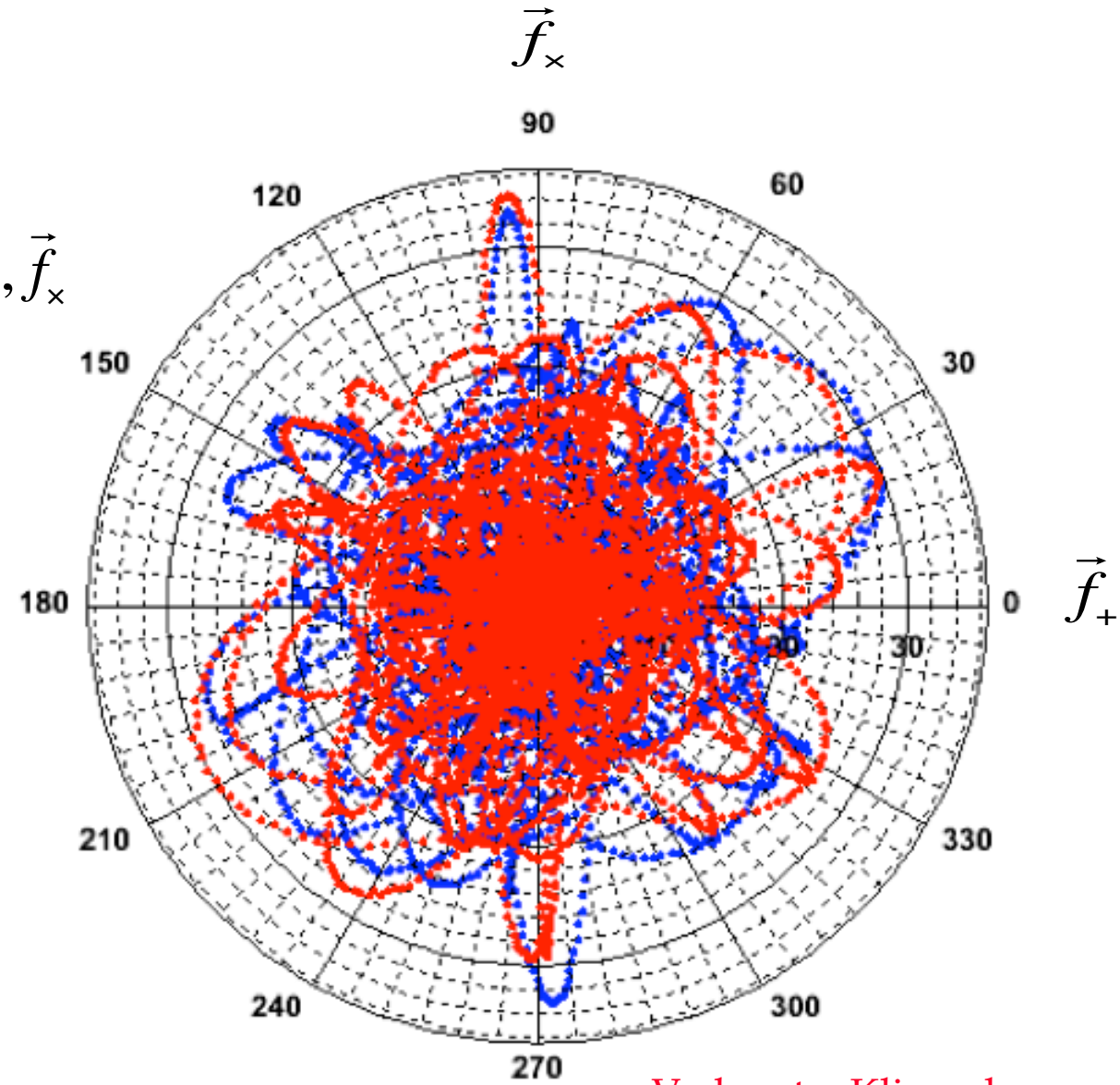


$$\left|\vec{f}_+(\psi)\right| \geq \left|\vec{f}_\times(\psi)\right|$$

Polargrams

- **Polargrams show evolution of the response vectors $\vec{\xi}$ in the network plane $\vec{f}_+, \vec{f}_\times$ (polarization state)**

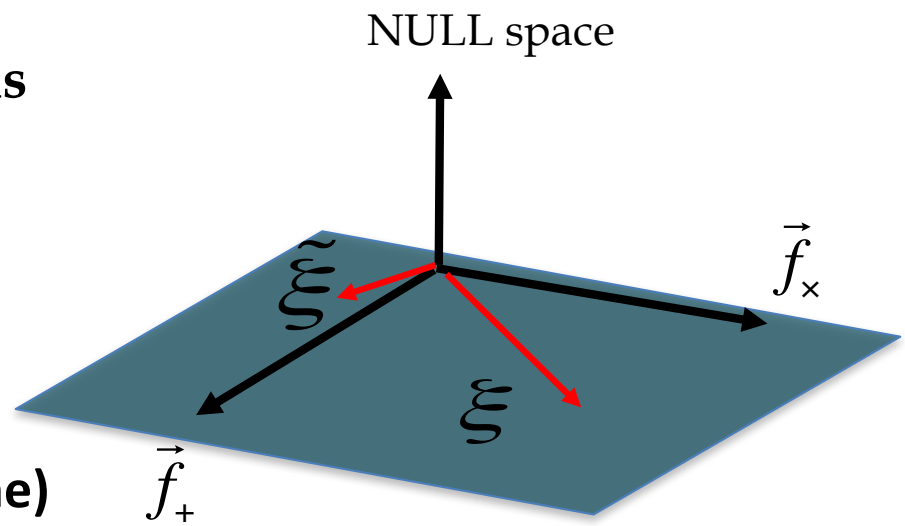
- **evolution of simulated GW signal with random polarization: blue – 0-phase response, red – 90-phase response (quadrature) – defined later**



Vedovato, Klimenko

Some Magic: Dual Stream Phase Transform

- **Dual data stream:** x and $\tilde{x}$ - quadrature
  - **quadrature data stream contains the same information as x**
  - **network response can be presented as pairs of vectors** $\vec{\xi}, \vec{\tilde{\xi}}$



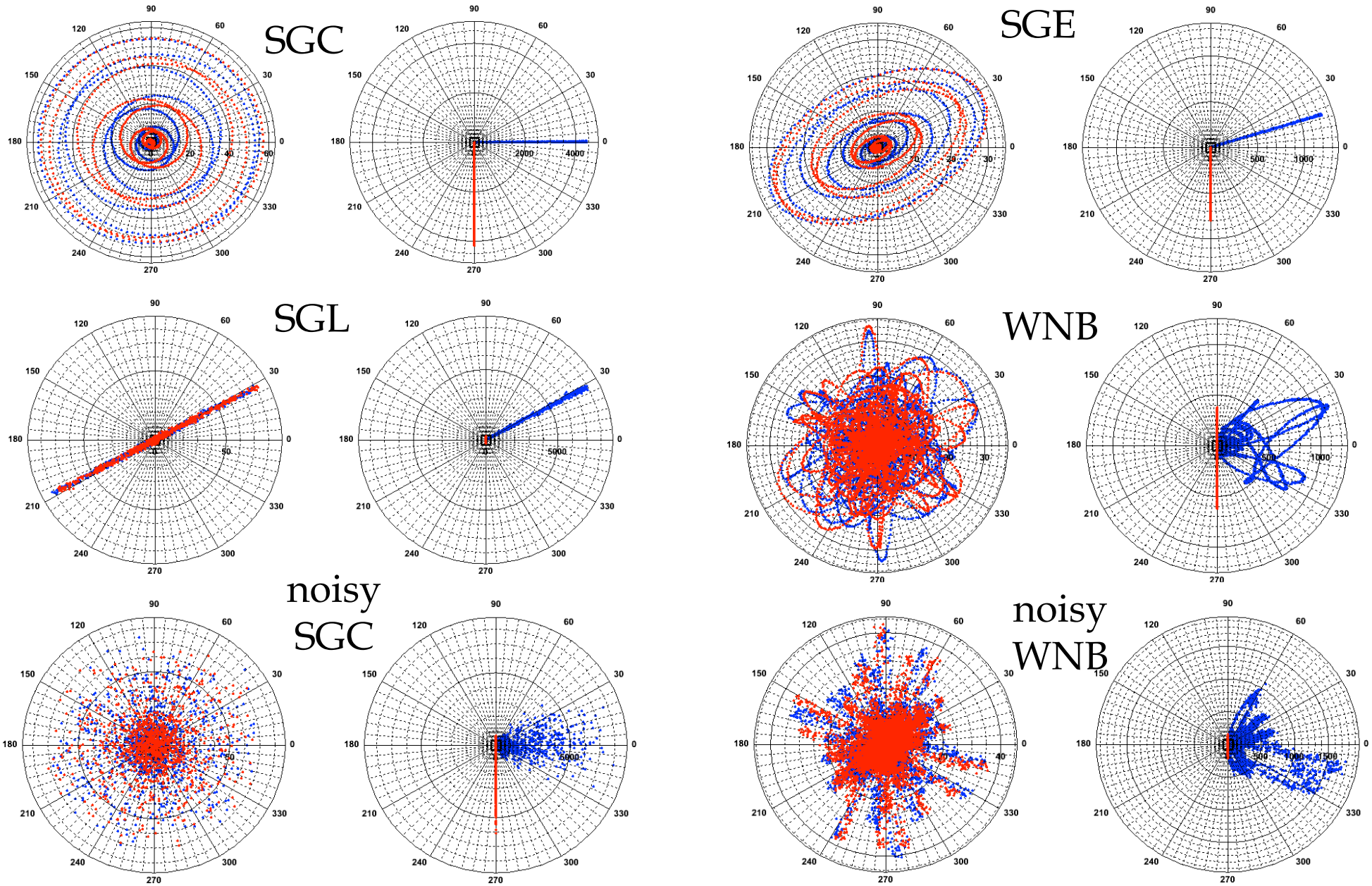
- **Phase transform**
  - **Apply phase transform to projections (don't care about projections out of plane)**

$$\xi = \xi' \cos(\lambda) + \tilde{\xi}' \sin(\lambda)$$
$$\tilde{\xi} = \tilde{\xi}' \cos(\lambda) - \xi' \sin(\lambda)$$

Phys. Rev. D 93, no. 4, 042004 (2016)

- **With appropriate phase transformation the polarization pattern is revealed**

Polarization pattern

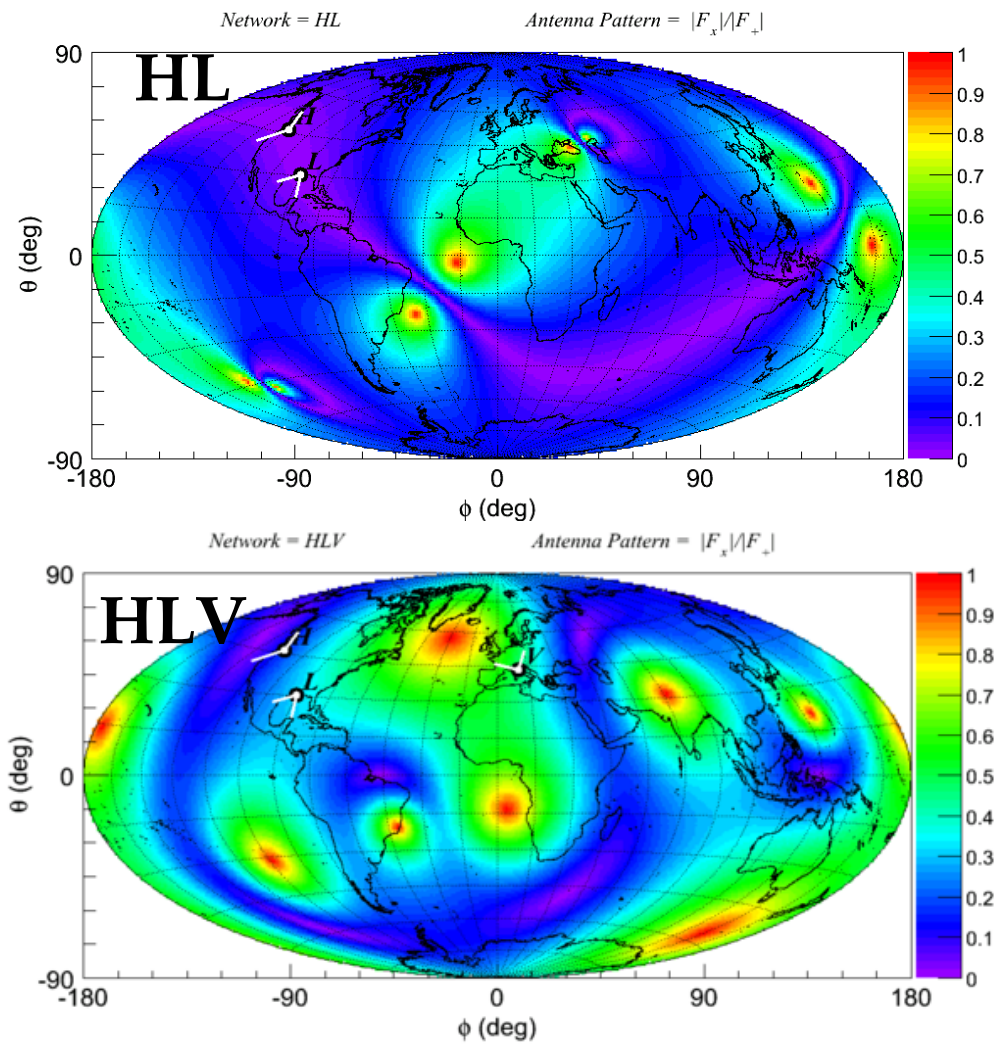


Network Alignment

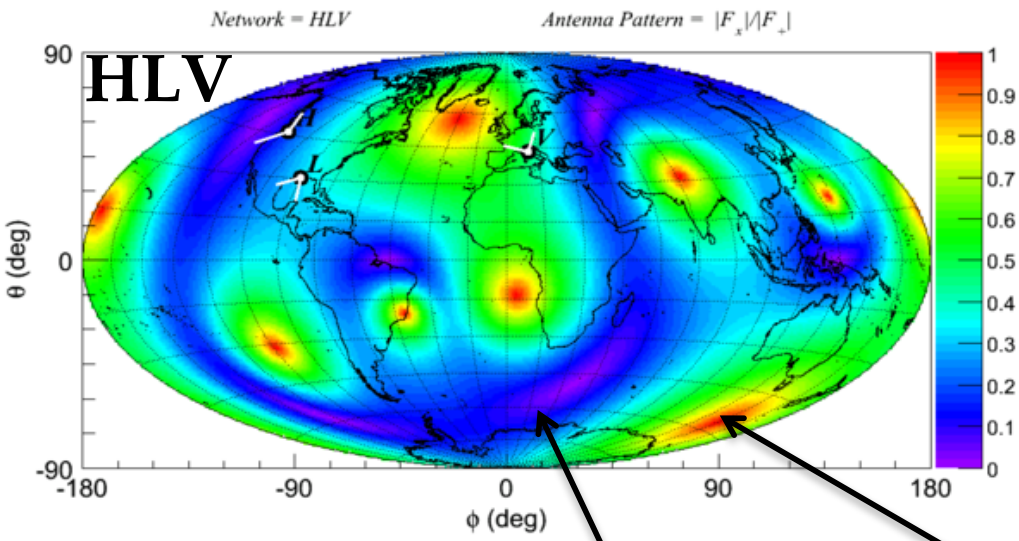
$$A = \frac{|f_\times|}{|f_+|}$$

- tells how well the second polarization is detected

- For co-aligned detectors A=0 – detect only one GW component
  - any incoming GW signal looks like a linearly polarized wave with fixed polarization angle
  - network can not distinguish polarization state of incoming wave
- A – fraction of total network SNR due to the second component



Capturing polarization state

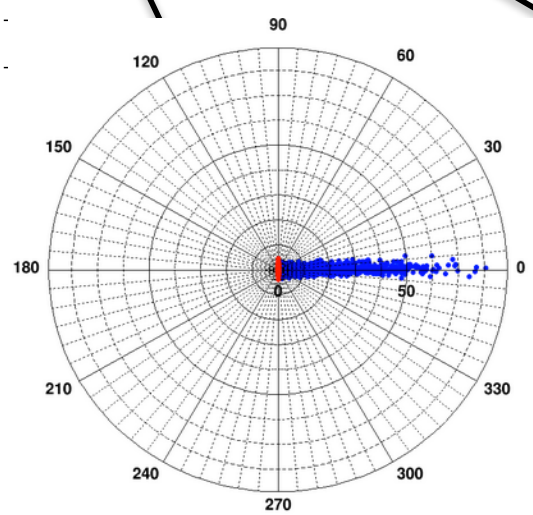


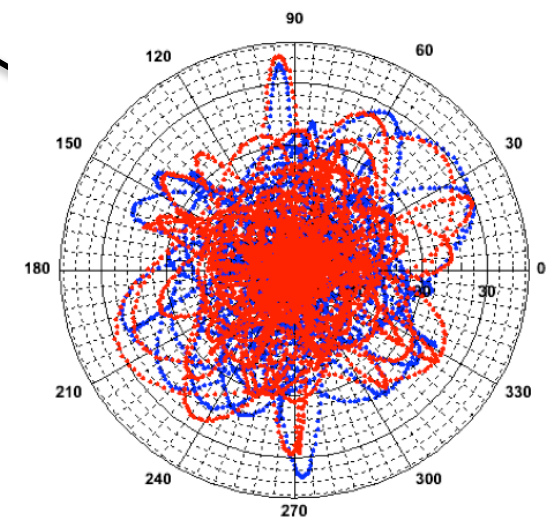
- GW polarization state is captured as a pattern of sampled responses on the network plane
- **Scientific value of detected events greatly depends on the network.**

$$\xi[i] = \vec{f}_+ h_+[i] + \vec{f}_\times h_\times[i]$$

$$\xi[i] \approx \vec{f}_+ h_+[i$$

$$\left|\vec{f}_+\right| >> \left|\vec{f}_\times\right|$$





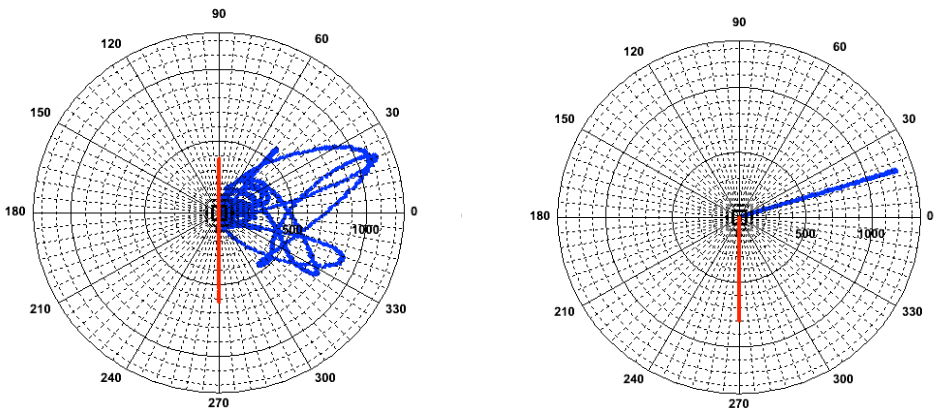
$$\left|\vec{f}_+\right| \approx \left|\vec{f}_\times\right|$$

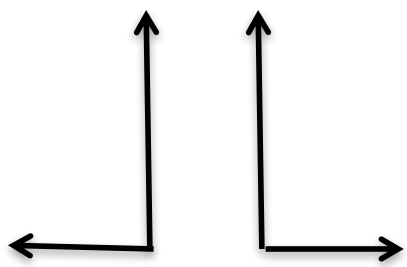
Full network coverage is important for reconstruction of gravitational wave polarization

How can we improve searches- constraints!

- Trivial constraints: time and sky location
- Less trivial example: fixed chirality

chirality





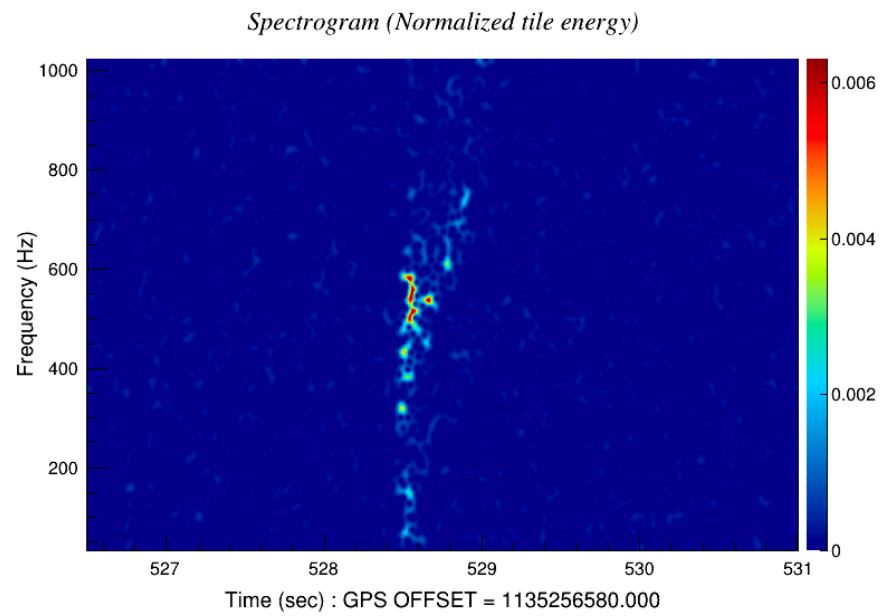
- Constraints based on signal TF patterns
- What characteristic signal features should we look at and measure?

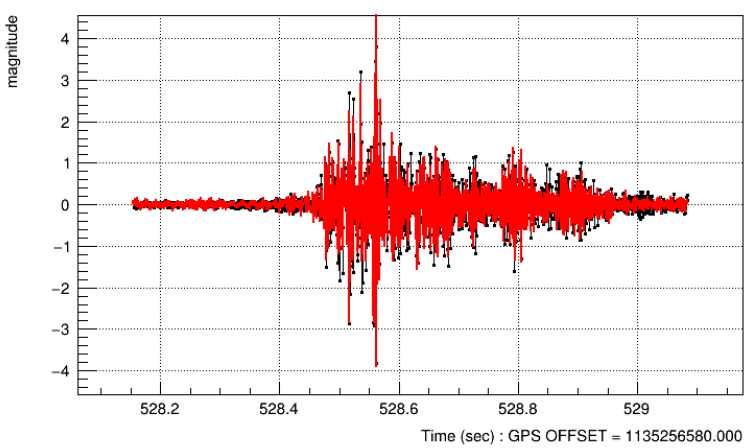
Reconstructed Waveforms

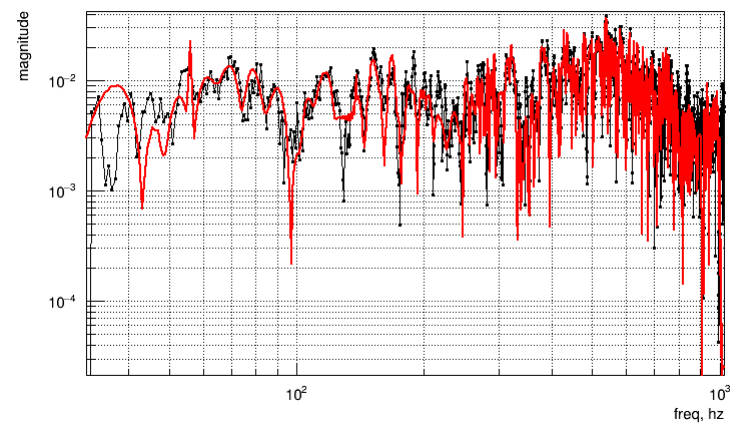
burst waveform reconstruction == de-noising
estimate $\xi(t)$ from network data

reconstruction can be improved
by using minimal signal assumptions
like chirality

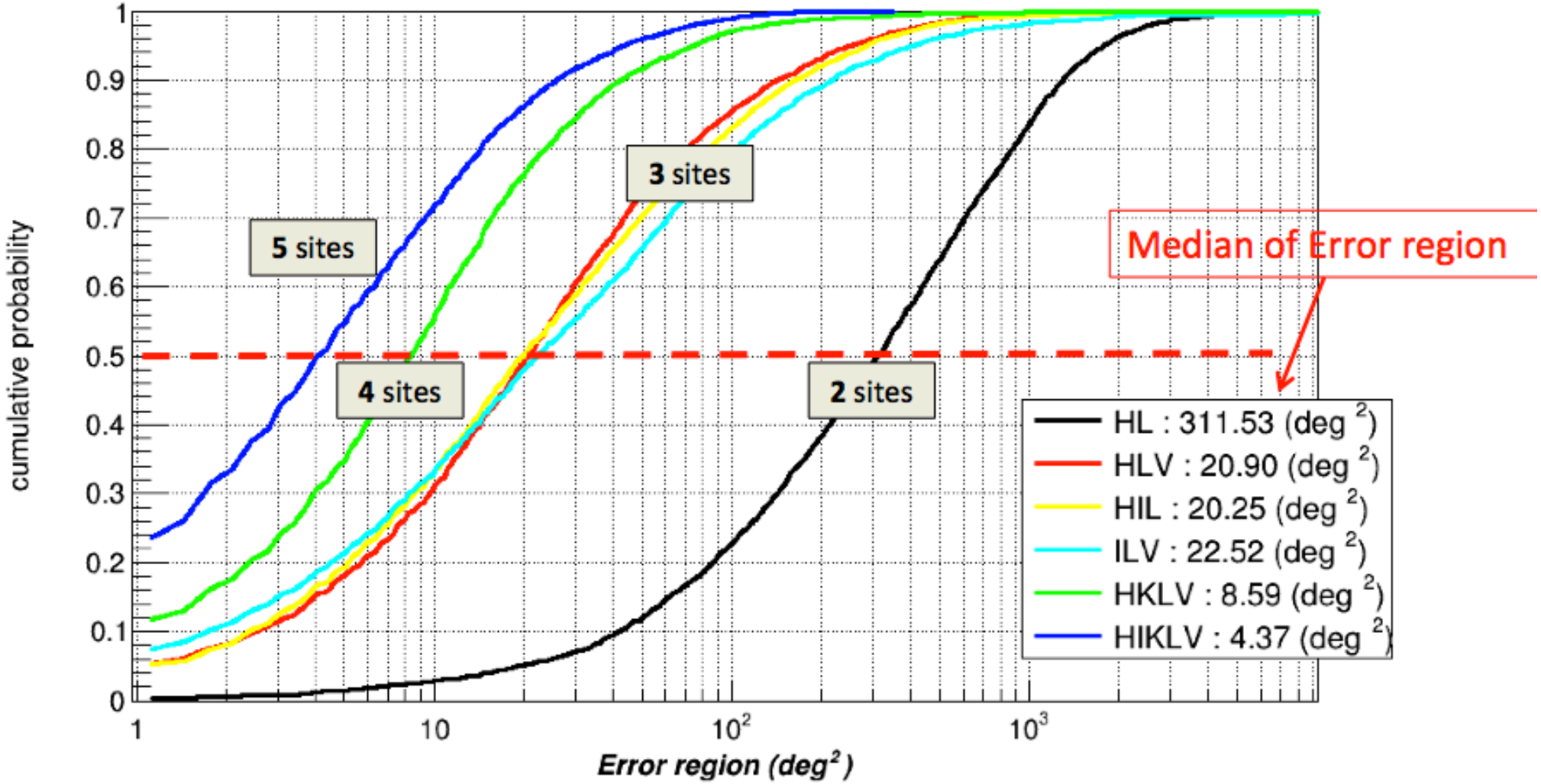
Yakunin20125







Sky localization



- Link source to possible optical or ν counterpart