Optimal detector networks for multi-messenger astronomy with transient gravitational waves

(impact of site topology)

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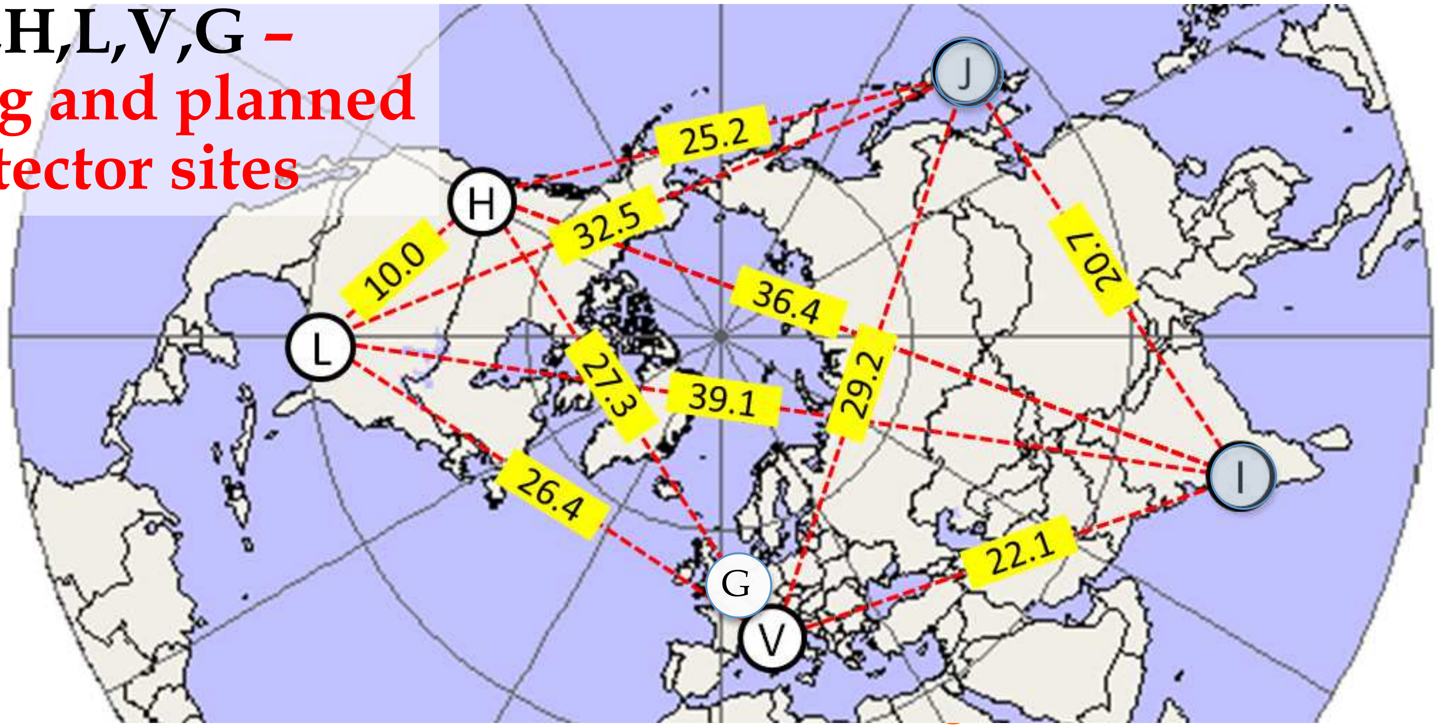
advanced (2G) detectors

I,J,H,L,V,G – existing and planned detector sites



- x10 better sensitivity than 1G
- aLIGO (H,L) and aVirgo(V) are being constructed. Plans for KAGRA (J) and LIGO-India (I), + GEO-HF (G)
  - target detection of anticipated NS-NS and possibly other sources after 2015.
  - extended network significantly enhances GW&MM (multi-messenger) observations

Network Characterization

- **Noise scaled network antenna vectors**

$$\vec{f}_+ = \frac{F_{1+}(\theta,\phi,\psi)}{\sqrt{S_1(\omega)}},\ldots,\frac{F_{K+}(\theta,\phi,\psi)}{\sqrt{S_K(\omega)}}, \quad \vec{f}_\times = \frac{F_{1\times}(\theta,\phi,\psi)}{\sqrt{S_1(\omega)}},\ldots,\frac{F_{K\times}(\theta,\phi,\psi)}{\sqrt{S_K(\omega)}}$$

S_k – single-sided power spectral density of detector noise

assume dominant polarization wave frame: $\left(\vec{f}_+(\psi)\cdot\vec{f}_\times(\psi)\right) = 0$

- **Network response** $\vec{h}_{\det}(\omega) = [\vec{f}_+,\vec{f}_\times]\begin{bmatrix} h_+(\omega) \\ h_\times(\omega) \end{bmatrix}$

- **Network noise** $S_{net} = \left(\sum_k S_k^{-1}\right)^{-1} \sim \frac{S_{\det}}{K}$

- **Network SNR** $\rho_{net} \approx \frac{F\cdot h_{rss}}{\sqrt{S_{net}}}, \quad h_{rss} = \sqrt{\int [h_+^2(\omega)+h_\times^2(\omega)]d\omega}$

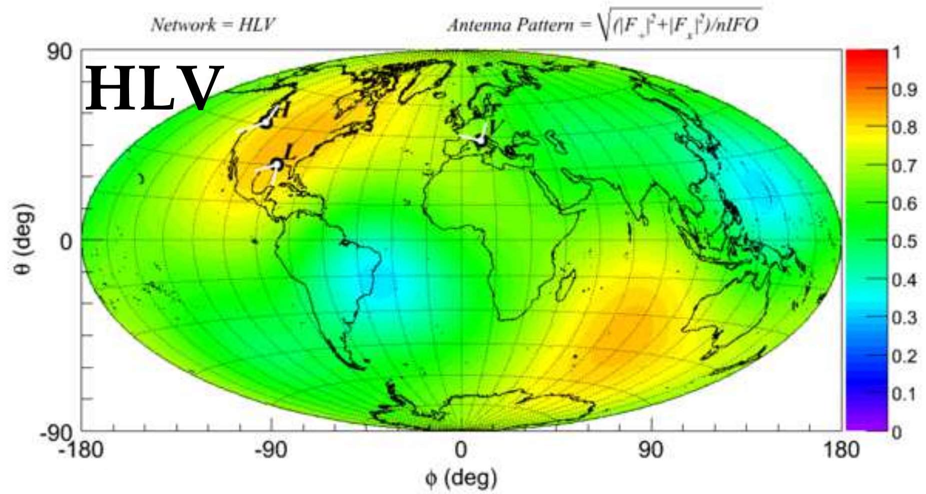
Klimenko, et al PRD 83, 102001 (2011)
Schutz, arXiv:1102.5421(2011)

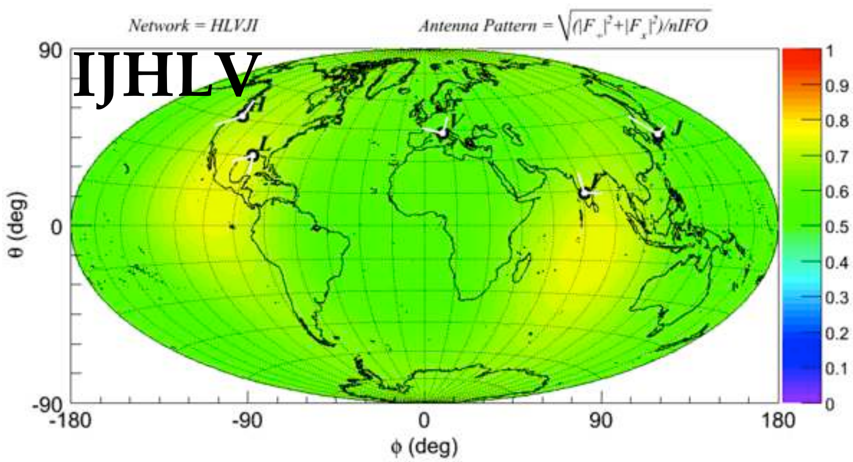
Network Acceptance

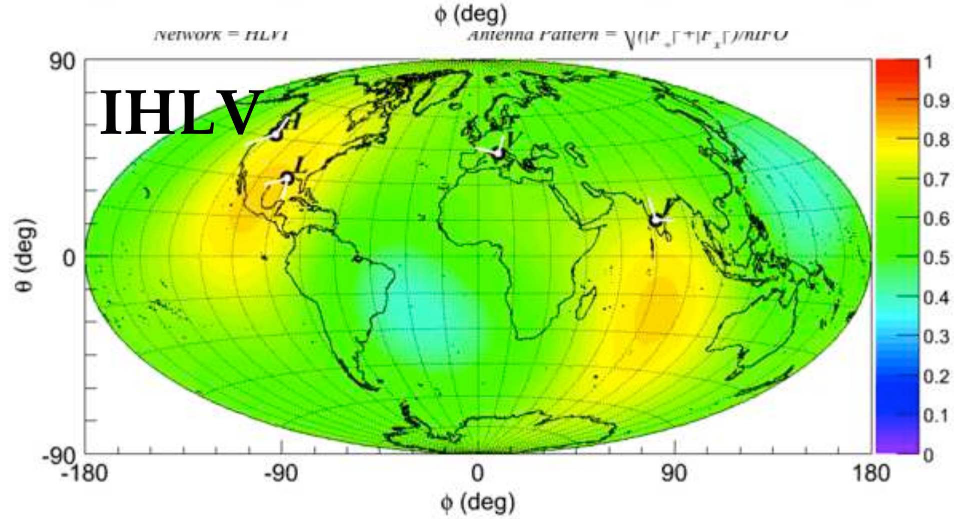
$$F = \sqrt{\left(|f_+|^2 + |f_\times|^2\right) S_{net}}$$

Antenna sensitivity w.r.t a network of omni-directional detectors (100% acceptance)

here and later for calculation of antenna patterns we assume equal sensitivity of all detectors – actual patterns are frequency dependent





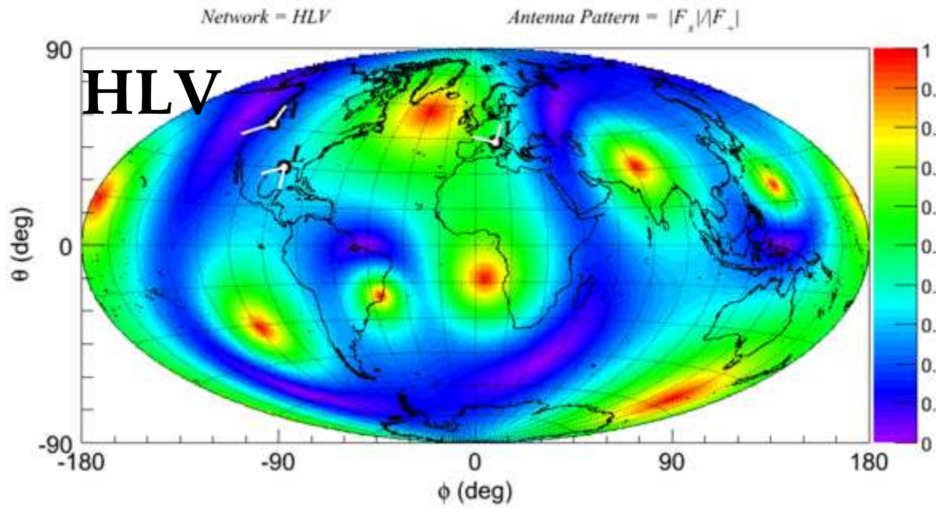


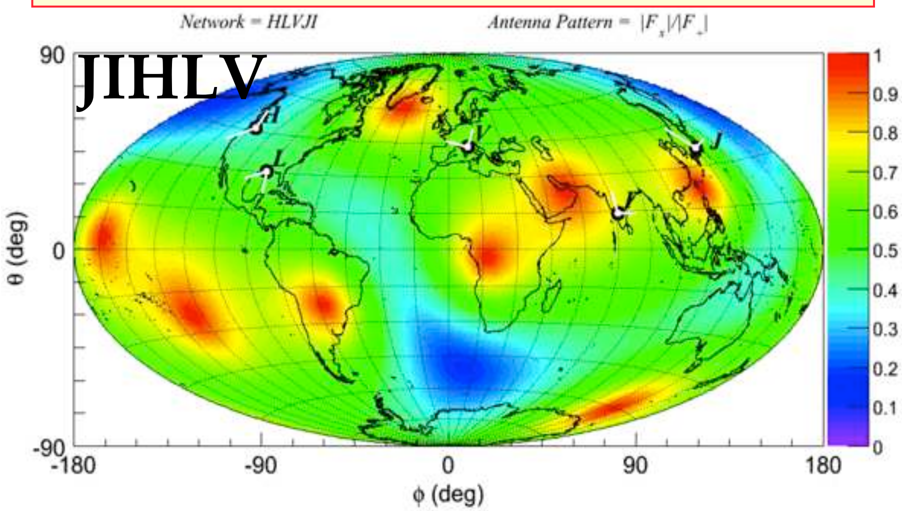
Network Alignment

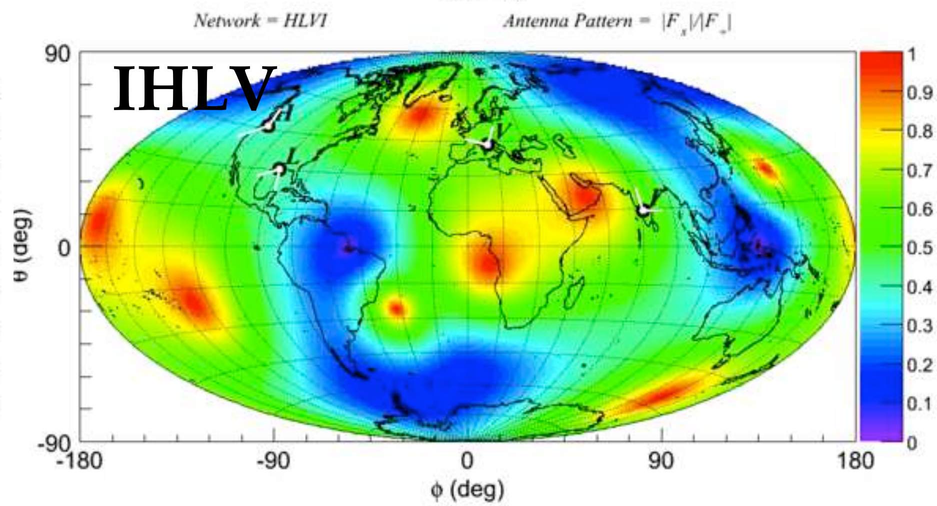
$$A = \frac{|f_\times|}{|f_+|}$$

important for reconstruction of both GW polarizations and sky localization

- **for perfectly co-aligned detectors A=0 – detect only one GW component**
- **A - contribution to total network SNR from the second component**

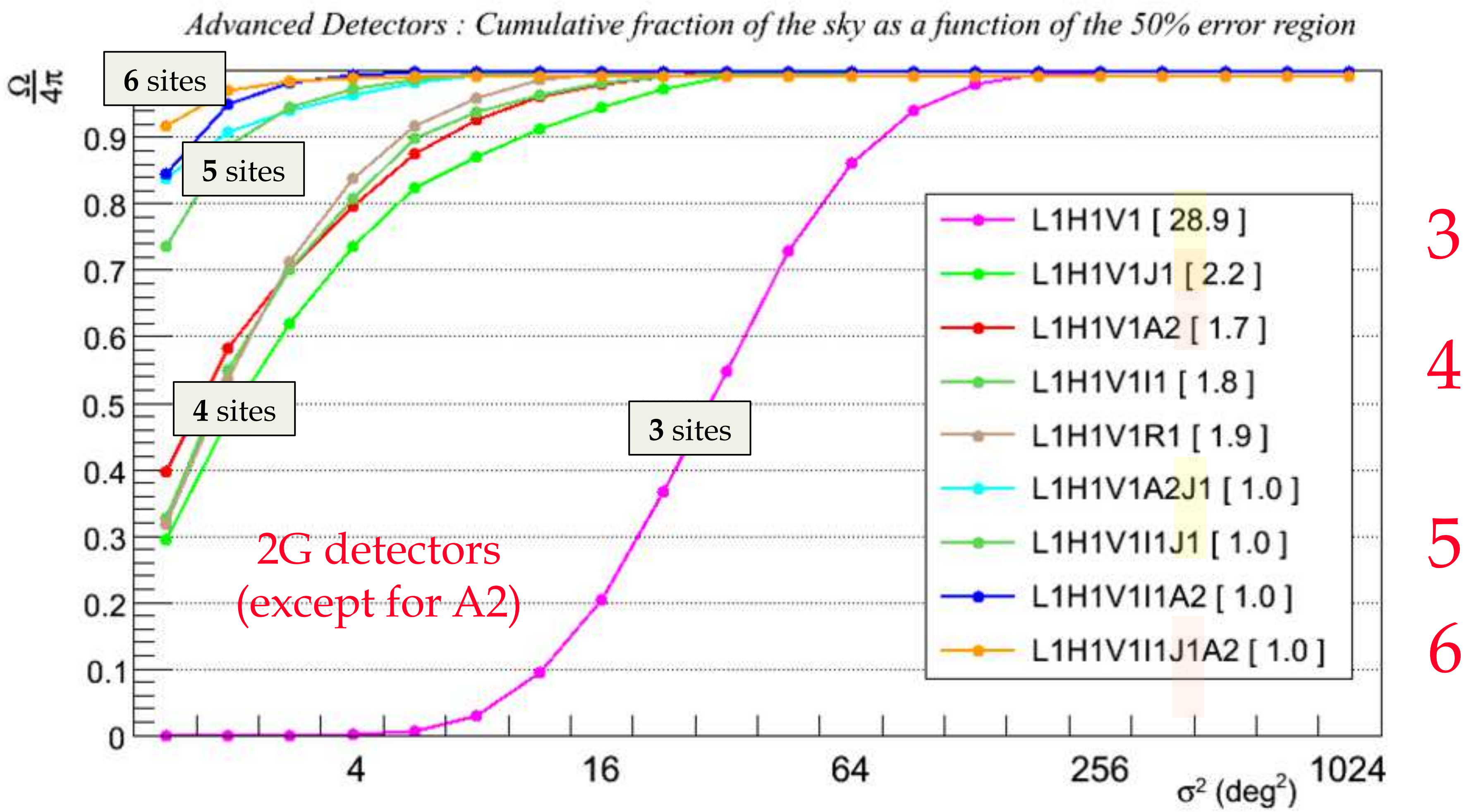






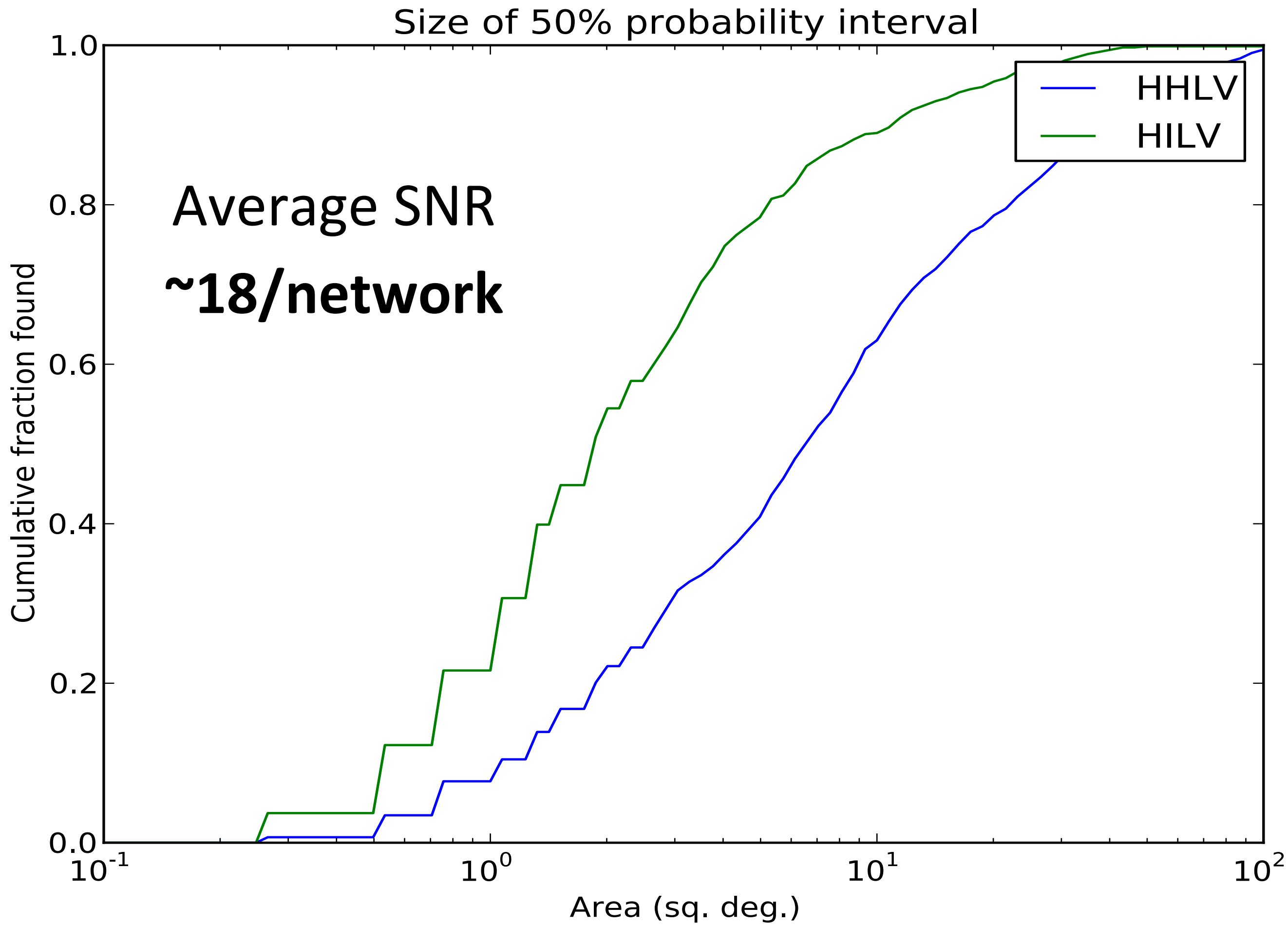
Sky localization – 50% Error Region

- Median error angle (50% CL, SNRnet<30, un-modeled sources) for reconstruction of ad-hoc signals (sine-Gaussians) in the bucket (200-300 Hz)
  - obvious observation – more sites is better



NS-NS localization (MCMC reconstruction)

Veitch et al Phys. Rev. D 85, 104045 (2012)



- **2G sky localization is compatible with FOV of many telescopes**

Optimal networks

- **2G network reconstruction performance**
  - **different detector tuning: broadband, NS-NS, HF.**
  - **fairly good source localization (~10 sq. degrees @90CL)**
    - ✓ **can be better for modeled sources**
    - ✓ **challenging for low frequency signals (150Hz and lower)**
  - **reconstruction of GW polarizations for a small fraction of sky**

- **2G network is a "discovery machine" – astroGW landscape is quite uncertain**
  - **may not be optimal in capturing astrophysics.**

However, how far is the 2G network from optimal?

3G detectors (and beyond)

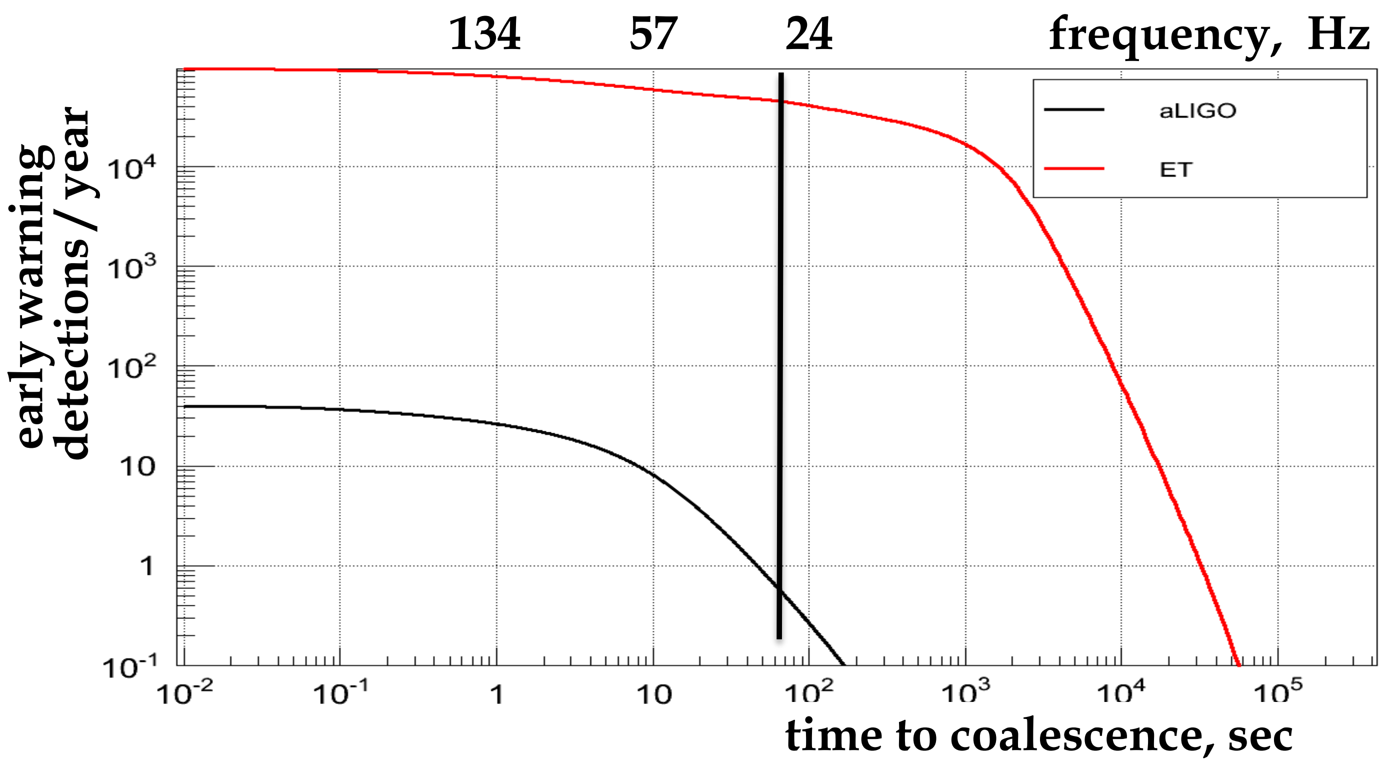
- **3G R&D has started (ET,LIGO-3G,..).**

  (detection of GWs is a prerequisite for construction of 3G detectors)

  - Improve high-frequency sensitivity (~1kHz) (high power, squeezing, tuning,..)
    - ✓core-collapse SN, NS EOS, NS f-modes,..
  - Extend 3G sensitivity to lower frequency (10Hz or less) (seismic super-isolation, underground/space, reduced thermal noise, Newtonian noise subtraction,…)
    - ✓IMBH sources (up to 10^4 Mo)
    - ✓eccentric binary black holes
    - ✓WD binaries (f<1Hz)
    - ✓NS-NS (to capture early inspiral stage f<30Hz)

Example: "Early warning" for NS-NS

- To capture EM signature, localize NS-NS before merger (T_{EM}-T_{GW} = ?)



- 1 minute warning: sky localization in frequency band f<30Hz: **λ/d ~ 1**
- 90% of SNR is accumulated before f < 150Hz (aLIGO)
- **Apart from improved sensitivity what other upgrades are desirable for MM astronomy? More sites? More detectors?**

What affects reconstruction?

- Source localization can be obtained with two methods

1. Triangulation (fails at low frequency where most of promising GW emitters – binary inspirals – are expected)

$$\Delta\Omega_{3f} = \frac{c^2}{8\pi}\frac{1}{f^2\rho_N^2 A_\perp}\sqrt{\frac{1}{\rho_1^2\rho_2^2\rho_3^2/\rho_N^6}}, \propto \left(\frac{\lambda}{d}\right)^2, \quad d = \sqrt{A_\perp}$$

L Wen, LIGO=P070020
S. Feirhurst, NJP. 11 (2009)

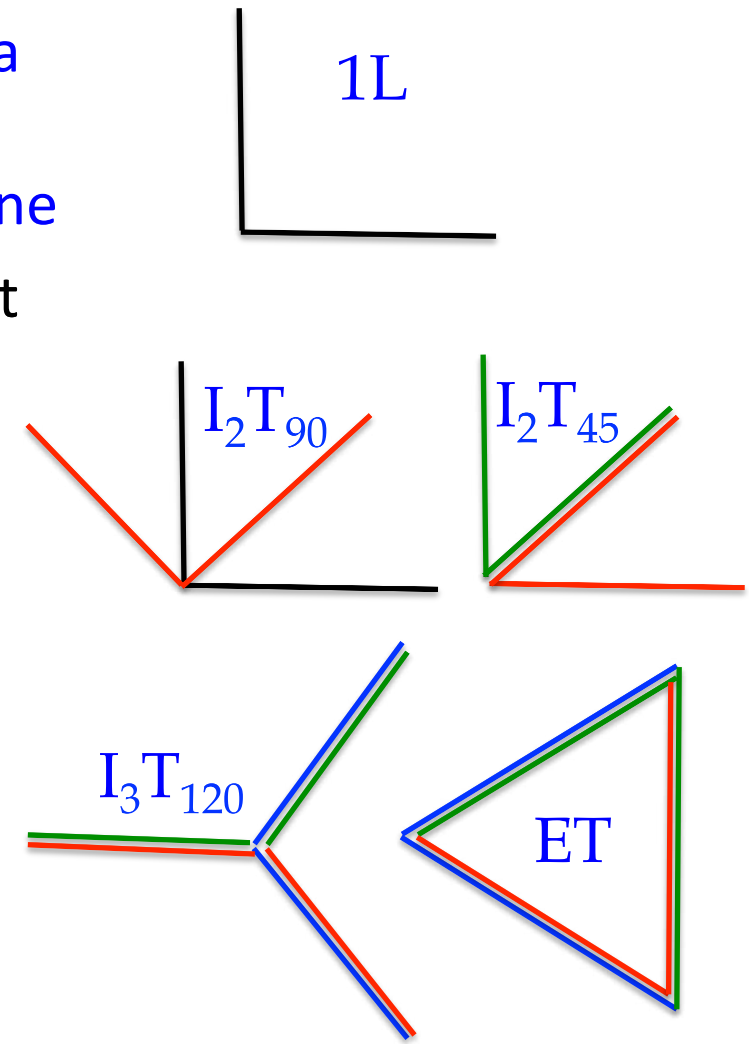
2. Network antenna coverage
    - Important for reconstruction of h+,hx and hence source parameters
    - Dominates localization at low frequency (not affected by diffraction limit)
    - Strongly depends on number of sites, locations and also site topology (number of detectors on site and orientation of their arms)
        - ✓ How do site topology affect detection & reconstruction?
        - ✓ What are optimal and potentially upgradable site topologies
        - ✓ Does it matter at all?

Invariant site topology

How to increase polarization coverage and improve sky localization?

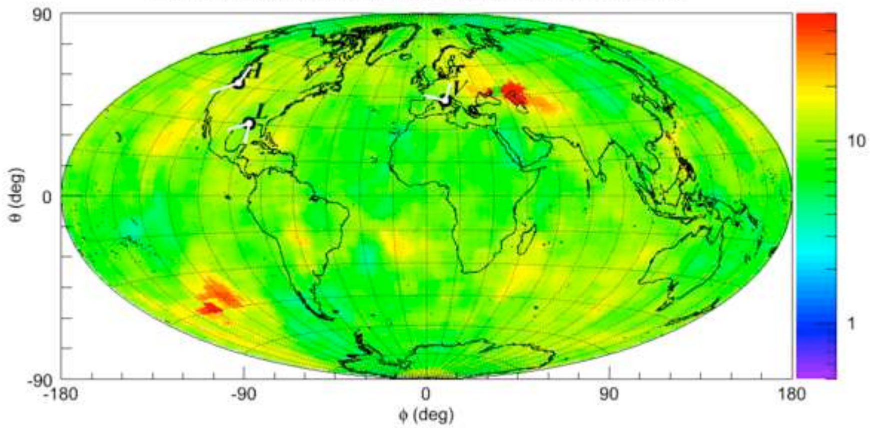
Use **invariant topology** where site antenna sensitivity does not depend on the global orientation of detector arms in the site plane

- one L-shape (1L) detector – not invariant
- Interferometric Telescopes (IT): many invariant topologies
  - 2 detectors (I_2T) - possible upgrade for L-site: build one/two more arms
  - 3 detectors (I_3T/ET)

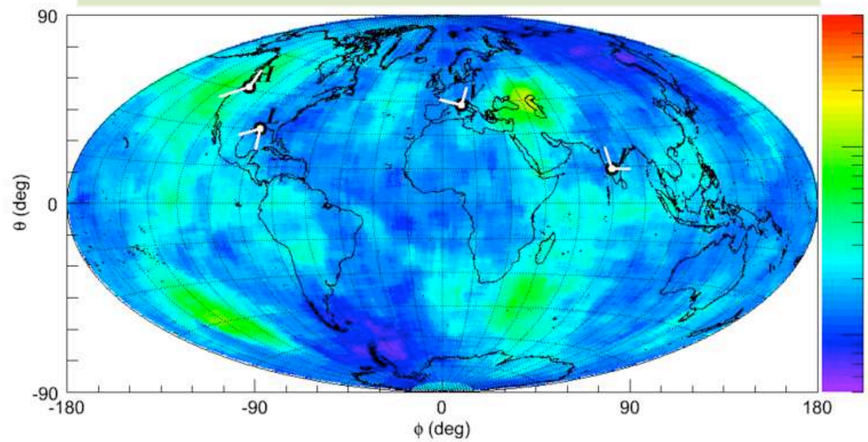


IT-India: Sky Localization @ SNR=10/detector & 50% CL

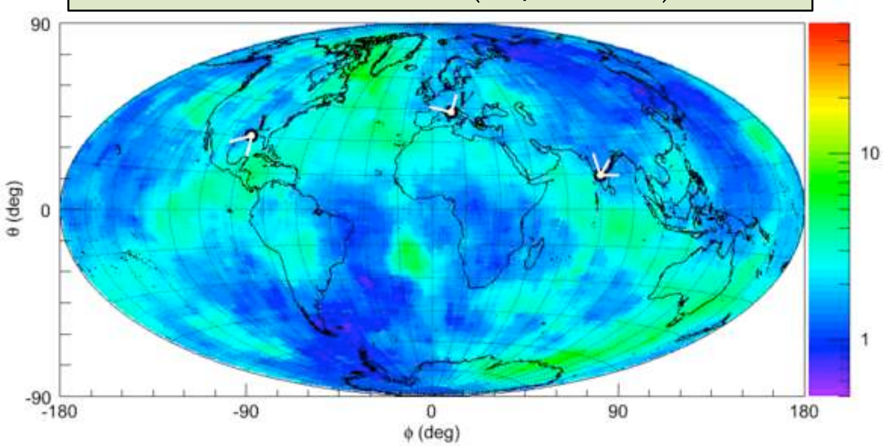
3 sites – HLV (1L sites)



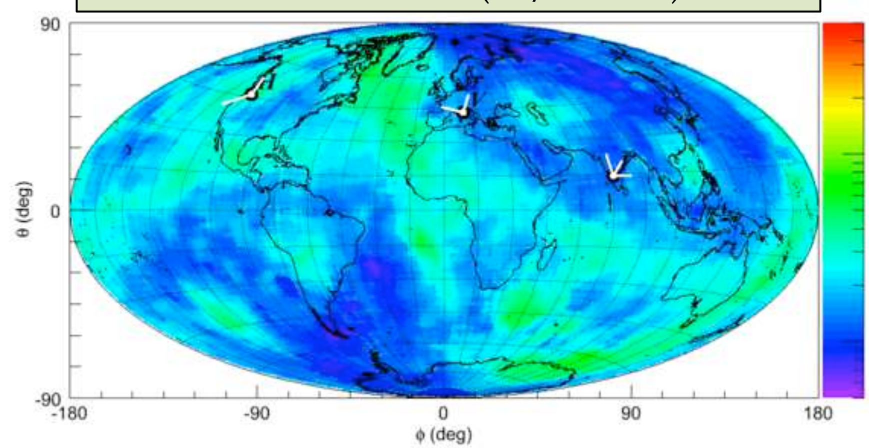
4 sites - IHLV (1L sites)



3 sites – I2I3LV (1L/IT sites)



3 sites –I2I3HV (1L/IT sites)

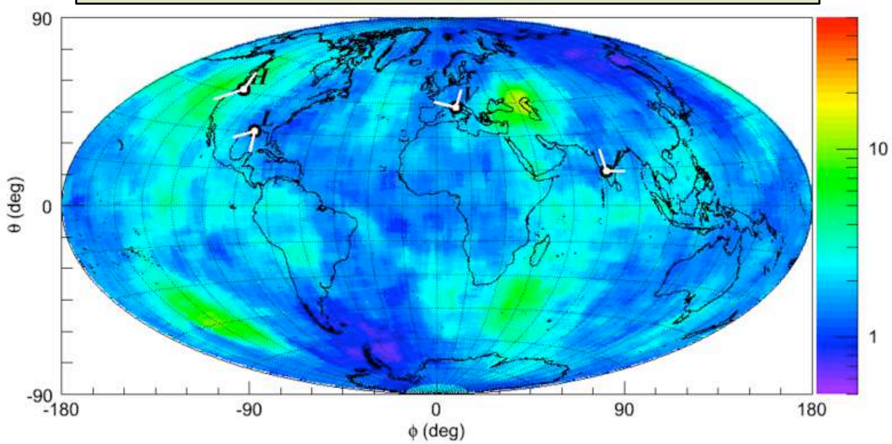


- **IT-India** (I2&I3 with $\mathbf{I_2T_{45}}$ topology) detectors instead of one L-shaped detector
  - provide resolution comparable with the 4 L-site network

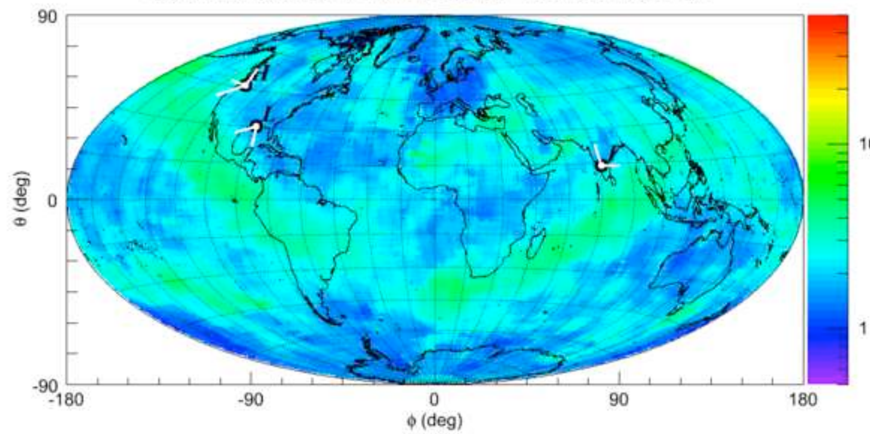
BIG EFFECT!!

IT-Hanford: Sky Localization @ SNR=10/detector & 50% CL

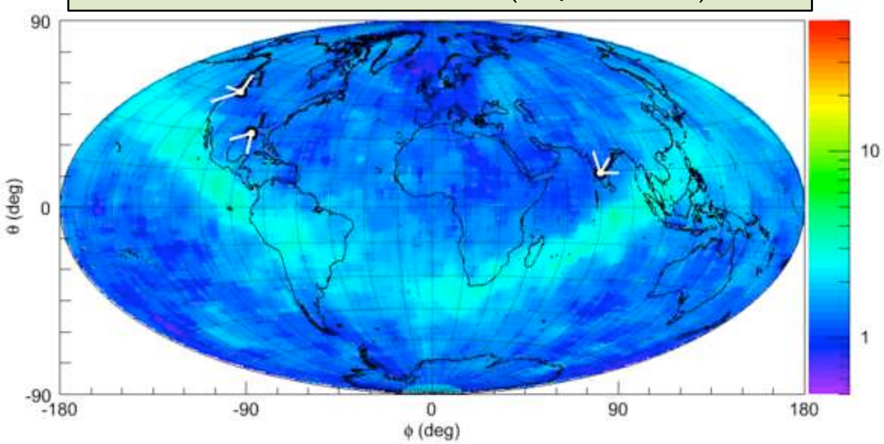
4 sites – IHLV (1L sites)



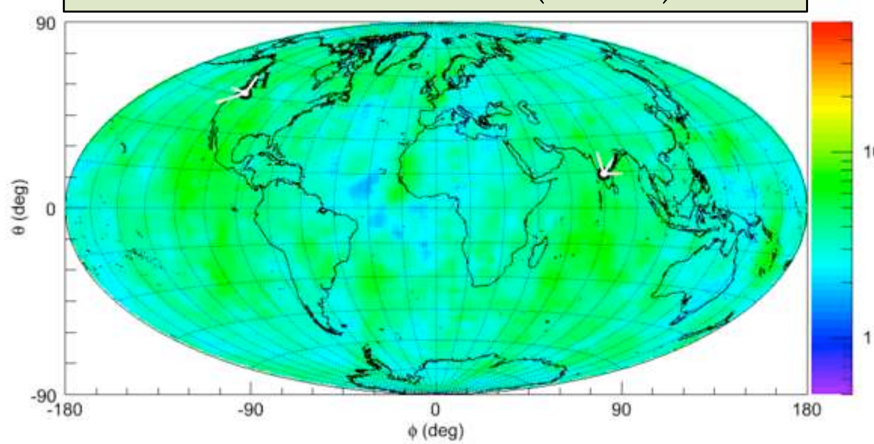
3 sites - H2H3LV (1L/IT sites)



3 sites – I2I3H2H3L (1L/IT sites)



2 sites!!! –I2I3H2H3 (IT sites)

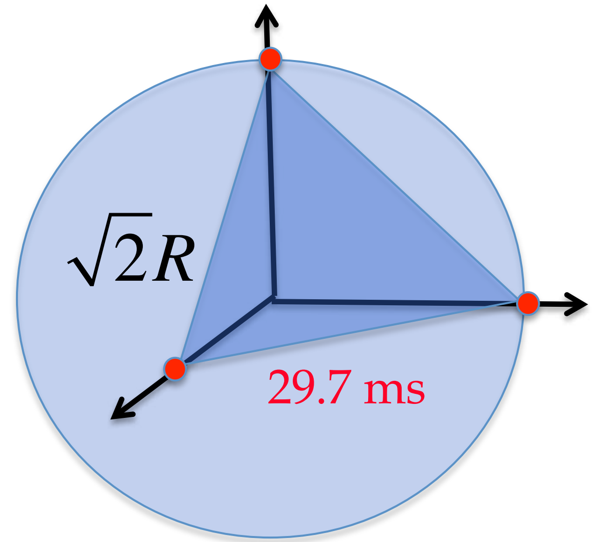


- Telescope in Hanford: **I_2T** - H2&H3
  - excellent reconstruction with 3-site networks
  - much better than the L-shape HLV

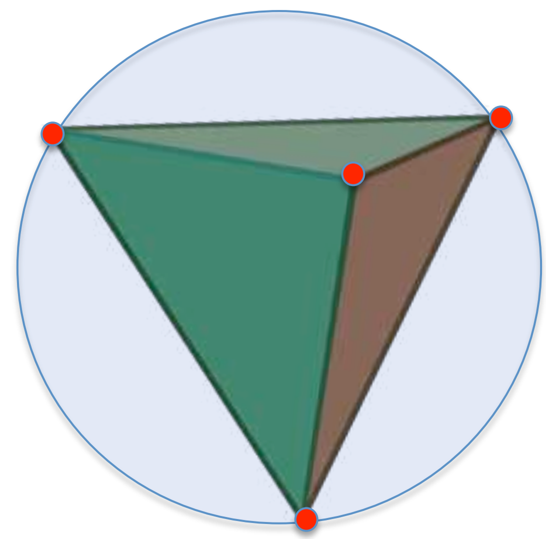
can't ignore site topology designing future networks

Optimal network configurations

- 3-site networks
  - triangulation is best for Big Circle network : $\sqrt{3}R$
  - But optimal network is Cartesian:
  - JLV&JHV very close to Cartesian

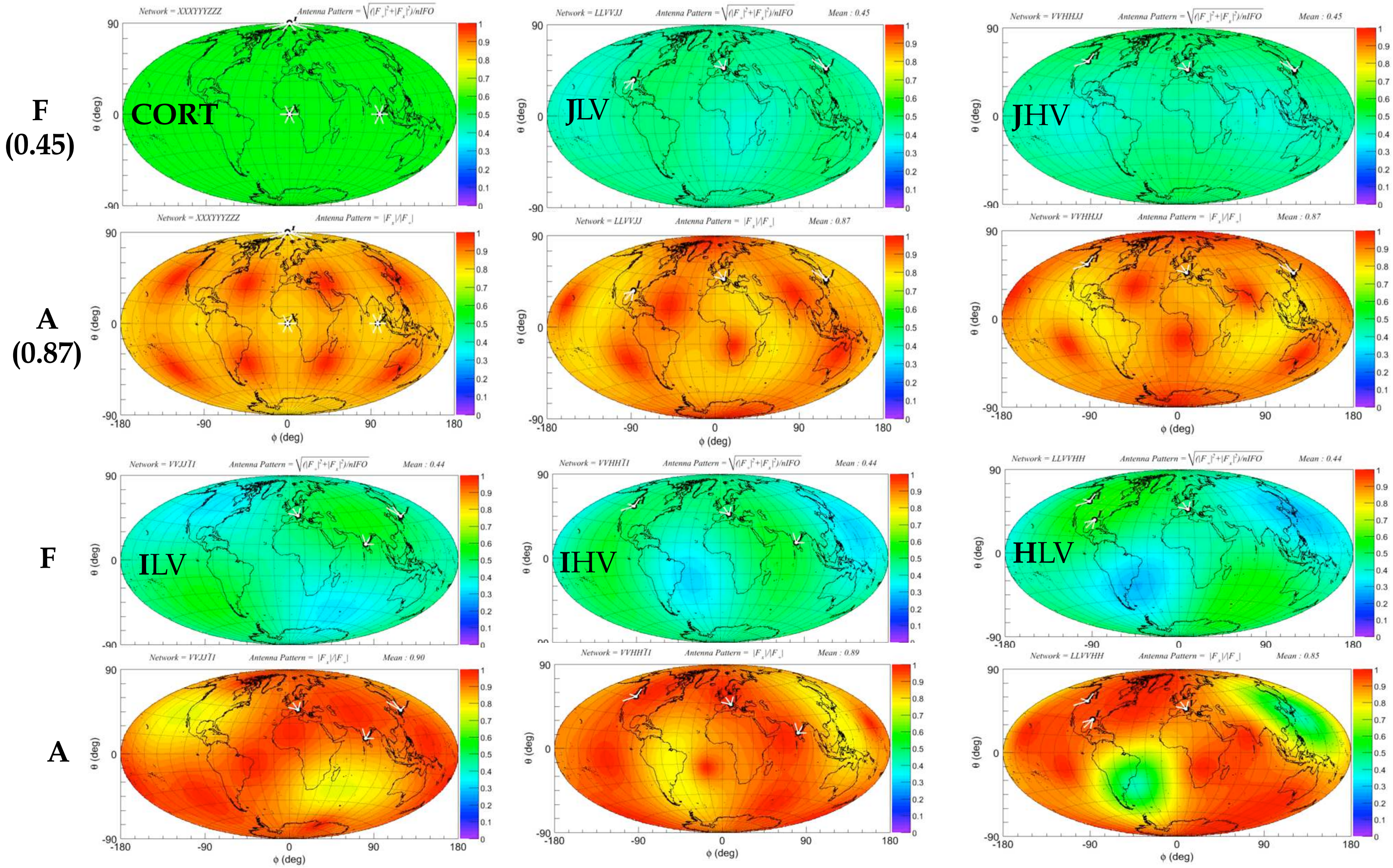


- 4-site networks
  - Best triangulation and antenna coverage is obtained for tetrahedron
  - Extending JLV/JHV sites, closest to tetrahedron is a site either in Australia or Argentina (excluding the most optimal location at South Pole)



- How far are existing and planned network sites from optimal?

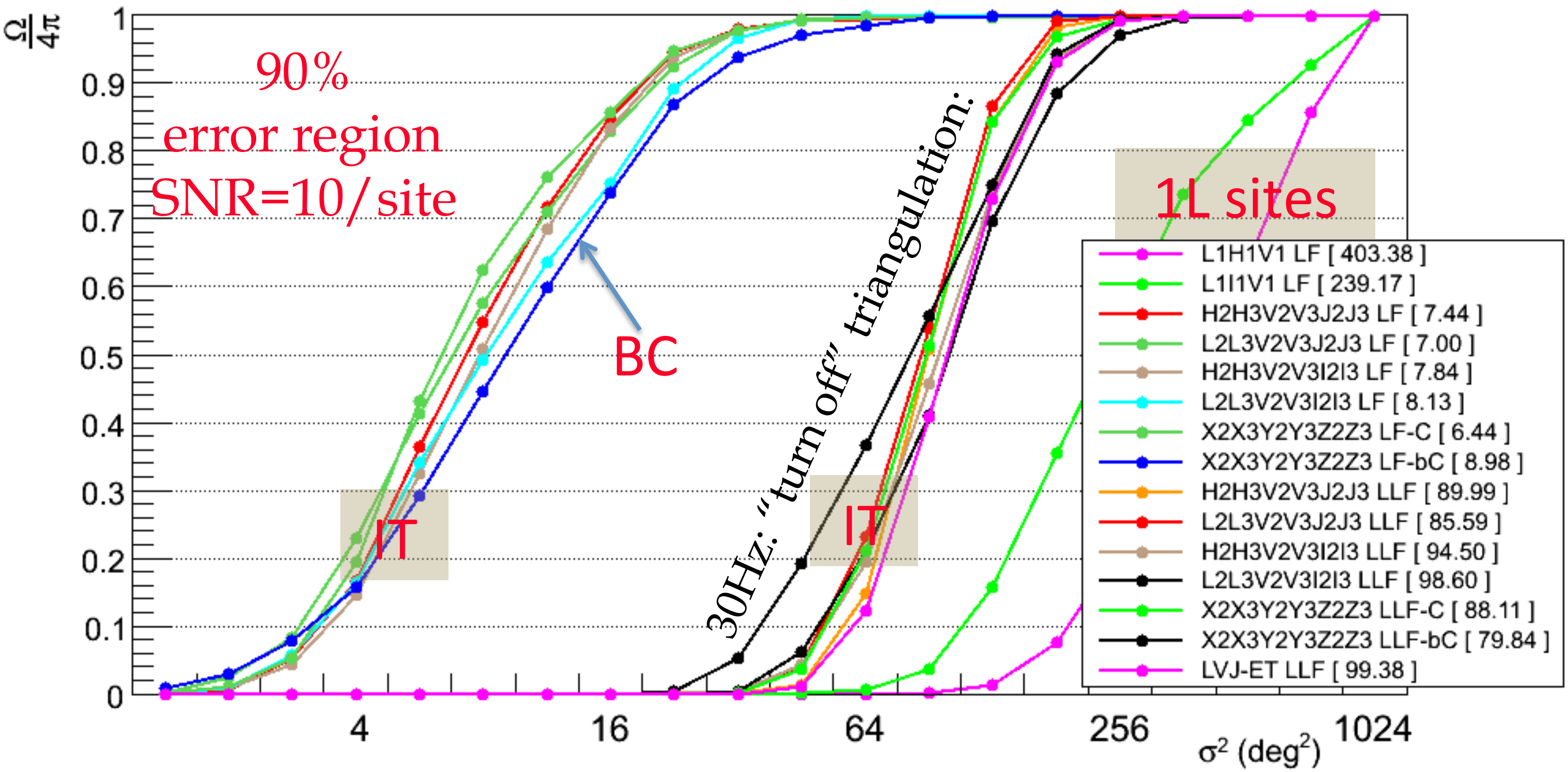
Coverage with 3 IT-site networks



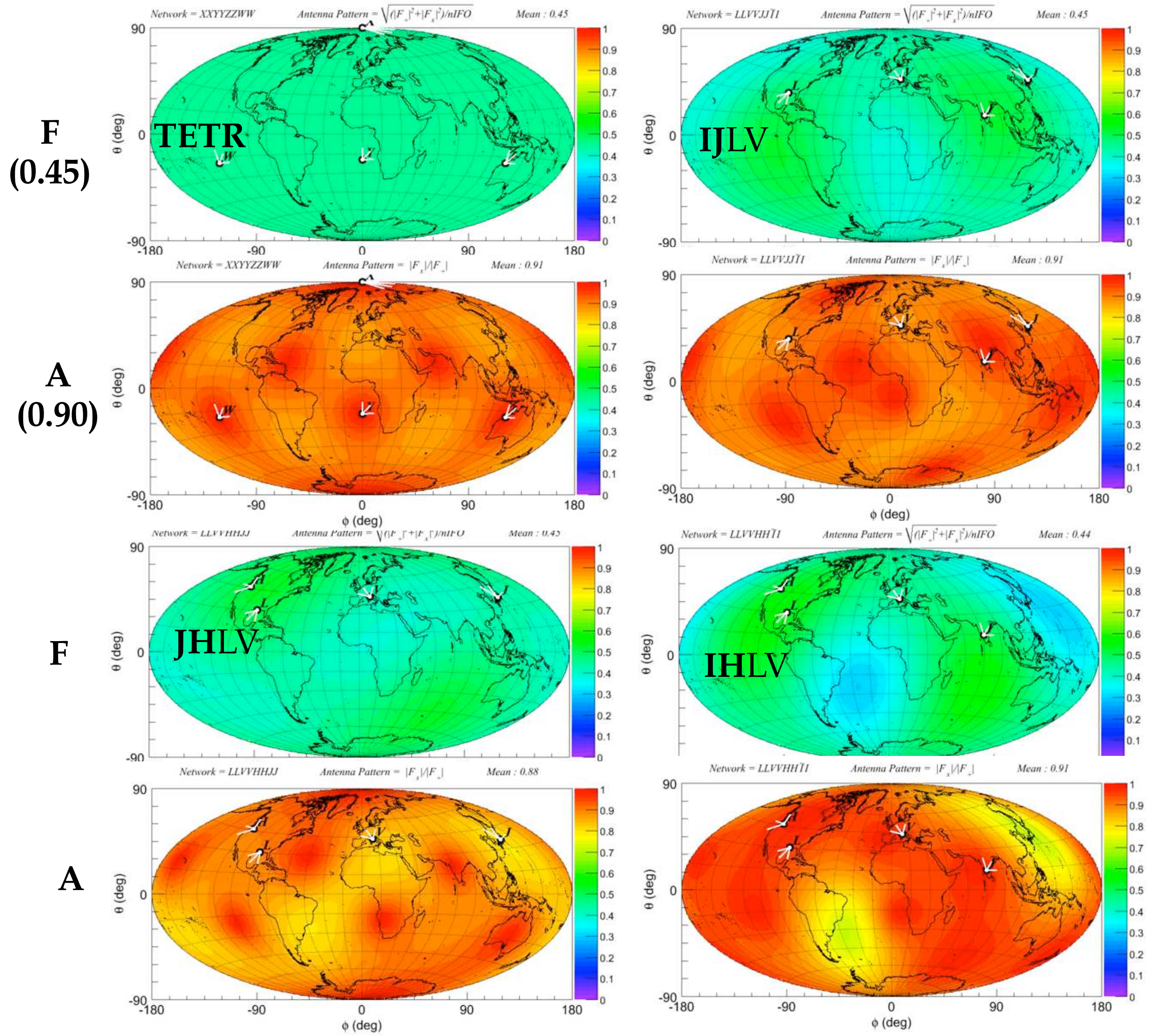
- JLV & JHV are close to optimal. IJH, IHV, ILV, HLV are less optimal but anyway provide much better coverage than 1L-topology networks

3-site networks: How far from optimal?

- Cartesian is better than BigCircle, which has better triangulation
- sky localization of 3 IT-site networks (including India) is close to optimal
  - >30x better than networks with 3 1L sites (same SNR 10/site)



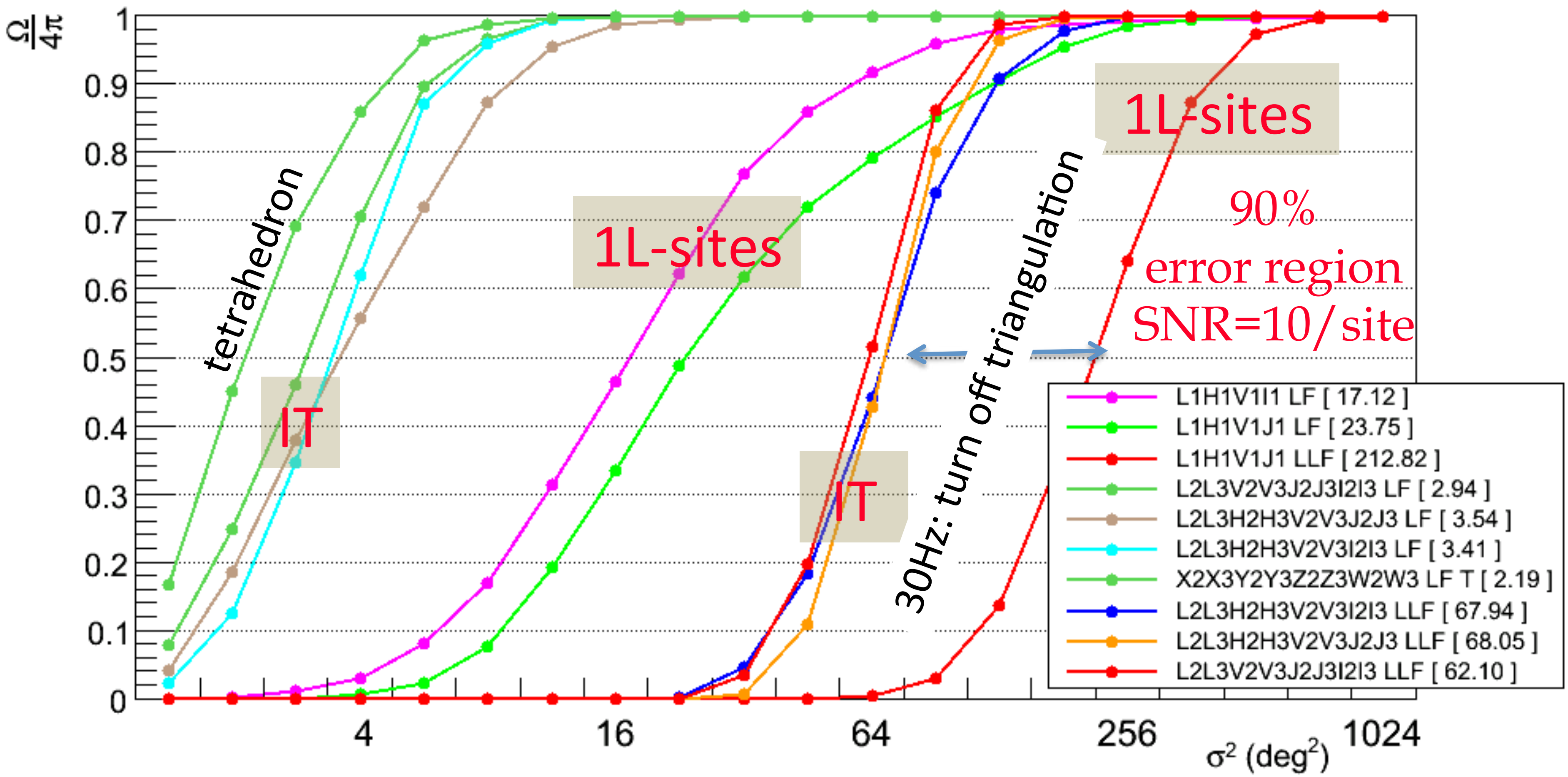
coverage with 4 IT-site networks



- Excellent coverage close to tetrahedron

4-site networks: How far from optimal?

- Tetrahedron is optimal, but 4 IT-site networks formed with the IJHLV sites are comparable
- Both 3&4 IT-sites are much better than 4 1L sites
- decent resolution @30Hz with both 3&4 IT sites



Summary

- Existing (H,L,V) and planned (I,J) site locations are close to optimal. This network has a great potential to produce exciting science … and a lot of room for improvement
- Localization of GW sources benefits (particularly at low frequency) from full coverage of source polarizations
- Invariant topology significantly improves reconstruction and could be a viable upgrade for 2G network after first detections:
  - upgrade of site topology is as important as building new sites
  - may not be possible for some existing sites due to hard constraints: geography, buildings, … A mixture of different site topologies can be used: more IT sites – better.