JGRG 20

GRAVITATIONAL ASTRONOMY WITH LIGO, VIRGO, AND LGCT

Bernard Schutz
Albert Einstein Institute, Potsdam, Germany
and
School of Physics and Astronomy, Cardiff University, Wales

2010
CONGRATULATIONS!

- Congratulations to Kei-Ichi and Takashi on their 60th!

2010
CONGRATULATIONS!

- Congratulations to Kei-Ichi and Takashi on their 60th!

- Congratulations to the JGRG meeting series for reaching 20!

2010
CONGRATULATIONS!

- Congratulations to Kei-Ichi and Takashi on their 60th!
- Congratulations to the JGRG meeting series for reaching 20!
- Congratulations to the LCGT detector for being born!

OUTLINE

OUTLINE

- Current progress on GW detection
  - LSC and VIRGO
  - LISA
  - LCGT

OUTLINE

- Current progress on GW detection
  - LSC and VIRGO
  - LISA
  - LCGT
- Networks of detectors and their capabilities
  - Expectations of the standard LIGO-VIRGO Advanced array
  - Gains from adding LCGT to it
  - New development: LIGO South in Australia

OUTLINE

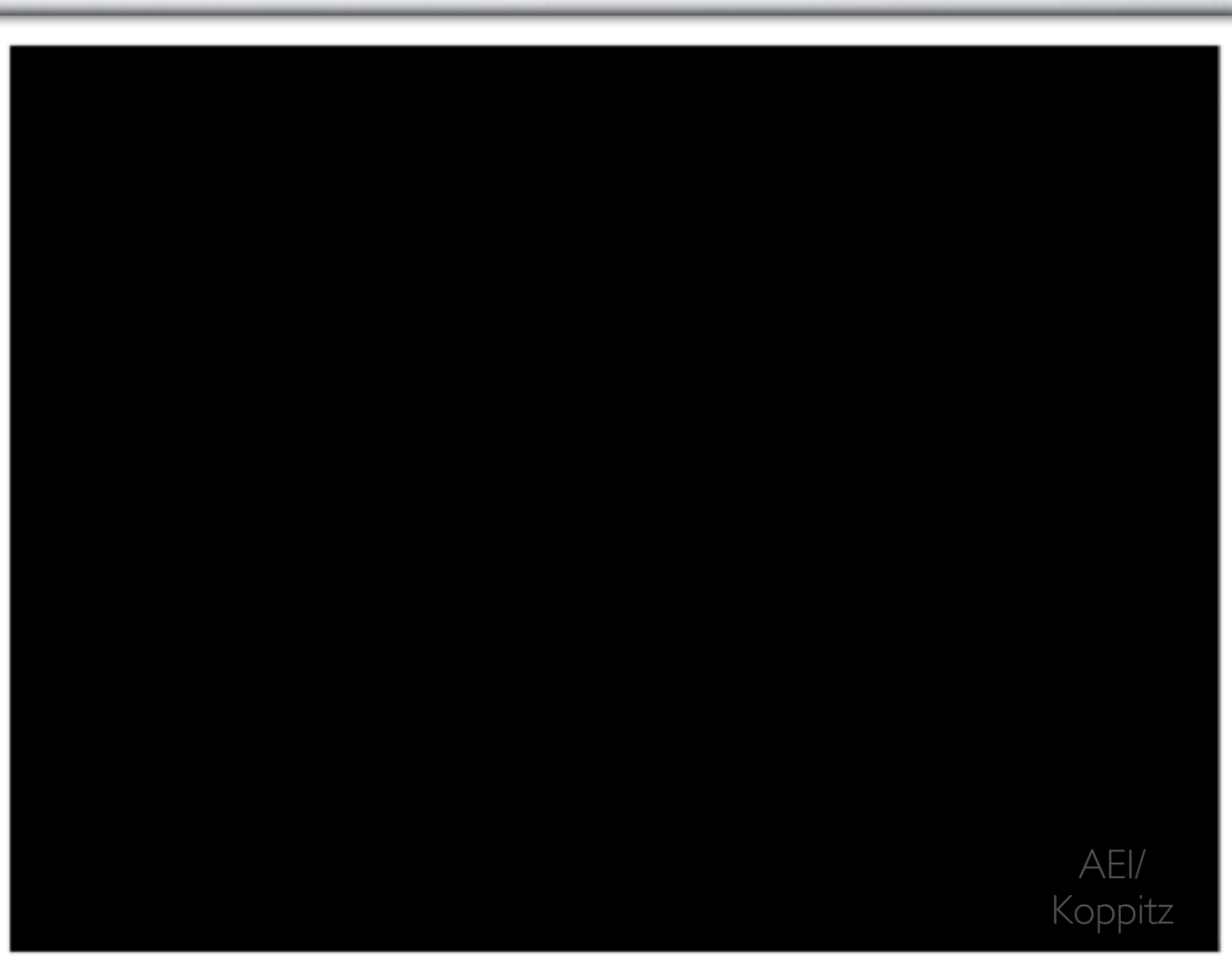
- Current progress on GW detection
  - LSC and VIRGO
  - LISA
  - LCGT
- Networks of detectors and their capabilities
  - Expectations of the standard LIGO-VIRGO Advanced array
  - Gains from adding LCGT to it
  - New development: LIGO South in Australia
- Physics and astronomy with a worldwide network
  - Importance of doing the data analysis with full data pooling

LISTENING TO THE UNIVERSE

The first time we actually *listen* to the universe, it is likely to sound like this.

LISTENING TO THE UNIVERSE

The first time we actually *listen* to the universe, it is likely to sound like this.



LISTENING TO GRAVITATIONAL WAVES

VIRGO, Pisa

LISTENING TO GRAVITATIONAL WAVES

- GW astronomy is all about listening to the spacetime vibrations emitted by distant objects.

LISTENING TO GRAVITATIONAL WAVES

- GW astronomy is all about listening to the spacetime vibrations emitted by distant objects.
- Our detectors are like microphones, or like our ears
  - receiving all the time: always "on"
  - omnidirectional, physically small compared to wavelength

LISTENING TO GRAVITATIONAL WAVES

- GW astronomy is all about listening to the spacetime vibrations emitted by distant objects.
- Our detectors are like microphones, or like our ears
  - receiving all the time: always "on"
  - omnidirectional, physically small compared to wavelength
- Our data is 1-D, all signals superimposed
  - analysis is helped by knowing what signal to expect
  - direction-finding from "tricks", like Doppler or time-delays

LISTENING TO GRAVITATIONAL WAVES

- GW astronomy is all about listening to the spacetime vibrations emitted by distant objects.
- Our detectors are like microphones, or like our ears
  - receiving all the time: always "on"
  - omnidirectional, physically small compared to wavelength
- Our data is 1-D, all signals superimposed
  - analysis is helped by knowing what signal to expect
  - direction-finding from "tricks", like Doppler or time-delays
- GW detection, like sound recording, offers
  - "seeing" in the dark
  - monitoring for unexpected transients

THINGS WE EXPECT

THINGS WE EXPECT

- Binary neutron star coalescence
  - "Best" rate density estimate: 10^{-4} yr^{-1}(MWEG)$^{-1}$ ~ 5×10^{-6} yr^{-1} Mpc^{-3} (Abbott et al 2010). Uncertainty: ×(0.01→10)
  - Could be associated with short hard gamma-ray bursts, but only when gamma-beam points at us (1% of the time?)
  - Physics: NS masses, EOS, populations, gamma-burst afterglows, local H_0

THINGS WE EXPECT

- Binary neutron star coalescence
  - "Best" rate density estimate: 10^{-4} yr^{-1}(MWEG)$^{-1}$ ~ 5×10^{-6} yr^{-1} Mpc^{-3} (Abbott et al 2010). Uncertainty: ×(0.01→10)
  - Could be associated with short hard gamma-ray bursts, but only when gamma-beam points at us (1% of the time?)
  - Physics: NS masses, EOS, populations, gamma-burst afterglows, local H_0
- NS-BH coalescence
  - Best rate density: 0.03×NS-NS rate density; also could be gamma-bursts

THINGS WE EXPECT

- Binary neutron star coalescence
  - "Best" rate density estimate: 10^{-4} yr^{-1}(MWEG)$^{-1}$ ~ 5×10^{-6} yr^{-1} Mpc^{-3} (Abbott et al 2010). Uncertainty: ×(0.01→10)
  - Could be associated with short hard gamma-ray bursts, but only when gamma-beam points at us (1% of the time?)
  - Physics: NS masses, EOS, populations, gamma-burst afterglows, local H_0
- NS-BH coalescence
  - Best rate density: 0.03×NS-NS rate density; also could be gamma-bursts
- BH-BH coalescence
  - Best rate density: 0.004×NS-NS rate density; merger event important for total signal to noise ratio (SNR)

THINGS WE MIGHT DETECT

THINGS WE MIGHT DETECT

- Supernovas from gravitational collapse.
  - signal expected to be weak, maybe detectable from nearest few galaxies: 1 per 10-50 years?
  - coincidence with neutrino observations would be helpful

THINGS WE MIGHT DETECT

- Supernovas from gravitational collapse.
  - signal expected to be weak, maybe detectable from nearest few galaxies: 1 per 10-50 years?
  - coincidence with neutrino observations would be helpful
- Spinning neutron stars: GW pulsars
  - already setting strong limits, few reliable predictions of *h*, long integration times required

THINGS WE MIGHT DETECT

- Supernovas from gravitational collapse.
  - signal expected to be weak, maybe detectable from nearest few galaxies: 1 per 10-50 years?
  - coincidence with neutrino observations would be helpful
- Spinning neutron stars: GW pulsars
  - already setting strong limits, few reliable predictions of *h*, long integration times required
- Accreting neutron stars in LMXBs (Bildsten)
  - very difficult signal analysis, marginal chance of detection

THINGS WE MIGHT DETECT

- Supernovas from gravitational collapse.
  - signal expected to be weak, maybe detectable from nearest few galaxies: 1 per 10-50 years?
  - coincidence with neutrino observations would be helpful
- Spinning neutron stars: GW pulsars
  - already setting strong limits, few reliable predictions of *h*, long integration times required
- Accreting neutron stars in LMXBs (Bildsten)
  - very difficult signal analysis, marginal chance of detection
- Vibrating NSs
  - excited by glitches, explosions of accreted gas, emit from quasi-normal modes
  - high-frequency source, could be seen by GEO during Advanced LIGO upgrade
  - asteroseismology: capable of giving first insight into NS interior

THINGS WE HOPE FOR

THINGS WE HOPE FOR

- Stochastic background if $\Omega_{gw} > 10^{-10}$
  - inflation predictions pessimistic, other mechanisms (phase transitions, branes) possible

THINGS WE HOPE FOR

- Stochastic background if $\Omega_{gw} > 10^{-10}$
  - inflation predictions pessimistic, other mechanisms (phase transitions, branes) possible
- Cosmic string bursts
  - characteristic waveform, easy to identify

THINGS WE HOPE FOR

- Stochastic background if $\Omega_{gw} > 10^{-10}$
  - inflation predictions pessimistic, other mechanisms (phase transitions, branes) possible
- Cosmic string bursts
  - characteristic waveform, easy to identify
- Low-mass primordial compact object binaries

THINGS WE HOPE FOR

- Stochastic background if $\Omega_{gw} > 10^{-10}$
  - inflation predictions pessimistic, other mechanisms (phase transitions, branes) possible
- Cosmic string bursts
  - characteristic waveform, easy to identify
- Low-mass primordial compact object binaries
- Other dark matter structures, evidence for branes, …

THINGS WE HOPE FOR

- Stochastic background if $\Omega_{gw} > 10^{-10}$
  - inflation predictions pessimistic, other mechanisms (phase transitions, branes) possible
- Cosmic string bursts
  - characteristic waveform, easy to identify
- Low-mass primordial compact object binaries
- Other dark matter structures, evidence for branes, …
- What is YOUR favorite?

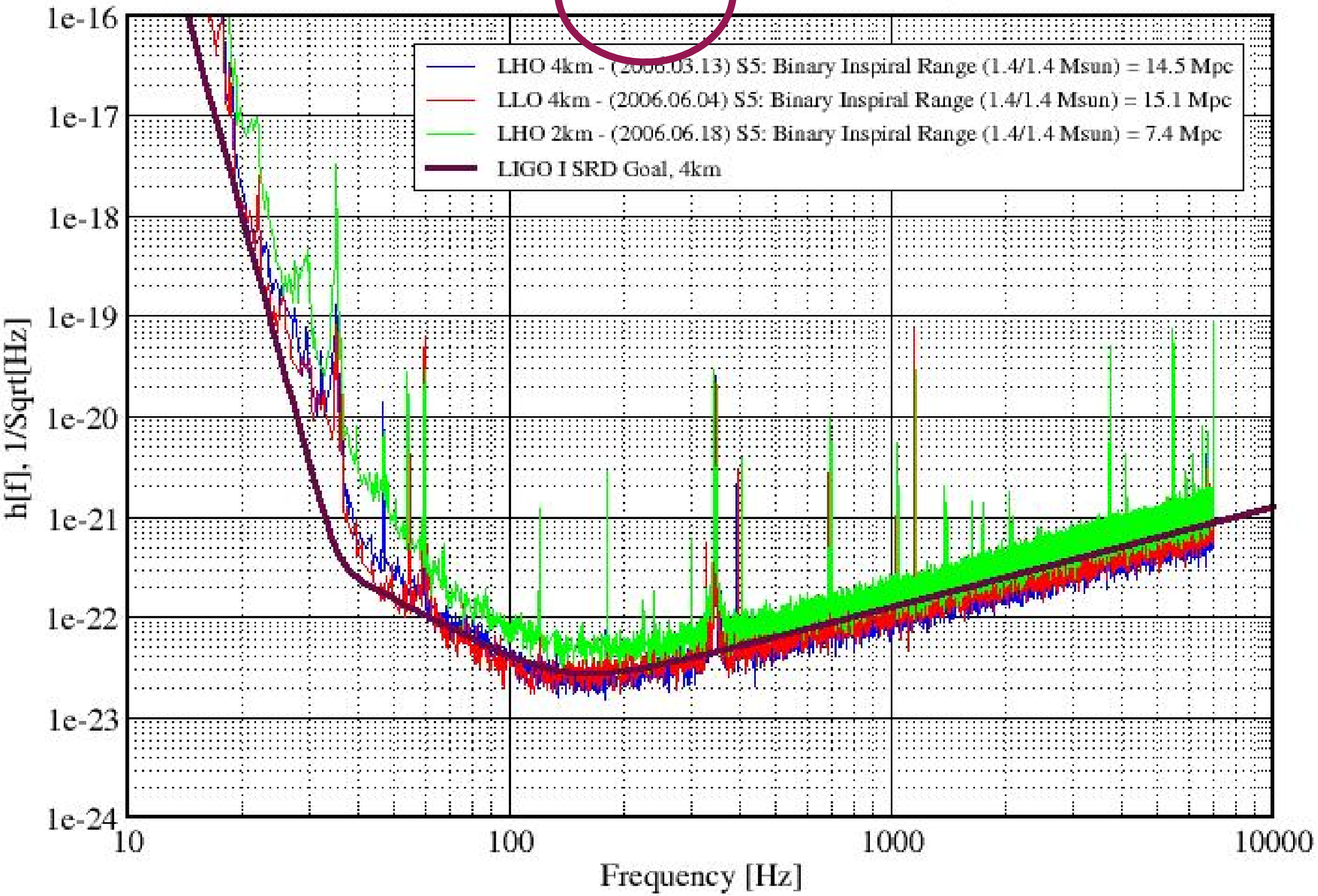
PROGRESS SO FAR: L-V

PROGRESS SO FAR: L-V

- LIGO + GEO (the detectors of the LSC) and VIRGO form the LSC-VIRGO collaboration, and publish jointly.
- 50 observational upper-limit papers published so far
- so far we have a few months of 3-detector data, 3 years of 2-detector data at first stage sensitivity
- best upper limits so far on Crab pulsar GW emission and on the GW stochastic background at any frequency

Strain Sensitivity for the LIGO 4km Interferometers

S5 Performance - June 2006 LIGO-G060293-01-Z



ADVANCED DETECTORS

ADVANCED DETECTORS

- Soon LIGO and VIRGO will rebuild for x5-10 improvement in sensitivity and range: Advanced detectors fully operational 2016 (?).

ADVANCED DETECTORS

- Soon LIGO and VIRGO will rebuild for x5-10 improvement in sensitivity and range: Advanced detectors fully operational 2016 (?).
- Mainly they will use technologies developed and tested in GEO600: signal recycling, monolithic suspensions, high-power lasers, squeezed light.

ADVANCED DETECTORS

- Soon LIGO and VIRGO will rebuild for x5-10 improvement in sensitivity and range: Advanced detectors fully operational 2016 (?).
- Mainly they will use technologies developed and tested in GEO600: signal recycling, monolithic suspensions, high-power lasers, squeezed light.
- During rebuild, GEO600 will operate with enhanced sensitivity above 1 kHz: GEO-HF.

ADVANCED DETECTORS

- Soon LIGO and VIRGO will rebuild for x5-10 improvement in sensitivity and range: Advanced detectors fully operational 2016 (?).
- Mainly they will use technologies developed and tested in GEO600: signal recycling, monolithic suspensions, high-power lasers, squeezed light.
- During rebuild, GEO600 will operate with enhanced sensitivity above 1 kHz: GEO-HF.
- LIGO plans 2 full-scale detectors at Hanford, 1 at Livingston.

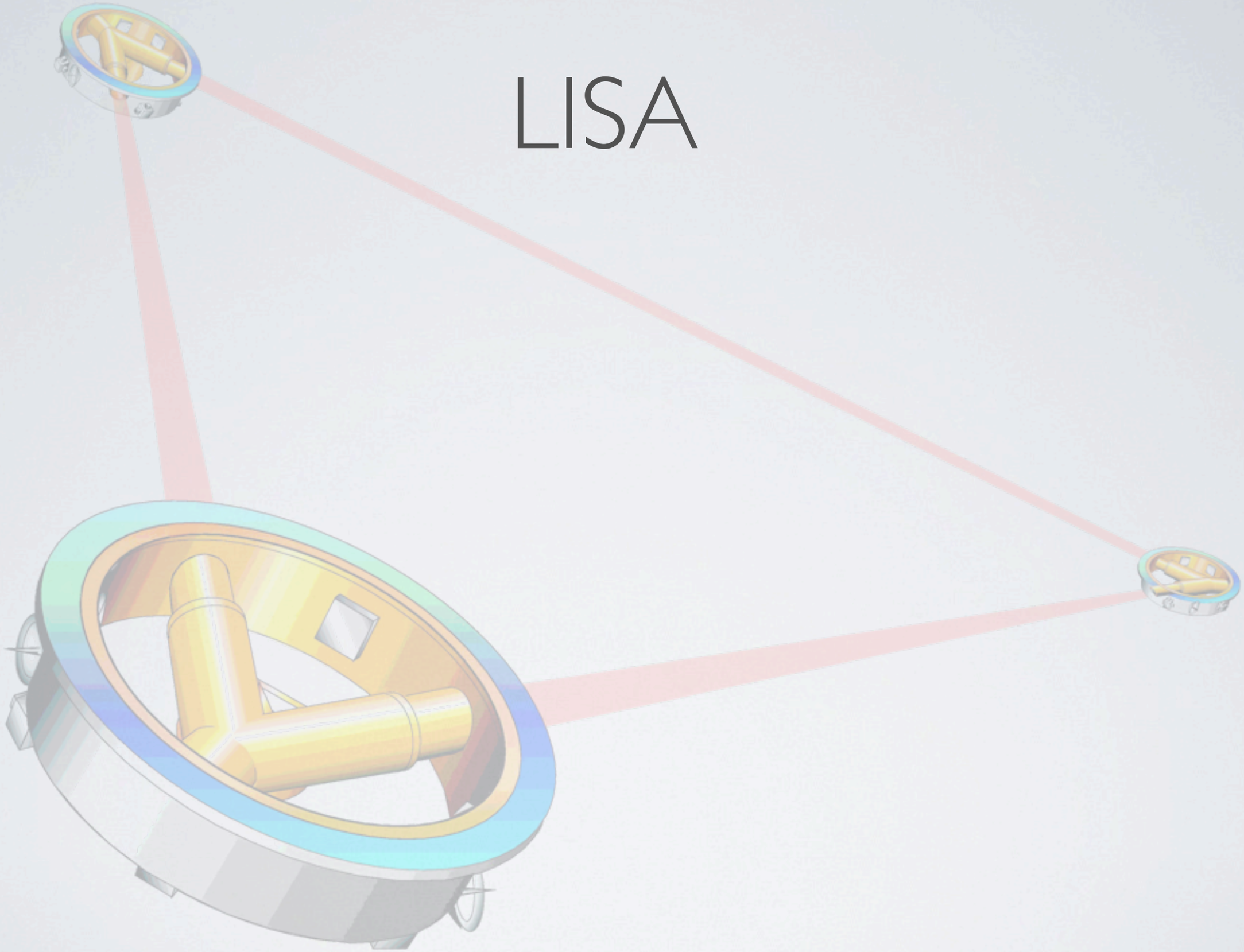
ADVANCED DETECTORS

- Soon LIGO and VIRGO will rebuild for x5-10 improvement in sensitivity and range: Advanced detectors fully operational 2016 (?).
- Mainly they will use technologies developed and tested in GEO600: signal recycling, monolithic suspensions, high-power lasers, squeezed light.
- During rebuild, GEO600 will operate with enhanced sensitivity above 1 kHz: GEO-HF.
- LIGO plans 2 full-scale detectors at Hanford, 1 at Livingston.
- *LCGT now funded*, will join with similar sensitivity as soon as possible.

ADVANCED DETECTORS

- Soon LIGO and VIRGO will rebuild for x5-10 improvement in sensitivity and range: Advanced detectors fully operational 2016 (?).
- Mainly they will use technologies developed and tested in GEO600: signal recycling, monolithic suspensions, high-power lasers, squeezed light.
- During rebuild, GEO600 will operate with enhanced sensitivity above 1 kHz: GEO-HF.
- LIGO plans 2 full-scale detectors at Hanford, 1 at Livingston.
- *LCGT now funded*, will join with similar sensitivity as soon as possible.
- *AND:* LIGO might move one of the Hanford detectors to Australia. Called LIGO-South or LIGO-Australia. Negotiations in progress.

LISA



LISA

- LISA opens the low-frequency window 10^{-4}-10^{-1} Hz.
  - massive BH mergers ($10^6 M_\odot$) at z=1, SNR ~ 10^3-10^4, ~1 per year
  - earliest BHs ($10^4 M_\odot$) at z = 15
  - stellar-mass BH captures onto massive BHs: test Kerr
  - census of compact-object binaries in Milky Way
  - physics: BH and galaxy evolution, stellar evolution, H_0 and dark energy, fundamental tests of GR

LISA

- LISA opens the low-frequency window 10^{-4}-10^{-1} Hz.
  - massive BH mergers ($10^6 M_\odot$) at z=1, SNR ~ 10^3-10^4, ~1 per year
  - earliest BHs ($10^4 M_\odot$) at z = 15
  - stellar-mass BH captures onto massive BHs: test Kerr
  - census of compact-object binaries in Milky Way
  - physics: BH and galaxy evolution, stellar evolution, H_0 and dark energy, fundamental tests of GR
- Very sensitive: many signals stronger than detector noise.
  - data analysis must resolve signal confusion as well as instrumental noise.

LISA'S ODYSSEY

LISA'S ODYSSEY

- Originally entered ESA program in 1995 with a launch foreseen before 2010.

LISA'S ODYSSEY

- Originally entered ESA program in 1995 with a launch foreseen before 2010.
- By 2000, NASA joined and ESA decided to launch LISA-Pathfinder.

LISA'S ODYSSEY

- Originally entered ESA program in 1995 with a launch foreseen before 2010.
- By 2000, NASA joined and ESA decided to launch LISA-Pathfinder.

- Combination of financial short-falls and delays to LPF have prevented LISA getting a start date. LPF now expected early 2013.

LISA'S ODYSSEY

- Originally entered ESA program in 1995 with a launch foreseen before 2010.
- By 2000, NASA joined and ESA decided to launch LISA-Pathfinder.

- Combination of financial short-falls and delays to LPF have prevented LISA getting a start date. LPF now expected early 2013.
- ESA will review its program next year; hoping funding will allow next major mission by 2020-2022.

LISA'S ODYSSEY

- Originally entered ESA program in 1995 with a launch foreseen before 2010.

- By 2000, NASA joined and ESA decided to launch LISA-Pathfinder.
- Combination of financial short-falls and delays to LPF have prevented LISA getting a start date. LPF now expected early 2013.
- ESA will review its program next year; hoping funding will allow next major mission by 2020-2022.
- Decadal review 2010 rated LISA highly, must wait for ill-defined W-FIRST dark energy mission. Probably fits with ESA.

BEYOND LISA

BEYOND LISA

- DECIGO proposal for higher frequency range (0.1-1 Hz) and with new technologies (e.g. Fabry-Perot cavities between separated spacecraft)
  - Attracting considerable interest, start date not yet clear.
  - Science very attractive: might be able to do stochastic background from inflation

BEYOND LISA

- DECIGO proposal for higher frequency range (0.1-1 Hz) and with new technologies (e.g. Fabry-Perot cavities between separated spacecraft)
  - Attracting considerable interest, start date not yet clear.
    - Science very attractive: might be able to do stochastic background from inflation
- NASA did Big Bang Observer (BBO) concept study, also with view to reaching inflation prediction. Will wait till after LISA.

BEYOND LISA

- DECIGO proposal for higher frequency range (0.1-1 Hz) and with new technologies (e.g. Fabry-Perot cavities between separated spacecraft)
  - Attracting considerable interest, start date not yet clear.
    - Science very attractive: might be able to do stochastic background from inflation
- NASA did Big Bang Observer (BBO) concept study, also with view to reaching inflation prediction. Will wait till after LISA.
- LPF technologies will be used on next geodesy satellites, improving sensitivity of measurement of Earth gravity. Applications in environment modeling (ice sheets, water tables).

37km from the Nippon Sea

LCGT!

Ikenoyama Mt.

1000m Underground

Mozumi area

XMASS

Kamland

SG

Super Kamiokande

CLIO

358m Altitude

3km

LCGT project

LCGT
Image

Atotsu
Entrance

Atotsu river

to Toyama

Takahara river

to Takaya

一(ichi)
分(bu)
厘(rin)
毛(mou)
糸(shi)
忽(kotsu)
微(bi)
纖(sen)
沙(sya)
塵(zin)
埃(ai)
渺(byou)
漠(baku)
模糊(moko)
逡巡(syunjun)
須臾(syuyu)
瞬息(syunsoku)
弾指(danshi)
刹那(setuna)

LCGT!

- Funding began this year

LCGT!

- Funding began this year
- Sometimes called a 2.5-generation instrument:
  - going underground reduces Newtonian gravity noise
  - cryogenic mirrors have lower thermal noise

LCGT!

- Funding began this year
- Sometimes called a 2.5-generation instrument:
  - going underground reduces Newtonian gravity noise
  - cryogenic mirrors have lower thermal noise
- Should have sensitivity competitive with or better than Advanced LIGO, especially at low frequencies.

LCGT!

- Funding began this year
- Sometimes called a 2.5-generation instrument:
  - going underground reduces Newtonian gravity noise
  - cryogenic mirrors have lower thermal noise
- Should have sensitivity competitive with or better than Advanced LIGO, especially at low frequencies.
- Will enormously increase science done by the network (see later).

LCGT!

- Funding began this year
- Sometimes called a 2.5-generation instrument:
  - going underground reduces Newtonian gravity noise
  - cryogenic mirrors have lower thermal noise
- Should have sensitivity competitive with or better than Advanced LIGO, especially at low frequencies.
- Will enormously increase science done by the network (see later).
- Ideal platform for gaining experience with technologies that are being discussed for 3rd generation instruments (the European Einstein Telescope design study).

NETWORK ASTRONOMY

NETWORK ASTRONOMY

- Why do all these groups work together?
  - Don't physicists compete, build big instruments, race against each other to get a big discovery?

NETWORK ASTRONOMY

- Why do all these groups work together?
  - Don't physicists compete, build big instruments, race against each other to get a big discovery?
- The science drives cooperation: GW astronomy is network astronomy
  - Confidence of detection requires more than one detector.
  - Full reconstruction of a short event (a "burst") requires 3 detectors: sky position (θ,ϕ), amplitudes $h_+(t)$, $h_\times(t)$.
  - Science return accrues nonlinearly with the investment.

HOW WE DETECT SIGNALS

HOW WE DETECT SIGNALS

For a single detector, optimum is matched filtering.

HOW WE DETECT SIGNALS

For a single detector, optimum is matched filtering.

- Noise: spectral noise density $S_h(f)$ = the <Fourier power spectrum> of noise.

HOW WE DETECT SIGNALS

For a single detector, optimum is matched filtering.

- Noise: spectral noise density $S_h(f)$ = the <Fourier power spectrum> of noise.
- $S_h(f)$ is scaled to the (dimensionless) GW amplitude^2, so that it has units of Hz^{-1}: noise power per unit frequency.

HOW WE DETECT SIGNALS

For a single detector, optimum is matched filtering.

- Noise: spectral noise density $S_h(f)$ = the <Fourier power spectrum> of noise.
- $S_h(f)$ is scaled to the (dimensionless) GW amplitude^2, so that it has units of Hz^{-1}: noise power per unit frequency.
- Signal: If we know the signal waveform h(t), hence its Fourier transform H(f), the optimum SNR is

$$\rho^2 = \int_{-\infty}^{\infty} \frac{|H(f)|^2}{S_h(f)} \mathrm{d}f$$

HOW WE DETECT SIGNALS

For a single detector, optimum is matched filtering.

- Noise: spectral noise density $S_h(f)$ = the <Fourier power spectrum> of noise.
- $S_h(f)$ is scaled to the (dimensionless) GW amplitude^2, so that it has units of Hz^{-1}: noise power per unit frequency.
- Signal: If we know the signal waveform h(t), hence its Fourier transform H(f), the optimum SNR is

$$\rho^2 = \int_{-\infty}^{\infty} \frac{|H(f)|^2}{S_h(f)} \mathrm{d}f$$

- Interpretation: each band *df* has independent noise. Rule is that you add up the noise-weighted signal power over all bands.

HOW WE DETECT SIGNALS

For a single detector, optimum is matched filtering.

- Noise: spectral noise density $S_h(f)$ = the <Fourier power spectrum> of noise.
- $S_h(f)$ is scaled to the (dimensionless) GW amplitude^2, so that it has units of Hz^{-1}: noise power per unit frequency.
- Signal: If we know the signal waveform h(t), hence its Fourier transform H(f), the optimum SNR is

$$\rho^2 = \int_{-\infty}^{\infty} \frac{|H(f)|^2}{S_h(f)} \mathrm{d}f$$

- Interpretation: each band *df* has independent noise. Rule is that you add up the noise-weighted signal power over all bands.
- For a network, the optimum is a simple extension of this rule. Noise in each detector is independent so we add up all bands across all detectors:

$$\rho_N^2 = \sum_k \int_{-\infty}^{\infty} \frac{|H_k(f)|^2}{S_{h,k}(f)} \mathrm{d}f$$

HOW WE DETECT SIGNALS

For a single detector, optimum is matched filtering.

- Noise: spectral noise density $S_h(f)$ = the <Fourier power spectrum> of noise.
- $S_h(f)$ is scaled to the (dimensionless) GW amplitude^2, so that it has units of Hz^{-1}: noise power per unit frequency.
- Signal: If we know the signal waveform h(t), hence its Fourier transform H(f), the optimum SNR is

$$\rho^2 = \int_{-\infty}^{\infty} \frac{|H(f)|^2}{S_h(f)} \mathrm{d}f$$

- Interpretation: each band *df* has independent noise. Rule is that you add up the noise-weighted signal power over all bands.
- For a network, the optimum is a simple extension of this rule. Noise in each detector is independent so we add up all bands across all detectors:

$$\rho_N^2 = \sum_k \int_{-\infty}^{\infty} \frac{|H_k(f)|^2}{S_{h,k}(f)} \mathrm{d}f$$

- Called coherent detection. Not same as thresholding: no test applied to individual detectors.

NETWORK SENSITIVITY

NETWORK SENSITIVITY

- For simplicity focus on just one class of sources with a known waveform, and assume all detectors have identical sensitivity.

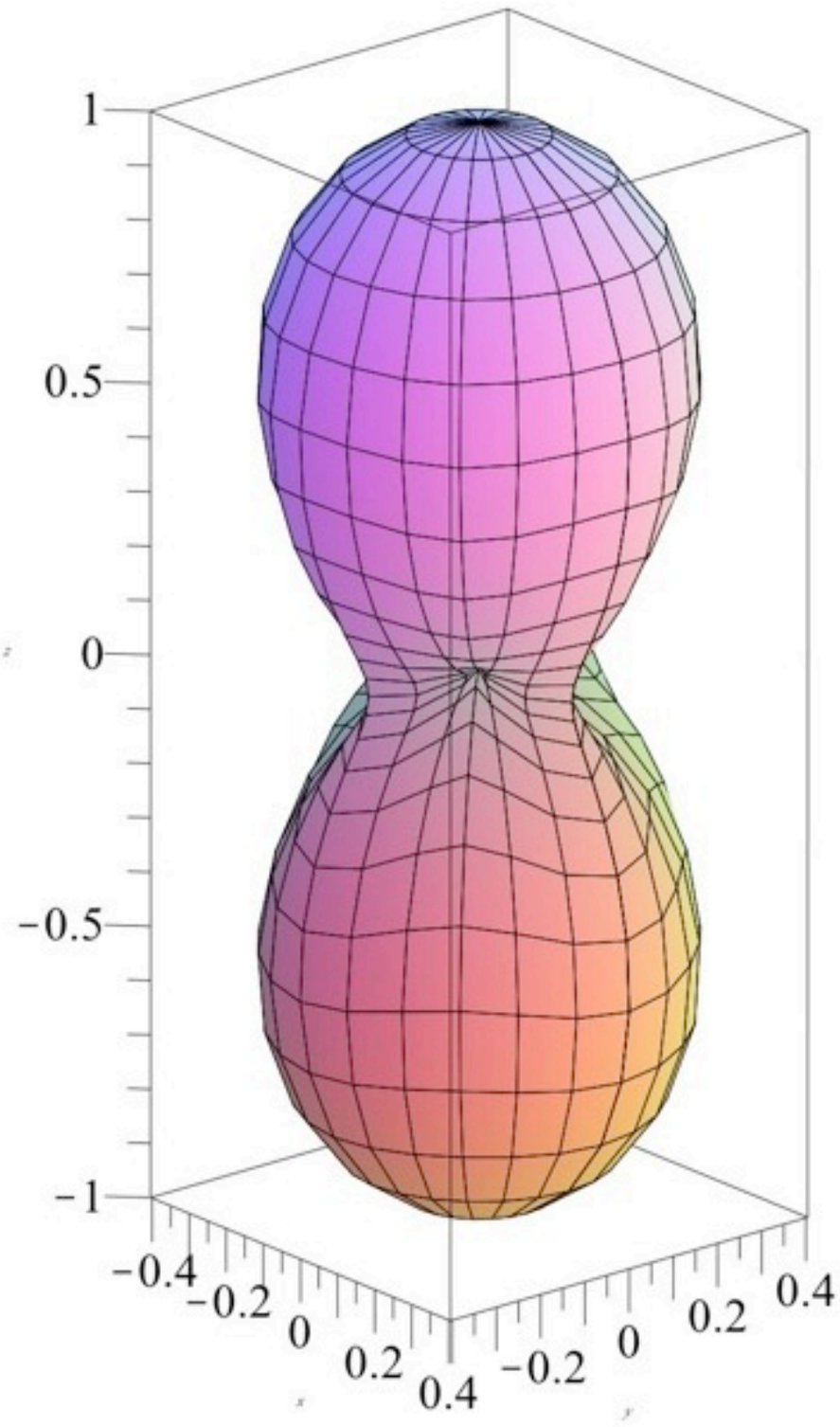
NETWORK SENSITIVITY

- For simplicity focus on just one class of sources with a known waveform, and assume all detectors have identical sensitivity.
- Polarization depends on orientation on sky, assume random.

NETWORK SENSITIVITY

- For simplicity focus on just one class of sources with a known waveform, and assume all detectors have identical sensitivity.
- Polarization depends on orientation on sky, assume random.
- Polarization-averaged SNR of a detector for a given source direction is

$$\langle \rho^2 \rangle = P(\theta, \phi) \int_{-\infty}^{\infty} \frac{|H(f)|^2}{S_h(f)} \mathrm{d}f$$


1
0.5
0
−0.5
−1
−0.4
−0.2
0
0.2
0.4
−0.2
0
0.2
0.4

NETWORK SENSITIVITY

- For simplicity focus on just one class of sources with a known waveform, and assume all detectors have identical sensitivity.
- Polarization depends on orientation on sky, assume random.
- Polarization-averaged SNR of a detector for a given source direction is

$$\langle \rho^2 \rangle = P(\theta, \phi) \int_{-\infty}^{\infty} \frac{|H(f)|^2}{S_h(f)} \mathrm{d}f$$

NETWORK SENSITIVITY

- For simplicity focus on just one class of sources with a known waveform, and assume all detectors have identical sensitivity.
- Polarization depends on orientation on sky, assume random.
- Polarization-averaged SNR of a detector for a given source direction is

$$\langle \rho^2 \rangle = P(\theta, \phi) \int_{-\infty}^{\infty} \frac{|H(f)|^2}{S_h(f)} \mathrm{d}f$$

- For the network this just gives

$$\langle \rho_N^2 \rangle = \left[\sum_k P_k(\theta, \phi) \right] \int_{-\infty}^{\infty} \frac{|H(f)|^2}{S_h(f)} \mathrm{d}f$$

NETWORK SENSITIVITY

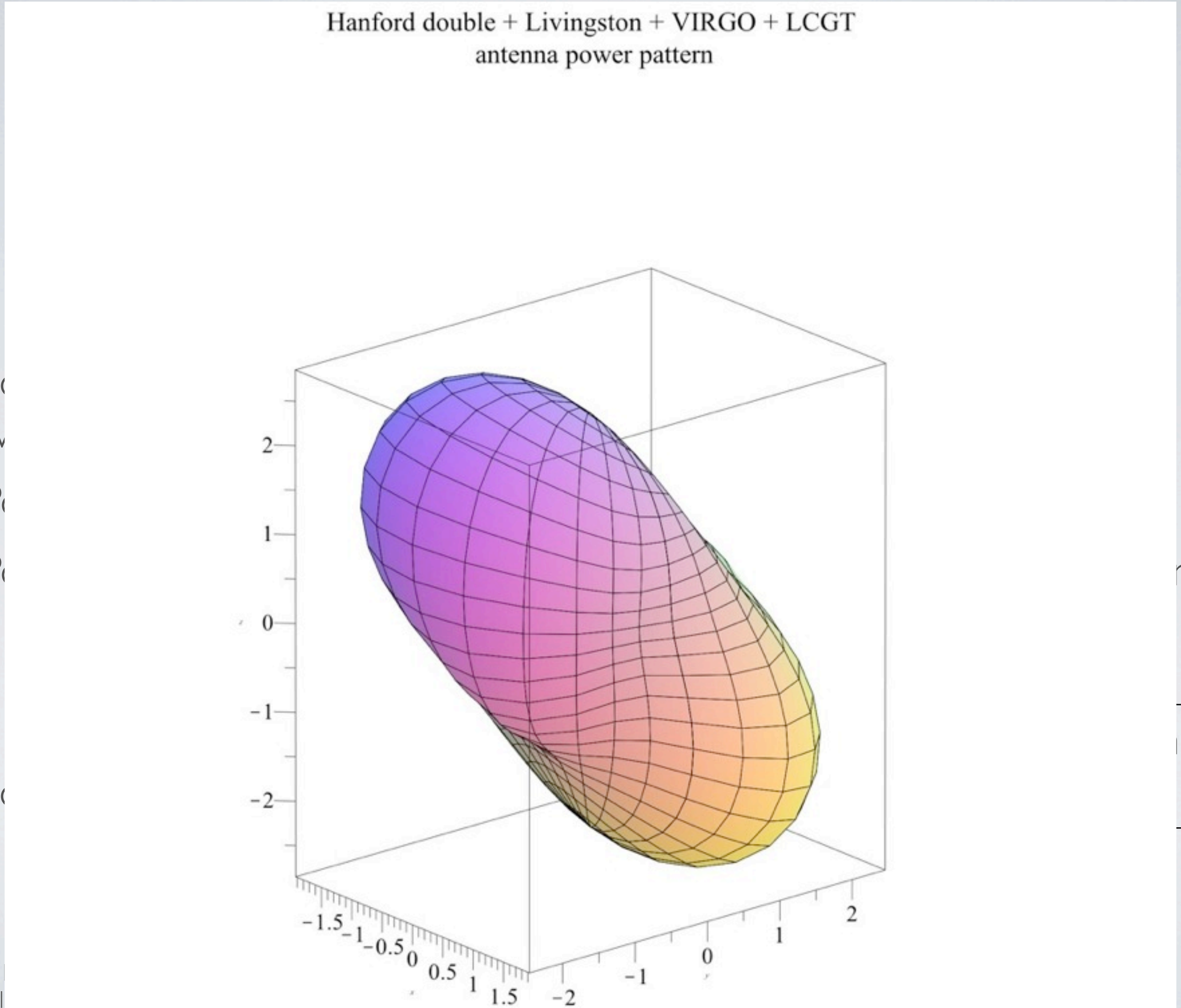
- For simplicity focus on just one class of sources with a known waveform, and assume all detectors have identical sensitivity.
- Polarization depends on orientation on sky, assume random.
- Polarization-averaged SNR of a detector for a given source direction is

$$\langle \rho^2 \rangle = P(\theta, \phi) \int_{-\infty}^{\infty} \frac{|H(f)|^2}{S_h(f)} \mathrm{d}f$$

- For the network this just gives

$$\langle \rho_N^2 \rangle = \left[\sum_k P_k(\theta, \phi) \right] \int_{-\infty}^{\infty} \frac{|H(f)|^2}{S_h(f)} \mathrm{d}f$$

Network antenna pattern



- Fo
  w
- Po
- Po
  n is
- Fo
  na

DISTRIBUTION OF SNR

DISTRIBUTION OF SNR

- Statistics of the noise will place a minimum confidence threshold on the network SNR, $\rho_{\text{threshold}}$.

DISTRIBUTION OF SNR

- Statistics of the noise will place a minimum confidence threshold on the network SNR, $\rho_{\text{threshold}}$.
- Because H(f) ~ 1/r, SNR $\rho \sim 1/r$, r ~ 1/ρ, number detected above a given $\rho \sim \rho^{-3}$, p.d.f.

$$p(\rho)d\rho = 3\rho_{\text{threshold}}^3 \rho^{-4} \mathrm{d}\rho$$

for $\rho > \rho_{\text{threshold}}$, 0 below.

DISTRIBUTION OF SNR

- Statistics of the noise will place a minimum confidence threshold on the network SNR, $\rho_{\text{threshold}}$.
- Because H(f) ~ 1/r, SNR $\rho \sim 1/r$, r ~ 1/ρ, number detected above a given $\rho \sim \rho^{-3}$, p.d.f.

$$p(\rho)d\rho = 3\rho_{\text{threshold}}^3 \rho^{-4} \mathrm{d}\rho$$

for $\rho > \rho_{\text{threshold}}$, 0 below.

- $\langle\rho\rangle = 1.5\rho_{\text{threshold}}$, $\langle\rho^2\rangle = 3(\rho_{\text{threshold}})^2$, median $= 2^{1/3}\ \rho_{\text{threshold}}$

DISTRIBUTION OF SNR

- Statistics of the noise will place a minimum confidence threshold on the network SNR, $\rho_{\text{threshold}}$.
- Because H(f) ~ 1/r, SNR $\rho \sim 1/r$, r ~ 1/ρ, number detected above a given $\rho \sim \rho^{-3}$, p.d.f.

$$p(\rho)d\rho = 3\rho_{\text{threshold}}^3 \rho^{-4} \mathrm{d}\rho$$

for $\rho > \rho_{\text{threshold}}$, 0 below.

- $\langle\rho\rangle = 1.5\rho_{\text{threshold}}$, $\langle\rho^2\rangle = 3(\rho_{\text{threshold}})^2$, median $= 2^{1/3}\ \rho_{\text{threshold}}$
- Median = most probably SNR of first detection.

FIGURES OF MERIT FOR NETWORKS

FIGURES OF MERIT FOR NETWORKS

Assuming coherent detection, identical detectors:

FIGURES OF MERIT FOR NETWORKS

Assuming coherent detection, identical detectors:

1. Triple Detection Rate [TDR]. Use detection volume ~$[P_N(\theta,\varphi)]^{3/2}$ but weight by duty cycle (initially ~80%) and include all sub-nets with detectors at three or more locations.
   - Effective volume = TDR · $(D_L/\rho_{threshold})^3$, D_L is the *visibility distance* of a single detector, i.e. distance where source would have best SNR = 1. Correction for averaging over all binary inclinations: multiply by 0.554.
- For Advanced LIGO, D_L = 3.6 Gpc (NS-NS), 17.5 Gpc (BH-BH).
- With $\rho_{threshold}$ =8, the volume scales are $V_{NS\text{-}NS}$=4.9x10^7 Mpc^3, $V_{BH\text{-}BH}$=5.5x10^9 Mpc^3

FIGURES OF MERIT FOR NETWORKS

Assuming coherent detection, identical detectors:

1. Triple Detection Rate [TDR]. Use detection volume ~$[P_N(\theta,\varphi)]^{3/2}$ but weight by duty cycle (initially ~80%) and include all sub-nets with detectors at three or more locations.
   - Effective volume = TDR · $(D_L/\rho_{threshold})^3$, D_L is the *visibility distance* of a single detector, i.e. distance where source would have best SNR = 1. Correction for averaging over all binary inclinations: multiply by 0.554.
   - For Advanced LIGO, D_L = 3.6 Gpc (NS-NS), 17.5 Gpc (BH-BH).
   - With $\rho_{threshold}$ =8, the volume scales are $V_{NS\text{-}NS}=4.9\times10^7$ Mpc^3, $V_{BH\text{-}BH}=5.5\times10^9$ Mpc^3
2. Sky Coverage [SC]. Fraction of sky covered by P_N at 50% power.

FIGURES OF MERIT FOR NETWORKS

Assuming coherent detection, identical detectors:

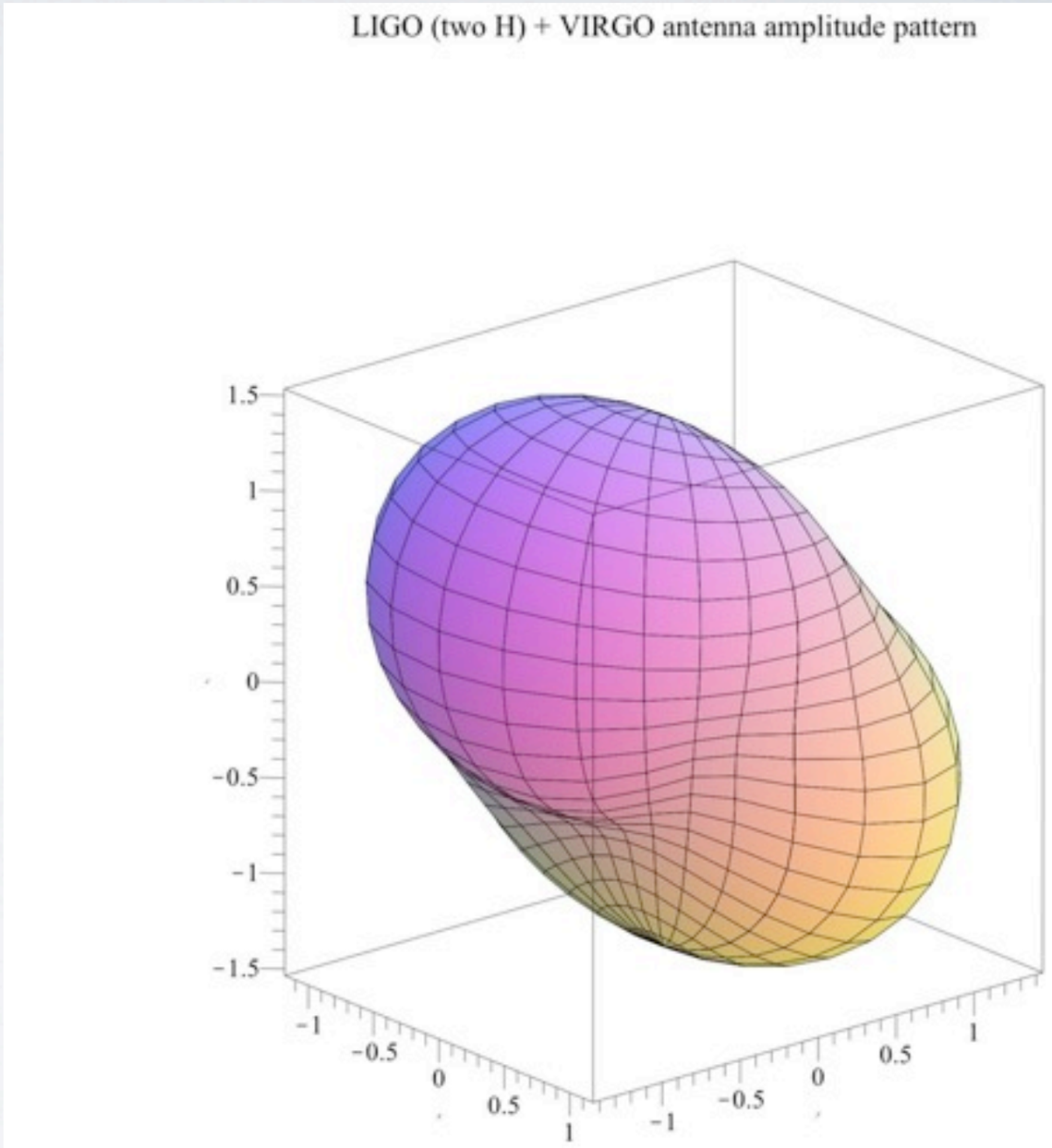
1. Triple Detection Rate [TDR]. Use detection volume ~$[P_N(\theta,\varphi)]^{3/2}$ but weight by duty cycle (initially ~80%) and include all sub-nets with detectors at three or more locations.
   - Effective volume = TDR · $(D_L/\rho_{threshold})^3$, D_L is the *visibility distance* of a single detector, i.e. distance where source would have best SNR = 1. Correction for averaging over all binary inclinations: multiply by 0.554.
   - For Advanced LIGO, D_L = 3.6 Gpc (NS-NS), 17.5 Gpc (BH-BH).
   - With $\rho_{threshold}$ =8, the volume scales are $V_{NS\text{-}NS}$=4.9x10^7 Mpc^3, $V_{BH\text{-}BH}$=5.5x10^9 Mpc^3
2. Sky Coverage [SC]. Fraction of sky covered by P_N at 50% power.
3. Directional Precision [DP]. Measure of typical size of angular error ellipse when network determines directions by time-delays. Actual error:

$$\left\langle |\delta\Omega|^{-1} \right\rangle \sim 20\rho^2_{\mathrm{threshold}} \frac{\left\langle f^2 \right\rangle}{(100\ \mathrm{Hz})^2}[DP] \quad \mathrm{sr}^{-1}$$

THE PLANNED L-V NETWORK

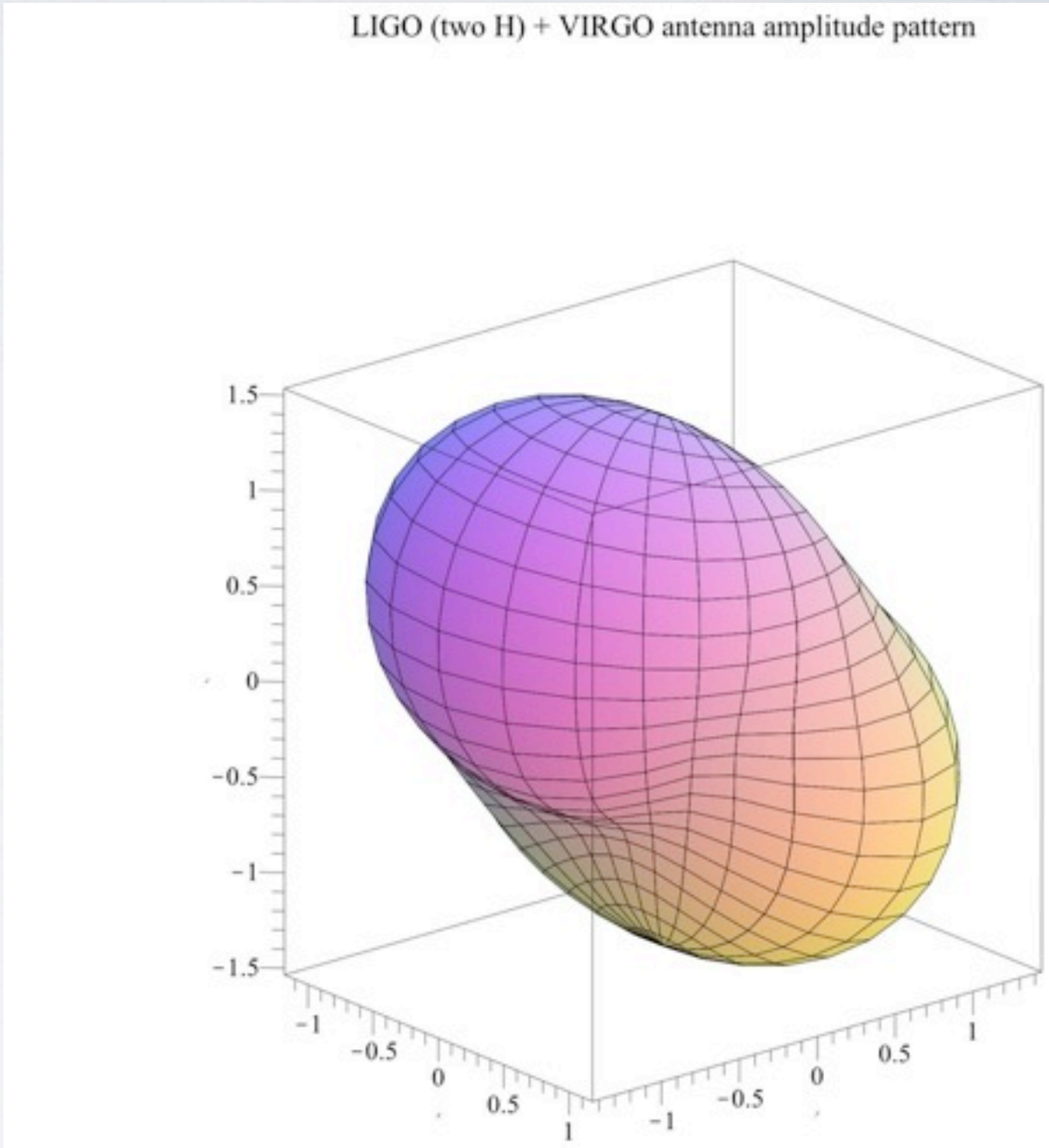
THE PLANNED L-V NETWORK

- TDR_{HHLV}=4.86. For NS-NS, V_{eff}=1.3x10^8 Mpc^3. rate = 730/yr!



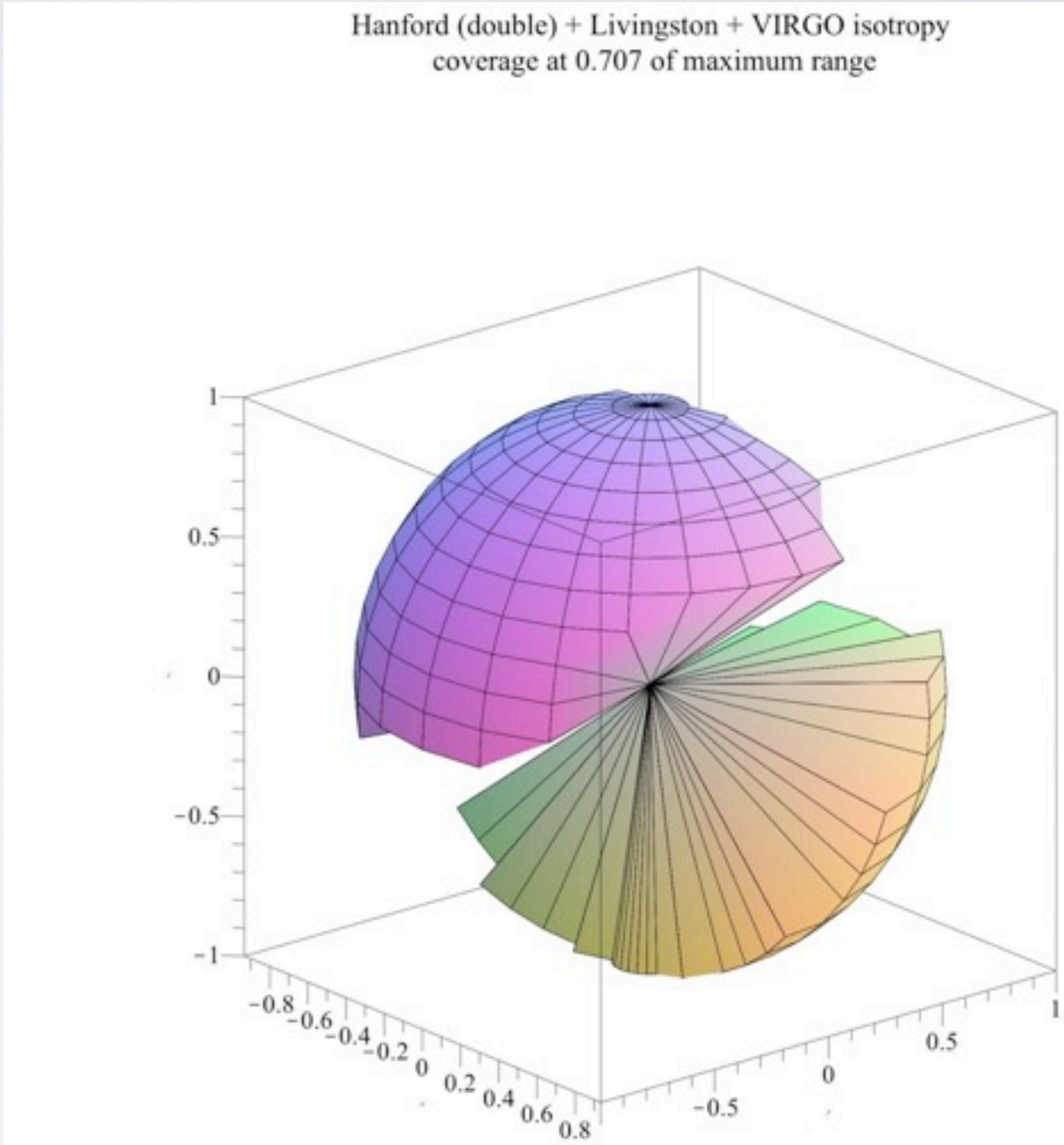
THE PLANNED L-V NETWORK

- TDR_{HHLV}=4.86. For NS-NS, V_{eff}=1.3x10^8 Mpc^3. rate = 730/yr!
- LSC (Abbott et al 2010) used $\rho_{threshold}$=8 in a single detector's volume. More conservative, brings down rate to 40/yr. Effect of thresholding is to reduce rate by factor of almost 20!



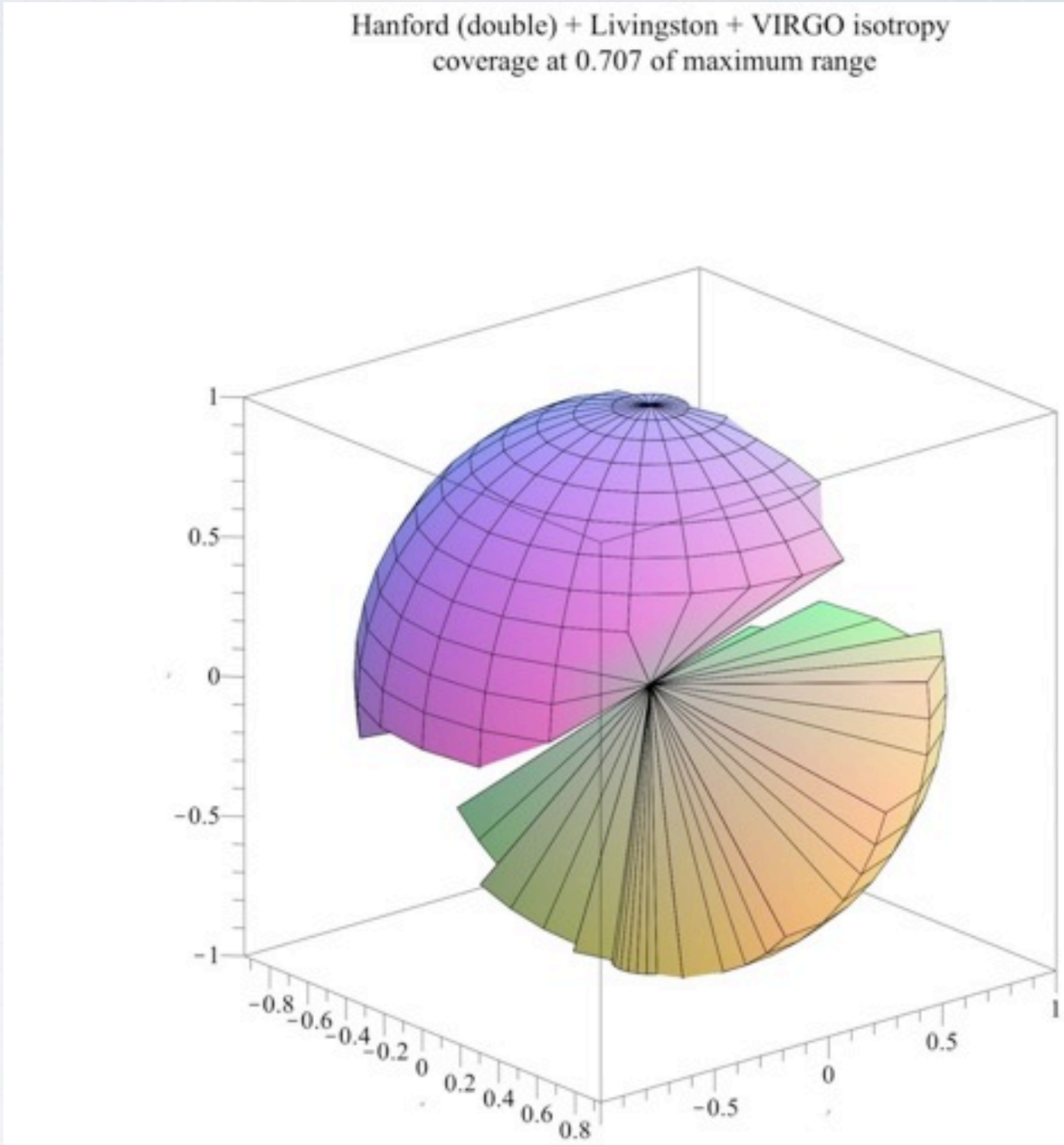
THE PLANNED L-V NETWORK

- TDR_{HHLV}=4.86. For NS-NS, V_{eff}=1.3x10^8 Mpc^3. rate = 730/yr!
- LSC (Abbott et al 2010) used $\rho_{threshold}$=8 in a single detector's volume. More conservative, brings down rate to 40/yr. Effect of thresholding is to reduce rate by factor of almost 20!
- SC_{HHLV}=47%.



THE PLANNED L-V NETWORK

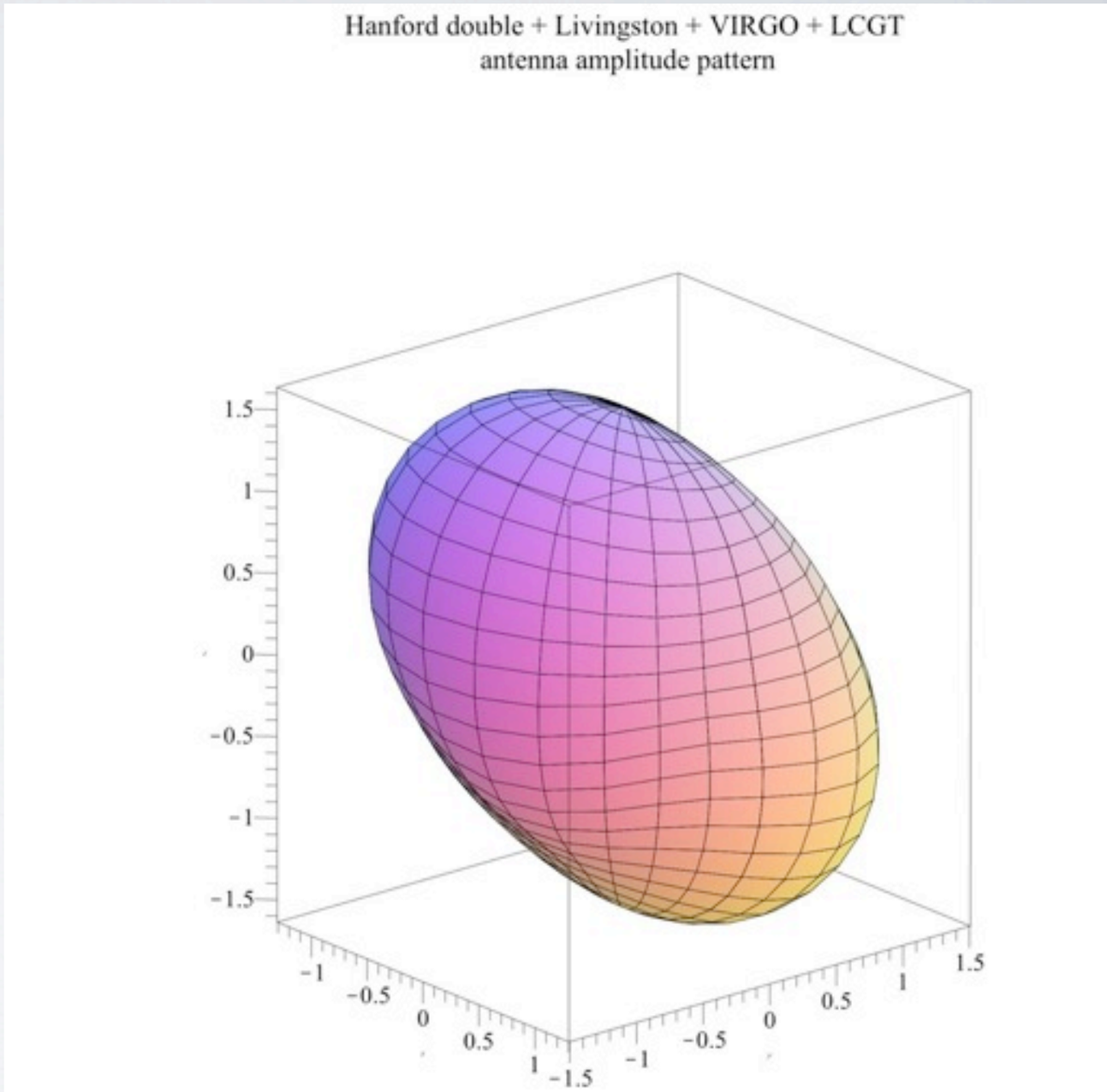
- TDR_{HHLV}=4.86. For NS-NS, V_{eff}=1.3x10^8 Mpc^3. rate = 730/yr!
- LSC (Abbott et al 2010) used $\rho_{threshold}$=8 in a single detector's volume. More conservative, brings down rate to 40/yr. Effect of thresholding is to reduce rate by factor of almost 20!
- SC_{HHLV}=47%.
- DP_{HHLV}=1.15. For $\rho_{threshold}$=8, <f> = 50 Hz, get $\delta\Omega$~0.003 sr, angles ~3°



. . . AND NOW WITH LCGT ...

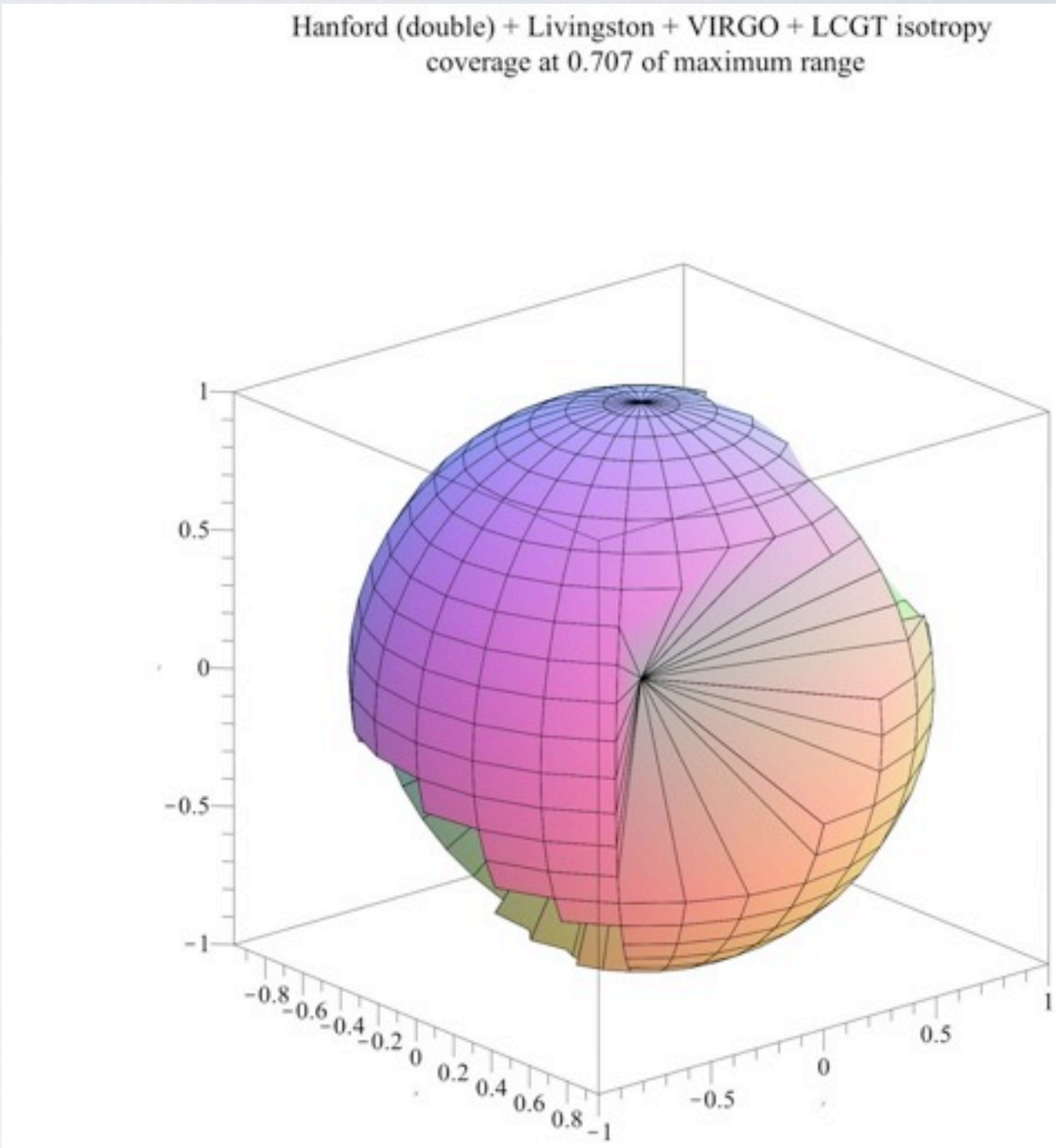
. . . AND NOW WITH LCGT ...

- TDR_{HHLVJ}=8.37. For NS-NS, rate = 1250/yr! For BH-BH, rate = 480/yr.



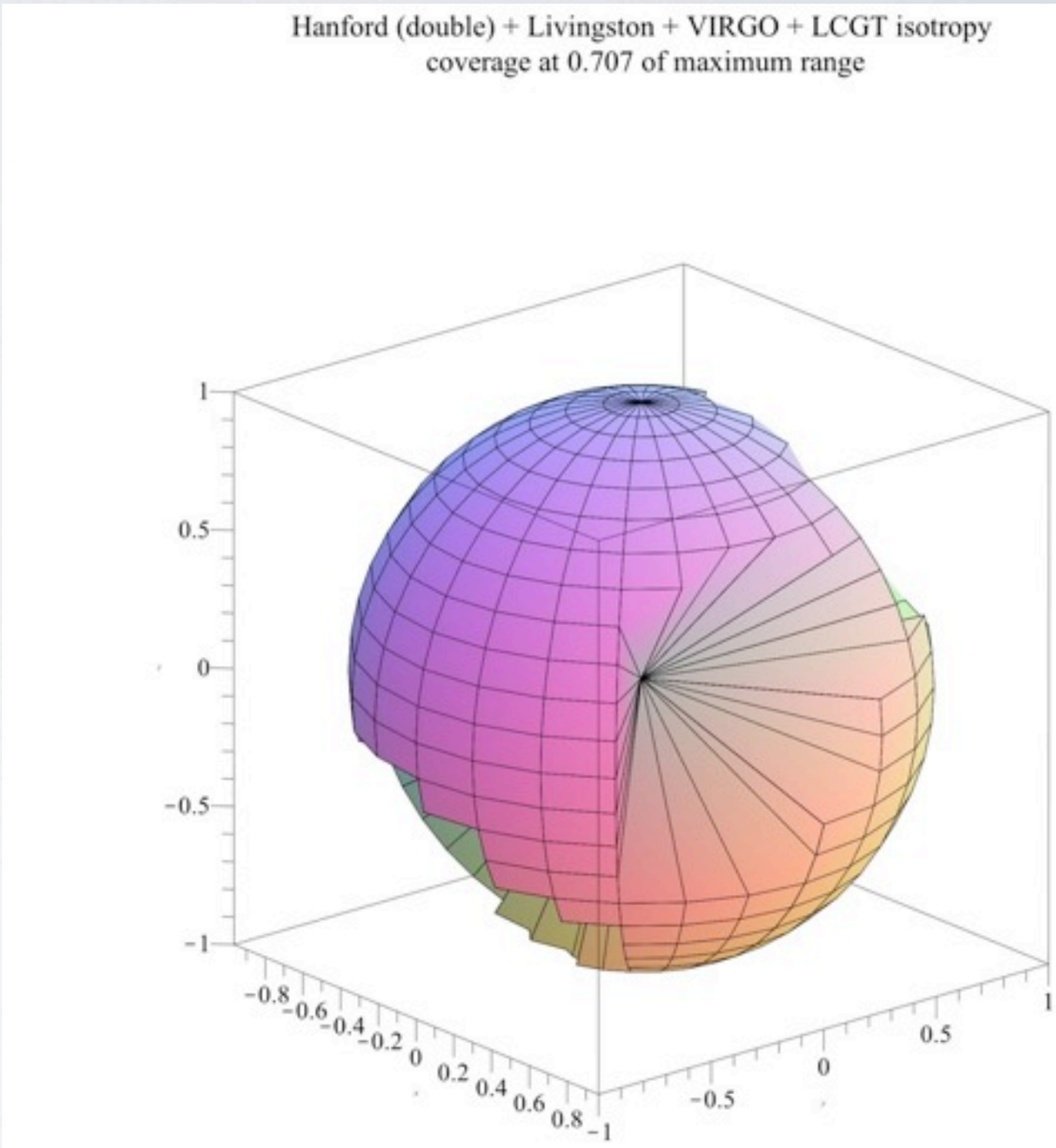
. . . AND NOW WITH LCGT ...

- TDR_{HHLVJ}=8.37. For NS-NS, rate = 1250/yr! For BH-BH, rate = 480/yr.
- SC_{HHLVJ}=74%.

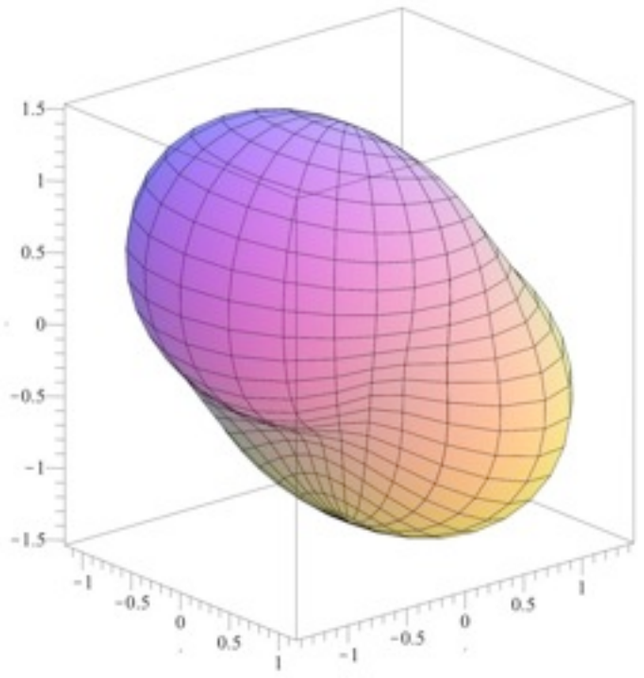


. . . AND NOW WITH LCGT ...

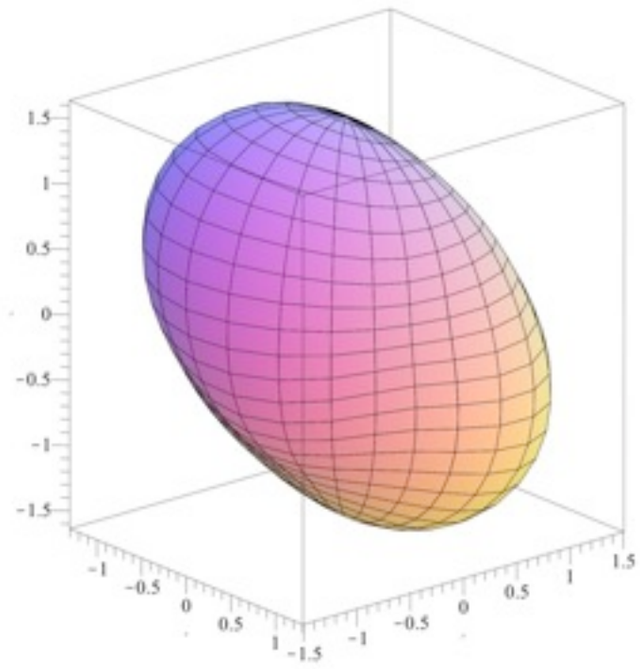
- TDR_{HHLVJ}=8.37. For NS-NS, rate = 1250/yr! For BH-BH, rate = 480/yr.
- SC_{HHLVJ}=74%.
- DP_{HHLVJ}=4.65. Get $\delta\Omega$~0.0007 sr, angles ~1.5°



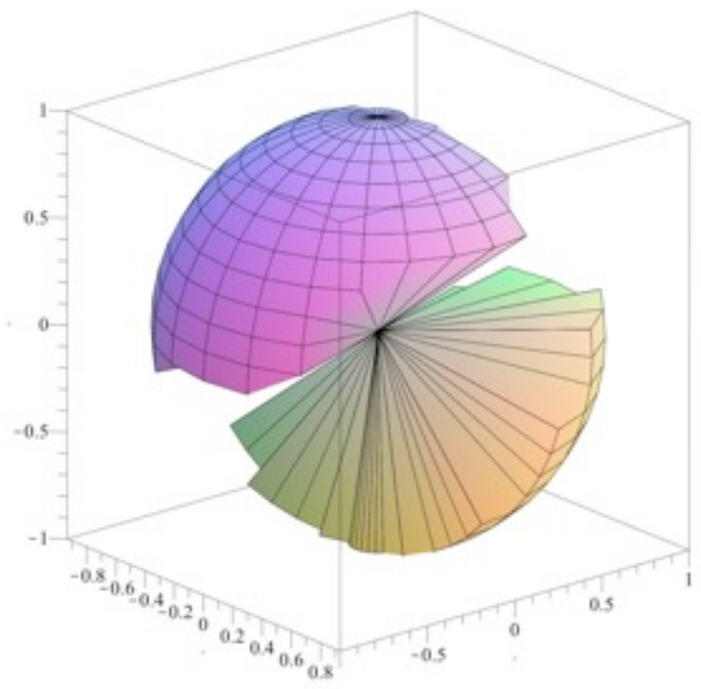
LIGO (two H) + VIRGO antenna amplitude pattern



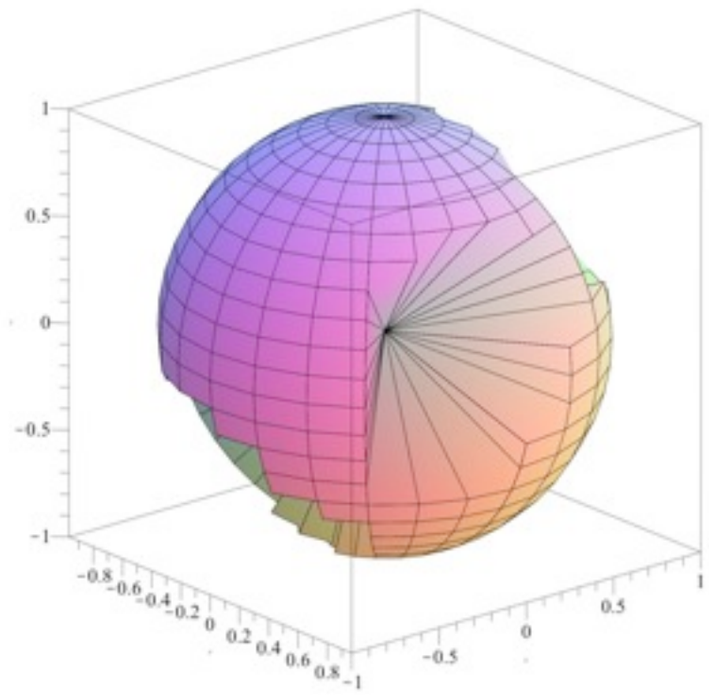
Hanford double + Livingston + VIRGO + LCGT
antenna amplitude pattern



Hanford (double) + Livingston + VIRGO isotropy
coverage at 0.707 of maximum range



Hanford (double) + Livingston + VIRGO + LCGT isotropy
coverage at 0.707 of maximum range



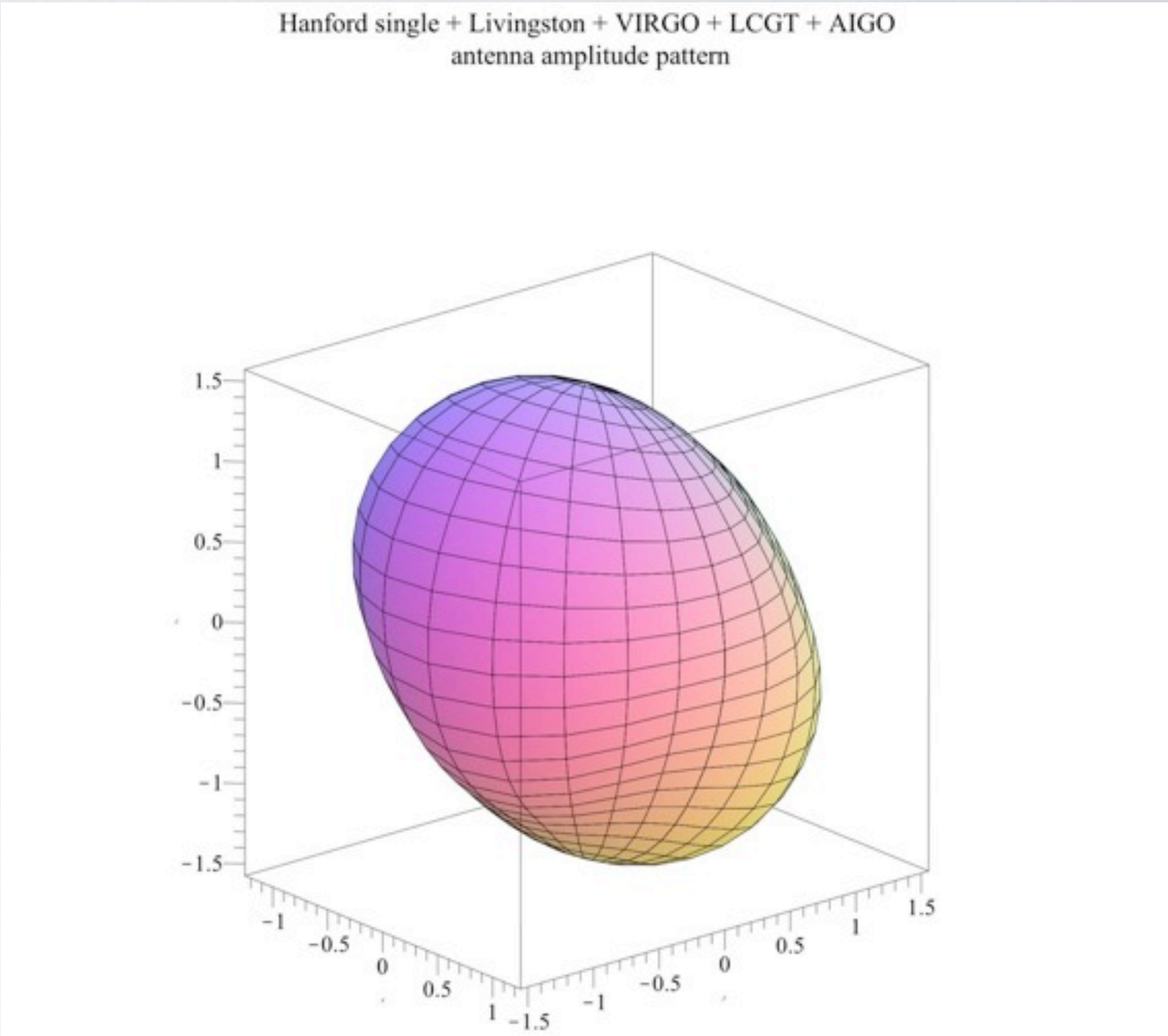
LIGO-AUSTRALIA

LIGO-AUSTRALIA

- If LIGO succeeds in moving a detector to Australia, the network gets even more powerful.

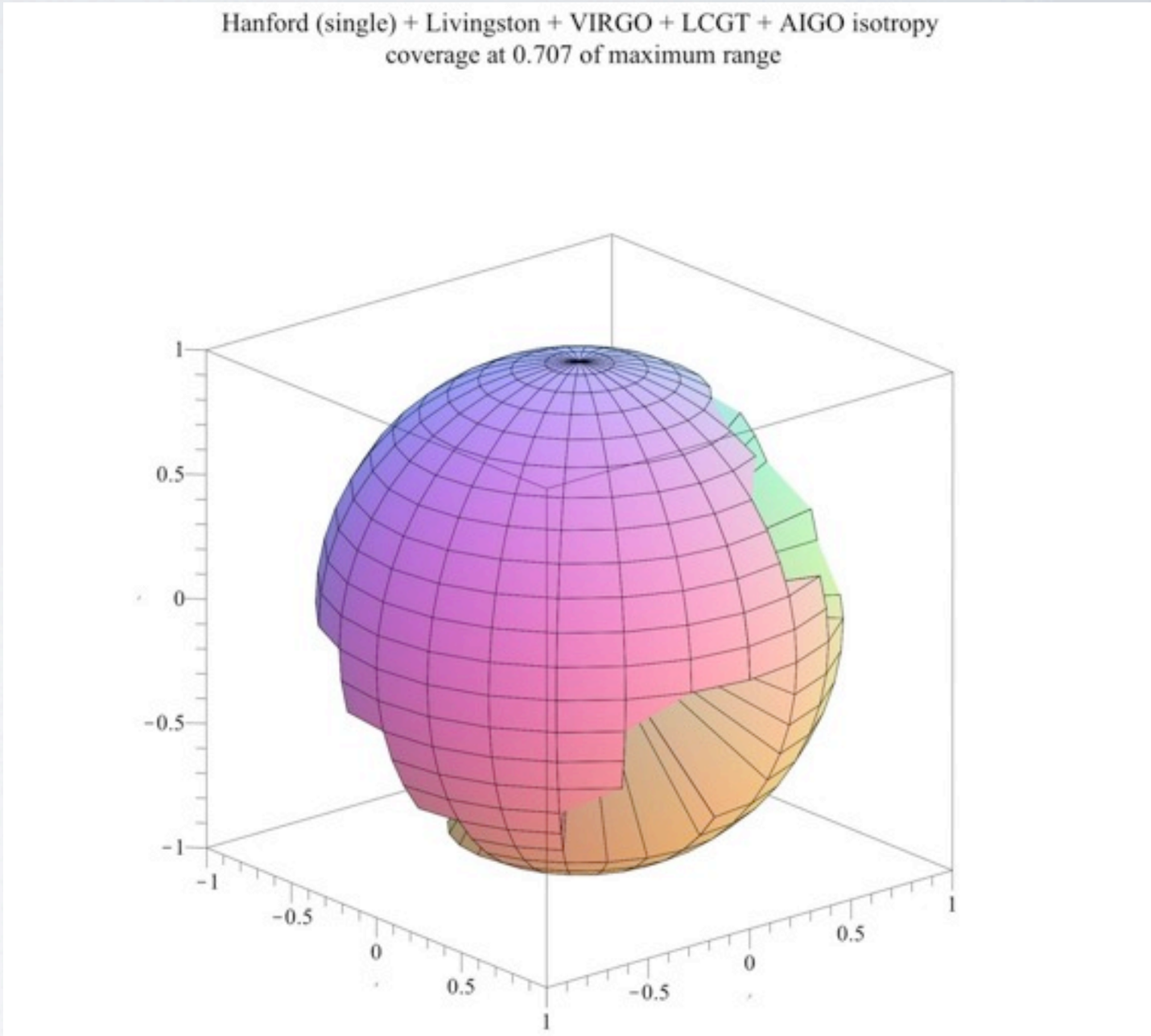
LIGO-AUSTRALIA

- If LIGO succeeds in moving a detector to Australia, the network gets even more powerful.
- TDR_{HLVJA} =8.71. Modest improvement on TDR_{HHLVJ}=8.37. For NS-NS, rate = 1300/yr! For BH-BH, rate = 500/yr.



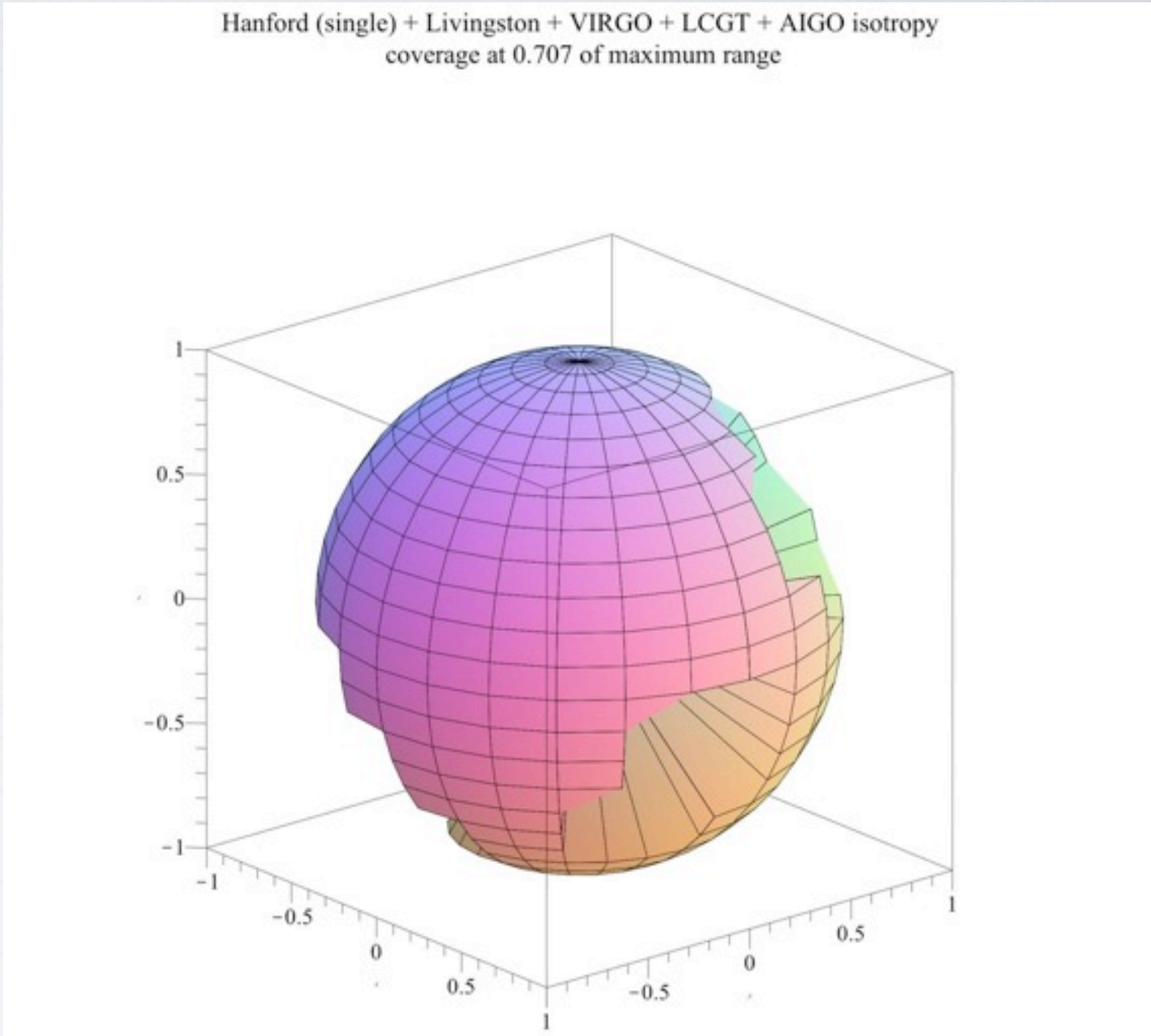
LIGO-AUSTRALIA

- If LIGO succeeds in moving a detector to Australia, the network gets even more powerful.
- TDR_{HLVJA} =8.71. Modest improvement on TDR_{HHLVJ}=8.37. For NS-NS, rate = 1300/yr! For BH-BH, rate = 500/yr.
- SC_{HLVJA} =85%. Again modest improvement on SC_{HHLVJ}=74%.

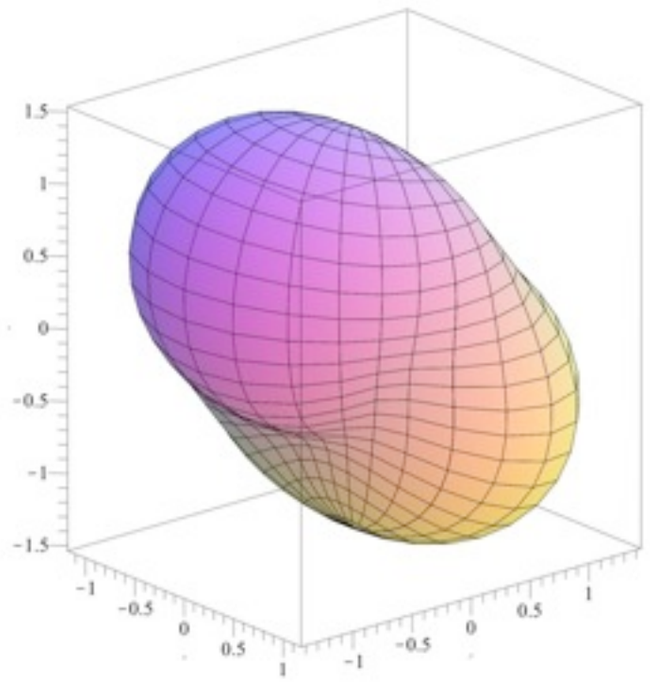


LIGO-AUSTRALIA

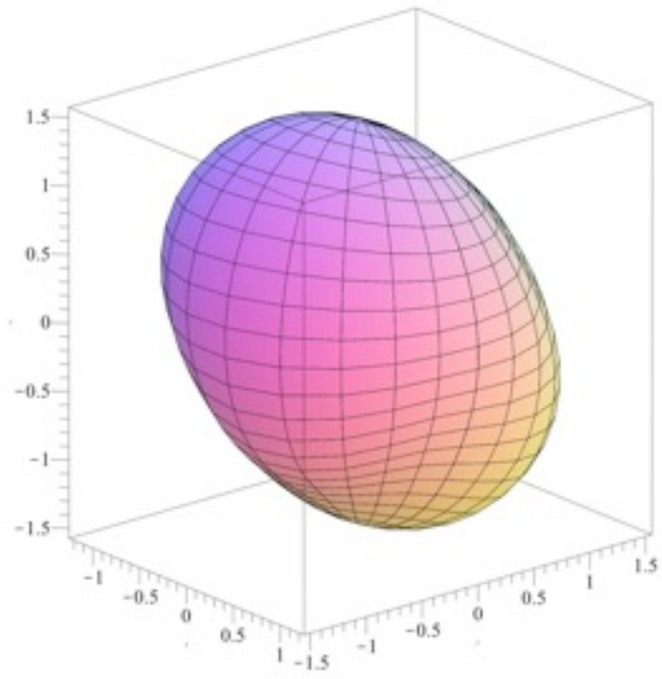
- If LIGO succeeds in moving a detector to Australia, the network gets even more powerful.
- TDR_{HLVJA} =8.71. Modest improvement on TDR_{HHLVJ}=8.37. For NS-NS, rate = 1300/yr! For BH-BH, rate = 500/yr.
- SC_{HLVJA} =85%. Again modest improvement on SC_{HHLVJ}=74%.
- DP_{HLVJA} =7.48. Significant improvement on DP_{HHLVJ}=4.65. Get $\delta\Omega$~0.0004 sr, angles ~1°



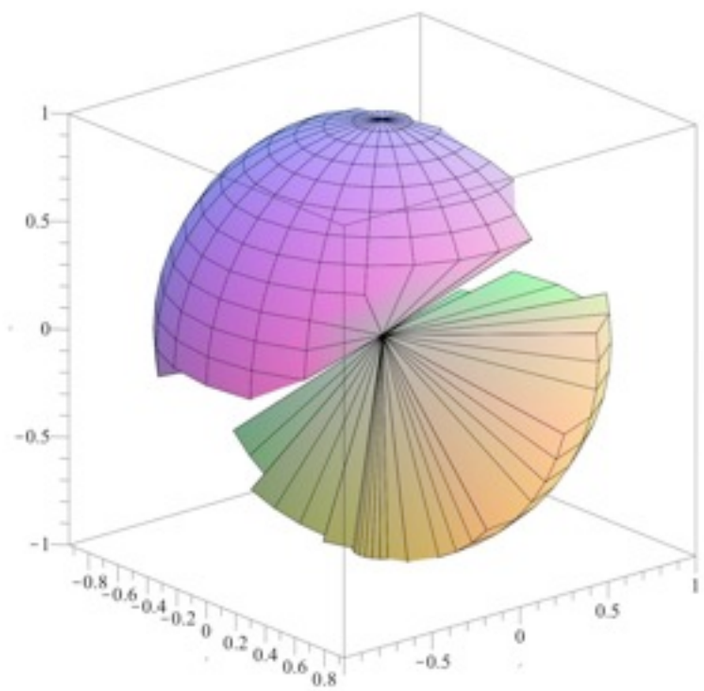
LIGO (two H) + VIRGO antenna amplitude pattern



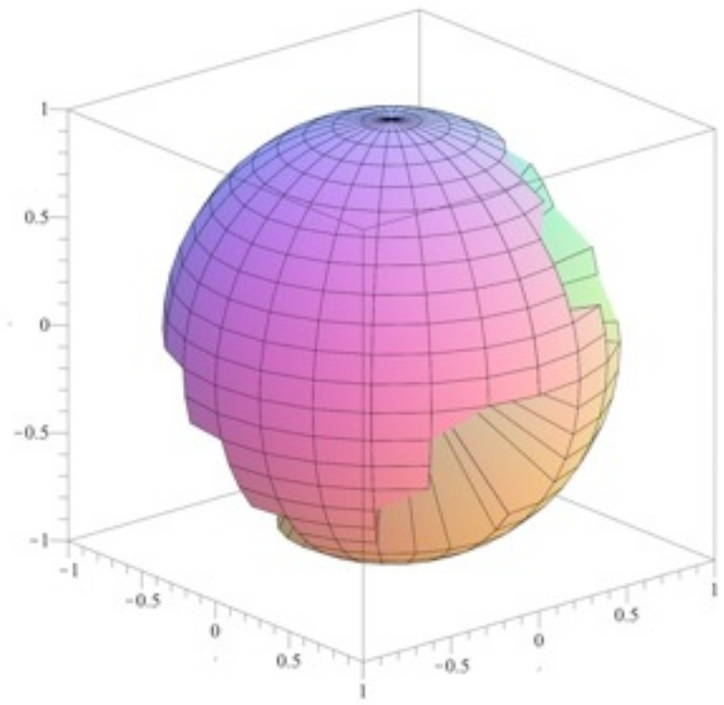
Hanford single + Livingston + VIRGO + LCGT + AIGO
antenna amplitude pattern



Hanford (double) + Livingston + VIRGO isotropy
coverage at 0.707 of maximum range



Hanford (single) + Livingston + VIRGO + LCGT + AIGO isotropy
coverage at 0.707 of maximum range



AND INDIA MIGHT JOIN

AND INDIA MIGHT JOIN

- A collaboration aimed at building IndIGO is taking shape.

AND INDIA MIGHT JOIN

- A collaboration aimed at building IndIGO is taking shape.
- 3m prototype approved: first experimental effort in India.

AND INDIA MIGHT JOIN

- A collaboration aimed at building IndIGO is taking shape.
- 3m prototype approved: first experimental effort in India.
- Already planning a larger-scale prototype.

AND INDIA MIGHT JOIN

- A collaboration aimed at building IndIGO is taking shape.
- 3m prototype approved: first experimental effort in India.
- Already planning a larger-scale prototype.
- Negotiations with AIGO are going on, so India might become a partner in LIGO-Australia.

AND INDIA MIGHT JOIN

- A collaboration aimed at building IndIGO is taking shape.
- 3m prototype approved: first experimental effort in India.
- Already planning a larger-scale prototype.
- Negotiations with AIGO are going on, so India might become a partner in LIGO-Australia.
- If there is an Advanced detector as well in India, it brings further benefits:
  - TDR would be 25% higher than either HHLVJ or HLVJA.
  - Sky coverage goes up to 91-95%.
  - DP improves by 25% on either HHLVJ or HLVJA.

DATA ANALYSIS FOR BIG NETWORKS

DATA ANALYSIS FOR BIG NETWORKS

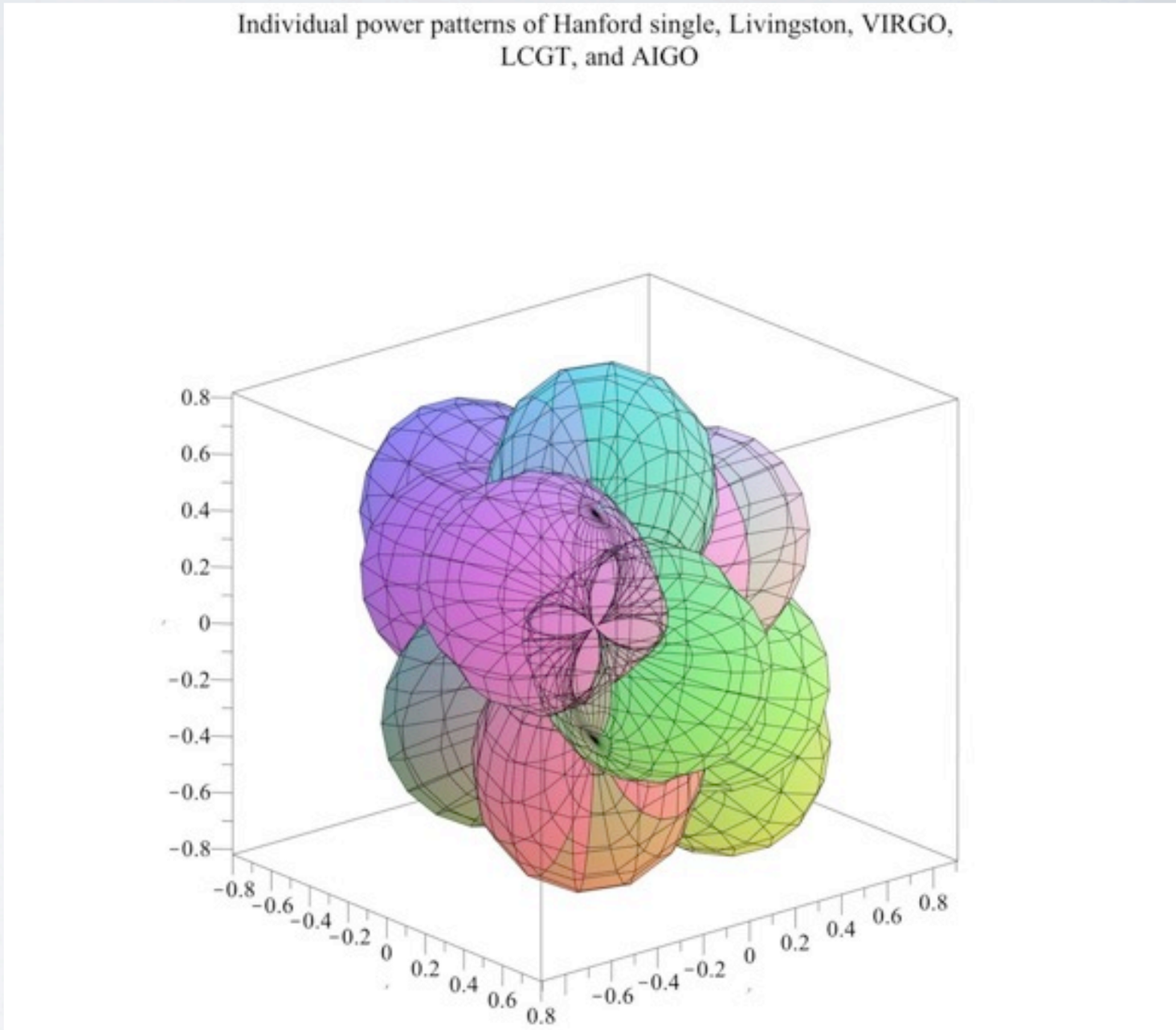
- Why is there such a difference between detection rates computed here and those in the LSC paper Abbott et al (2010)?

DATA ANALYSIS FOR BIG NETWORKS

- Why is there such a difference between detection rates computed here and those in the LSC paper Abbott et al (2010)?
- It is the difference between *coherent* and *threshold* analysis.

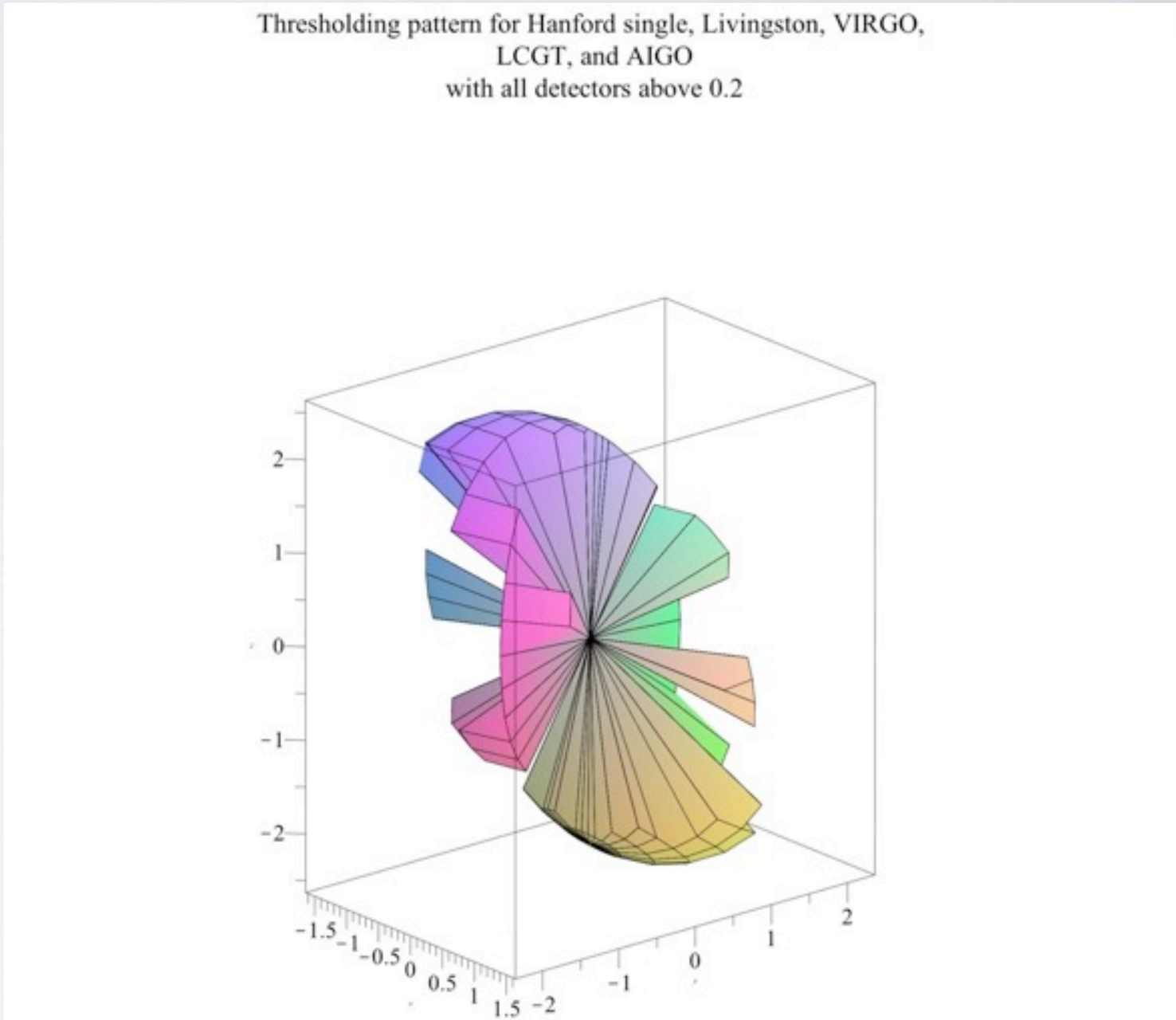
DATA ANALYSIS FOR BIG NETWORKS

- Why is there such a difference between detection rates computed here and those in the LSC paper Abbott et al (2010)?
- It is the difference between *coherent* and *threshold* analysis.
- Current searches have to deal with frequent "glitches", which are vetoed by comparison between detectors. Data only pass to analysis if there is a large coincident event in, say, three detectors. But this cuts down antenna pattern.



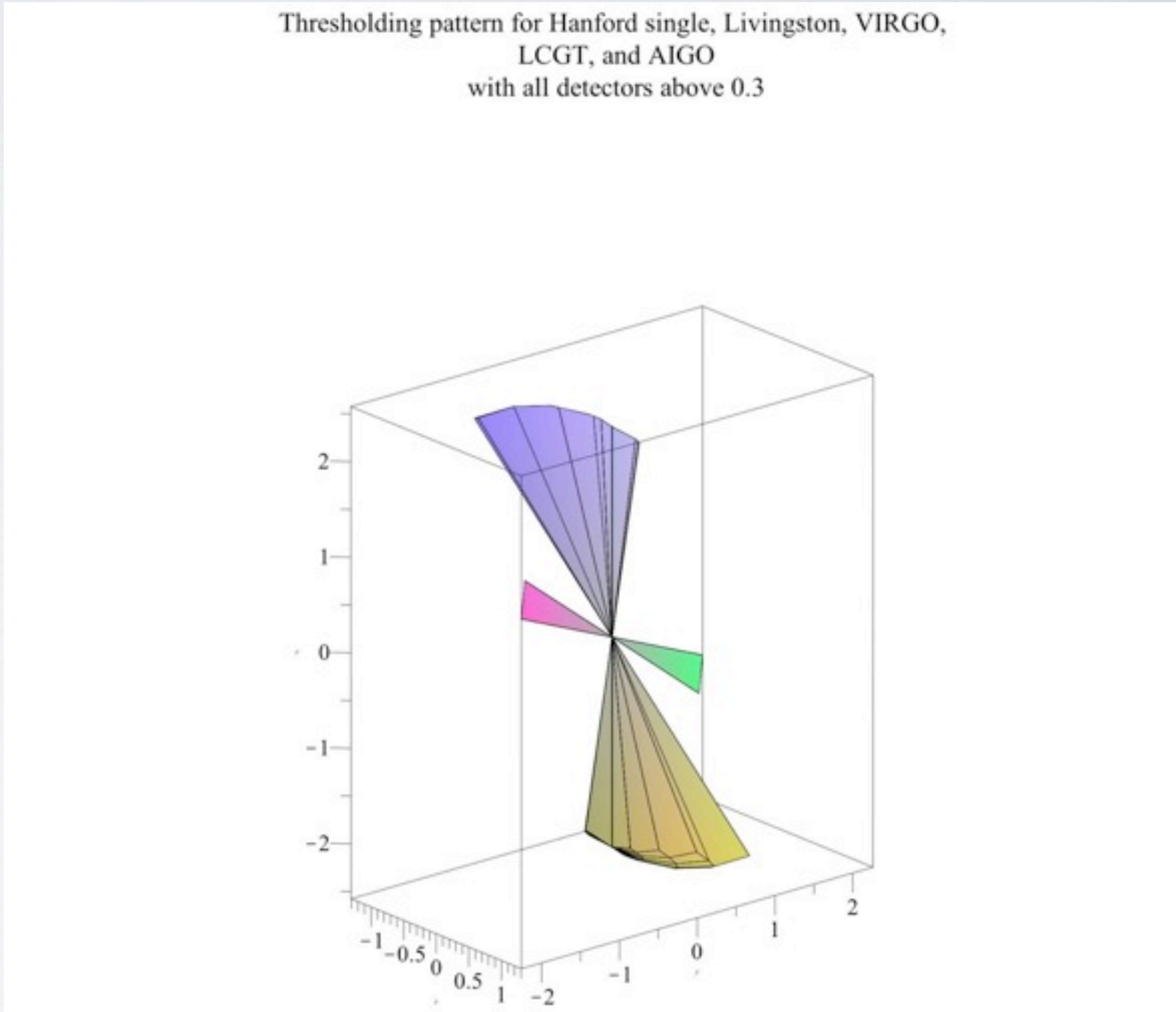
DATA ANALYSIS FOR BIG NETWORKS

- Why is there such a difference between detection rates computed here and those in the LSC paper Abbott et al (2010)?
- It is the difference between *coherent* and *threshold* analysis.
- Current searches have to deal with frequent "glitches", which are vetoed by comparison between detectors. Data only pass to analysis if there is a large coincident event in, say, three detectors. But this cuts down antenna pattern.



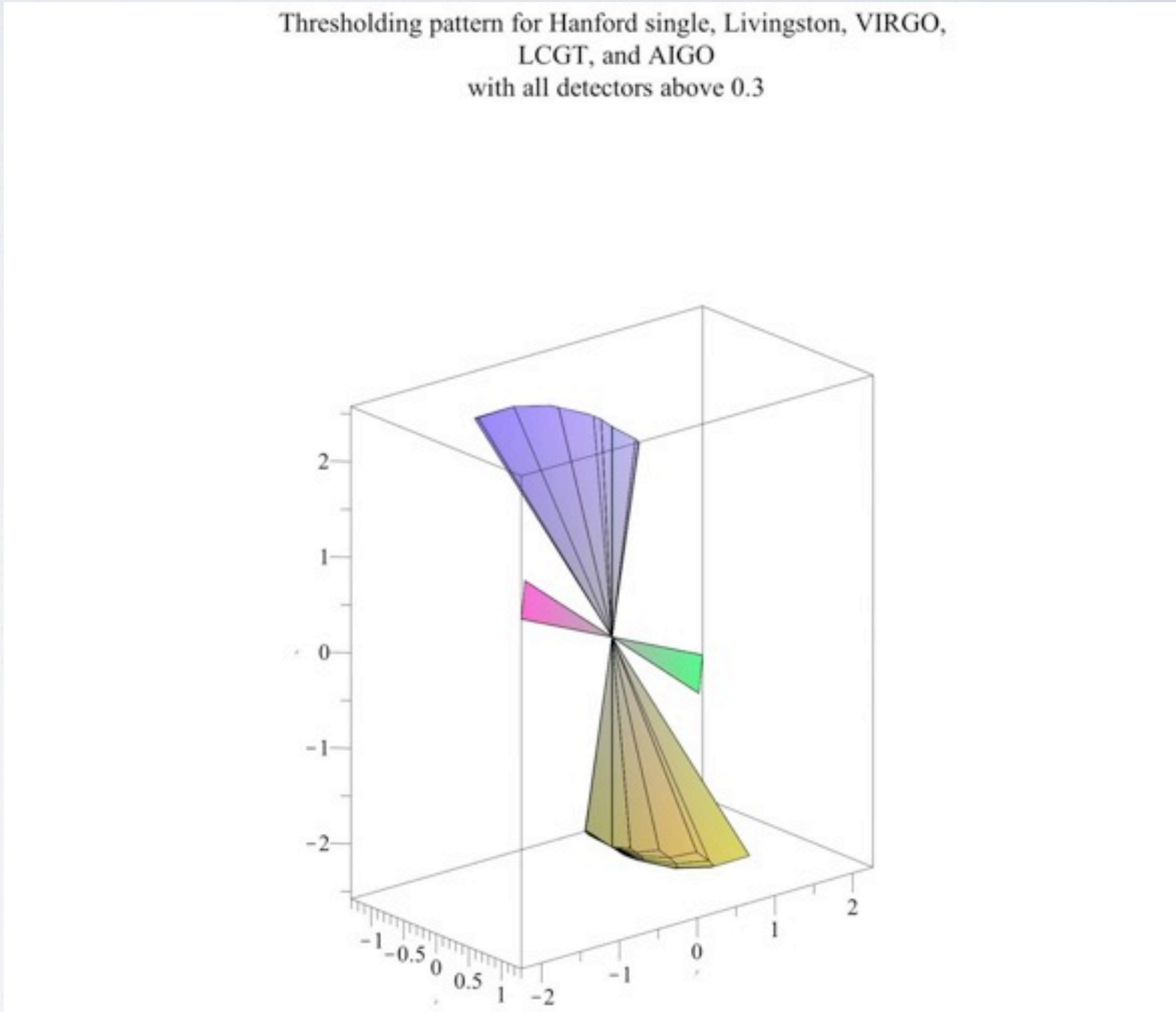
DATA ANALYSIS FOR BIG NETWORKS

- Why is there such a difference between detection rates computed here and those in the LSC paper Abbott et al (2010)?
- It is the difference between *coherent* and *threshold* analysis.
- Current searches have to deal with frequent "glitches", which are vetoed by comparison between detectors. Data only pass to analysis if there is a large coincident event in, say, three detectors. But this cuts down antenna pattern.



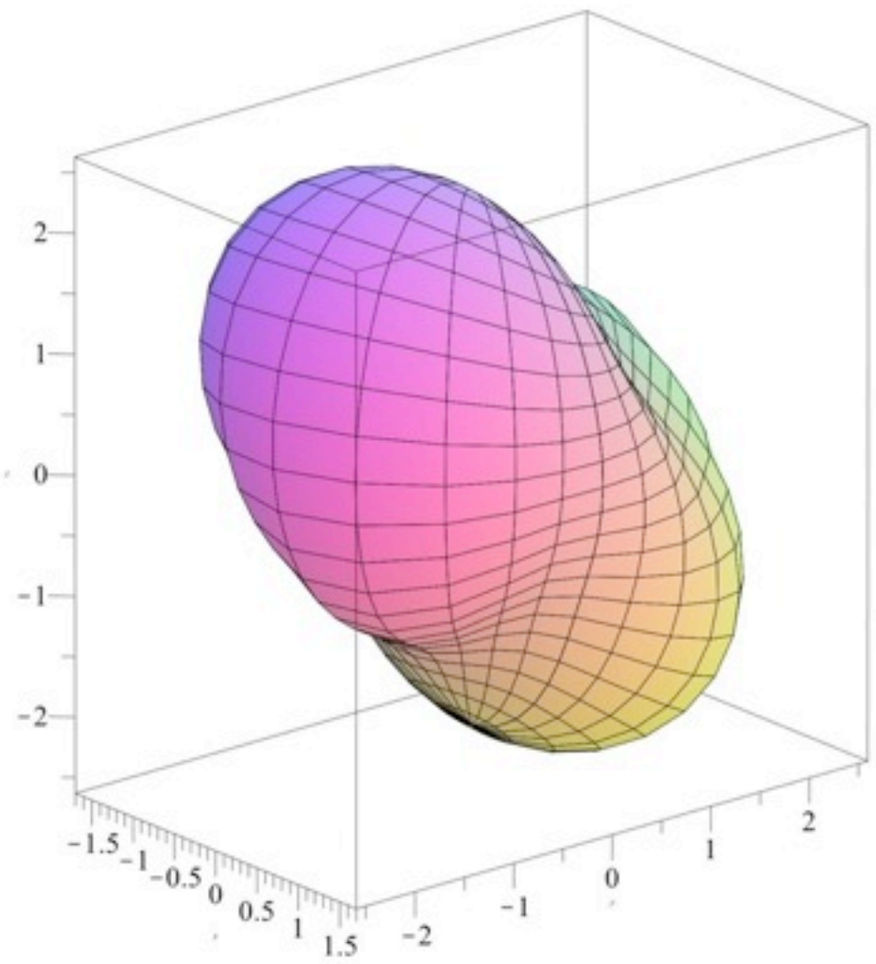
DATA ANALYSIS FOR BIG NETWORKS

- Why is there such a difference between detection rates computed here and those in the LSC paper Abbott et al (2010)?
- It is the difference between *coherent* and *threshold* analysis.
- Current searches have to deal with frequent "glitches", which are vetoed by comparison between detectors. Data only pass to analysis if there is a large coincident event in, say, three detectors. But this cuts down antenna pattern.
- Coherent detection uses entire network antenna pattern. With many detectors, consistency checks (null streams) allow vetoing of glitches.

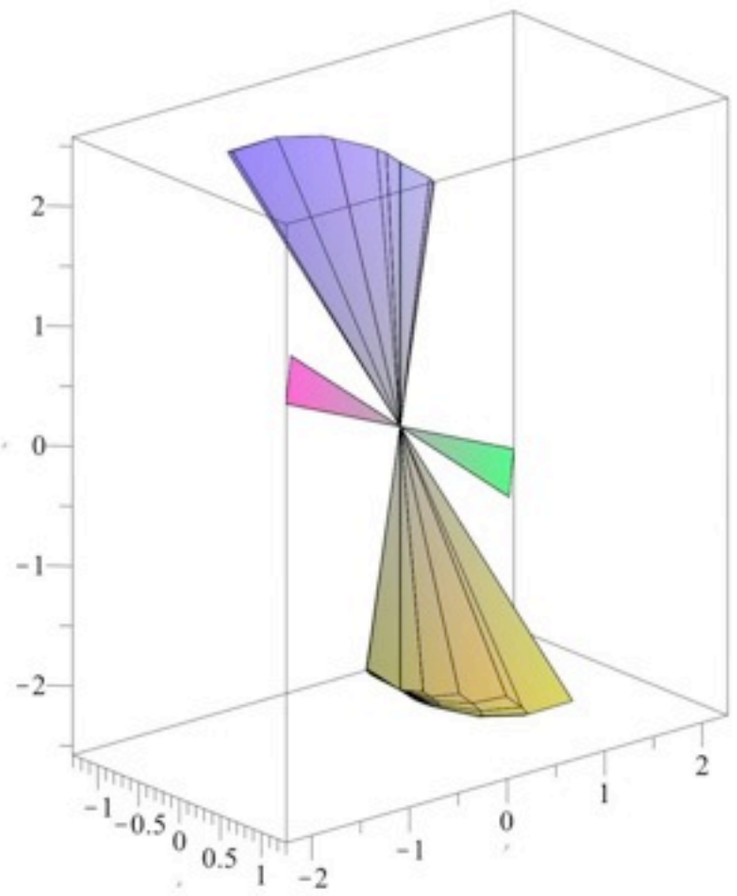


DATA ANALYSIS FOR BIG NETWORKS

Hanford single + Livingston + VIRGO + LCGT + AIGO
antenna power pattern

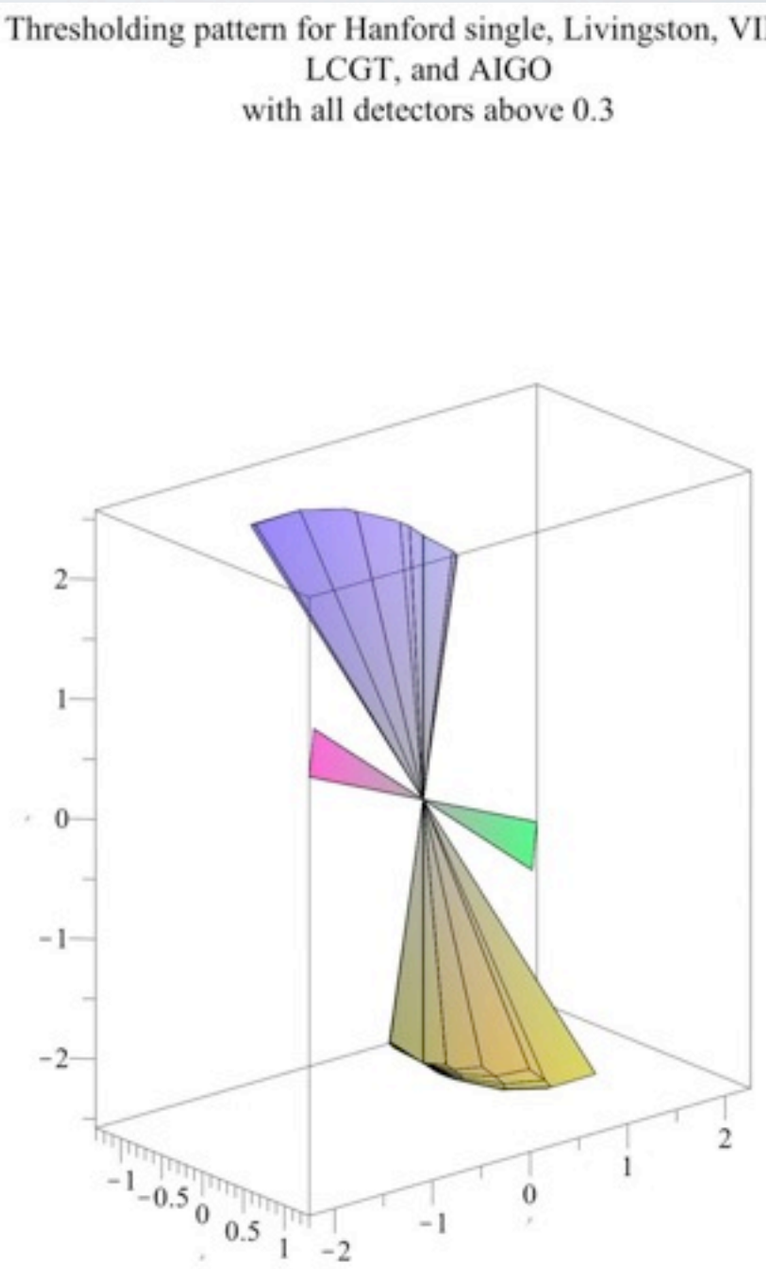


Thresholding pattern for Hanford single, Livingston, VIRGO,
LCGT, and AIGO
with all detectors above 0.3



DATA ANALYSIS FOR BIG NETWORKS

- Why is there such a difference between detection rates computed here and those in the LSC paper Abbott et al (2010)?
- It is the difference between *coherent* and *threshold* analysis.
- Current searches have to deal with frequent "glitches", which are vetoed by comparison between detectors. Data only pass to analysis if there is a large coincident event in, say, three detectors. But this cuts down antenna pattern.
- Coherent detection uses entire network antenna pattern. With many detectors, consistency checks (null streams) allow vetoing of glitches.
- Networks with LCGT will lose huge amounts of science unless the teams agree on coherent data analysis. This needs project-level agreements on data pooling. L-V already have these. Negotiations are going on to widen this to include LCGT.



SCIENCE WITH A WORLD NET

SCIENCE WITH A WORLD NET

- Bringing LCGT online may bring not only increased sensitivity but also push the existing projects to do fully coherent data analysis sooner.

SCIENCE WITH A WORLD NET

- Bringing LCGT online may bring not only increased sensitivity but also push the existing projects to do fully coherent data analysis sooner.
- Event rates of 1200 NS-NS mergers per year out to 800 Mpc and 500 BH-BH mergers per year out to 4 Gpc are possible.
  - Remember the error bars: ×(0.01→10).
  - The best rates imply that the closest events will have SNR > 60, can be studied in great detail.
  - Follow-up by optical/X-ray/γ-ray/radio/IR astronomers could become a big industry. Error boxes of large network match fields of view of many instruments better.
  - Monitoring instruments (Pan-Starrs, LOFAR, Swift, …) will trade triggers with the GW network.
  - Insight into neutron-matter EOS (hot and cold), population statistics (masses and numbers) of NSs and BHs, physics of gamma-ray bursts seem likely.
  - Detection of rare and weak events much more likely: supernovae, NS vibrations. Discovery space much bigger.

SCIENCE WITH A WORLD NET

- Bringing LCGT online may bring not only increased sensitivity but also push the existing projects to do fully coherent data analysis sooner.
- Event rates of 1200 NS-NS mergers per year out to 800 Mpc and 500 BH-BH mergers per year out to 4 Gpc are possible.
  - Remember the error bars: ×(0.01→10).
  - The best rates imply that the closest events will have SNR > 60, can be studied in great detail.
  - Follow-up by optical/X-ray/γ-ray/radio/IR astronomers could become a big industry. Error boxes of large network match fields of view of many instruments better.
  - Monitoring instruments (Pan-Starrs, LOFAR, Swift, …) will trade triggers with the GW network.
  - Insight into neutron-matter EOS (hot and cold), population statistics (masses and numbers) of NSs and BHs, physics of gamma-ray bursts seem likely.
  - Detection of rare and weak events much more likely: supernovae, NS vibrations. Discovery space much bigger.
- To achieve this, projects have to pool data fully, data analysis pipelines need to be re-worked, and instruments have to have reasonably low glitch rates. These are already well-established goals inside the LSC-VIRGO collaboration. Prospects are therefore very bright for a robust GW astronomy with a worldwide GW network.

FUTURE: LCGT AND 3G

FUTURE: LCGT AND 3G

- The international GW community is used to long-term planning, so they are already preparing for 3G detectors.

FUTURE: LCGT AND 3G

- The international GW community is used to long-term planning, so they are already preparing for 3G detectors.
- The EU funded the Einstein Telescope (ET) design study. ET is now in various European roadmaps, for completion during the 2020s.

EINSTEIN TELESCOPE
gravitational wave observatory

CENTRAL FACILITY

COMPUTING CENTRE

DETECTOR STATION

END STATION

Length ~ 10 km

TUNNEL Ø ~5 m

SEVENTH FRAMEWORK PROGRAMME

FUTURE: LCGT AND 3G

- The international GW community is used to long-term planning, so they are already preparing for 3G detectors.
- The EU funded the Einstein Telescope (ET) design study. ET is now in various European roadmaps, for completion during the 2020s.
- The world may need 2 ET-type detectors, working with existing Advanced instruments, especially LCGT.

FUTURE: LCGT AND 3G

- The international GW community is used to long-term planning, so they are already preparing for 3G detectors.
- The EU funded the Einstein Telescope (ET) design study. ET is now in various European roadmaps, for completion during the 2020s.
- The world may need 2 ET-type detectors, working with existing Advanced instruments, especially LCGT.
- LCGT introduces key technologies that ET assumes will be available: cryogenically cooled mirrors, underground construction.

FUTURE: LCGT AND 3G

- The international GW community is used to long-term planning, so they are already preparing for 3G detectors.
- The EU funded the Einstein Telescope (ET) design study. ET is now in various European roadmaps, for completion during the 2020s.
- The world may need 2 ET-type detectors, working with existing Advanced instruments, especially LCGT.
- LCGT introduces key technologies that ET assumes will be available: cryogenically cooled mirrors, underground construction.
- Advanced LIGO/VIRGO/LCGT probably should be thought of as facilities with 50-year lifetimes, that will eventually work with one or two 3G instruments.

Thank You!