Title: Cross-Correlation Methods in Continuous Gravitational-Wave Searches

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Abstract: Cross-correlation of gravitational-wave (GW) data streams has been used to search for stochastic backgrounds, and the same technique was applied to look for periodic GWs from the low-mass X-ray binary (LMXB) Sco X-1. Recently a technique was developed which refines the cross-correlation scheme to take full advantage of the signal model for periodic gravitational waves from rotating neutron stars. By varying the time window over which data streams are correlated, the search can "trade off" between parameter sensitivity and computational cost. I describe this cross-correlation method and potential applications to search LIGO and Virgo data for periodic GWs from systems with partially-known parameters, such as supernova remnants without an associated known pulsar, the center of the Milky Way Galaxy, and LMXBs

CENTER FOR COMPUTATIONAL RELATIVITY AND GRAVITATION

A Cross-Correlation Technique to Search for Periodic Gravitational Waves

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Strong Gravity Seminar
Perimeter Institute, Waterloo, Ontario, Canada
2011 April 14

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CENTER FOR COMPUTATIONAL RELATIVITY AND GRAVITATION

Outline

1. Searches for Gravitational Waves
   - Crash Course in Gravitational Wave Physics
   - Gravitational-Wave Sources & Signals
   - Gravitational-Wave Observations & Detectors
2. Cross-Correlation Method
   - Application to Stochastic Background
   - Application to Quasiperiodic Gravitational-Wave Signals
   - Tuning Search by Choice of Data Segments to Correlate
3. Applications and Outlook
   - Directed Search for Young Neutron Stars
   - Accreting Neutron Stars in Low-Mass X-Ray Binaries
   - Summary

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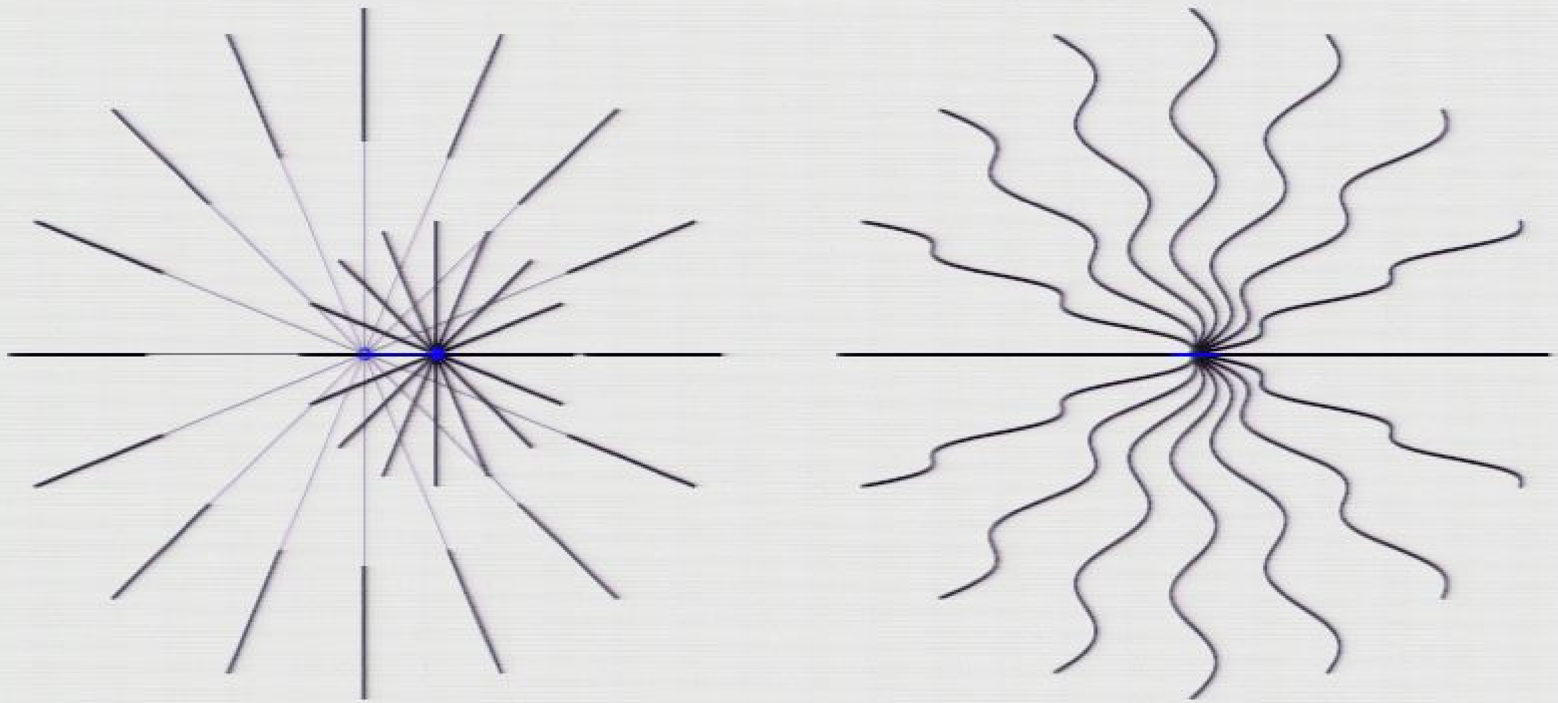
Motivation



- In Newtonian gravity, force dep on distance btwn objects
- If massive object suddenly moved, grav field at a distance would change instantaneously
- In relativity, no signal can travel faster than light
  $\longrightarrow$ time-dep grav fields must propagate like light waves

Gravity as Geometry

- Minkowski Spacetime:

$$ds^2 = -c^2(dt)^2 + (dx)^2 + (dy)^2 + (dz)^2$$

$$= \begin{pmatrix} dt \\ dx \\ dy \\ dz \end{pmatrix}^{\mathrm{tr}} \begin{pmatrix} -c^2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} dt \\ dx \\ dy \\ dz \end{pmatrix} = \eta_{\mu\nu} dx^\mu dx^\nu$$

- General Spacetime:

$$ds^2 = \begin{pmatrix} dx^0 \\ dx^1 \\ dx^2 \\ dx^3 \end{pmatrix}^{\mathrm{tr}} \begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{10} & g_{11} & g_{12} & g_{13} \\ g_{20} & g_{21} & g_{22} & g_{23} \\ g_{30} & g_{31} & g_{32} & g_{33} \end{pmatrix} \begin{pmatrix} dx^0 \\ dx^1 \\ dx^2 \\ dx^3 \end{pmatrix} = g_{\mu\nu} dx^\mu dx^\nu$$

Gravitational Wave as Metric Perturbation

- For GW propagation & detection, work to 1st order in $h_{\mu\nu} \equiv$ difference btwn actual metric $g_{\mu\nu}$ & flat metric $\eta_{\mu\nu}$:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

  ($h_{\mu\nu}$ "small" in weak-field regime, e.g. for GW detection)
- Convenient choice of gauge is transverse-traceless:

$$h_{0\mu} = h_{\mu 0} = 0 \qquad \eta^{\nu\lambda} \frac{\partial h_{\mu\nu}}{\partial x^{\lambda}} = 0 \qquad \eta^{\mu\nu} h_{\mu\nu} = \delta^{ij} h_{ij} = 0$$

  In this gauge:
  - Test particles w/constant coörds are freely falling
  - Vacuum Einstein eqns $\Longrightarrow$ wave equation for $\{h_{ij}\}$:

$$\left(-\frac{1}{c^2} \frac{\partial^2}{\partial t^2} + \nabla^2 \right) h_{ij} = 0$$

Gravitational Wave Polarization States

- Far from source, GW looks like plane wave prop along $\vec{k}$
  TT conditions mean, in convenient basis,

$$\{k_i\} \equiv \mathbf{k} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \qquad \{h_{ij}\} \equiv \mathbf{h} = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

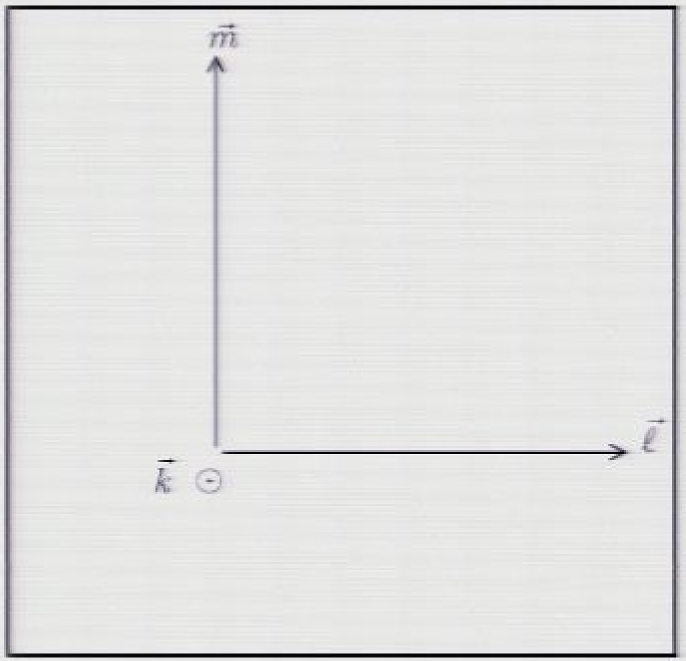
  where $h_+\left(t - \frac{x^3}{c}\right)$ and $h_\times\left(t - \frac{x^3}{c}\right)$ are components in "plus" and "cross" polarization states
- More generally

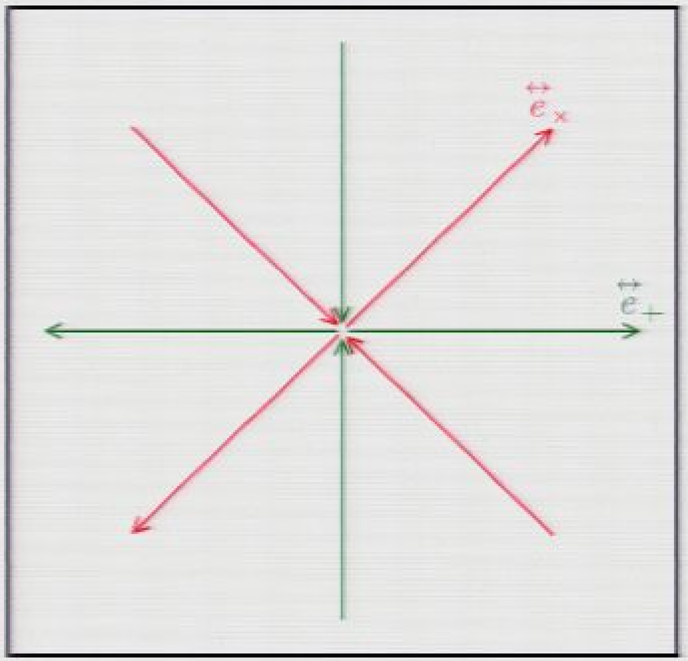
$$\overleftrightarrow{h} = \left[h_+\left(t - \frac{\vec{k}\cdot\vec{r}}{c}\right)\overleftrightarrow{e}_+ + h_\times\left(t - \frac{\vec{k}\cdot\vec{r}}{c}\right)\overleftrightarrow{e}_\times\right]$$

The Polarization Basis

- wave propagating along $\vec{k}$;
  construct $\overleftrightarrow{e}_{+,\times}$ from $\perp$ unit vectors $\vec{\ell}$ & $\vec{m}$:

$$\overleftrightarrow{e}_{+} = \vec{\ell} \otimes \vec{\ell} - \vec{m} \otimes \vec{m} \qquad \overleftrightarrow{e}_{\times} = \vec{\ell} \otimes \vec{m} + \vec{m} \otimes \vec{\ell}$$





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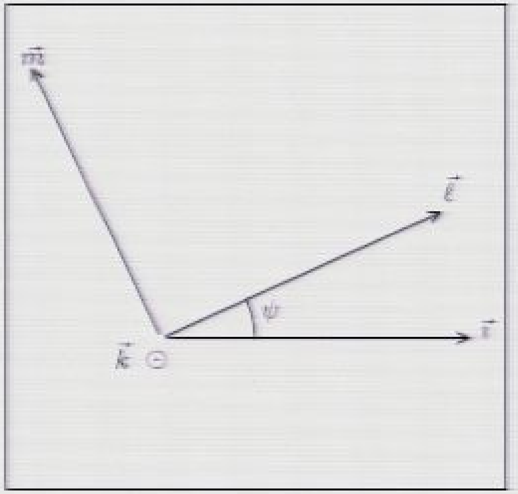
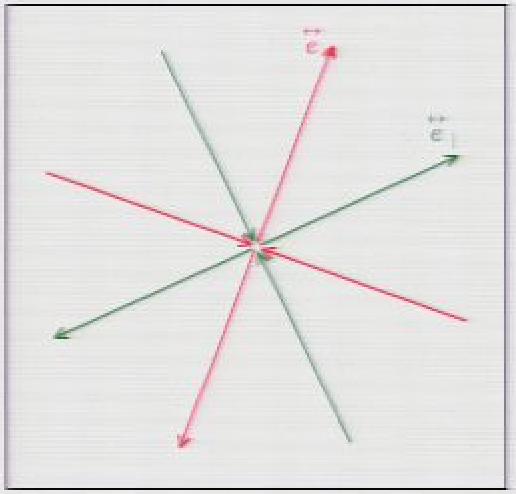
- arbitrary choice of $\vec{\ell}$ within plane $\perp \vec{k}$ (fixes $\vec{m} = \vec{k} \times \vec{\ell}$)
  Free to choose polarization basis convenient to situation
  Pol angle ψ relates $\vec{\ell}$ to some reference direction $\vec{\imath}$



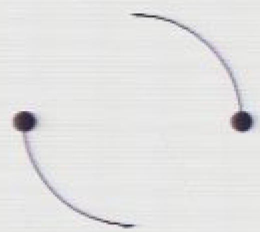


Gravitational Wave Generation

- Generated by moving/oscillating mass distribution
- Lowest multipole is quadrupole

$$h_{ab} = \frac{2G}{c^4 d} P^{\mathrm{TT}\vec{k}\,cd}{}_{ab}\, \ddot{I}_{cd}(t - d/c)$$

- Classic example: orbiting binary system



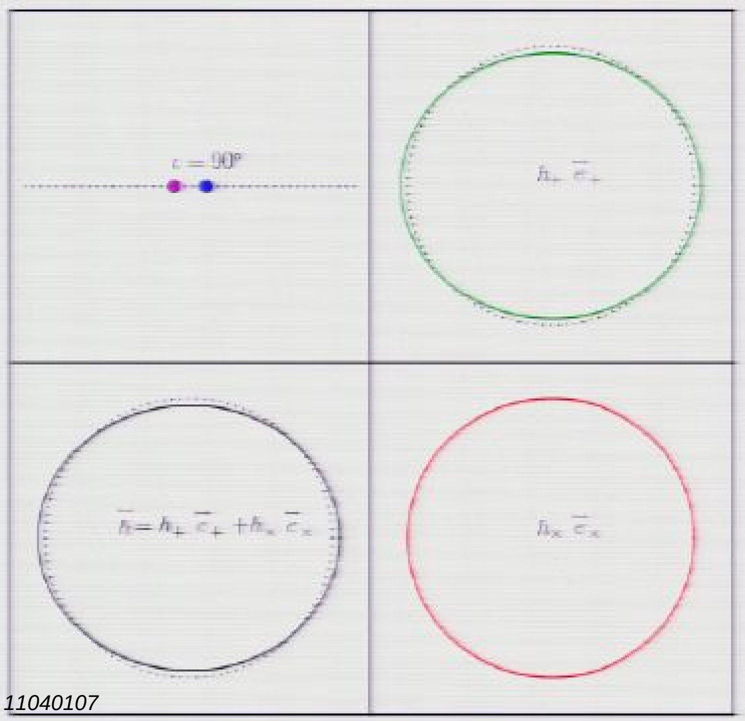
(e.g., Binary Pulsar 1913+16
– Observed energy loss agrees w/GW prediction)

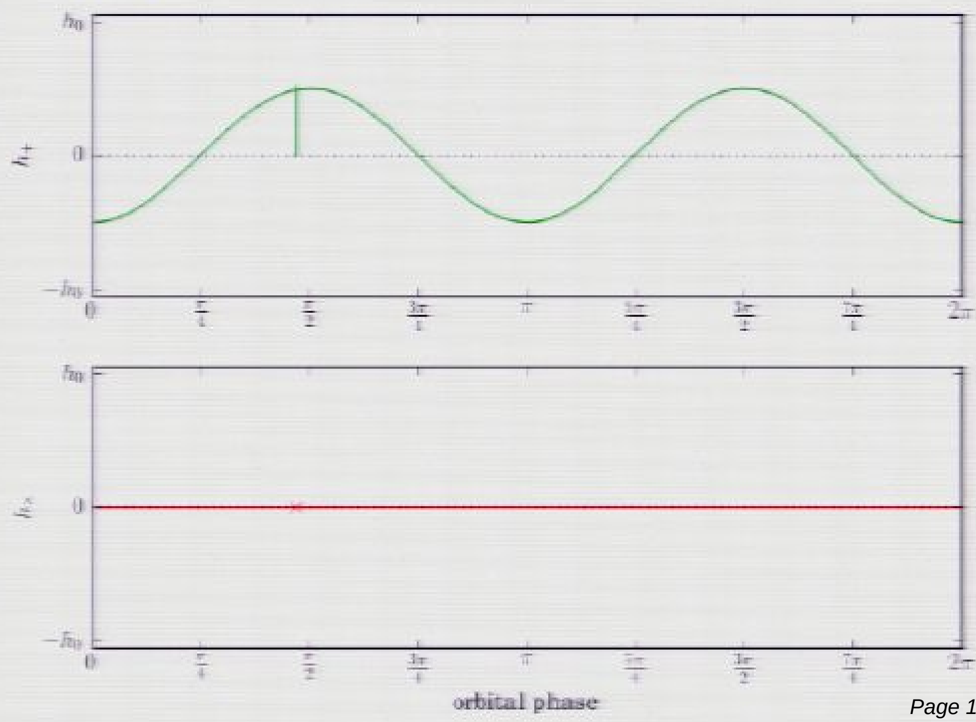
- Rotating neutron star w/non-axisymmetric perturbation also gives sinusoidally-varying quadrupole moment

Example: Linear polarization

- Consider binary system seen edge on:
  masses seen going back & forth in one direction; call that $\vec{\ell}$
- In that pol basis, $h_\times = 0$ and only h_+ **linear polarization**

$$h_+ = A\cos\Phi(t) \qquad h_\times = 0$$





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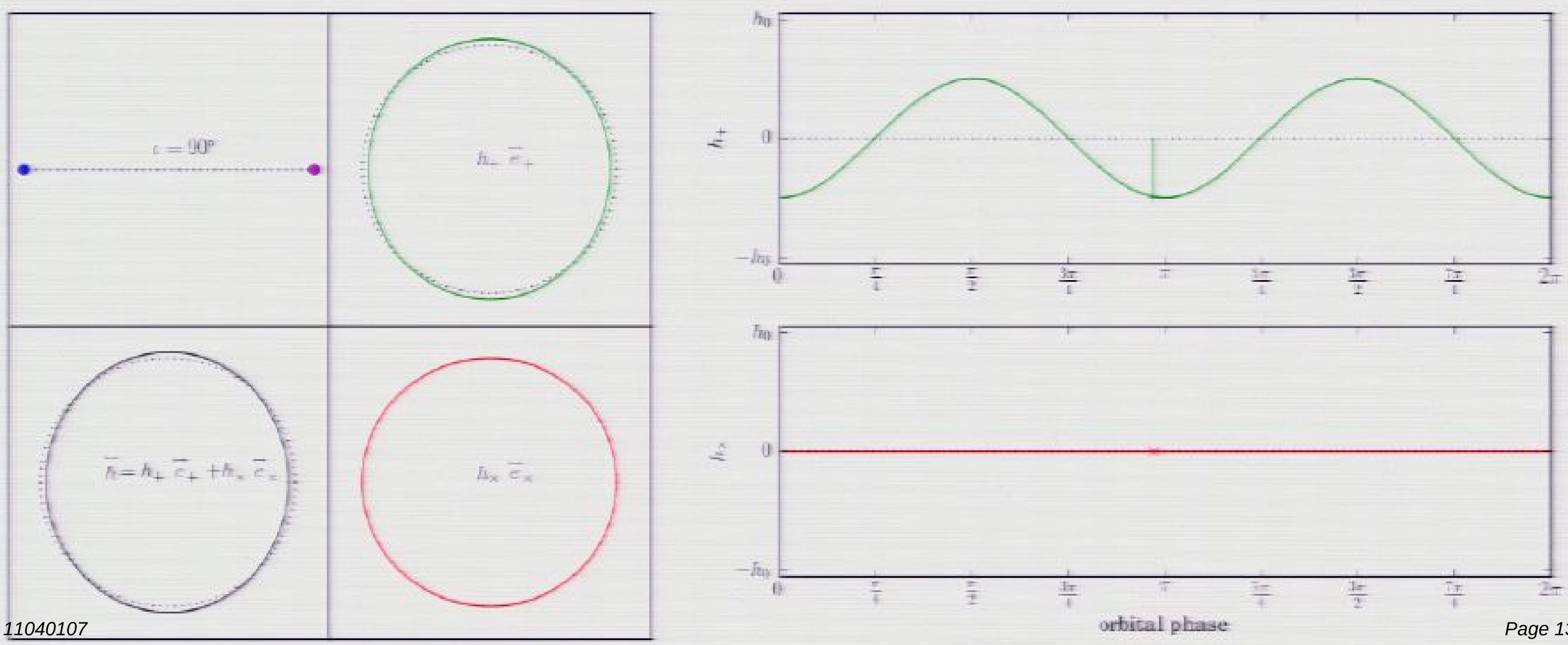

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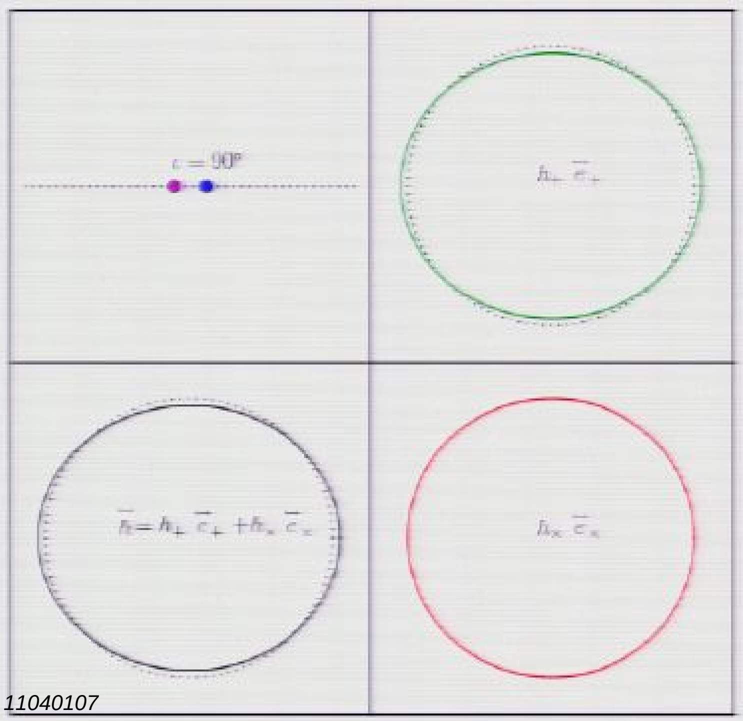

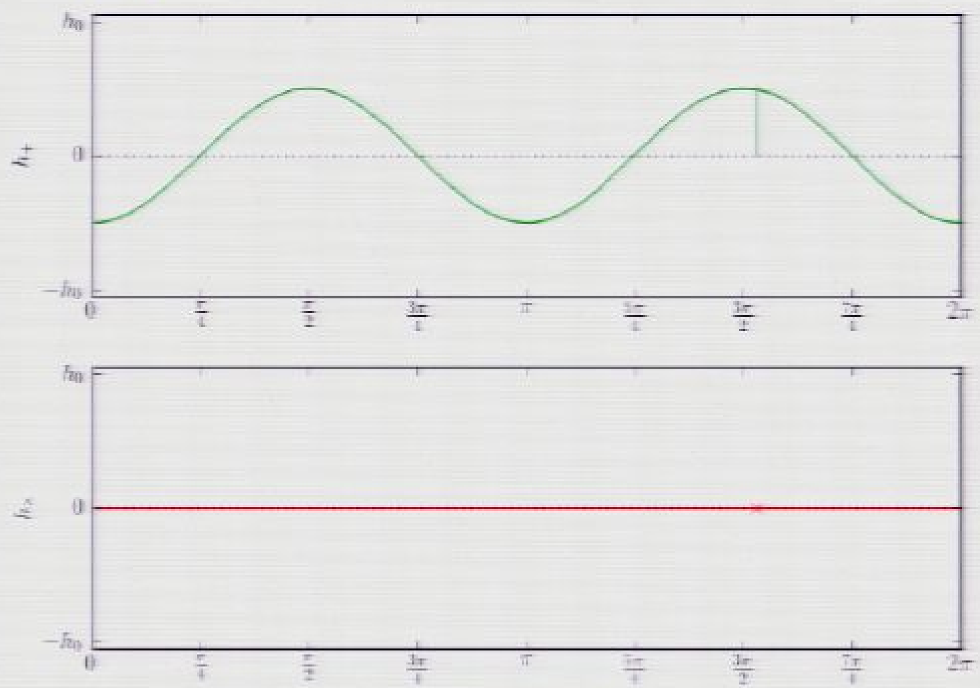

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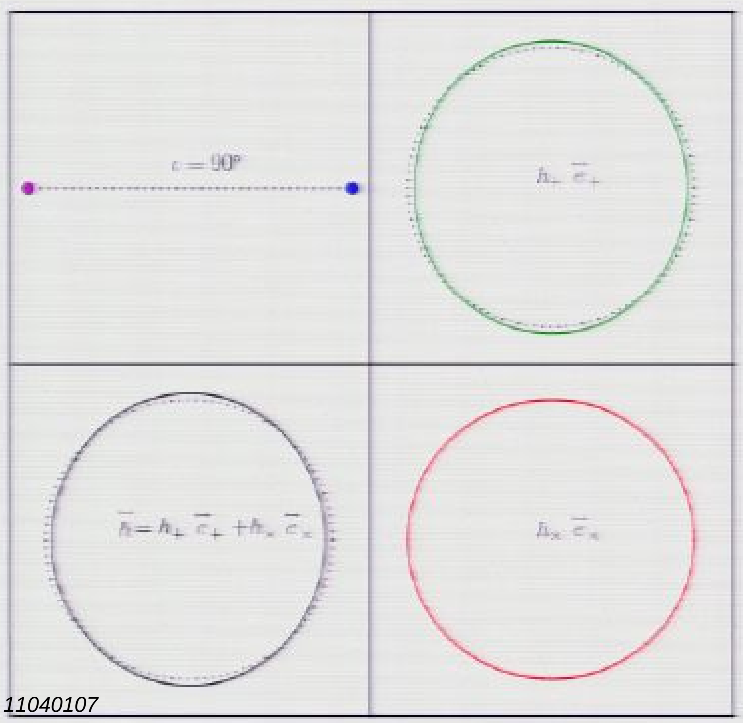

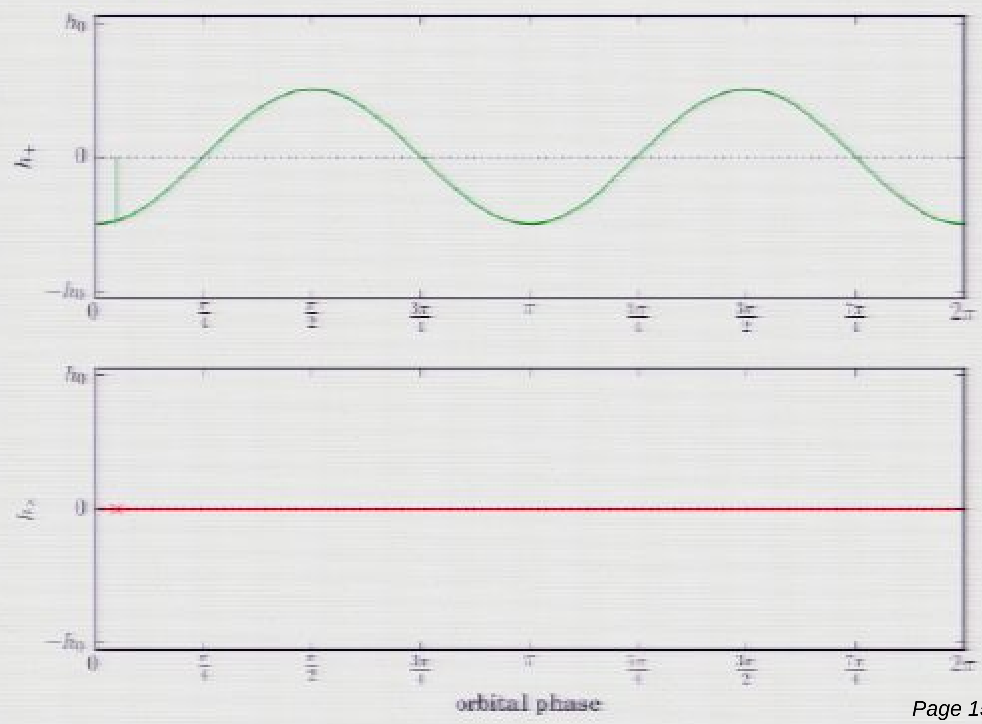

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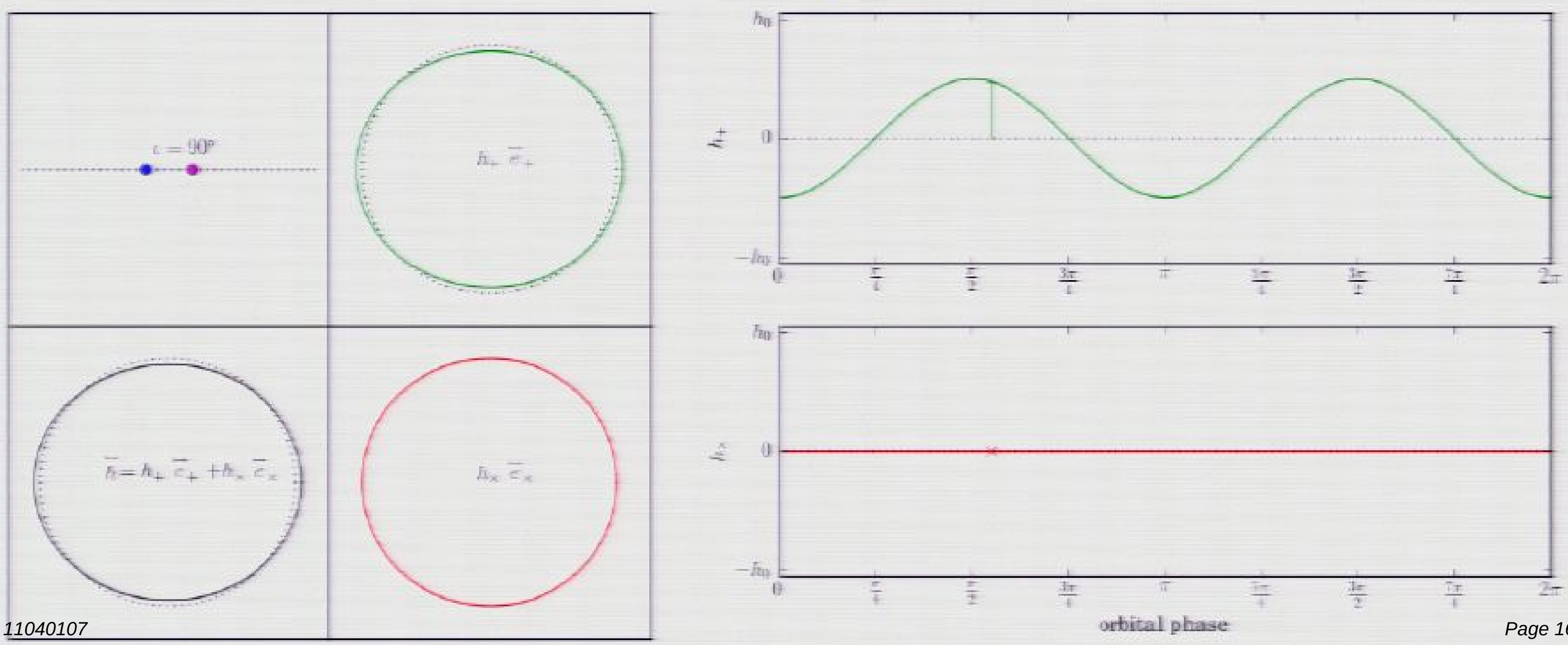

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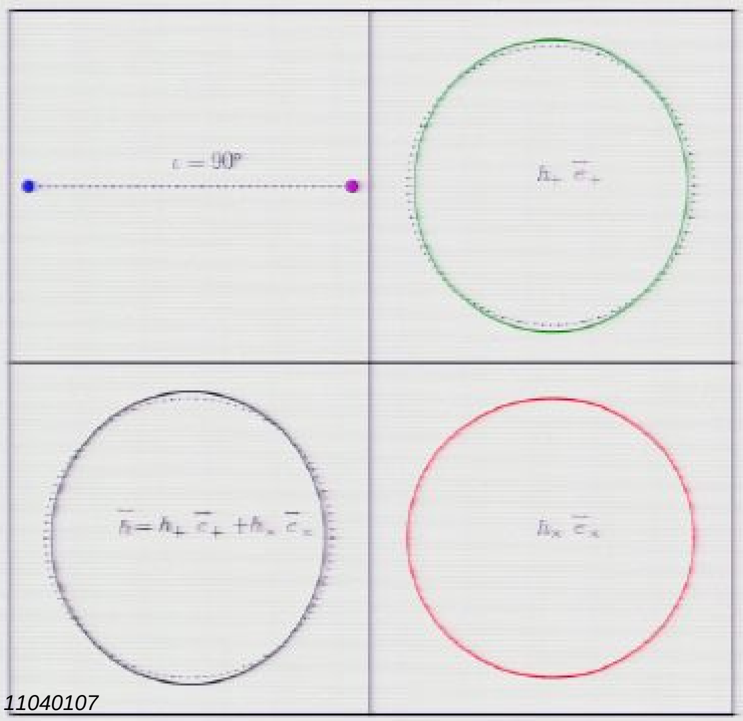

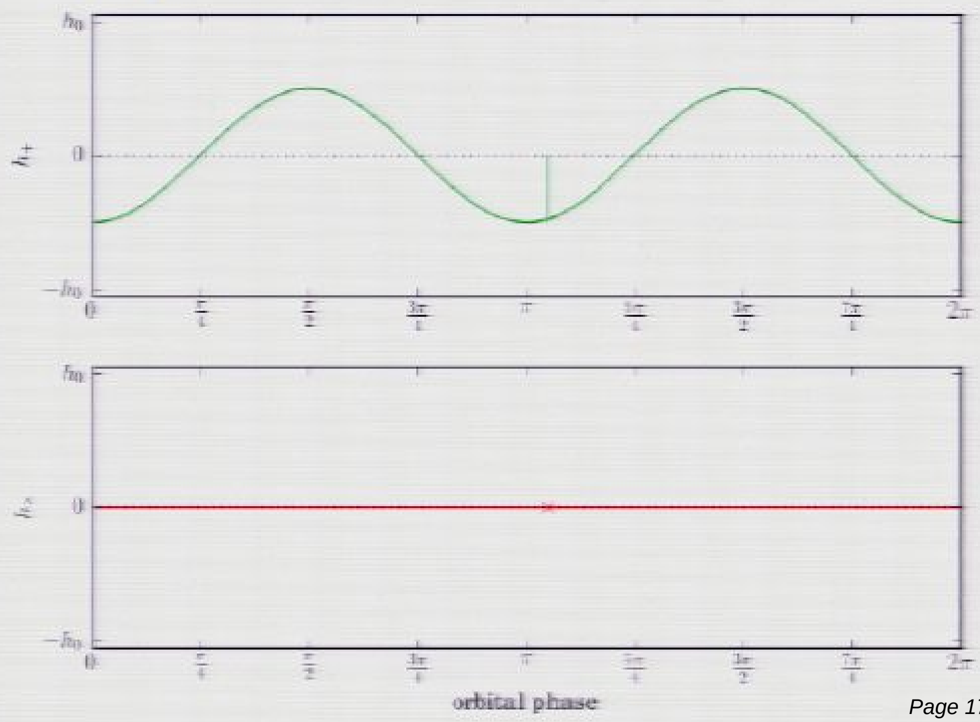

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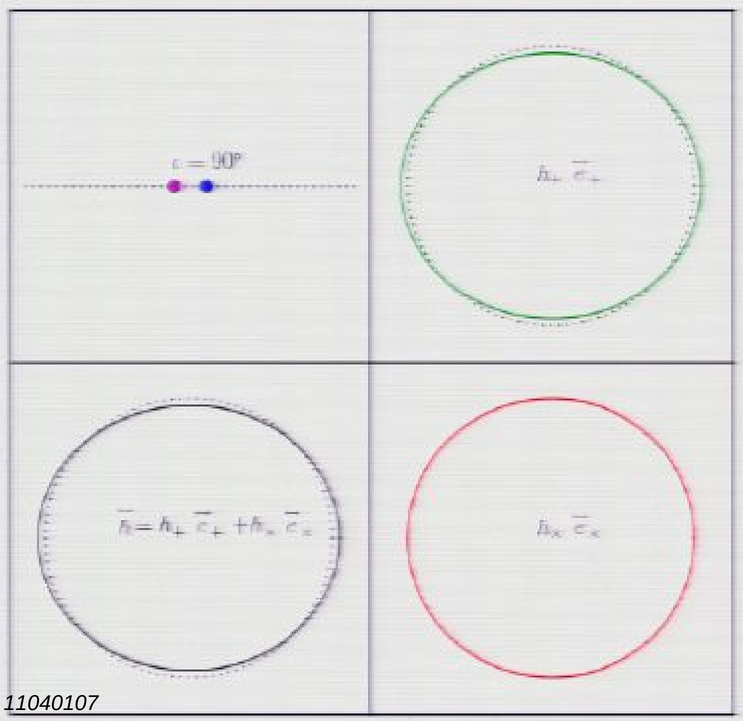

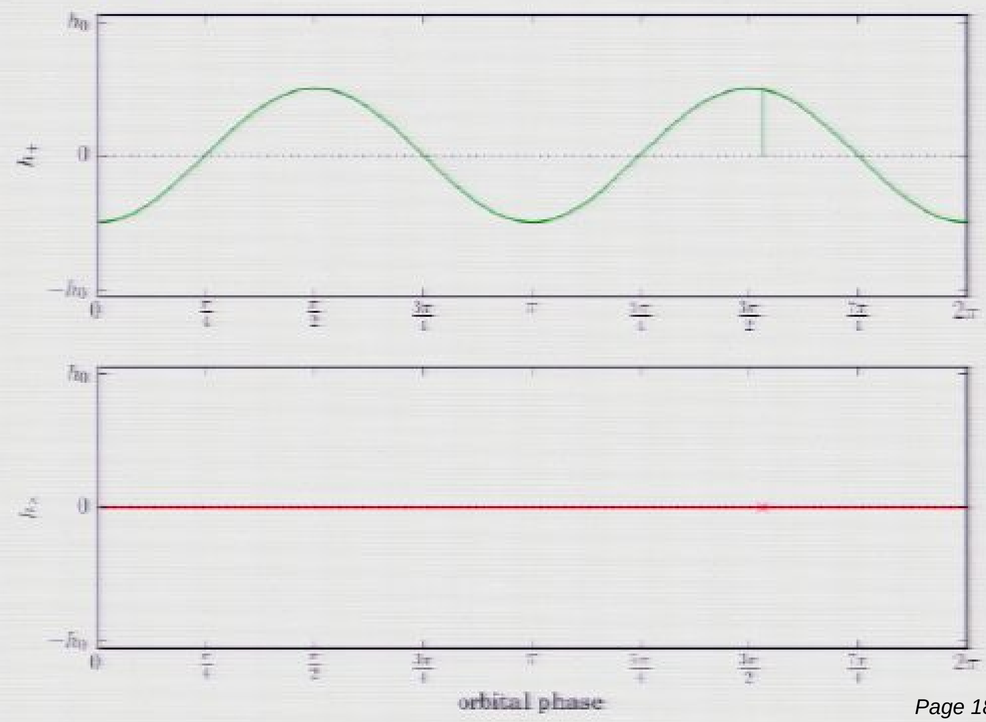

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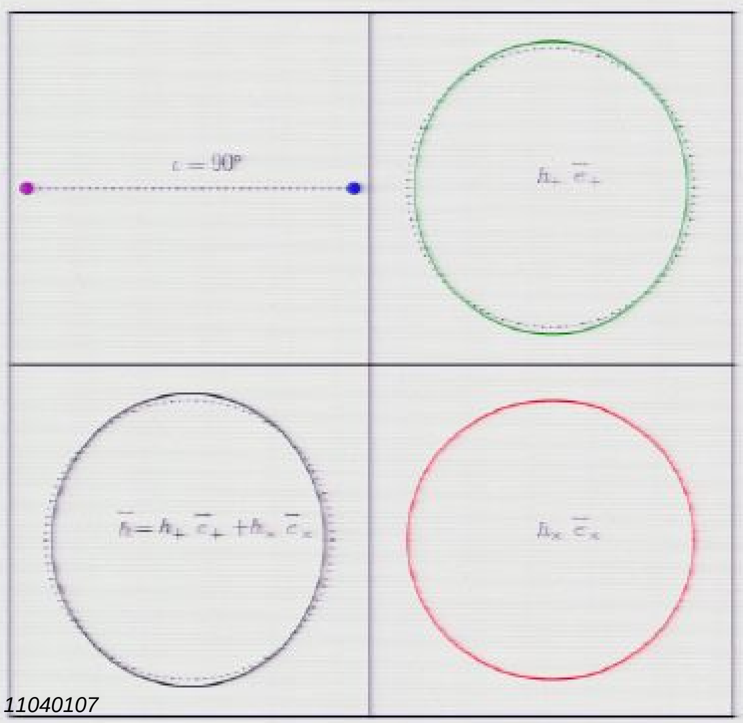

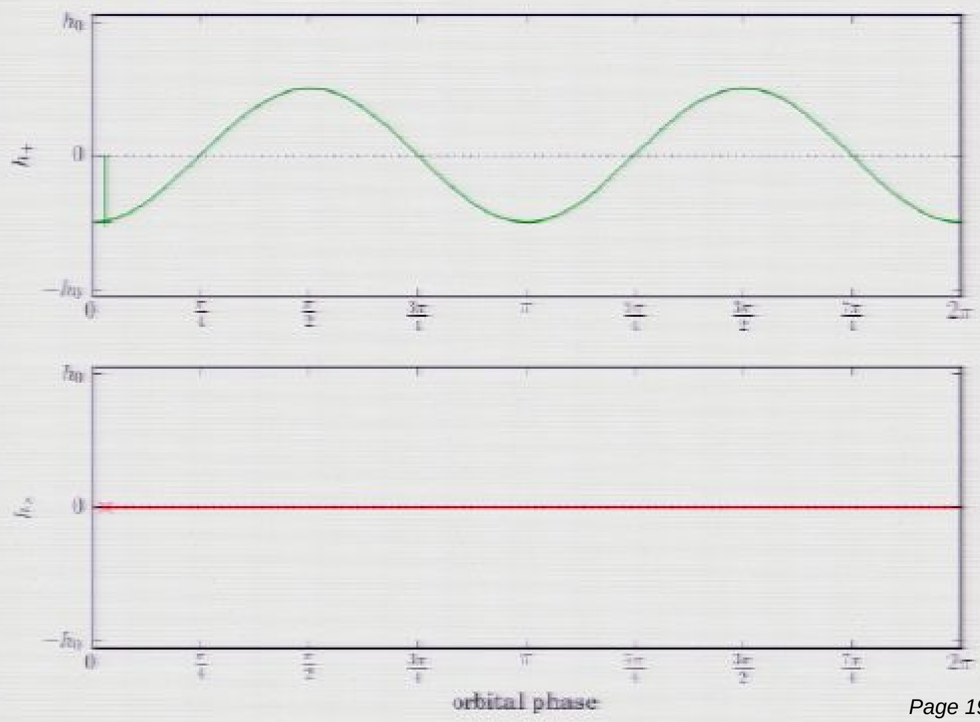

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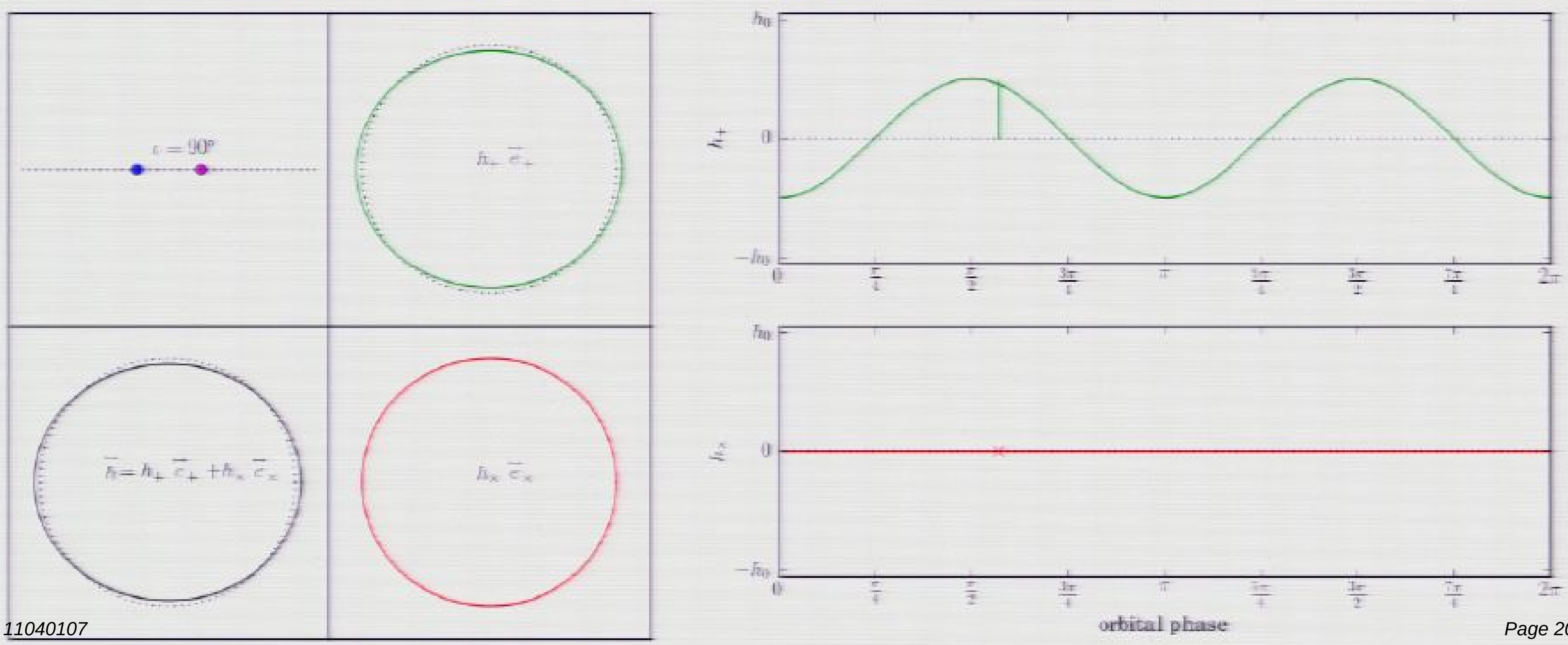

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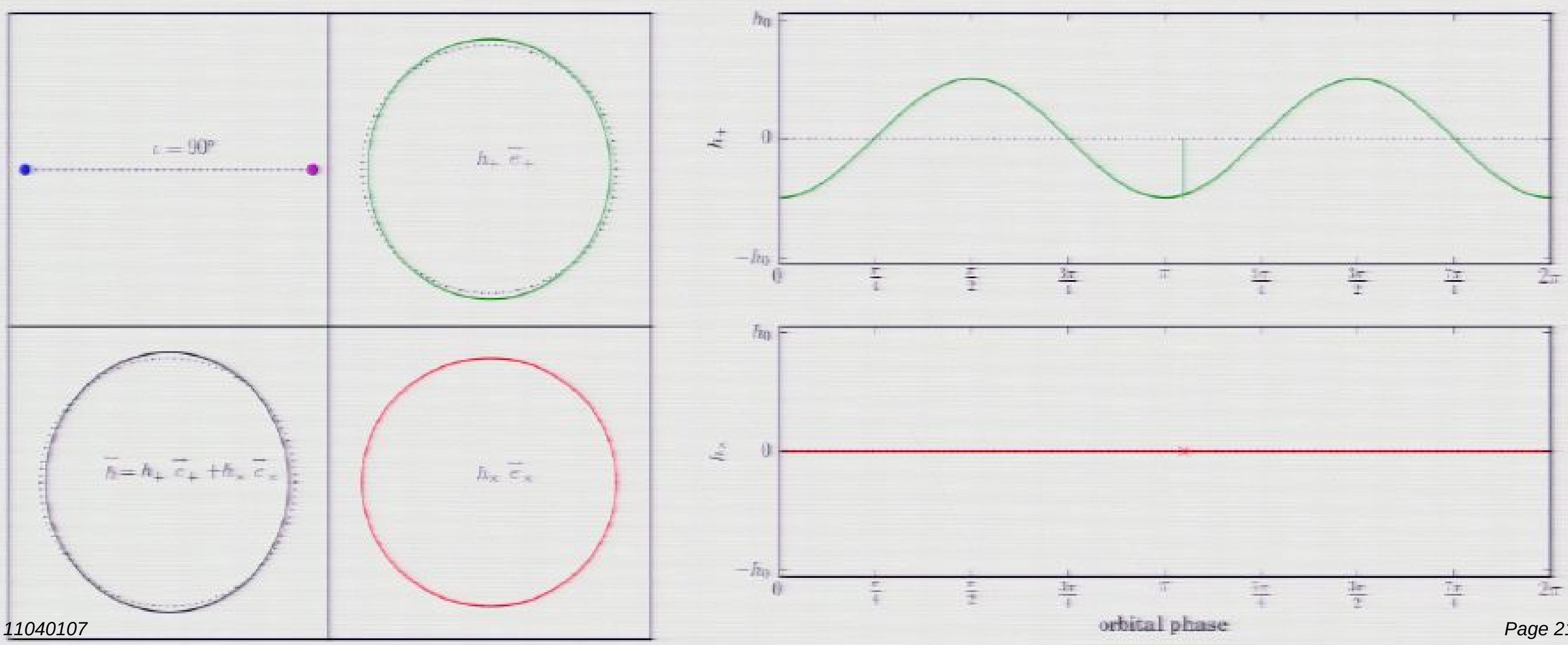

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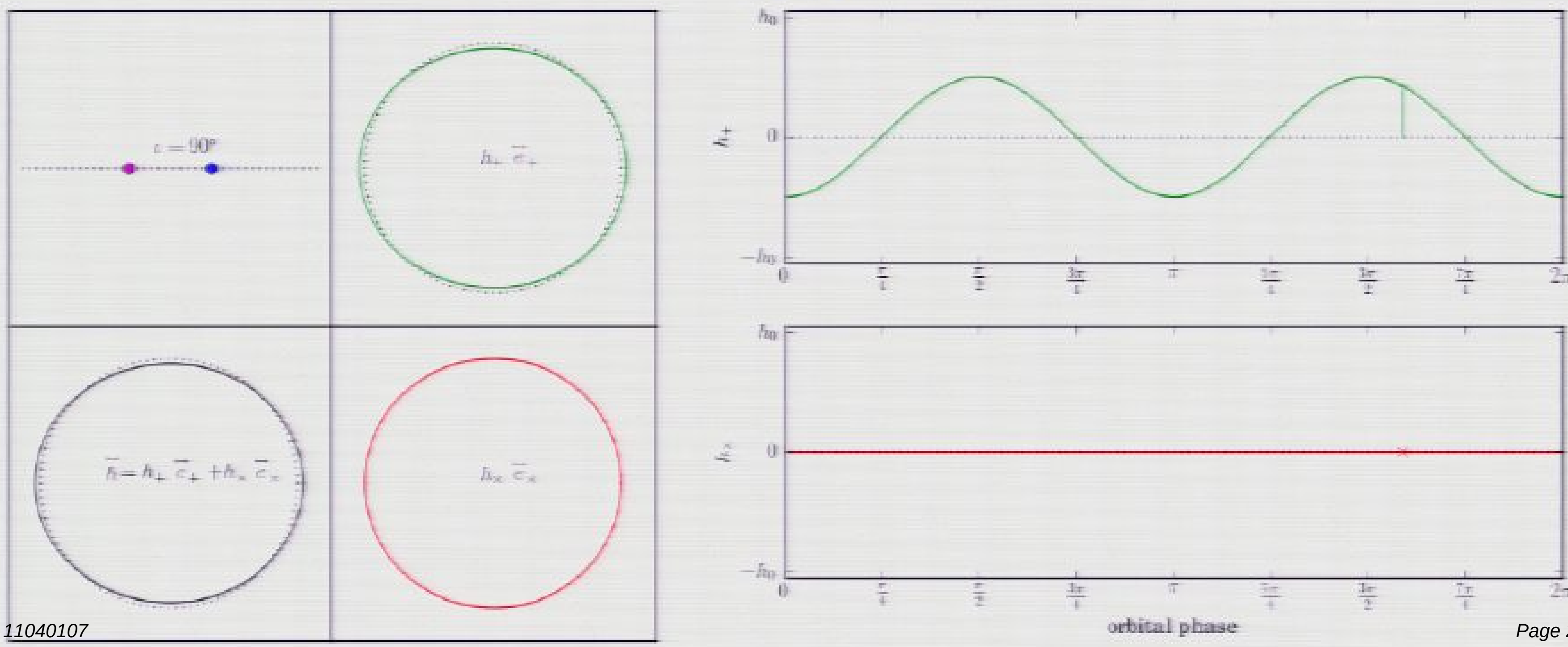

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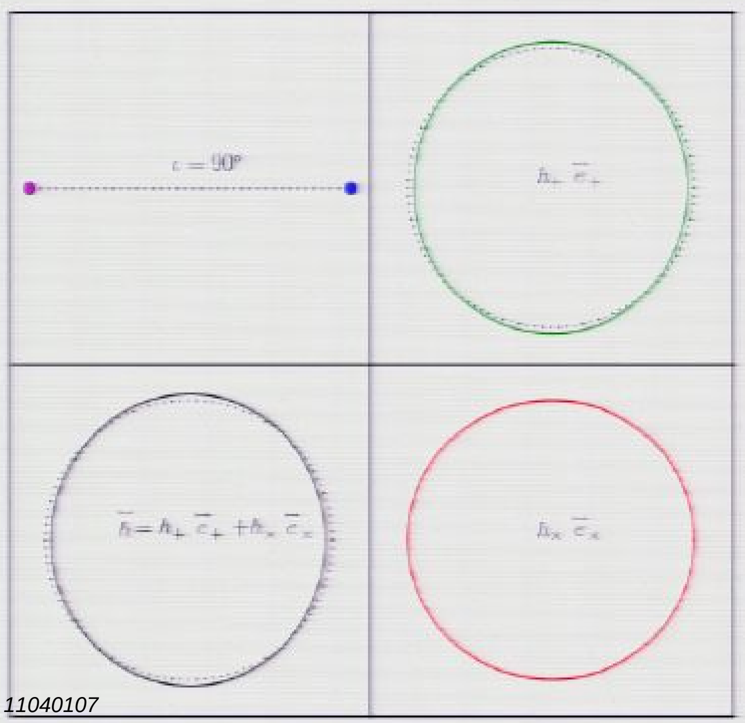

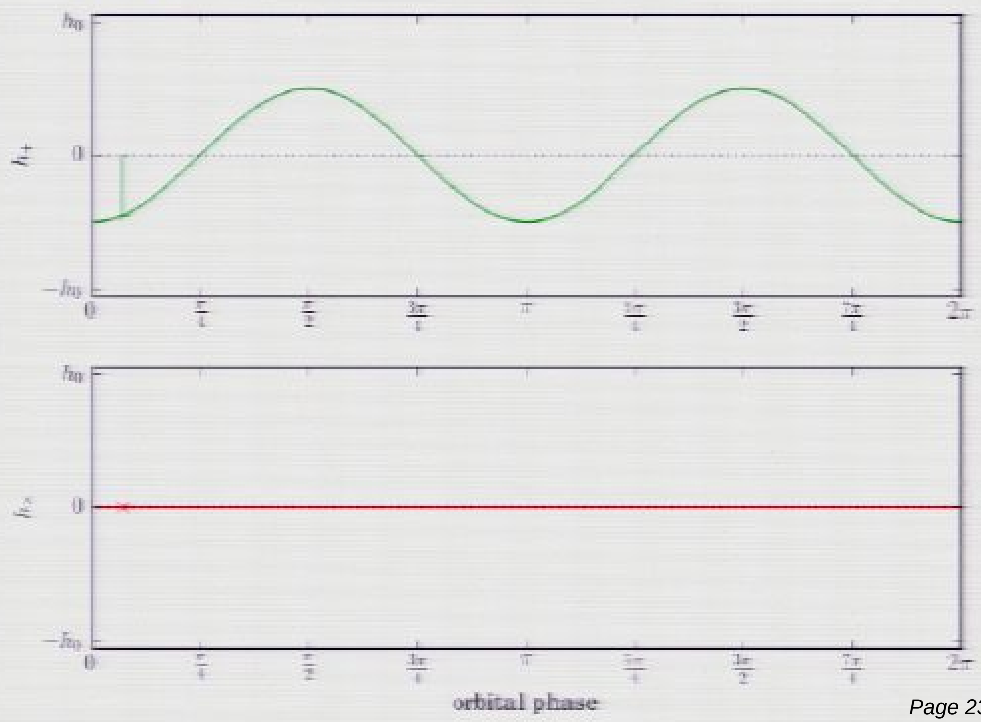

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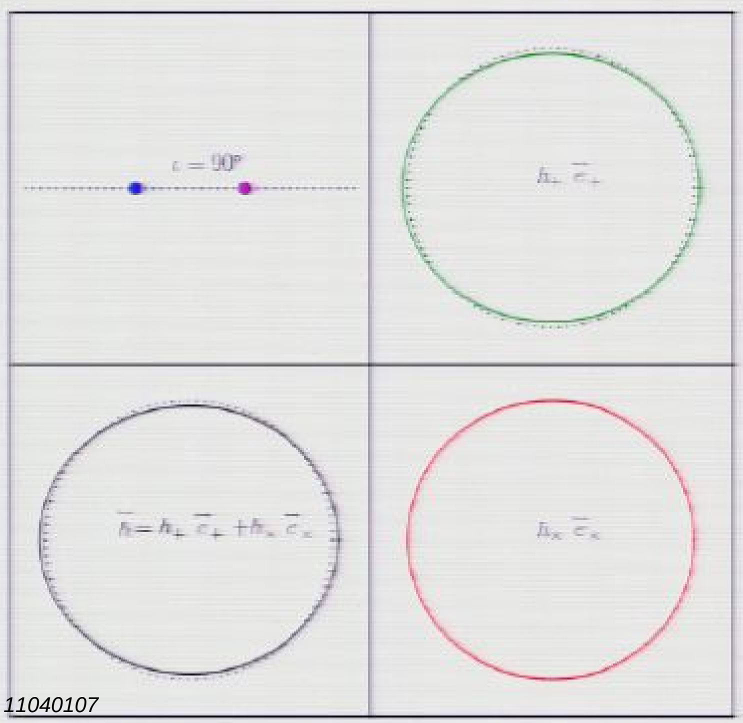
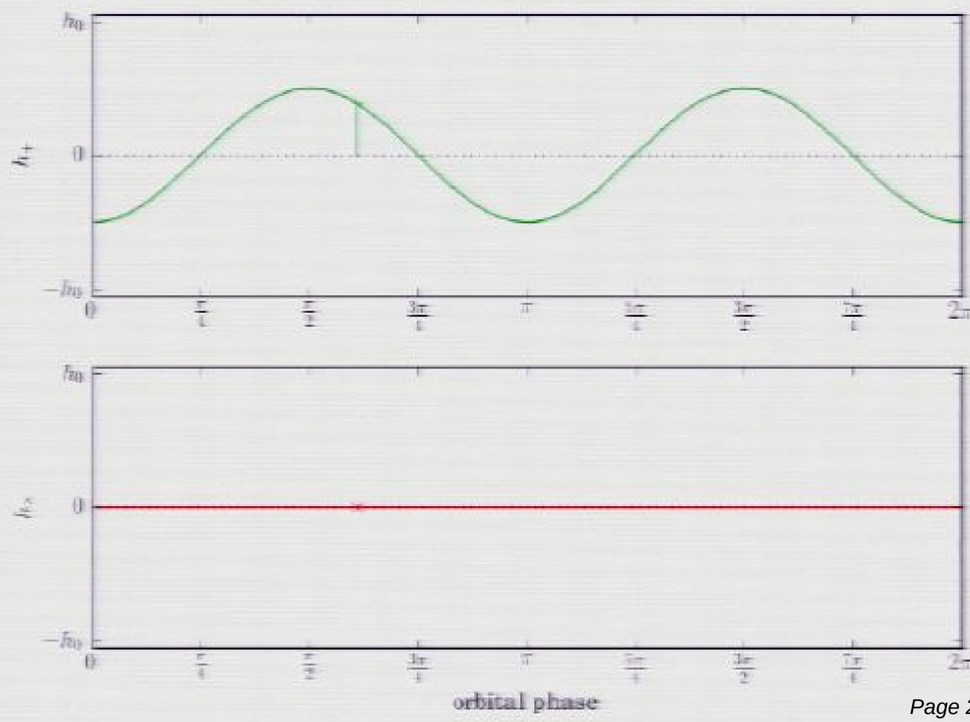
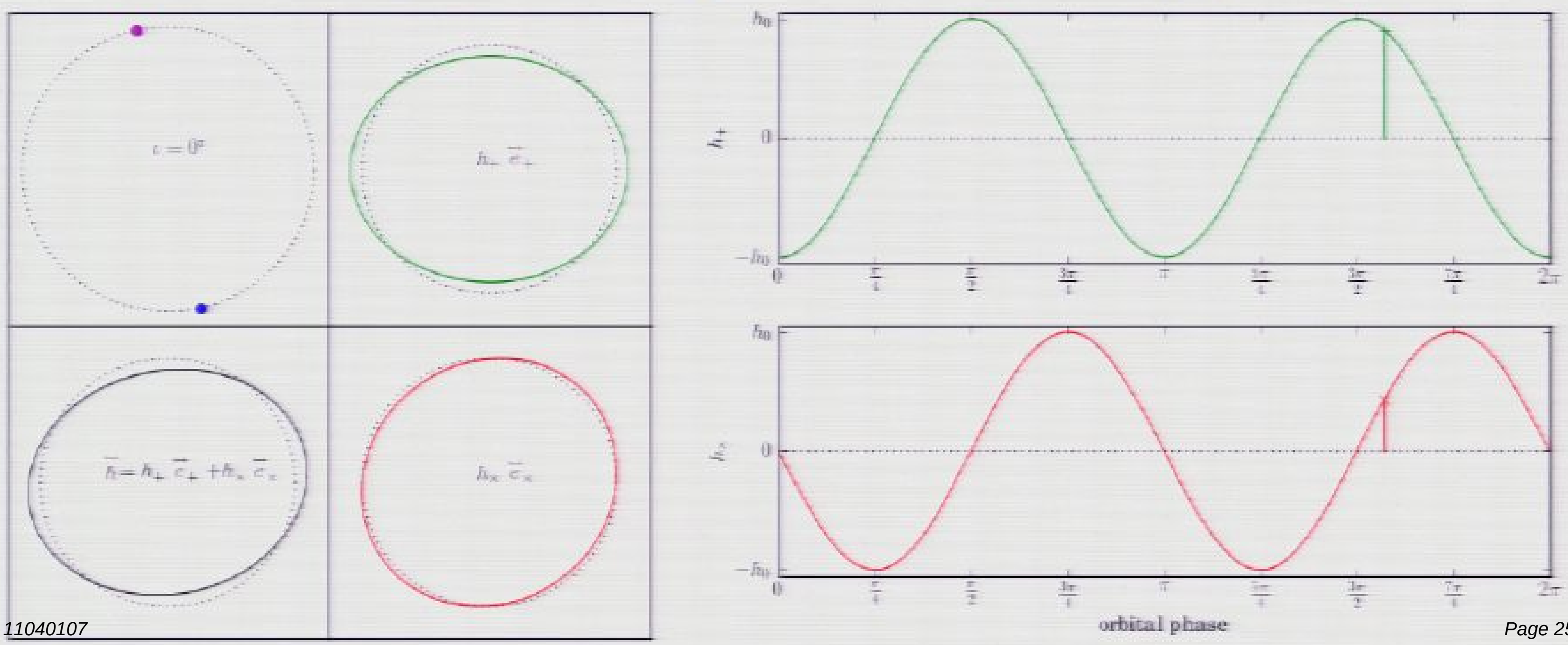




Example: Circular polarization

- Consider binary seen face on: masses seen going in circle
- In any pol basis, h_+ & $h_\times$ have same amp; out of phase **circular polarization**

$$h_+ = A\cos\Phi(t) \qquad h_\times = A\sin\Phi(t)$$



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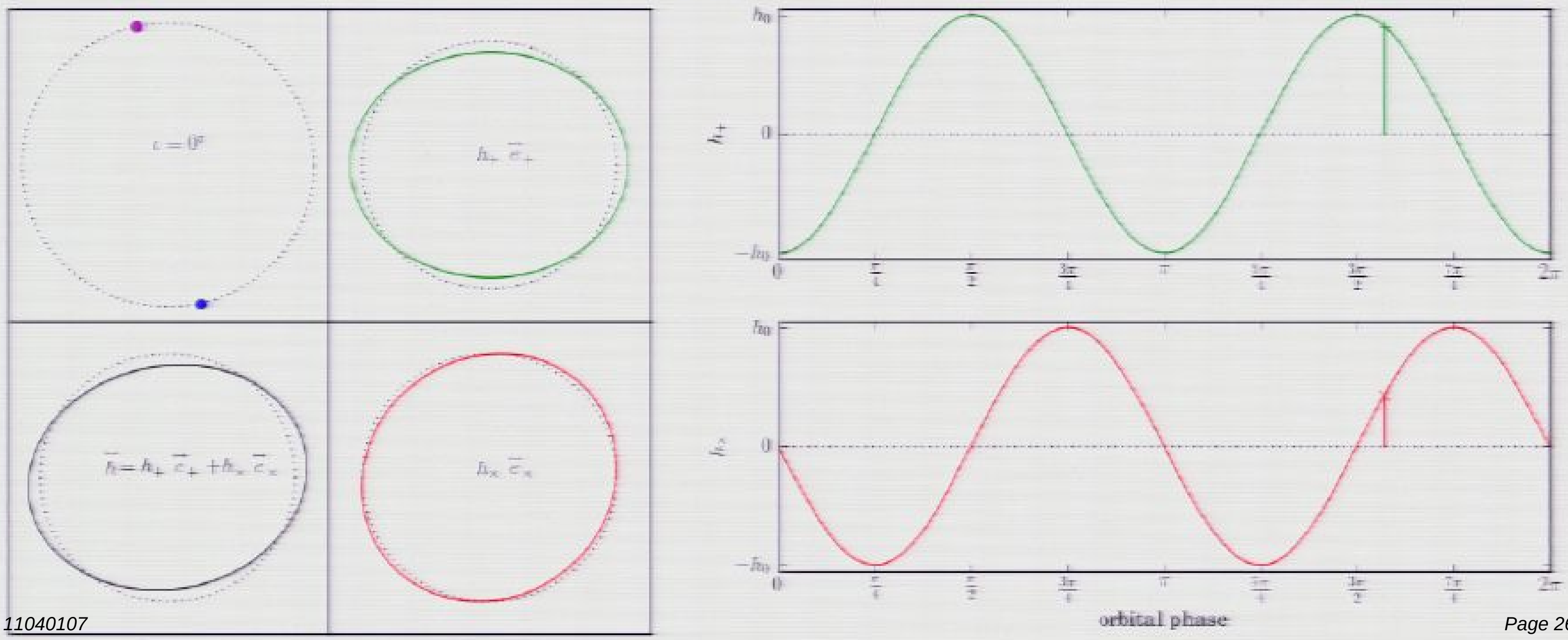
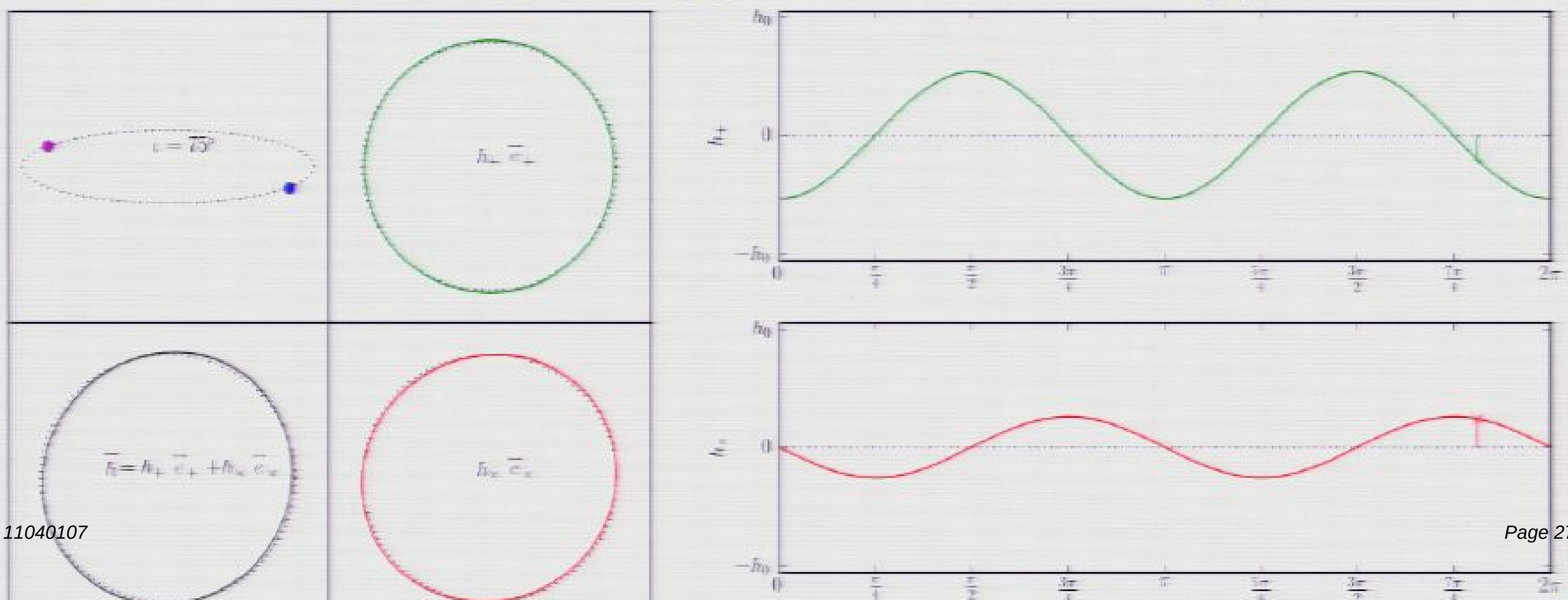


Example: Elliptical polarization

- General case: binary system seen at an angle: masses seen going around an ellipse; long axis of that ellipse picks preferred direction $\vec{\ell}$ for pol basis
- In that pol basis, h_+ & $h_\times$ out of phase; h_+ has greater amp **elliptical polarization** $[|A_+| > |A_\times|]$

$$h_+ = A_+ \cos\Phi(t) \qquad h_\times = A_\times \sin\Phi(t)$$



Classification of GW Signals

At freqs relevant to ground-based detectors (10s-1000s of Hz), natural division of sources:

	modelled	unmodelled
long	Periodic Sources (e.g., Rotating Neutron Star)	Stochastic Background (Cosmological or Astrophysical)
short	Binary Coälescence (Black Holes, Neutron Stars)	Bursts (Supernova, BH Merger, etc.)

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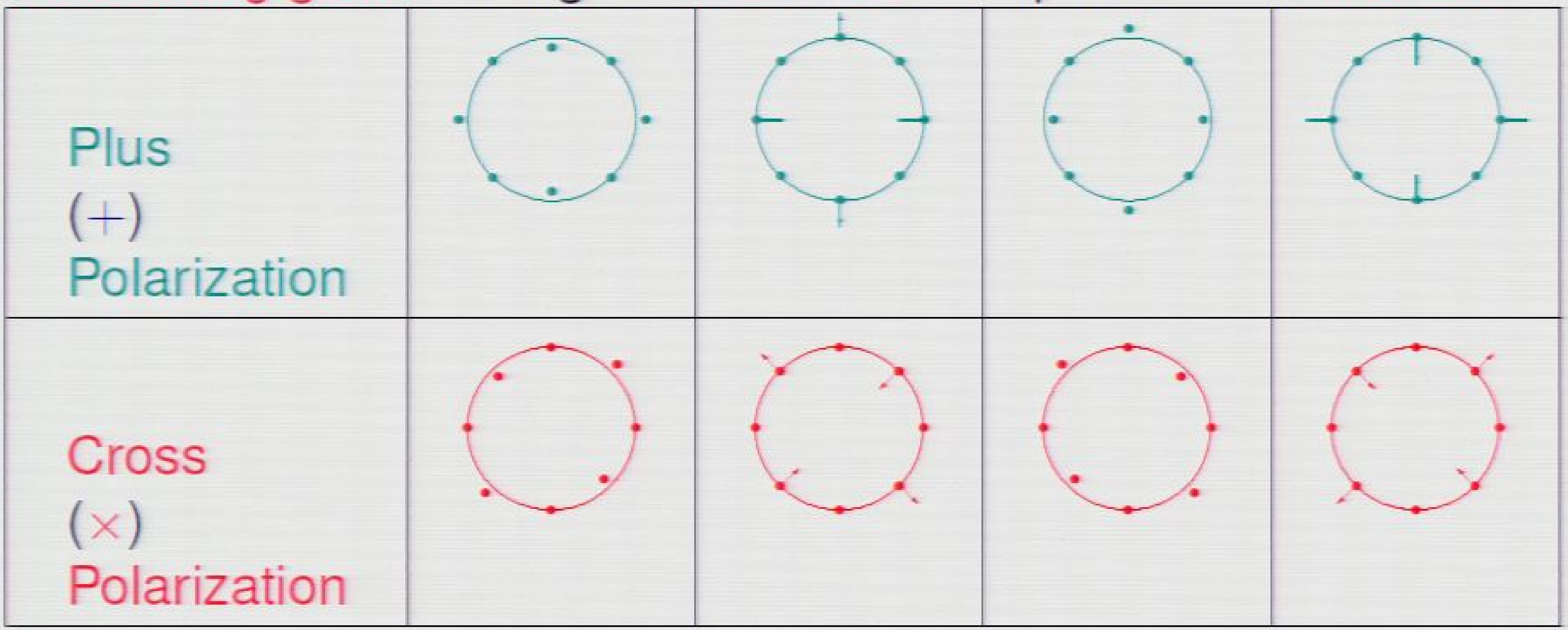
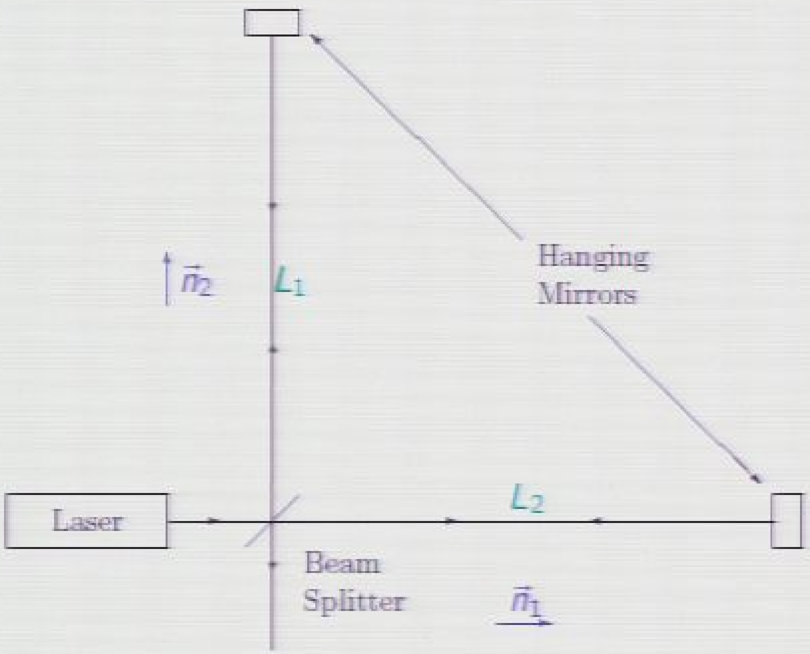
Effects of Gravitational Wave

Fluctuating geom changes distances btwn particles in free-fall:



Measuring GWs w/Laser Interferometry

Interferometry: Measure GW-induced distance changes



- Measure small change in

$$L_1 - L_2 = \sqrt{g_{11} L_0^2} - \sqrt{g_{22} L_0^2}$$
$$= \sqrt{(1+h_{11})L_0^2} - \sqrt{(1+h_{22})L_0^2}$$
$$\approx L_0 \frac{h_{11} - h_{22}}{2} \sim L_0 h_+$$

- More gen,

$$(L_1 - L_2)/L_0 = \overleftrightarrow{h} : \overleftrightarrow{d}$$

with "response tensor"

$$\overleftrightarrow{d} = \frac{\vec{n}_1 \otimes \vec{n}_1 - \vec{n}_2 \otimes \vec{n}_2}{2}$$

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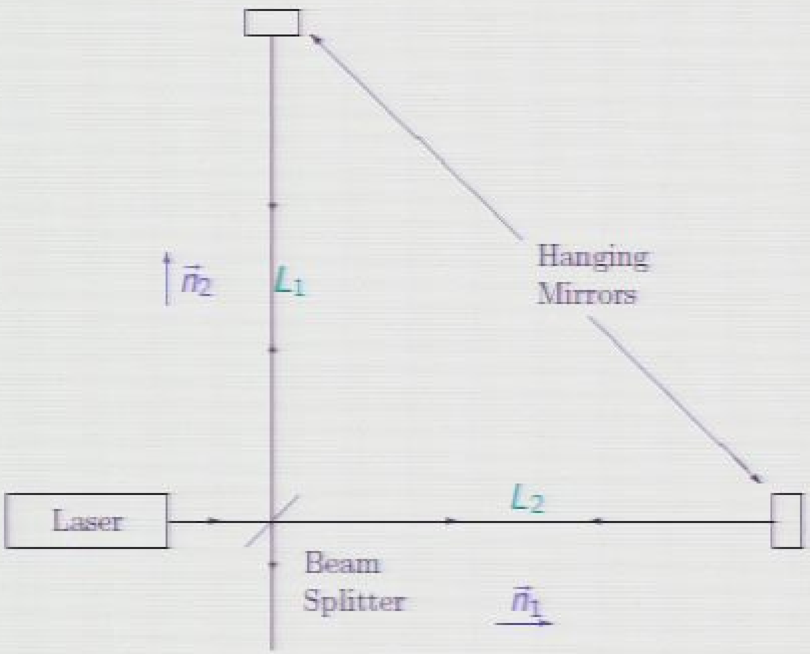

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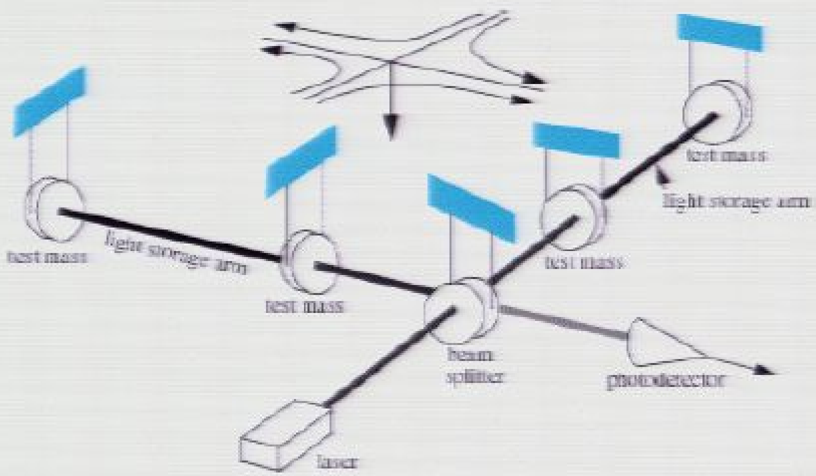

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Rogues' Gallery of Ground-Based Interferometers

LIGO Hanford (Wash.)

LIGO Livingston (La.)

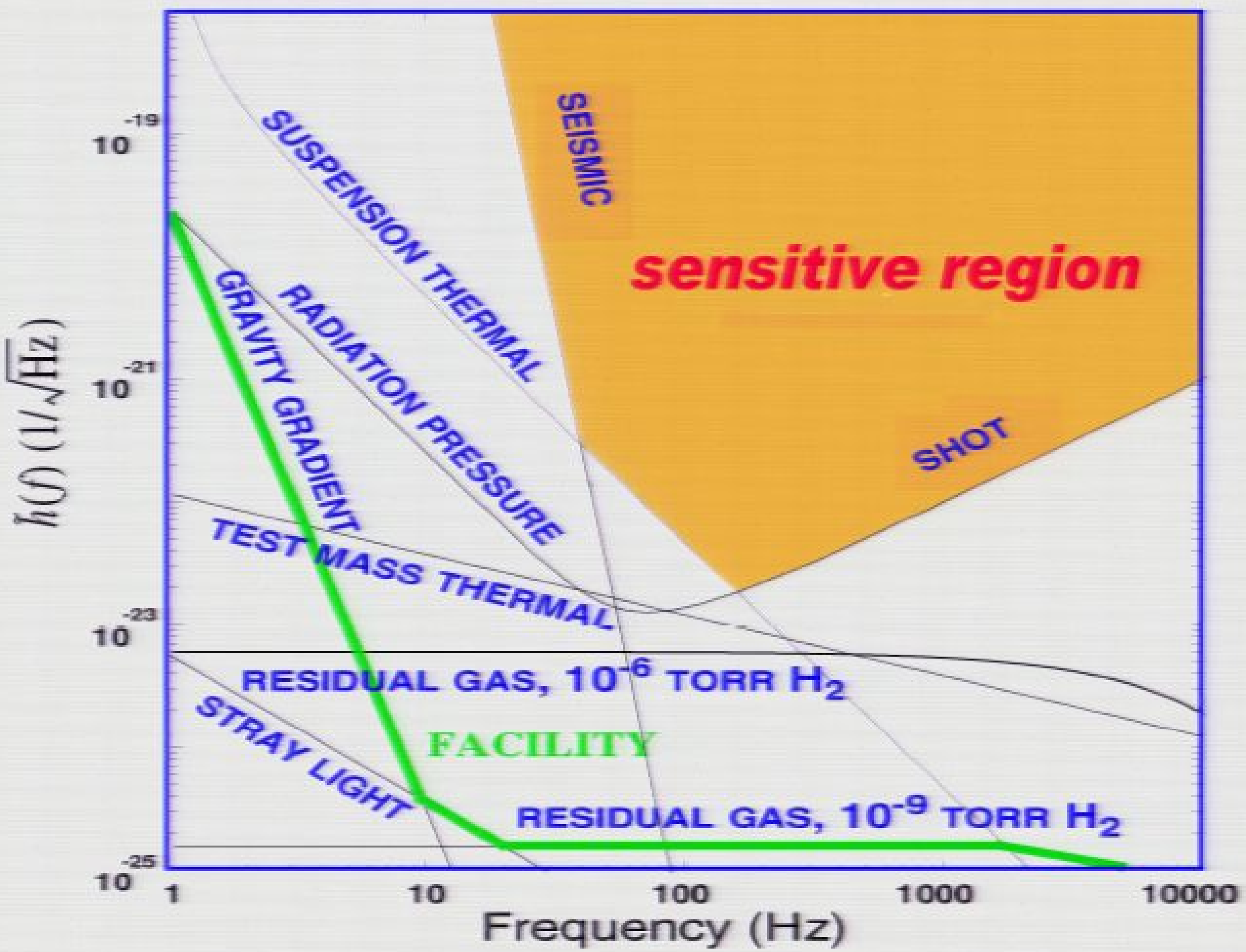
GEO-600 (Germany)

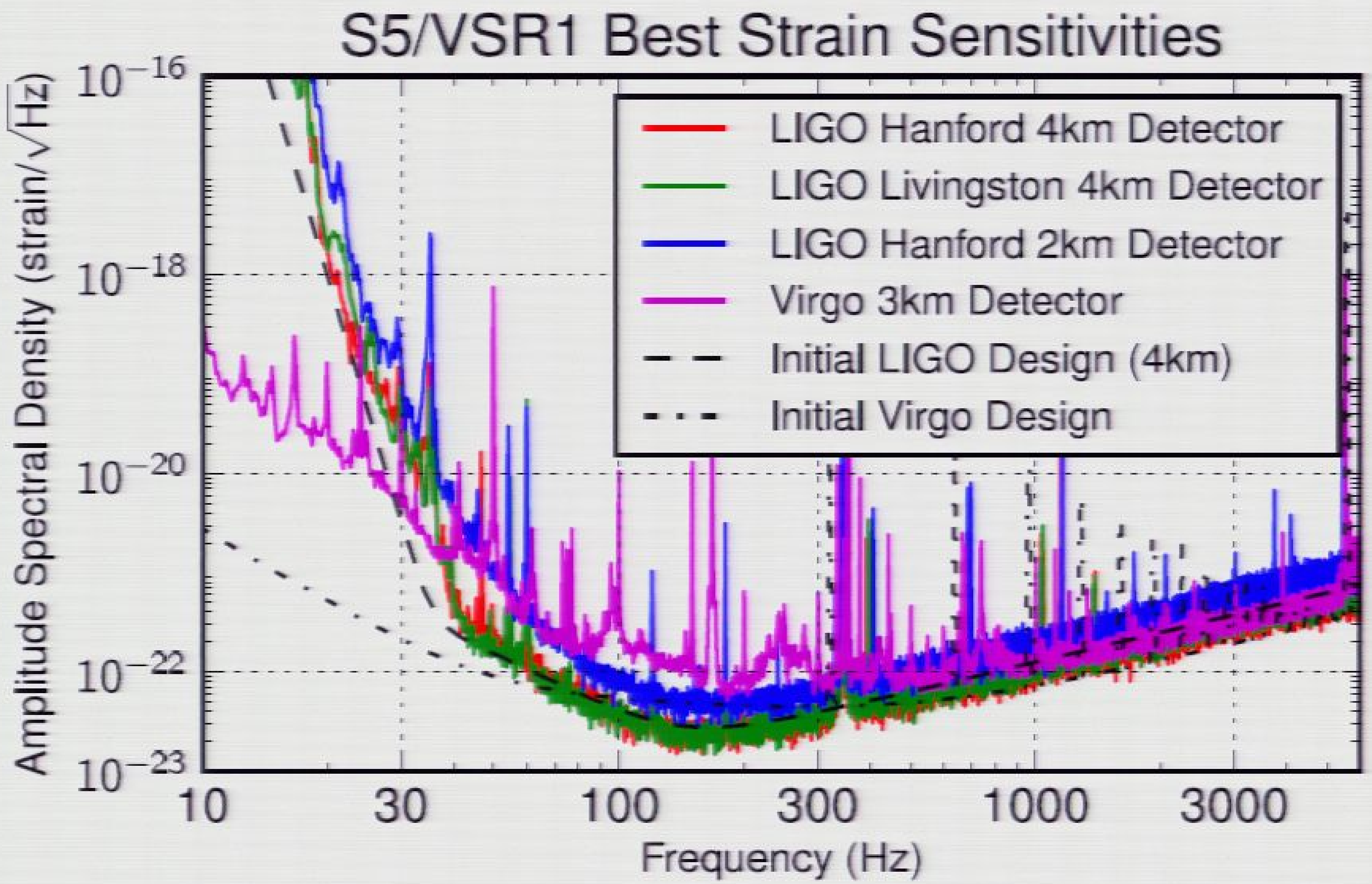
Virgo (Italy)

GW Observatory Network

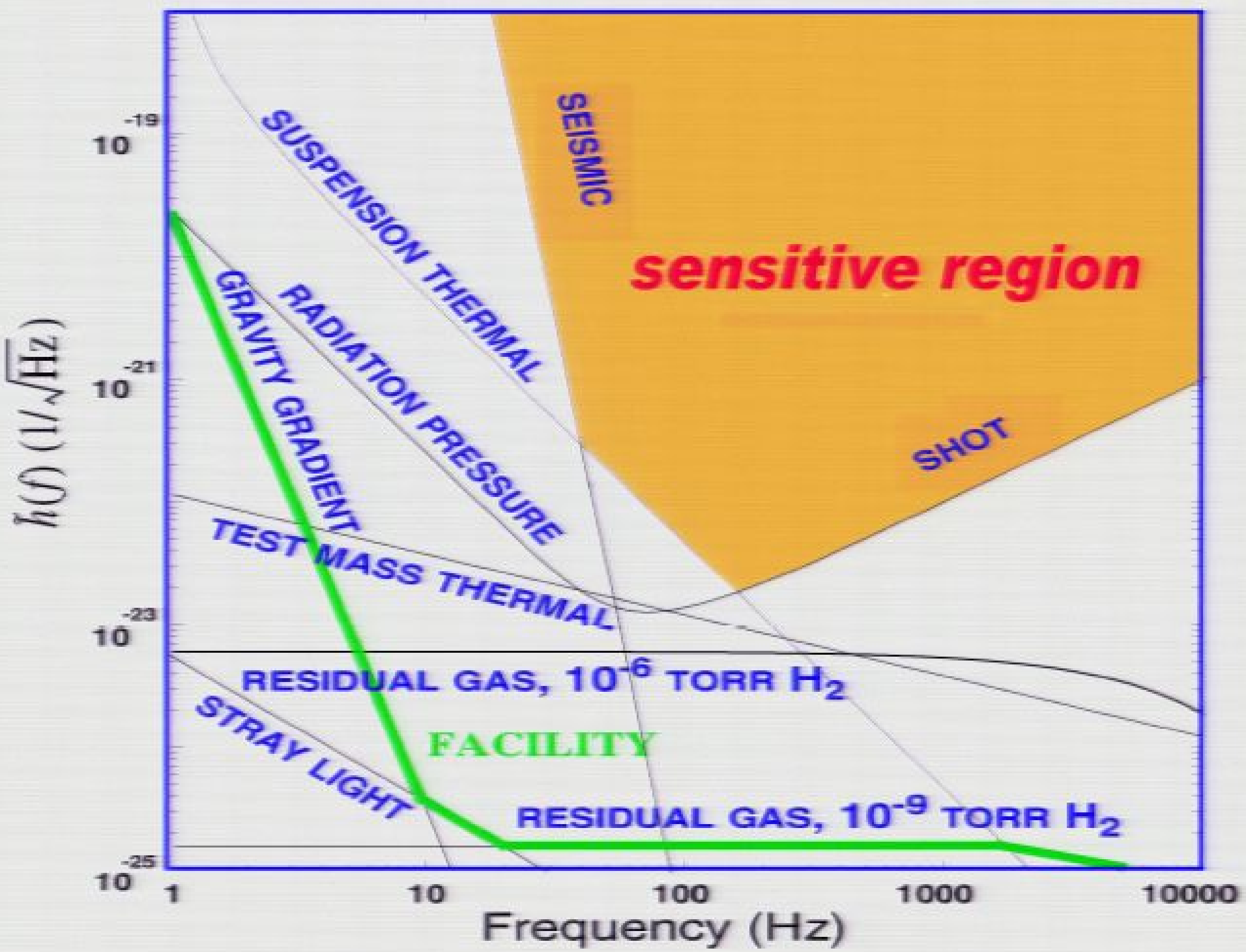
- LSC detectors conducting science runs since 2002
  - LIGO Hanford (4km H1 & 2km H2)
  - LIGO Livingston (4km L1)
  - GEO-600 (600m G1)
- Virgo (3km V1) started science runs in 2007
- Recent long runs:
  - LIGO/GEO S5: Nov 2005-Sep 2007: LIGO @ design sens
  - Virgo VSR1: May-Sep 2007: Begin joint LSC-Virgo analysis
  - LIGO (H1 & L1) S6: Jul 2009-Oct 2010
  - Virgo VSR2 Jul 2009-Jan 2010 & VSR3 Aug-Oct 2010
- LIGO & Virgo going offline 2010 & 2011
  to begin upgrade to Advanced Detectors
  expect $\sim 10\times$ sensitivity

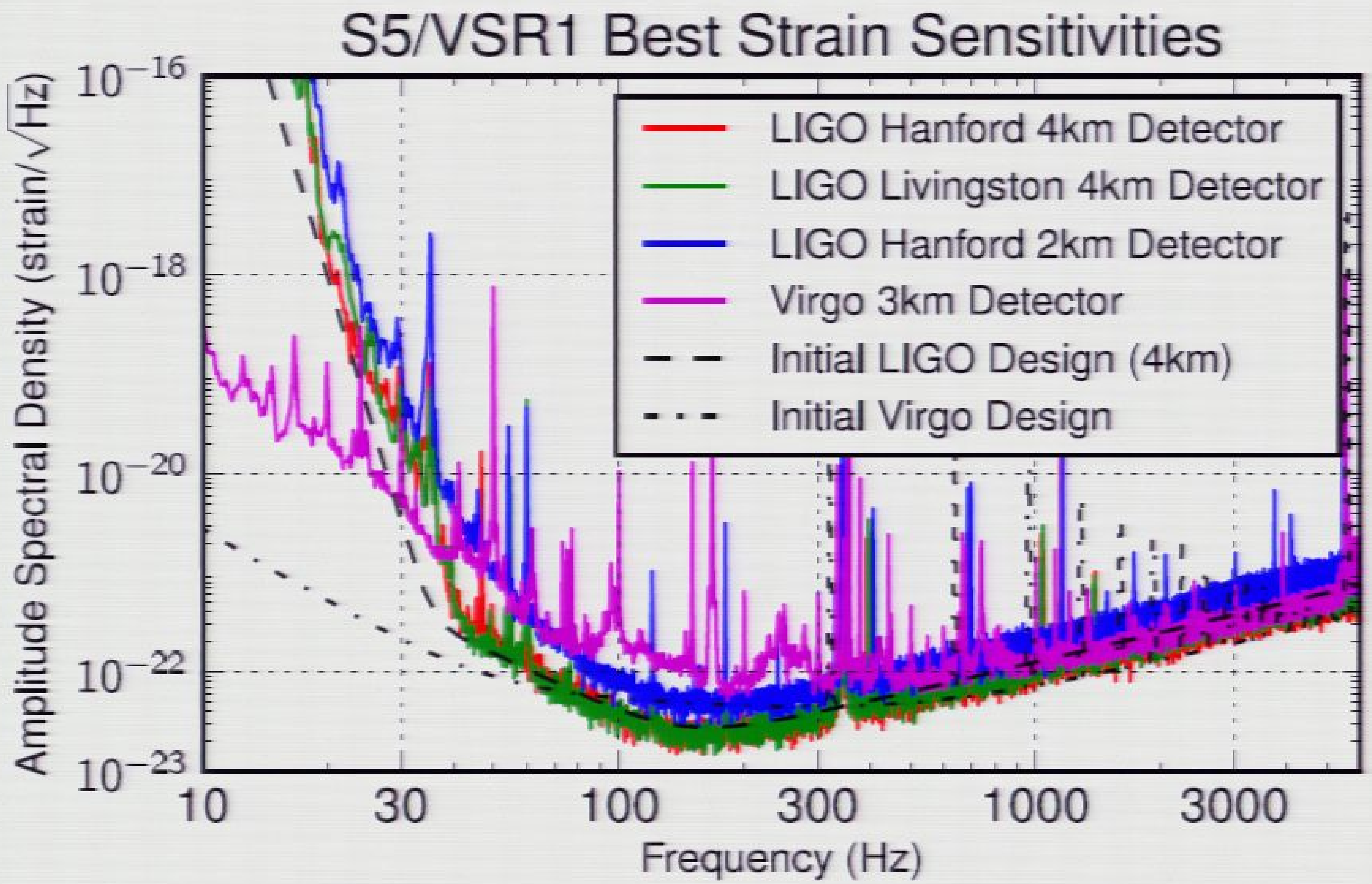
LIGO's Sensitive Frequency Band




S5/VSR1 Best Strain Sensitivities
Amplitude Spectral Density (strain/√Hz)
10^−16
10^−18
10^−20
10^−22
10^−23
10
30
100
300
1000
3000
Frequency (Hz)
LIGO Hanford 4km Detector
LIGO Livingston 4km Detector
LIGO Hanford 2km Detector
Virgo 3km Detector
Initial LIGO Design (4km)
Initial Virgo Design

LIGO's Sensitive Frequency Band

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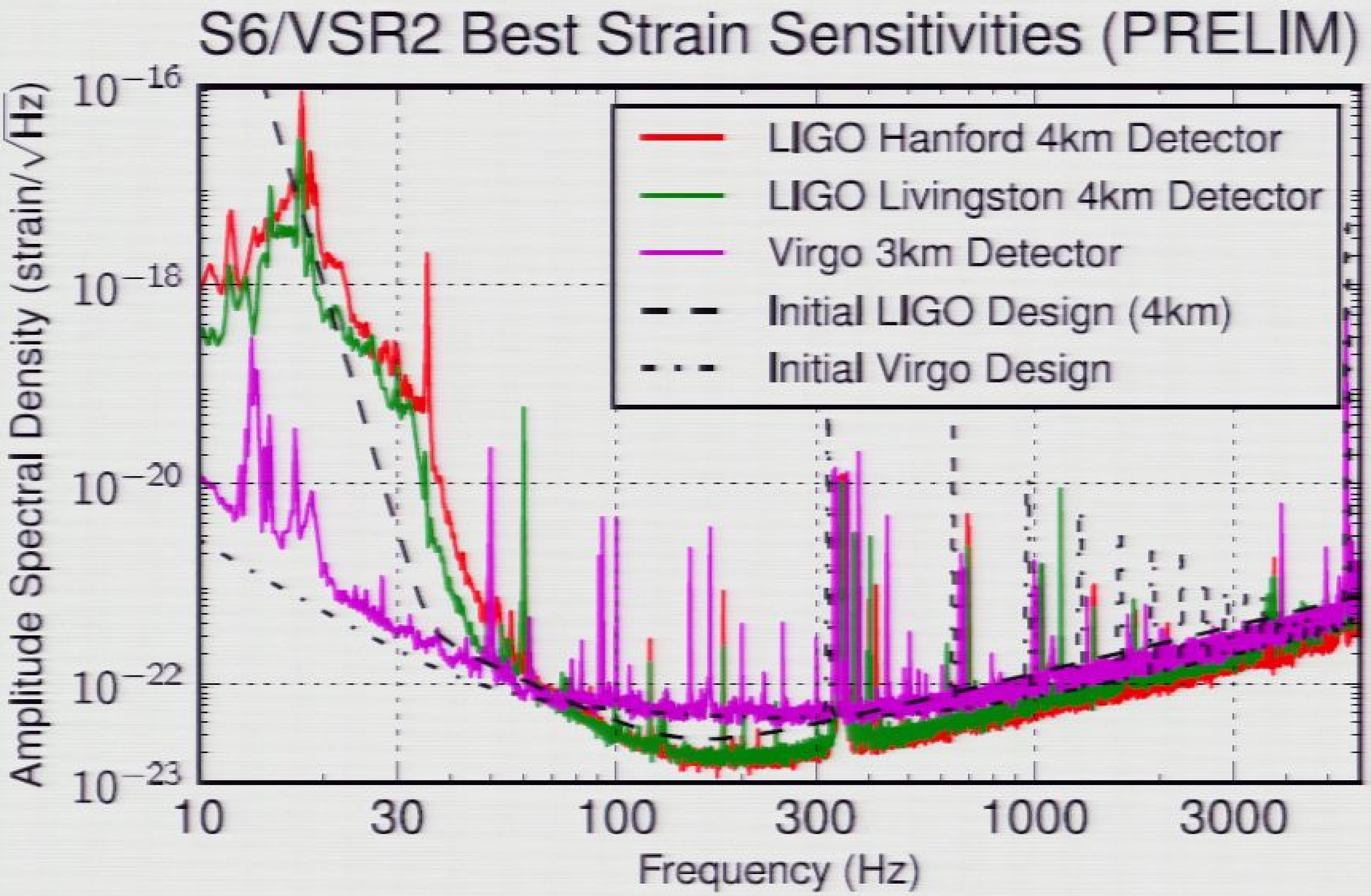
S6/VSR2 Best Strain Sensitivities (PRELIM)
Amplitude Spectral Density (strain/√Hz)
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10^{-22}
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Frequency (Hz)
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Virgo 3km Detector
Initial LIGO Design (4km)
Initial Virgo Design

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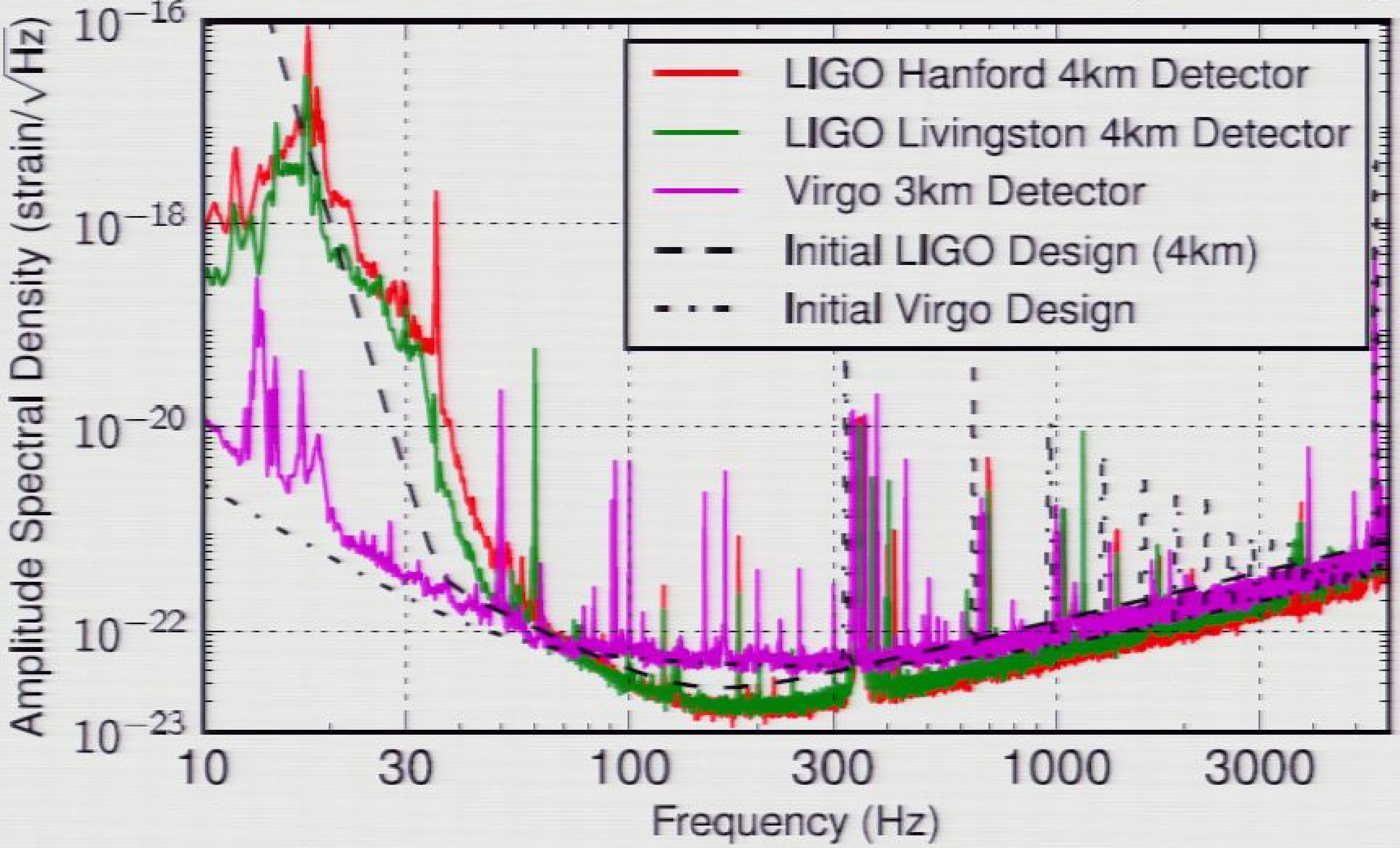

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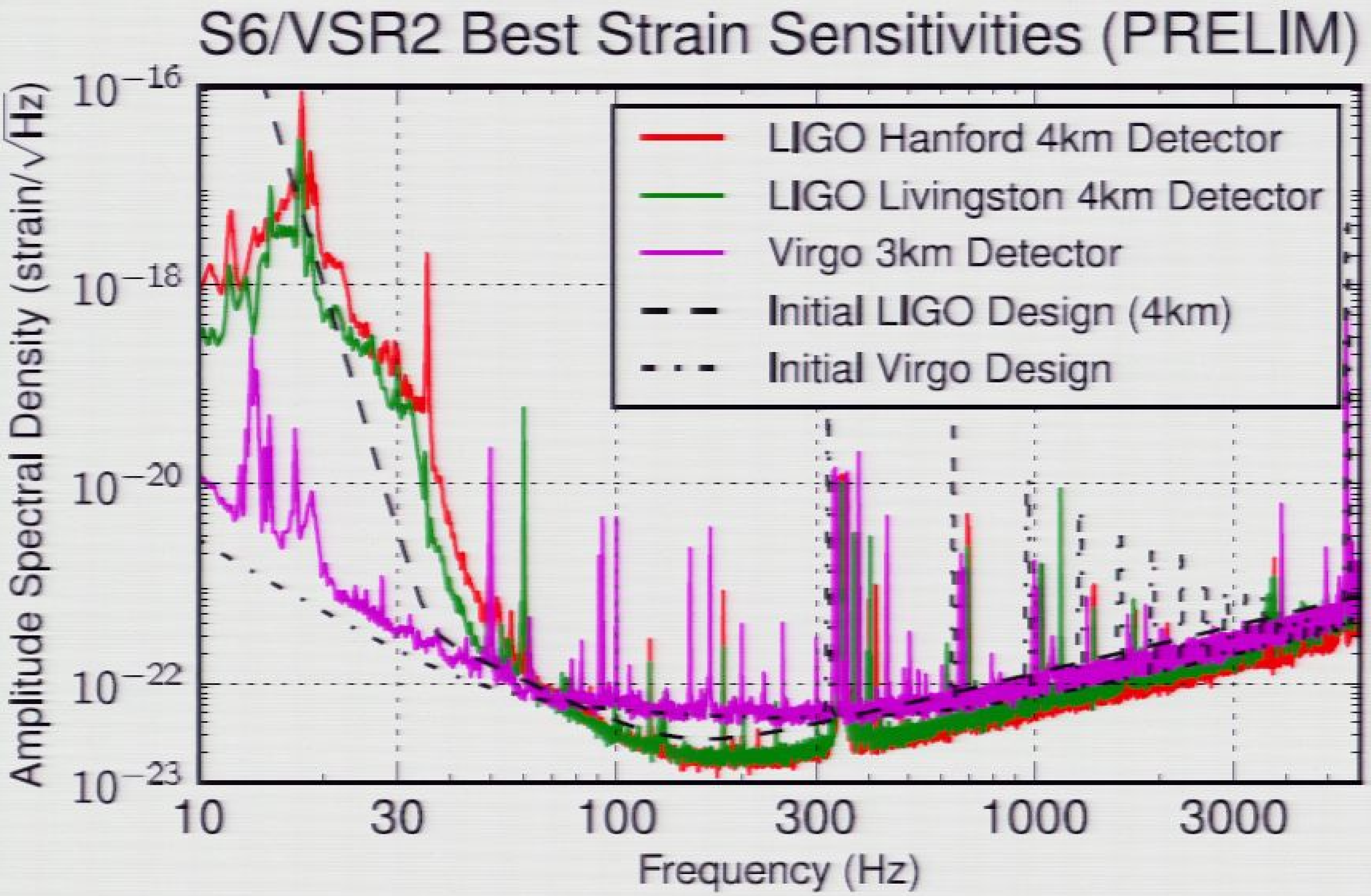
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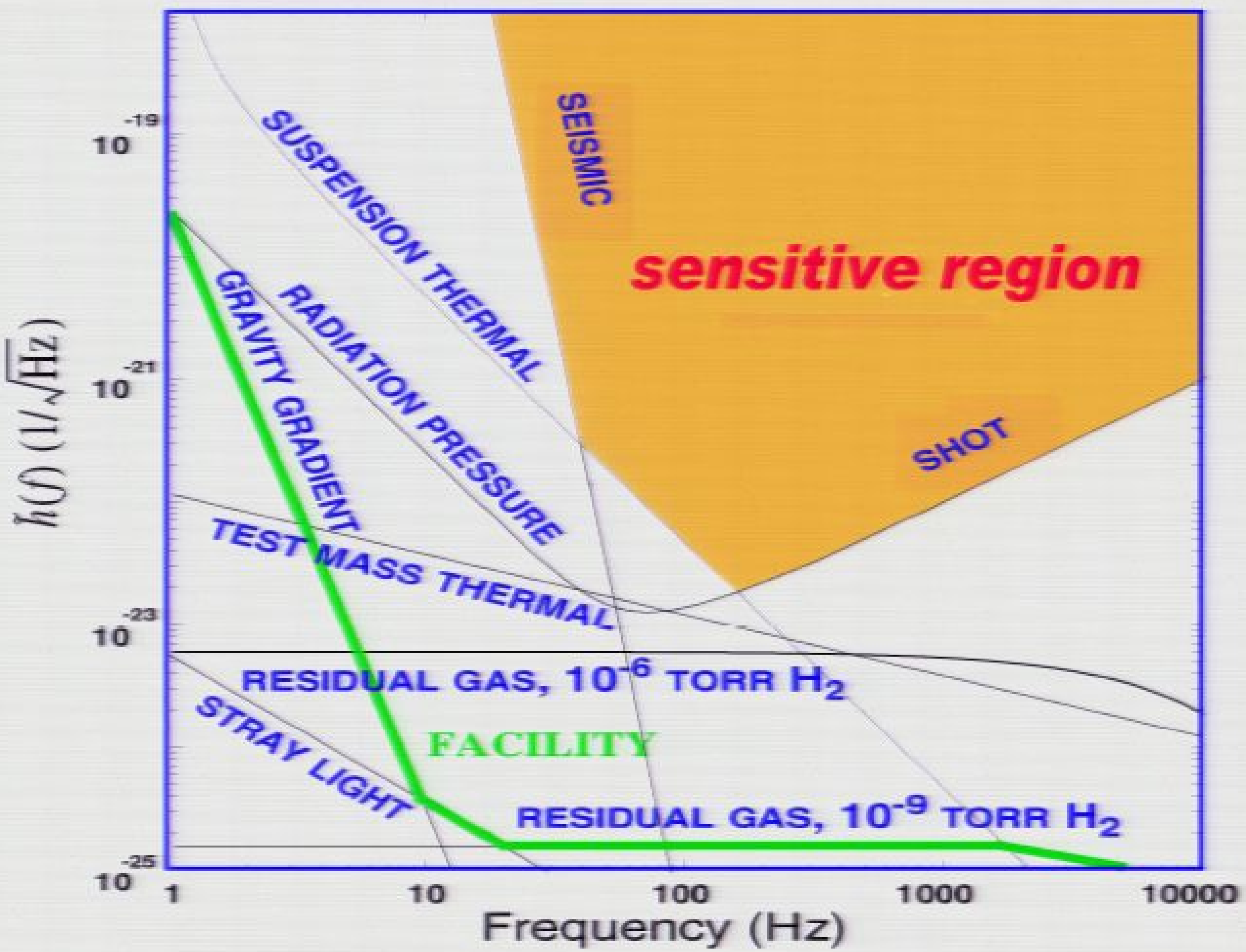
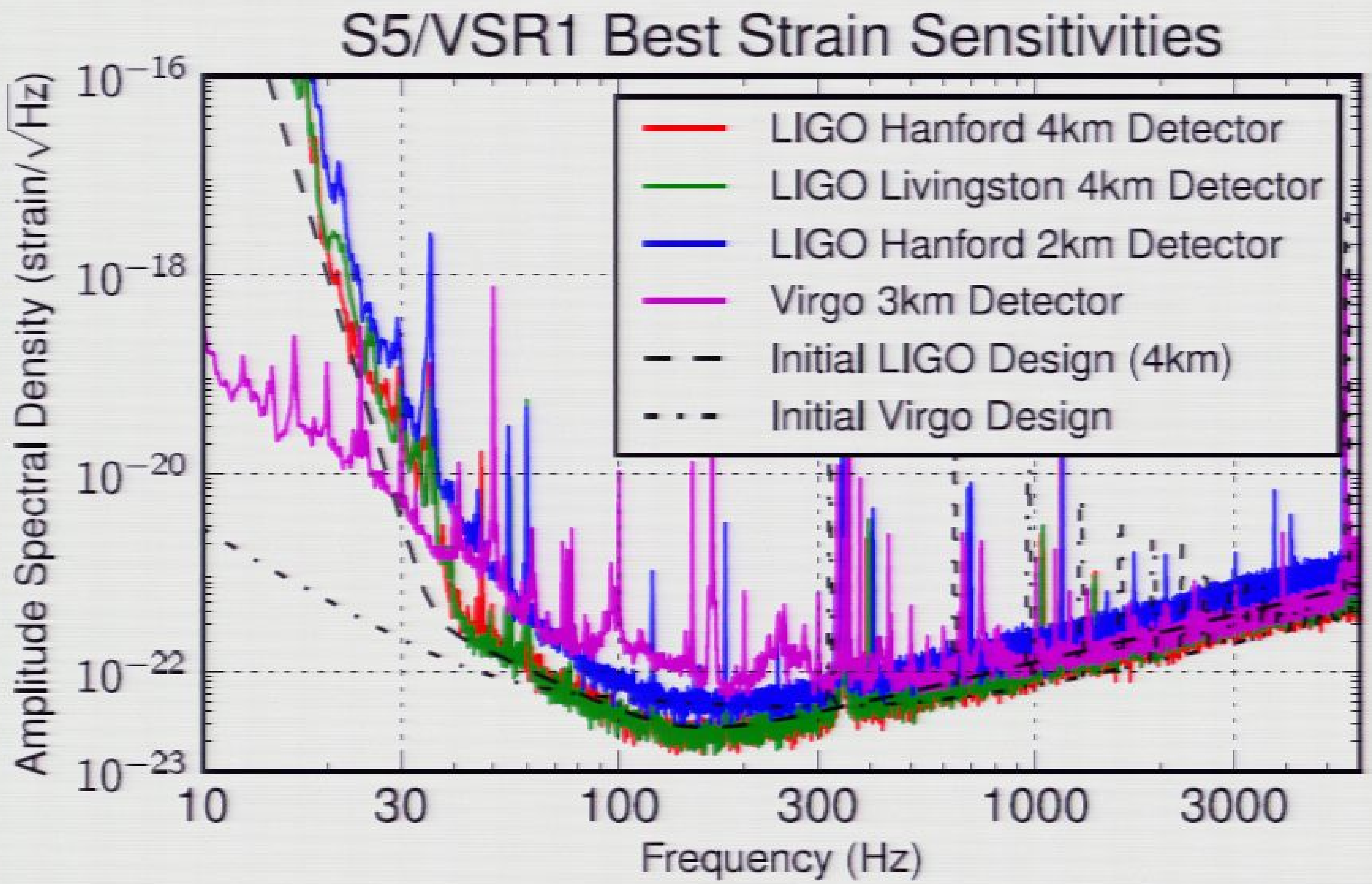
GW Observatory Network

- LSC detectors conducting science runs since 2002
  - LIGO Hanford (4km H1 & 2km H2)
  - LIGO Livingston (4km L1)
  - GEO-600 (600m G1)
- Virgo (3km V1) started science runs in 2007
- Recent long runs:
  - LIGO/GEO S5: Nov 2005-Sep 2007: LIGO @ design sens
  - Virgo VSR1: May-Sep 2007: Begin joint LSC-Virgo analysis
  - LIGO (H1 & L1) S6: Jul 2009-Oct 2010
  - Virgo VSR2 Jul 2009-Jan 2010 & VSR3 Aug-Oct 2010
- LIGO & Virgo going offline 2010 & 2011
  to begin upgrade to Advanced Detectors
  expect $\sim 10\times$ sensitivity

LIGO's Sensitive Frequency Band

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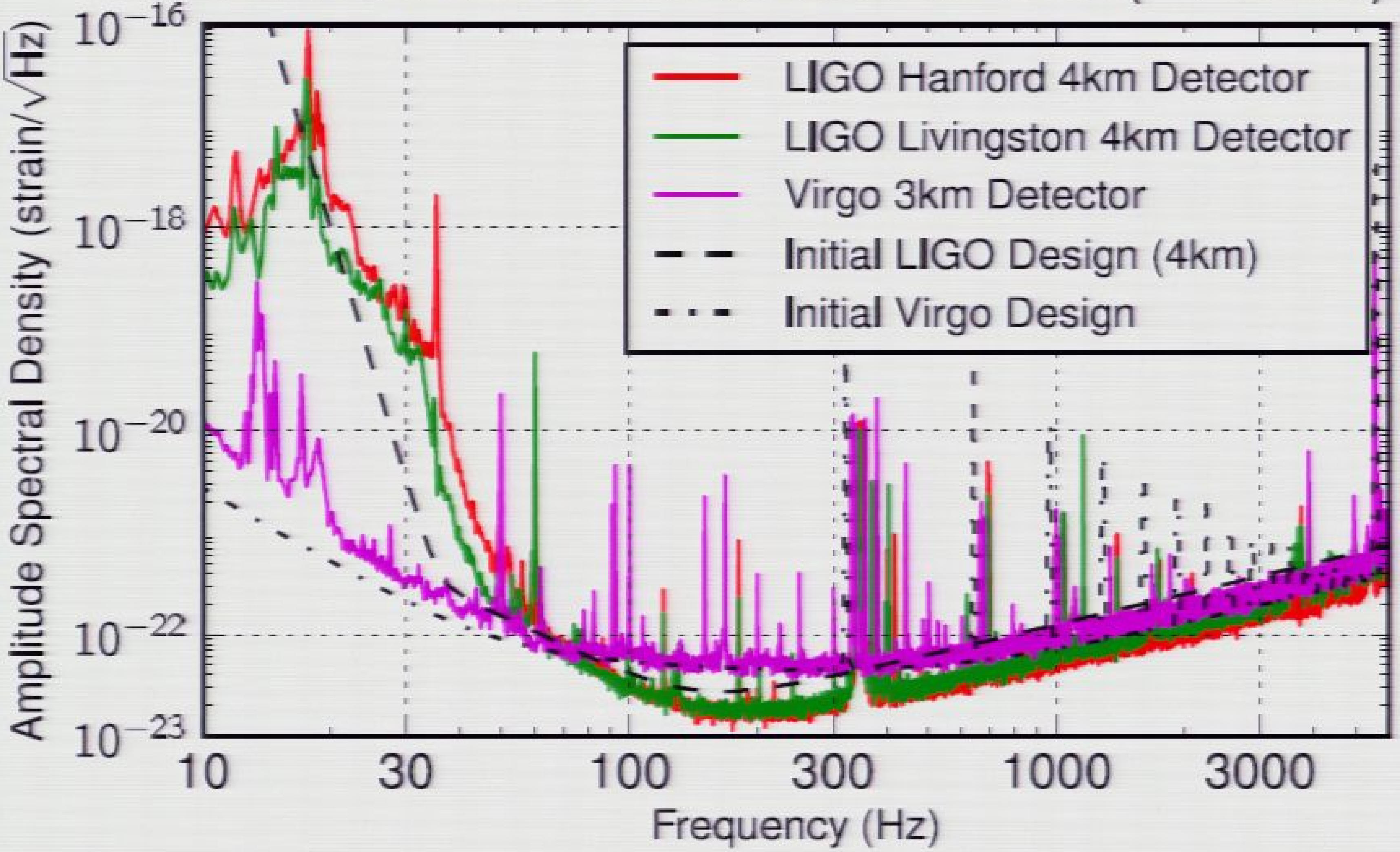

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Cross-Correlation Search for Stochastic Background

- Noisy data from GW Detector:
  $x(t) = n(t) + h(t) = n(t) + \overleftrightarrow{h}(t) : \overleftrightarrow{d}$
- Correlate data btwn detectors (Fourier domain)

$$\langle \tilde{x}_1^*(f)\tilde{x}_2(f')\rangle = \langle \tilde{h}_1^*(f)\tilde{h}_2(f')\rangle = \overleftrightarrow{d}_1 : \langle \tilde{\overleftrightarrow{h}}_1^*(f) \otimes \tilde{\overleftrightarrow{h}}_2(f')\rangle : \overleftrightarrow{d}_2$$

- For stochastic backgrounds

$$\langle \tilde{h}_1^*(f)\tilde{h}_2(f')\rangle = \delta(f-f')\gamma_{12}(f)\frac{S_{\text{gw}}(f)}{2}$$

$S_{\text{gw}}(f)$ encodes spectrum; $\gamma_{12}(f)$ encodes geometry

Detection Statistic

- Optimally filtered cross-correlation statistic

$$Y = \int df\, \tilde{x}_1^*(f)\, Q(f)\, \tilde{x}_2(f)$$

- Filter encodes expected spectrum & spatial distribution (isotropic, pointlike, spherical harmonics . . .)

$$Q(f) \propto \frac{\gamma_{12}^*(f) S_{\text{gw}}^{\text{exp}}(f)}{S_{n1}(f) S_{n2}(f)}$$

- "Radiometer" search for ptlike srcs incl targeting Sco X-1: known sky location, unknown frequency
Ballmer, *CQG* **23**, S179 (2006); LSC, *PRD* **76**, 082003 (2007)

Gravitational Waves from Quasiperiodic Sources

- Sco X-1 is Low-Mass X-Ray Binary: accreting neutron star in orbit w/companion
- Rotating NS w/deformation emits nearly sinusoidal signal

$$\overleftrightarrow{h}(t) = h_0 \left[\frac{1+\cos^2\iota}{2} \cos\Phi(\tau(t)) \overleftrightarrow{e}_+ + \cos\iota \sin\Phi(\tau(t)) \overleftrightarrow{e}_\times \right]$$

  - $\Phi(\tau)$: phase evolution in rest frame;
  - $\tau(t)$: Doppler mod from detector motion (& binary orbit)
- Features of signal model missing from stoch search:
  - Doppler shift @ each detector: correlations peaked @ different freqs
  - Long-term coherence: can correlate data @ different times

Cross-Correlation of Continuous GW Signals

- Cross-correlation of signal w/intrinsic frequency f_0:

$$\langle \tilde{x}_I^*(f_I)\, \tilde{x}_J(f_J) \rangle = \tilde{h}_I^*(f_I)\, \tilde{h}_J(f_J)$$
$$= h_0^2\, \tilde{\mathcal{G}}_{IJ}\, \delta_{T_{\text{sft}}}(f_0 - f_I - \delta f_I)\, \delta_{T_{\text{sft}}}(f_0 - f_J - \delta f_J)$$

  - $\tilde{h}_I(f)$ is Short Fourier Transform, duration T_{sft}
  - $\delta_{T_{\text{sft}}}(f - f') = \int_{-T_{\text{sft}}/2}^{T_{\text{sft}}/2} dt\, e^{i2\pi(f-f')t}$
  - $\tilde{h}_I$ & $\tilde{h}_J$ can be same or different times or detectors
  - δf_I is relevant Doppler shift
- For given set of params, can add products of all SFT pairs

$$Y = \sum_{IJ} Q_{IJ} \tilde{x}_I^*(f_0 - \delta f_I) \tilde{x}_J(f_0 - \delta f_J) \qquad Q_{IJ} \propto \frac{\tilde{\mathcal{G}}_{IJ}^*}{S_{n,I}(f_0) S_{n,J}(f_0)}$$

Dhurandhar, Krishnan, Mukhopadhyay & JTW *PRD* **77**, 082001 (2008)

Doppler Modulation in Cross-Correlation Searches

- Max Doppler shift from Earth's rotation: $\frac{|\vec{v}_{\oplus\text{rot}}|}{c} \lesssim 1.5 \times 10^{-6}$
  Doppler shift at 2000 Hz is $\lesssim 0.003$ Hz.
- Max Doppler shift from Earth's orbit: $\frac{|\vec{v}_{\oplus\text{orb}}|}{c} \lesssim 1.0 \times 10^{-4}$
  Doppler shift at 2000 Hz is $\lesssim 0.2$ Hz.
- Stochastic searches use FTs of e.g., 120 s duration, so

  $$\delta f \approx 0.0083\,\text{Hz}$$

  Cross-correlation between detectors uses same freq bin
- Stochastic search combines fine bins into coarse bins of

  $$\Delta f = 0.25\,\text{Hz}$$

  Cross-corr power collected in single bin for most freqs
- Correlating detectors at different times, or with longer FTs means including Doppler effects

Computational Costs and Frequency Resolution

- If freq, sky pos etc known, can do most sensitive fully coherent search (correlate all data)
- If some params unknown, have to search over them
- Long coherent observation → fine resolution in freq etc → need too many templates → computationally impossible

$$\text{e.g.} \qquad N_{\text{tmplts}} \sim \frac{1}{\Delta f}\frac{1}{\Delta \dot{f}}\frac{1}{\Delta \text{sky}} \sim T \cdot T^2 \cdot (fT)^2$$

- Most CW searches semi-coherent: deliberately limit coherent integration time & param space resolution to keep number of templates manageable

Tuning the Cross-Correlation Search

- Computational considerations limit coherent time, i.e., possible time lag between correlated segments
- Detectable signal

$$h_0^{\mathrm{th}} \propto \left(\sum_{IJ} |\tilde{\mathcal{G}}_{IJ}|^2\right)^{-1/4} \sqrt{\frac{S_n}{T_{\mathrm{sft}}}} \propto N_{\mathrm{pairs}}^{-1/4} {T_{\mathrm{sft}}}^{-1/2}$$

(T_{sft} is duration of fourier transformed data segment)

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  like coherent search of duration $N_{\mathrm{sft}} T_{\mathrm{sft}}$

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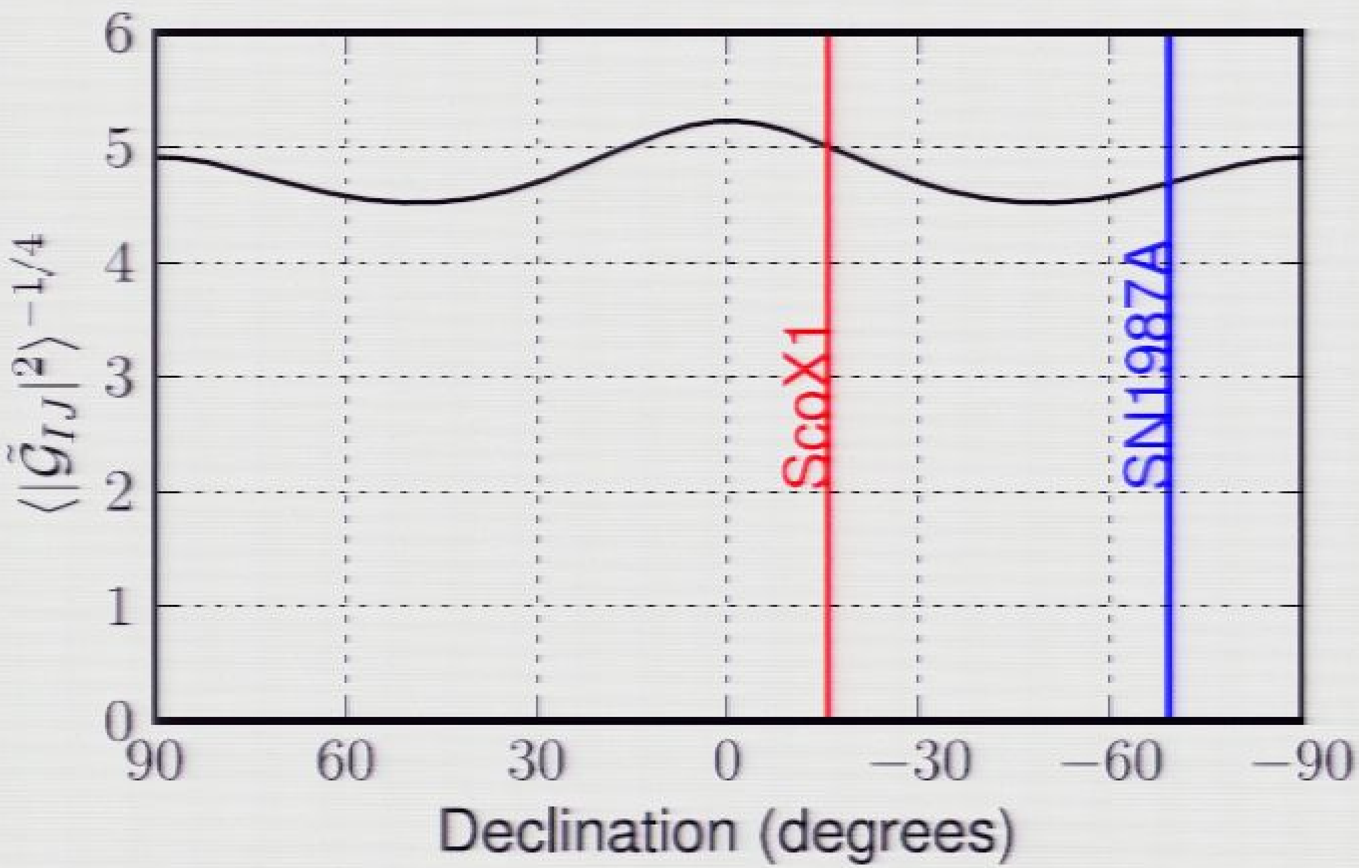

(Assumes H1-L1, simultaneous, uniform sidereal time coverage)

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Dhurandhar, Krishnan, Mukhopadhyay & JTW *PRD* **77**, 082001 (2008)

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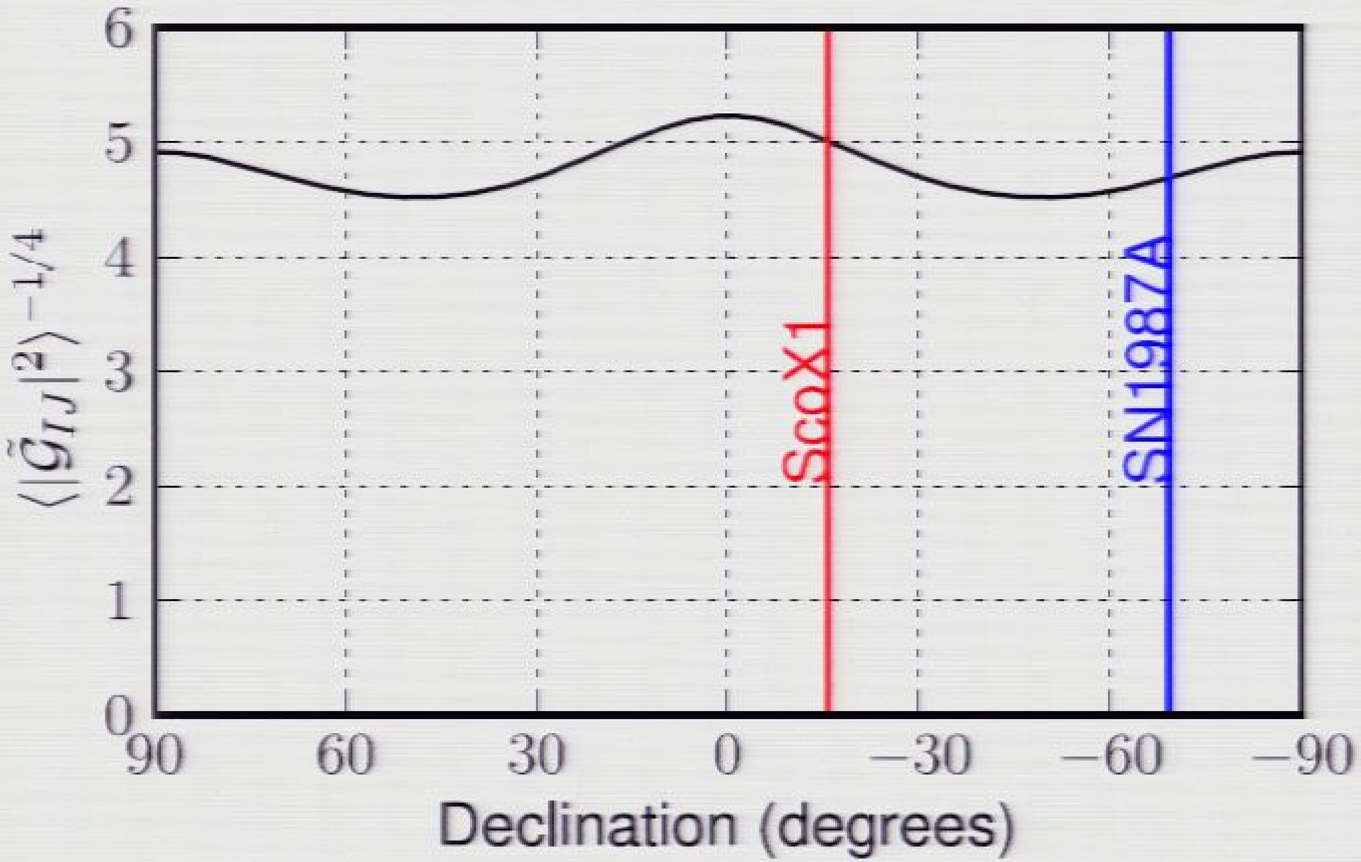

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Searching for Young Neutron Stars

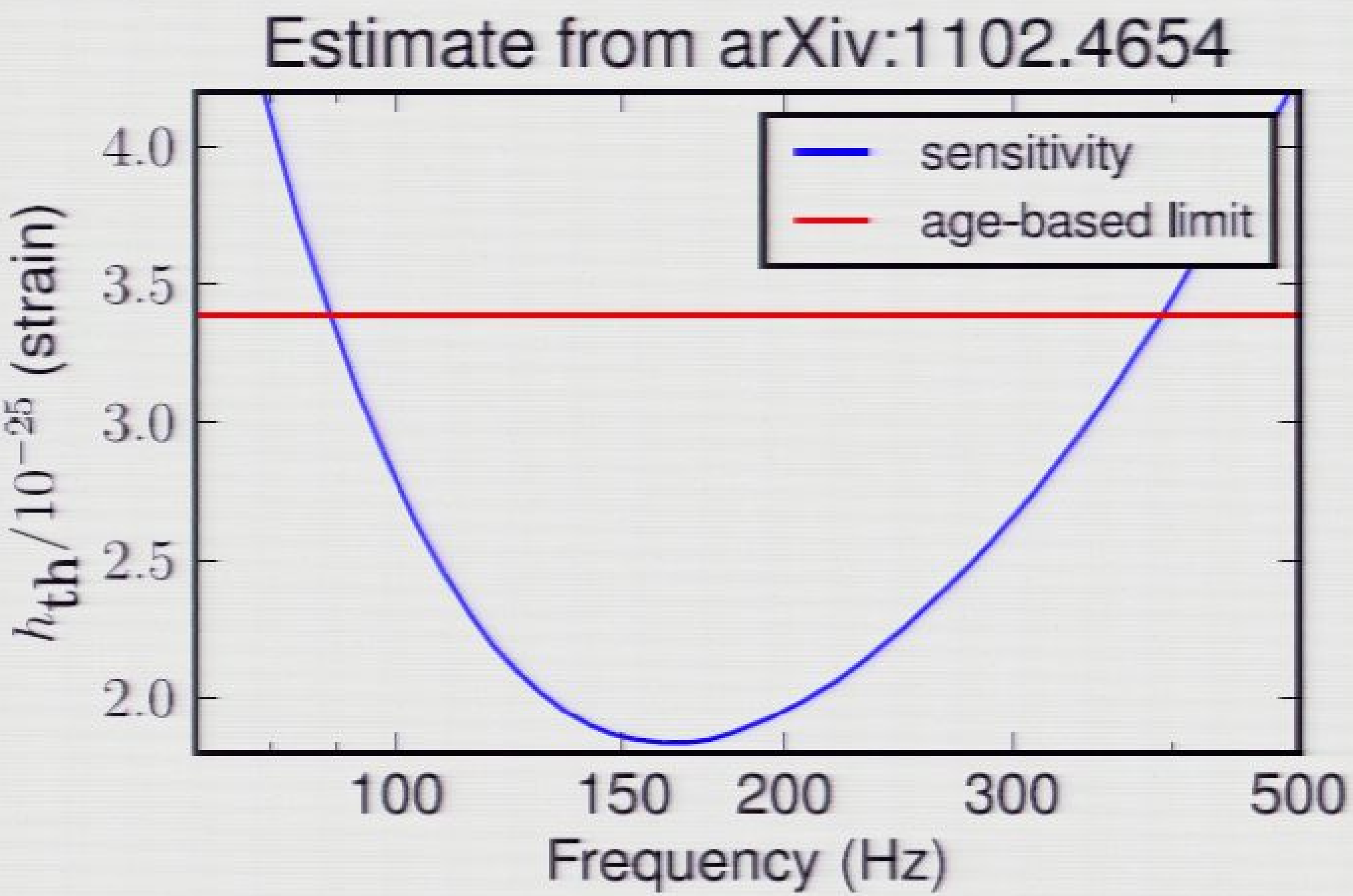
- Young ($\lesssim 100\,\mathrm{yr}$) NSs should be spinning rapidly
  LIGO/Virgo band $50\,\mathrm{Hz} \lesssim f_{\mathrm{GW}} \lesssim 1500\,\mathrm{Hz}$
- Look in likely sky locations for NSs not seen as pulsars:
  SN1987A should have one; galactic ctr could have $\mathcal{O}(1)$
- Spinning down rapidly; inefficient to search over f, $\dot{f}$, $\ddot{f}$, ...
  Phase model: GW spindown $\propto f^5$; EM spindown $\propto f^{\approx 3}$

$$\frac{df}{d\tau} = Q_{\mathrm{GW}} \left(\frac{f}{f_{\mathrm{ref}}} \right)^5 + Q_{\mathrm{EM}} \left(\frac{f}{f_{\mathrm{ref}}} \right)^n$$

Search over f_0, Q_{GW}, Q_{EM}, n

Chung, Melatos, Krishnan & JTW to appear in MNRAS arXiv:1102.4654

Ballpark sensitivity of SN1987A search w/initial LIGO



Compares favorably to indirect age-based limit $h_0 < 3.4 \times 10^{-25}$

Summary

- Cross-correlation method adapted to periodic GWs
- Tuning max time-lag between cross-correlated data allows tradeoff of sensitivity for computing time
- Can search for young NSs (e.g., SN1987A) (search over f_0 & braking model params)
- Can search for LMXBs (e.g., Sco X-1) (search over f_0 & binary orbit params)

Semi Coherent Search

	$x_1(t_0)$	$x_2(t_0)$	$x_1(t_1)$	$x_2(t_1)$	$x_1(t_2)$	$x_2(t_2)$	$x_1(t_3)$	$x_2(t_3)$
$x_1(t_0)$	Y	Y	Y	Y	N	N	N	N
$x_2(t_0)$	Y	Y	Y	Y	N	N	N	N
$x_1(t_1)$	Y	Y	Y	Y	N	N	N	N
$x_2(t_1)$	Y	Y	Y	Y	N	N	N	N
$x_1(t_2)$	N	N	N	N	Y	Y	Y	Y
$x_2(t_2)$	N	N	N	N	Y	Y	Y	Y
$x_1(t_3)$	N	N	N	N	Y	Y	Y	Y
$x_2(t_3)$	N	N	N	N	Y	Y	Y	Y

Coherently combine within epochs

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Fully Coherent Search

	$x_1(t_0)$	$x_2(t_0)$	$x_1(t_1)$	$x_2(t_1)$	$x_1(t_2)$	$x_2(t_2)$	$x_1(t_3)$	$x_2(t_3)$
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$x_2(t_1)$	Y	Y	Y	Y	Y	Y	Y	Y
$x_1(t_2)$	Y	Y	Y	Y	Y	Y	Y	Y
$x_2(t_2)$	Y	Y	Y	Y	Y	Y	Y	Y
$x_1(t_3)$	Y	Y	Y	Y	Y	Y	Y	Y
$x_2(t_3)$	Y	Y	Y	Y	Y	Y	Y	Y

Combine all SFT pairs; as with standard $\mathcal{F}$-statistic, quadratic combination of all SFTs

Semi Coherent Search

	$x_1(t_0)$	$x_2(t_0)$	$x_1(t_1)$	$x_2(t_1)$	$x_1(t_2)$	$x_2(t_2)$	$x_1(t_3)$	$x_2(t_3)$
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Coherently combine within epochs

Tuning the Cross-Correlation Search

- Computational considerations limit coherent time, i.e., possible time lag between correlated segments
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	$x_1(t_0)$	$x_2(t_0)$	$x_1(t_1)$	$x_2(t_1)$	$x_1(t_2)$	$x_2(t_2)$	$x_1(t_3)$	$x_2(t_3)$
$x_1(t_0)$	Y	N	N	N	N	N	N	N
$x_2(t_0)$	N	Y	N	N	N	N	N	N
$x_1(t_1)$	N	N	Y	N	N	N	N	N
$x_2(t_1)$	N	N	N	Y	N	N	N	N
$x_1(t_2)$	N	N	N	N	Y	N	N	N
$x_2(t_2)$	N	N	N	N	N	Y	N	N
$x_1(t_3)$	N	N	N	N	N	N	Y	N
$x_2(t_3)$	N	N	N	N	N	N	N	Y

Only consider “diagonal” auto-correlations

Tuning the Cross-Correlation Search

- Computational considerations limit coherent time, i.e., possible time lag between correlated segments
- Detectable signal

$$h_0^{\text{th}} \propto \left(\sum_{IJ} |\tilde{\mathcal{G}}_{IJ}|^2\right)^{-1/4} \sqrt{\frac{S_n}{T_{\text{sft}}}} \propto N_{\text{pairs}}^{-1/4} {T_{\text{sft}}}^{-1/2}$$

(T_{sft} is duration of fourier transformed data segment)

  - If all data used, $N_{\text{pairs}} \sim N_{\text{sft}}^2$, so

$$h_0 \propto (N_{\text{sft}} T_{\text{sft}})^{-1/2}$$

    like coherent search of duration $N_{\text{sft}} T_{\text{sft}}$
  - If only simultaneous SFTs correlated, $N_{\text{pairs}} \sim N_{\text{sft}}$, so

$$h_0 \propto N_{\text{sft}}^{-1/4} {T_{\text{sft}}}^{-1/2}$$

    like semi-coherent search w/N_{sft} coherent segs of T_{sft} each
  - Can “tune” sensitivity vs comp time by choosing SFT pairs