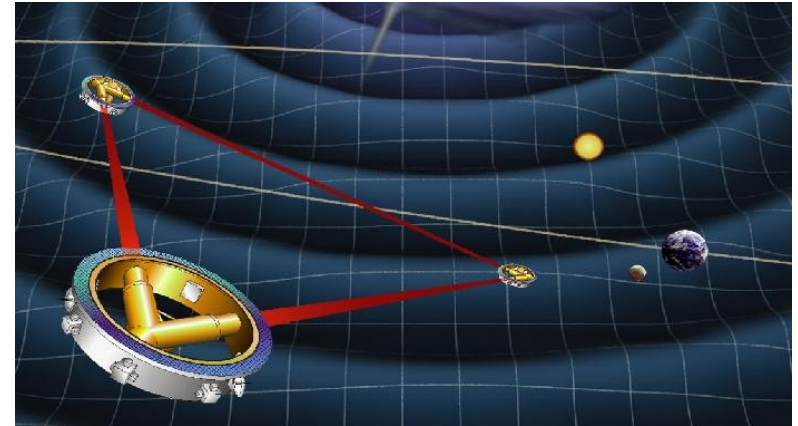


Gravitational Wave Astronomy: The Role of Minisats

E. Sterl Phinney
Caltech

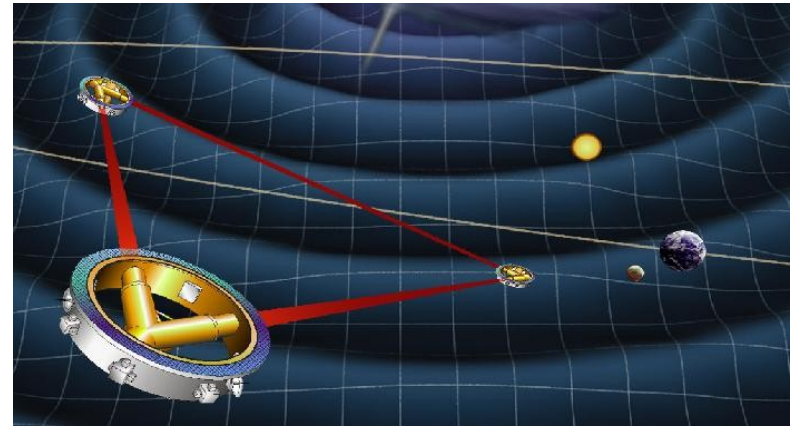
Two very different frequency bands



- “LIGO” +GEO+VIRGO
- 20-2000 Hz
- Initial LIGO S5 run (1 yr triple coincidence) 11/2005-9/2007.
NS-NS to 15Mpc. [arXiv 1005.4655](#)
- eLIGO S6 run (7/2009-12/2010)
NS-NS to 20Mpc.
- **Adv LIGO: construction start 2008, install 10/2010-2013.
Science operation 2014 ? (Low f first).** NS-NS to 150Mpc

- “LISA” (space)
- 0.0001-0.1 Hz
- LISA pathfinder launch 2012
- LISA launch 2020?

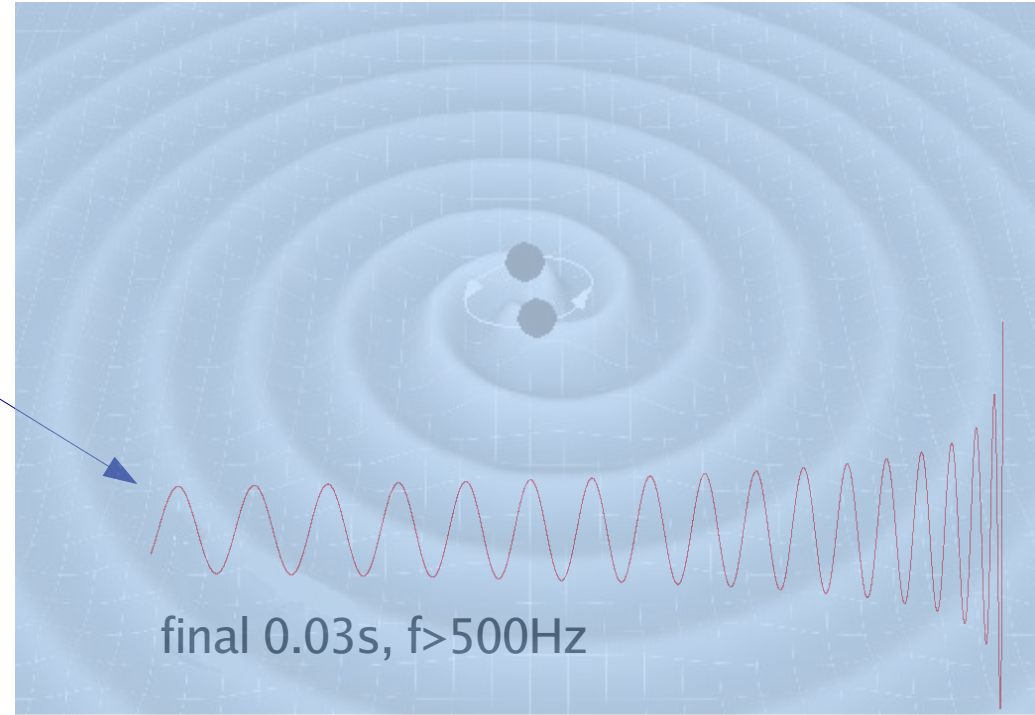
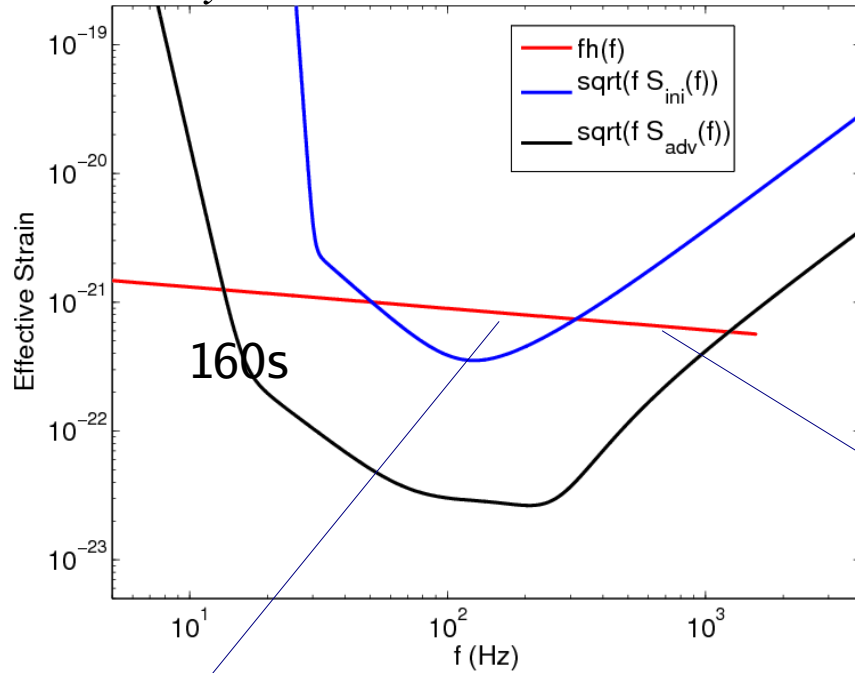
Two very different frequency bands



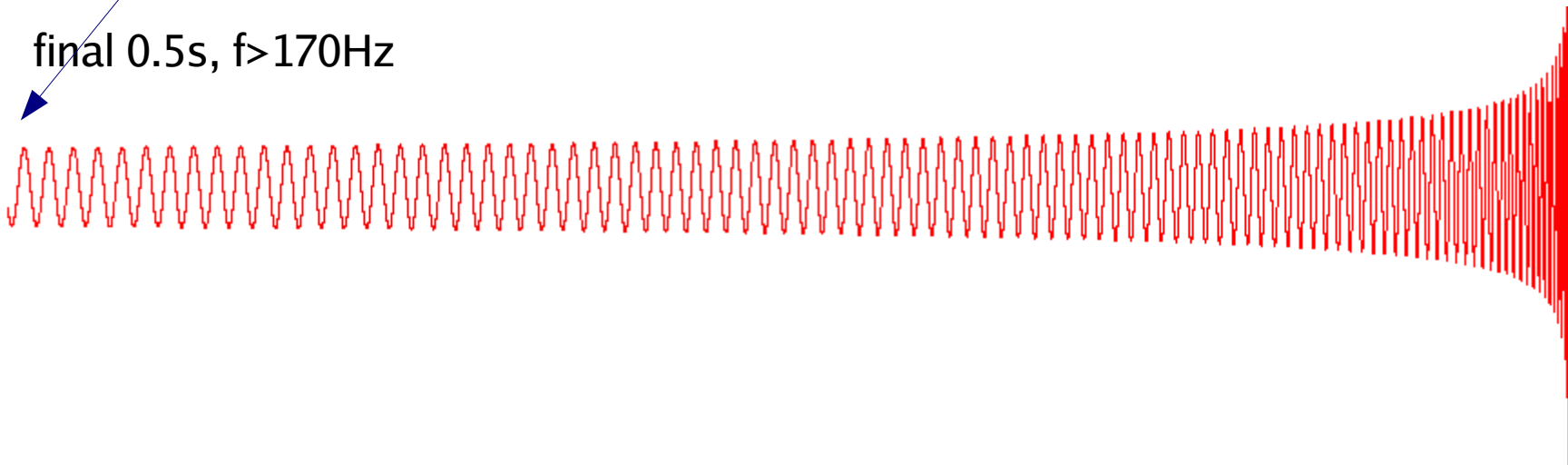
- “LIGO” +GEO+VIRGO
- 20-2000 Hz
- Last minute of merging neutron star and stellar mass black holes. (<200Mpc)
- Supernovae (<3Mpc)?
- Accretion induced collapse (<10Mpc)?
- Pulsar, LMXB mountains (<kpc)?
- “LISA” (space)
- 0.0001-0.1 Hz
- Last years of merging SMBH to $z=25$, SMBH+stellar mass to $z=0.3$ (IMBH to $z=3$)
- Last Myr of binary white dwarfs in Milky Way
- TeV universe?

Gravitational wave strain: NS-NS merger at 25 Mpc

$$h_{eff}(f) = \sqrt{N_{cycles}(f)} h(f)$$



final 0.5s, $f > 170$ Hz



Sky localisation measurements

- Measured GW strain at detector (ground/space):

$$h_M(t) = F_+(\theta, \phi, \psi) h_+(t) + F_\times(\theta, \phi, \psi) h_\times(t)$$

where

$$h_+(t) = \frac{2 \mathcal{M}^{5/3} (\pi f(t))^{2/3}}{D_L} (1 + \cos^2(\hat{\mathbf{L}} \cdot \hat{\mathbf{n}})) \cos \Phi(t)$$

$$h_\times(t) = -4 \frac{\mathcal{M}^{5/3} (\pi f(t))^{2/3}}{D_L} \cos(\hat{\mathbf{L}} \cdot \hat{\mathbf{n}}) \sin \Phi(t).$$

$$\cos(\text{inc}) \equiv \hat{\mathbf{L}} \cdot \hat{\mathbf{n}}$$

- GW polarisation gives inclination angle.
- Network (timing of signals) gives source localisation and polarisation.

Gravitational Wave Astronomy

- Gravitational waveforms give for binaries:
 - (redshifted) Masses
 - Orbit inclination to sky (incl spin-orbit precession if present)
 - Position angle on sky (mod 90 deg, ditto)
 - Luminosity Distance to source (in meters; % error $\sim 1/\text{SNR}$)
 - crude localization on sky (details later)
 - Date of merger
 - (redshifted) orbit frequency at merger (i.e mean stellar density \rightarrow Radius).
 - Other orbit dissipation (tides, mass transfer) if significant

Grav. Waves give info not reliably obtainable from electromagnetic obs:

- - (redshifted) Masses
 - Orbit inclination to sky (incl spin-orbit precession if present)
 - Position angle on sky (mod 90 deg, ditto)
 - Luminosity Distance to source (in meters; % error $\sim 1/\text{SNR}$)
 - crude localization on sky (details later)
 - Exact time of merger
 - (redshifted) orbit frequency at merger (i.e mean stellar density \rightarrow Radius).
 - Other orbit dissipation (tides, mass transfer) if significant

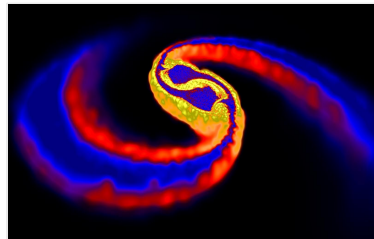
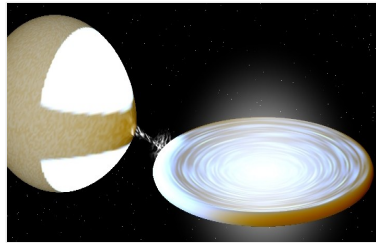
Electromagnetic observations give complementary info to Grav waves:

- - accurate localization on sky:
 - Environment, host galaxy, progenitor...
 - Composition (spectroscopy)
 - Gas dynamics and velocities
 - Magnetic fields

Electromagnetic Counterparts of Gravitational Wave Sources: 1

- Examples (LIGO: 30-2000 Hz gravitational waves):
 - Neutron star-Neutron star mergers.
 - Black hole- Neutron stars mergers and tidal disruption.
 - Accretion-induced collapse (white dwarf to neutron star)
 - Magnetars (quakes on neutron stars with strong B fields)
 - Possibly some Low Mass X-ray Binaries (accreting neutron stars)
 - Possibly some supernovae

Events that definitely occur in the universe, and produce gravitational waves with **reliable** or **unreliable** waveforms.



LMXB

NS-NS
NS-BH

WD - WD

AIC

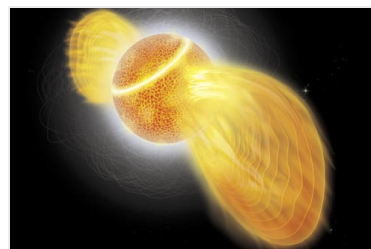
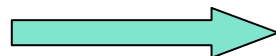
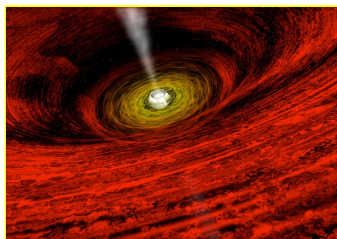
Merger

**Merger
(AIC)**

Accretion disk +
Black Hole

disk+msec NS,
magnetar

SN Ia,
magnetic WD

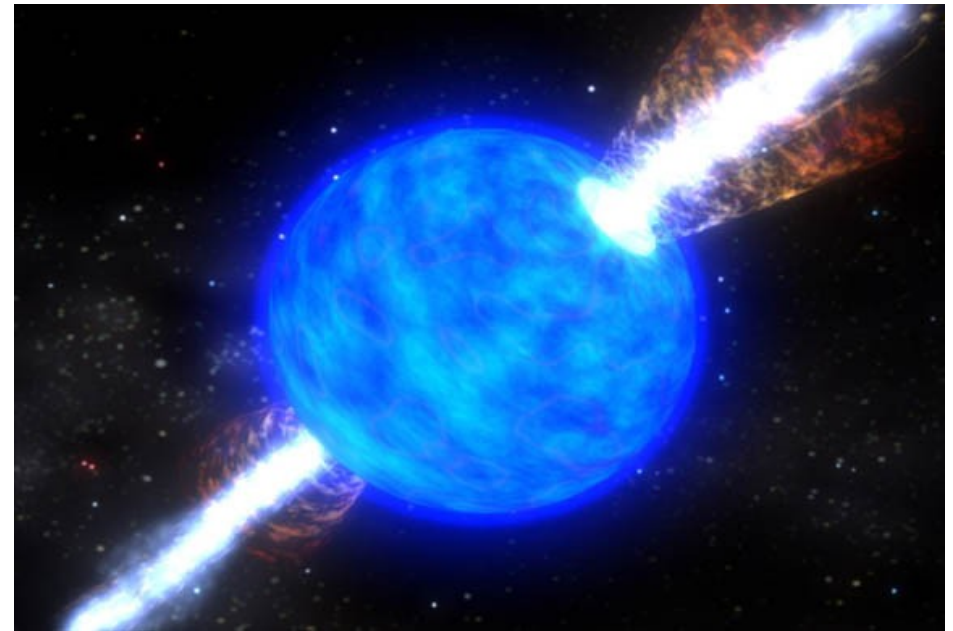


Burning questions

- What happens to the mass which does not promptly collapse in NSNS, NSBH mergers?
 - Degenerate tori
 - Ejected material
 - (short-hard) gamma ray bursts
 - nuclear-powered afterglows
 - ISM powered afterglows

More events that occur and *may* produce significant gravitational waves

- Core collapse supernovae or AIC
 - Collapsars (long-soft gamma-ray burst model)
 - secondary neutron star formation from collapsar disk fragmentation (cf Piro & Pfahl astro-ph/0610696, $h \sim 0.3h(\text{NS-NS})$)
 - acoustic g-modes (cf Ott, Burrows et al 2006), $h \sim 0.1h(\text{NS-NS})$)
 - MHD (cf Ott et al 2009, $h \sim 0.1h(\text{NS-NS})$)
 - r-mode or bar instability



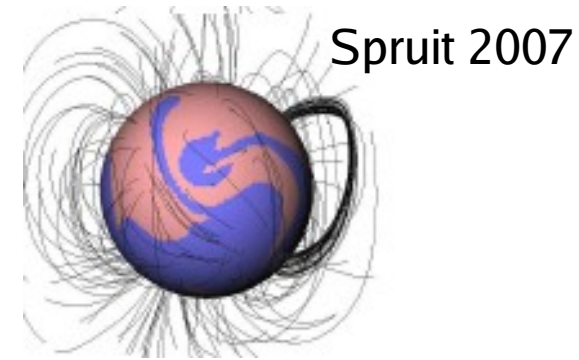
These do not have to be common: interesting for Advanced LIGO if even 3% of SNaE have $h \sim 0.1h(\text{NS-NS})$, or 0.01% have $h \sim h(\text{NS-NS})$.

cf Ott arXiv:0809.0695

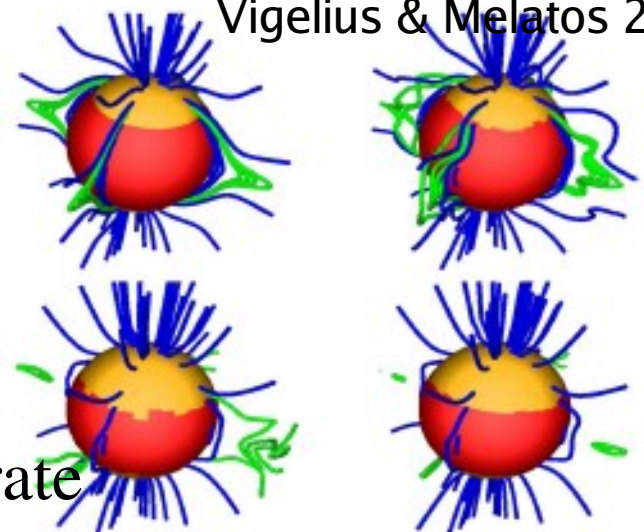
Continuous Wave Sources (LIGO)

- **Pulsars/Magnetars with Mountains and quakes**

- origin/growth/decay of B field
- superfluids, superconductors,
- magnetic field movement, pinning
- crust breaking, magnetar eruptions



Vigelius & Melatos 2008



- **Accreting** LMXB

- Magnetic tutas, magnetic deformations
- boundary layer physics. Limiting spin rate

Electromagnetic Counterparts of Gravitational Wave Sources: 2

- Examples (LISA: 0.1-30mHz gravitational waves):
 - Massive black hole-white dwarf mergers and tidal disruption
 - detached close white dwarf binaries (tidal interactions and eclipses only)
 - Interacting white dwarf binaries (AMCVn, direct impact accretion, close polars, exotic supernova progenitors)
- Related: Tidal disruptions of main sequence stars

So What's the problem?

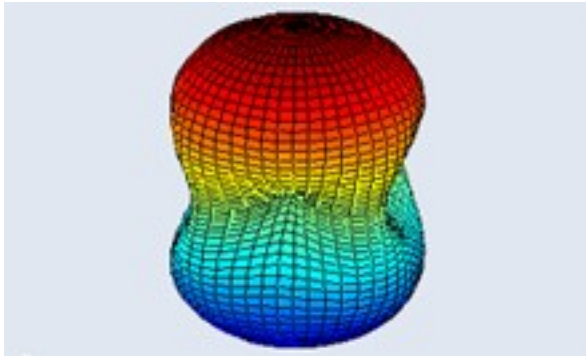
1. Gravitational Wave Source Localization

Errors: at best a few degrees for LIGO, minutes after the event (10' weeks before for LISA).

2. Low Rates: for LIGO need all sky, all the time to ensure even few/year.

Direction finding for GW signals

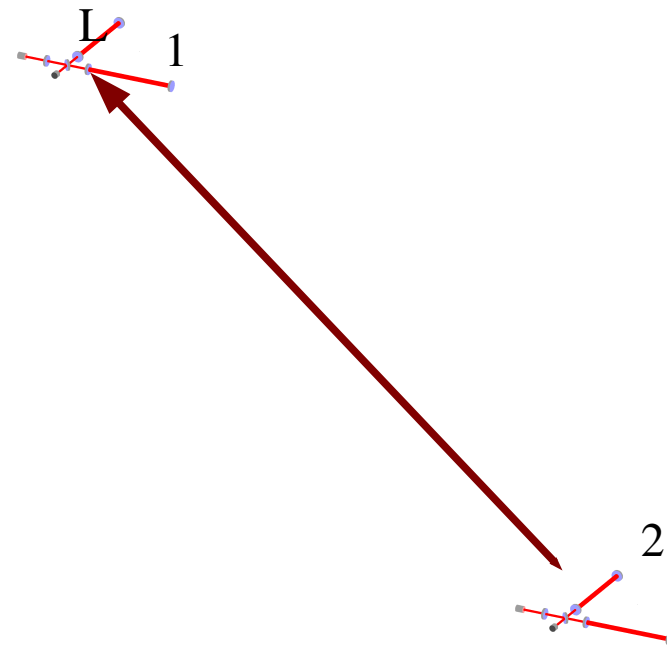
One interferometer



Sensitivity as function of sky direction for single ($L \ll \lambda$) interferometer: quadrupole pattern.

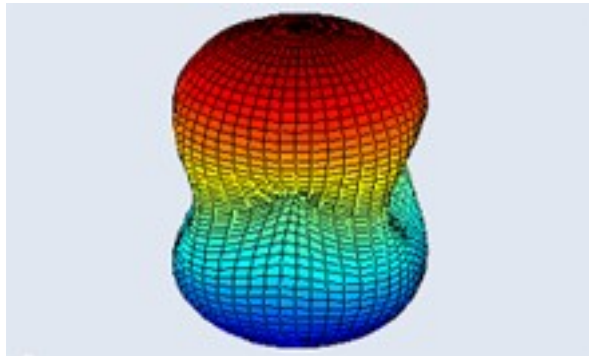
-sucks for localisation.

Two interferometers:
use time delay to
improve localization:



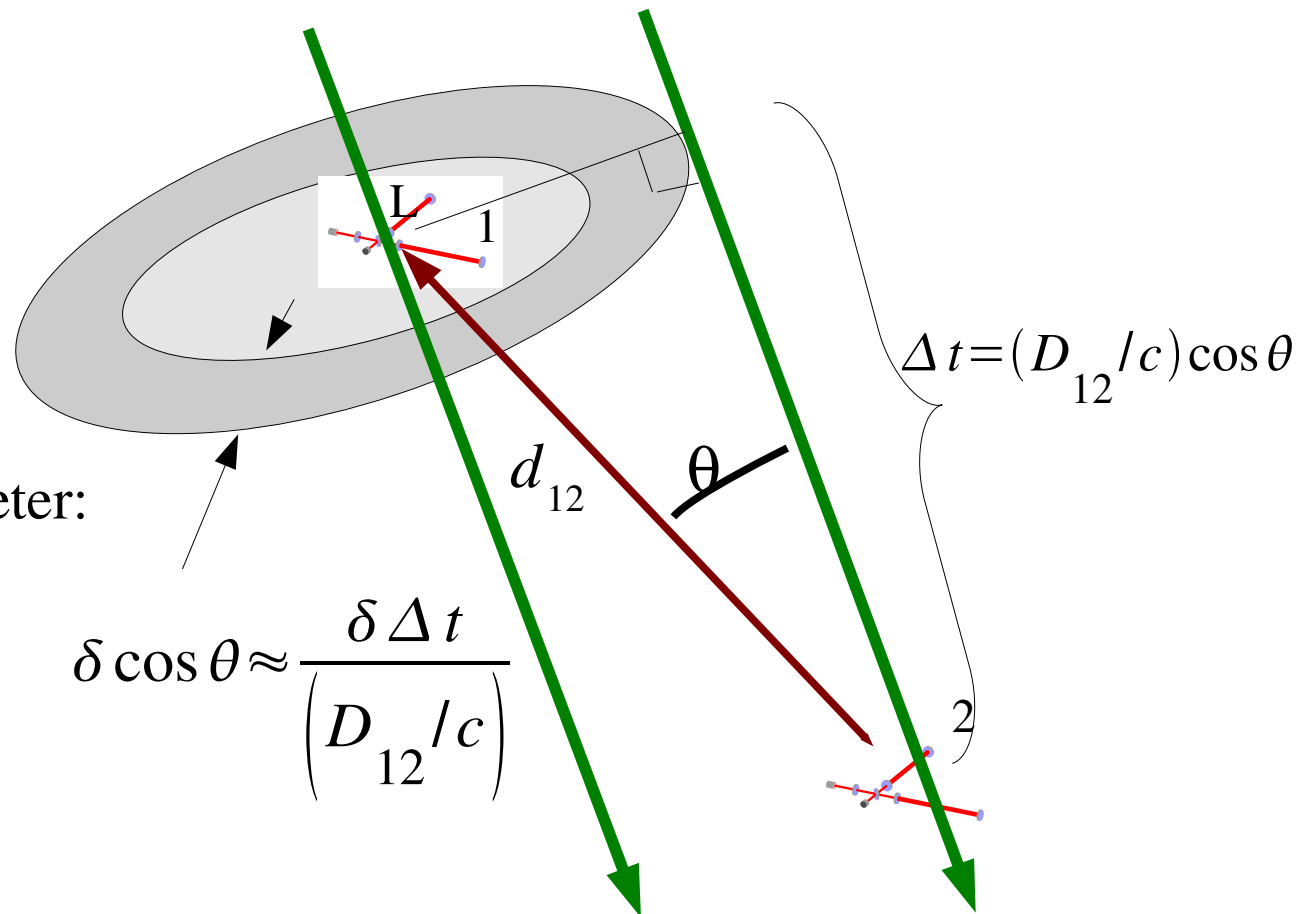
Direction finding for GW signals

Time delay between interferometer pairs localizes to circle on the sky



Sensitivity as function of sky direction for single ($L \ll \lambda$) interferometer: quadrupole pattern.

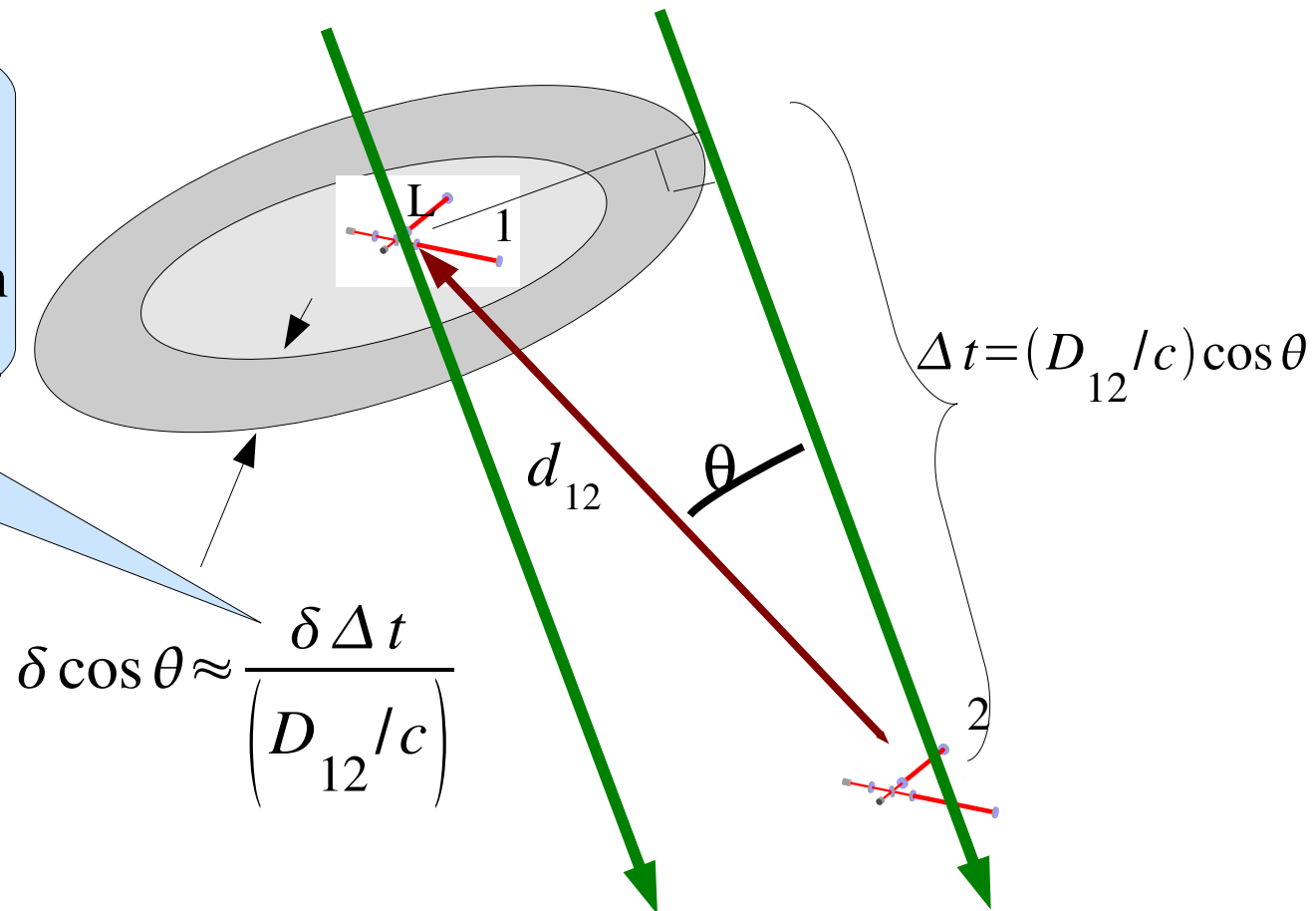
-sucks for localisation.



Direction finding for GW signals

Time delay between interferometer pairs localizes to circle on the sky

Sky localization accuracy depends on precision of determination of the arrival time difference.



$$\delta \cos \theta \approx \frac{\delta \Delta t}{(D_{12}/c)}$$

Localization Principles

Consider simple BEST case when template perfectly known, and only ARRIVAL TIME is to be fitted. Consider two illustrative cases

1. Gaussian Burst

2. Signal with rapidly varying phase and slowly varying amplitude

(e.g. inspiral)

Fourier transform of $x(t)$

Optimal filtering: cross correlate $(x||y) \equiv 4 \Re \int_0^\infty \frac{\tilde{x}(f) \tilde{y}^{cc}(f)}{S(f)} df$

Optimal SNR $\rho^2 = (h||h) = 4 \int_0^\infty df \frac{|\tilde{h}(f)|^2}{S(f)}$

One-sided spectral density of strain noise

likelihood function signal h is present in noisy data x : $\Lambda = \frac{p(x|h)}{p(x|0)} = \frac{\exp-(x-h||x-h)/2}{\exp-(x||x)/2}$

Gaussian Burst

$$h(t) = \frac{1}{\sqrt{2\pi\sigma_t}} e^{-(t-\tau)^2/2\sigma_t^2}$$

$$\tilde{h}(f) = e^{-2\pi i f \tau} e^{-2\pi^2 f^2 \sigma_t^2} = e^{-2\pi i f \tau} e^{-f^2/2\sigma_f^2}$$

$$\sigma_f = \frac{1}{2\pi\sigma_t}$$

$$M(\tau) = \frac{(h(t-\tau) \| h(t))}{(h(t) \| h(t))} = \Re W(-\tau/2\sigma_t) = 1 - (\tau/2\sigma_t)^2 + \frac{1}{2}(\tau/2\sigma_t)^4 \dots$$

Fisher Matrix: near true delay τ Likelihood

$$\Lambda \approx \exp \frac{\rho^2}{2} (1 - (\delta\tau)^2/\sigma_t^2) = \exp(-\delta\tau^2/2\sigma_t^2)$$

$$\text{Delay measurement accuracy } \delta\tau \sim \sigma_\tau \equiv \frac{\sigma_t}{\rho} = \frac{1}{2\pi\sigma_f\rho}$$

Rapidly varying phase, slowly varying amplitude (cf inspiral)

Consider simple BEST case when template perfectly known, and only ARRIVAL TIME is to be fitted. Can show Fisher Matrix for arrival time

has same form as for Gaussian burst if we define $\sigma_\tau \equiv \frac{1}{2\pi \Delta f_e \rho}$

where ρ is the amplitude signal-to-noise ratio,

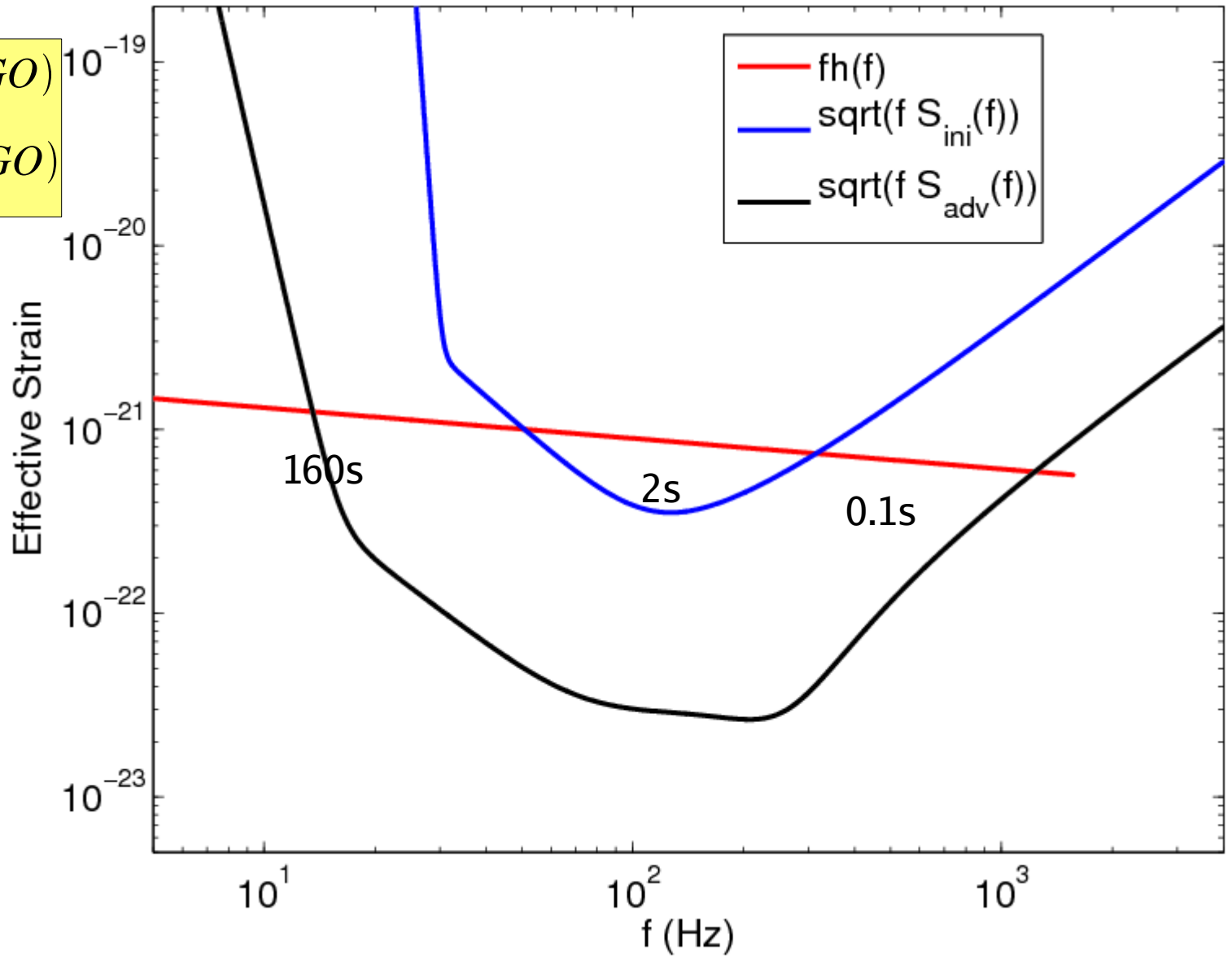
$\Delta f_e = \sqrt{\langle f^2 \rangle - \langle f \rangle^2}$ is the effective bandwidth (120Hz for NS-NS Adv LIGO) and

$$\langle f^n \rangle \equiv 4 \int_0^\infty df \frac{|\tilde{h}(f)|^2}{S(f)} f^n.$$

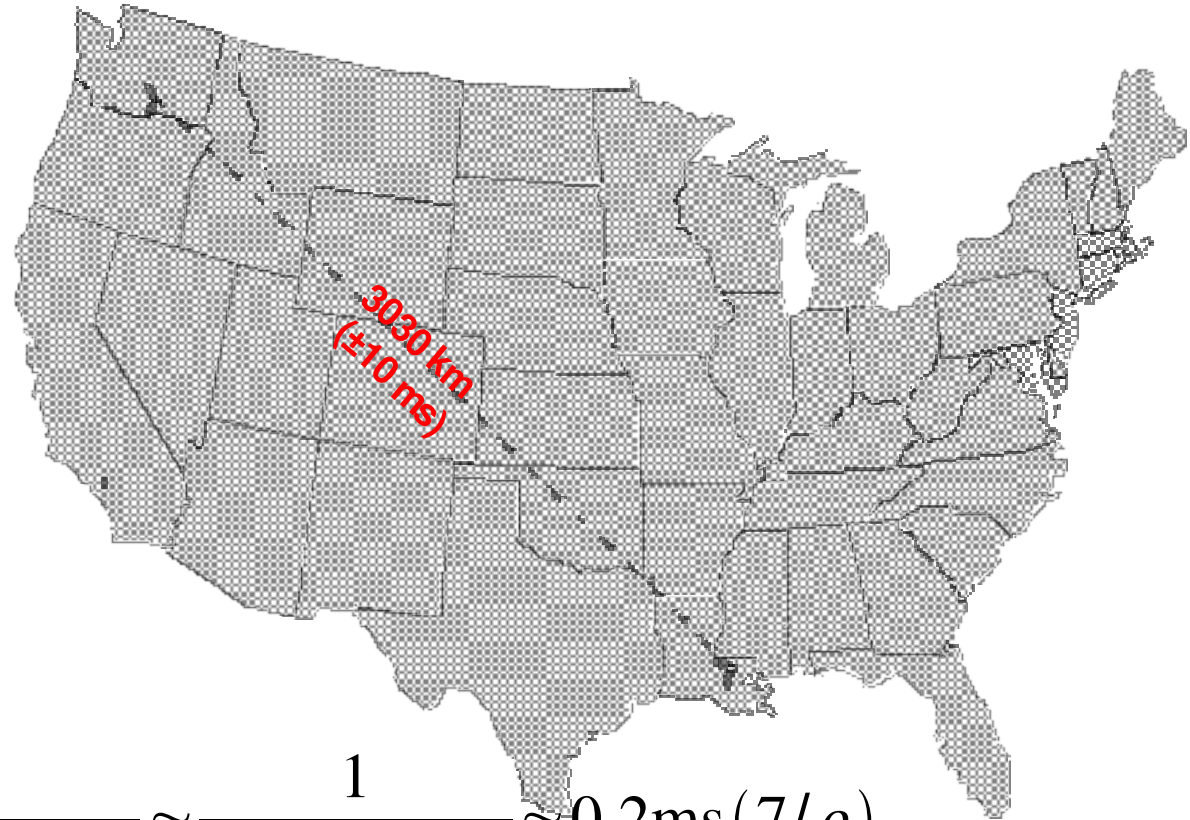
Thus again the delay measurement accuracy $\delta\tau \sim \sigma_\tau = \frac{1}{2\pi \Delta f_e \rho}$

NS-NS merger at 25 Mpc

$\Delta f_e = 100\text{Hz} (iLIGO)$
 $\Delta f_e = 120\text{Hz} (aLIGO)$



LIGO Hanford & Louisiana



$$\sigma_{\tau 1} \sim \frac{1}{2\pi \Delta f_{el} \rho_1} \sim \frac{1}{2\pi 120\text{Hz} 7} \sim 0.2\text{ms} (7/\rho)$$

$$\delta \cos \theta = \sin \theta \delta \theta = \frac{c}{D_{12}} \sqrt{\sigma_{\tau 1}^2 + \sigma_{\tau 2}^2} \sim 2^\circ (7/\rho) \quad (\text{x3 for 95\% confidence})$$

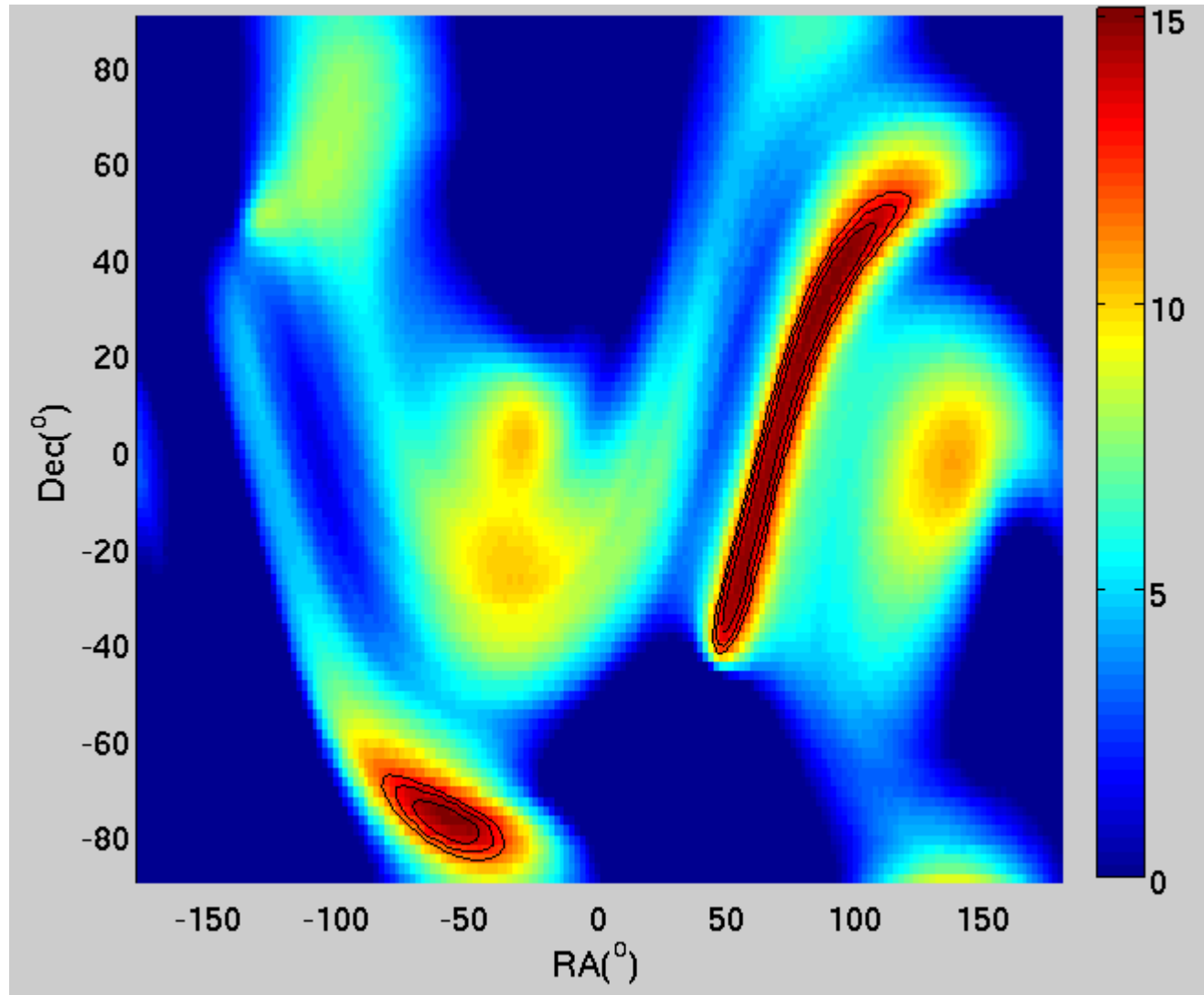
Note: sky area independent of sky position for timing alone.

LIGO Hanford & Louisiana

Initial LIGO
noise.
 $D=25\text{Mpc}$.
net SNR=15 !

Sky position
Contours:
1 , 2, 3
sigma

NS-NS merger
2.5PN



Network of gravitational wave detectors



LIGO

Hanford, WA
4 km interferometer
2 km interferometer



GEO

Hannover, Germany
600 m interferometer



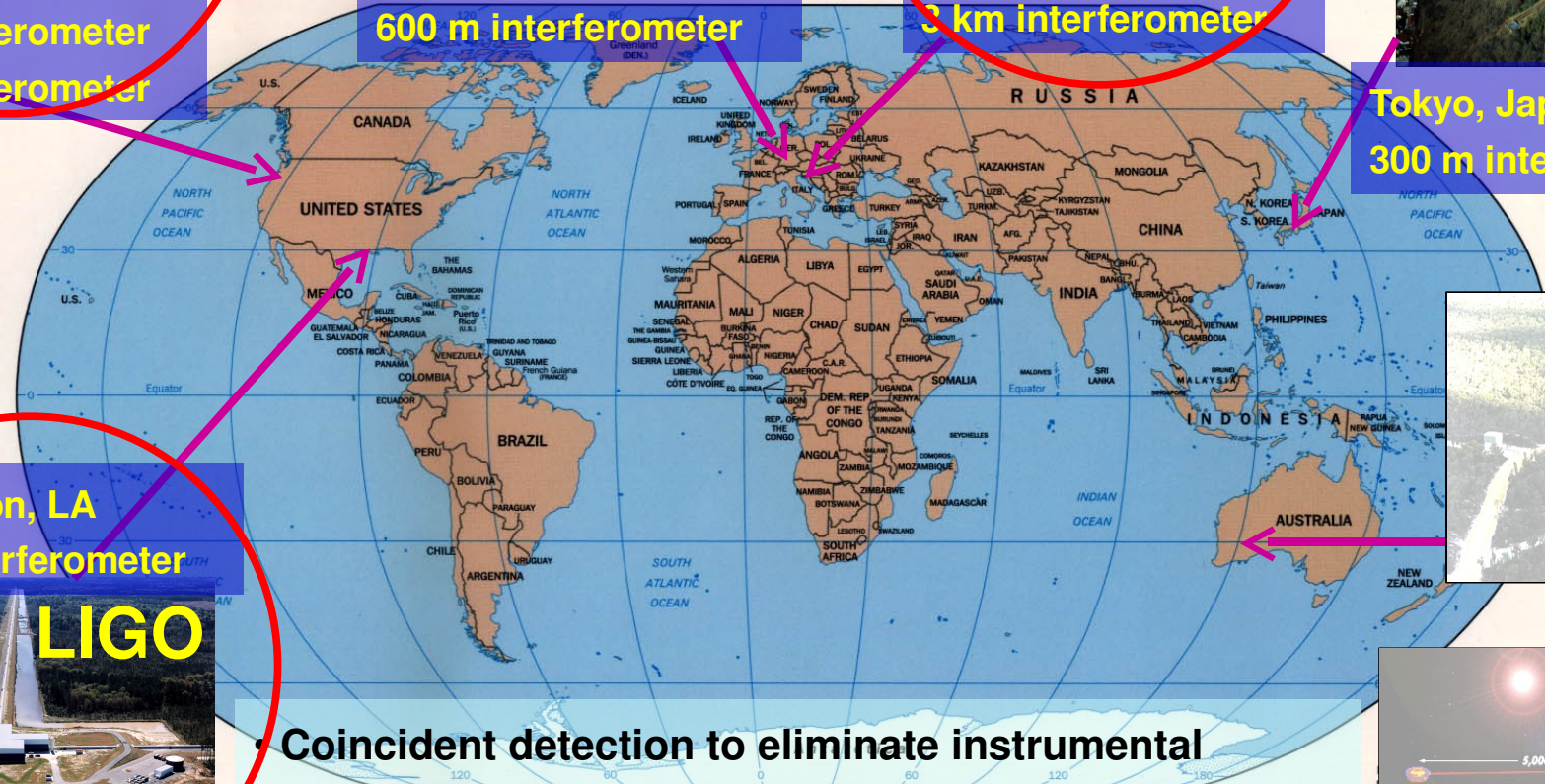
VIRGO

Pisa, Italy
3 km interferometer



TAMA

Tokyo, Japan
300 m interferometer



Livingston, LA
4 km interferometer



LIGO



AIGO

- Coincident detection to eliminate instrumental artifacts
- Source localization in the sky
- Wave polarization

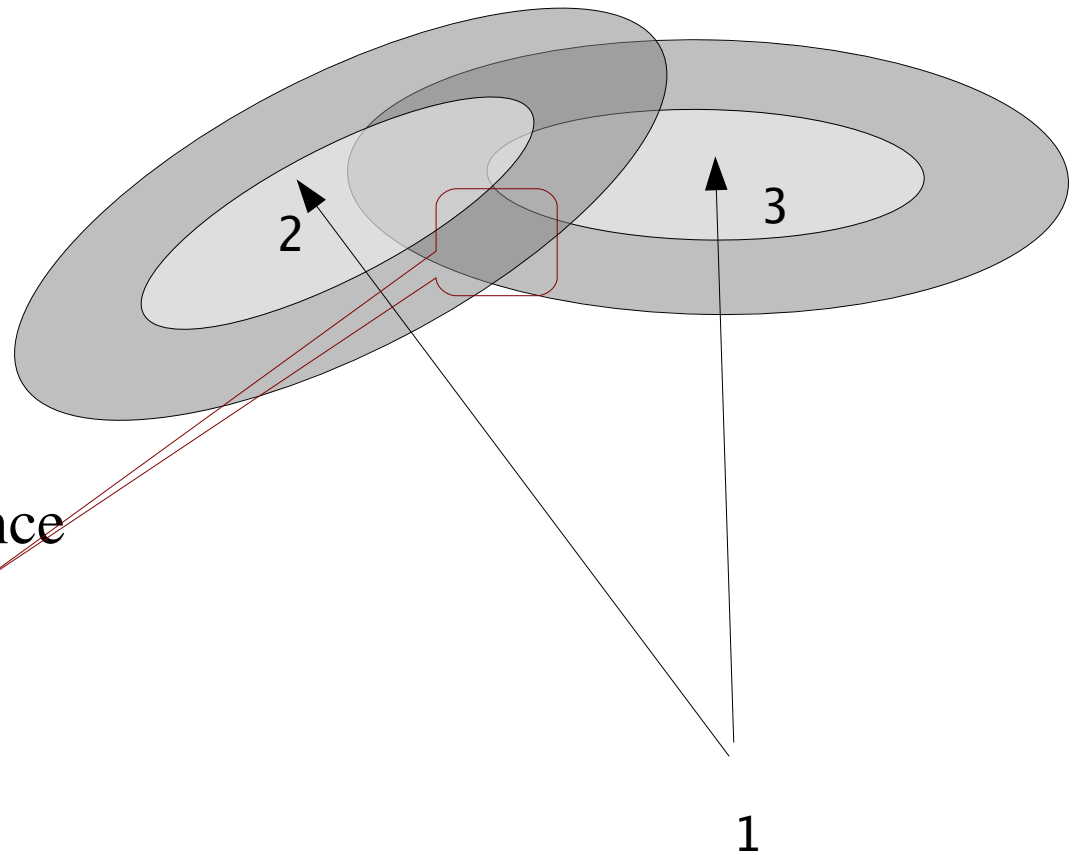


3 Interferometers, 3 Baselines (2 indep)

Recall $\delta\tau \sim \sigma_\tau = \frac{1}{2\pi\Delta f_e \rho}$

\vec{B}_{12} sets $\vec{n} \cdot \vec{B}_{12}$ to $c\sqrt{\sigma_{\tau 1}^2 + \sigma_{\tau 2}^2}$

\vec{B}_{23} sets $\vec{n} \cdot \vec{B}_{23}$ to $c\sqrt{\sigma_{\tau 1}^2 + \sigma_{\tau 3}^2}$



Solid angle of overlap 90% confidence

$$\frac{20c^2\sigma_{\tau 12}\sigma_{\tau 13}}{(\vec{B}_{12} \times \vec{B}_{23}) \cdot \vec{n}} \sim \frac{10 \text{ deg}^2 (7/\rho)^2}{\sin \psi}$$

Projected area of detector triangle
as seen from source.

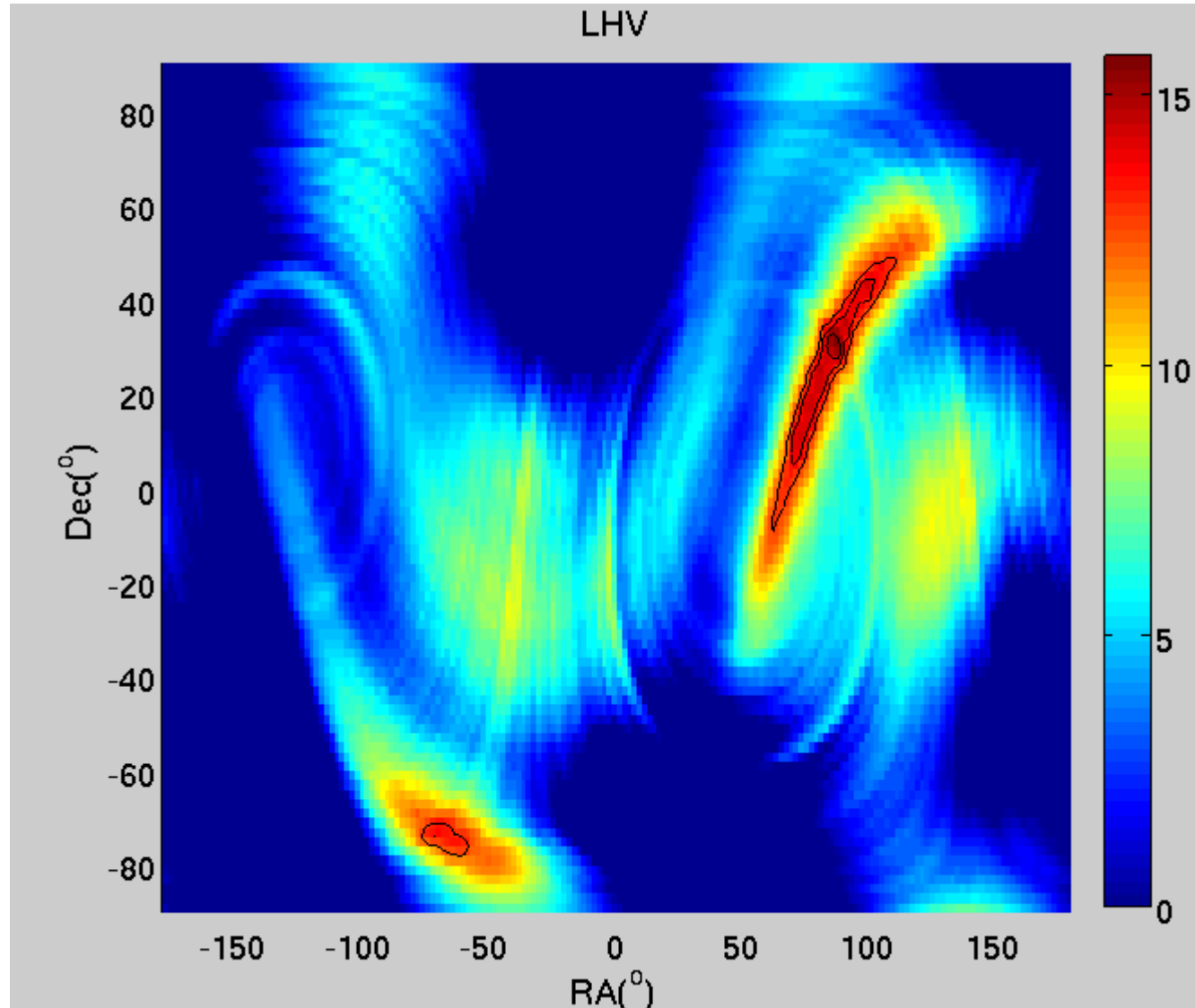
LH $B/c = 10\text{ms}$, LV $B/c = 27\text{ms}$

Virgo + LIGO Hanford + Louisiana

Initial LIGO
noise.
D=25Mpc.
net SNR=15

Sky position
Contours:
1, 2, 3
sigma

NS-NS merger
2.5PN

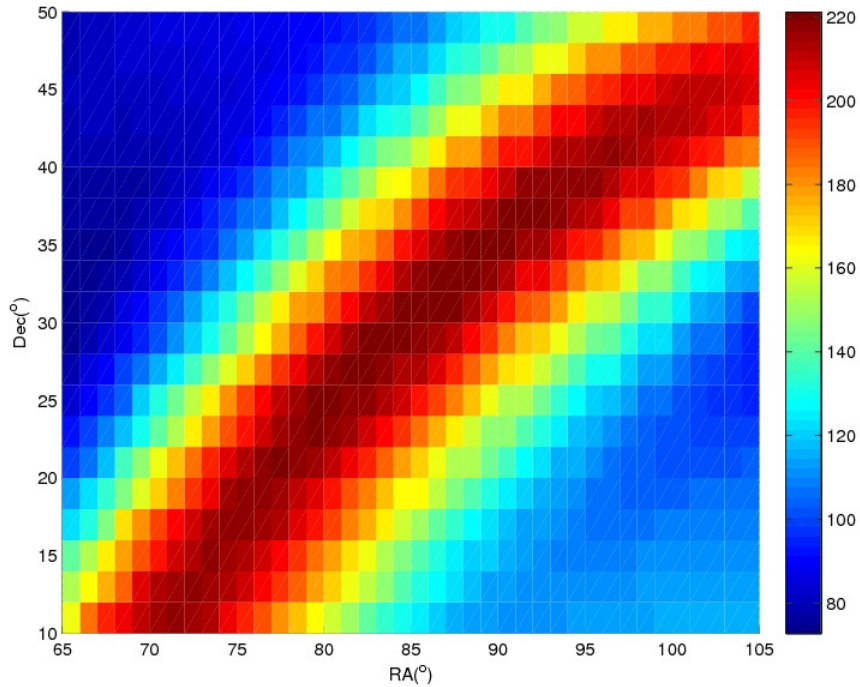


Very similar results for Advanced LIGO+Advanced Virgo at same network SNR=15 (D=266Mpc) S. Phinney, Weizmann Inst, 6/7/2010

Best possible case: a really high SNR=220 source

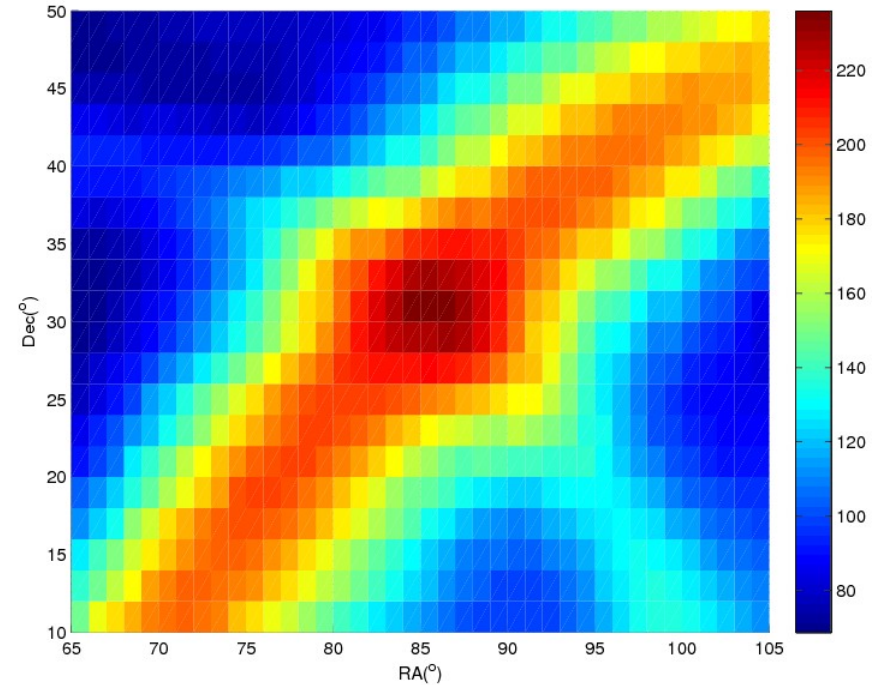
Adv LIGO Hanford+Louisiana

LH



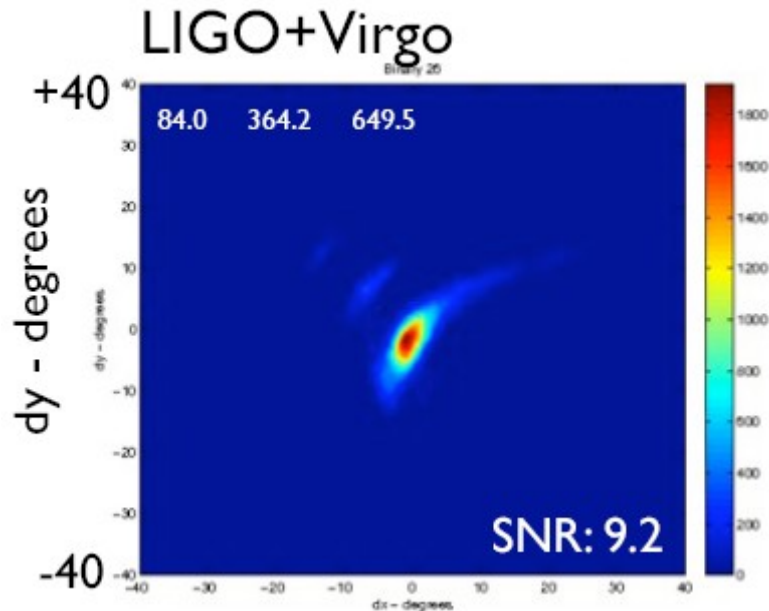
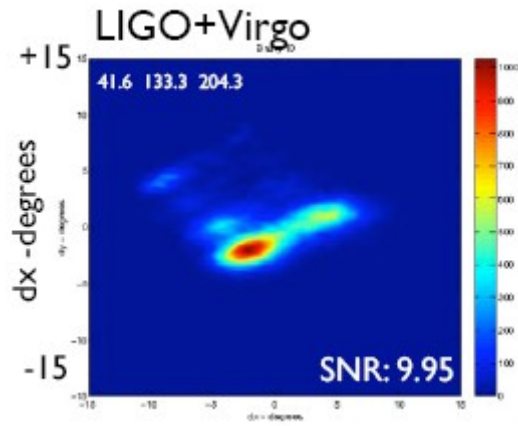
Adv Virgo + LIGO H & L

LHV



Advanced detectors, NS+NS merger at $D=25\text{Mpc}$. 2.5PN waveform.

MC-MC fitting for Adv LIGO NS-NS



- 50% of binaries detected by Adv LIGO+Adv Virgo localized to 40 sq deg (68% conf); 100 sq deg (95% conf)
 - (S. Nissanke, p.c.)

Event rates and luminosities

Event rates $R_{-6} 10^{-6} \text{Mpc}^{-3} \text{y}^{-1}$

To ensure $4N_{4/yr}$ /yr all-sky, need to observe to

$$d \sim 100 \text{Mpc} N_{4/yr} f_c(d)^{-1/3} R_{-6}^{-1/3} \text{ where}$$

$f_c(d)$ is the local overdensity correction, $f_c(20\text{Mpc})=3$, $f_c(100\text{Mpc})=1$

Flux limit for $D=20_{20}$ cm modest minisat ($A=300D_{20}^2 \text{cm}^2$)

To get $10 \pm \sqrt{10}$ photons in Δt_s sec, efficiency ϵ in fractional bandpass $\Delta \nu / \nu$

$$\nu L_\nu = 10^{42} \text{erg s}^{-1} \frac{d_{100\text{Mpc}}^2 (0.5 \mu\text{m}/\lambda)(\nu/3 \Delta \nu)}{\epsilon_{0.5} D_{20}^2 \Delta t_s}$$

$$(10^{45} \text{erg s}^{-1} \text{ at } 2\text{keV})$$

What else goes wrong?

- 1) Above estimates assume all template parameters except arrival time known *a priori*.
 - 2) Actually they are not: must be fitted for, and many degenerate/correlate with sky position (nondiagonal Fisher matrix).
 - 3) At low SNR, Fisher matrix underestimates; many peaks, not one (cf sinusoidal signal).
 - 4) Unfavorable position angles (polarizations): big difference in SNR between differently oriented sites for some sources and sky positions.
- 4,3 helped by 4 or more interferometers. Also helps in-plane degeneracy of 3.

Source	$\log_{10}(R_{-6})$	$\log_{10} \nu L_{\nu}$	timescale	band	f_{gw}/Hz	d_{gw}/Mpc
NS-NS	-0.5+-0.5	41.5	1 day	opt	10-2000	200(ALIGO)
NS-BH tidal	-0.5+-1	41.5	1 day	opt	10-1000	200(ALIGO)
MS-SMBH tidal disr	0+-1	43	10day	FUV-UV	0.0001Hz	
MS-SMBH tidal comp	0+-1	41	10 sec	Xray	0.0001Hz	
WD-MBH tidal disr	-0.5+-1.5				0.1HZ	200 (LISA)
“ -stripping of bound “		43	1d	X-ray	“	“
“ -thermonuclear SN “		42(Opt) 41(X)	1-3month	Opt+X-ray	“	“
“ -ioniz of unbound “		41	1yr	opt	“	“
“ -tidal compression “		41.5	1s	Xray	“	“
AIC (Ni rich outflow)	-0.5+-0.5	41	4 d	opt	0.01-0.1Hz	300 (LISA)
SN breakout II-RG	2	46	2000s	UV	400-1000Hz	5? (ALIGO)
SN breakout Ibc	1	43.5	20s	Xray-1kev	400-1000Hz	5?(ALIGO)
SN breakout Ia	1	42	0.01s	20keV	400-1000Hz	20?(ALIGO)
SN20005E-type	0.5+-0.5	42	weeks	opt	0.1-0.01Hz	150 (LISA)

References to the models (beware!)

- NS-NS and BH-NS disruption. r process ejecta:
 - Metzger et al arXiv 1001.5029
- SMBH-MS tidal:
 - shocks: Kobayashi et al 2004ApJ 615, 855
 - streams: Cannizzo et al 1990 ApJ 351, 38
 - reprocessing: Strubbe & Quataert 2009 arXiv 0905.3735
 - recombination: Kasen & Ramirez-Ruiz 2009 arXiv 0911.5358

References -2

- MBH-WD
 - Rates: Sesana et al 2008 MN 391, 718
 - Tidally induced thermonuclear supernovae: Rosswog et al arXiv 0811.2129
 - Gradual stripping: Zalamea et al arXiv 1005.3987
 - shocks: Kobayashi et al 2004ApJ 615, 855
 - Note also: tidal disruption of giants/subgiants -> WD core

References -3

- AIC Ni-rich outflows
 - Darbha et al arXiv 1005.1081
- Supernova shock breakout
 - Nakar & Sari arXiv 1004.2496
- WD+WD merger -> SN 2005E-type
 - Perets et al 2010 Nature 465, 322

Summary

- EM-GW events will occur at rate only few/year over all sky.
- LISA will give weeks notice of events, but
- LIGO will give just seconds, if any notice.
- **So have to monitor all sky, and/or slew in seconds**
- X-rays not accessible to small satellite except MBH-WD tidal disruption fallback. Existing sats suffice?
- **UV-Optical fluxes compatible with small satellite**

Thinking out of the satellite box

- Want to monitor many galaxies over all sky, but covering in total only small fraction of sky? Image postage stamps on single CCD:
 - simultaneously: spherical or fisheye lens, pair of cylindrical mirrors, followed by programmable micromechanical mirrors to image array of selected galaxies onto CCD.
 - non-simultaneously: movable coelostat (can use for pointing instead of satellite attitude control?) or micromechanical mirrors step through sources (very short timescales possible -cf arXiv:0912.0773)