Windows on the universe :

Gravitational wave sky and recent results from ground based detectors

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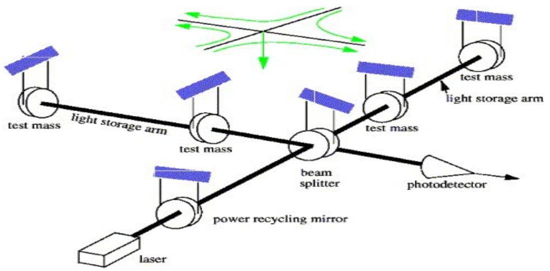
for the LIGO Scientific Collaboration
and the Virgo Collaboration

Outline



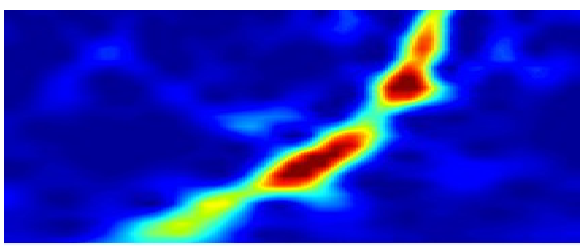
Searching for gravitational waves

Sources

Multi-messenger astronomy

Challenges

Ground based detector



Selected results

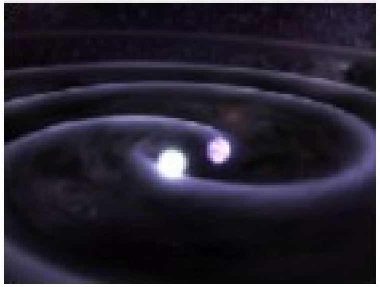
Future prospects

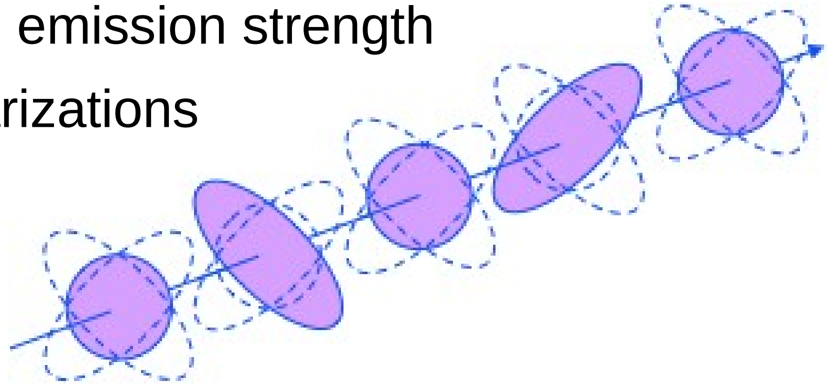
The network extension

Schedule

GW – Ripple in space-time

- Gravitational waves are propagating solutions to Einstein equation in GR ('ripples in space-time')
  - Emission from rapidly accelerating mass distributions (quadrupolar momentum)
  - Need relativistic objects to maximize emission strength
- Propagation at speed of light with 2 polarizations





- Physically, gravitational waves are strains $h = \delta l/L$
  - Kilometric interferometers are the most sensitive device so far
  - Sense of scale : neutron stars merging at 50 Mly

f_{orb} = 400 Hz
M = 1.4 M⊙
R =20 km
r = 50 Mly

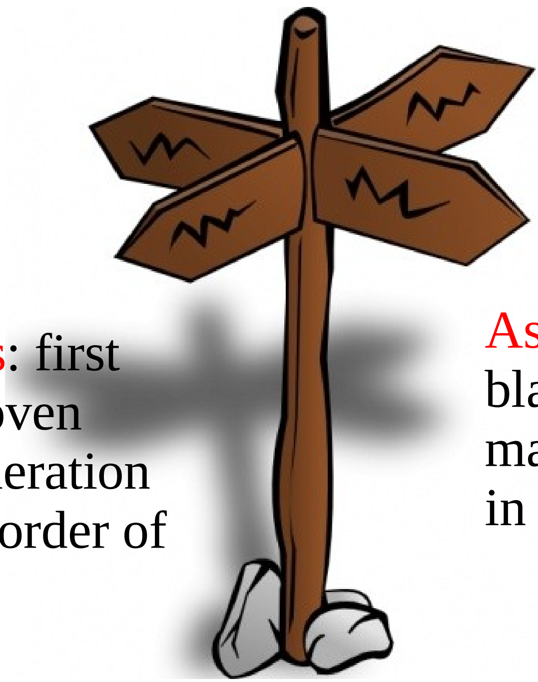
$$h \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{c^4 r} \Rightarrow h \sim 10^{-21}$$

GW- Challenges

Searching for gravitational waves with ground based detectors is a cross-road of science frontiers:

General relativity: relativistic & compact objects (strong field relativity tests).

Cosmology: reach cosmological distances for black hole GW sources.



Laser interferometric detectors: first generation of detectors has proven technology works. Second generation should be more sensitive by 1 order of magnitude.

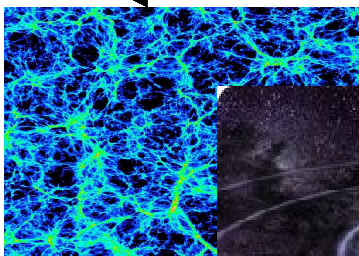
Astrophysics of compact objects: black holes & neutron stars with matter effects. Most energetic objects in the Universe.

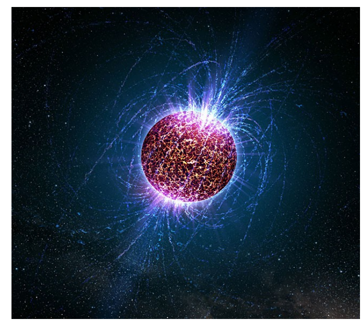
Data analysis: how to extract low signal-to-noise ratio signals in high dimensional parameter space & in non-Gaussian/non-stationary data environment.

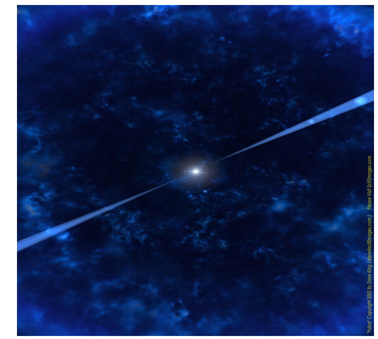
GW searches zoology

Short duration (~1s) ⟷ Long duration (∞)

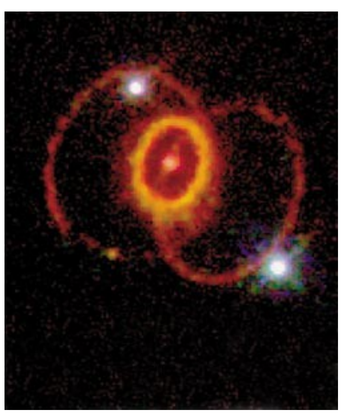
Waveform known







Waveform unknown



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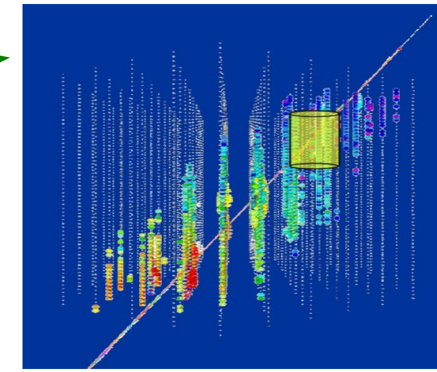
Multi-messenger astronomy

γ-rays

HE (>1 TeV) ν



GRB

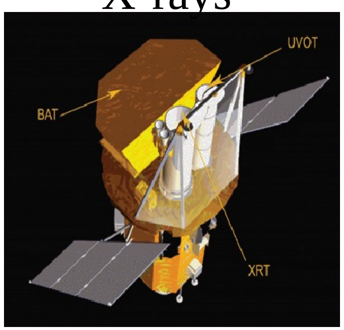
SGR/AXP

Type II
supernova

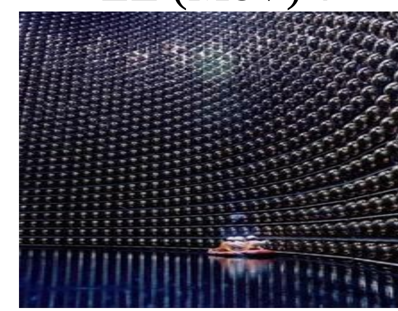
Giant flare

Pulsar glitch

X-rays



LE (MeV) ν

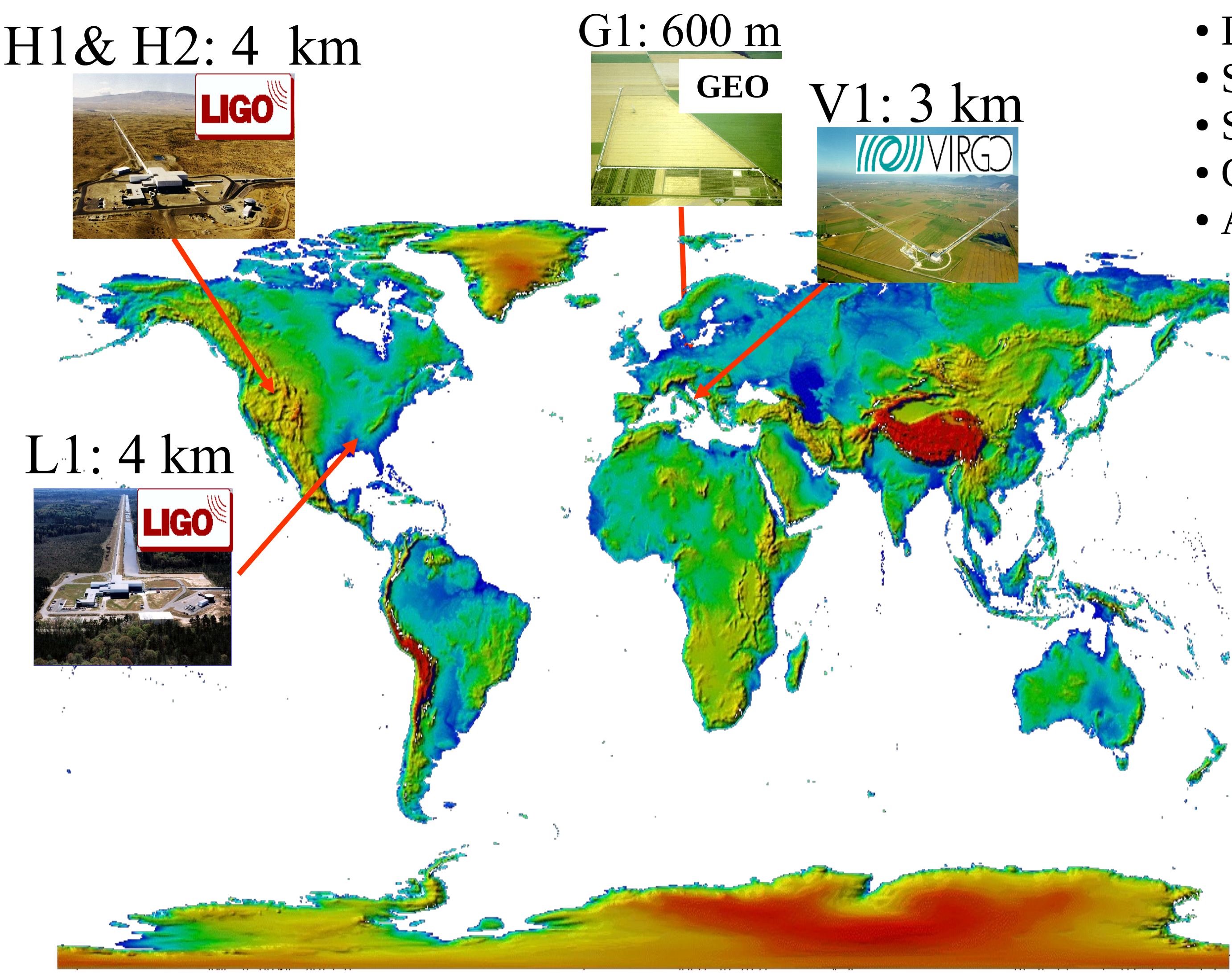


Optical/IR

radio

→ probing the progenitor structure
→ probing the stellar density
→ ruling out models
→ Astrophysics measurements:
Hubble constant, GW speed, ...

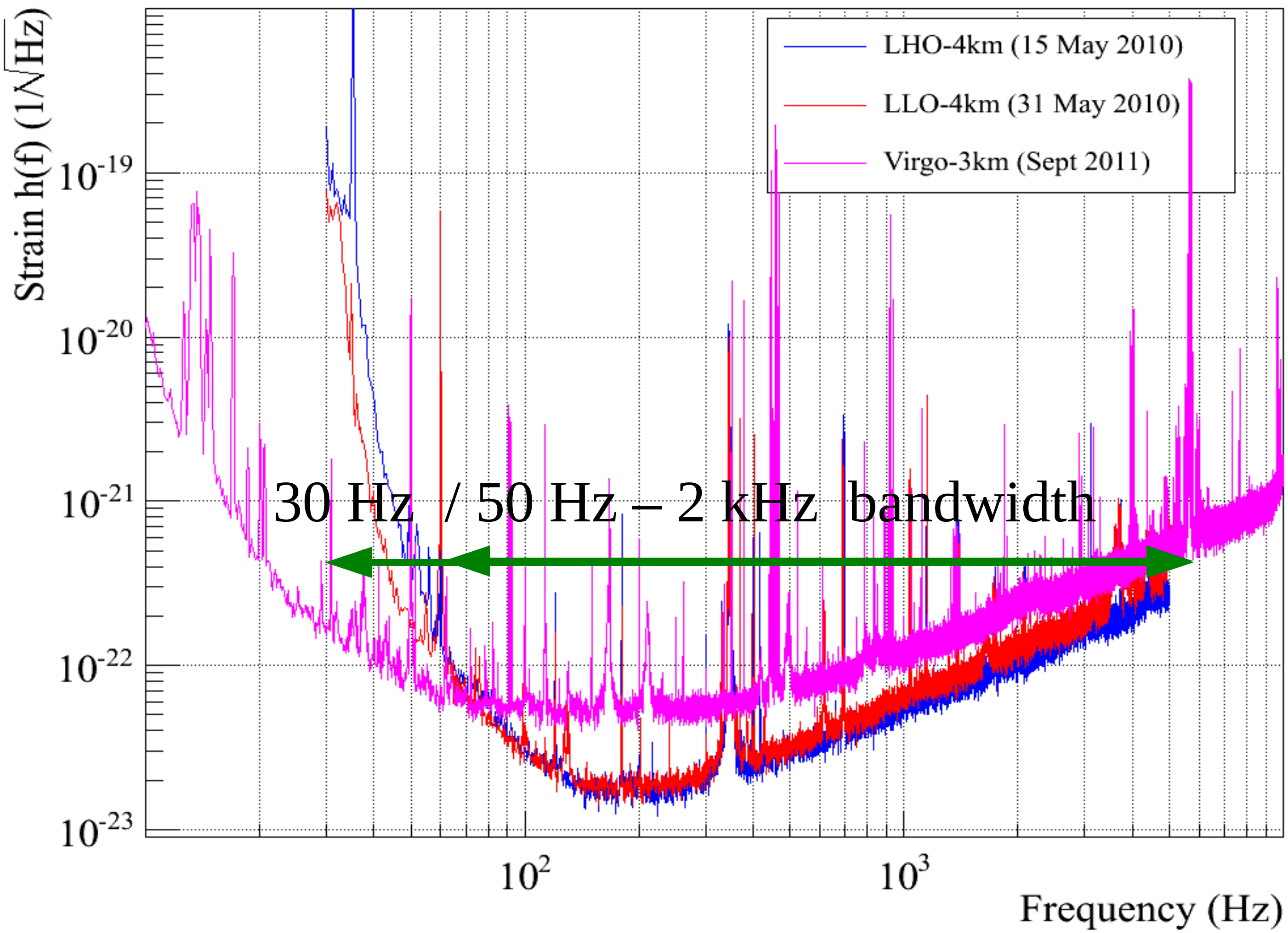
Network of ground based detectors



- Increase the detection confidence
- Source sky localization
- Source parameters inference
- GW polarization determination
- Astrophysics of the sources

Since 2007, LIGO, GEO & Virgo data are jointly analyzed by the LIGO Scientific Collaboration and the Virgo Collaboration.

GW detectors' sensitivities

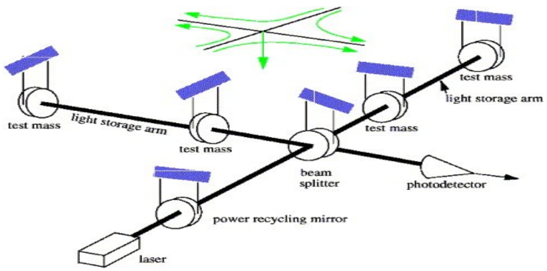


Best noise spectrum achieved by LIGO Hanford, LIGO Livingston and Virgo.

Sky localization :
tens of square degrees

Range of detections for binary neutron stars :
40 Mpc - LIGO
20 Mpc - Virgo

Outline



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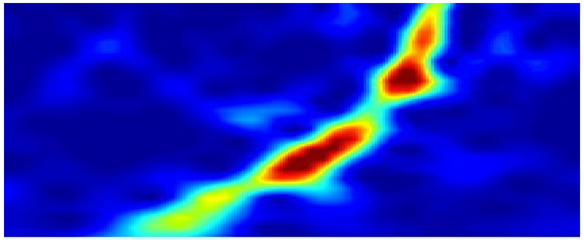

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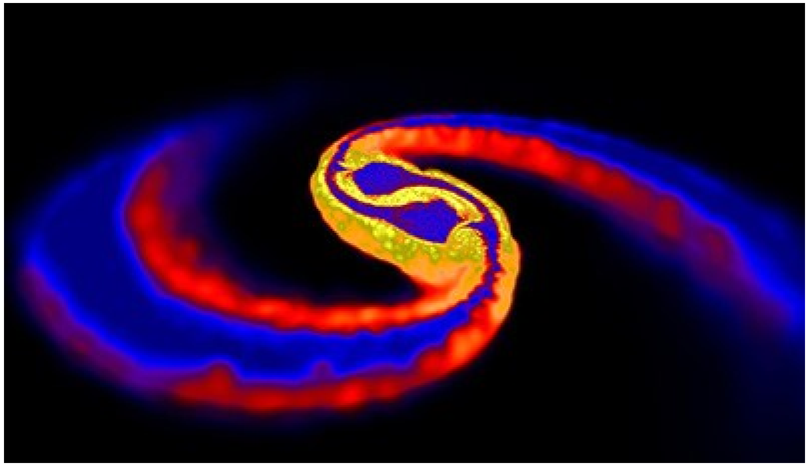
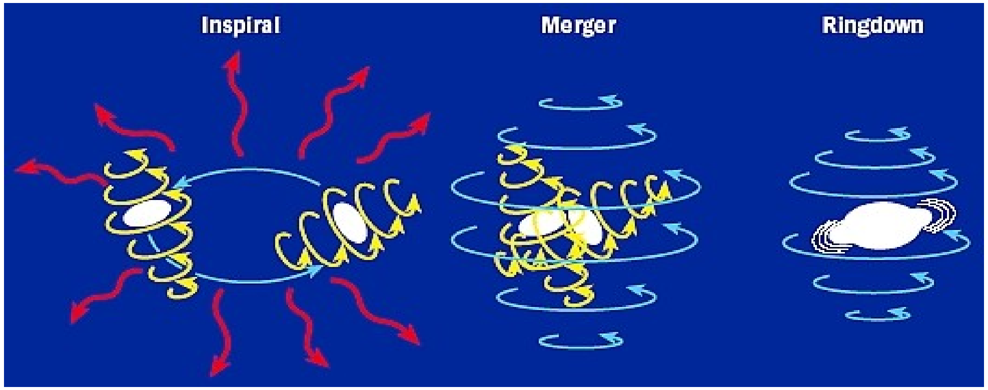
Compact binary systems



Daniel Price (U/Exeter) and Stephan Rosswog (Int. U/Bremen)

GWs from coalescing compact binary systems (NS/NS, NS/BH, BH/BH)

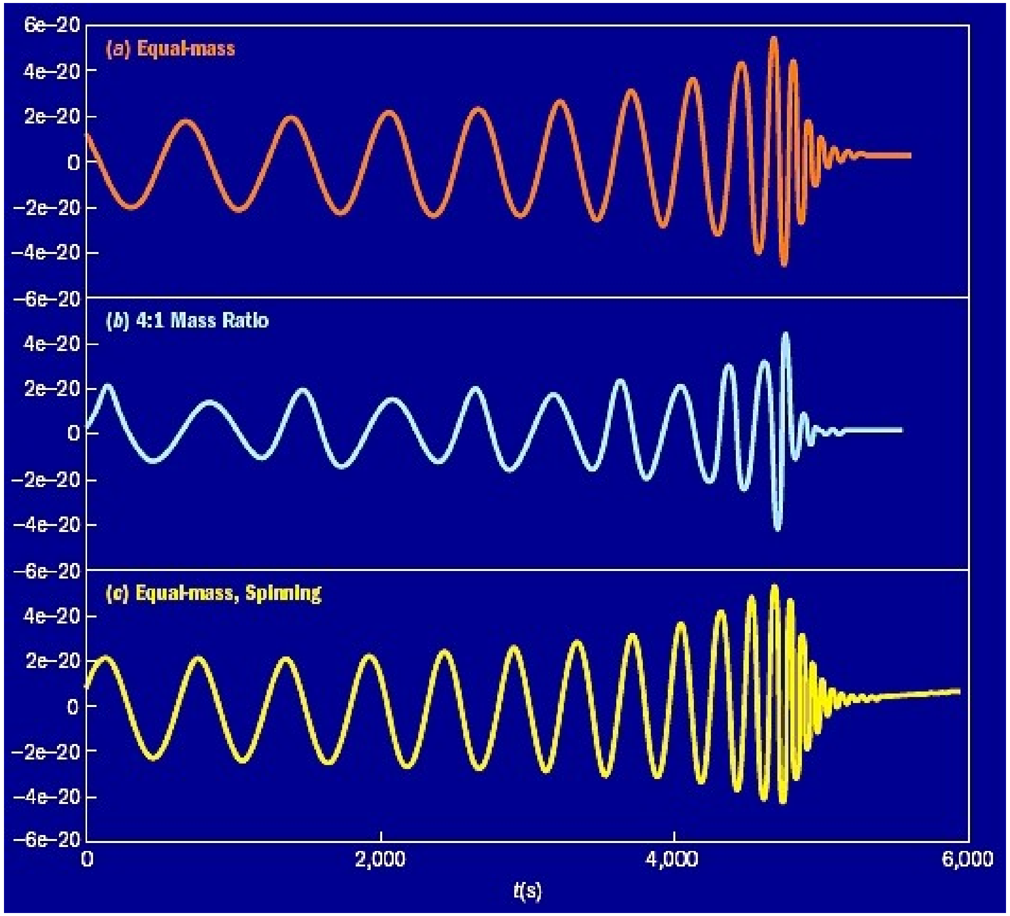
What can LIGO-Virgo detect? The last minutes of the coalescence, the merger and the ring-down for a certain regime of masses [1 M⊙ – 400 M⊙]



Unique way to study strong field GR, nuclear matter effects in extreme conditions (NS tidal disruption)

Complete (inspiral, merger, ringdown) waveforms available

→ template bank matched filtering search



[Credit: GWAL NASA's Goddard Space Flight Center]

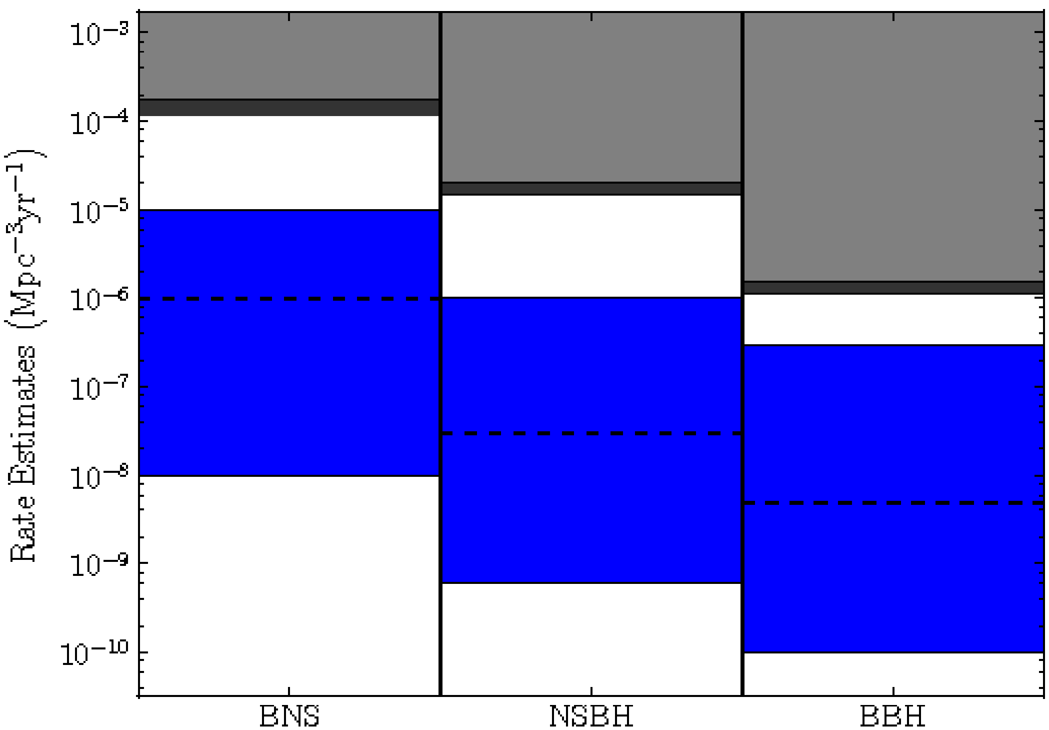
S6/VSR2-3 low mass CBC search

Phys. Rev. D 85, 082002 (2012)

- Search for 2-25 $M_\odot$ total mass CBC
- PN restricted waveforms
- No evidence for a GW signal
- 90% upper limits on the events rate

BH: 5 $M_\odot$

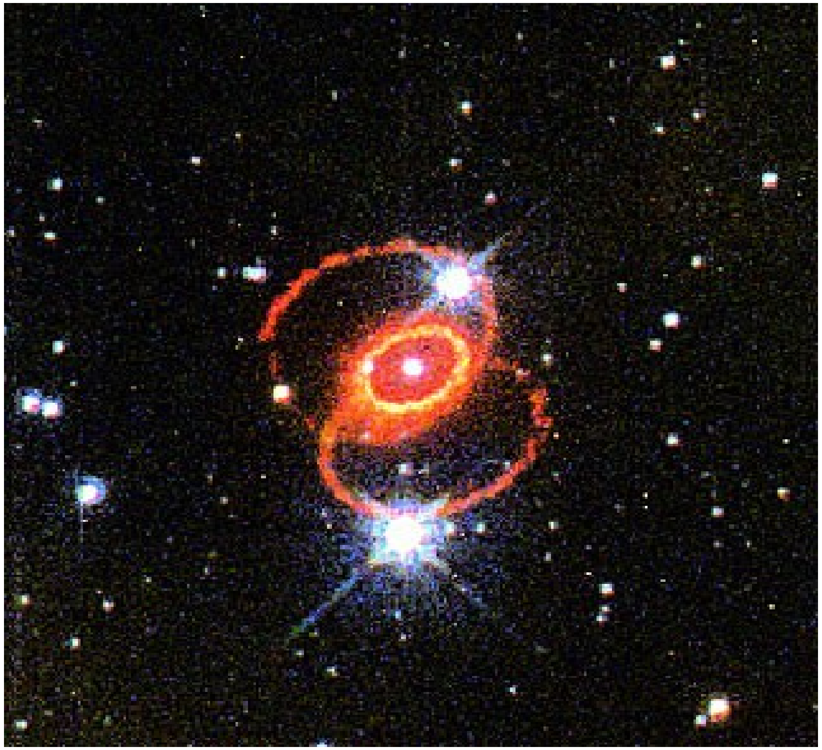
NSNS: 1.3 x 10^{-4} Mpc^{-3} yr^{-1}
NSBH: 3.1 x 10^{-5} Mpc^{-3} yr^{-1}
BHBH: 6.4 x 10^{-6} Mpc^{-3} yr^{-1}



Still 2 orders of magnitude above "realistic" rate

BH: 10 $M_\odot$

Un-modelled burst searches



1987A supernova seen by Hubble telescope

George Sonneborn (Goddard Space Flight Center), Jason Pun (NOAO), the STIS Instrument Definition Team, and NASA/ESA

“Un-modelled” GW transient searches

All-sky/all-time searches: to get all kind of short (<1s) GW signals happening any time: core collapse supernova, intermediate black hole mergers, still unkown source ...

Triggered searches:

- GRB: 39 GRBs during S2/S3/S4, 137 during S5/VSR1, 150 during S6/VSR2+3, GRB 030329, GRB 070201, GRB 051103.
- Magnetar flare GW burst searches: SGR 1806–20 giant flare QPO search, SGR 1900+14 storm “stack” search. GW bursts from flares emitted by six different magnetars.
- Bursts associated with (Vela) pulsar glitches.
- Burst associated with core collapse supernovae.
- Burst associated with high-energy neutrinos.

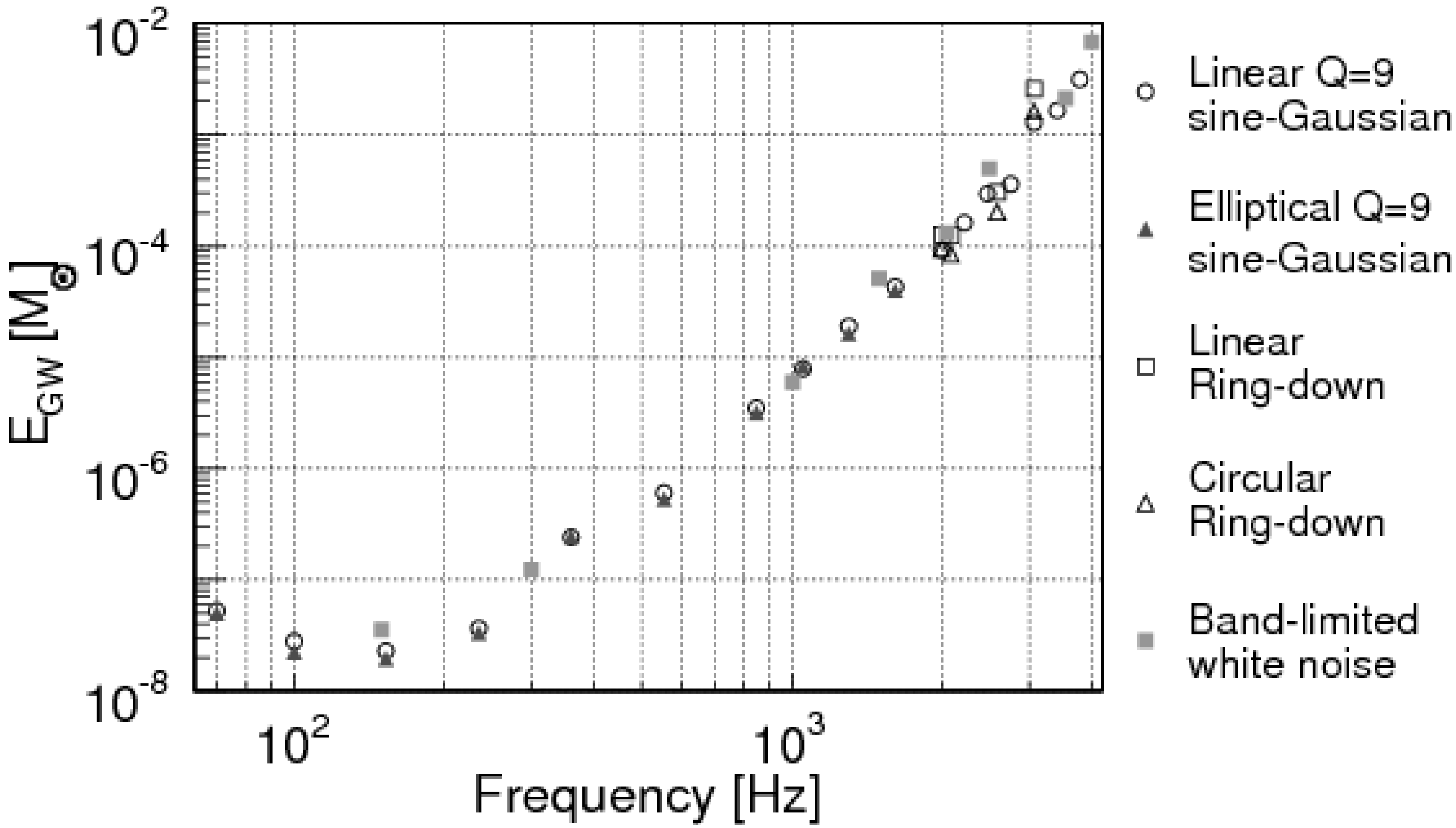
Search sensitivity in energy units

Phys. Rev. D 85 (2012) 122007

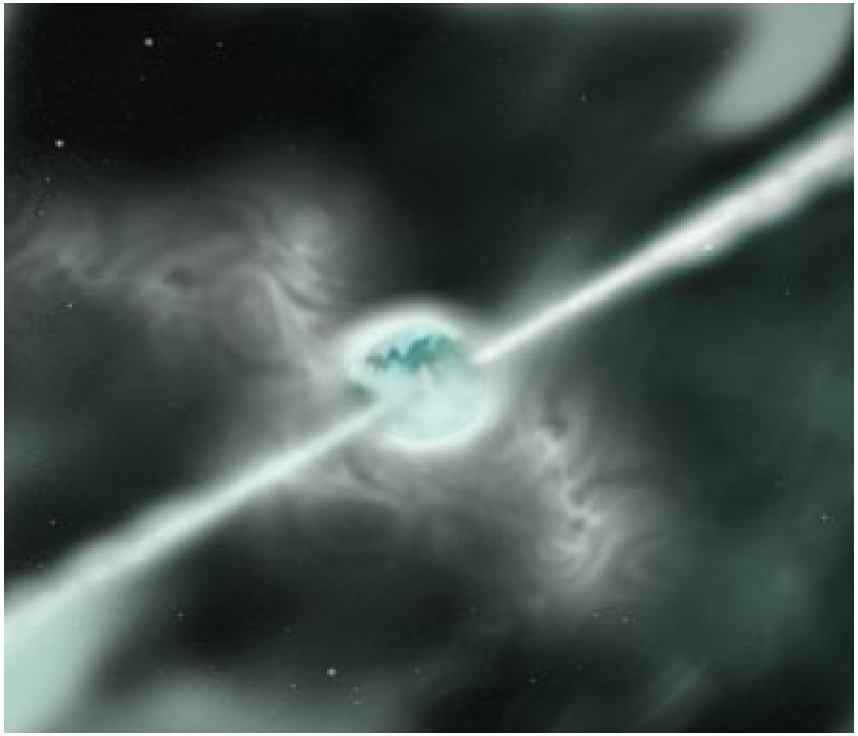
GW energy emission assuming a Galactic source (10 kpc) that could have been detected with 50% efficiency

$$E_{\rm GW} = \frac{r^2 c^3}{4G} (2\pi f_0)^2 h_{\rm rss}^2$$

d=10 kpc → E_{GW} ~10^{-8} M_{sun} c^2 → CCSN
d=15 Mpc → E_{GW} =10^{-1} M_{sun} c^2 → BBH

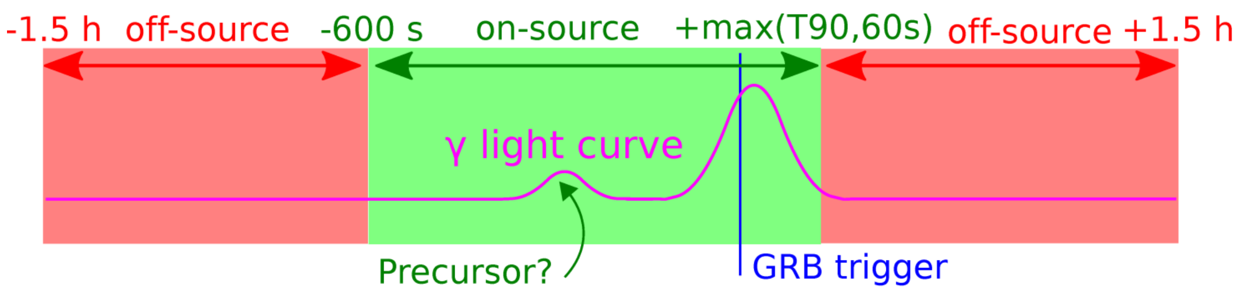


GW transient triggered searches

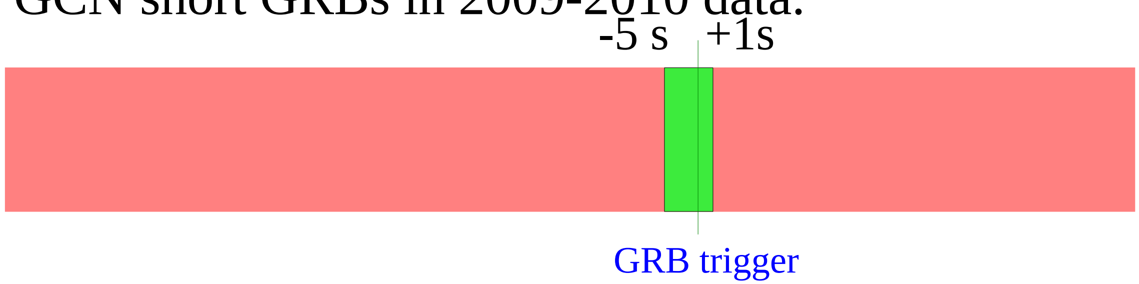


Triggered searches: GRB-GW searches

- Study ~300 GRBs since 2003 (Swift & Fermi mainly)
- Long-soft GRB – GW "un-modelled" burst search
  - Possible "collapsar" progenitor → poorly modelled.
  - Strongly beamed + rotation → circularized polarized.
  - 150 GCN long GRBs in 2009-2010 data.

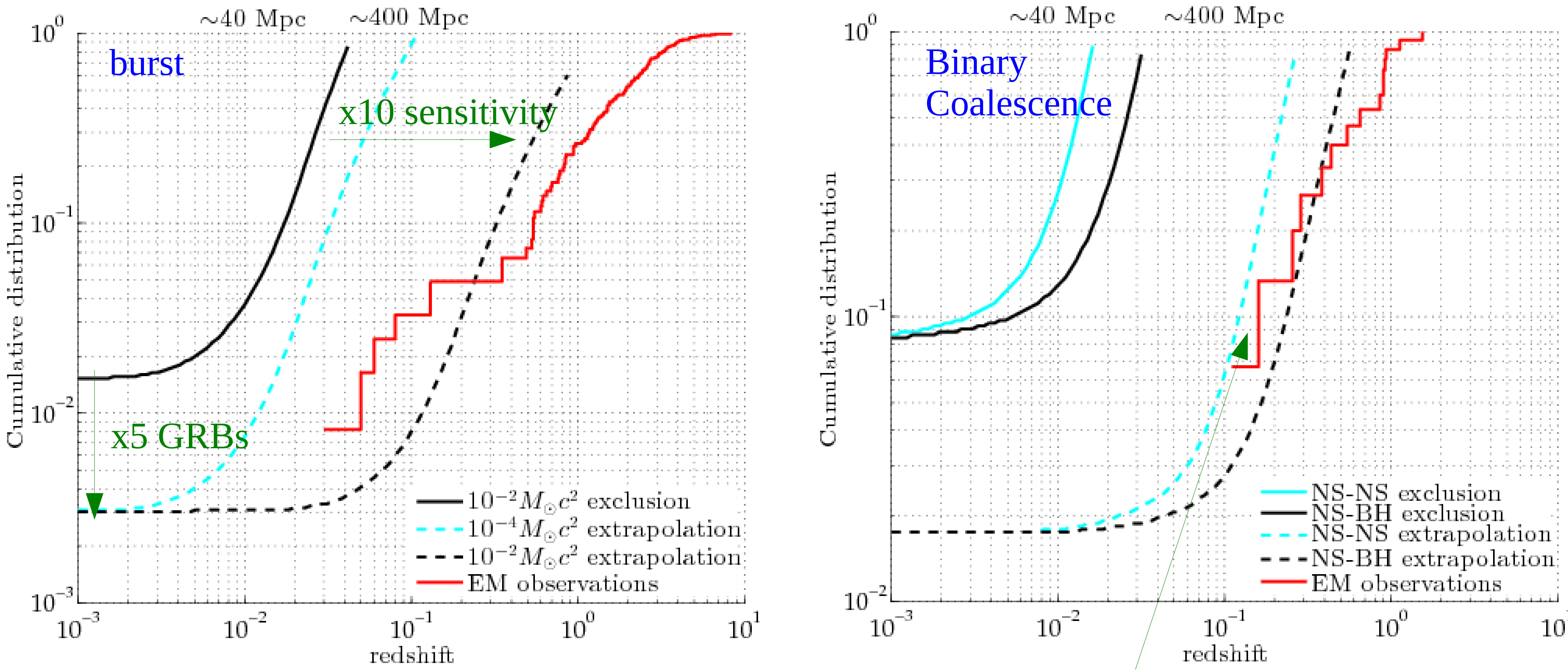


- Short-hard GRB – GW NSNS and NSBH search
  - Possible binary merger progenitors → NSNS and NSBH waveforms.
  - Beamed?
  - 26 GCN short GRBs in 2009-2010 data.



GRB-GW searches – results & prospectives

Astrophys. J. 760, 12 (2012)



No subset of the most significant GRB stands out compared to the background.

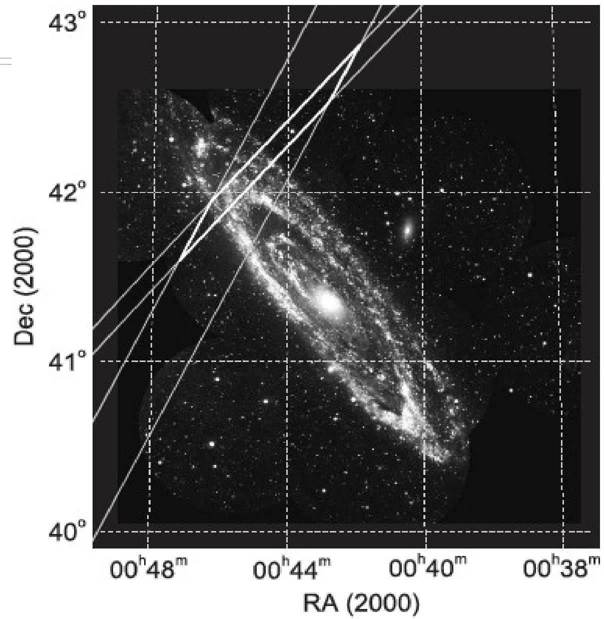
Short-hard GRB: with advanced detectors, we will be sensitive to events seen by EM observations!

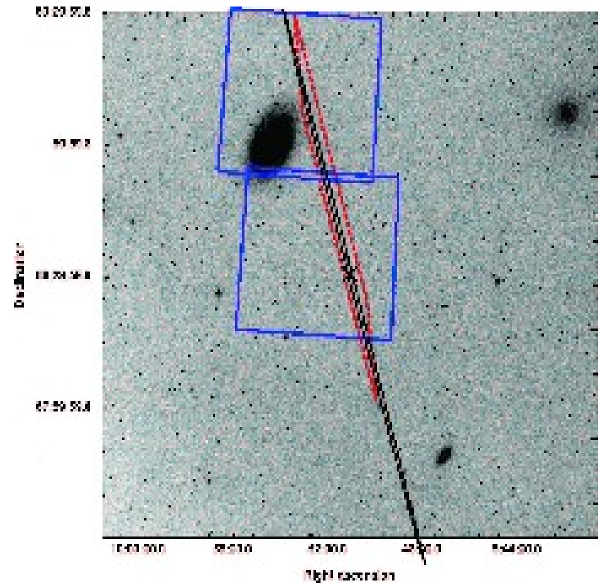
GRB 070201 / GRB 051103

Astrophys. J. 755, 2 (2012) / Astrophys. J. 681, 1419 (2008)

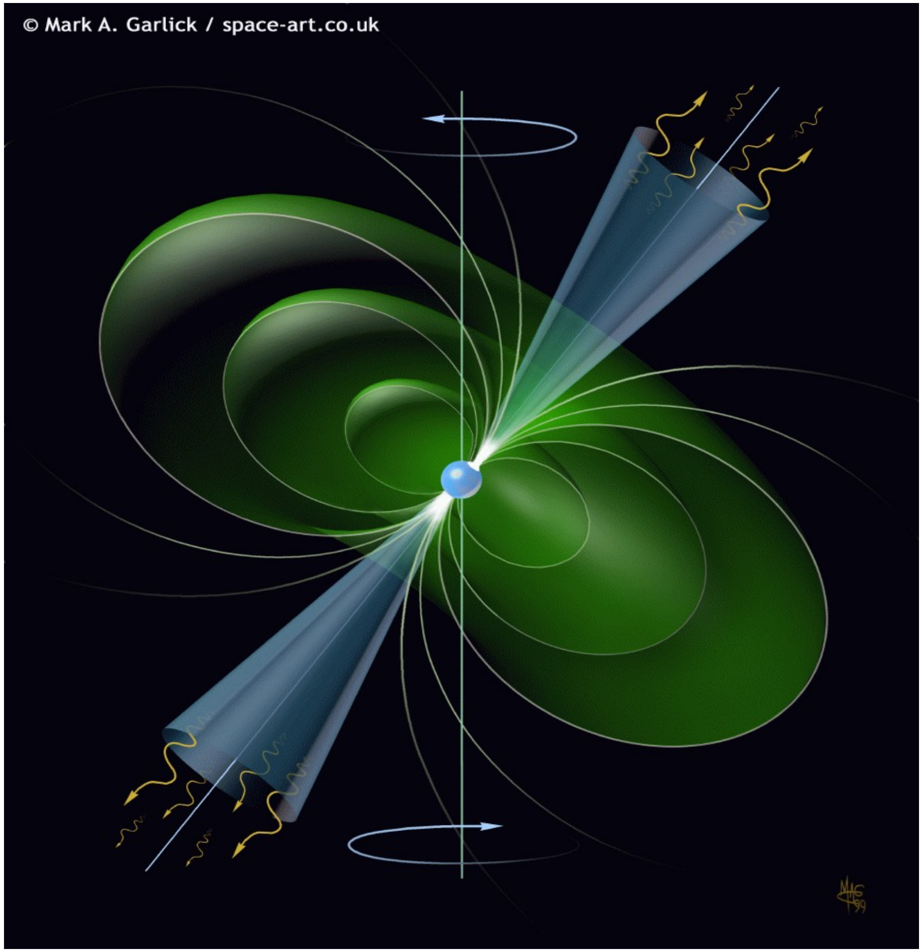
Significant non-detection results

- Short GRBs search.
  - GRB 070201 overlaps M31 (0.77 Mpc).
  - GRB 051103 overlaps M81 (~3.6 Mpc).
- No GW found.
  - Binary coalescence in M31 excluded at 99% CL and 98% CL in M81.
- Observations compatible with:
  - SGR giant flare in M31/M81.
  - Coalescence in galaxy behind M31/M81.





Continuous GW searches



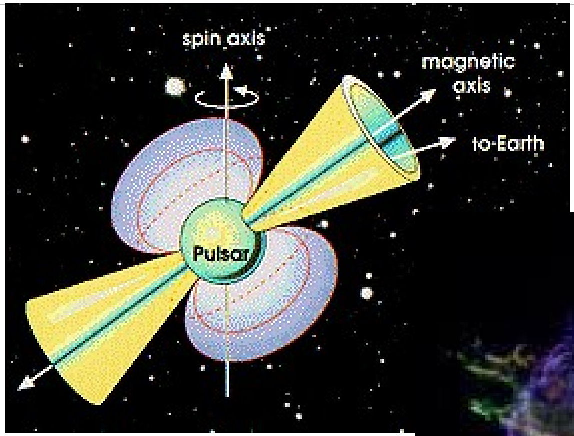
Pulsars and continuous GW sources

- GW emission: time-varying quadrupole can be generated by
  - Non-axisymmetric deformation (elastic stress and/or magnetic fields in NS crust/core).
  - GW driven instabilities of normal oscillation modes (r-modes, f-modes CFS).
  - Matter accretion.
- GW signal: long-lasting (permanent) quasi-monochromatic signals at $f=2f_{rot}$ (or f_{rot}). Typical amplitude:

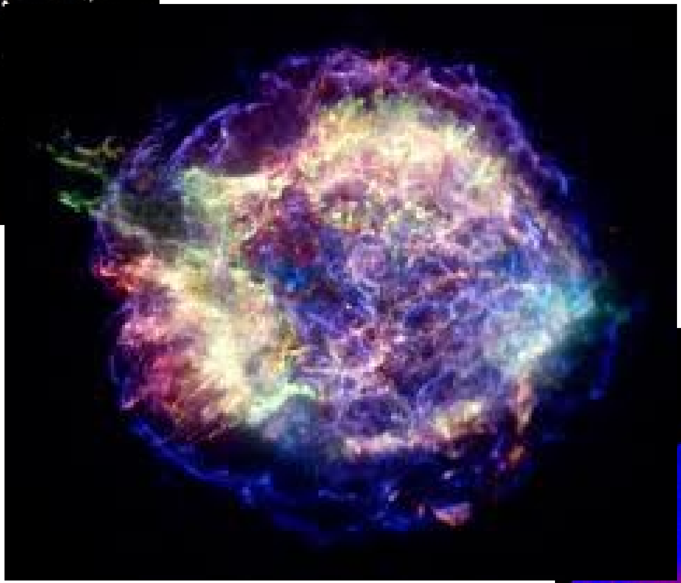
$$h = 4 \times 10^{-25} \left(\frac{\epsilon}{10^{-6}}\right) \left(\frac{I}{10^{45}\ \mathrm{g\ cm}^2}\right) \left(\frac{f}{100\ \mathrm{Hz}}\right)^2$$

- Theoretical maximal values for ε: Normal matter: $\varepsilon \leq 10^{-7} - 10^{-6}$
  Quark matter: $\varepsilon \leq 10^{-5} - 10^{-4}$
- Actual values?: ms pulsars low period derivatives observations → $\varepsilon < 10^{-8}$

Continuous wave searches

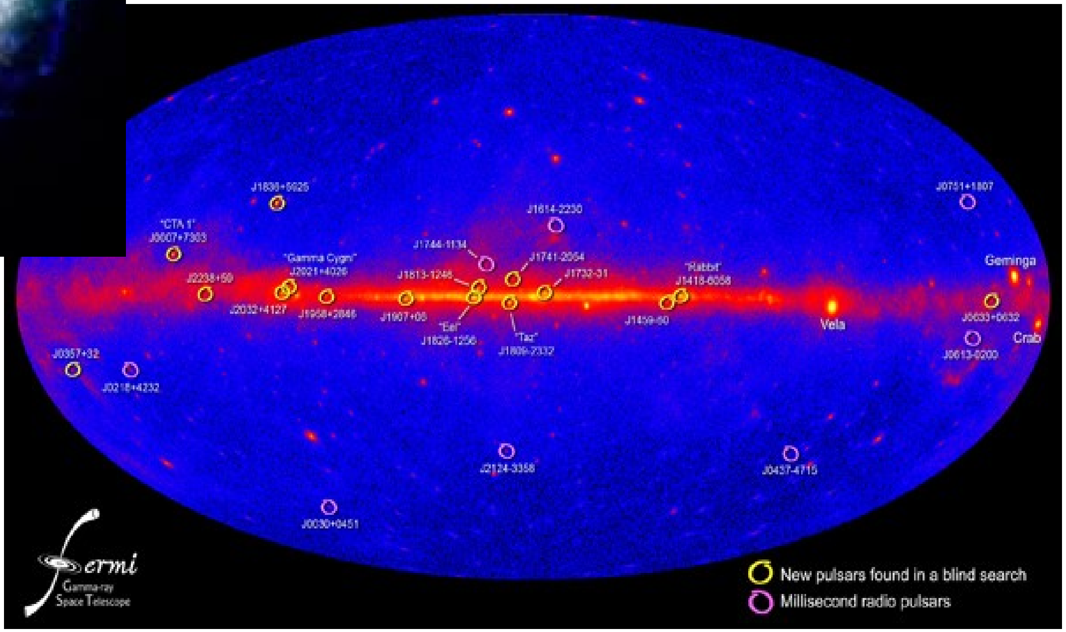


Targeted searches: Crab, Vela, etc ...



Cas A / Chandra

Directed searches: known position,
unknown frequency



All-sky searches: wide parameter space
The presence of a companion adds complexity!

Continuous waves: targeted searches

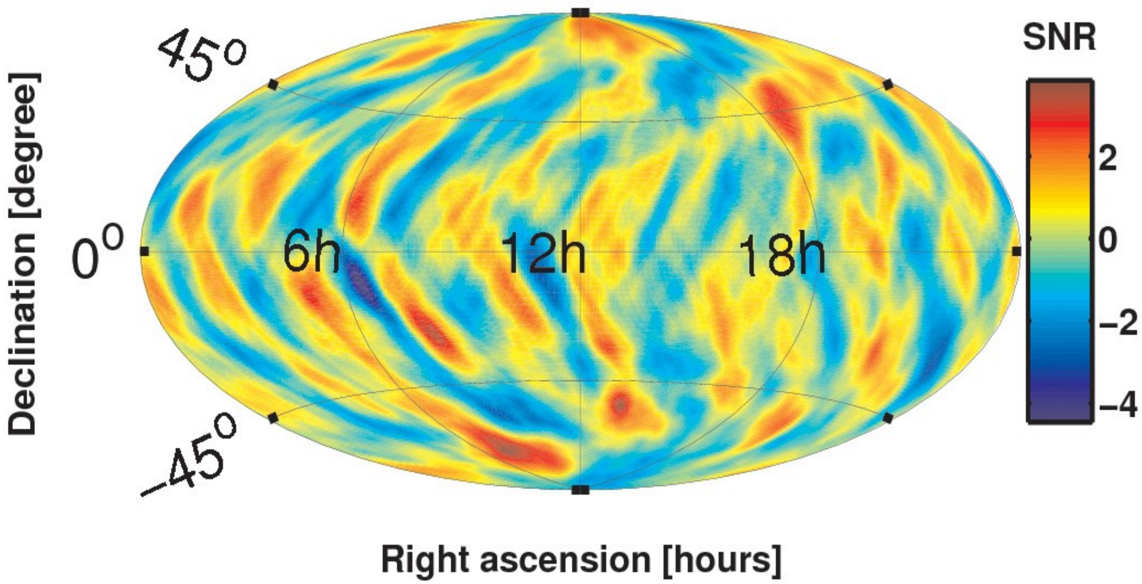
Astrophys. J. 737 (2011) 93, Astrophys. J. 713 (2010) 671

- ~120 (young) pulsars have been studied in LIGO/Virgo data
- Upper limit on the GW strain have been derived:
  - Spin-down upper limit has been beaten for few pulsars:

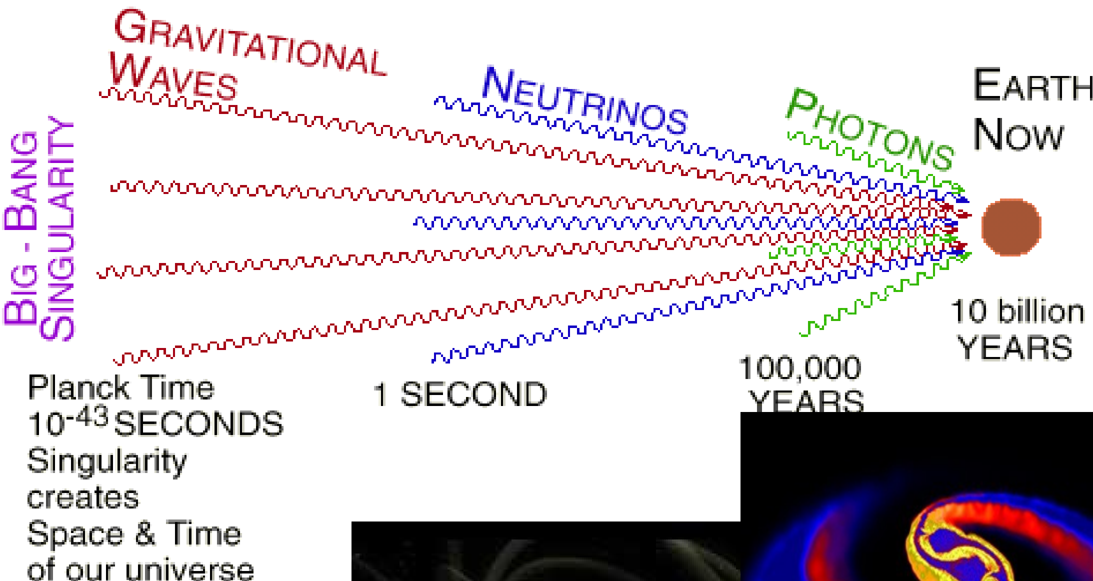
Pulsar name	$h_0^{95\%}$	$\epsilon^{95\%}$	$h_0^{95\%}/h_{sd}$	Fraction of energy loss due to GW emission
Crab (29.78 Hz)	2.4×10^{-25}	1.3×10^{-4}	0.15	$< 2\%$
Vela (11.2 Hz)	$2.2 - 2.4 \times 10^{-24}$	$1.19 - 1.30 \times 10^{-3}$	0.7	$< 35\%$

  - Lowest upper-limit on amplitude: 2.3×10^{-26} (PSR J1603-7202)
  - Lowest upper-limit on ellipticity: 7.0×10^{-8} (PSR J2124-3358)

Stochastic GW background searches



Stochastic GW background searches



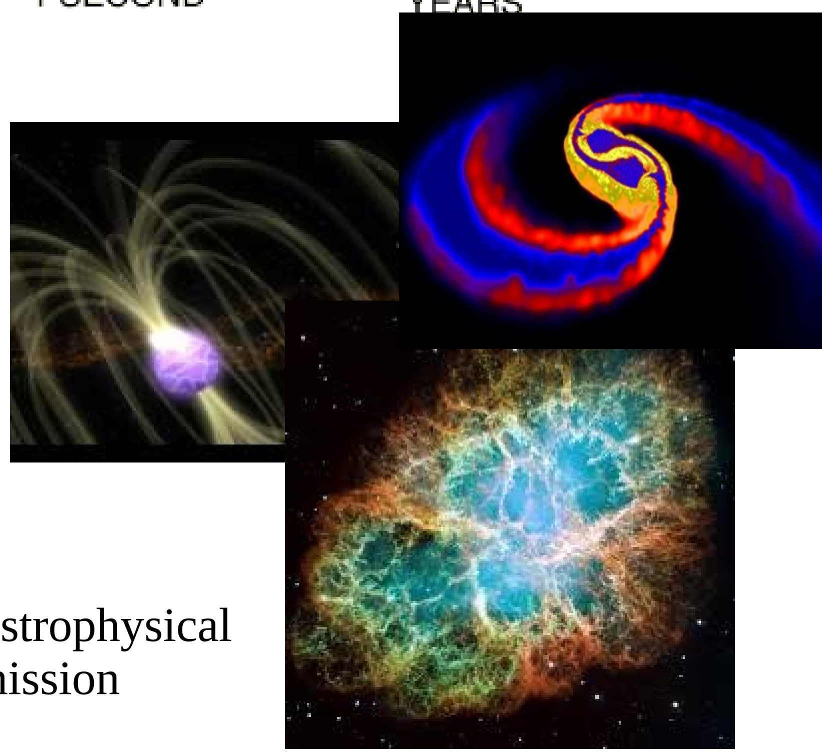
What do we try to measure?

$$\Omega_{GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$$

$$\Omega_{GW} = A(f/f_{ref})^{\alpha}$$

How?

Correlation between pairs of detectors



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Unresolved astrophysical GW emission

The SGWB analyses probe the history of the universe …

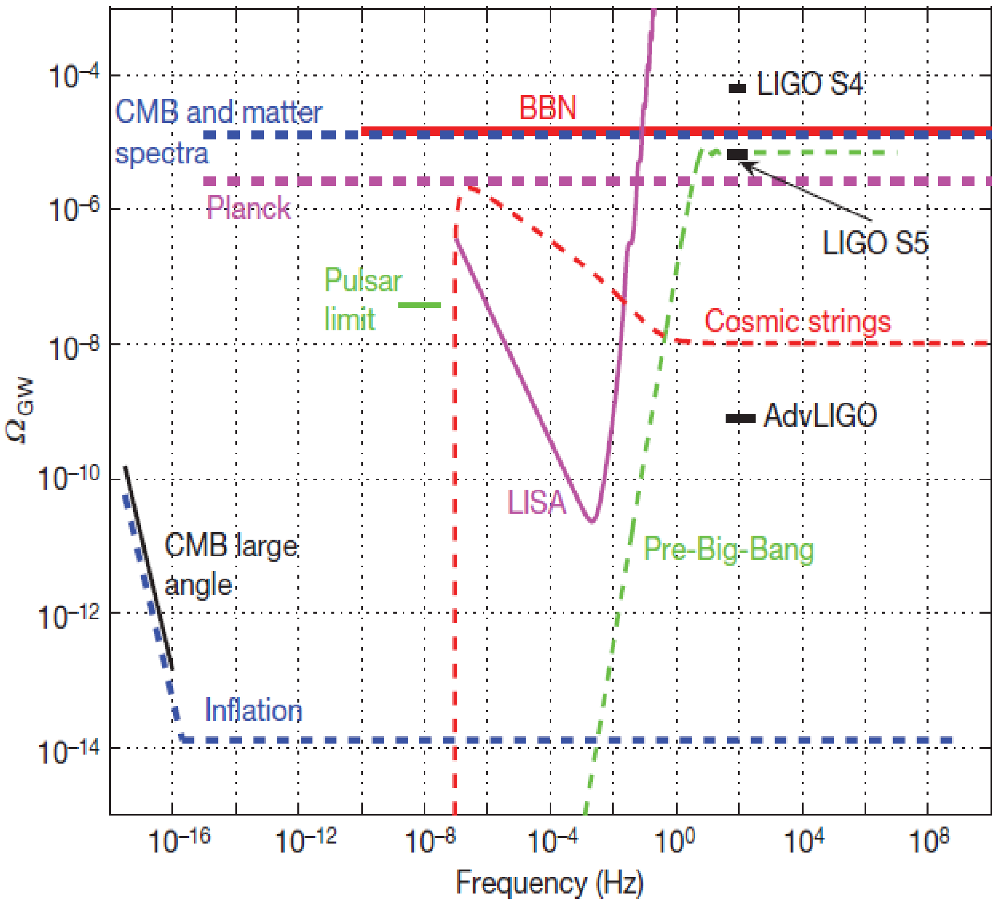
Stochastic GW background: isotropic search results

Nature 460 (2009) 990, PRD 85 (2012) 122011

- LIGO S5 only observations (most sensitive at low frequency)
- LIGO S5 limit $\Omega_{GW} < 6.9 \times 10^{-6}$ (41-169 Hz, α=0), a result that improves on the indirect limits from Big Bang Nucleosynthesis (BBN) and CMB.
- LIGO S5, Virgo VSR1 limit (test of high frequency region)

$$\Omega_{GW} = \Omega_3 (f/900\text{Hz})^3$$

$$\Omega_3 < 0.32 \text{ (600-1000 Hz, } \alpha=3)$$



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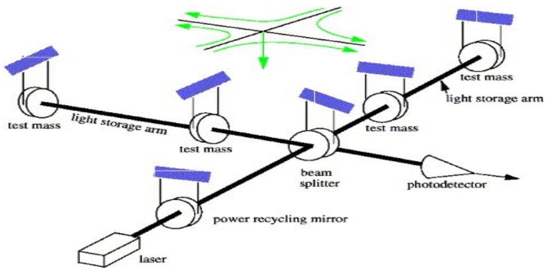

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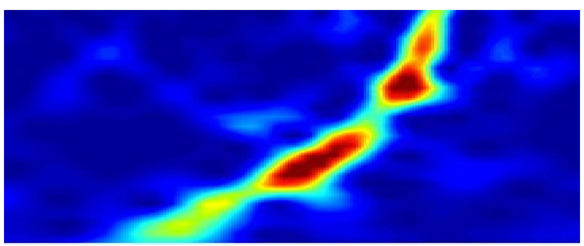

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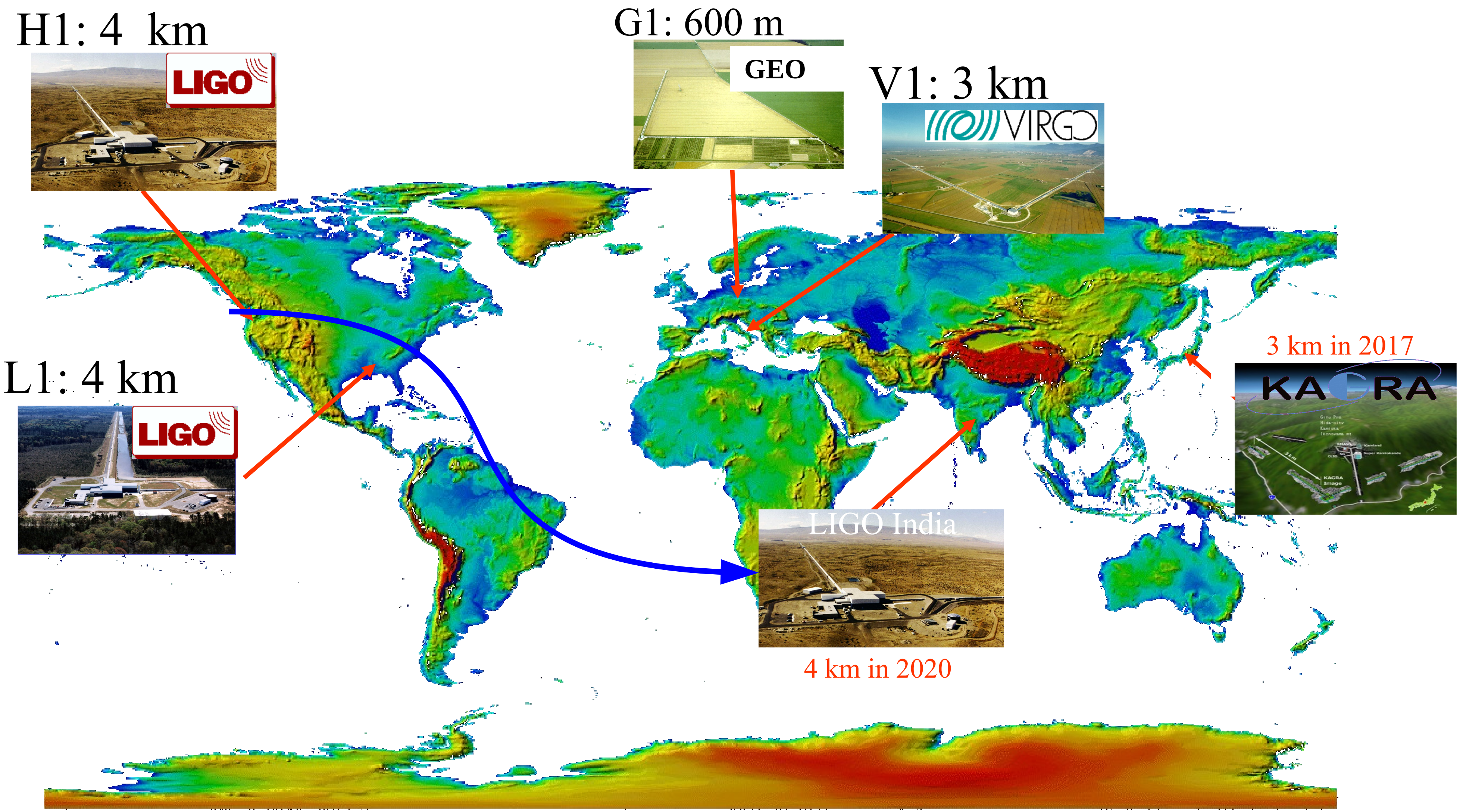
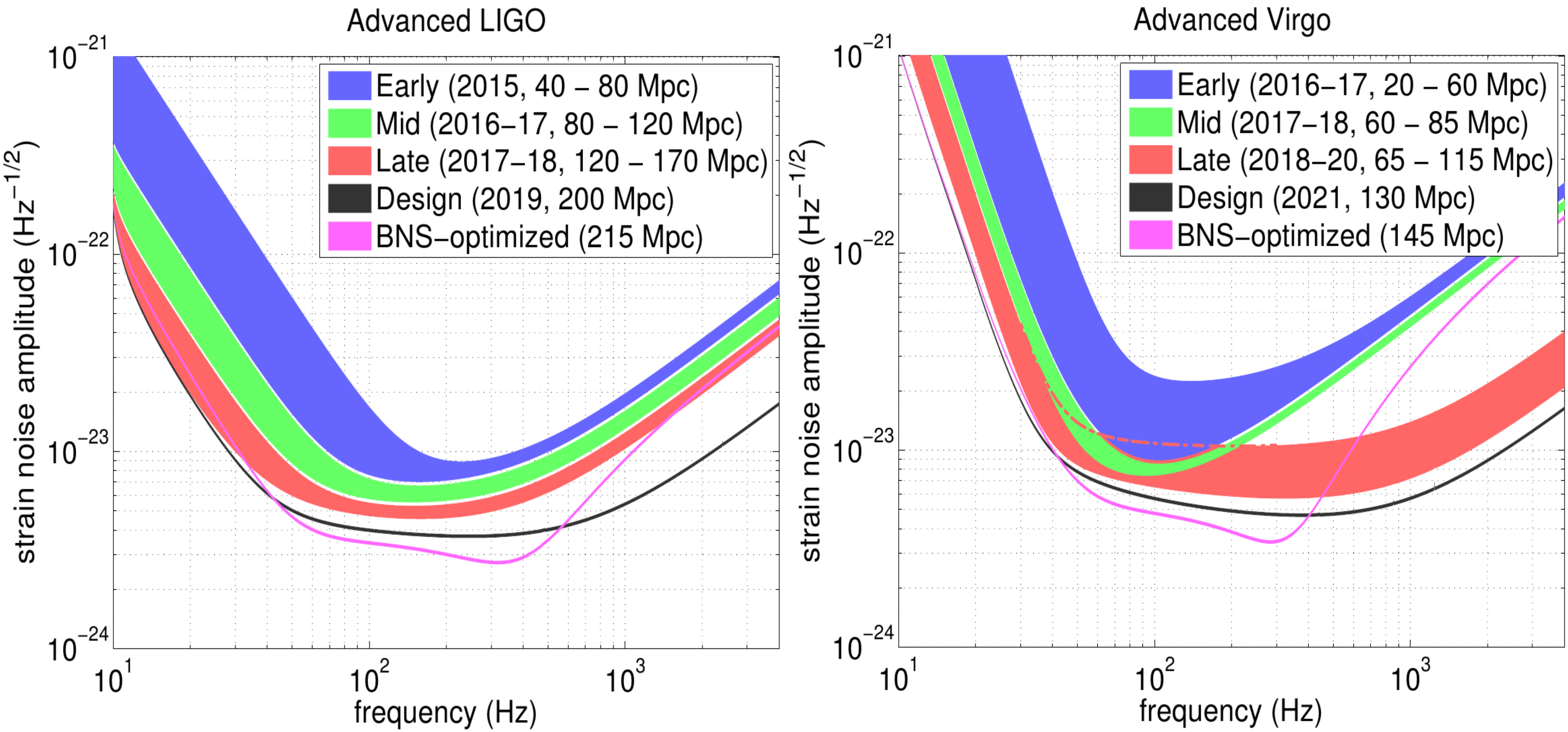
The GW detectors networks in the next decade



Advanced detectors sensitivities

arXiv:1304.0670



distance x 10 → volume x 10^3

Compact binary rate expectation

ArXiv:1304.0670 + CQG 27 173001 (2010)

Epoch	Estimated Run Duration	Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within	
		LIGO	Virgo	LIGO	Virgo		5 deg^2	20 deg^2
2015	3 months	40 – 60	—	40 – 80	—	0.0004 - 3	-	-
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 - 20	2	5-12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 - 100	1-2	10-12
2019+	(per year)	105	40 – 70	200	65 – 130	0.2 - 200	3-8	8-28
2022+ (India)	(per year)	105	80	200	130	0.4 - 400	17	48

@ designed sensitivity : ~40 BNS / year

Compact binary rate expectation

ArXiv:1304.0670 + CQG 27 173001 (2010)

Epoch	Estimated Run Duration	Burst Range (Mpc) LIGO	Burst Range (Mpc) Virgo	BNS Range (Mpc) LIGO	BNS Range (Mpc) Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	% BNS Localized within 20 deg^2
2015	3 months	40 – 60	—	40 – 80	—	0.0004 - 3	-	-
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 - 20	2	5-12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 - 100	1-2	10-12
2019+	(per year)	105	40 – 70	200	65 – 130	0.2 - 200	3-8	8-28
2022+ (India)	(per year)	105	80	200	130	0.4 - 400	17	48

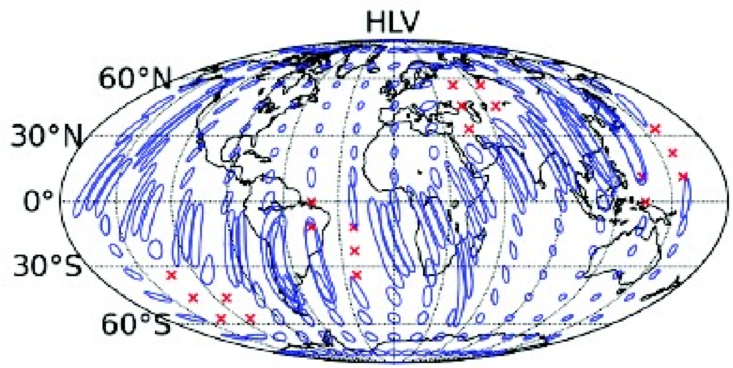
First discovery in 2016?

Need to be lucky for
EM follow-up ?

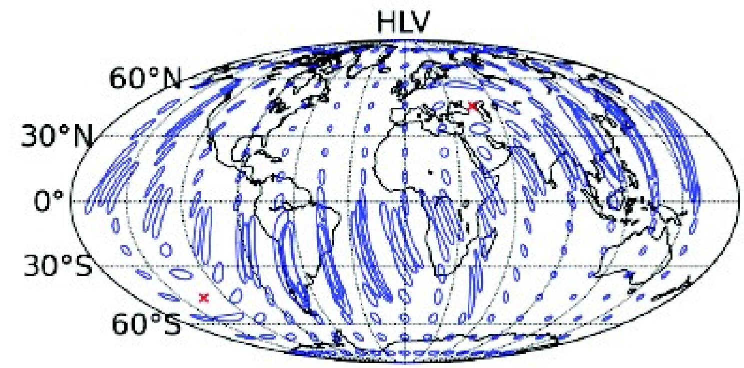
Advanced LIGO/Virgo sky localization

BNS source @ 80 Mpc

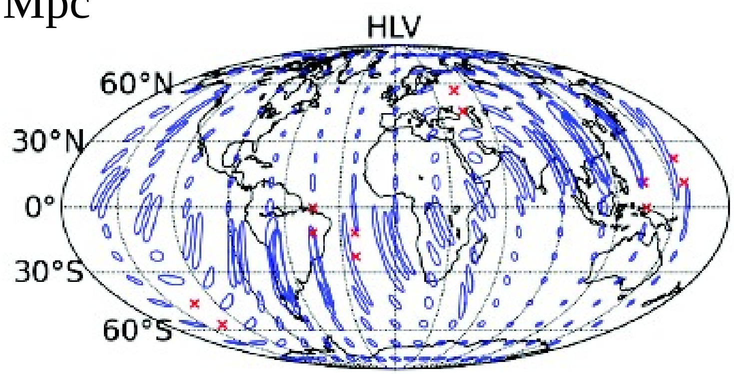
2016-2017 runs

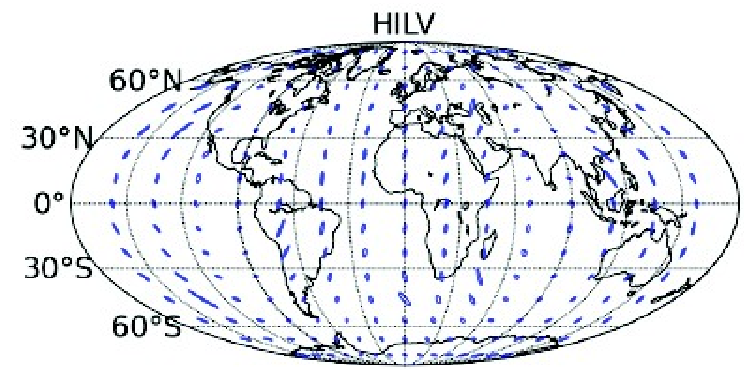


2018-2019 runs



BNS source @ 160 Mpc





2019+ runs

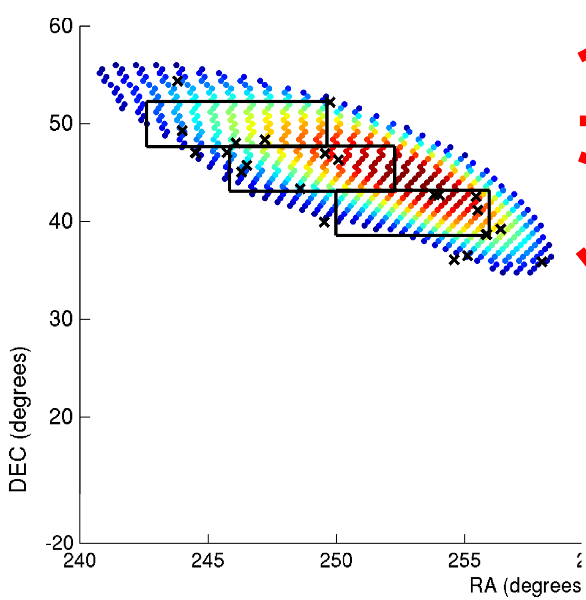
HLV + LIGO India 2022+

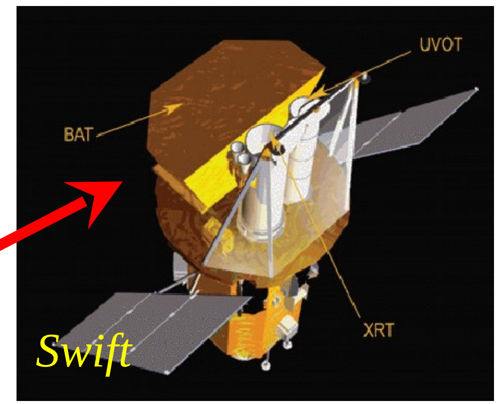
Electromagnetic follow-ups to GW triggers

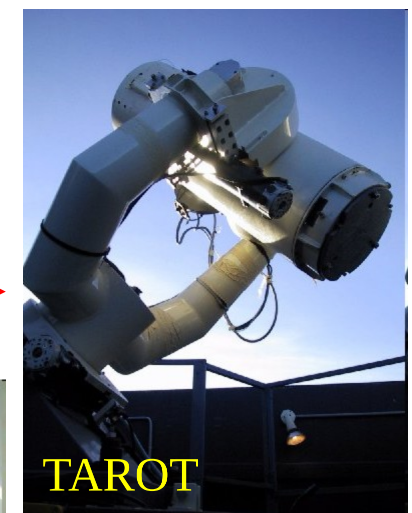
ApJ. L. 734:L35 (2011)

Analyze GW data promptly to identify possible event candidates and reconstruct their apparent sky position → send alerts to telescopes

Try to capture an EM transient that would otherwise have been missed!
First tests during S6/VSR3 runs







Other telescopes...

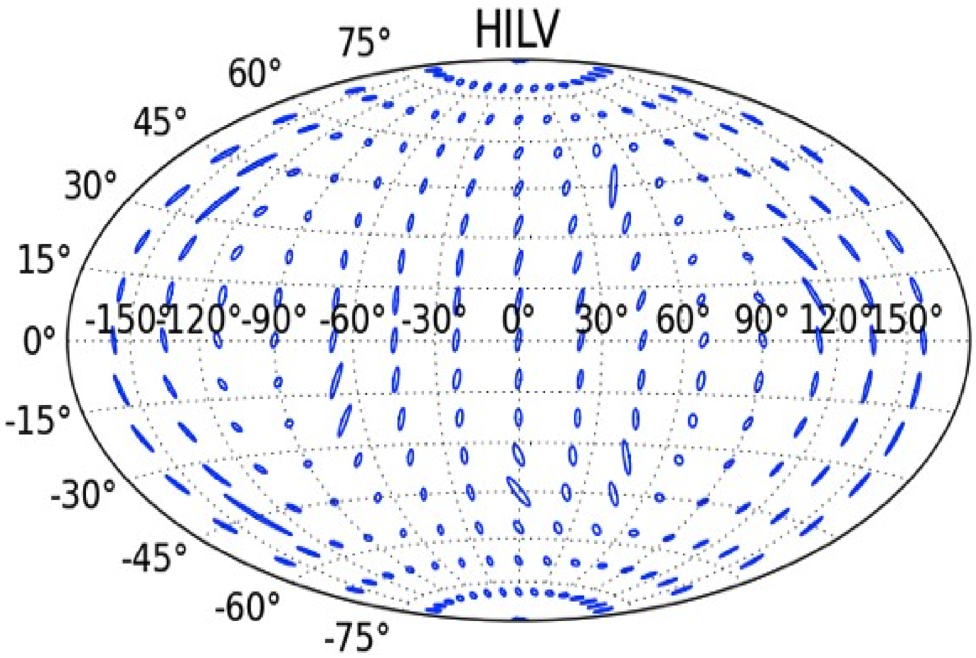
Conclusion: beyond the first detection

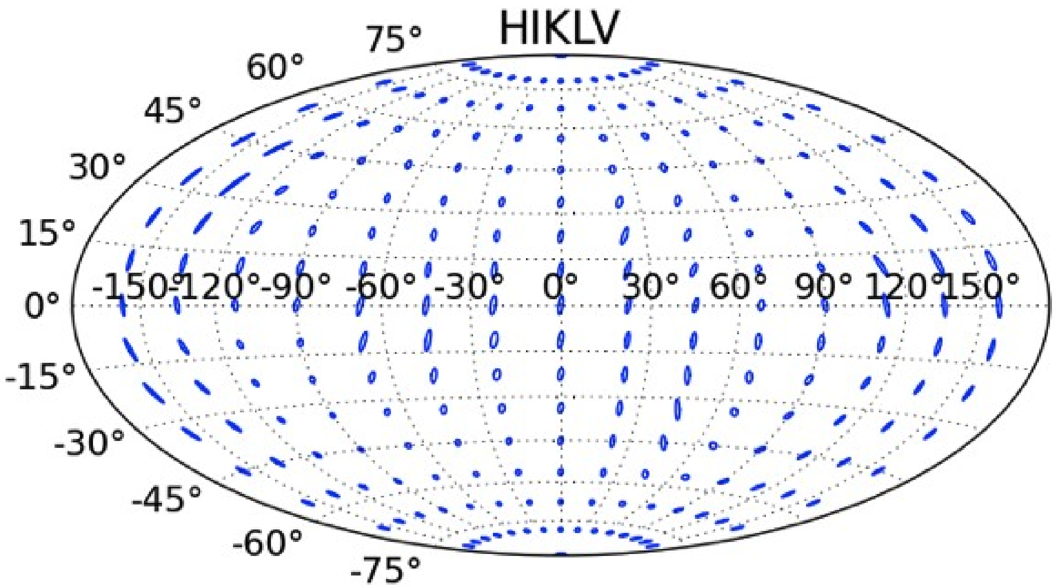
- Source parameter estimation/inverse problem:
  - All sources concerned (compact binaries, core collapse, stochastic, pulsar...)
  - Derive information about the progenitors (GRB engine, NS), effect of matter, EOS...
  - Infer source rate
- Test of General Relativity
  - No hair theorem
  - Test of PostNewtonian approximation (inspiral phase)
  - GW speed measurement
  - Hubble constant measurement (not as precise as CMB, but independent)
- Low latency transient GW searches with electro-magnetic follow-ups

Very exciting coming years … with great detectors!

Backup

Adding Kagra to the newtork





5 sites network :
Slightly better localization
Better sensitivity
Increase duty cycle !