Transient Gravitational-Wave Astronomy in 2015-2020: Challenges and Opportunities

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and the Virgo Collaboration

LIGO-G1200105

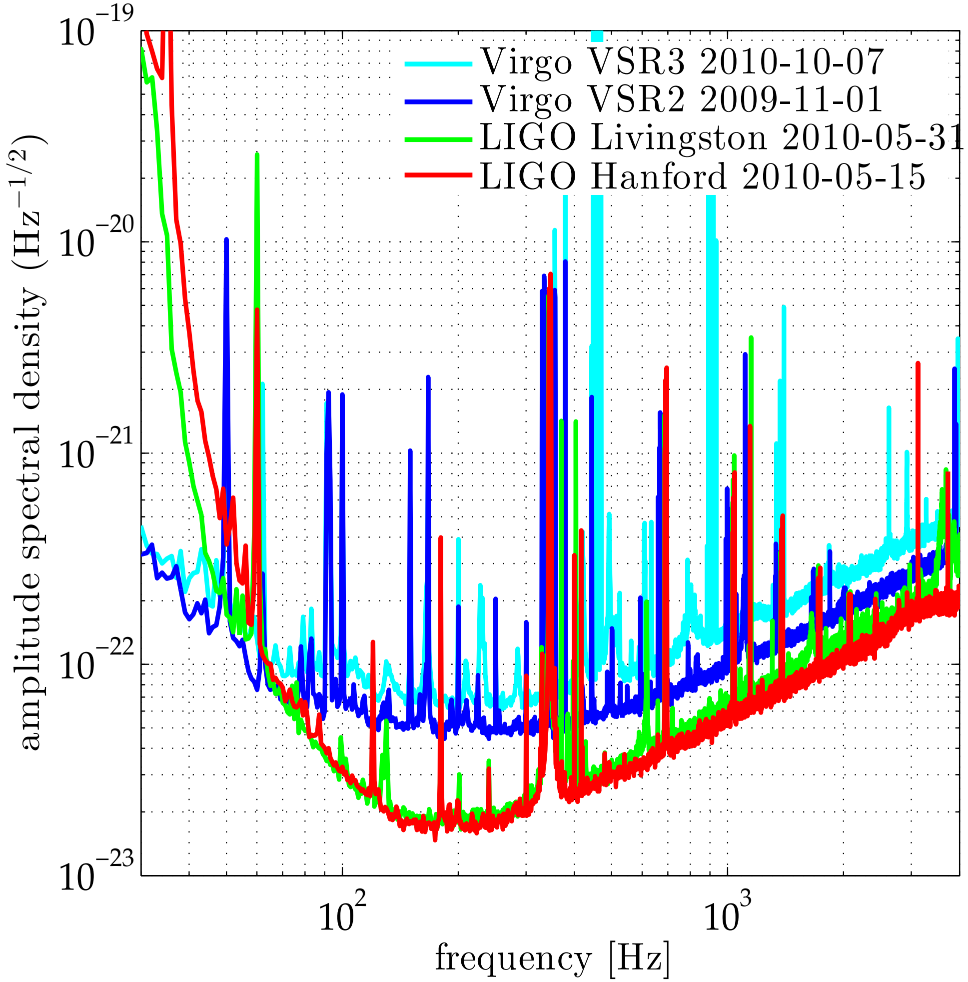
GWs as Astrophysical Probes

- GWs trace the bulk motion of their source
  - non-imaging
  - not scattered / absorbed.
- GW detectors are all-sky, low bandwidth.
  - archival searches: easy.
  - source localization: hard.
- Complementary to properties of photons.

GW Detectors: 2009-2010

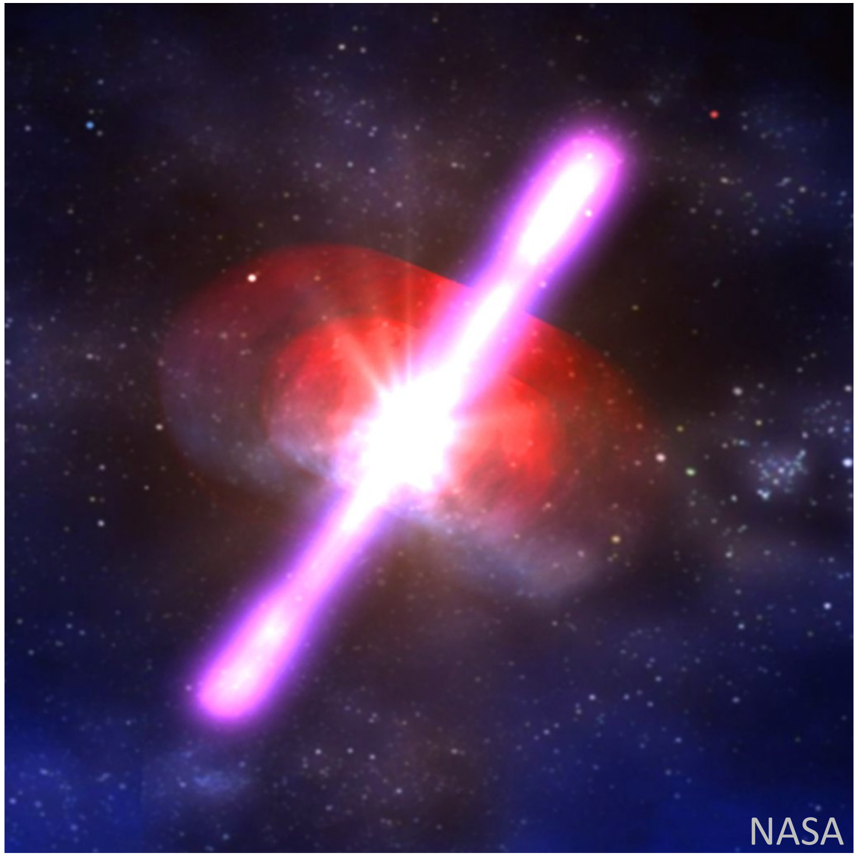
- LIGO's maximum range for binary coalescences:
  - neutron star – neutron star: 40 Mpc
  - neutron star – black hole: 90 Mpc
  - Virgo: about half that
- Expected detection rates < 1 yr^{-1}.

Abadie et al., [arXiv:1111.7314]
Abadie et al., [arXiv:1003.2480]



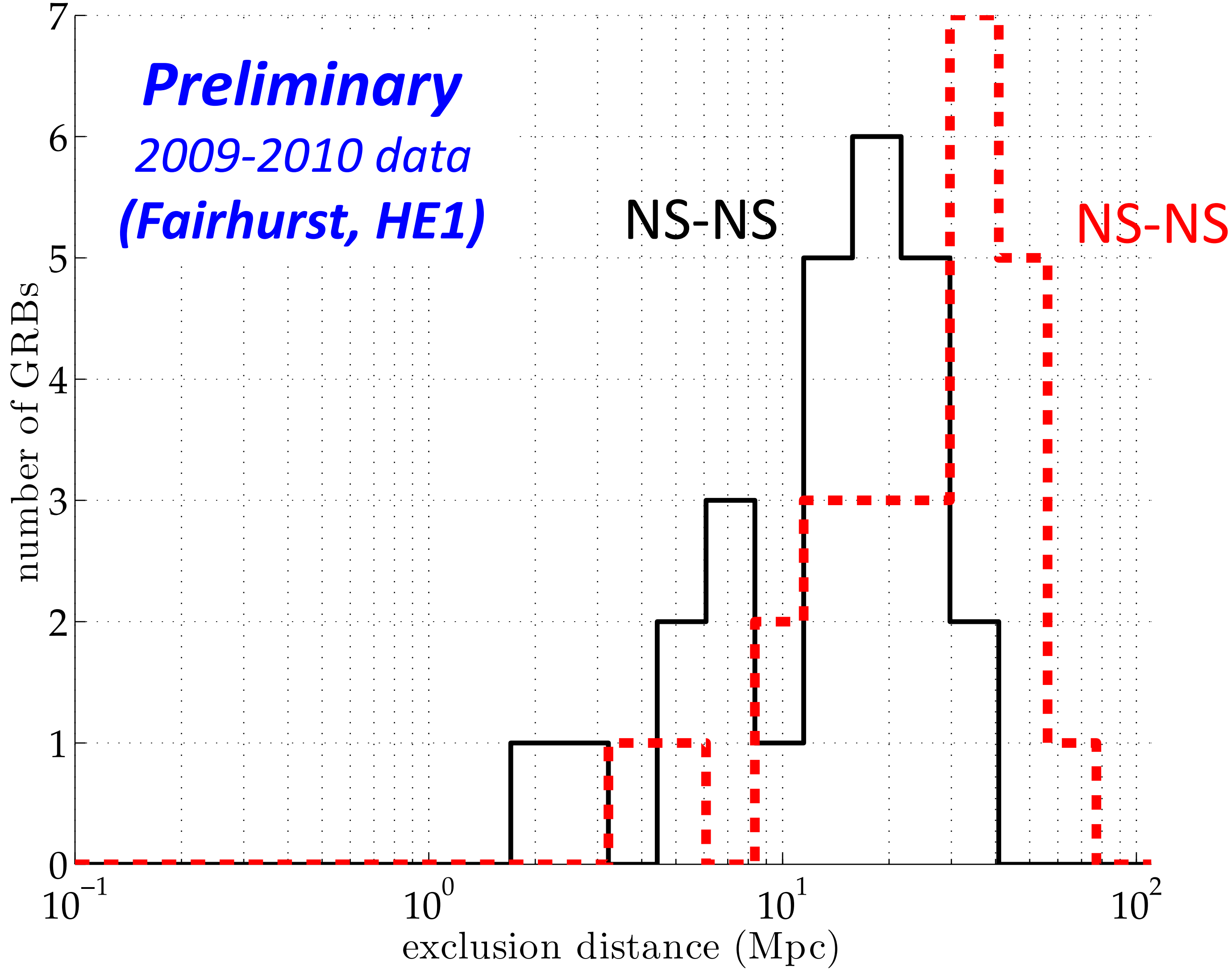
Gamma-Ray Bursts

- Short GRBs: Binary mergers.
  - Very strong GW emission [1].
- Long GRBs: Collapsars / magnetar formation.
  - GW emission speculative, possibly strong [2].
- Use time & sky position from GRB satellites for focused, more sensitive search for GWs.
  - Up to 2 x distance reach



[1] Blanchet 2006. [2] Davies et al. 2002; Fryer et al. 2002; Shibata et al. 2003; Kobayashi & Meszaros 2003; Piro & Pfahl 2007; Corsi & Meszaros 2009; Romero et al. 2010

LIGO-Virgo: Short GRB Distance Limits

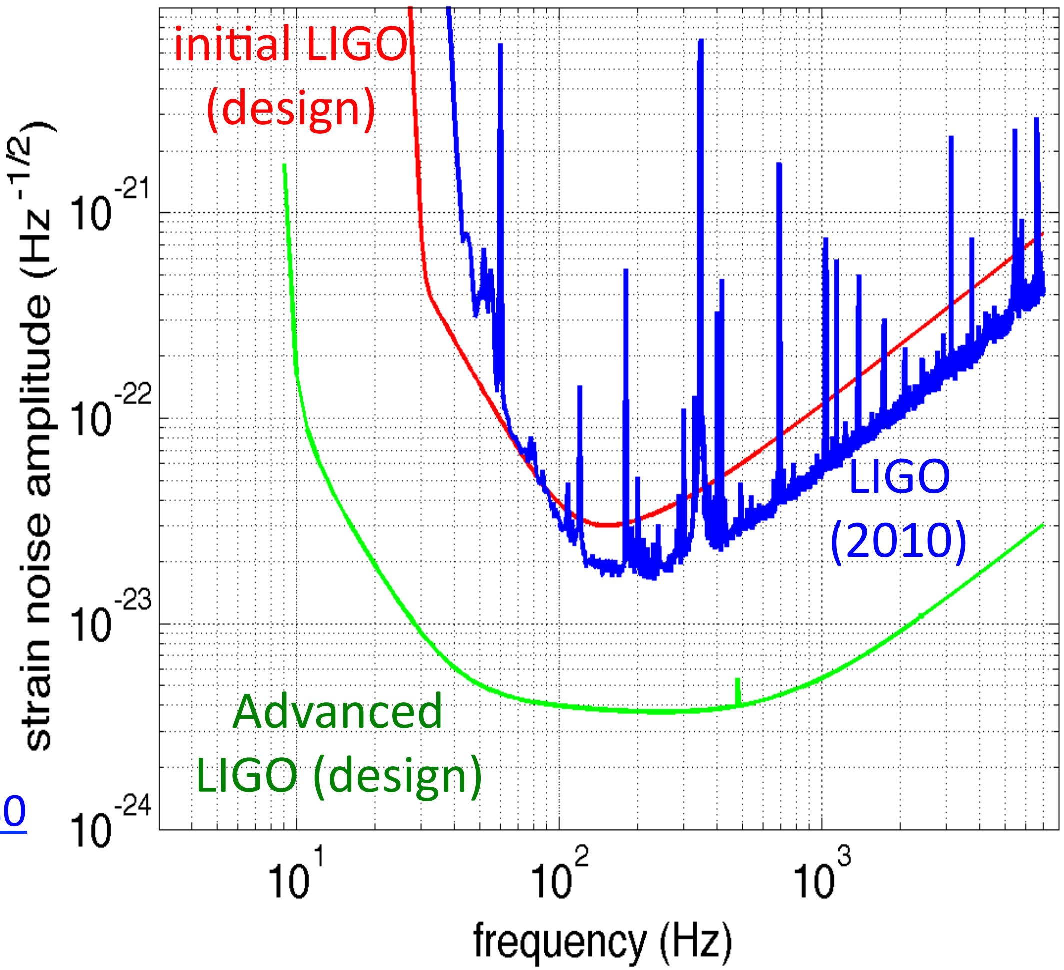


GW Detectors: 2015-2020

- LIGO's maximum sensitive ranges:
  - NS-NS: 450 Mpc
  - NS-BH: 930 Mpc

- Expected detection rates:
  - NS-NS: 0.4 - 400 yr^{-1}
  - NS-BH: 0.2 – 300 yr^{-1}

Abadie et al., arXiv:1003.2480

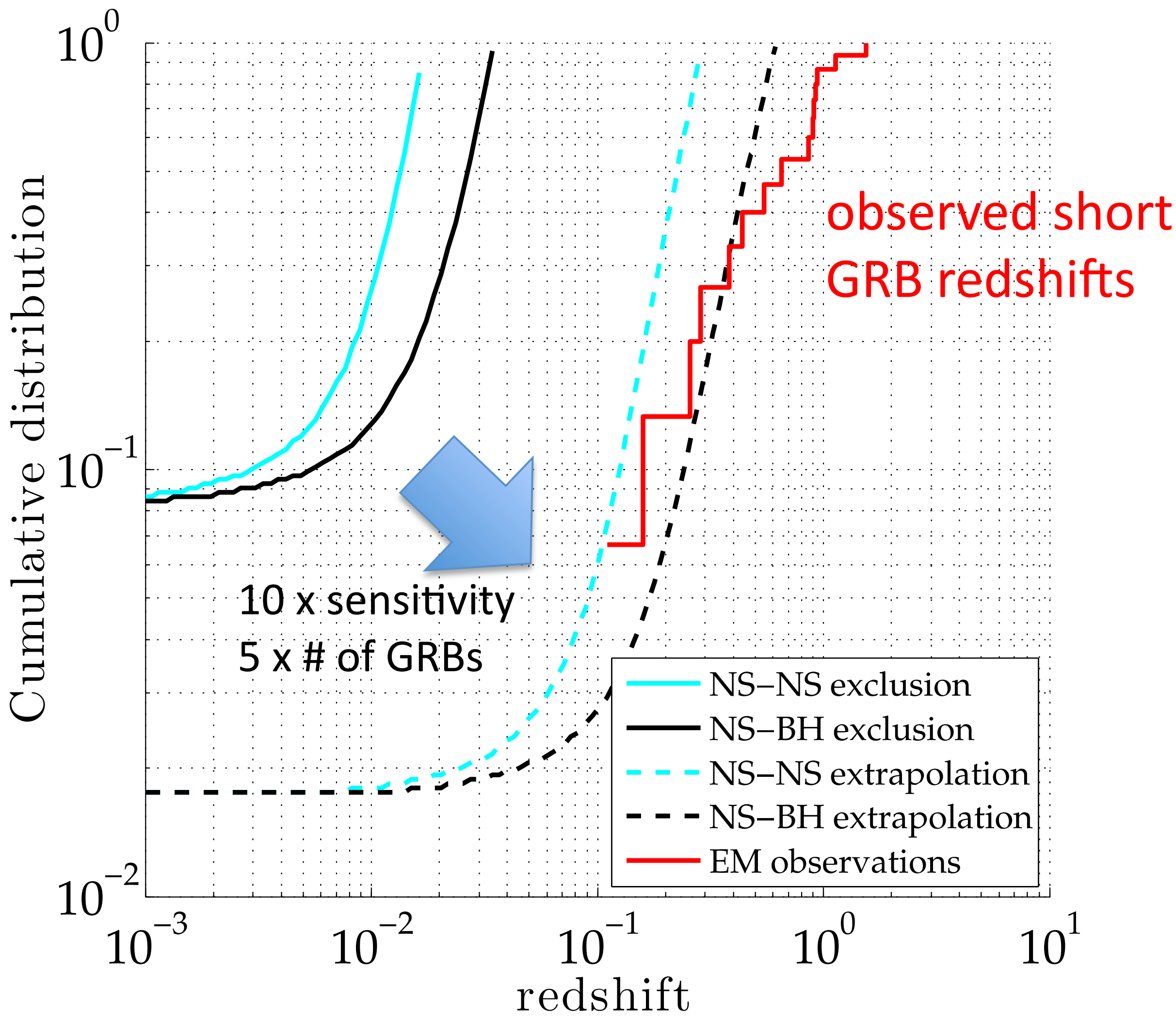


Short Gamma-Ray Bursts, Redux

Preliminary

2009-2010 data

(Fairhurst, HE1)

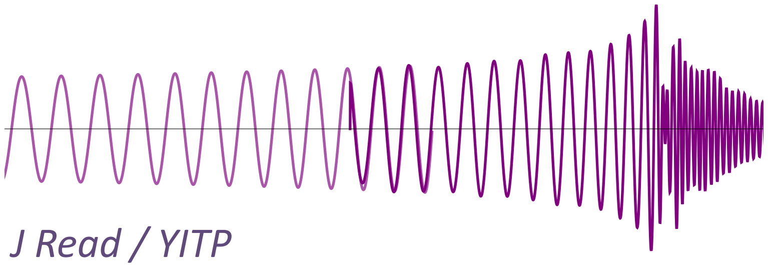


Extrapolation

to 2015-2020

What will advanced detectors tell us?

- A characteristic "chirp" GW coincident with short GRB:



J Read / YITP

- Smoking gun proof for a binary progenitor!

- Pattern of chirp tells us chirp mass (≈0.01%)

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

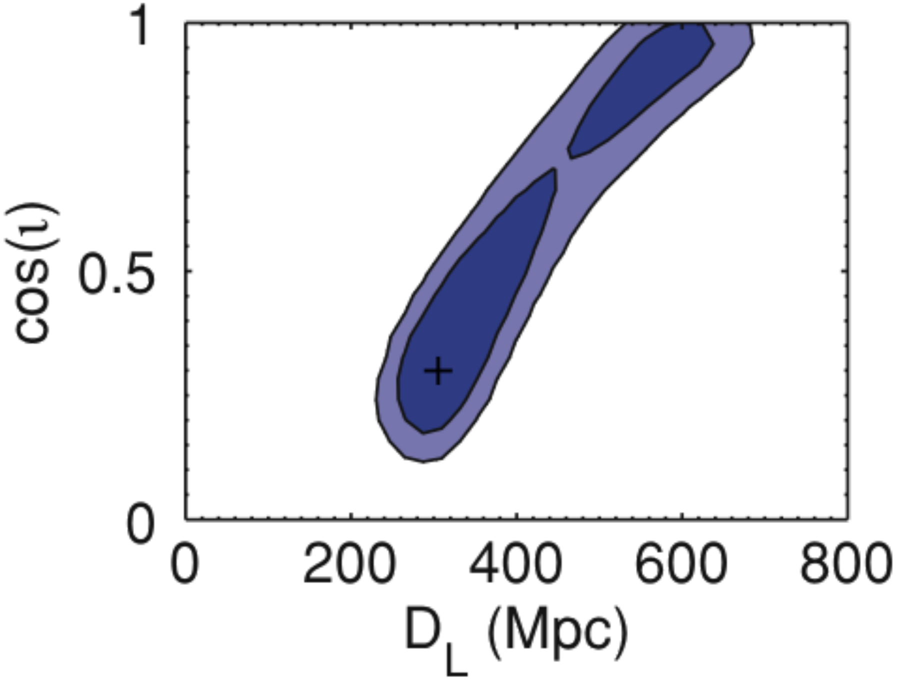
- May measure BH spin.
- Constrain beaming angle from fraction of GW detections coincident with SGRBs.

Finn & Chernoff, PRD 47, 2198 (1993)

GWs + GRBs = cosmology

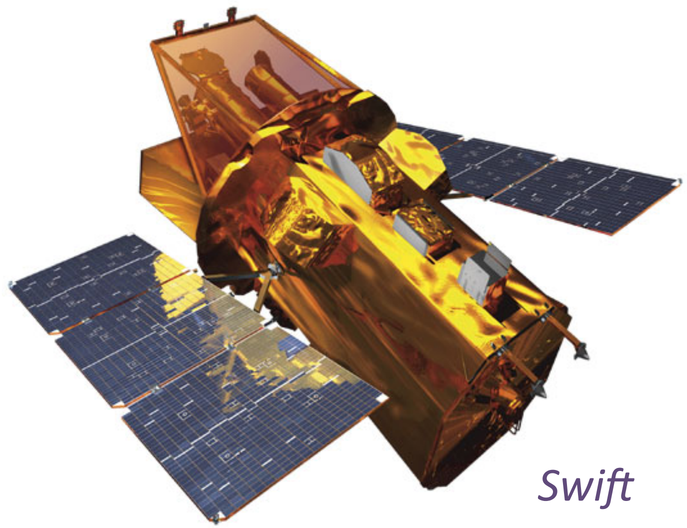
- Binaries are "standard sirens" (candles)
  - GW amplitude gives luminosity distance (≈10%) if GRB observed.
- Side-step cosmological distance ladder.
  - Measure H0 with to 13% (5%) with 4 (15) GW-GRB detections.

inclination-distance degeneracy from Nissanke et al. (2010)



Schutz, B. F. 1986, Nature, 323, 310
Nissanke et al., ApJ 725 496–514 (2010)

Challenges for GRB Science



- Need satellites for GRB detection!
  - Short GRBs particularly hard to see in EM: lower fluence, spectrum peaked at higher energy than optimal for Swift-BAT, Fermi-GBM instruments.
  - Nearby low-luminosity GRB population especially interesting for generic GW "burst" searches.
- Low-latency GW analysis for quick alert release.
- Better modeling of effects of black-hole spin on GW signal.
- Better modeling of possible GW emission from long GRBs, including range of possible γ - GW – neutrino delays.

Soft Gamma Repeaters

& Anomalous X-ray Pulsars

- Thought to be magnetars – isolated neutron stars with enormous B fields (10^{15} G).
- Can emit hard X-ray flares (10^{42} erg) & giant flares (10^{46} erg).
- Energy available for GW emission:
  - Crust-cracking < 10^{47} – 10^{50} erg — Corsi & Owen, arXiv:1102.3421
  - Magnetic rearrangement < 10^{45} – 10^{48} erg — Ioka, MNRAS 327, 639
- Best upper limits from LIGO-GEO-Virgo on GW *f*-mode emission of 10^{47} erg (at 1 kHz).
- Advanced LIGO/Virgo: improve by factor 10^2.

Abbott et al. PRL 101 (2008) 21110
Abbott et al. ApJ 701 (2009) L68
Abadie et al. Astrophys. J. 734 (2011) L35

Core-Collapse Supernovae

- GW emission uncertain.
  - Robust: $10^{-8}\ M_\odot$ (kpc range)
  - Speculative: $10^{-4}\ M_\odot$ (Mpc)
- Galactic SN: ($10^{-2}\ yr^{-1}$)
  - Large low-energy ν flux in Super-K, IceCube, etc.
  - ν & GWs: independent sky position and timing, before shock breakout.
  - GWs probe collapse physics .

  Ott 2009, Logue talk

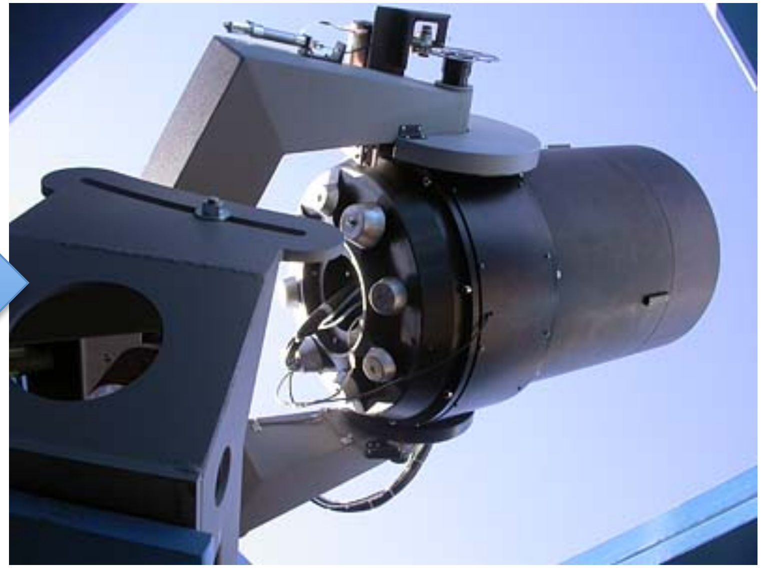
- SN at few Mpc: (≈1 yr^{-1})
  - ≈0.2 low-energy ν, possibly marginally detectable GW.

  Leonor et al. CQG 27 084019 (2010)

- Challenges:
  - Nightly scanning of nearest 100 galaxies to catch SNe.
  - Better modelling of SN GWs.

Phase II: Looc Up!

Locating & Observing Optical Counterparts to GW Bursts



ROTSE IIIb, McDonald Observatory. Credit: ROTSE Collaboration

Benefits of EM followups

Observation of an EM counterpart to a candidate GW could …

- Help confirm the GW detection.
- Provide precise source position -> host galaxy -> redshift.
  - Also improves GW parameter estimation.
- Reveal progenitor of EM phenomena
  - Binary progenitor of short GRBs
  - Insights into central engine of long GRBs.

Kanner et al (2008)
Bloom et al. 0902.1527
Abadie et al. 1109.3498 (in press)

Joint EM – GW Emission Models

Neutron star / neutron star – black hole binaries

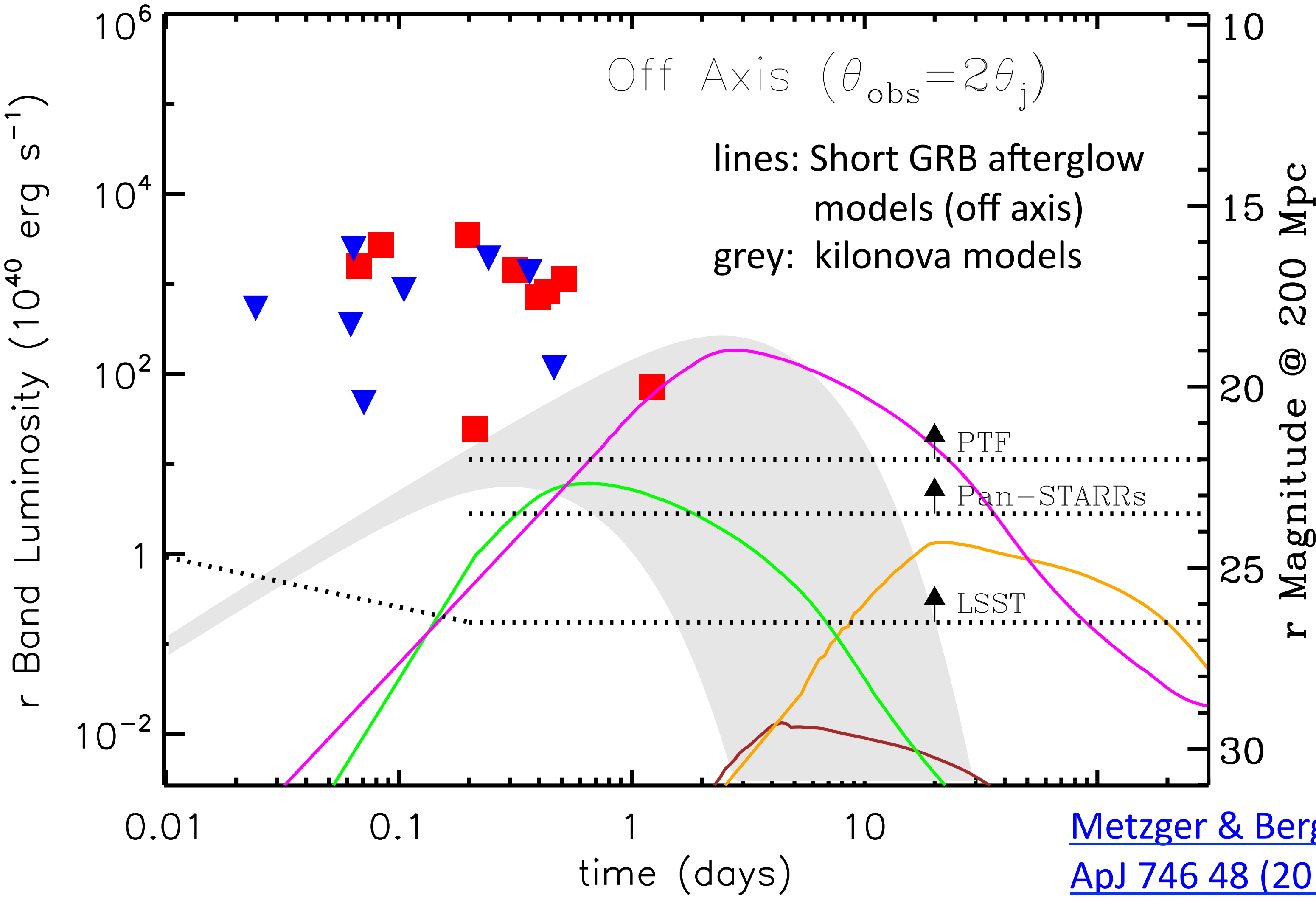
- short GRB, with x-ray, optical, radio afterglow
  - m = 12 – 20 at 1 day, 50 Mpc
- optical "kilonova" from radioactive decay of heavy elements
  - m ≈ 18 at 1 day, 50 Mpc

  Li & Paczyński (1998), Metzger et al. (2010)

- also various scenarios for radio emission before / after coalescence

  Predoi et al. (2010)

Short GRBs: Off-axis Emission



[Metzger & Berger ApJ 746 48 (2012)]

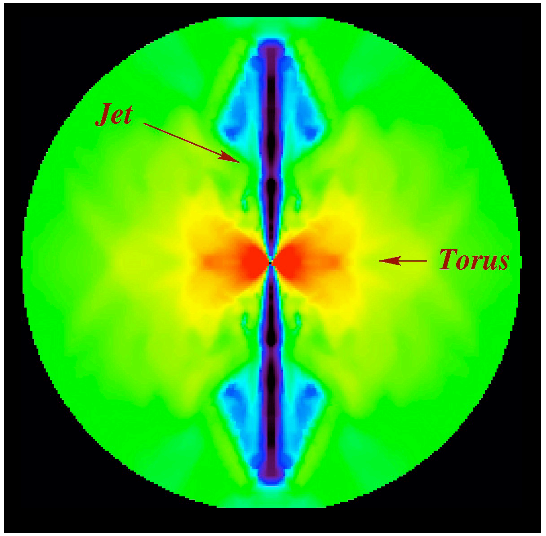
Other Joint EM – GW – ν Sources

Core-collapse Supernovae:

- Optical emission beginning hours after collapse, prompt neutrino emission

GRBs & High-Energy Neutrinos:

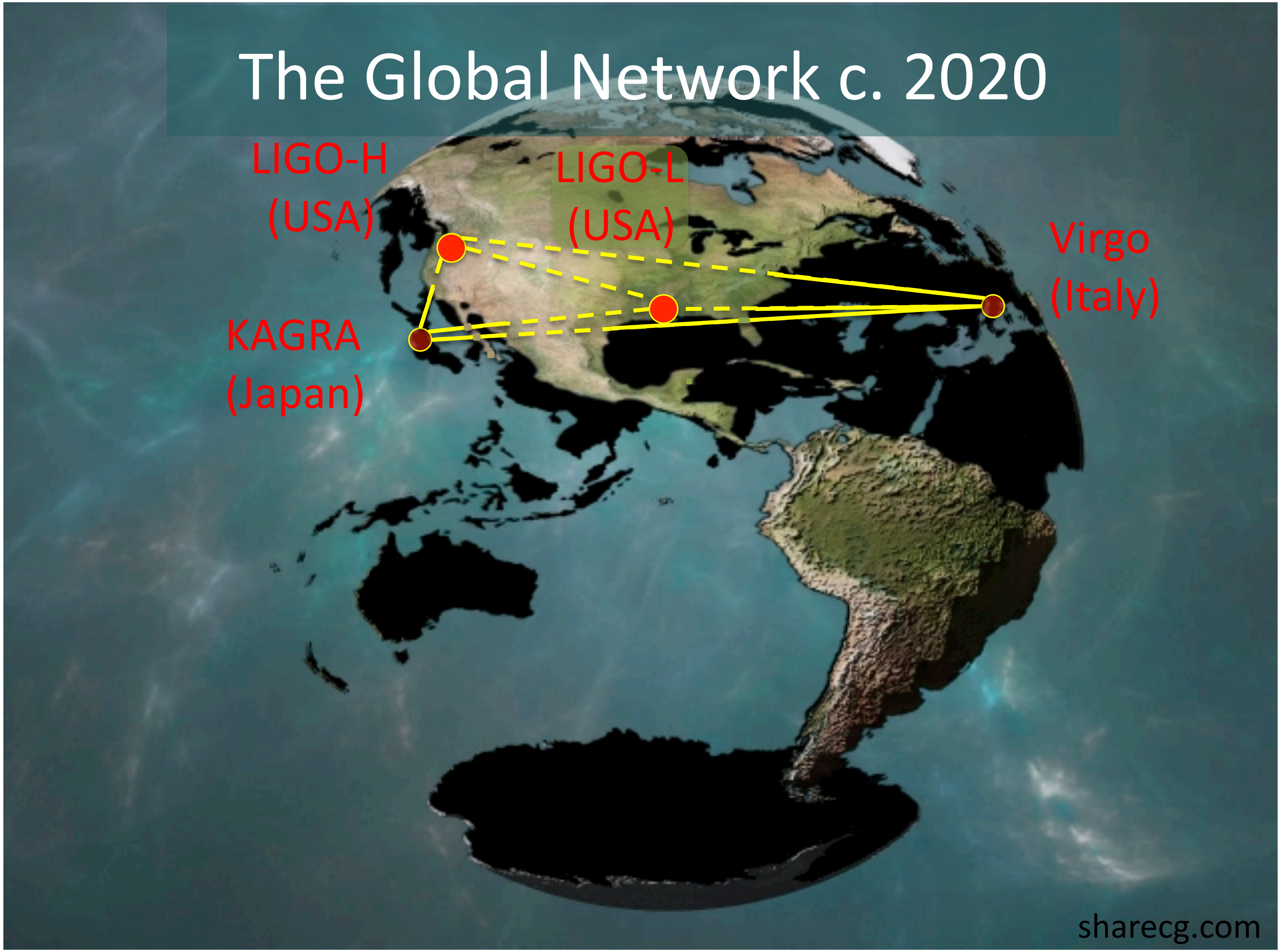
- choked GRBs
- long GRBs: precursor, prompt, afterglow phases.



Cosmic string cusps:

- photon, high-energy neutrinos.

Want to stay open to the unexpected.


The Global Network c. 2020
LIGO-H
(USA)
LIGO-L
(USA)
Virgo
(Italy)
KAGRA
(Japan)
sharecg.com

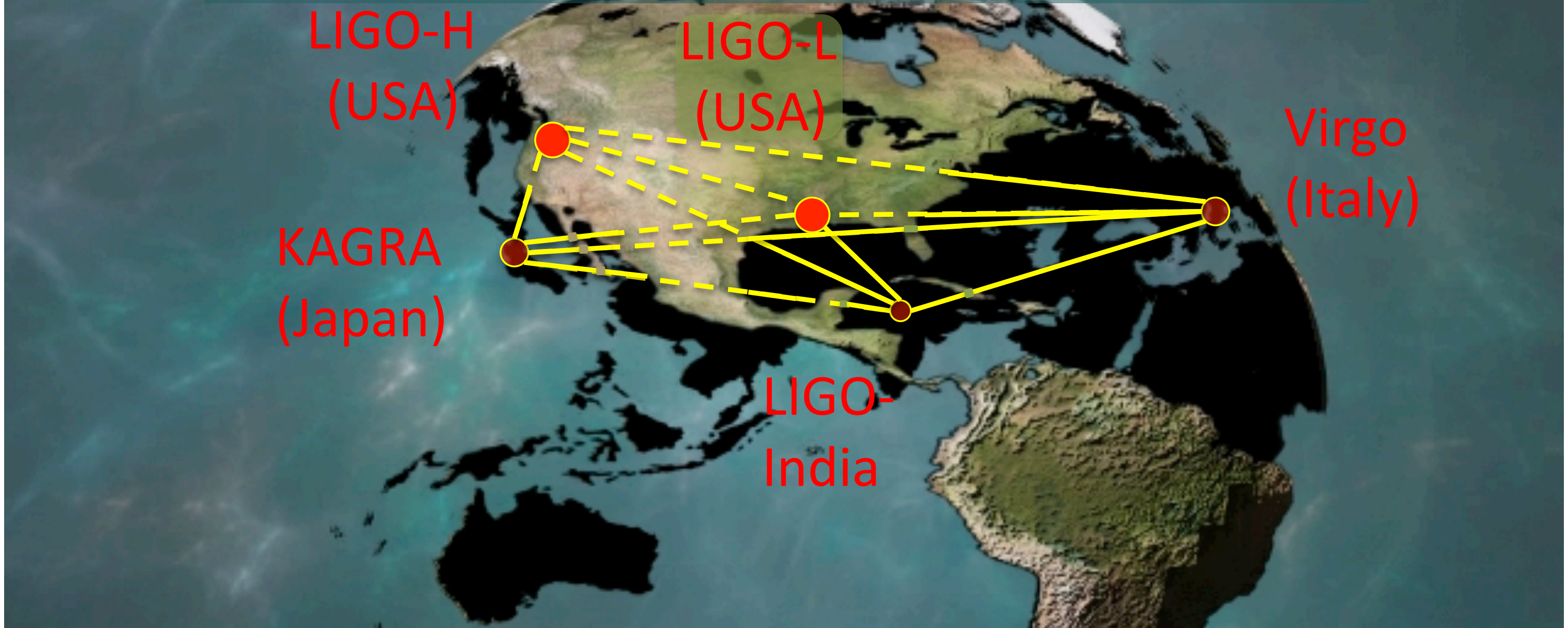
The Global Network c. 2020

Source localization from timing-based triangulation. Near threshold:

$$\Delta\Theta \sim 1^\circ \left(\frac{100\,\mathrm{Hz}}{\Delta f}\right)\left(\frac{10\,\mathrm{ms}}{d}\right)$$

sharecg.com

The Global Network c. 2020



March 2012: The LSC & LIGO Lab have endorsed transferring one of the three Advanced LIGO instruments to India!

Needs approval from NSF (US) & formal announcement of funding (India); hopefully by May/June 2012

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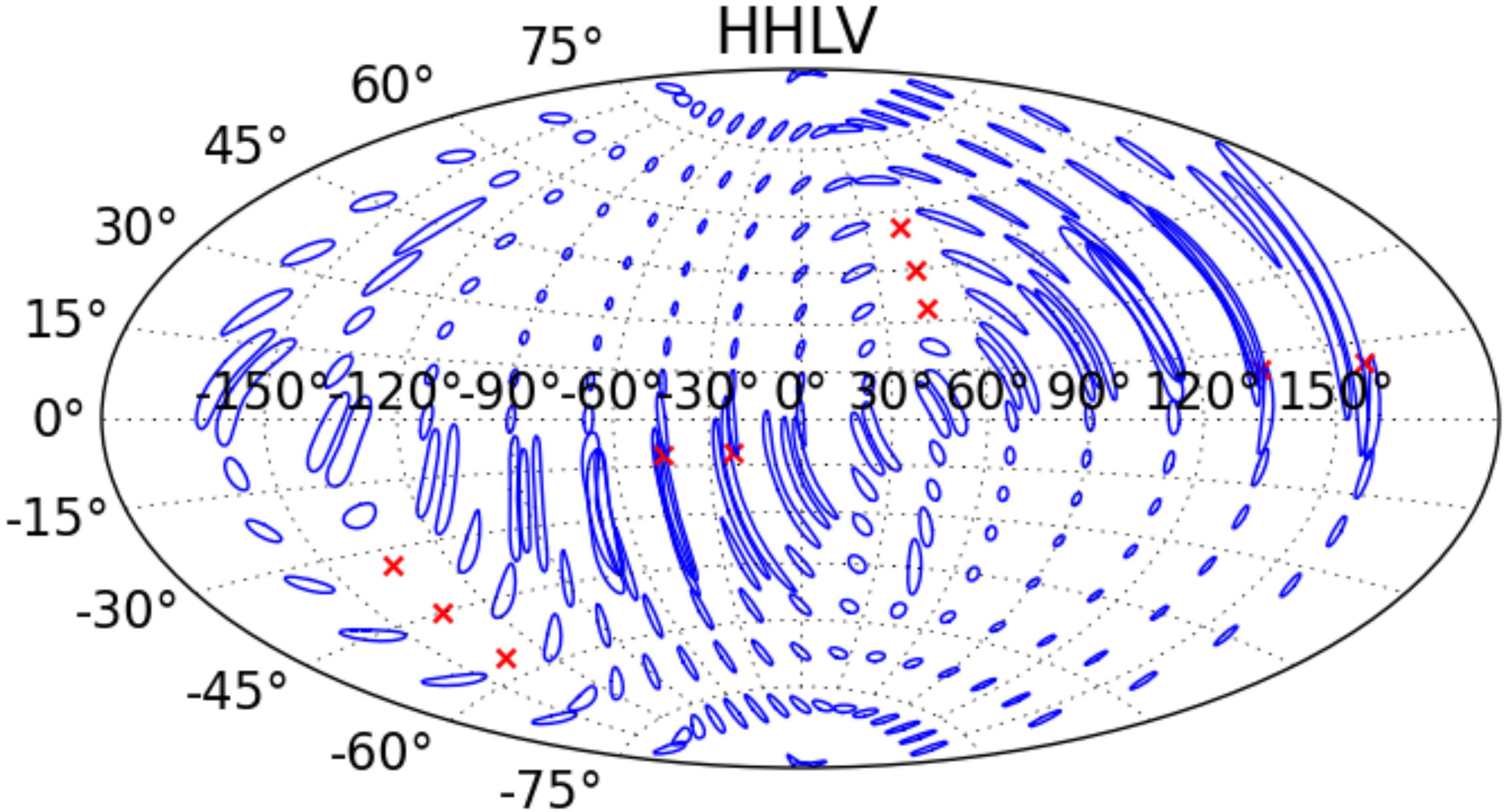
Sky localization with 3 sites …

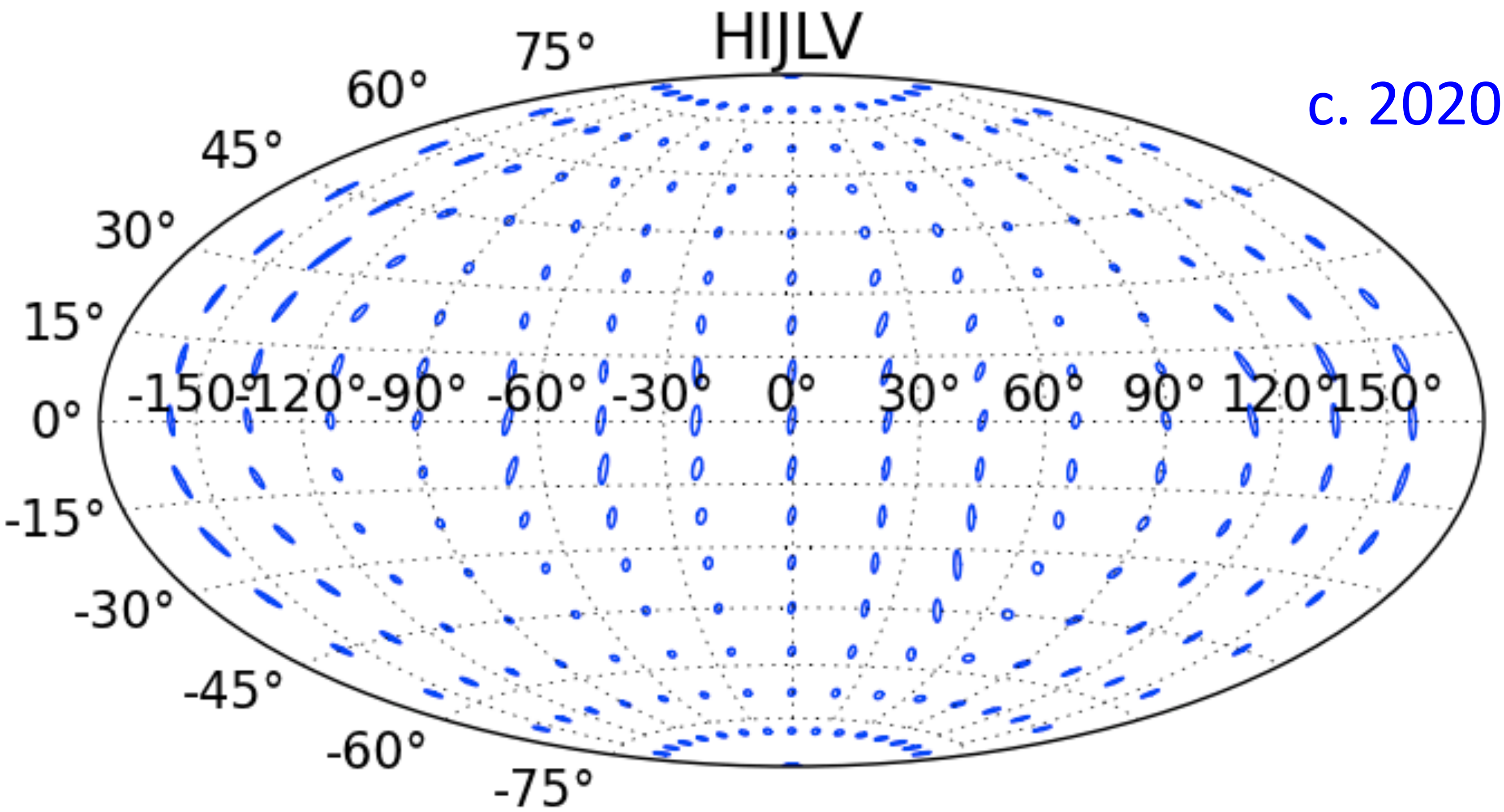


Typical 90% error box areas for NS-NS binaries

– median > 20 sq deg

Fairhurst, CQG 28 105021 (2011)

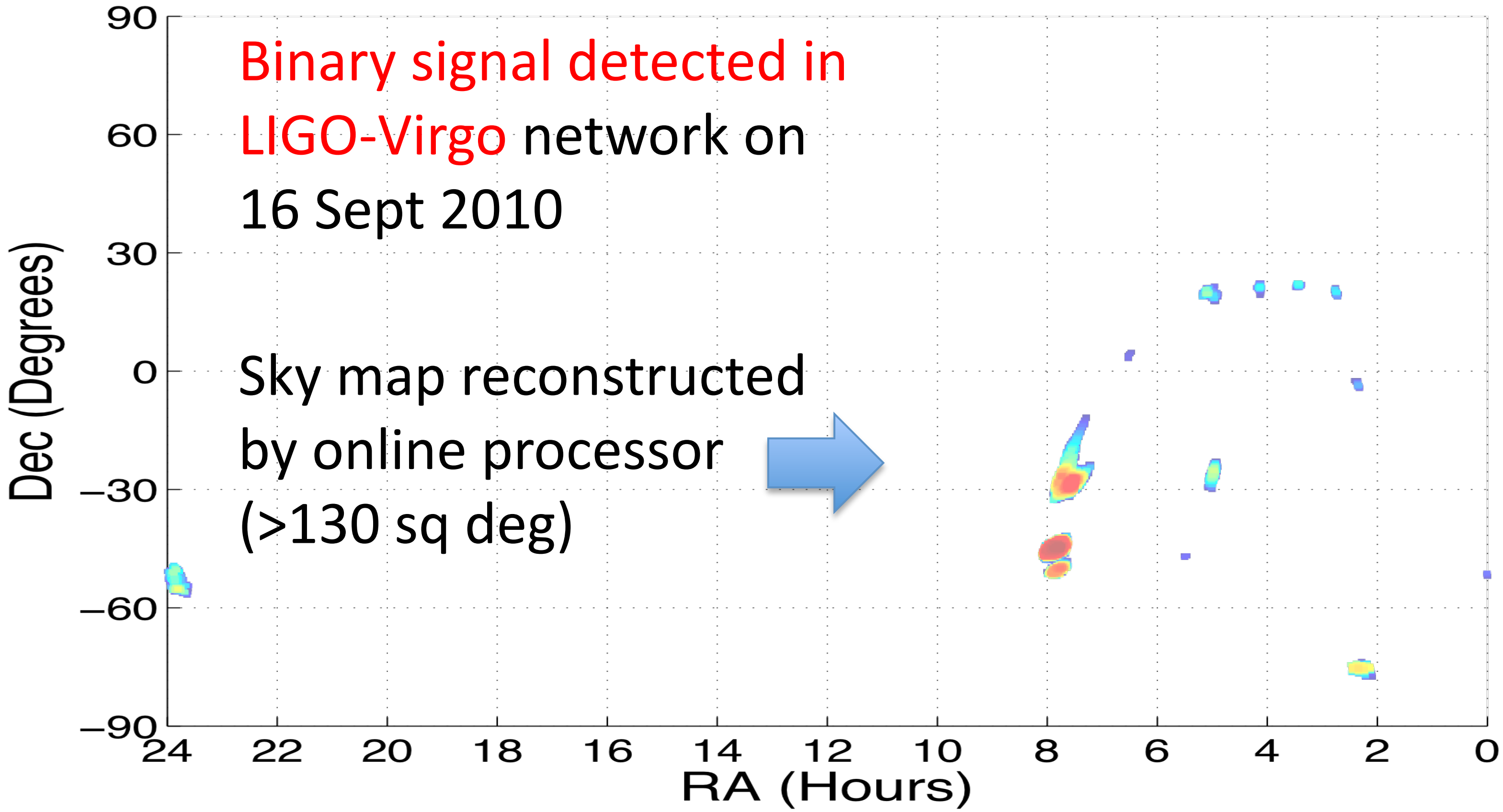
… and with 5 sites



c. 2020

Fairhurst (2011)

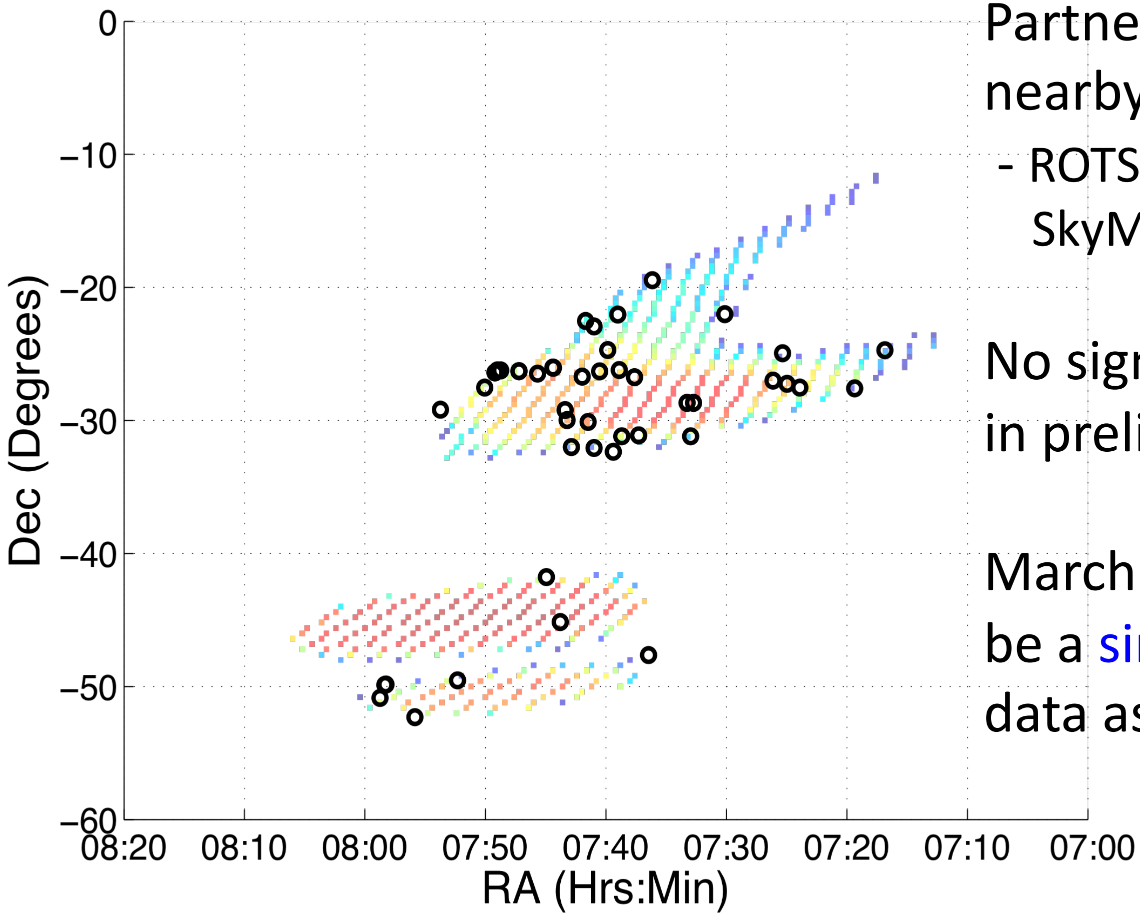
Case study: GW 100916, “The Big Dog”



Binary signal detected in LIGO-Virgo network on 16 Sept 2010

Sky map reconstructed by online processor (>130 sq deg)

The Big Dog: EM Follow-up



Partner telescopes pointed at nearby galaxies (<50 Mpc)

- ROTSE, TAROT, QUEST, Zadko, SkyMapper, Liverpool, *Swift*

No significant EM transients seen in preliminary analysis.

March 2011: Big Dog revealed to be a simulated GW added to the data as a detection test.

http://ligo.org/science/GW100916/

Challenges

- Low-latency GW analysis to identify significant events with robust background rejection, send alerts (sec-min).
- Better models of expected EM emission to help find the right needle in the haystack of background transients.
- Strategies for scanning large error boxes repeatedly to find transients of *a priori* unknown type.
  - Automated EM transient identification, spectral follow-ups.
  - Rely on high-cadence surveys (Pan-STARRS, LSST, LOFAR)?
  - Coordinated followups by MOU?
  - Public trigger release after first detections?
- *Need to start talking to EM astronomy community* ***NOW*** *to be ready for 2015.*

(Draft) LSC–Virgo Policy on GW Trigger Release

- Before first published detections: trigger release by MoU.
  - "*Both Collaborations … will partner with astronomers to carry out an inclusive observing campaign for potentially interesting GW triggers, with MoUs to ensure coordination and confidentiality of the information. They are open to all requests from interested astronomers or astronomy projects which want to become partners through signing an MoU.*"

- After first published detections:
  - public: high-quality triggers (false alarm rate < 1 / 100 years).
  - by MoU: lower threshold triggers, possibly lower latency.

Proposal: policy not yet approved by all relevant agencies.

Concluding Remarks

- Multi-messenger observations will enable us to extract the most physics from the advanced GW detectors.
  - probe source engines
  - galaxy hosts, redshifts
  - binaries: luminosity distance, measure cosmological parameters

- Full exploitation of GW data presents many challenges.
  - low latency GW analysis
  - better GW, EM emission models
  - strategies & partnerships for electromagnetic follow-up of GW events

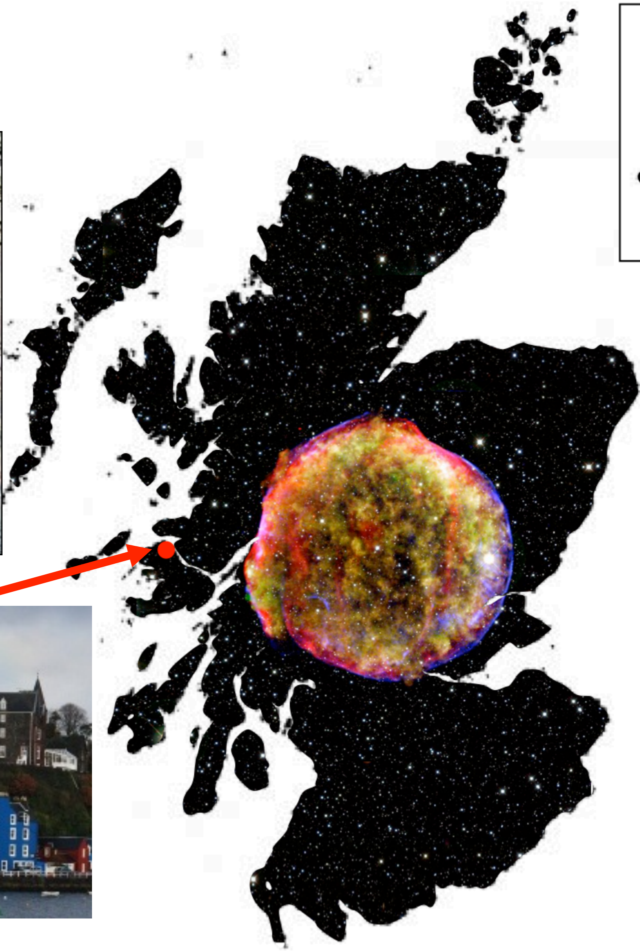
Gravitational Wave Bursts Workshop 2012
May 28-30 at Tobermory, Isle of Mull, Scotland

http://www.physics.gla.ac.uk/igr/GWbursts2012/index.php

Tobermory attractions:





Various aspects of gravitational wave astronomy will be discussed, including:

- Waveform modelling
- Source populations
- Source dynamics
- EM counterparts (GRBs, radio, neutrinos, optical…)

Bringing together astronomers, numerical relativists and gravitational wave data analysts to work towards gravitational wave astronomy

email: gwb-soc@gwbursts.org