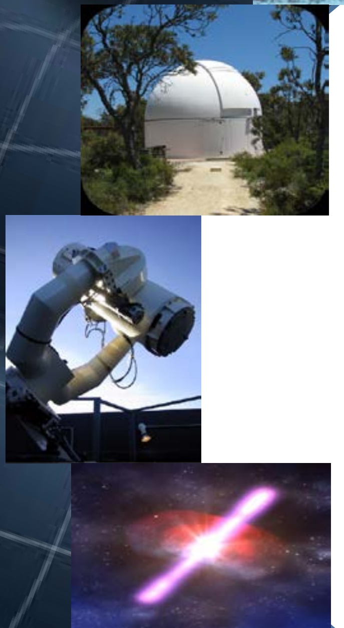


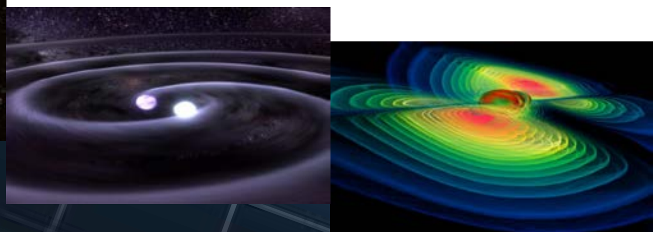
Gravitational waves and high-energy photons: *the multimessenger connection*

Massimiliano Razzano[(1)]

With many thanks to Marica Branchesi[(2)] & Francesco Fidecaro[(1)]
[(1)]University of Pisa & INFN [(2)]University of Urbino & INFN

On behalf of the LIGO Scientific Collaboration and Virgo Collaboration

10th SciNeGHE – Lisbon 4-6 June 2014

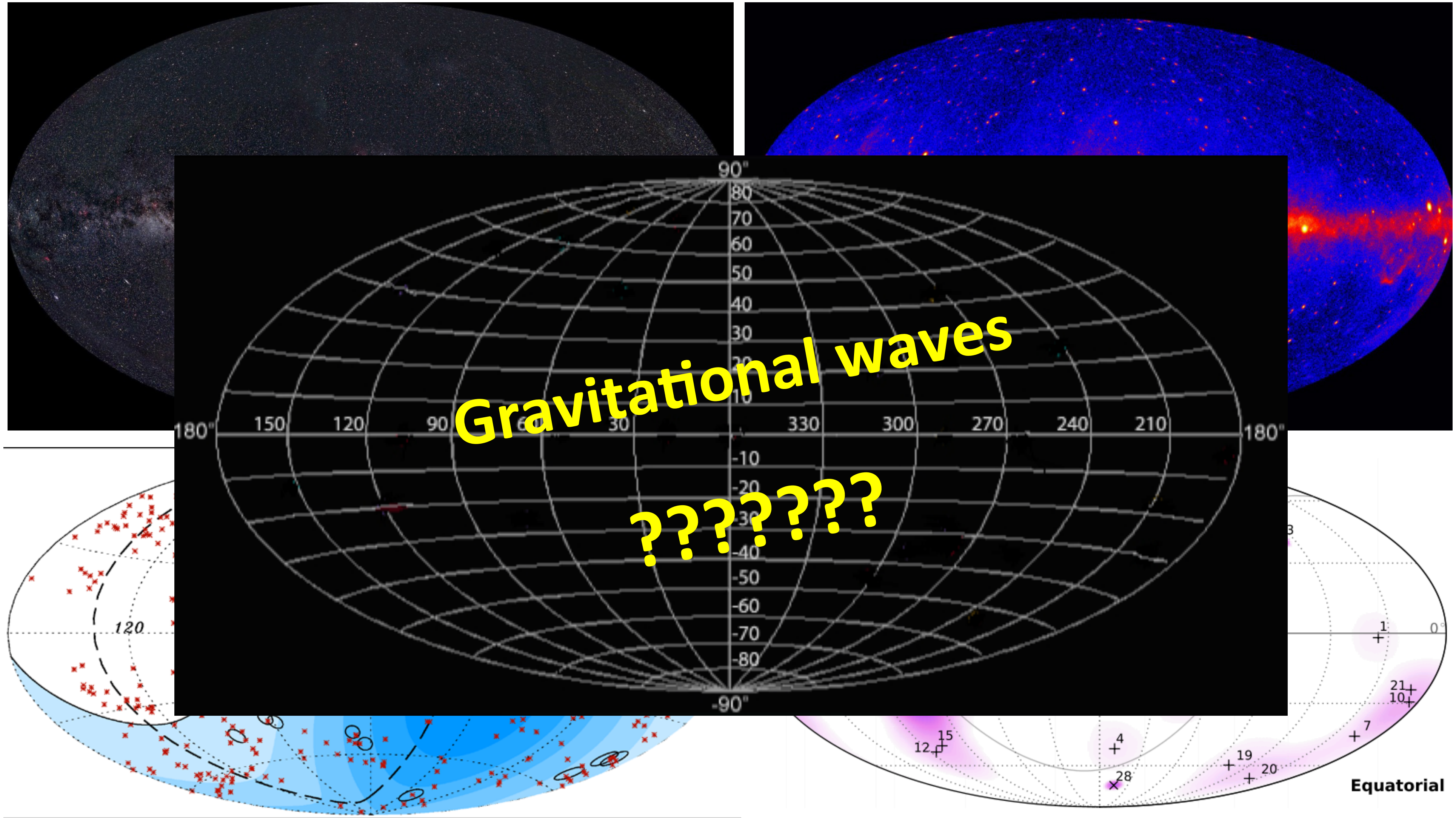


DCC LIGO-G1400591

A multi-messenger sky

Optical (APOD)

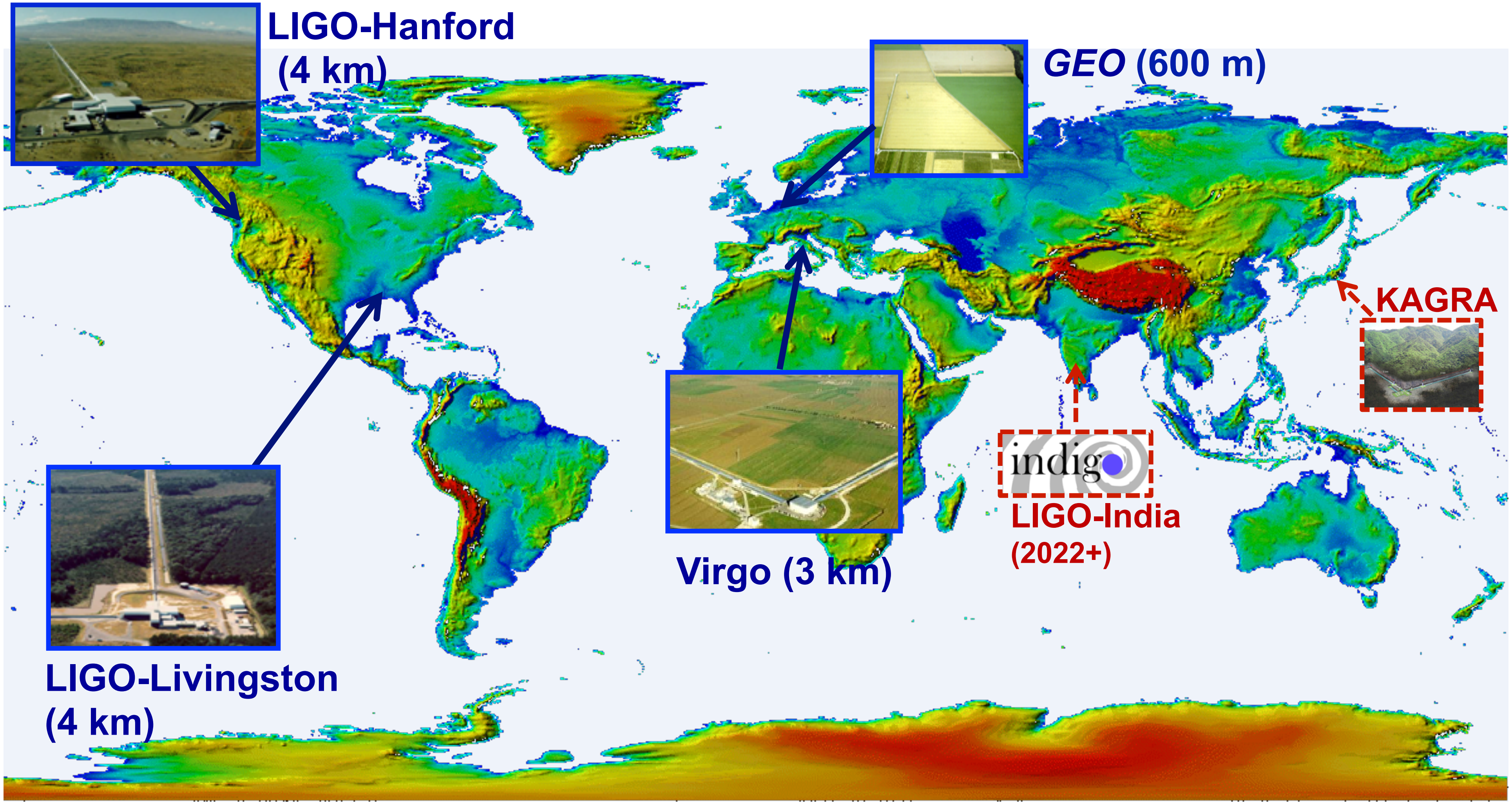
Gamma rays > 0.1 GeV (Fermi-LAT, 2013)



Cosmic rays > 57 Eev (Auger, 2007)

Neutrinos > 30 Tev (Icecube, 2013)

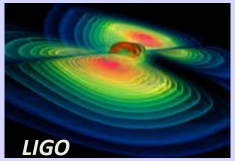
A network of Gravitational Wave detectors



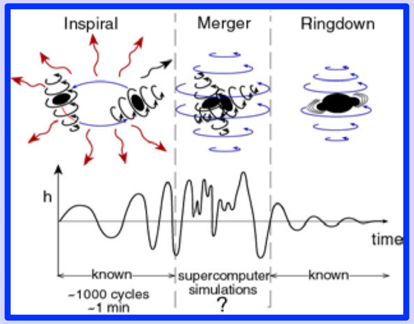
LIGO and **Virgo** currently under upgrade
They will observe the sky (10-1000 Hz) as a single network
aiming at the first direct detection of GWs

Expected GW sources detectable by LIGO/Virgo

Coalescence of Compact Objects
Neutron-Stars and/or Black-Holes

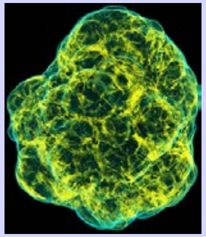


- Known waveform
- Energy emitted in GW: $\mathbf{10^{-2} M_o c^2}$



Initial LIGO/Virgo
detectable to **50 Mpc**
likely rate $\mathbf{0.02\ yr^{-1}}$

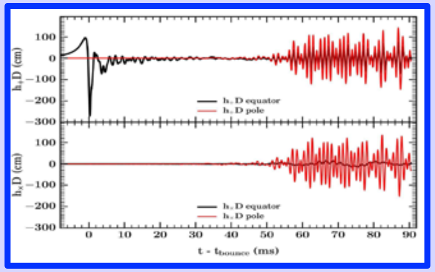
Core-collapse of Massive Stars



Ott et al. 2013

Waveform and energy emitted in GW uncertain:
- Likely $\mathbf{10^{-8} M_o c^2}$
- Optimistic $\mathbf{10^{-4} M_o c^2}$

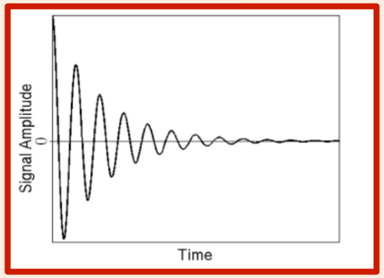
Initial LIGO/Virgo
detectable within
our Galaxy (10 kpc)

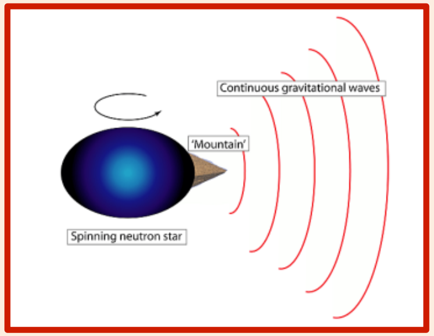


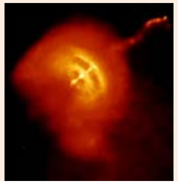
Ott, C. 2009

Transient signals

Neutron Stars

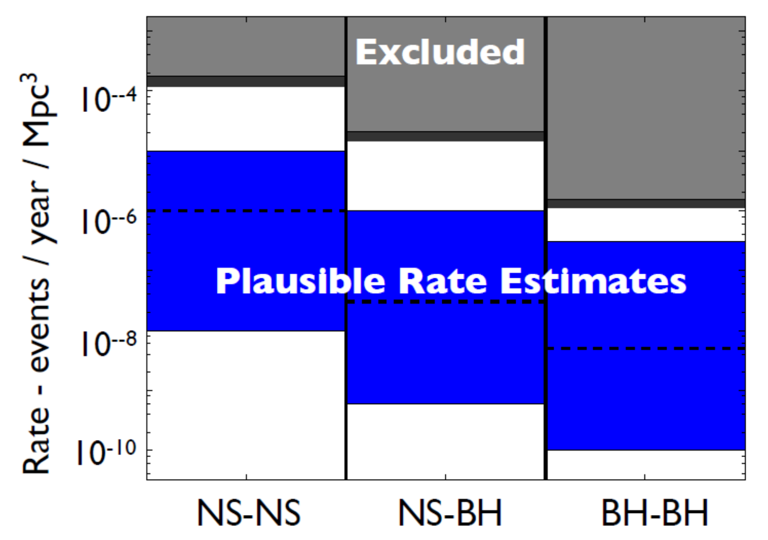






Continuous signals

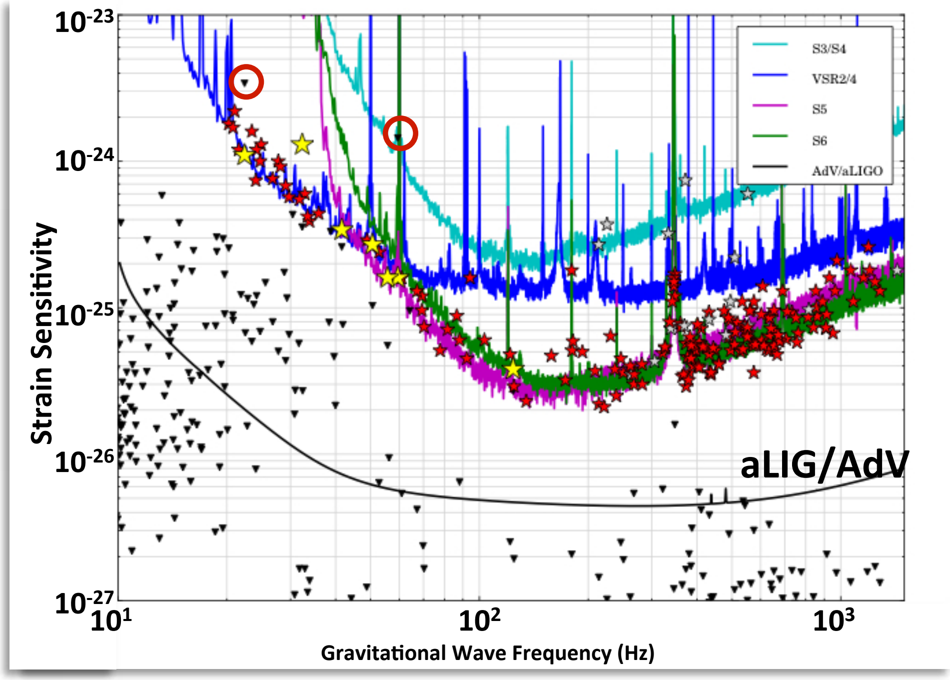
Examples of GW science from previous LIGO/Virgo runs (2005-2010)



Upper limits on the rate of low mass compact binary coalescence total mass 2-25 M_{sun}

Abadie et al. 2012, *Phys. Rev. D*, 85

GW amplitude upper limits from 195 known Pulsars



Crab limit at 1% of total energy loss!

Vela limit at 10% of total energy loss!

Aasi et al. 2014, ApJ, 785

Advanced Era GW-detectors (ADE)

LIGO-H

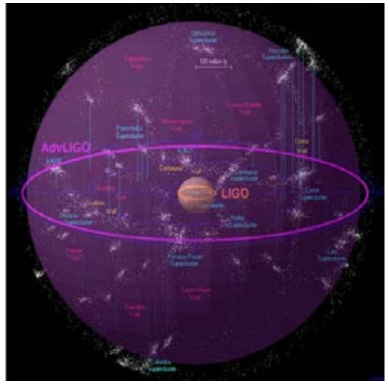
LIGO-L

Virgo

LIGO and **Virgo** detectors
are currently being **upgraded**

⬇

boost of sensitivity
by a **factor of ten**
(of 10^3 in number of detectable sources)



Advanced era
Detection rates of compact binary coalescences

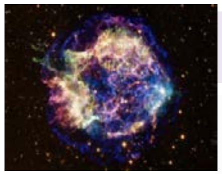
	Source	Low yr^{-1}	Real yr^{-1}	High yr^{-1}	Max yr^{-1}
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	

(Abadie et al. 2010, CQG 27)

Mass: NS = 1.4 Mo
BH = 10 Mo

Advanced era
Sky location and orientation averaged range

197 Mpc for NS-NS
410 Mpc for NS-BH
968 Mpc for BH-BH



Core-Collapse Supernovae

2-4 yr^{-1} EM-observed within **20 Mpc**

Rate of GW-detectable events unknown

GW-signal detectable **< Milky Way** (Ott et al. 2012, Phy.R.D.)
few Mpc (Fryer et al. 2002, ApJ, 565)

LONG-GRB core-collapse **(?) 10 - 100 Mpc** (Piro & Pfahl 2007)

Why joint GW/electromagnetic observations?

LIGO

- Complementary information:
  - GW → mass distribution
  - EM → emission processes, environment

- Give a precise (arcmin/arcsecond) localization
  - Localize host galaxy of a merger
  - Identify an EM counterpart with timing signature (e.g. pulsars)

- Provide a more complete insight into the most energetic events in the Universe

- Explore the physics of the progenitors (mass, spin, distance..) and their environment (temperature, density, redshift..)

- Open a new era of multi-messenger (GW and photon) astronomy

Transient sources: Gamma Ray Bursts

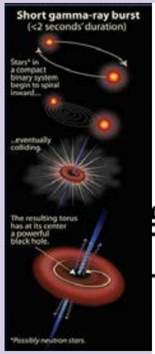
Merger of NS-NS / NS-BH

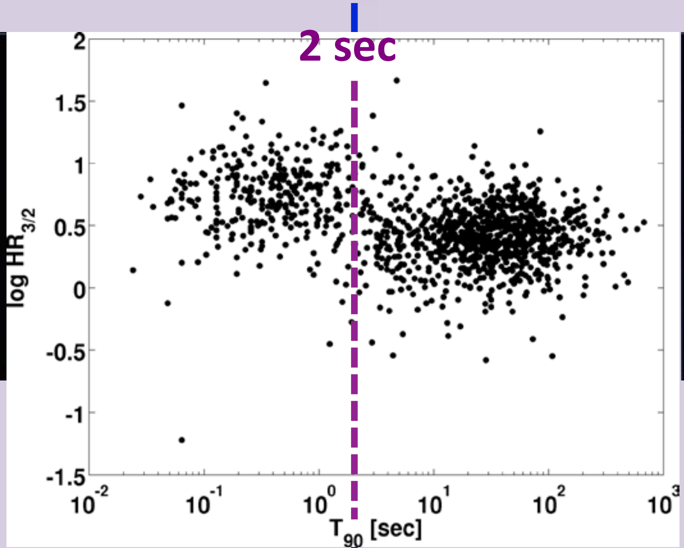
Core collapse of massive star

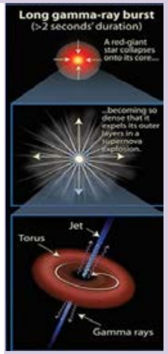
Gamma-Ray Burst: flashes of gamma-rays
isotropic-equivalent energy up to 10^{53} erg

Short Hard GRB

Progenitor indications:
- lack of observed SN
- association with older stellar population
- larger distance from the host galaxy center (~ 5-10 kpc)







Long Soft GRB

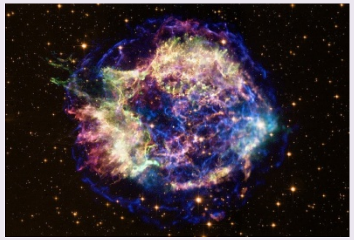
Progenitor strong evidence: observed Type Ic SN spectrum

Kilonovae

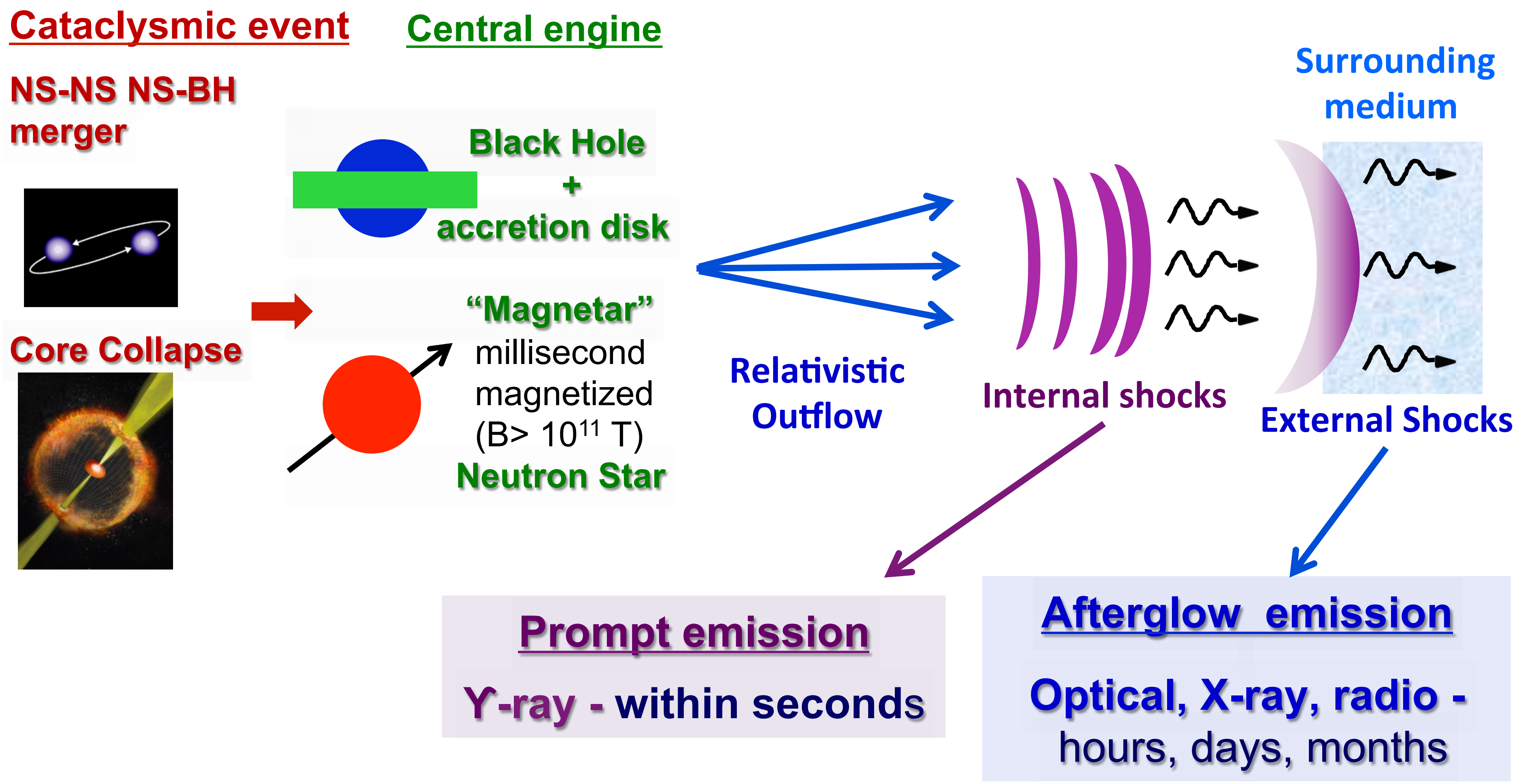
(Optical/IR, radio remnant)

Supernovae

Type II, Ib/c



GRBs emission - Fireball Model



EM signals from GRBs

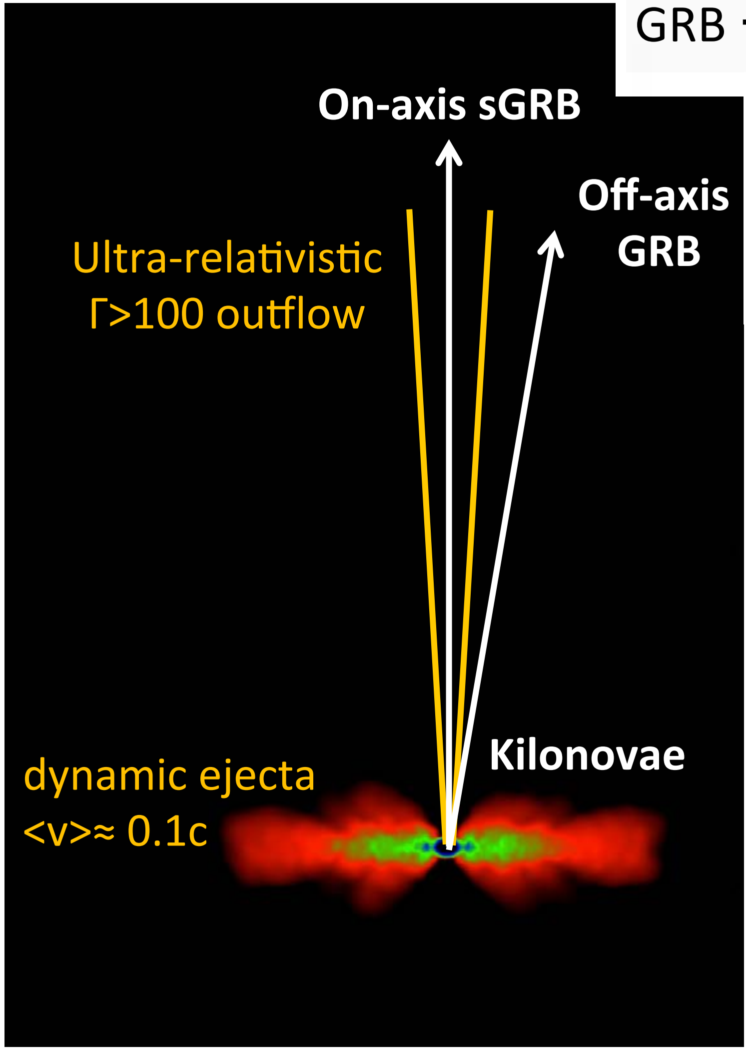
- ❖ **Prompt ϒ-ray emission (beamed):**

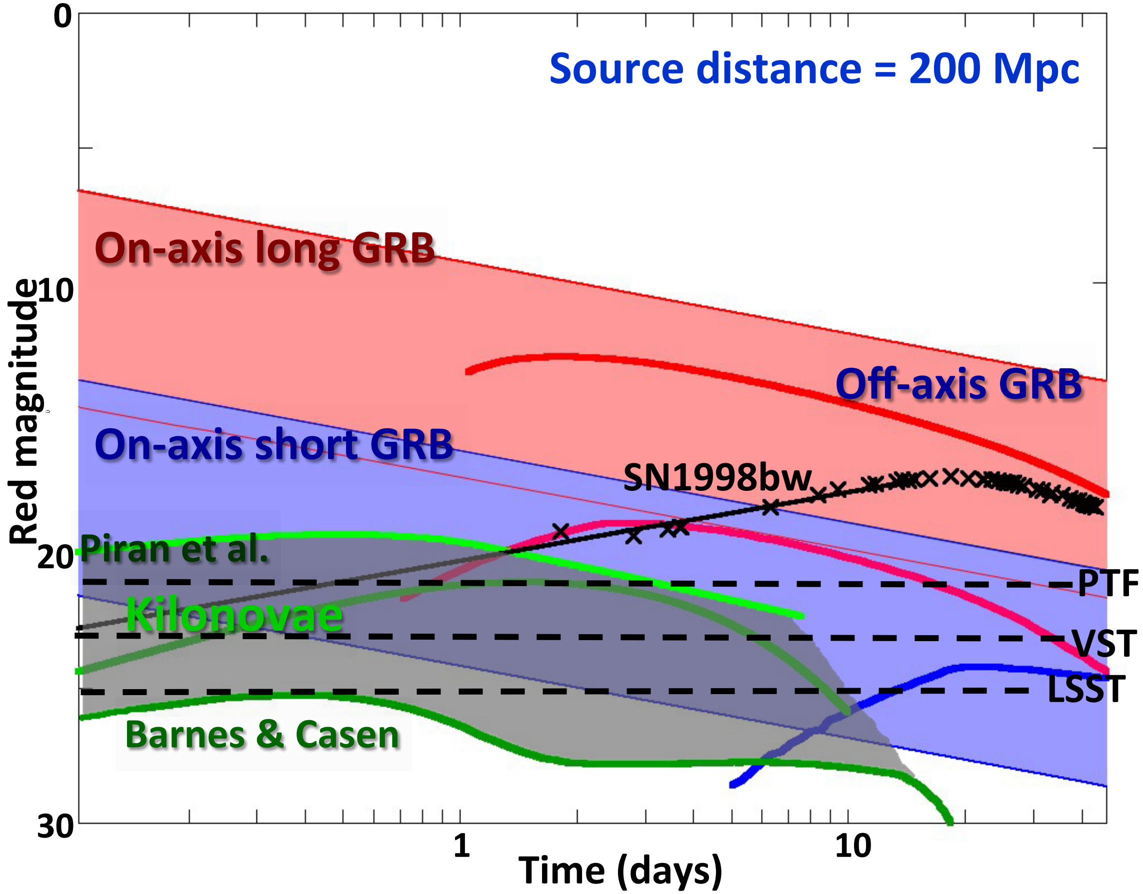
GRB → GW search **"GRB Triggered analysis"**

- ❖ **GRB afterglow emission, kilonovae:**

GW trigger → EM search

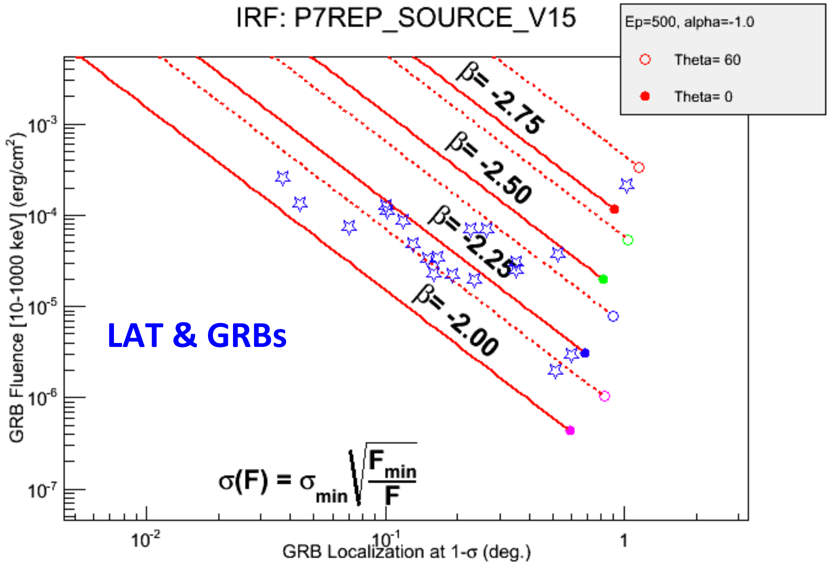
"Low-latency EM follow-up"





GRB observations: the case of Fermi

- ***Fermi's* Gamma-ray Burst Monitor (GBM) and Large Area Telescope (LAT) excellent for GRBs**
  - Large FoV & sensitivity
  - Huge energy coverage (7 decades)
  - Precise timing (~1 us)



- GW → EM
  - Confirm GRB
  - Better constrain time & localization
- EM → GW
  - Provide GW candidate for search

Characteristic	Capability
Low Energy Limit	<10 keV
High Energy Limit	>25 MeV
Energy Resolution (FWHM, 0.1-1 MeV)	<10%
Field of View (Co-aligned with LAT FOV)	>8 sr
Time Accuracy (Relative to spacecraft time)	<10 microseconds
Average Dead Time	<10 microsecond/count
Burst Sensitivity (Peak 50-300 keV flux for 5σ detection in ph cm^{-2} s^{-1})	<0.5 cm^{-2} s^{-1}
Burst Alert Locations (1σ systematic error radius)	<15°
Burst Alert Time Delay (Time from burst trigger to spacecraft notification (used to notify ground or LAT)	<2 s

GBM performance

References:

LAT: http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

GBM: http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Introduction/GBM_overview.html

GRBs in the Fermi era

- First LAT GRB Catalog (Ackermann+13, ApJS)

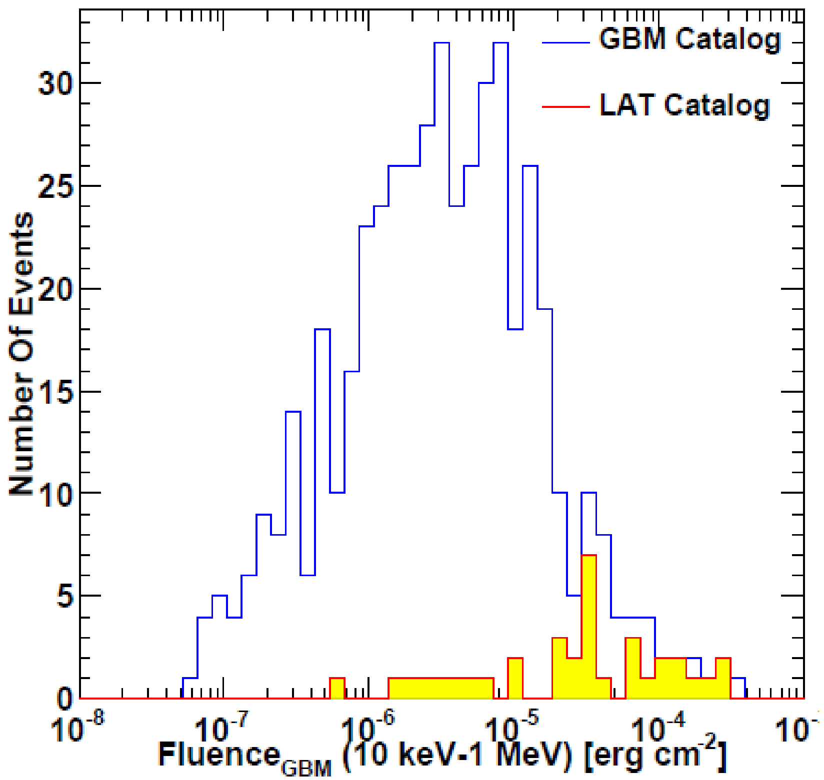
- 35 GRBs detected by the LAT (28 >100 MeV)
- 5 of them are short GRBs ($T_{90,GBM} < 2$ s)
- 733 detected by the GBM

Main results:

- Spectra:
  - Deviation from Band function at low E
  - Additional power law at high-E
  - High-E photons by the LAT (e.g. 95 GeV from GRB130427A)
  - High-E cutoff

- Temporally-extended high-E emission

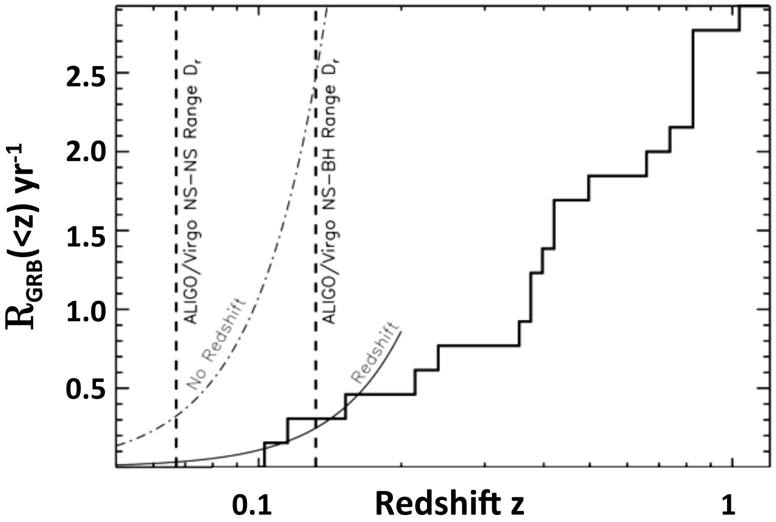
- LAT GRBs among the brightest ones



See also: GBM 2-yr catalog (Goldstein +12, ApJS)

GW detection rate based on short GRB observations

GW/on-axis short GRB detection rate



All-sky gamma-ray monitor

→ **0.3 short GRBs per year** (NS-NS range)

→**3 short GRBs per year** (NS-BH range)

Metzger & Berger 2012, ApJ 746

aLIGO and Virgo NS-NS detection rate

Short GRB observations → NS-NS merger rate

$$R_{NS\text{-}NS}=R_{GRB}/(1-\cos(\theta))$$

$R_{NS\text{-}NS}$

8 -1100 Gpc^{-3}yr^{-1} (Coward et al. 2012)

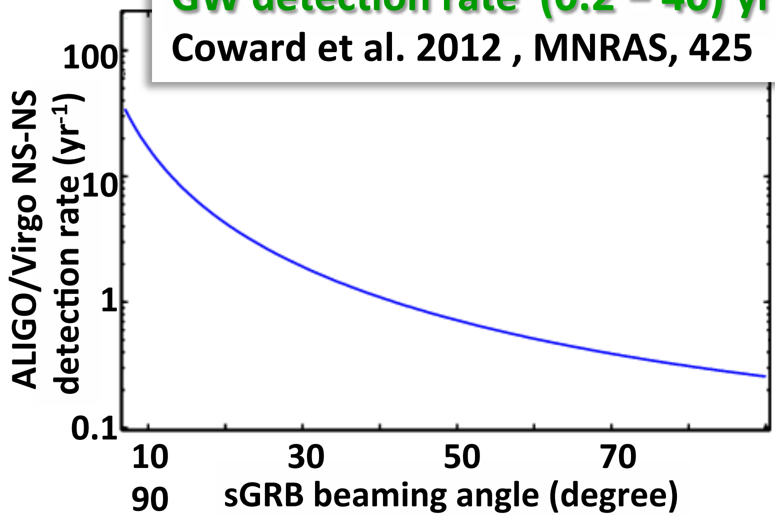
92–1154 Gpc^{-3} yr^{-1} (Siellez et al. 2013)

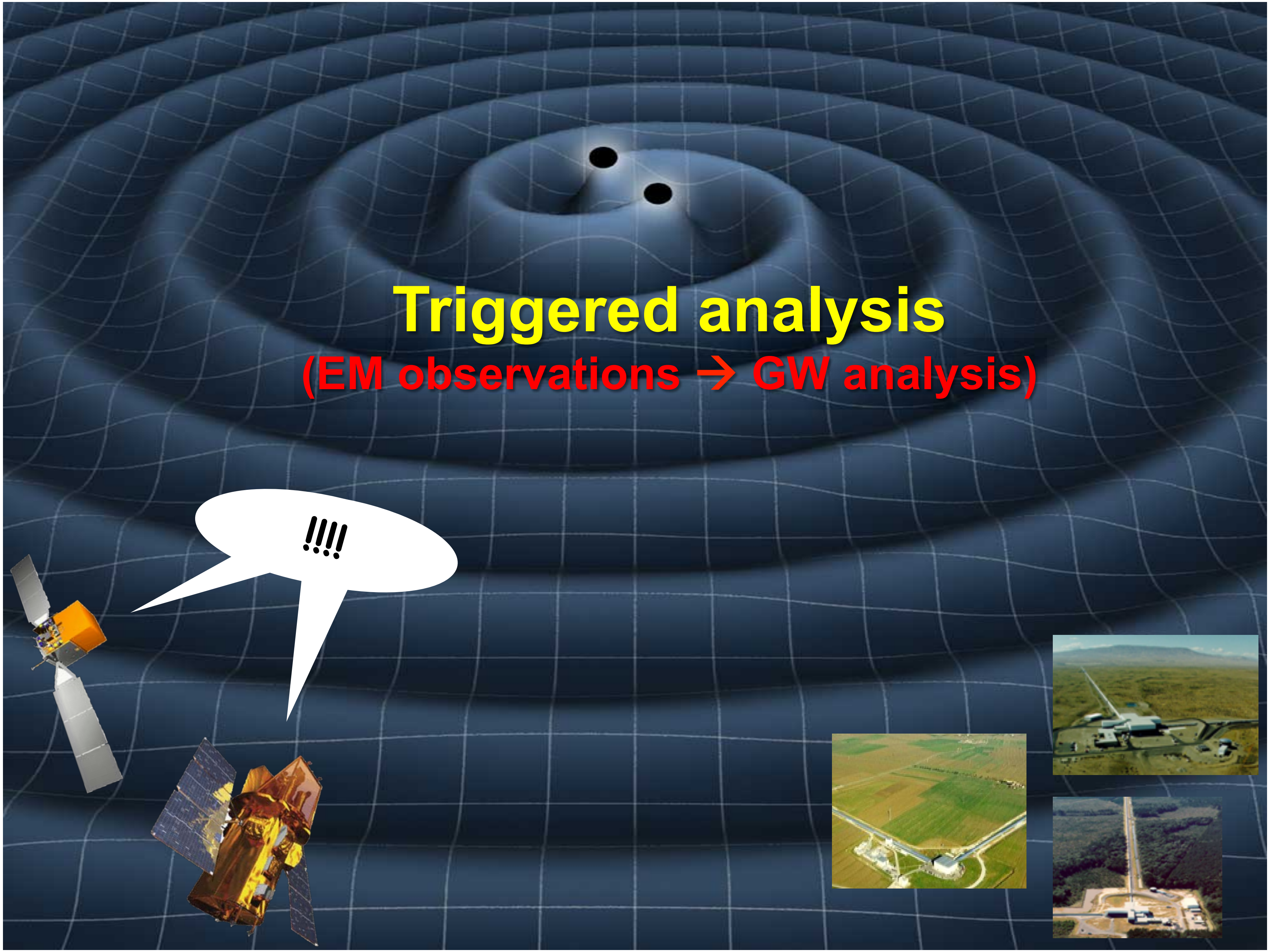
Theoretical prediction

10-10000 Gpc^{-3} yr^{-1} (Abadie et al. 2010)

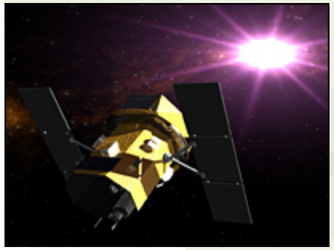
GW detection rate (0.2 – 40) yr^{-1}

Coward et al. 2012 , MNRAS, 425




Triggered analysis
(EM observations → GW analysis)
!!!!

GRB prompt emission → TRIGGERED GW SEARCH

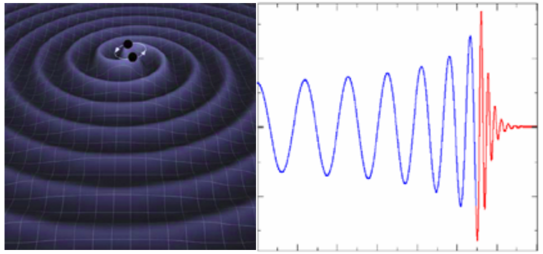


Known **GRB event time** and **sky position:**

→ **reduction in search parameter space**

→ **gain in search sensitivity**

GW transient searches

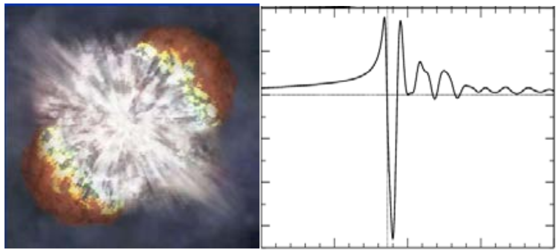


Unmodeled GW burst

(< 1 sec duration)

Arbitrary waveform

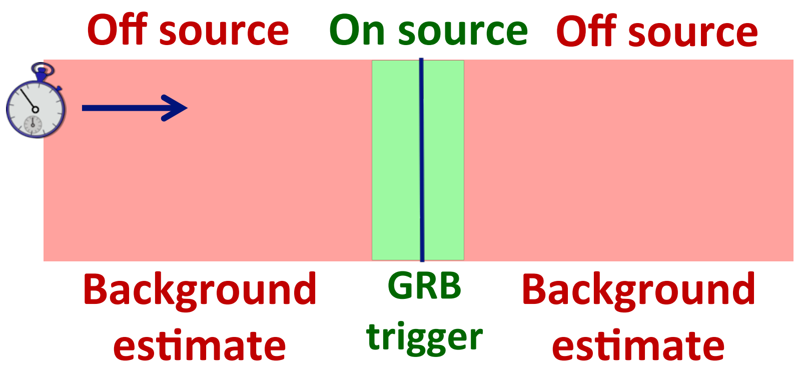
→ **Excess power**



Compact Binary Coalescence

Known waveform

→ **Matched filter**



Analyzed 154 GRBs detected by gamma-ray satellites during **2009-2010** while 2 or 3 LIGO/Virgo detectors were taken good data

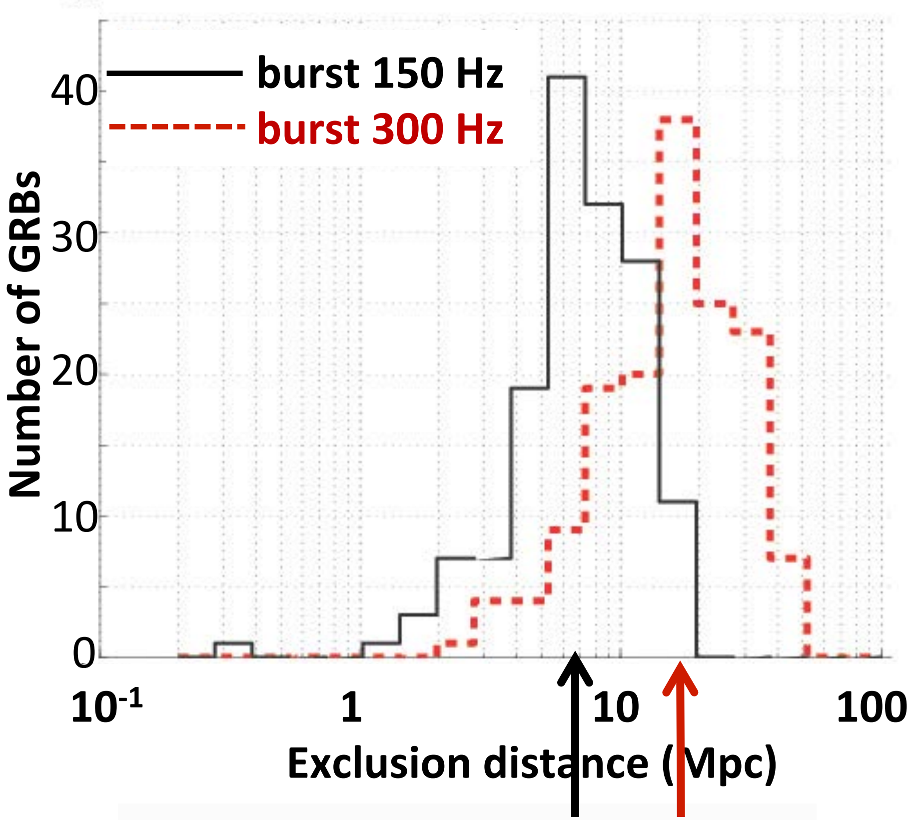
No evidence for gravitational-wave counterparts Abadie et al. 2012, ApJ, 760

GRB prompt emission - TRIGGERED SEARCH

Non GW-detection result: **lower bounds on the progenitor distance**

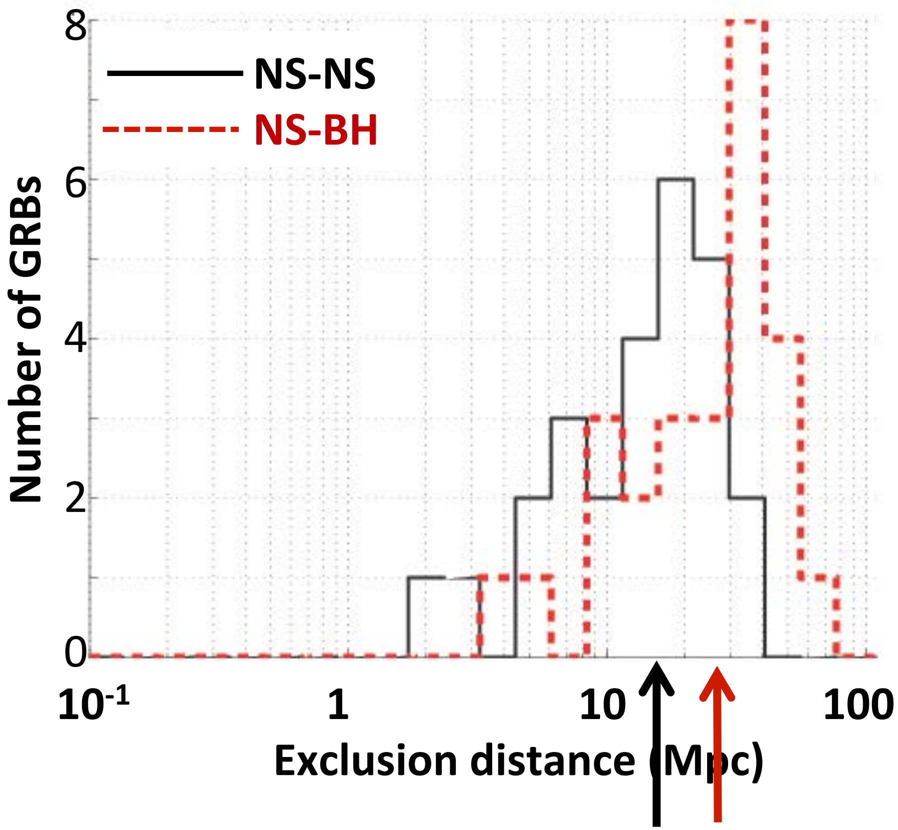
Abadie et al. 2012, ApJ, 760

Unmodeled GW burst (150 GRBs)
with **10^{-2} Moc^2 energy in GW** (optimistic)

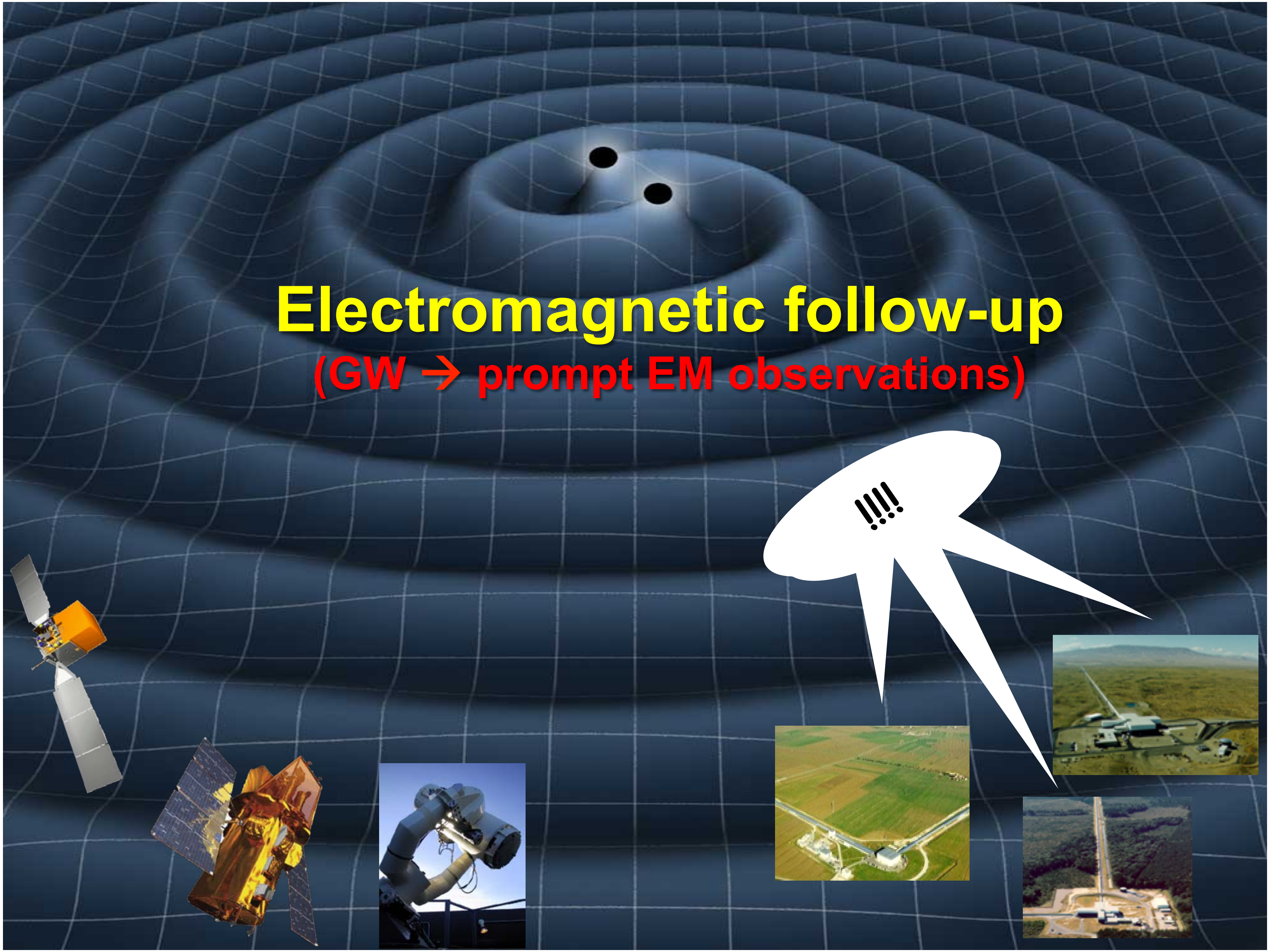


Median distances: 7 17 Mpc

Binary system coalescence
(26 short GRBs)



Median distances: 16 28 Mpc


Electromagnetic follow-up
(GW → prompt EM observations)
!!!!

EM-follow up challenges:

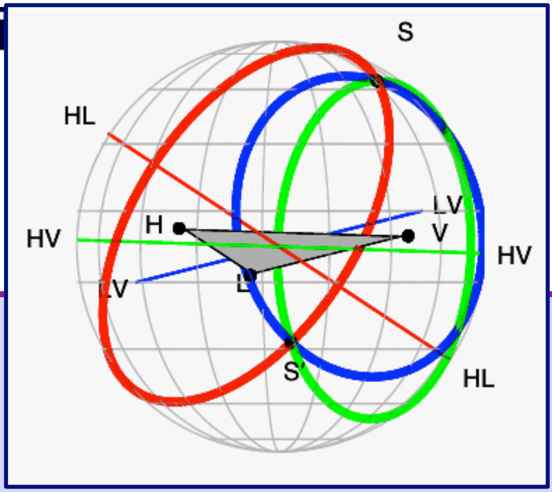
- ❖ Fast faint transient counterparts
- ❖ Large GW error box → difficult to be covered
  → many transient contaminants
- ❖ Larger Universe observed by LIGO/Virgo

EM-follow up key points:

- ❖ How to set up an optimal observational strategy? to image the whole GW error box or the most propable galaxy hosts?
- ❖ How to uniquely identify the EM counterpart?

TIGHT LINK is required between GW/EM/Theoretical COMMUNITIES!!

Sky Localization of GW transients

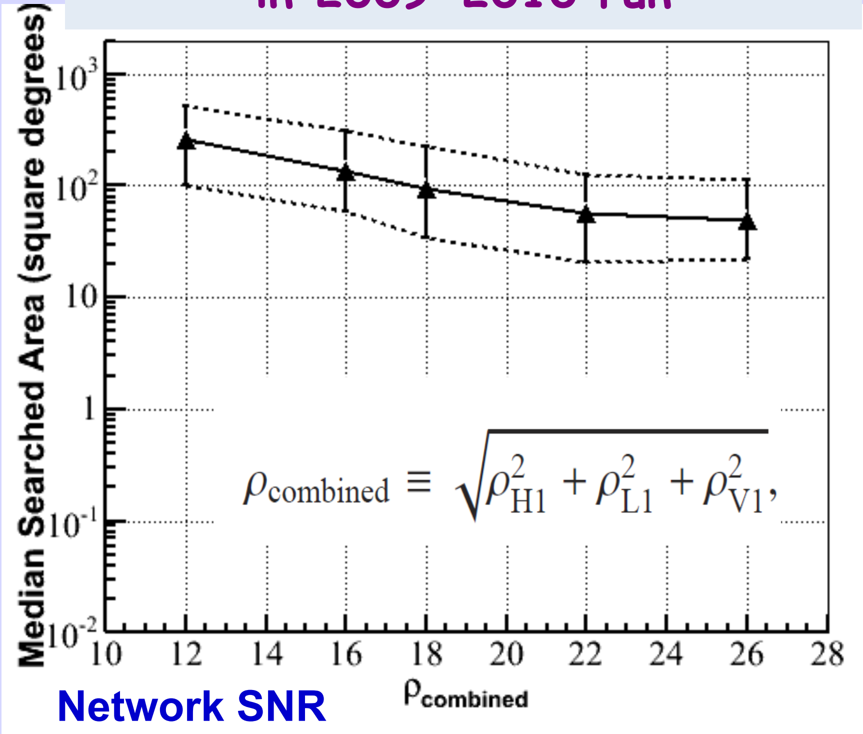


The **sky position of a GW source** is mainly evaluated by **"triangulation"** based on **arrival time delay between detector sites**

low SNR signals were localized into regions of **tens to hundreds of sq. degrees** possibly in several disconnected patches

Necessity of wide field of view EM telescopes

Binary coalescence localization in 2009-2010 run



Abadie et al. 2012, A&A 539

2009-2010 first EM follow-up of candidate GW events

Low-latency GW data analysis pipelines enabled us to: 1) identify GW candidates in "real time" and 2) obtain prompt EM observations

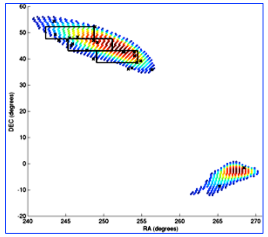
GW triggers

Sky Pointing Position

EM facilities

LIGO-H LIGO-L

Virgo



Event validation

"Search Algorithms" to identify the GW-triggers:

- **Unmodeled Burst Search**
- **Matched Filter Search** for Compact Binary Coalescence

"Software" to identify GW-trigger for the EM follow-up:

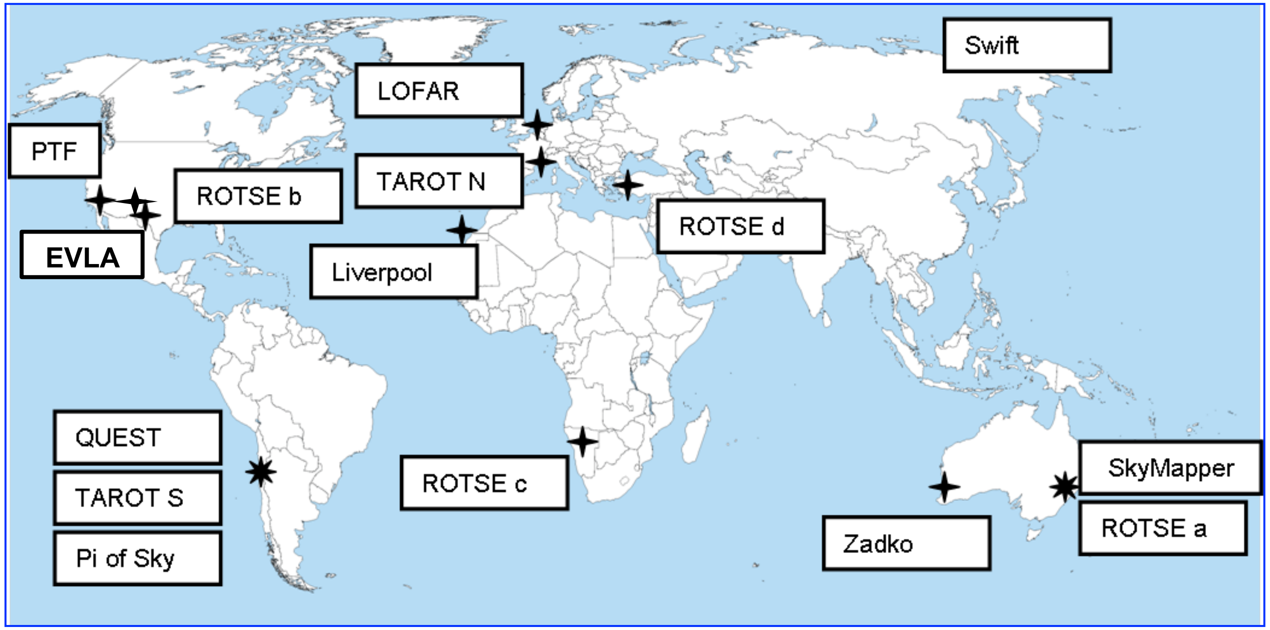
- select statistically significant triggers wrt background
- determine telescope pointing

~ 10 min. → ~ 30 min.

ADE latency expected to be improved!

Abadie et al. 2012, A&A 539
Abadie et al. 2012, A&A 541
Evans et al. 2012, ApJS 203
Aasi et al. 2014, ApJS, 211

Ground-based and space EM facilities involved in 2009-2010 follow-up program



Optical Telescopes

(FOV, limiting magnitude)

TAROT SOUTH/NORTH

3.4 deg^2 , **17.5** mag

Zadko

0.17 deg^2, **20.5** mag

ROTSE

3.4 deg^2 , **17.5** mag

QUEST

9.4 deg^2 , **20.5** mag

SkyMapper

5.7 deg^2 , **21** mag

Pi of the Sky

400 deg^2 , **11.5** mag

Palomar Transient Factory

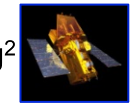
7.8 deg^2 , **20.5** mag

Liverpool telescope

21 arcmin^2 , **21** mag

X-ray and UV/Optical Telescope

Swift Satellite



XRT-FOV **0.16** deg^2

Flux **10^{-13}** ergs/cm^2/s

Radio Interferometer

LOFAR

30 - 80 MHz

110 - 240 MHz

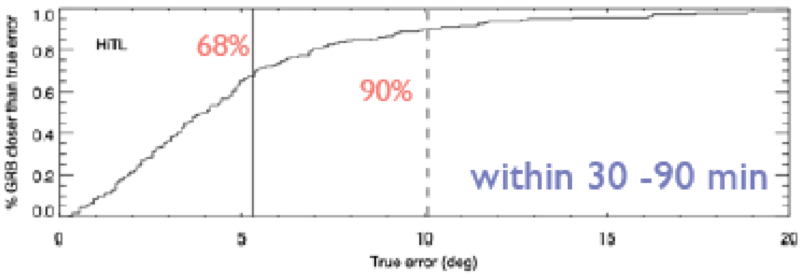
Maximum **25** deg^2

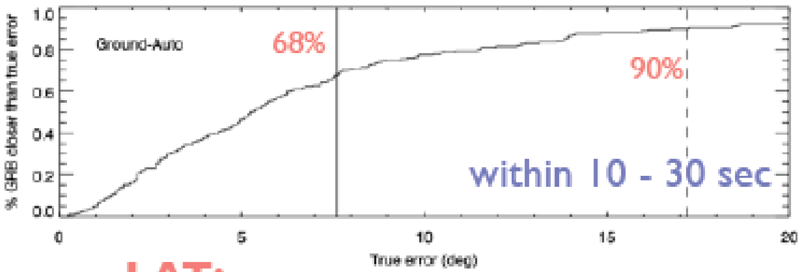
EVLA

5 GHz - **7** arcmin^2

Fermi Gamma-Ray Space Telescope: Detecting GRBs with GBM and LAT between 8 keV and 30+ GeV since 2008.   Until... 2018 + ??

GBM:

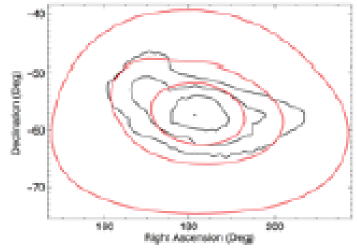




GBM: 240 GRBs per year, 45 short

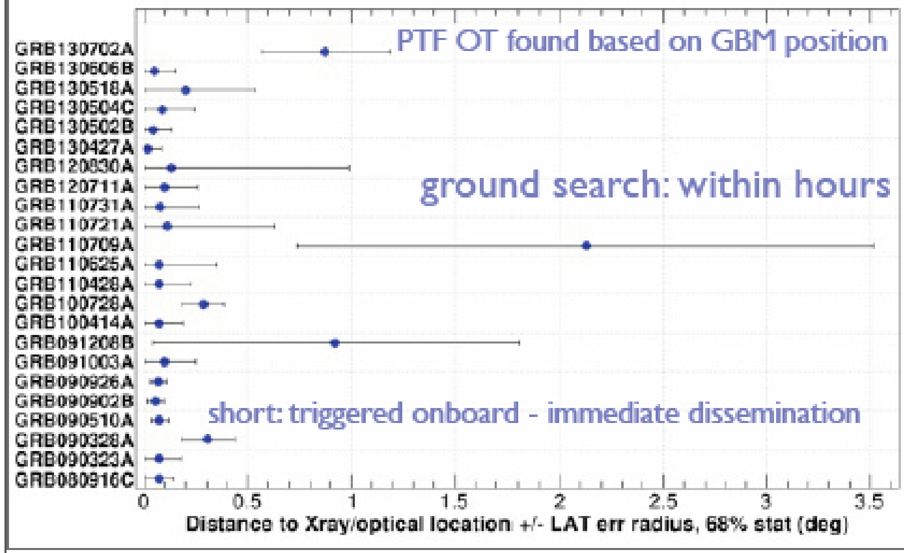
50% duty cycle on any sky position

Localization: Improved Ground-Auto. New data product: contours on sky that include systematic error.



New offline search: TTE data for weaker short transients. Will search for any LIGO GW candidate

LAT:



LAT: Fewer GRBs (~12 per year) but well-localized.

Followed up successfully with XRT/OT. Afterglows are bright

New event selections: Expect 20-50% more GRBs using new searches.

Courtesy of V. Connaughton of GBM team (presented @ Chicago Meeting Sept. 13)

LIGO-Virgo EM-follow up plan

➢ **Agreed LVC Policy for releasing GW triggers** (dcc.ligo.org/M1200055, VIR-0173A-12)

"**Until first four GW events** have been published, **triggers will be shared** promptly only with astronomy partners who have signed an **MoU** with LVC "

➢ **Opened call to sign MoU** for the identification of EM counterparts to GW triggers found in the next science runs of aLIGO/Virgo, which will start in 2015 **Deadline 16 Feb, 2014**

➢ More than

sixty MoU applications

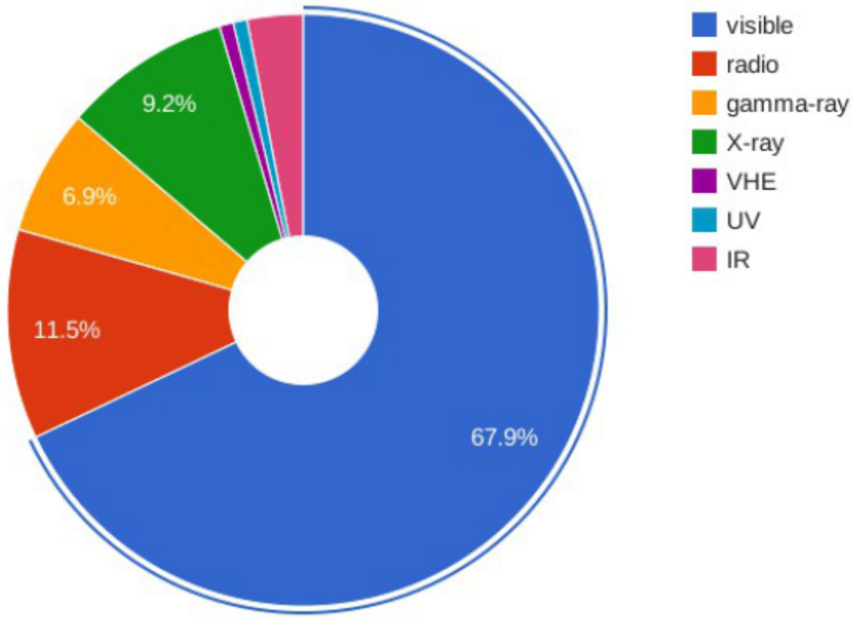
from **19 countries**

about **150 instruments**

covering the full spectrum

from radio to

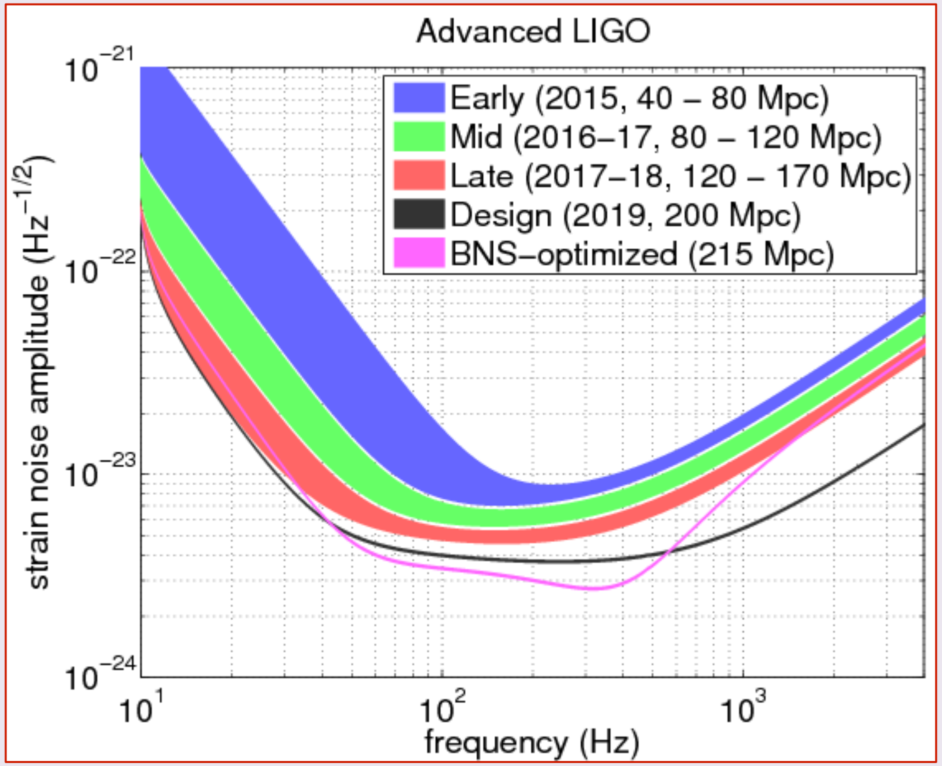
very high-energy gamma-rays!

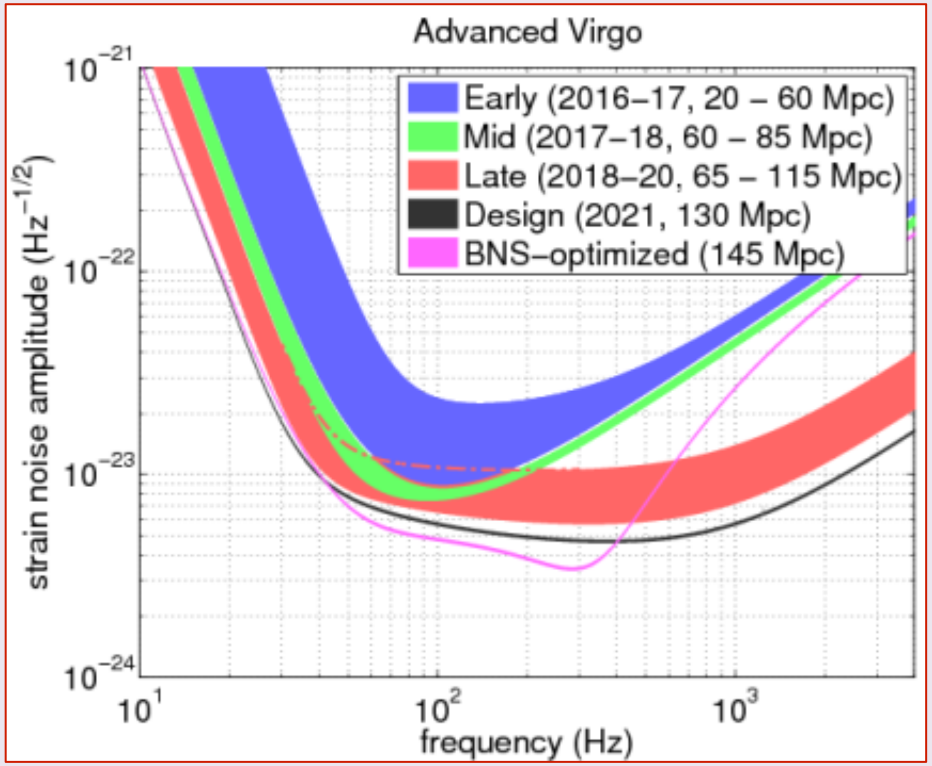


Advanced GW Detectors: Observing scenario

LSC & Virgo Collaborations, arXiv:1304.0670

Progression of sensitivity and range for Binary Neutron Stars

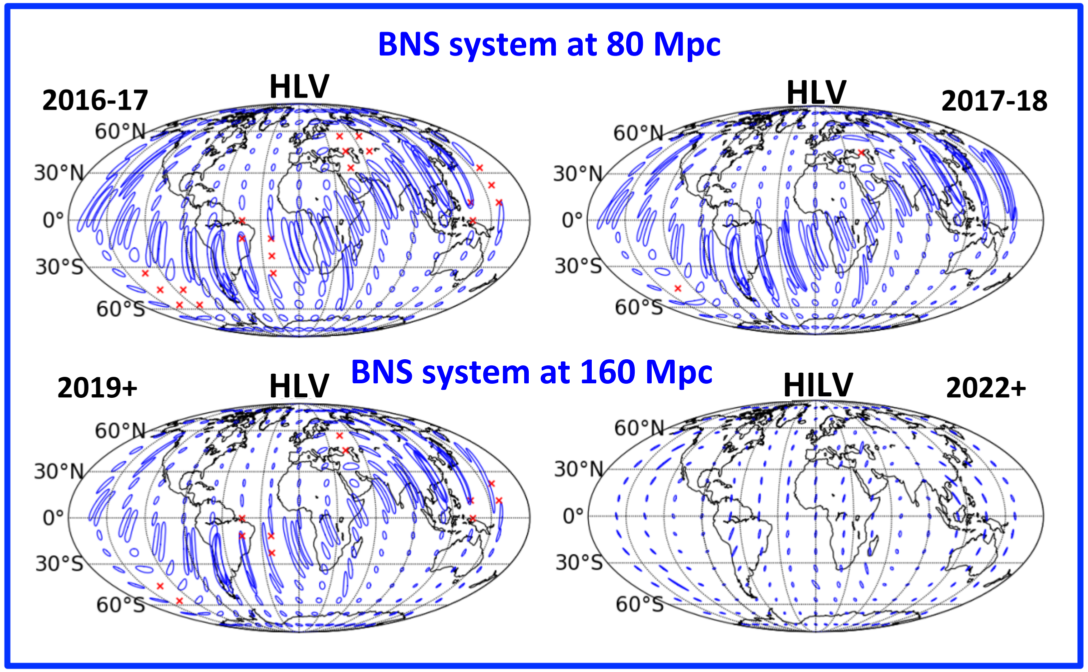




Larger GW-detectable Universe

Sky Localization of Gravitational-Wave Transients

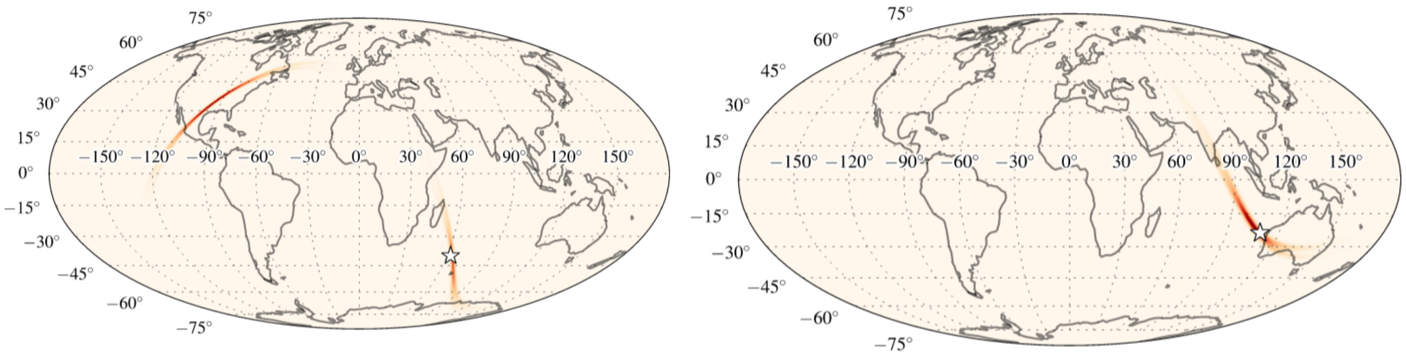
Position uncertainties with areas of **tens to hundreds of sq. degrees**



→ 90% confidence localization areas

X → signal not confidently detected

Example of skymaps for the first two years of operation, 2015 through 2016



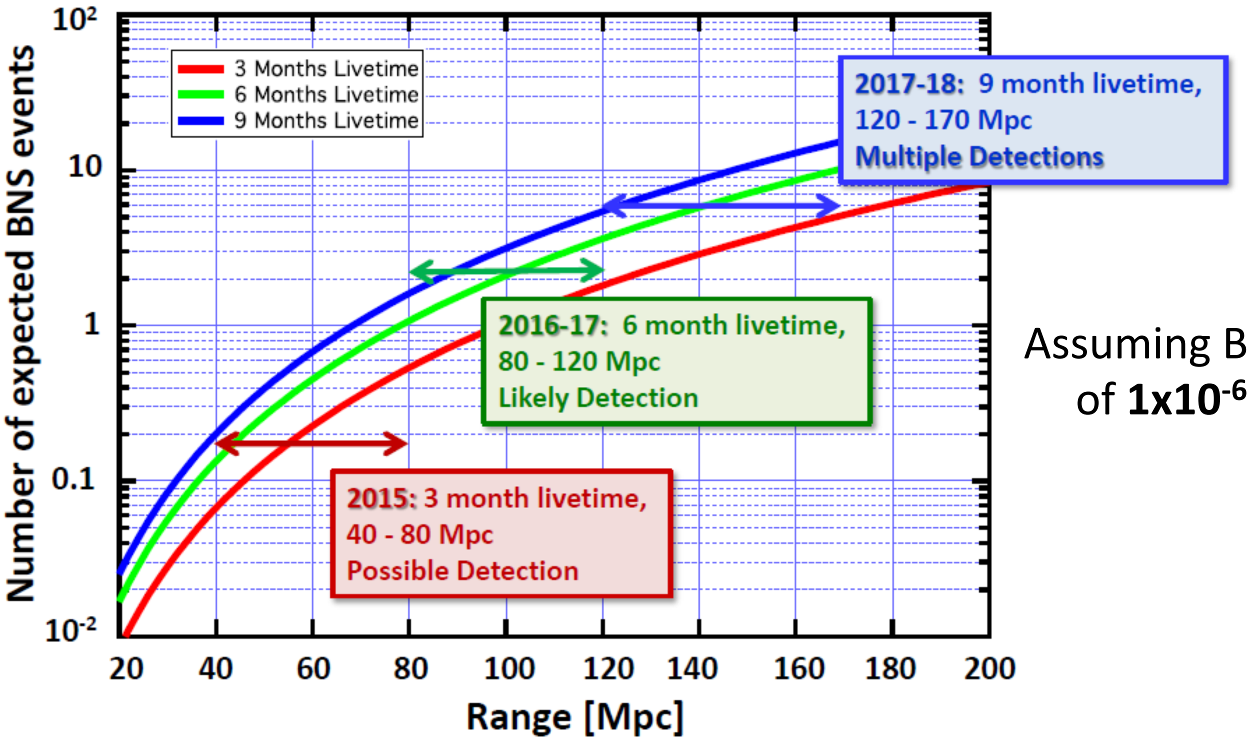
Median 90% CR of:
about **500 deg²** in 2015
about **200 deg²** in 2016

Singer et al. arXiv:1404.5623 http://www.ligo.org/science/first2years

A plausible scenario

LSC & Virgo collaboration
arXiv:1304.0670

		aLIGO/Virgo Range				Rate	Localization	
Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 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 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

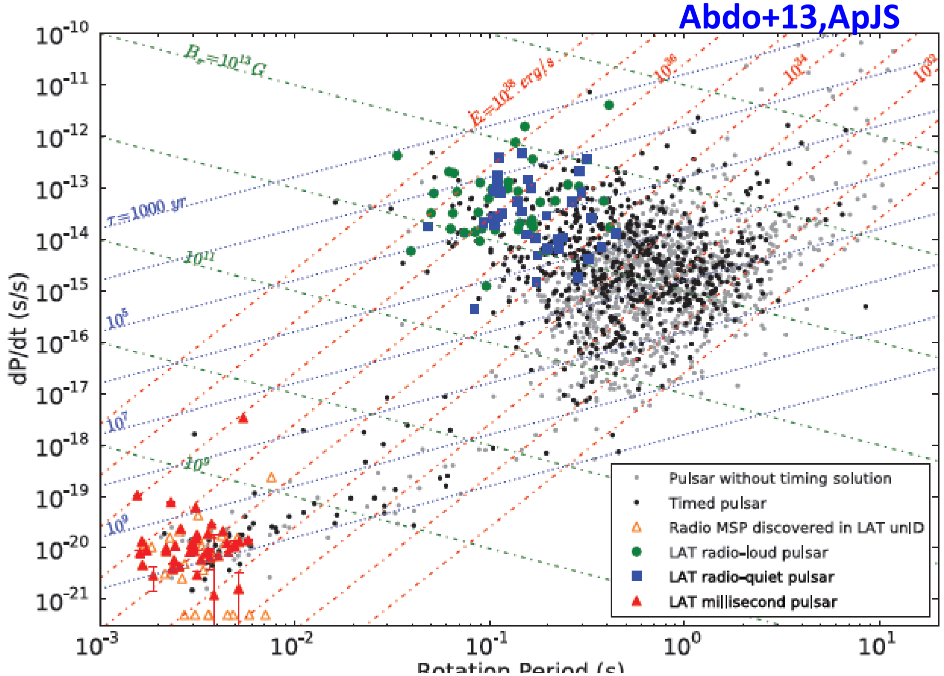


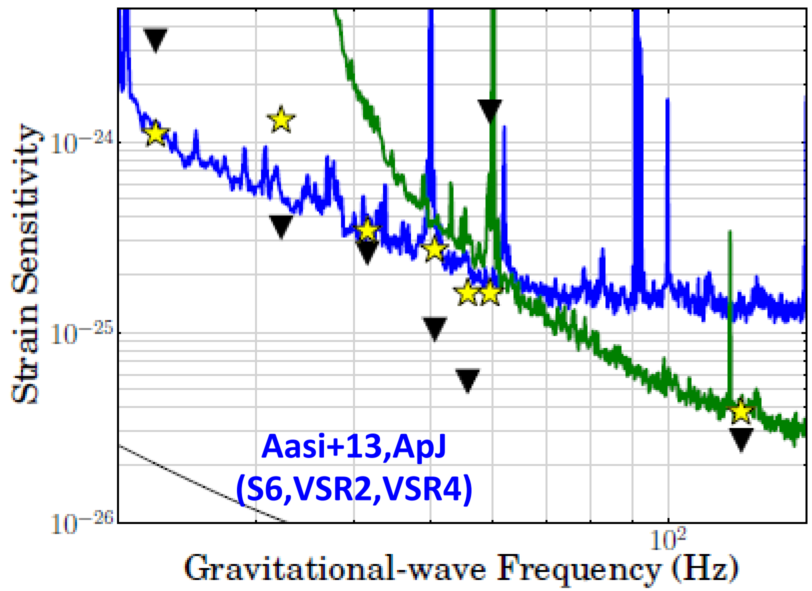
Assuming BNS merger rate of **1x10^{-6}** Mpc^{-3} year^{-1}

The pulsar connection

- **Quadrupole momentum from oblate neutron stars**
- **Periodic continuous GW signal**
- **Complementary information**
  - GWs from neutron star
  - Gamma rays from magnetosphere
- **EM →GW**
  - Many Fermi pulsars are young, energetic, and relatively nearby, i.e. good GW candidates
  - Fermi continuously monitors pulsars, providing timing solutions
  - Fermi is the only instrument capable of timing radio-quiet pulsars

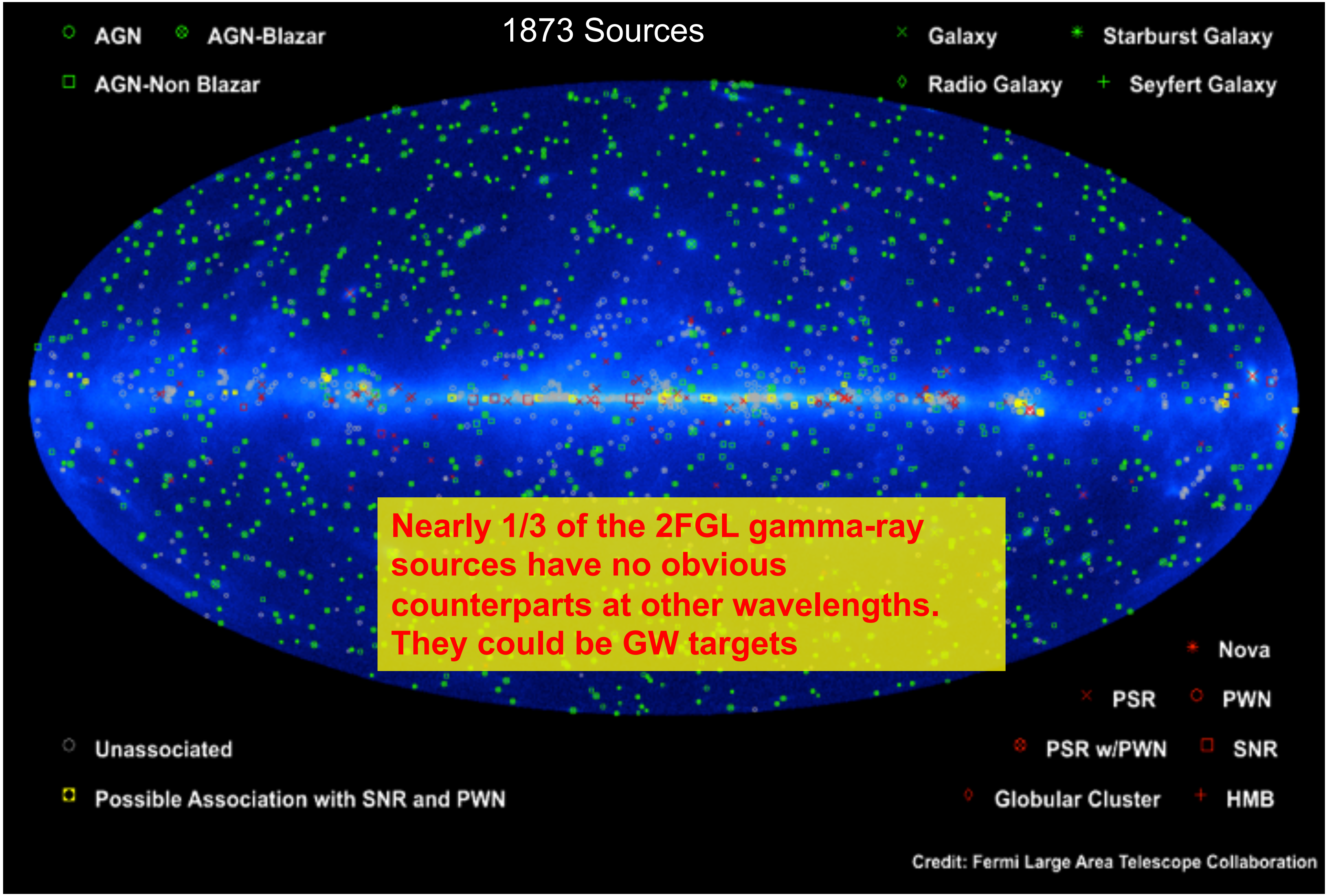
Abdo+13,ApJS





Aasi+13,ApJ
(S6,VSR2,VSR4)

…and a lot of unidentified sources

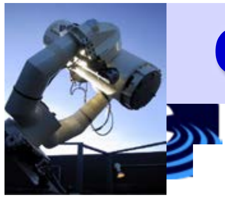


Many GW/gamma rays connections

- GW and photons provide complementary information
  - Multimessenger observations extremely promising
- Multimessenger approach is key to study the most extreme objects in the Universe
  - Natural laboratories to probe fundamental physics
  - Transients (e.g. GRBs)
  - Neutron stars
  - Unidentified sources?
- Virgo and LIGO are undergoing major upgrades
  - Increased sensitivity → Larger volumes to probe
  - Joint observations planned for 2016
- Good availability of instruments
  - Many optical/radio telescopes in EM-followup program
  - From space, Swift & Fermi mission extended (Senior Review 2014)

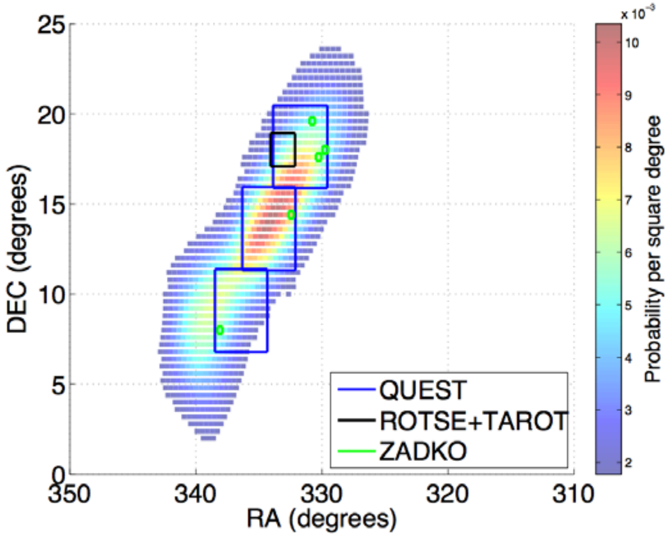
A new, big community is growing,
to be ready for the challenges of the multimessenger era !

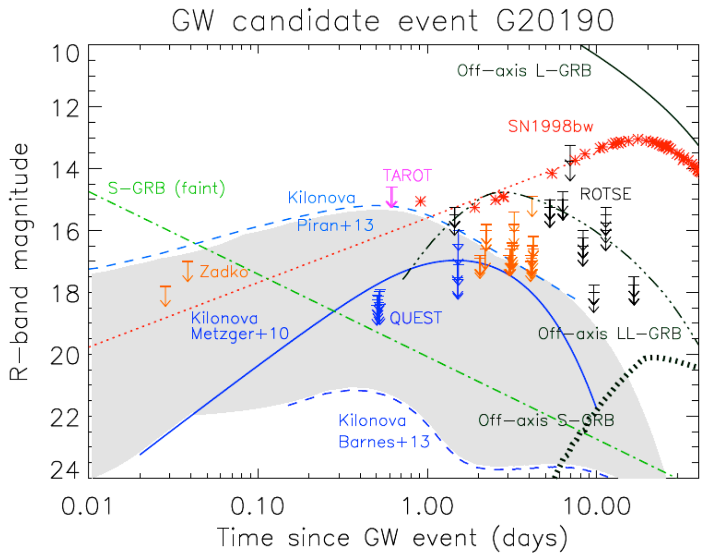
Backup

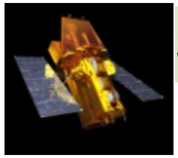


Optical telescope 8 GW alerts

Aasi et al. 2014, ApJS, 211







Swift Satellite: XRT-UVOT

2 GW alerts

Evans et al. 2012, ApjS, 203

Radio Interferometers

LOFAR

5 GW alerts

E-VLA

2 GW alerts

Lazio et al. , 2012 IAUS, 285

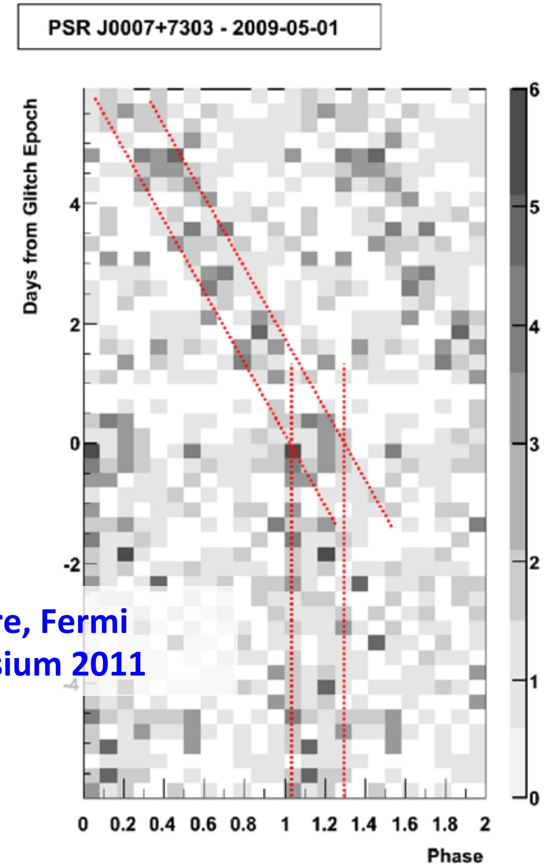
GW/EM transient data analysis results:

- **Off-line analysis of the GW data** alone → GW candidates show **no evidence of an astrophysical origin**
- **EM transients** detected in the images **consistent with the EM background**

GWs & pulsar glitches

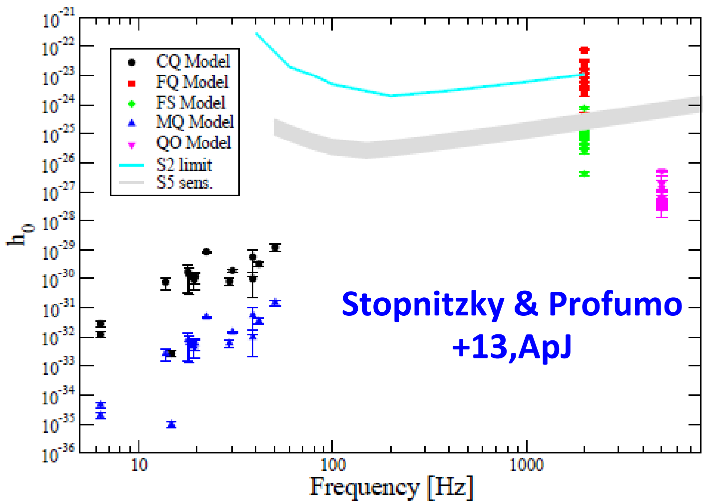
- **Burst-like signal from pulsar glitches**
- **Loss of coherence**
- **GW Upper limits for some pulsars (e.g. Vela)**

- **Complementary information**
  - GWs from neutron star
  - Gamma rays from magnetosphere



Belfiore, Fermi Symposium 2011

- **EM →GW**
  - Fermi continuously monitors the sky, detects glitches "on the fly"
  - Extract glitch parameters from gamma-ray data, crucial for addressing GW searches
  - Unique instrument for radio-quiet pulsars



Stopnitzky & Profumo +13,ApJ

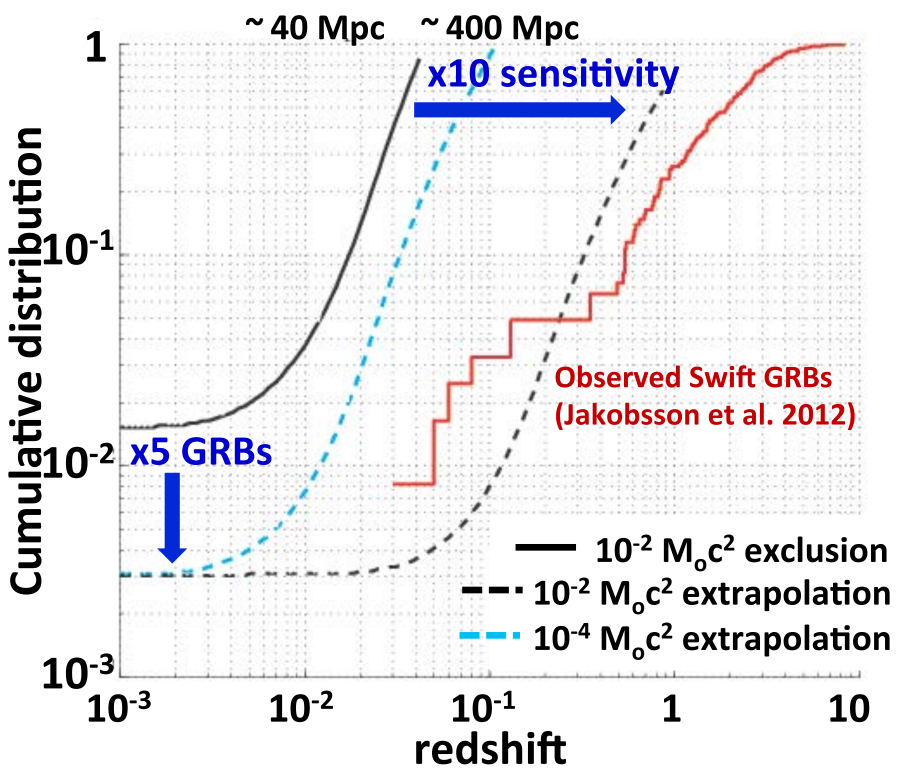
GRB prompt emission - TRIGGERED SEARCH

Population exclusion on cumulative redshift distribution

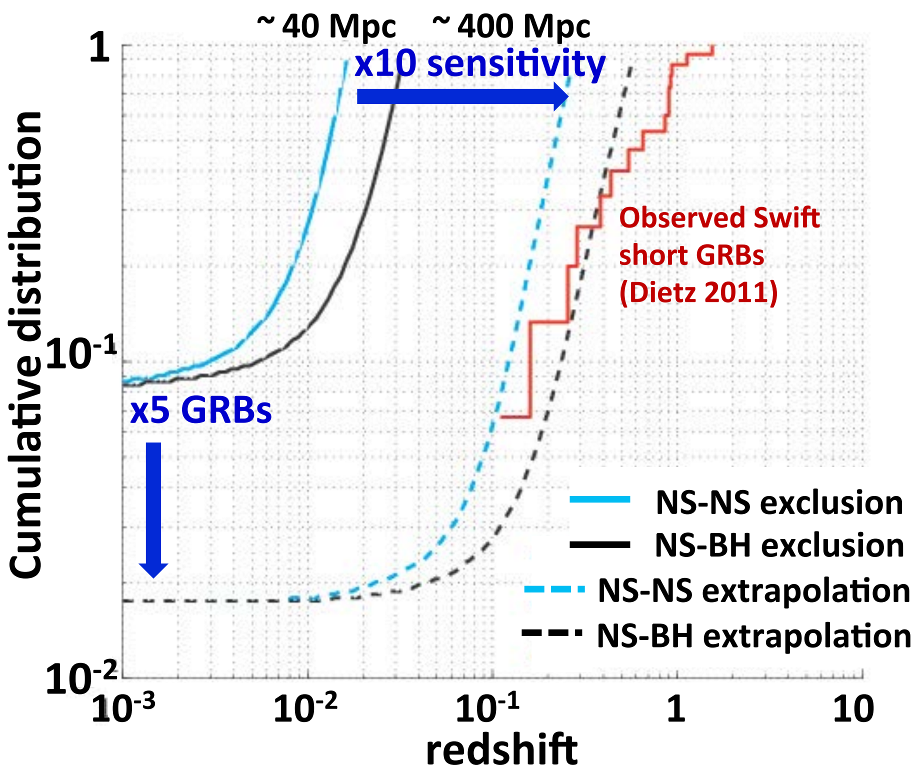
Results 2009-2010 & prospects for Advanced LIGO/Virgo

Abadie et al. 2012, ApJ, 760

Unmodeled GW burst (150 GRBs)



Binary system coalescence (26 GRBs)



→ Detection is quite possible in the advanced detector era

→ No detection will place relevant constraints on GRB population models