Multi-Messenger Observations of GRBs: The GW connection

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Outline

1. Introduction: GRBs in the **multi-wavelength** context

2. The **GW – GRB connection**

3. Start of the GW/EM **multi-messenger era**
   - **GW150914**
   - **GW170817 / GRB 170817A**

4. Current **status** and future **prospects**

PROCEEDINGS OF SCIENCE

Multi-Messenger Observations of GRBs: The GW connection

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Two years ago, the astronomical community witnessed a historical breakthrough observation: the detection of a short Gamma-Ray Burst (GRB) by gamma-ray instruments in coincidence with the detection of a Gravitation Wave (GW) signal produced by the coalescence of two binary neutron stars. This joint GRB-GW observation paved the way to a new chapter in modern astrophysics: the "Multi-Messenger" era. In this contribution, I will review the main results by gamma-ray experiments obtained from 2015 to 2017 during the first two observational runs of the LIGO-Virgo experiments (O1/O2), and highlight strategies and status during the current run (O3) which will cover a 1-year period starting April 2019. Finally, I will focus on future prospects for gamma-ray missions dedicated to GW counterpart studies.

36th International Cosmic Ray Conference -ICRC2019-
July 24th - August 1st, 2019
Madison, WI, U.S.A.

*Speaker.

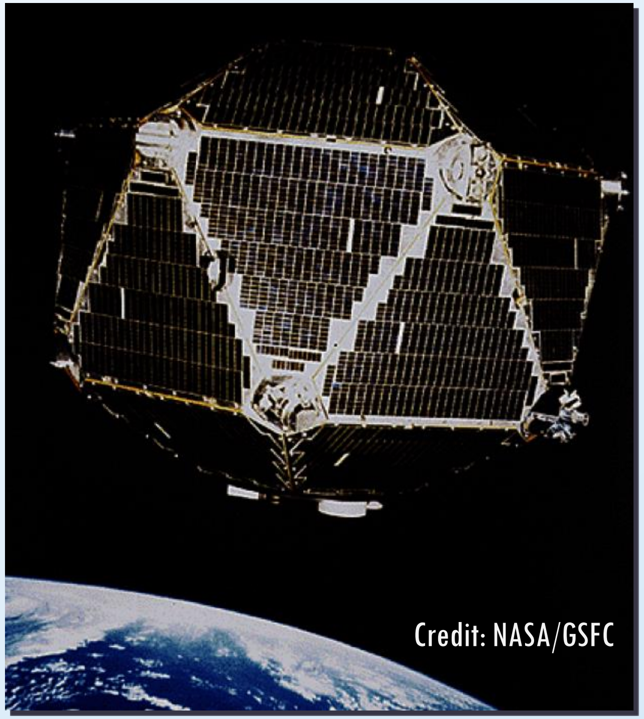
http://pos.sissa.it/

https://pos.sissa.it/358/003

Gamma–Ray Bursts

→ The keV emission kicked off the GRB show in the '70s!

VELA-5B satellite (1969) in low earth orbit



THE ASTROPHYSICAL JOURNAL, **182**:L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

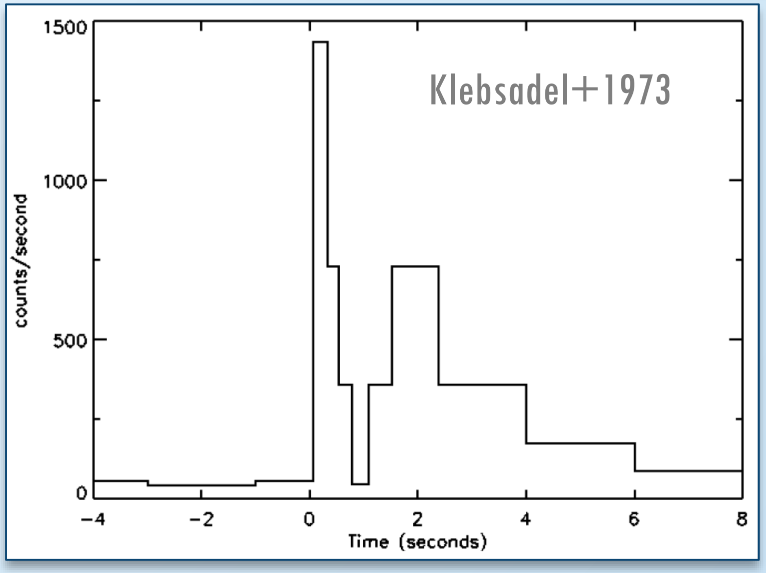
RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

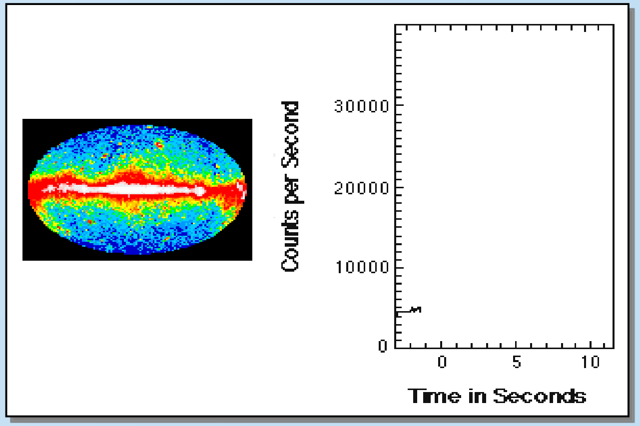
Received 1973 March 16; revised 1973 April 2

ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.



Light curve of the first Gamma-Ray Burst

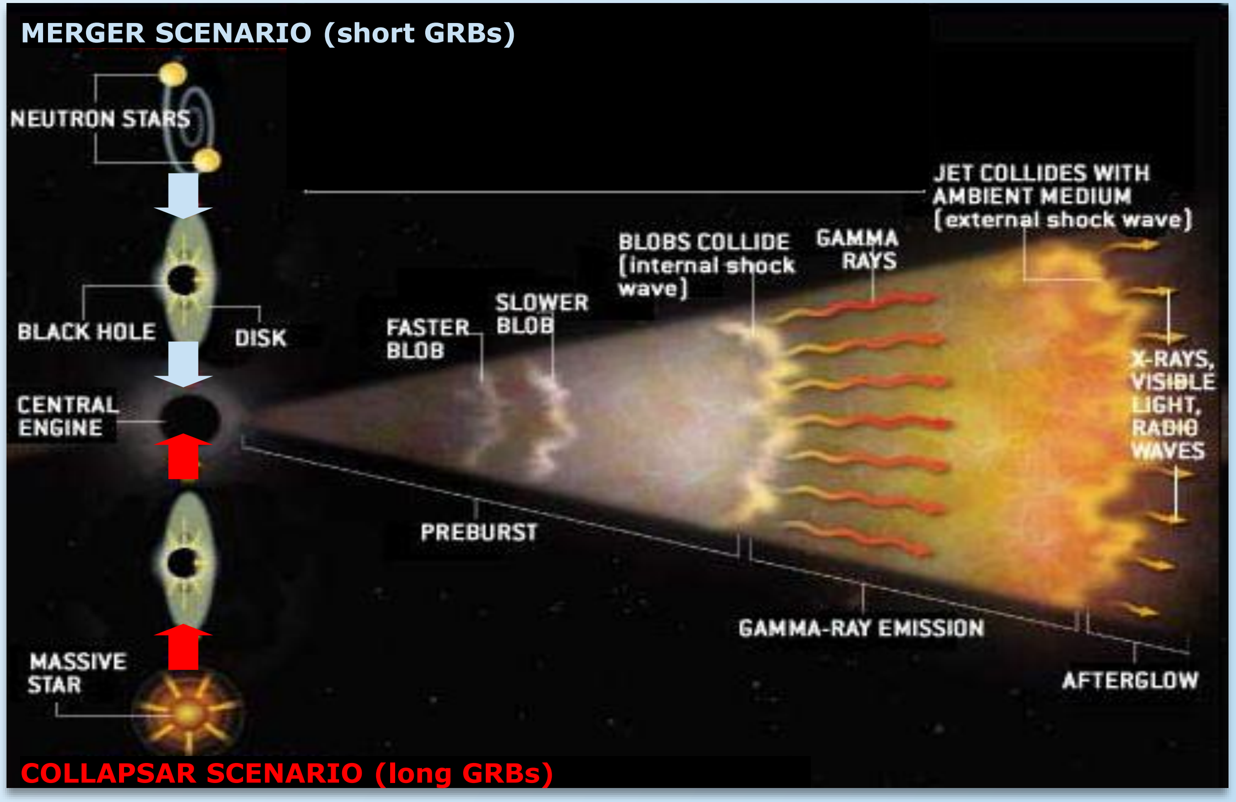


Gamma–Ray Bursts

→ The keV emission kicked off the GRB show in the '70s!

- What we know now:
  1. GRBs are cosmological (Optical)
  2. GRBs have large bulk Lorentz factors (Radio/GeV)
  3. 2 emission phases: Prompt and afterglow (Optical/GeV)
  4. Long and short GRBs (keV/MeV)
  5. Spikes have same durations
  6. Supernova connection (Optical)
  7. Common behaviors and trends (X-ray/keV)

«Pillars of knowledge» [Ghisellini 2010]



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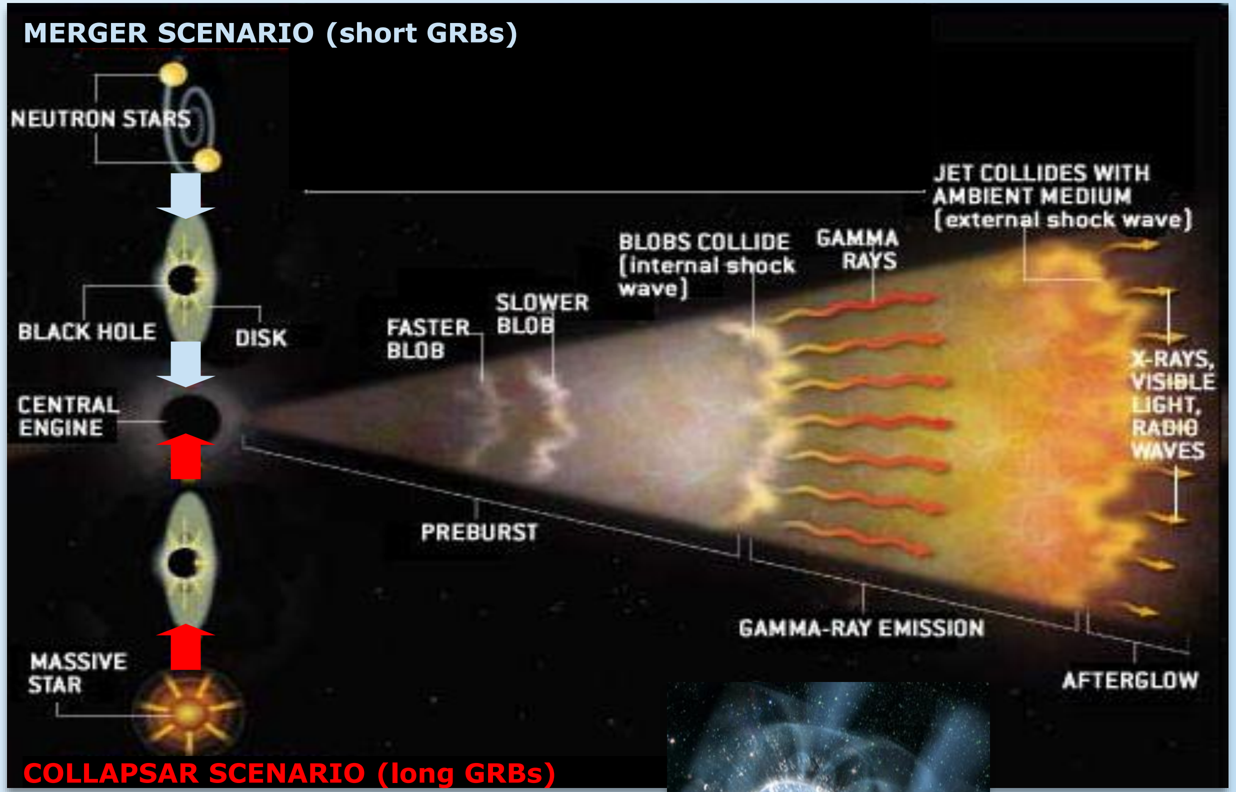

Multi-Wavelength has always been the key!
Synergy between instruments (and community!) is crucial

Gamma–Ray Bursts

→ Unveiling the GRB phenomenon still represents a **large field of research**

- **Multi-wavelength/multi-messenger** observations **crucial** to answer many **open questions**
  - What is the physics behind?
    - **Prompt**: mechanism, jet properties, central engine
    - **Early afterglow**: mechanism (plateau phase), particle acceleration, B field generation
  - Tools to probe the Universe
    - **Cosmological** relations
    - **Extragalactic background light** (deeper than AGN)
  - Tests of UHECR origin, fundamental physics
    - Signatures of **accelerated hadrons**
    - **Lorentz invariance violation**

GRB observations in the gamma-ray regime

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  - **BATSE** [1991–2000; 20–2000 keV]
    2704 GRBs **(~300 GRBs/yr)**

  - **BeppoSAX** [1996–2003; 40–700 keV]
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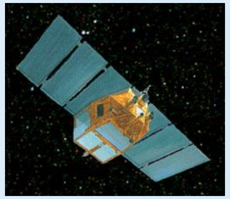

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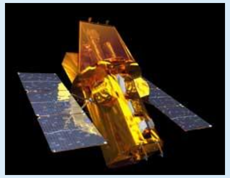
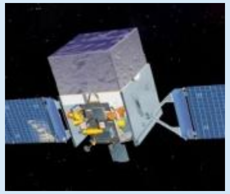
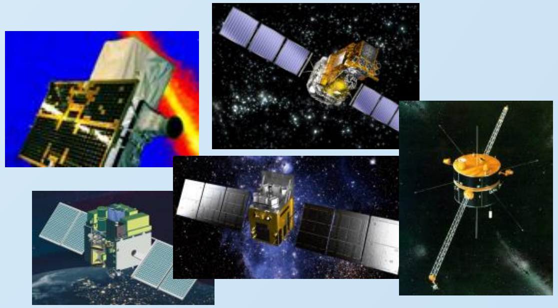


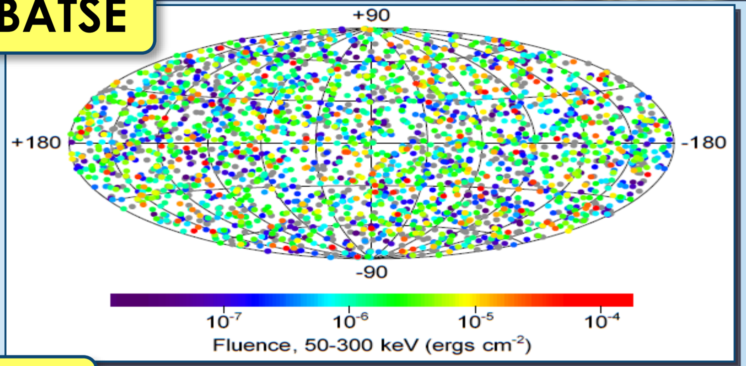
  - **Fermi-GBM** [since 2008; 8 keV–40MeV]
    ~2630 GRBs **(~240 GRBs/yr)**



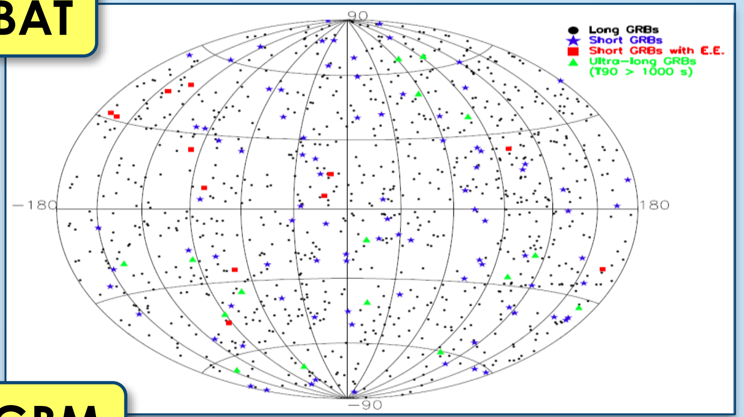
  - **Other Missions:** HETE-2, INTEGRAL, Konus, Suzaku, AGILE, MAXI-GSC, Astrosat-CZTI, Insight-HXMT, CALET-GRBM **(~150 GRBs/yr)**



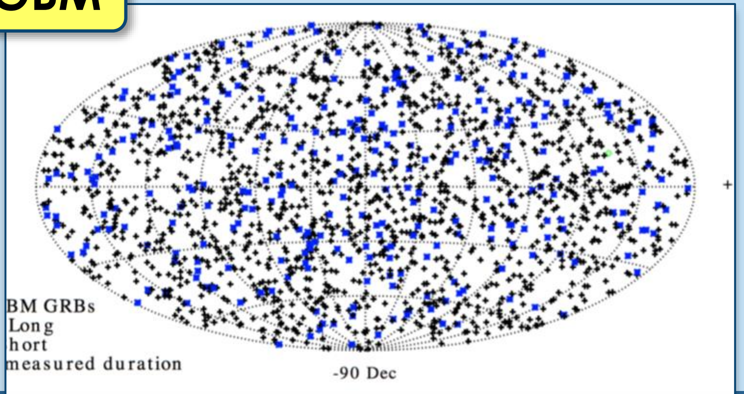
BATSE



BAT



GBM



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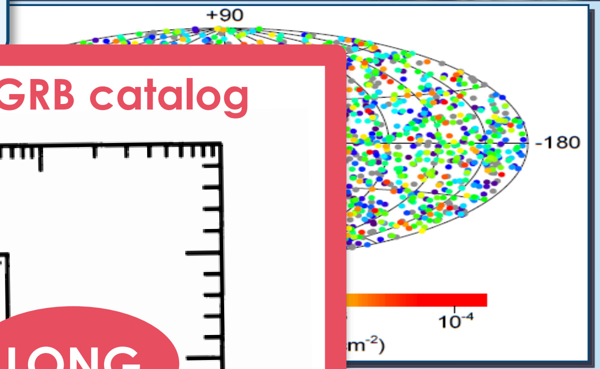
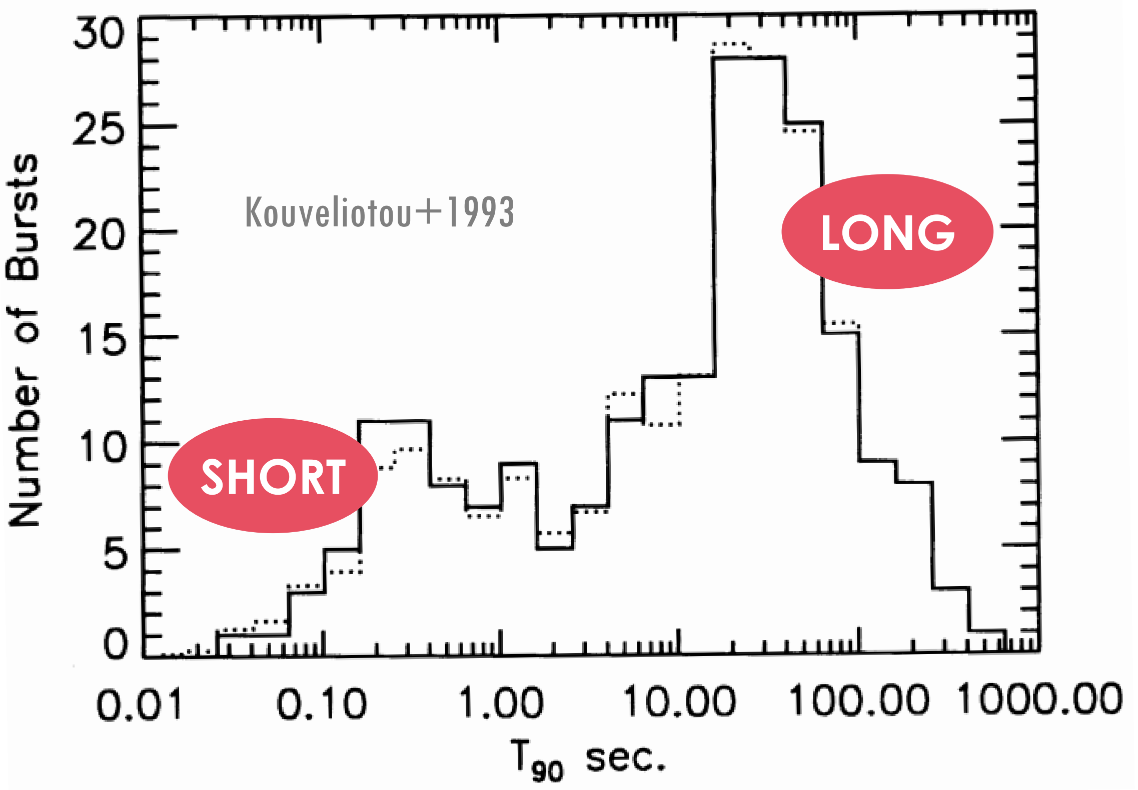
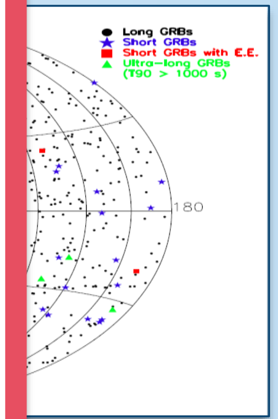
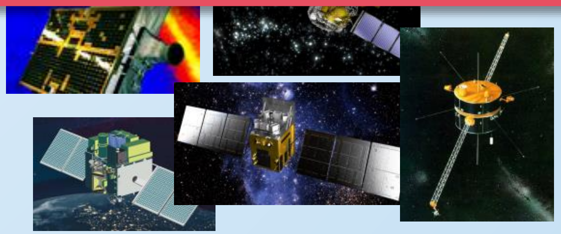
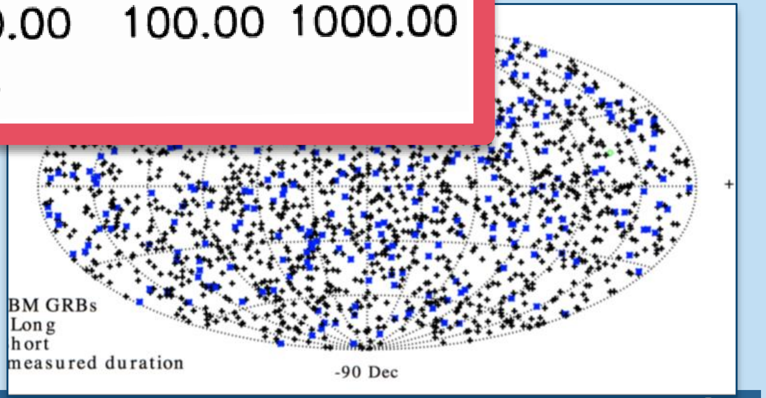


Duration distribution of the first BATSE GRB catalog









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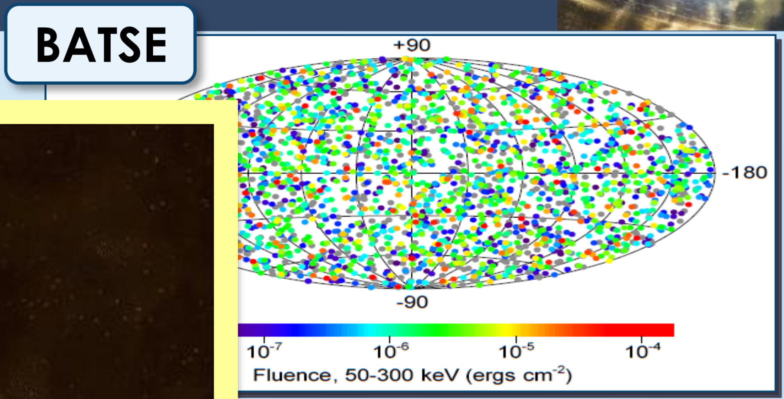

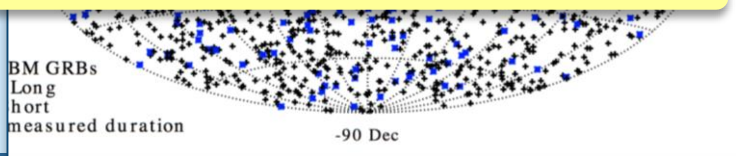

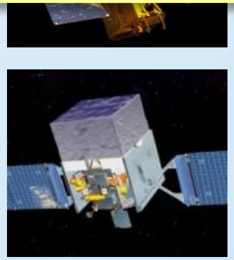

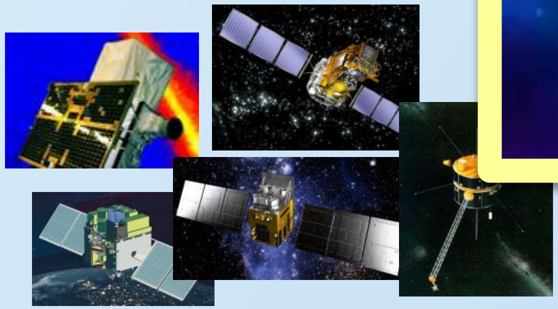

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  - ***Short GRB afterglow discovery***
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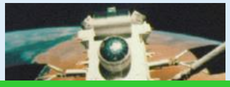
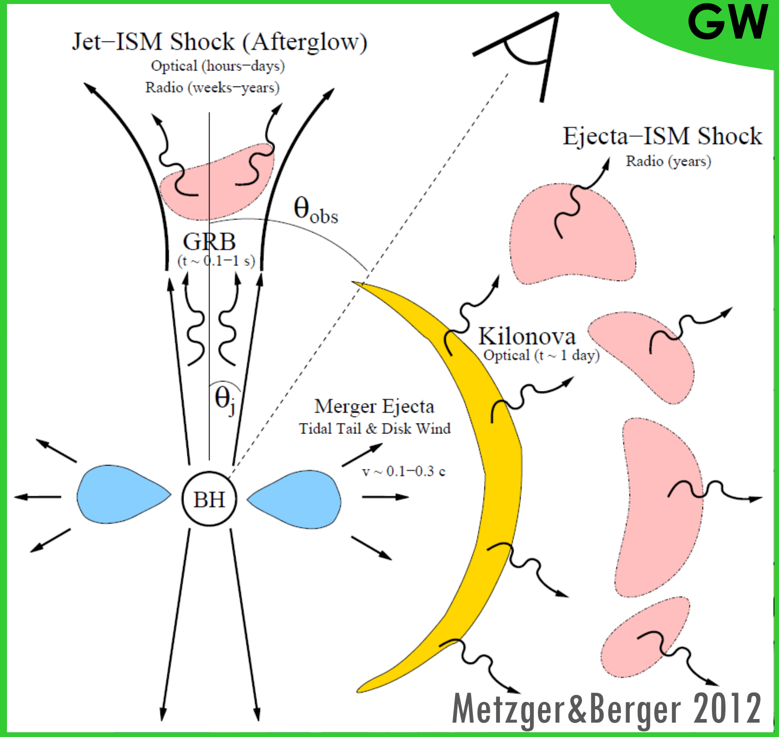
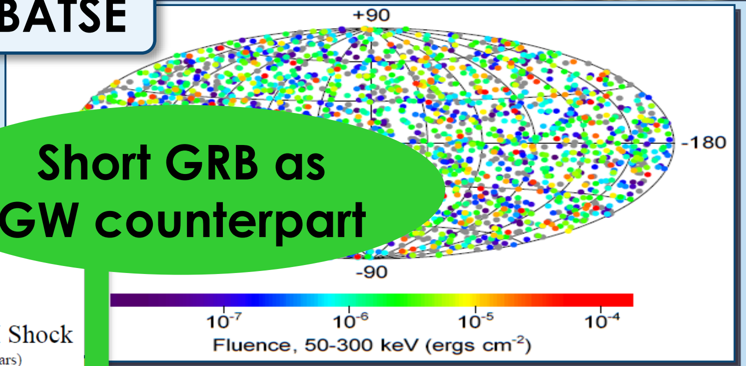
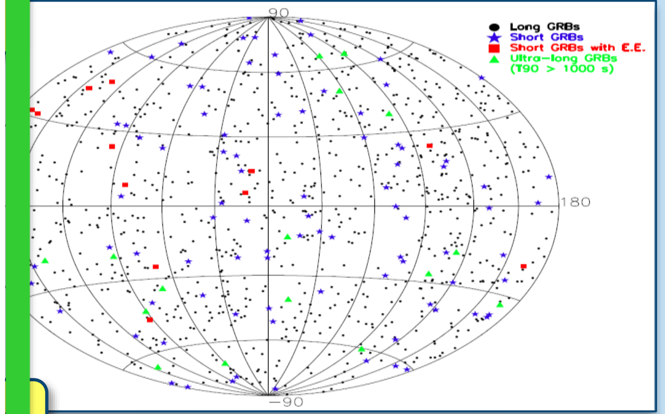


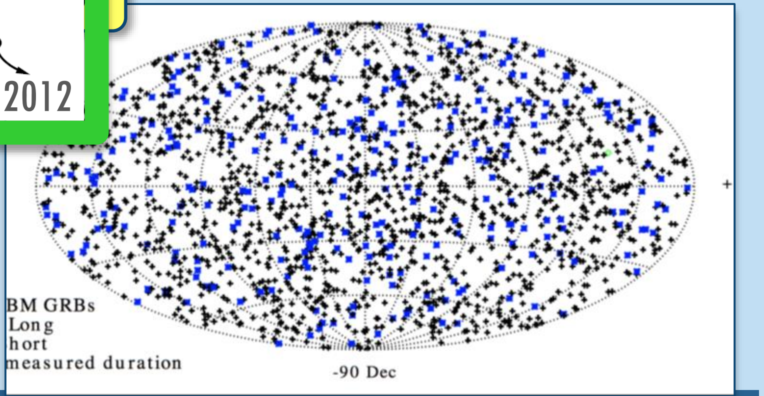


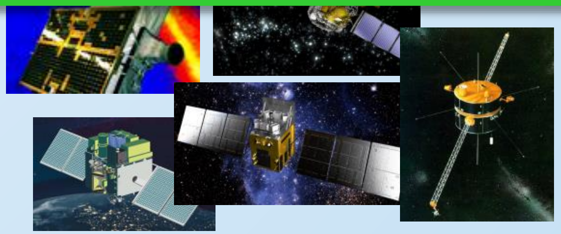
Short GRB as GW counterpart

BATSE









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Most prolific short GRB detector

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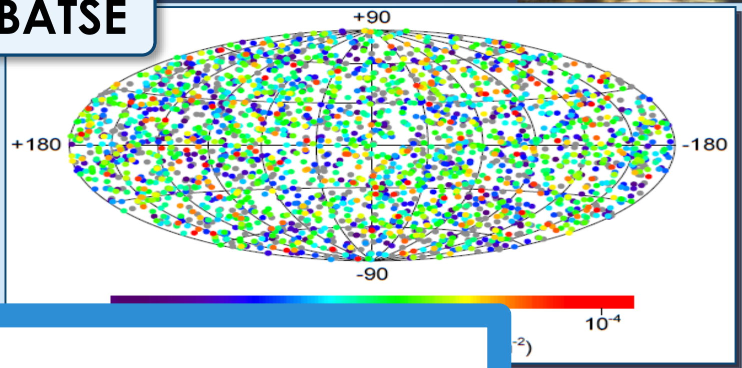
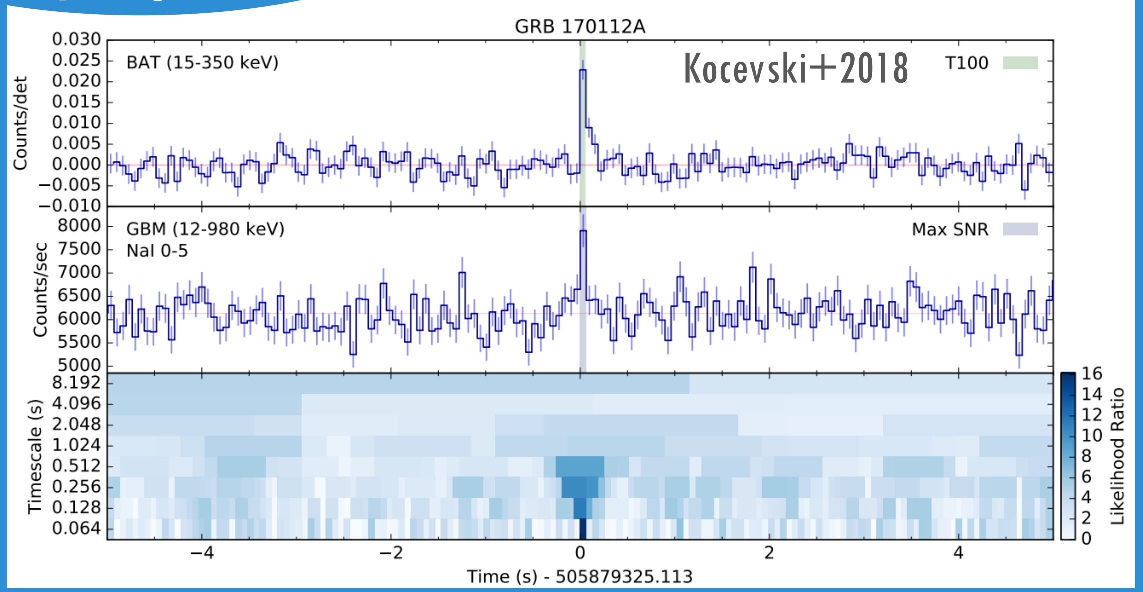
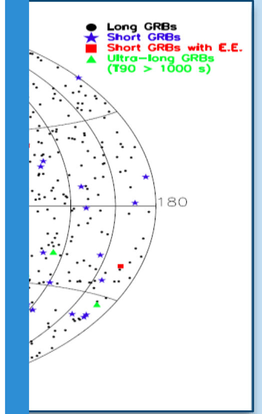
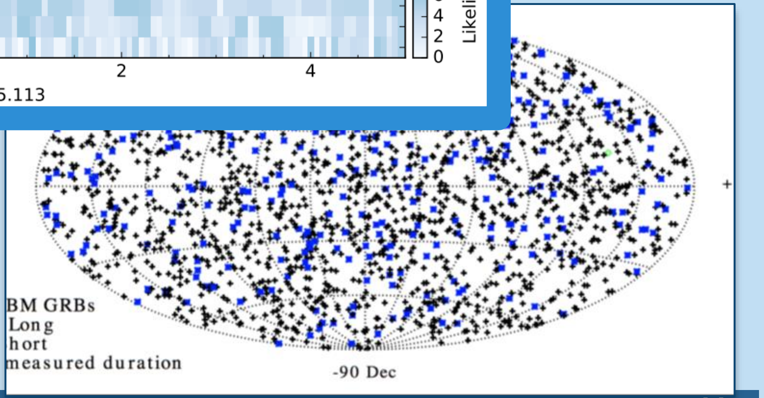
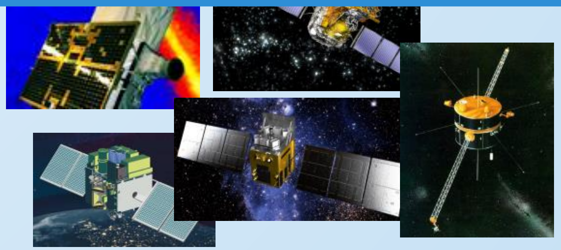


Short GRB rates
~40 yr⁻¹ (trig)
~80 yr⁻¹ (subthr)









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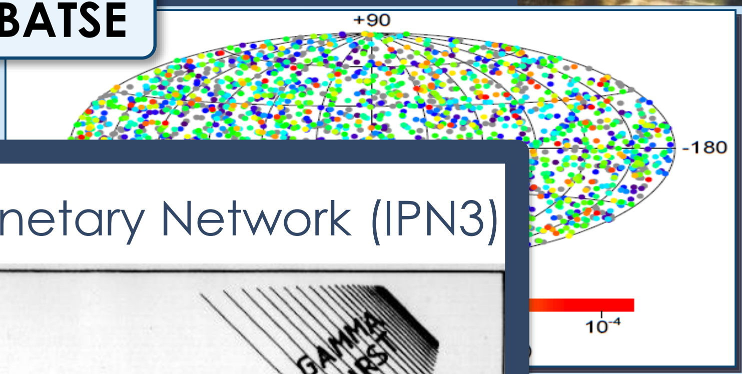
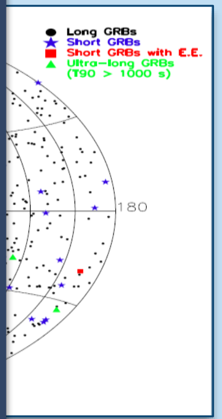
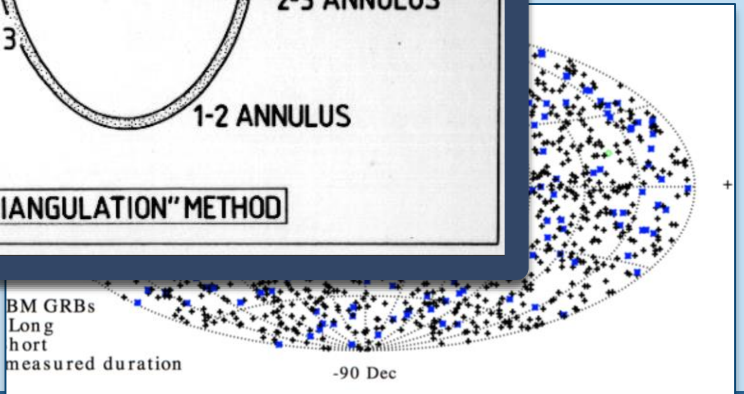
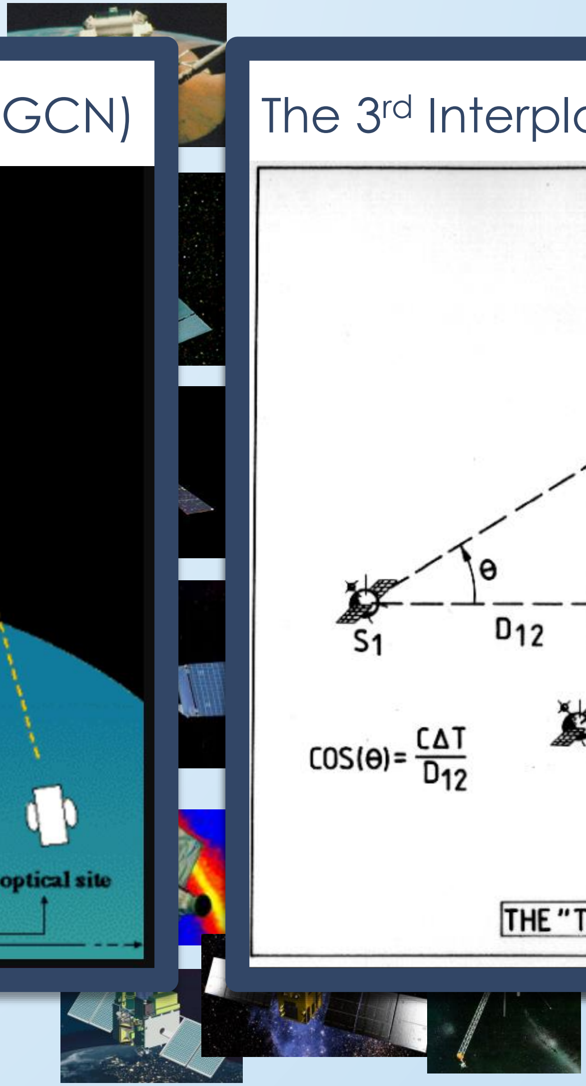
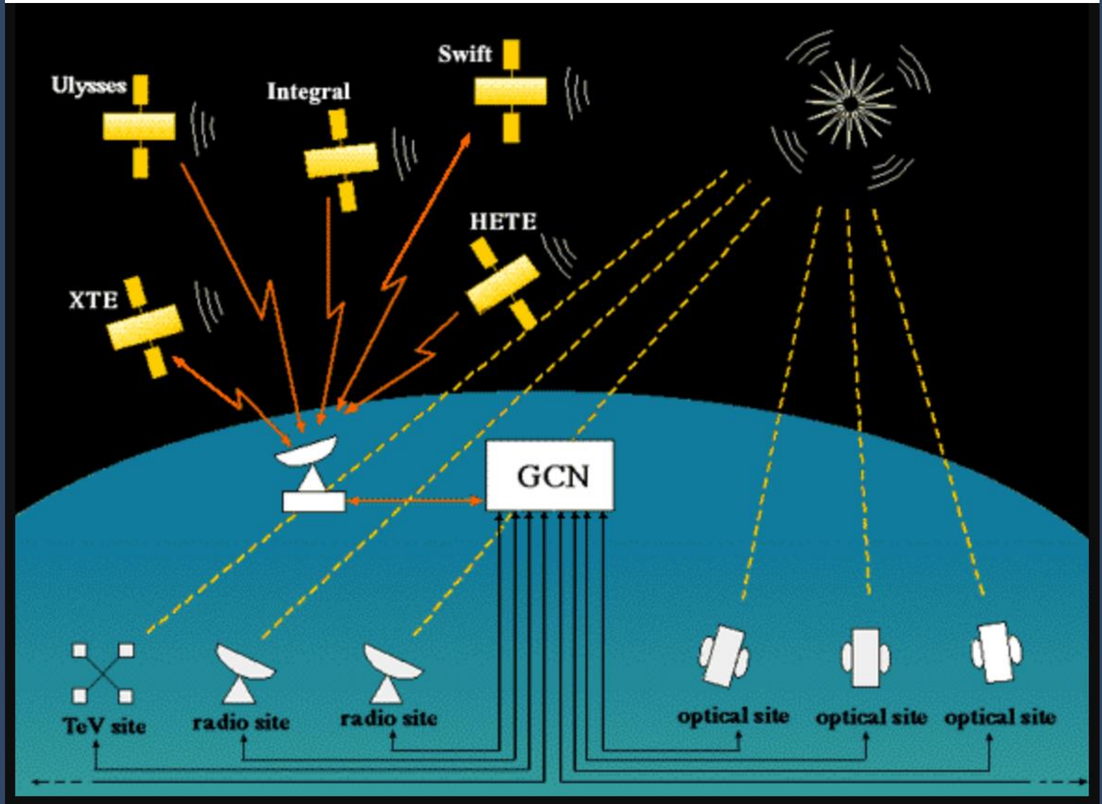




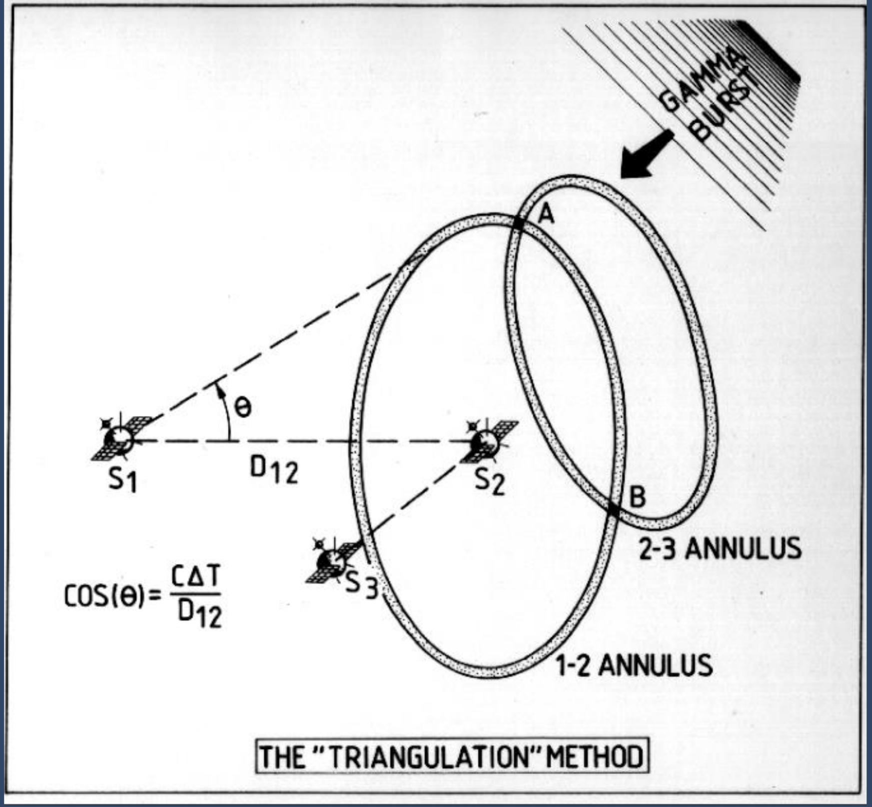




The Gamma-ray Coordinates Network (GCN)



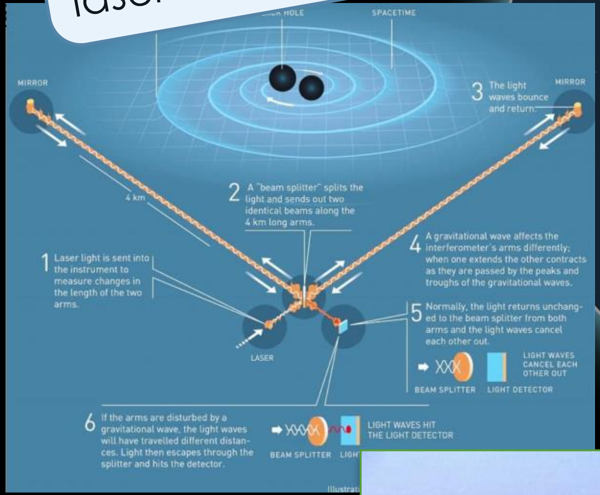
The 3rd Interplanetary Network (IPN3)



A new window into the Universe

Operational
Under construction
Planned

1970s: **Early work** on GW detection by laser interferometers



2000s: **First** Science Runs
Since 2015:
Advanced Detectors

4 km

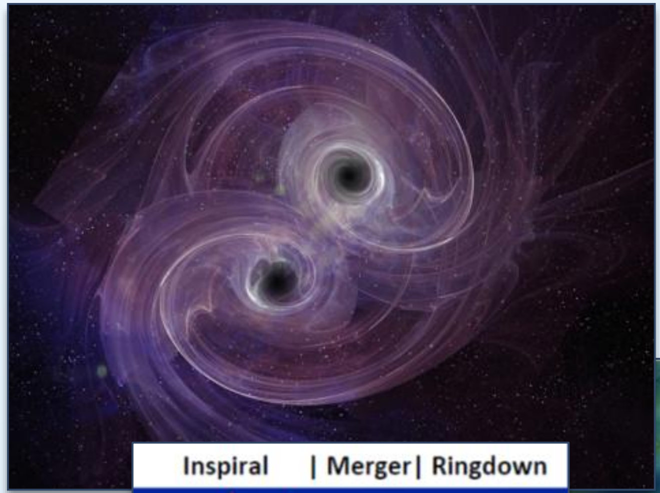
3 km

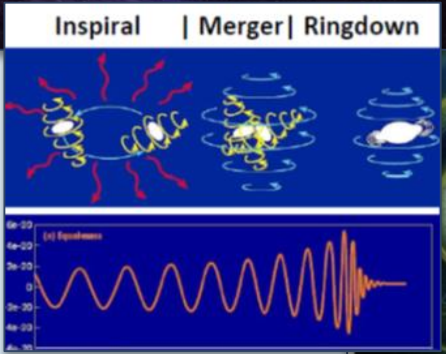
Credit: LIGO–Virgo

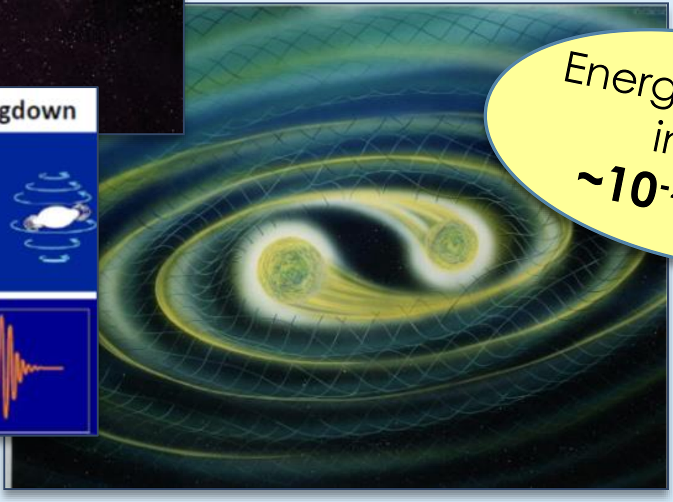
Expected «transient» GW sources by LIGO/Virgo

- "Transient GW signal": signal with duration in the detector sensitive band significantly shorter than the observation time and that cannot be re-observed

Compact Binary Coalescence (CBC)







binary system
of neutron stars (NS)
and/or
stellar-mass
black-hole (BH)

Energy emitted in GW $\sim 10^{-2}\ M_{\odot}\ c^2$

Core-collapse of massive stars

Energy emitted in GW uncertain $10^{-8} - 10^{-4}\ M_{\odot}\ c^2$

Isolated neutron-star

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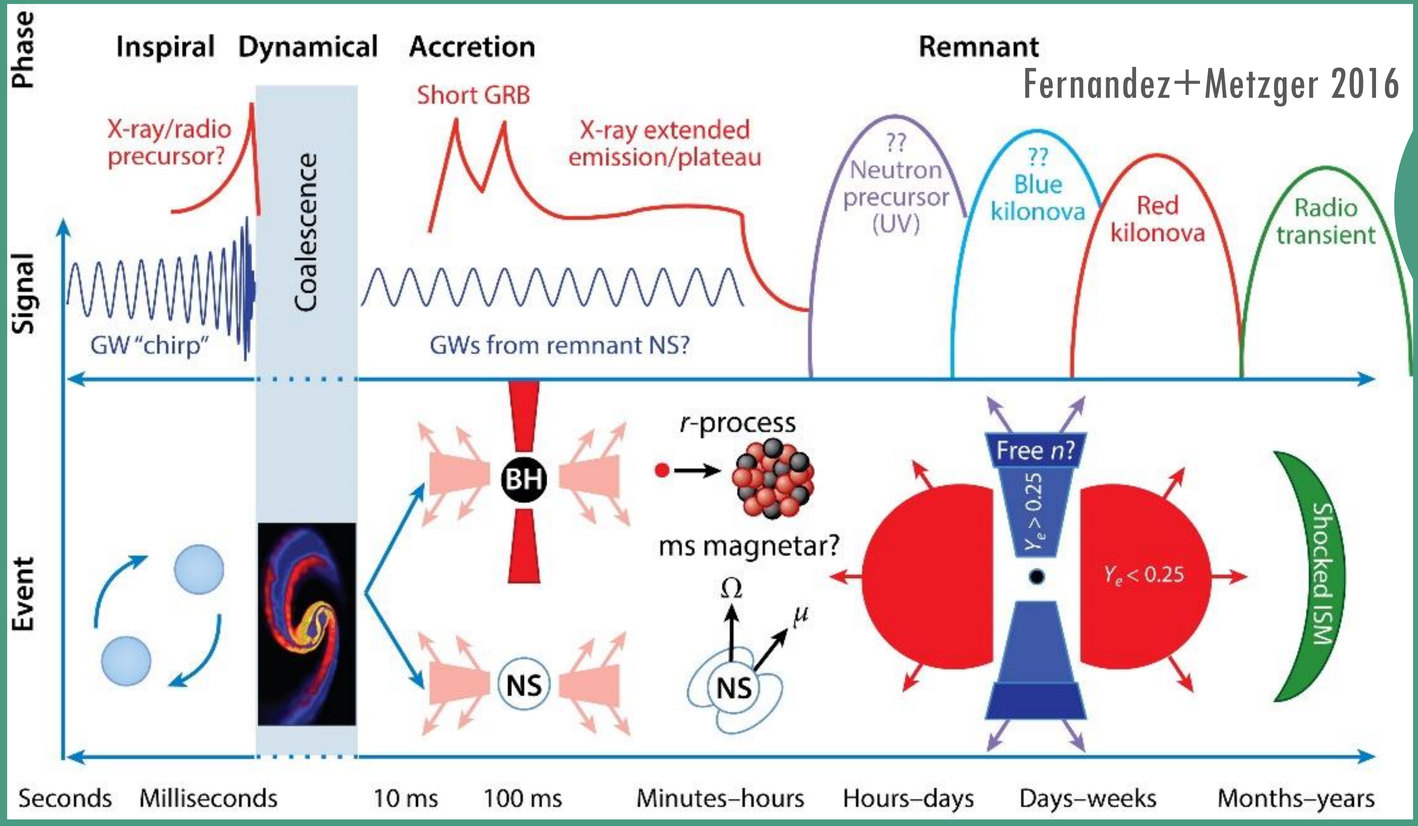
BNS and NSBH – A global picture



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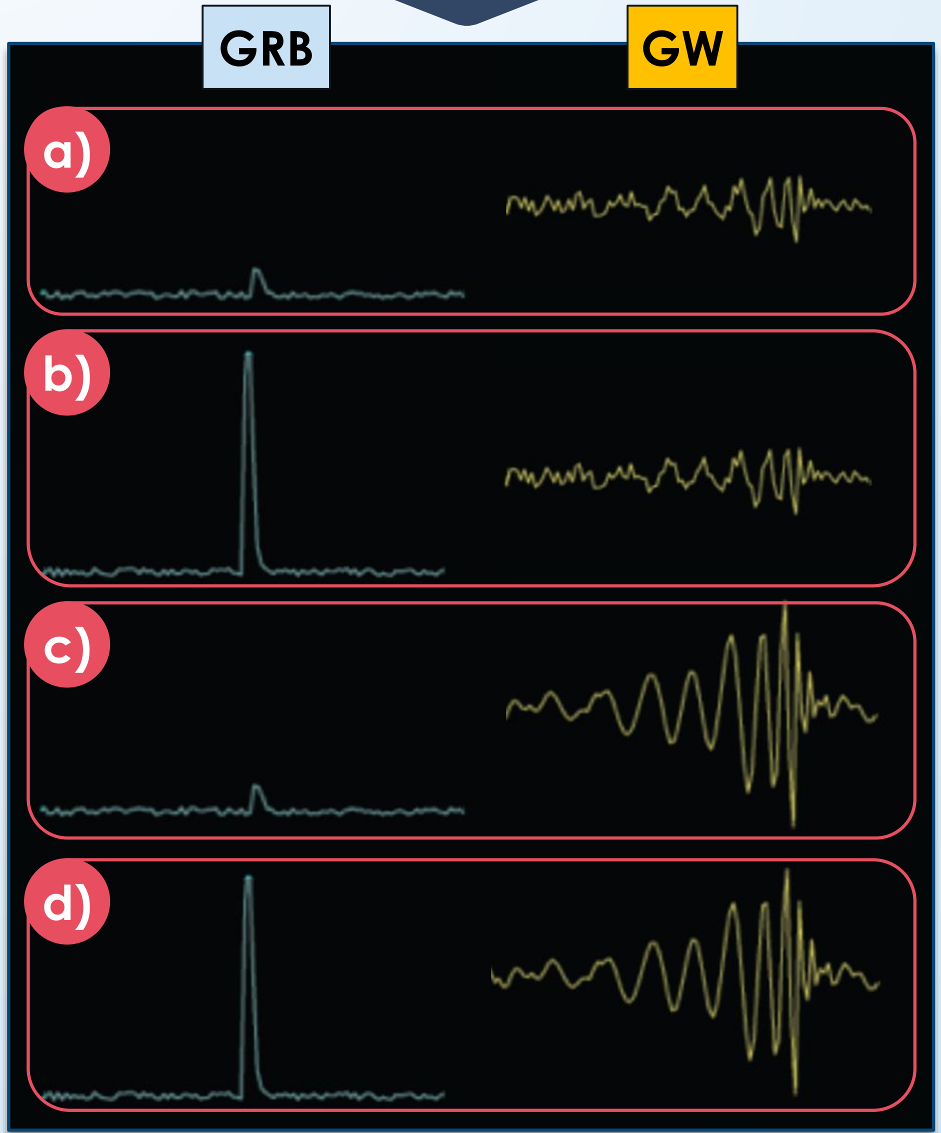
Request for network of **multiwavelength observatories**
- covering **huge regions of the sky**
- repeating observations over **different timescales**

n-star

The path towards joint GW-GRB detections

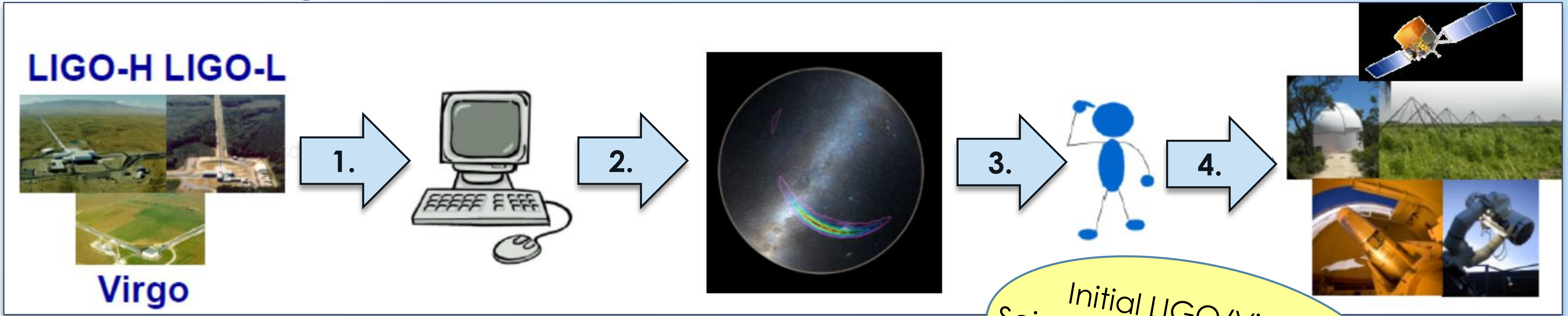


- **Possible observing scenarios**
  a) Subthreshold **GRB** + subthreshold **GW** signal
  b) Triggered **GRB** + subthreshold **GW** signal
  c) Subthreshold **GRB** + triggered **GW** signal
  d) Triggered **GRB** + triggered **GW**

  ➔ In all cases, the presence of a **coincident** signal **raises the significance** of the signal **being real** in the other instrument

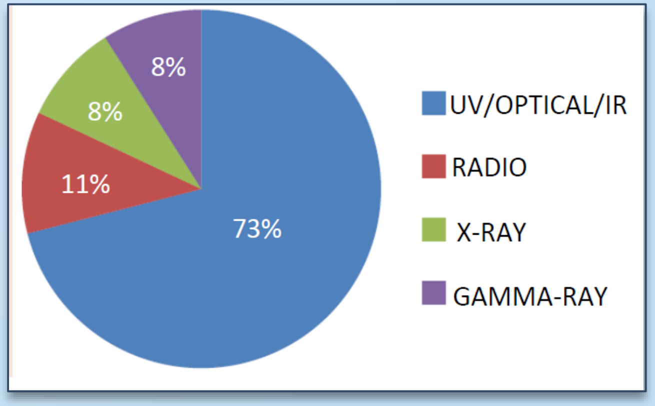
- A confident gamma-ray signal allowing a fainter GW signal **pushes the LV detection distance limit further**, in turn **increasing the event rate** by a factor of distance cubed

GRB/GW Observing scenarios: 1. GW signal → GRB searches



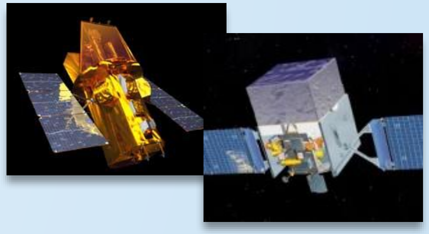
Initial LIGO/Virgo Science Runs (2001 – 2010)
No GW detection

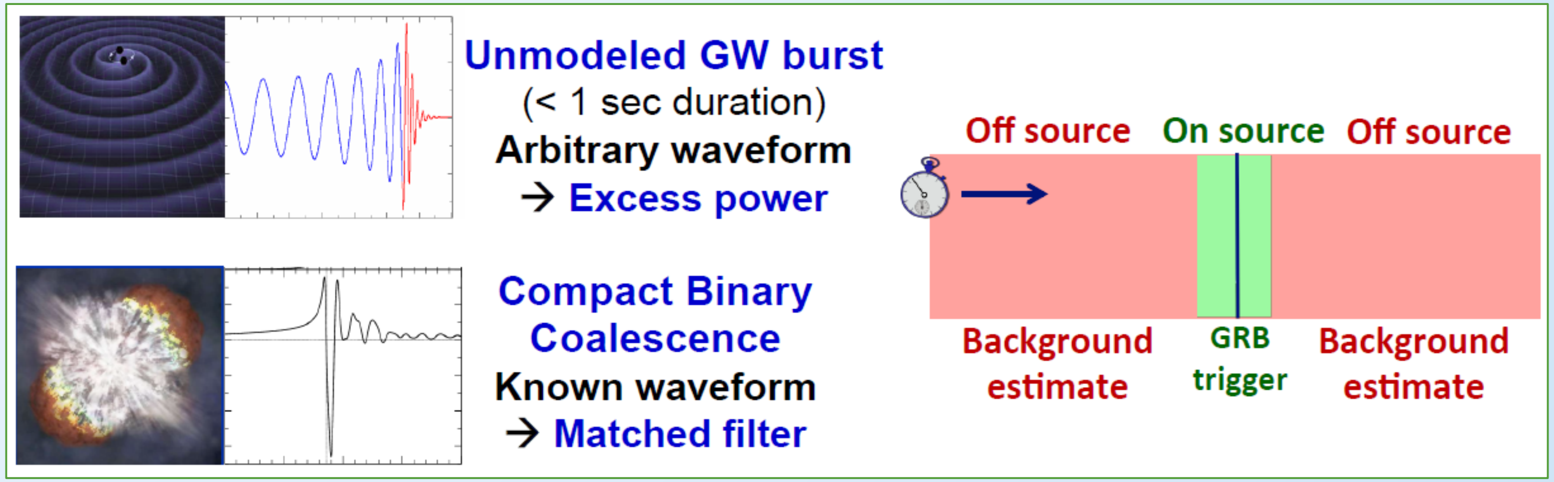
1. **Low-latency searches** for GW candidates
2. **GW skymaps**
3. **Event validation**
   - Low SNR signals in the first LV runs localized into regions of **tens to hundreds of sq. degrees**, possibly in several disconnected patches
     ➔ Necessity of wide FOV EM telescopes
4. **EM follow-ups ➔**Initially: GW triggers promptly shared only with partners having signed an **MoU with LVC** (>150 instruments)



GRB/GW Observing scenarios: 2. GRB trigger → GW searches

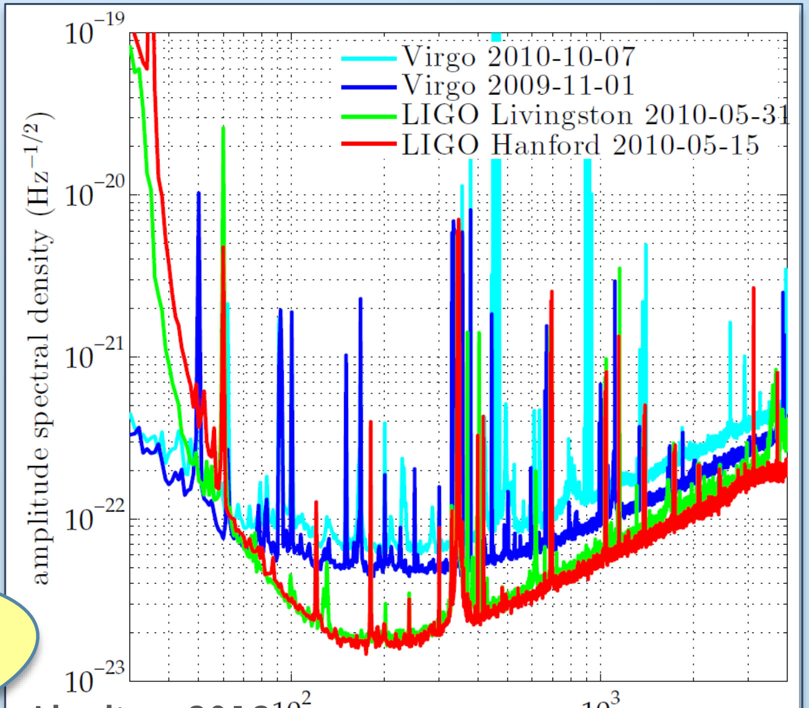
- **GRB prompt emission → "Triggered" GW search**
  - Known **GRB event time** and **sky position:**
    - Reduction in search parameter space + Gain in search sensitivity





- **Analysis of GRB samples** detected by gamma-ray satellites **prior 2010** while 2 or 3 LV detectors were taking good data [Abbott+2010, Abadie+2012]

No GW counterpart



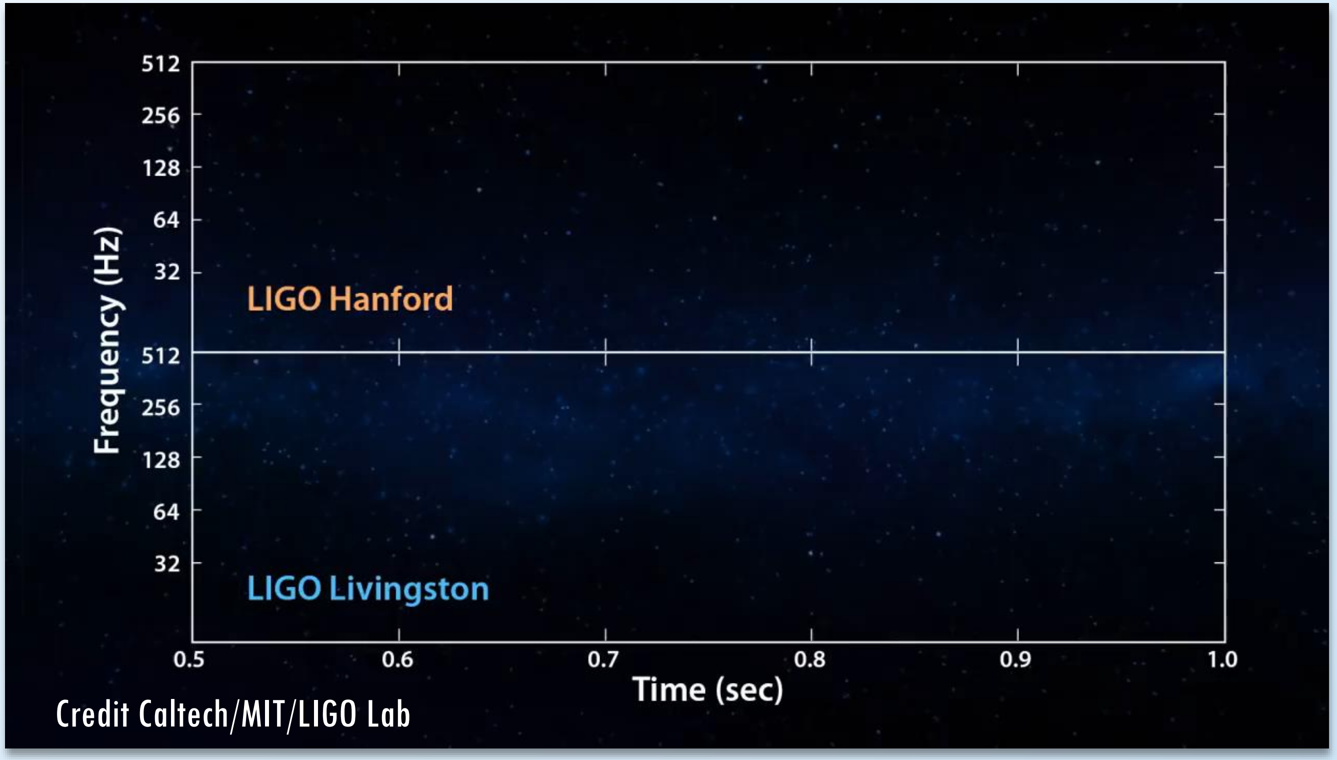
Abadie+2012

The beginning of the GW Era!

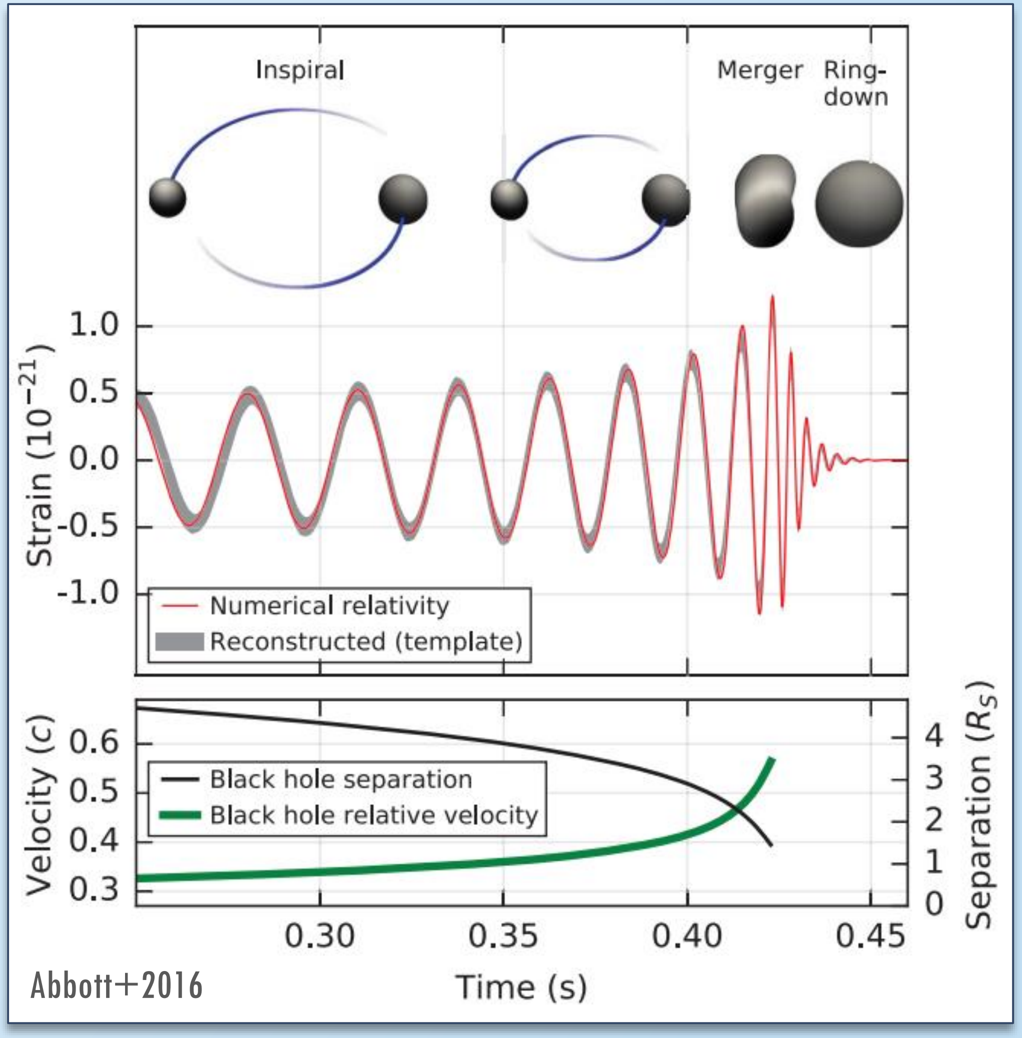
PRL **116,** 061102 (2016) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

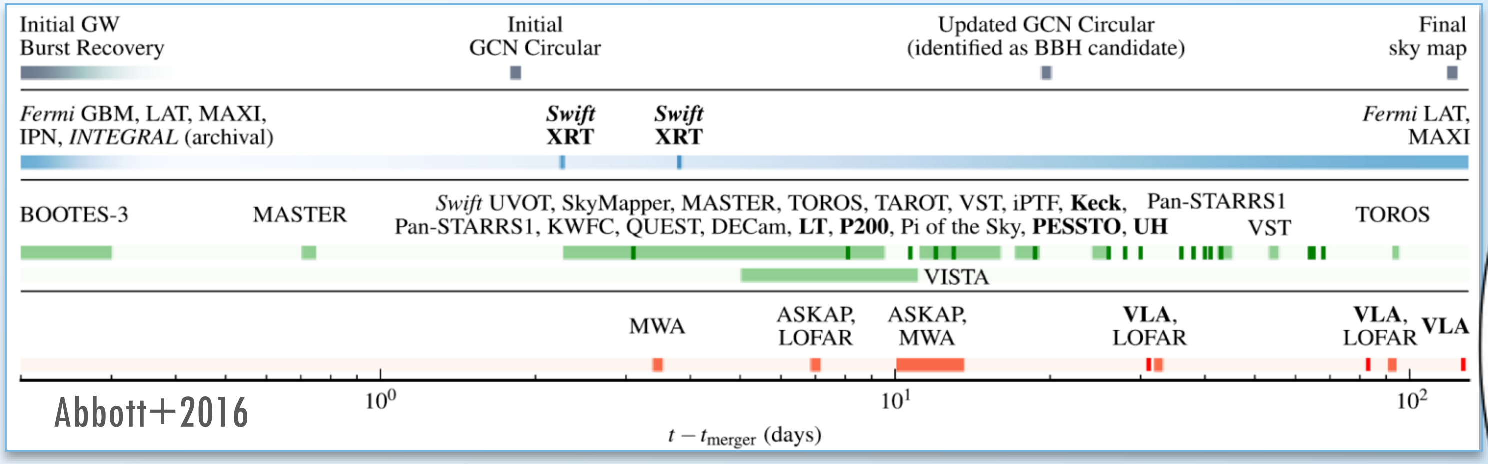


GW150914



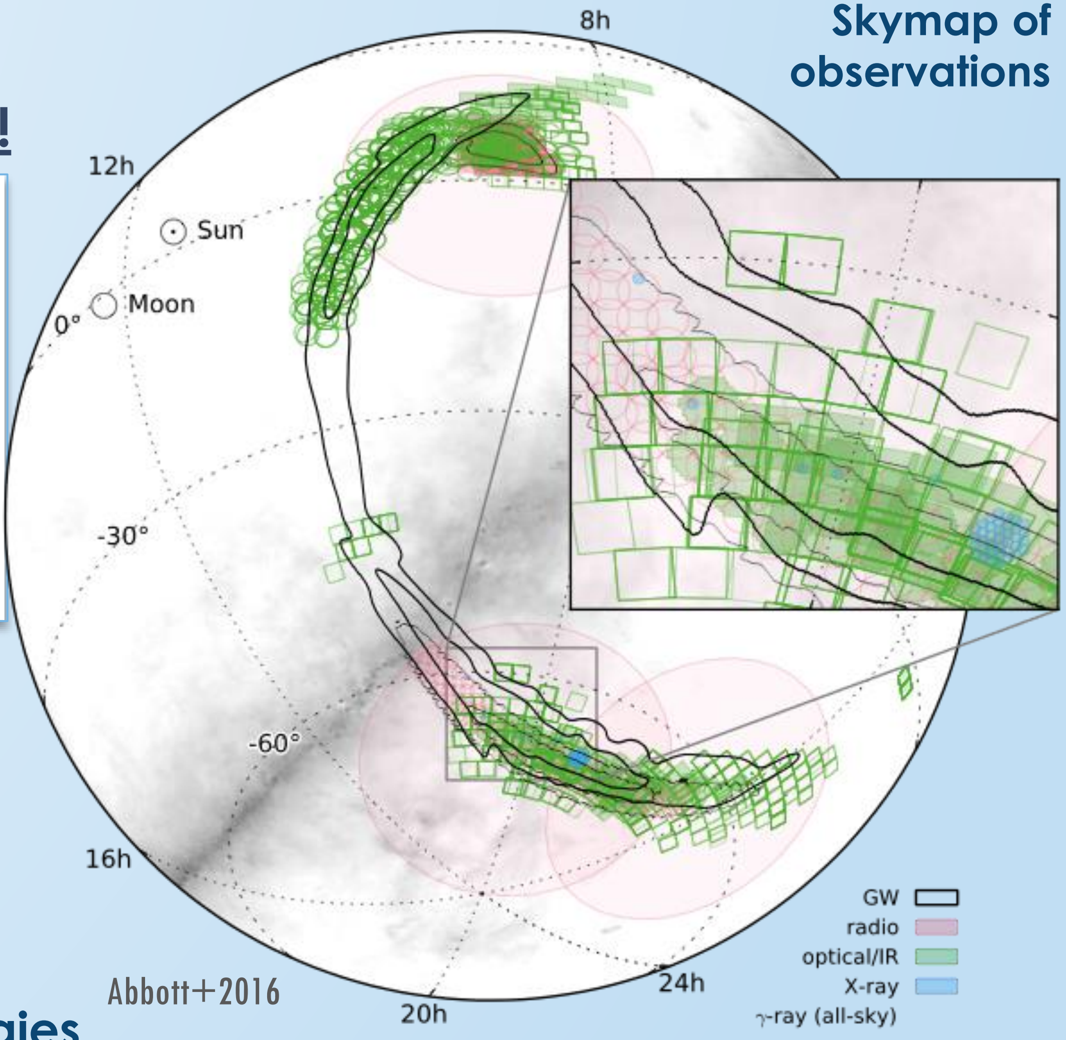
The EM follow-up of GW150914

- **No coincident triggers** from space-based observatories → Offline searches
- Follow-up observations reported by **25 teams** via private GCN circulars: **<u>NO counterpart detected!</u>**



Abbott+2016

Skymap of observations



Abbott+2016

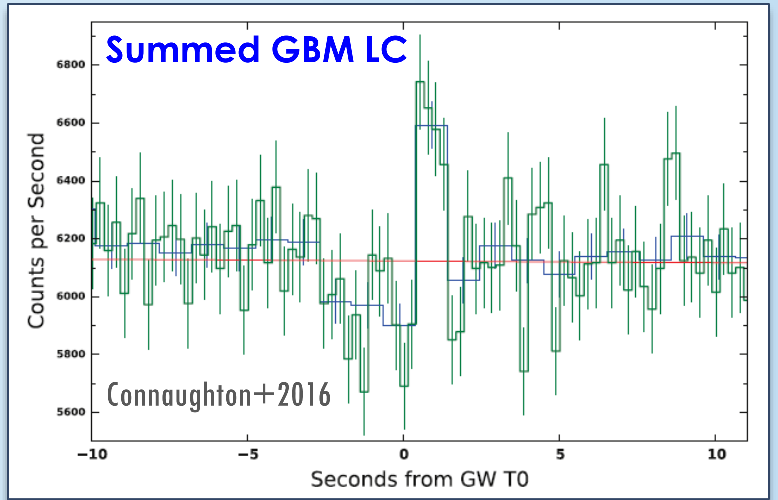
  - Event nature (**BBH merger)** → Little expectation of a detectable EM signature

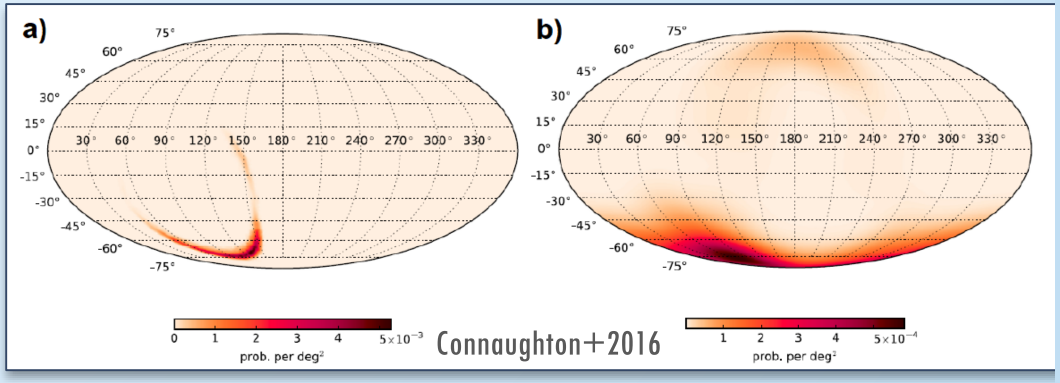
→ But: **<u>Milestone achieved</u>**! **First broadband** EM counterpart search **campaign**!

- Proving broad capabilities of the transient astronomy community and their **observing strategies**

The transient "GW150914-GBM"

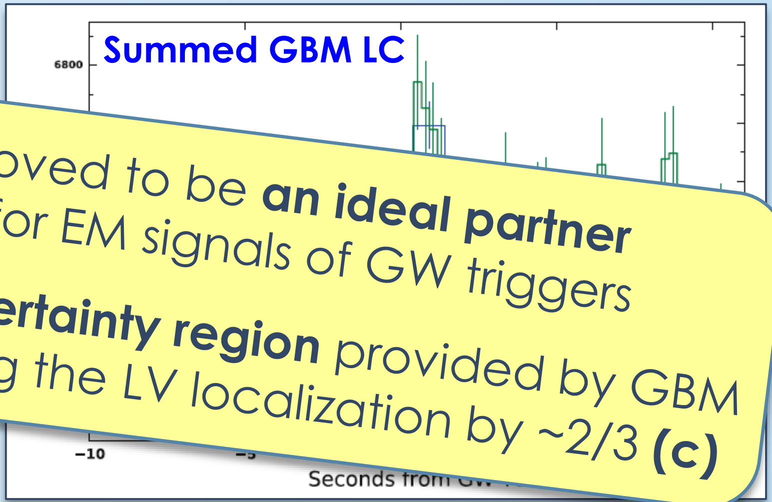
- **Fermi-GBM "Targeted" search** around **GW150914**:
  - **Best candidate**: Hard transient **0.4 s after GW trigger**
    - → **Association significance: 2.9 σ**
  - **Classified as short GRB**
    - Spectral parameters **average** for short GRBs but fluence **weaker than average** for short GRBs
  - **Localization**: source direction **underneath the spacecraft (b), but consistent with LIGO map (b)**
- Association with GW150914 **largely debated**:
  - **Lack** of corroboration by other experiments (Integral, AGILE, etc…)
  - Nature of the LIGO event being BBH merger





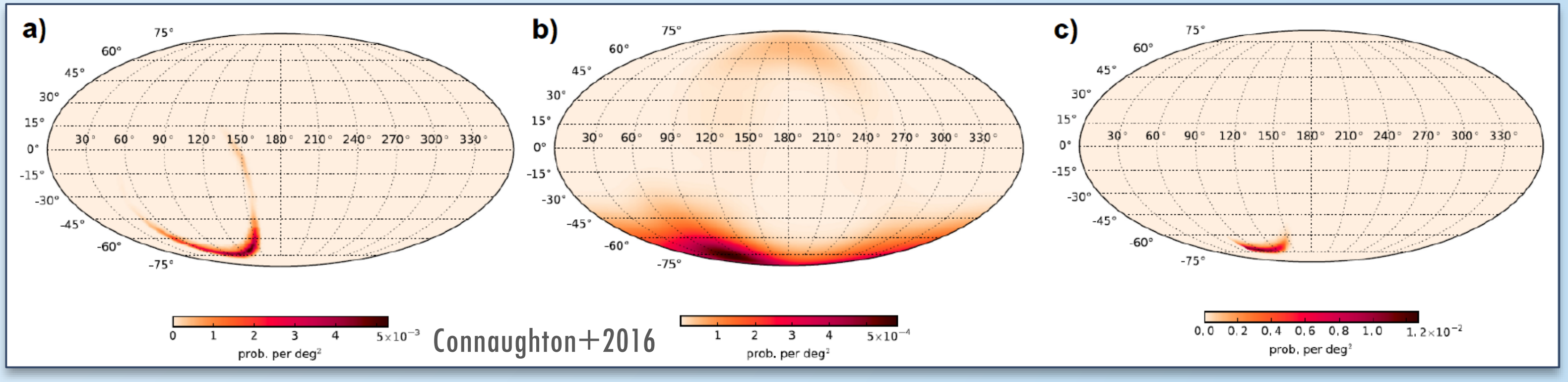
The transient “GW150914-GBM”

- **Fermi-GBM “Targeted” search** around **GW150**
  - **Best candidate**: Hard transient <u>**0.4 s after GW t**</u>
    - → **Association significance: 2.9 σ**
  - **Classified as short GRB**
    - Spectral parameters **average** for short GRBs but fluence **weaker than average** for short GRBs
  - **Localization**: source direction **underneath the spacecraft (b), but consistent with LIGO map (b)**
- Association with GW150914 **largely debated**:
  - **Lack** of corroboration by other experiments (Integral, AGILE, etc…)
  - Nature of the LIGO event being BBH merger



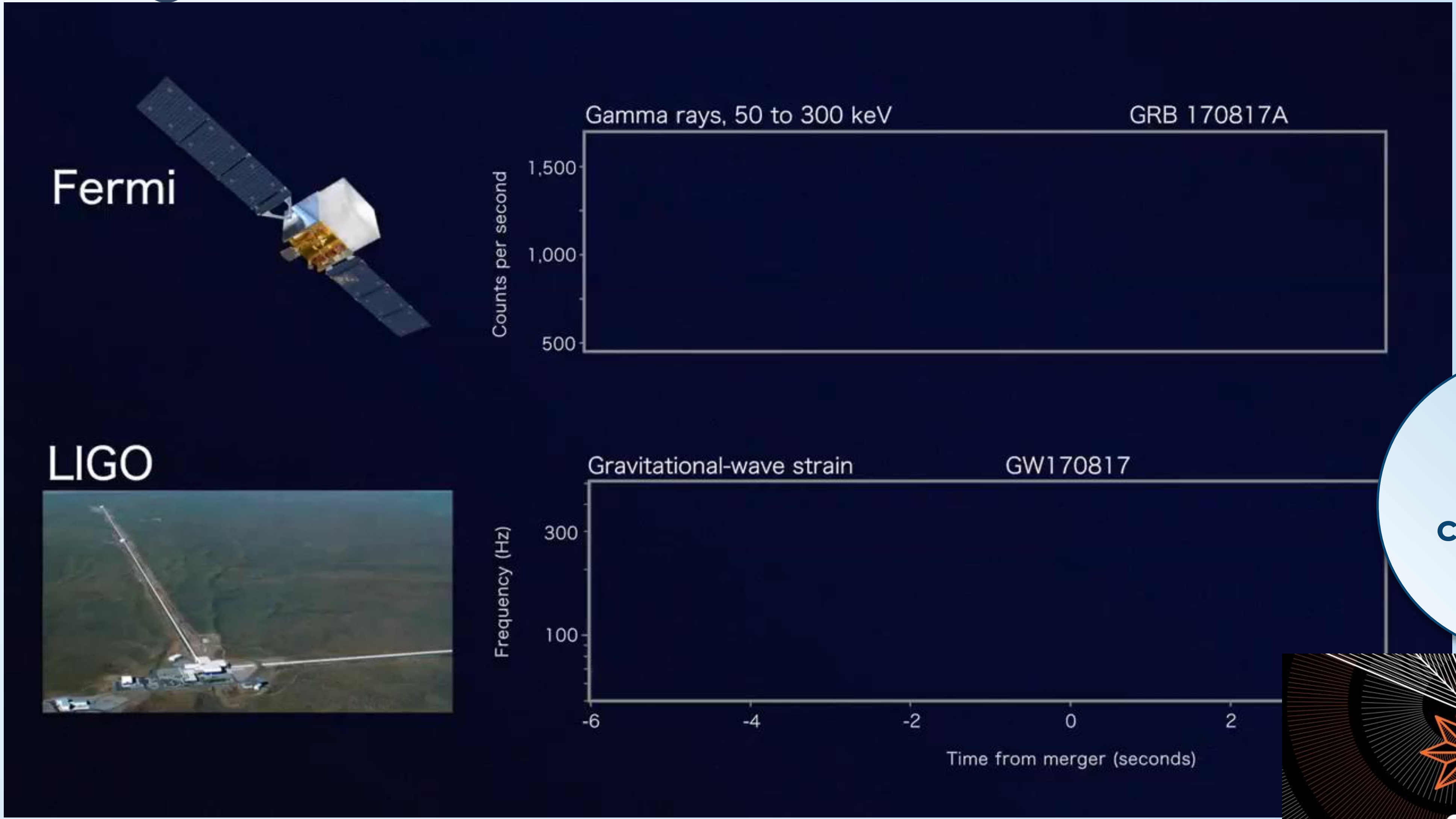
Fermi-GBM proved to be **an ideal partner** in the search for EM signals of GW triggers

➔ Even a **large uncertainty region** provided by GBM would help shrinking the LV localization by ~2/3 **(c)**



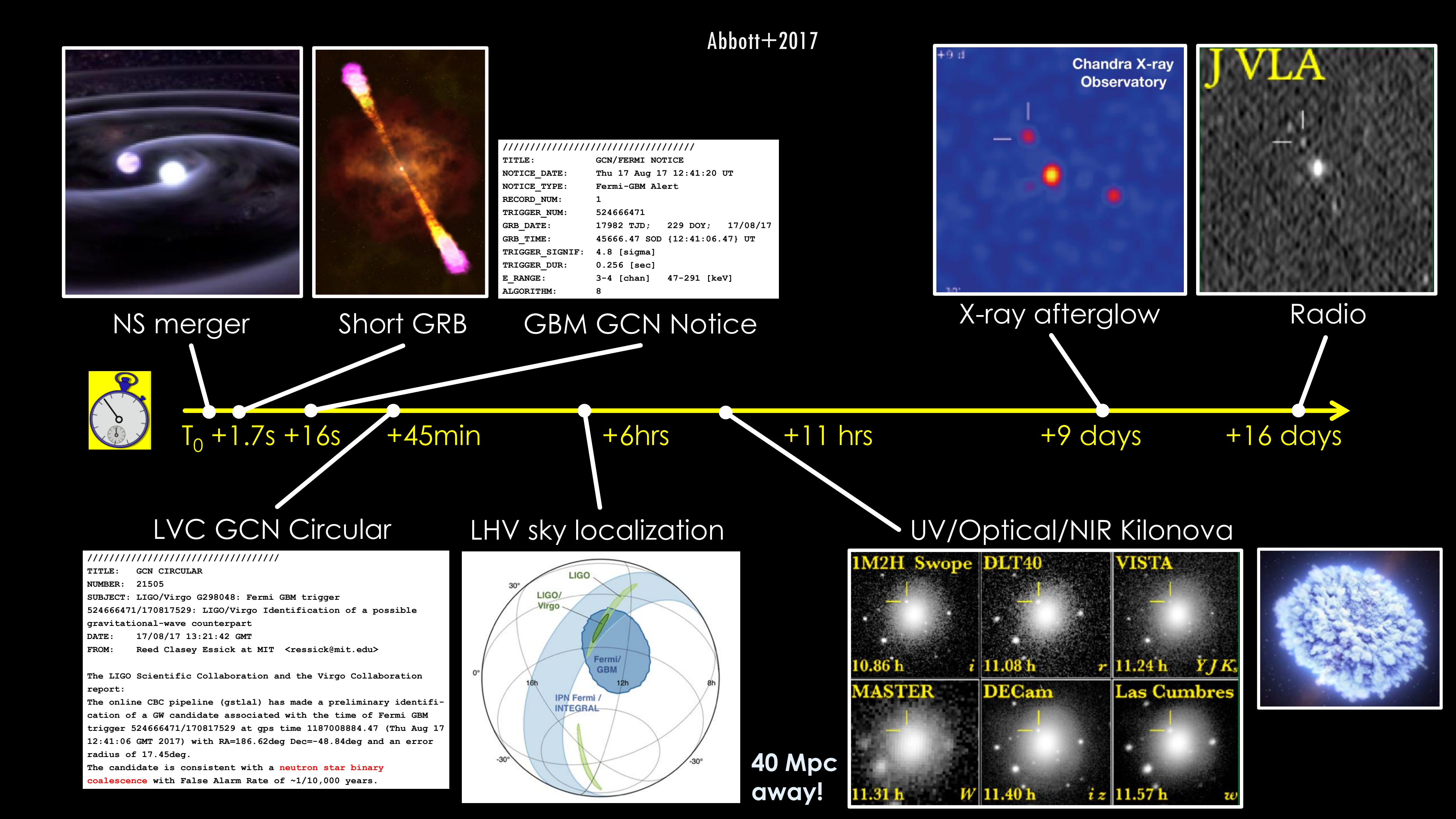
Connaughton+2016

August 17, 2017: A historic date!

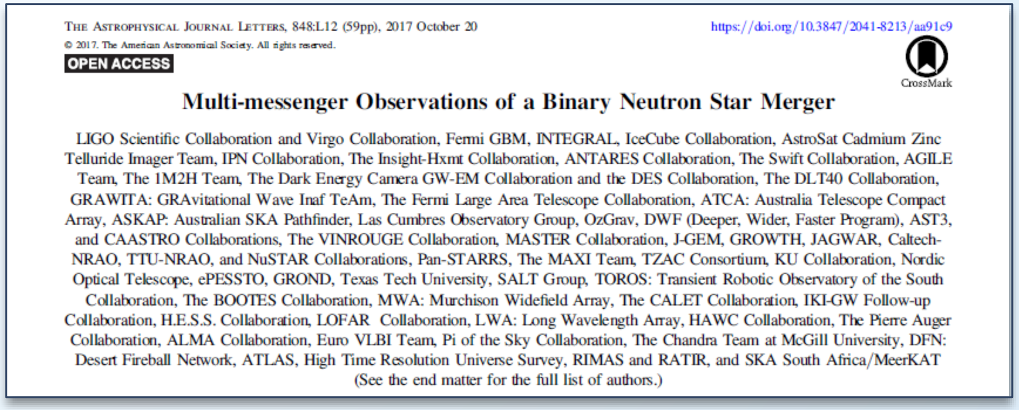


Credit: LIGO; Virgo; Fermi; NASA/DOE; NSF; EGO; ESA

Theory confirmed!


Abbott+2017
NS merger
Short GRB
////////////////////////////////////
TITLE: GCN/FERMI NOTICE
NOTICE_DATE: Thu 17 Aug 17 12:41:20 UT
NOTICE_TYPE: Fermi-GBM Alert
RECORD_NUM: 1
TRIGGER_NUM: 524666471
GRB_DATE: 17982 TJD; 229 DOY; 17/08/17
GRB_TIME: 45666.47 SOD {12:41:06.47} UT
TRIGGER_SIGNIF: 4.8 [sigma]
TRIGGER_DUR: 0.256 [sec]
E_RANGE: 3-4 [chan] 47-291 [keV]
ALGORITHM: 8
GBM GCN Notice
Chandra X-ray Observatory
JVLA
X-ray afterglow
Radio
T0 +1.7s +16s
+45min
+6hrs
+11 hrs
+9 days
+16 days
LVC GCN Circular
LHV sky localization
UV/Optical/NIR Kilonova
////////////////////////////////////
TITLE: GCN CIRCULAR
NUMBER: 21505
SUBJECT: LIGO/Virgo G298048: Fermi GBM trigger 524666471/170817529: LIGO/Virgo Identification of a possible gravitational-wave counterpart
DATE: 17/08/17 13:21:42 GMT
FROM: Reed Clasey Essick at MIT <ressick@mit.edu>
The LIGO Scientific Collaboration and the Virgo Collaboration report:
The online CBC pipeline (gstlal) has made a preliminary identification of a GW candidate associated with the time of Fermi GBM trigger 524666471/170817529 at gps time 1187008884.47 (Thu Aug 17 12:41:06 GMT 2017) with RA=186.62deg Dec=-48.84deg and an error radius of 17.45deg.
The candidate is consistent with a neutron star binary coalescence with False Alarm Rate of ~1/10,000 years.
LIGO
LIGO/ Virgo
30°
0°
-30°
16h
12h
8h
Fermi/ GBM
IPN Fermi / INTEGRAL
40 Mpc away!
1M2H Swope
10.86 h
i
DLT40
11.08 h
r
VISTA
11.24 h
YJKs
MASTER
11.31 h
W
DECam
11.40 h
iz
Las Cumbres
11.57 h
w

The first Multi-Messenger paper!



The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9
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OPEN ACCESS
CrossMark

Multi-messenger Observations of a Binary Neutron Star Merger

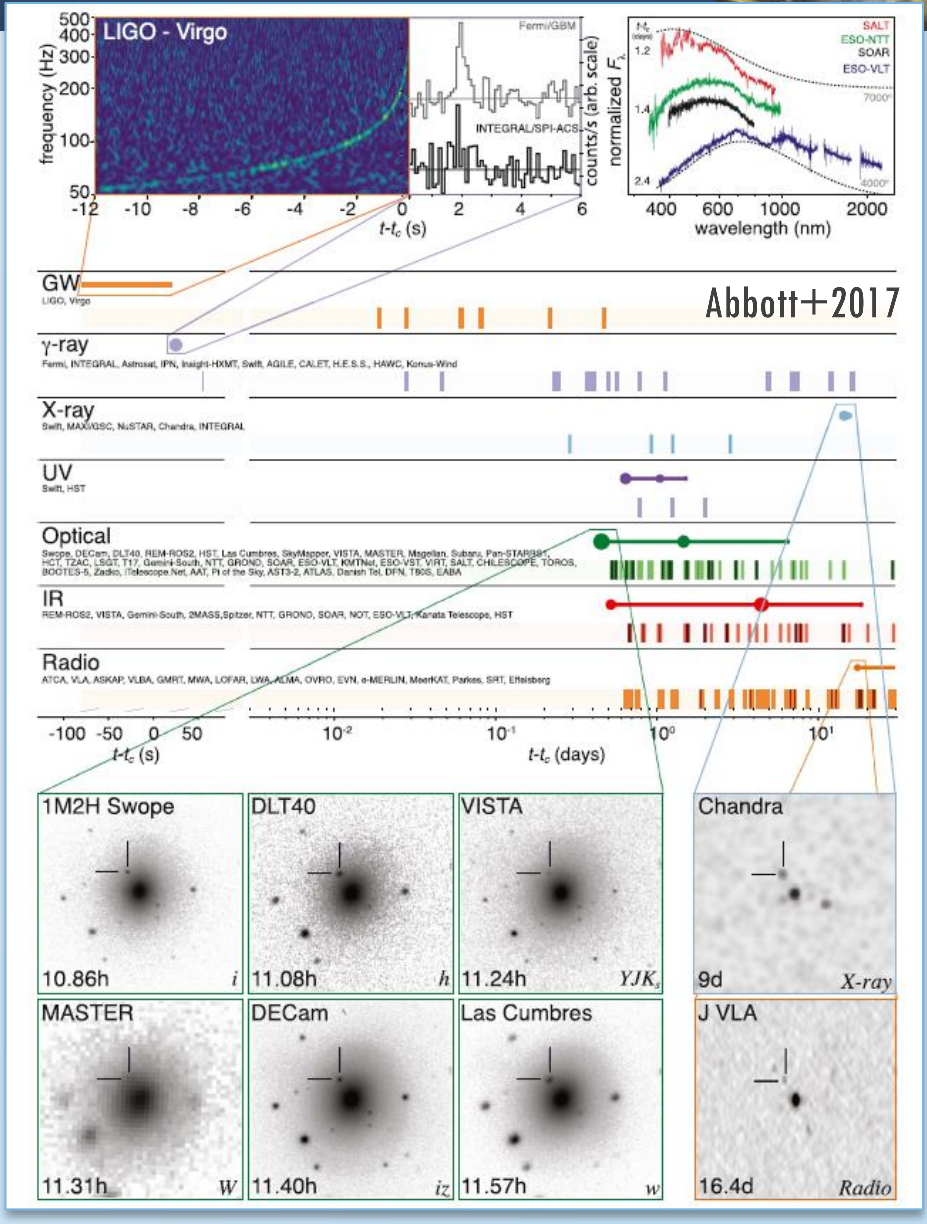
LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

50 teams
>3600 authors

~20 orders of magnitude in wavelength

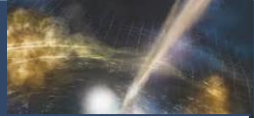
Including **VHE** and **neutrino** follow-up

Credit: LIGO-Virgo



Abbott+2017

Science from GW170817/GRB 170817A



Fundamental physics/Cosmology

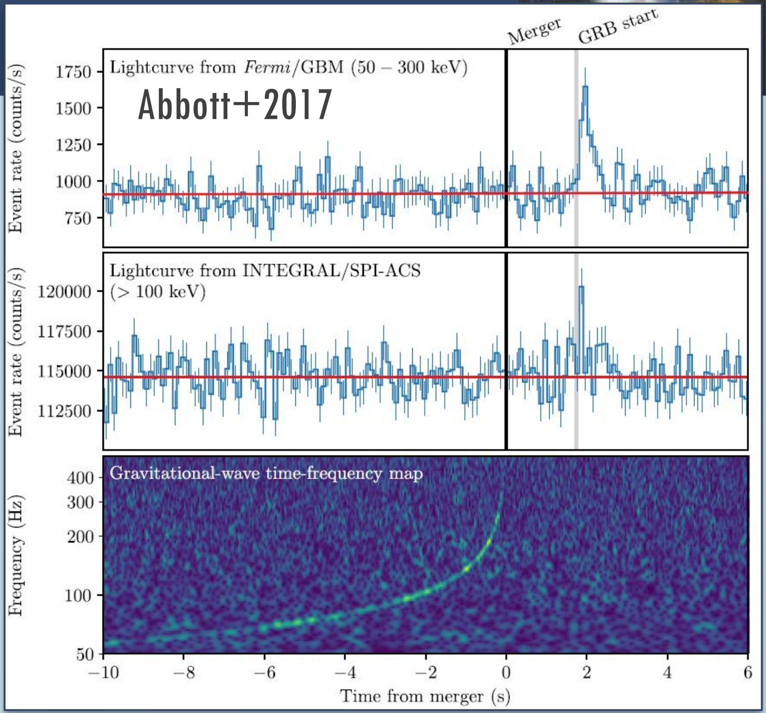
1. Direct measurement of **the speed of gravity**
   - Is the same as the speed of light within one part in one quadrillion
2. Test of **equivalence Principle:**
   - Gravitational mass = inertial mass
3. Measure of cosmological constant H0

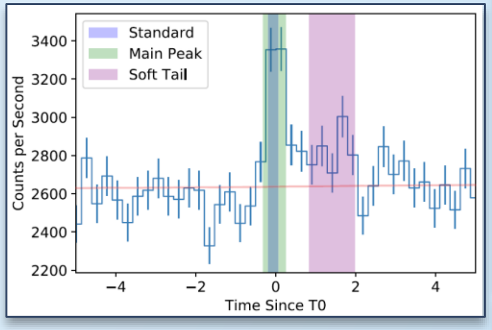
Probe of the **NS equation of state**:

- Joint GW/short GRB observations constrain the maximum mass of a NS

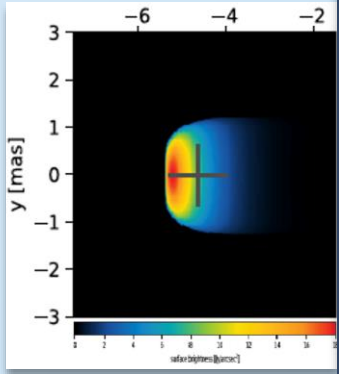
Investigation of the emission physics of relativistic jets and the **engine** that produces **short GRBs**

- GRB 170817A is **extremely under-luminous**
- Very late radio high-resolution imaging unveiling structured jet viewed off-axis

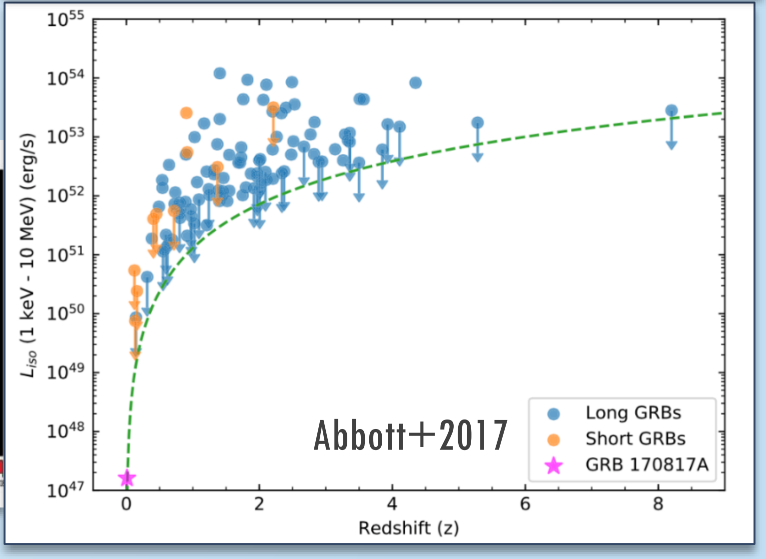




Goldstein+2017

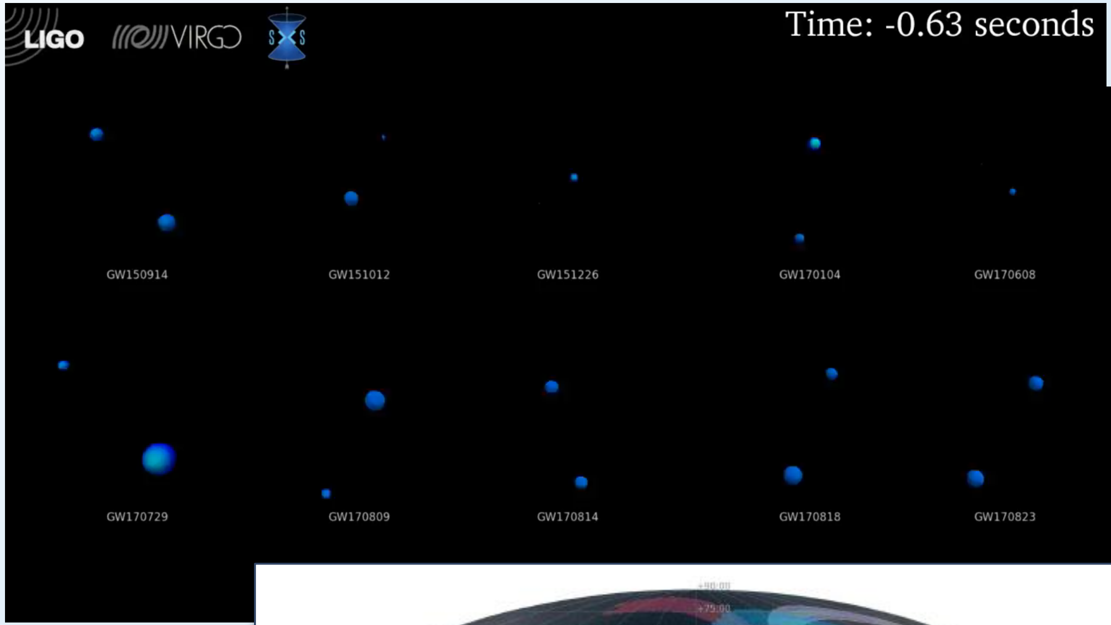


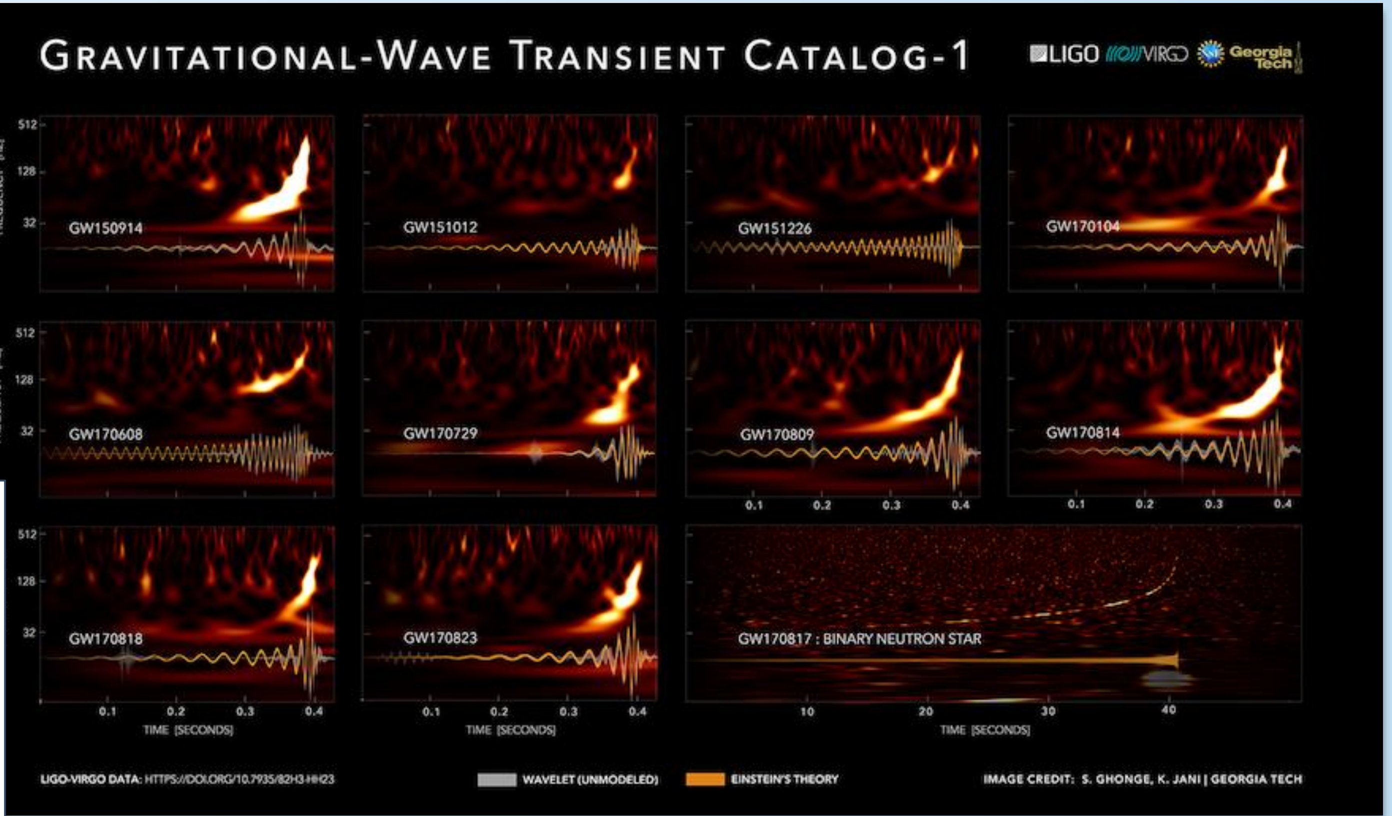
Ghirlanda+2018

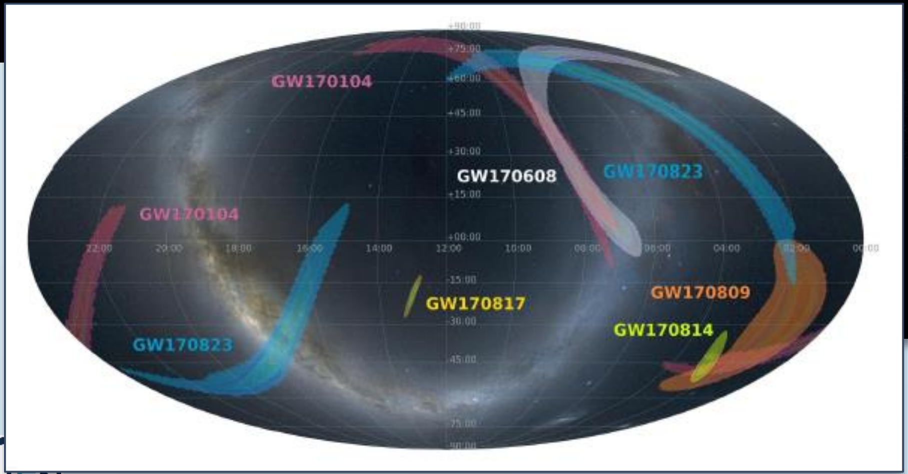


LVC results after O1 and O2

- **GWTC-1**: 17 candidates, 11 firm detections (10 BBH, 1 BNS) [LVC arXiv:1811.12907]

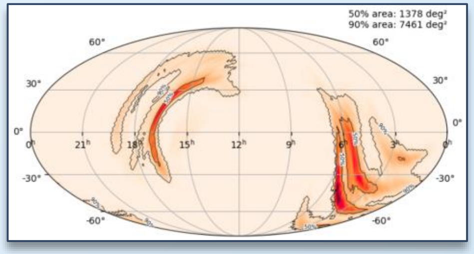






O3 is here!

- Start: 1st April 2019
- LVC **public GW Alerts**
  - **[20 detection candidates](https://gracedb.ligo.org/superevents/public/O3/)**
    GW Candidate Event Database
    - 16 BBH, 1 BNS, 3 Other
      - More analysis needed to confirm uncertain signals
- **S190425z** (BNS, >99%)
  - **No coincident trigger** from space-based observatories
    - E.g. GBM observing only 55% of the probability region at event time
  - **No other MM counterpart** reported ➔ large **follow-up campagin** resulting in ~ **120 GCNs**



LIGO/Virgo Public Alerts

Detection candidates: 20

SORT: EVENT ID (A-Z)

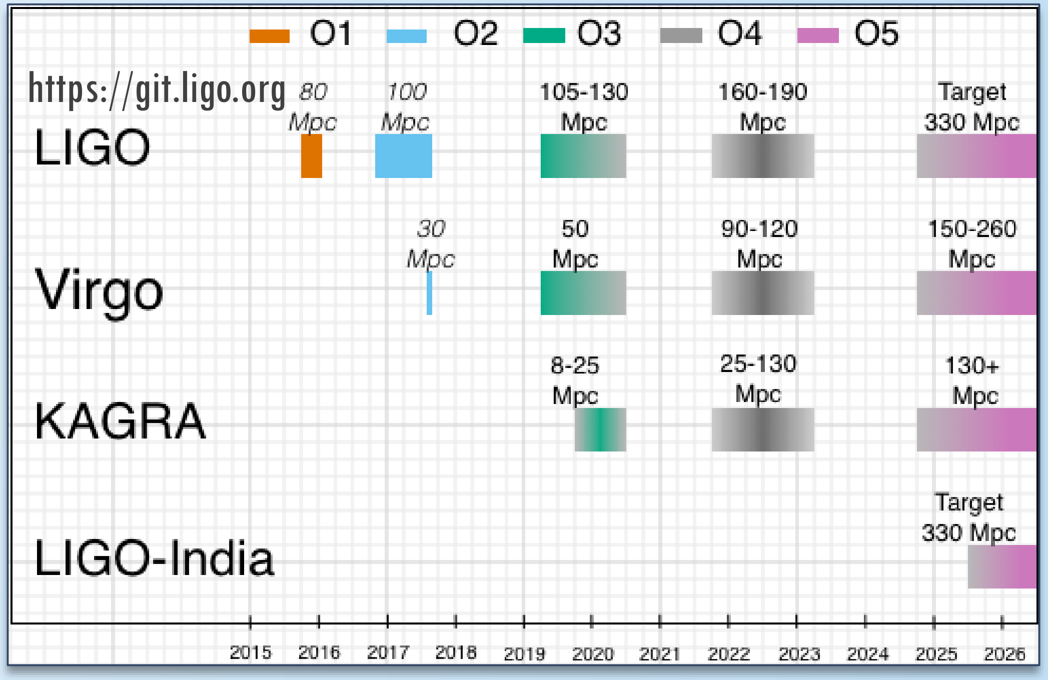
https://gracedb.ligo.org/superevents/public/O3/

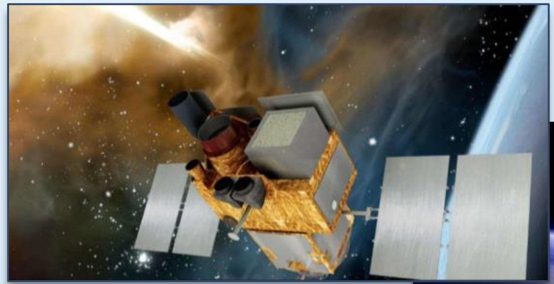
Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S190720a	BBH (99%), Terrestrial (1%)	July 20, 2019 00:08:36 UTC	GCN Circulars Notices | VOE		1 per 8.3367 years	
S190718y	Terrestrial (98%), BNS (2%)	July 18, 2019 14:35:12 UTC	GCN Circulars Notices | VOE		1.1514 per year	
S190707q	BBH (>99%)	July 7, 2019 09:33:26 UTC	GCN Circulars Notices | VOE		1 per 6018.9 years	
S190706ai	BBH (99%), Terrestrial (1%)	July 6, 2019 22:26:41 UTC	GCN Circulars Notices | VOE		1 per 16.673 years	
S190701ah	BBH (93%), Terrestrial (7%)	July 1, 2019 20:33:06 UTC	GCN Circulars Notices | VOE		1 per 1.6543 years	

Future prospects and conclusions (1)

- Expectations for **4/5-site detector network** at design sensitivity
  - Improved **sky localizations**
  - Much larger fraction of **coincident observational time windows**
- Requirements for gamma-ray observatories
  - **Wide field of view** (“monitors”)
  - **Rapid repointing** capabilities
  - Possibility to carry onboard instruments observing **other wavelengths (X, UV, O, IR)**

Expected BNS range





- **Currently funded** missions:

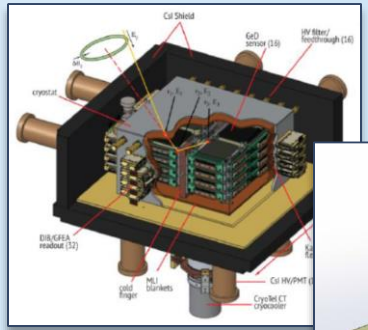
SVOM (2021) – BurstCube (2021) – Glowbug (2023)

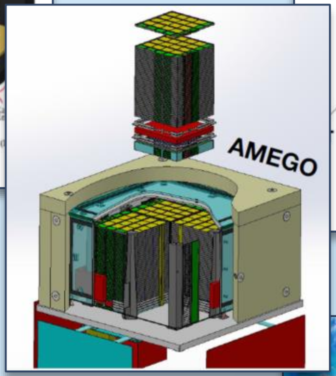
➔ **Fermi extended to 2022 (with planning >2023)**

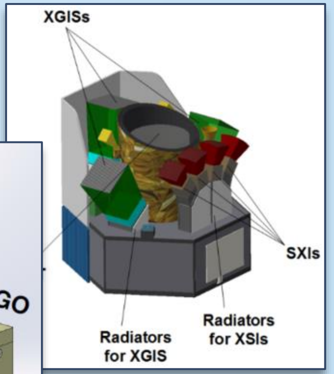
Future prospects and conclusions (2)

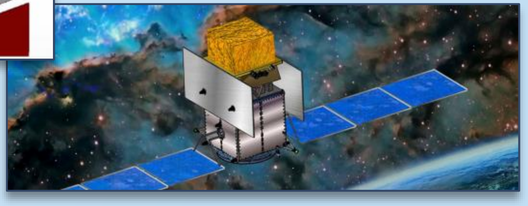
- GRB understanding has come a long way since the '70s, but **there is still a lot to learn**!
  - Short GRBs are a **prime target** for combined GW-EM observations

    ➔ **GRB170817A** was not a typical GRB - but showed us the <u>**power of joint observations**</u>
  - BNS mergers seem much less common than expected
- More joint observations are needed!
  - **Proposed future missions**
    - COSI, AMEGO, Theseus, eAstrogam, etc.
- O3 is up and running!
  - **We look forward to more discoveries ahead!**



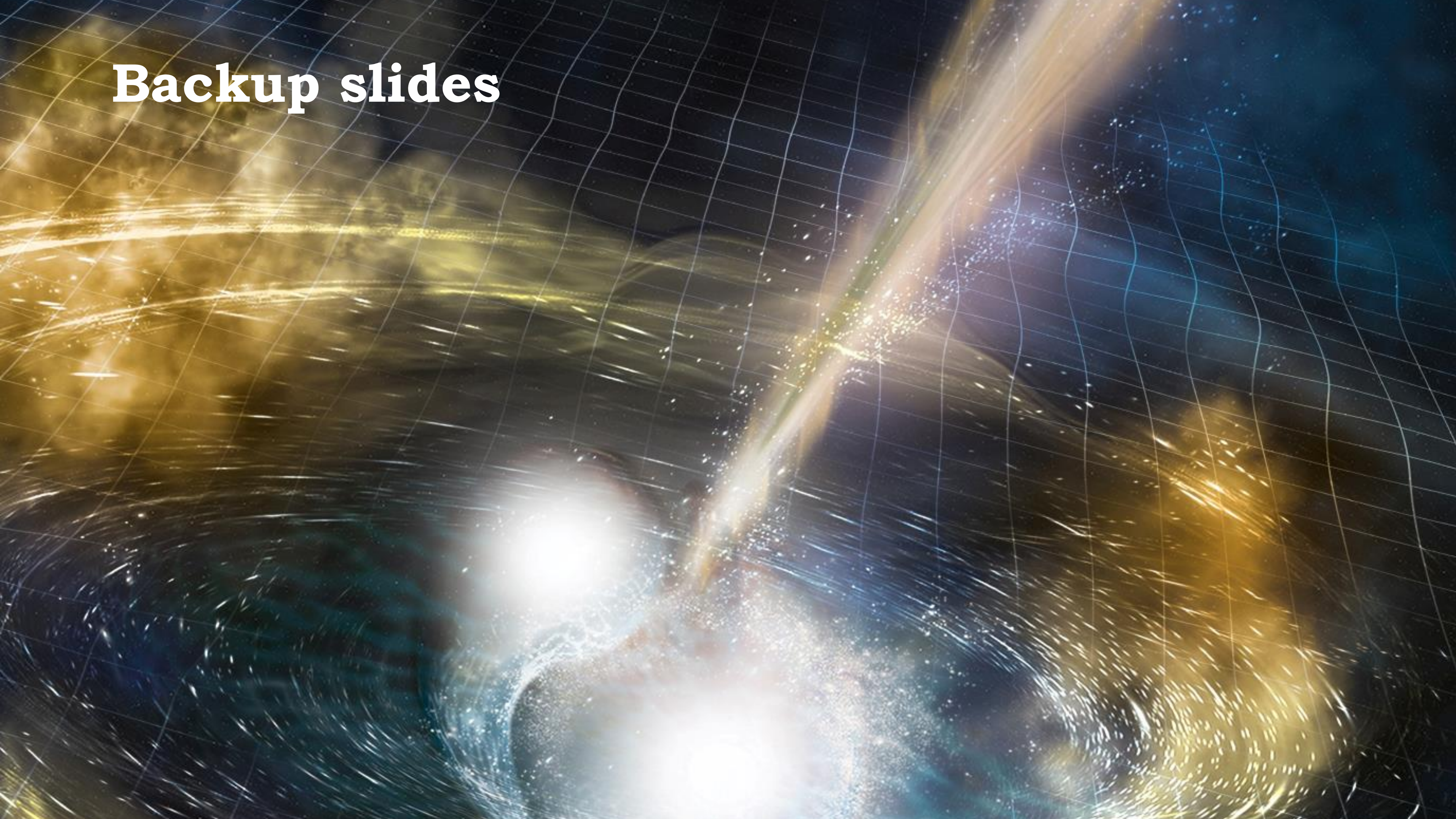






Thank you!

Backup slides



- Summary of a plausible observing schedule, expected sensitivities, and source localization with aLIGO, AdV and KAGRA detectors, which will be strongly dependent on the detectors' commissioning progress
- From Abbott+2018 Living Reviews in Relativity 21 arxiv1304.0670

Epoch			2015–2016	2016–2017	2019–2020	2020+	2024+
Planned run duration			4 months	9 months	12 months	(per year)	(per year)
Expected burst range/Mpc		LIGO	40–60	60–75	75–90	105	105
		Virgo	–	20–40	40–50	40–70	80
		KAGRA	–	–	–	–	100
Expected BNS range/Mpc		LIGO	40–80	80–120	120–170	190	190
		Virgo	–	20–65	65–85	65–115	125
		KAGRA	–	–	–	–	140
Achieved BNS range/Mpc		LIGO	60–80	60–100	–	–	–
		Virgo	–	25–30	–	–	–
		KAGRA	–	–	–	–	–
Estimated BNS detections			0.05–1	0.2–4.5	1–50	4–80	11–180
Actual BNS detections			0	1	–	–	–
90% CR	% within	5 deg^2	< 1	1–5	1–4	3–7	23–30
		20 deg^2	< 1	7–14	12–21	14–22	65–73
	Median/deg^2		460–530	230–320	120–180	110–180	9–12
Searched area	% within	5 deg^2	4–6	15–21	20–26	23–29	62–67
		20 deg^2	14–17	33–41	42–50	44–52	87–90

- Summary of representative active, funded and proposed gamma-ray missions.
  † denotes missions with on-board follow-up instruments which enable more accurate localizations

Mission/ Instrument	Mission Class	Start Year	γ-ray Detector; Other Coverage	Energy Range	Average View	SGRB Rate	Location Accuracy	Sky View	Cadence
Swift/BAT	MIDEX	2004-	Coded Mask; XUVO	15-150 keV	15%	8.1	$\sim$2'†	88%	Daily
Fermi/GBM	Probe	2008-	Scintillators; γ	8-40,000 keV	50%	39.5[1]	$\sim$12°		
Fermi/LAT	Probe	2008-	Pair conversion; γ	0.04-300 GeV	20%	1.7	$\sim$0.5°	100%	3 Hours
IACTS[2]		2004-	Cherenkov (Air)	0.1-100 TeV	Pointed	?	<0.1°		
HAWC		2015-	Cherenkov (Water)	0.1-100 TeV	15%	?	<1°	67%	Daily
BurstCube	CubeSat	2021	Scintillators	30-1000 keV	>30%	>20	$\sim$20°		
SVOM/ECLAIRS		2021	Coded Mask; γXO	4-120 keV	15%	7	<14'	$\sim$50%	Variable
SVOM/GRM		2021	Scintillators; γXO	50-5000 keV	15%	15			
Glowbug	MoO	2023	Scintillators	30-2000 keV	50%	50	$\sim$9-12°		
CTA		2022	Cherenkov (Air)	0.05-300 TeV	Pointed	?	<0.05°		
SGSO		2022	Cherenkov (Water)	0.1-100 TeV	24%	?	<0.4°	67%	Daily
Bia (2)	MoO	2025	Scintillators	20-2000 keV	80%	80-120	$\sim$10-12°		
COSI-SMEX	SMEX	2025	Compton	100-5000 keV	25%	10-20	$\sim$0.5°	80%[3]	1.5 Hours
			Scintillators	150-5000 keV	50%	10-20			
MoonBEAM	MoO	2025	Scintillators	30-1000 keV	100%	35-40	$\sim$1°[4]		
Nimble/HAM	SMEX	2025	Scint.; UVOIR	20-3000 keV	40%	25-45	$\sim$12-15°†		
AMEGO	Probe	2030	Compton, Pair	0.2-30,000 MeV	20%	60-100	$\sim$0.5°	100%	3 Hours
STROBE-X	Probe	2030	Coded Mask; X	2-50 keV	30%	7-10	$\sim$2'	67%	Variable
THESEUS		2032	Coded Mask; XIR	2-20,000 keV	30%	15-35	5'†	64%	4.5 Hours

From Burns+2019 arxiv 1903.04472