Image Credit: NASA Goddard Space Fight Center / CI Lab

Multi-messenger studies of compact objects

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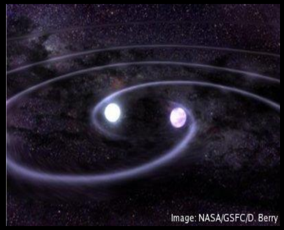
Thanks for M. Branchesi, S. Vergani

What is multi-messenger astronomy

Transient phenomena: shortest times scales (milliseconds to several years)

To emit GWs, a source must be compact, relativistic and asymmetric



Merger (NS-NS; NS-BH; BH-BH)

- Short GRBs, Kilonovae
- Other cases ? FRBs ?

Collapse of a single star

- Type Ib, Ic, II supernovae
- Long GRBs

Neutron star instabilities

- Soft Gamma-ray repeaters
- Radio/ Gamma-ray pulsar glitches

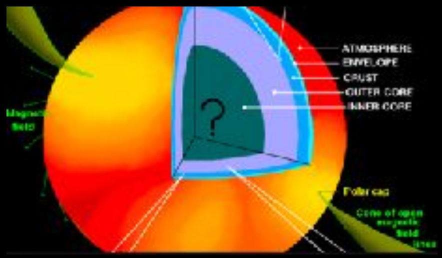
Radioactively powered transients

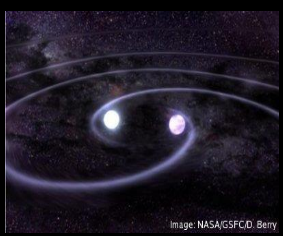
Relativistic astrophysics

Nucleosynthesis and enrichment of the Universe

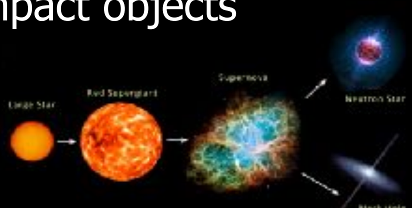
Multi-messenger observations

Nuclear matter physics

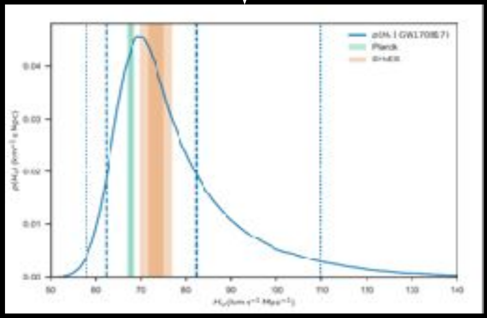




Compact objects



Stellar evolution



Cosmology

Gamma-ray burst

Relativistic astrophysics

Kilonova

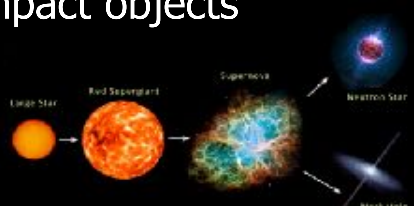
Radioactively powered transients

Nucleosynthesis and enrichment of the Universe

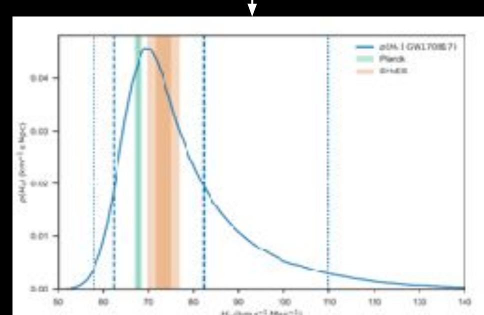
Multi-messenger observations

GWs

Compact objects

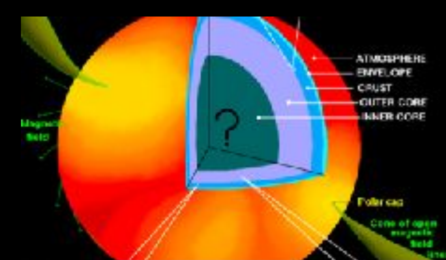


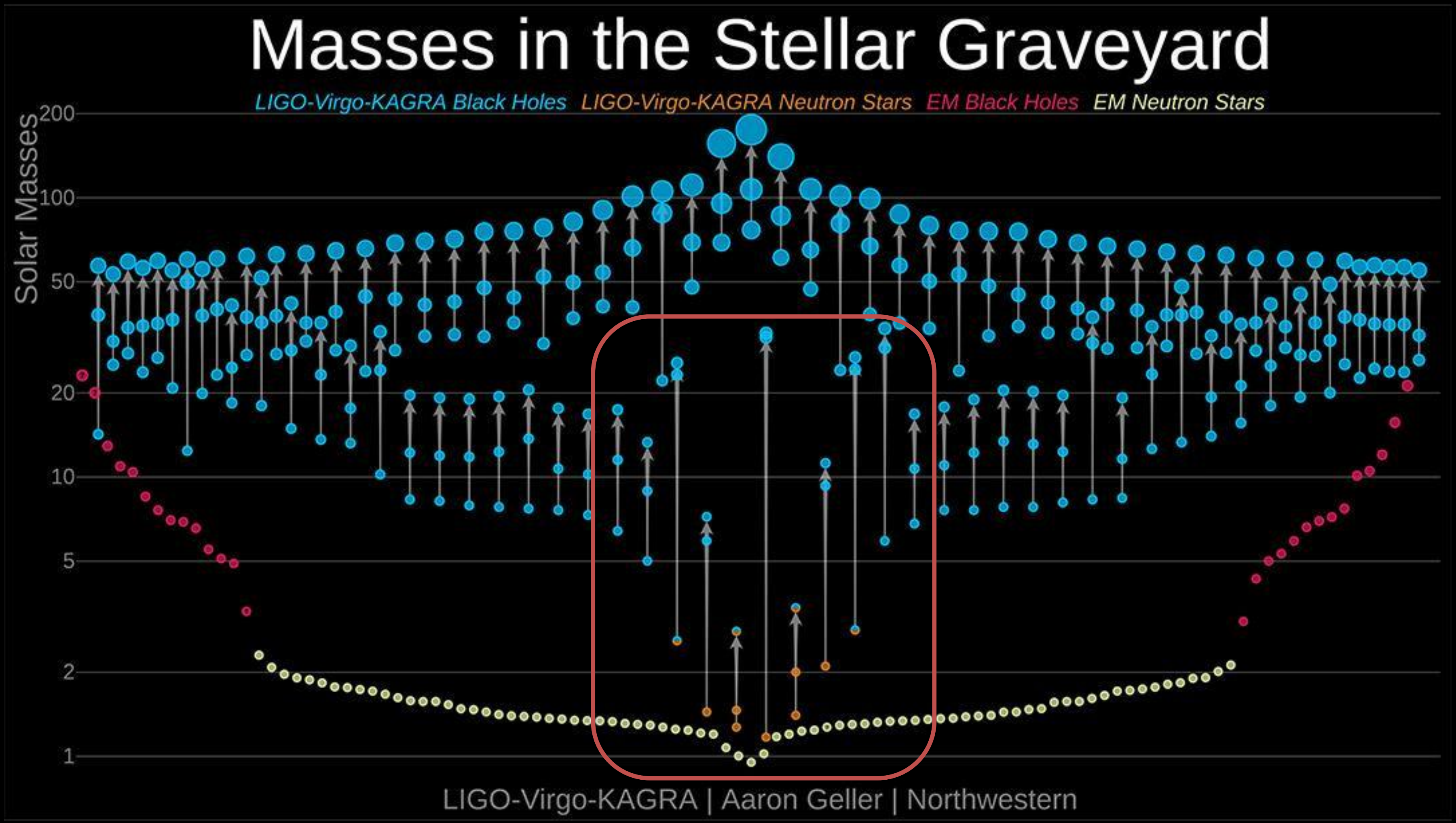
Stellar evolution



Cosmology

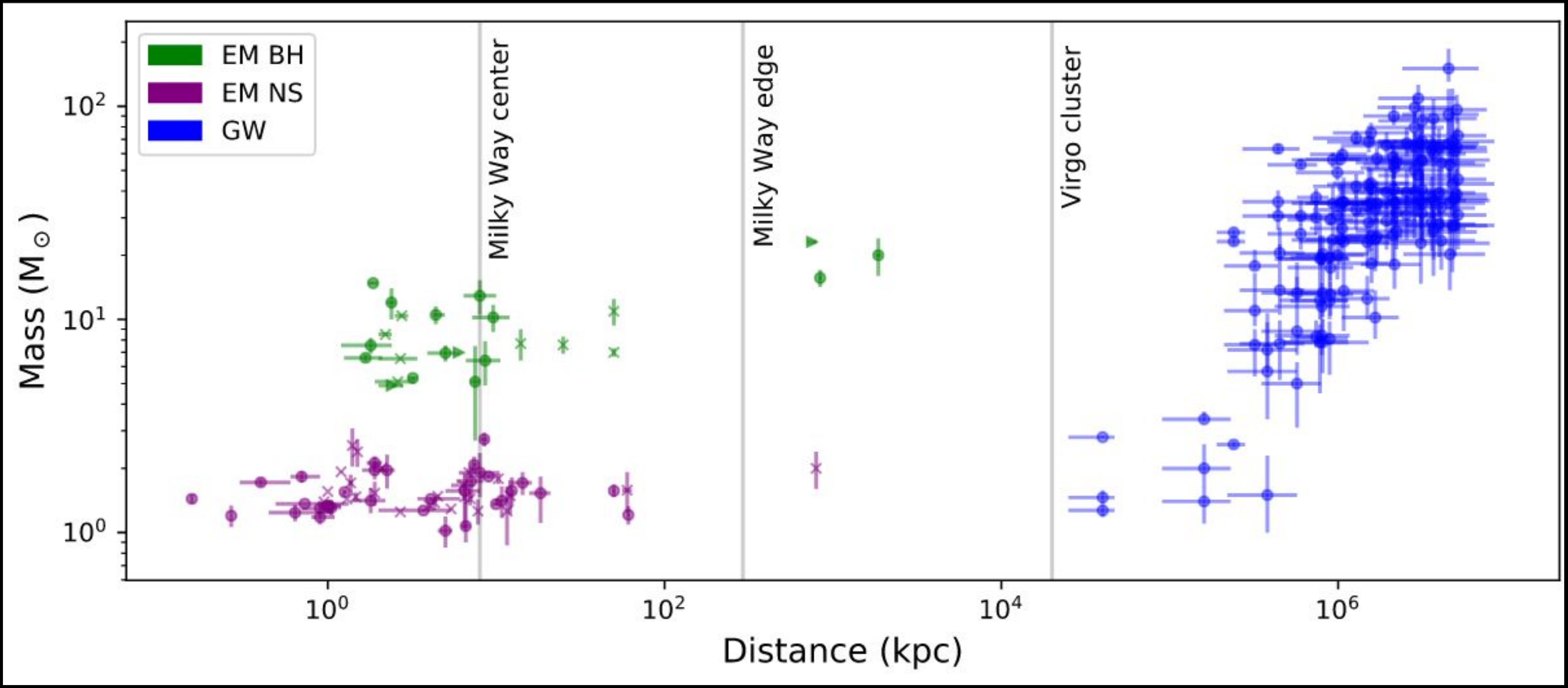
Nuclear matter physics





Multi-messenger
opportunities ?

Known compact object masses vs. estimated distance



McIver and Shoemaker, in prep.

Multi-messenger astronomy with LIGO-Virgo

COINCIDENCE SEARCH

Compare sets of candidate events

TRIGGERED ANALYSIS

Search that uses EM or neutrino observations to drive the detection of GWs *GRB prompt emission, SN explosion in local galaxies, flares SGR, pulsar glitches, low and high energy neutrino*

Known event time and sky position

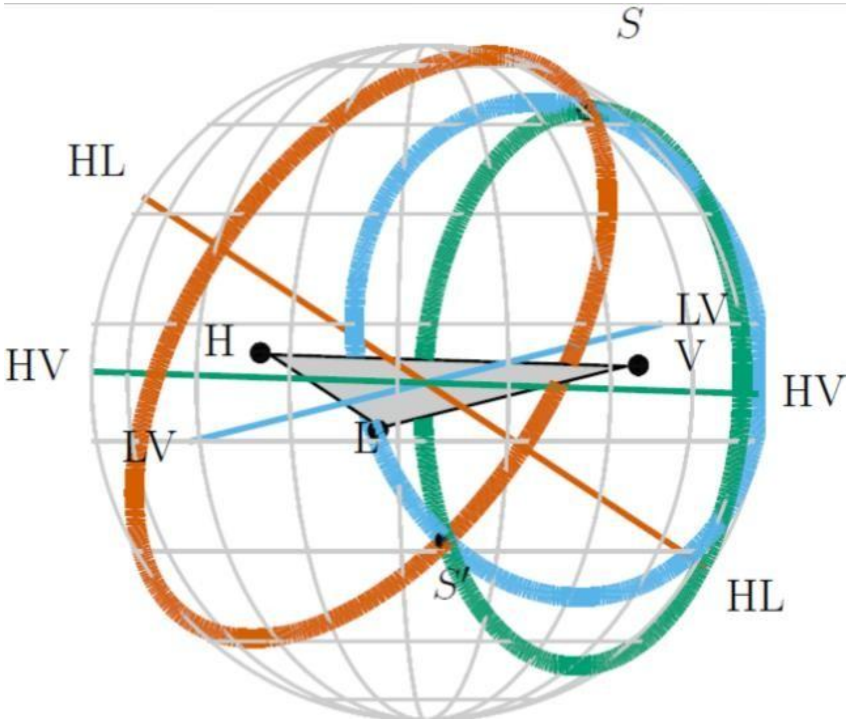
 reduction in search parameter space for GW searches

 gain in search sensitivity

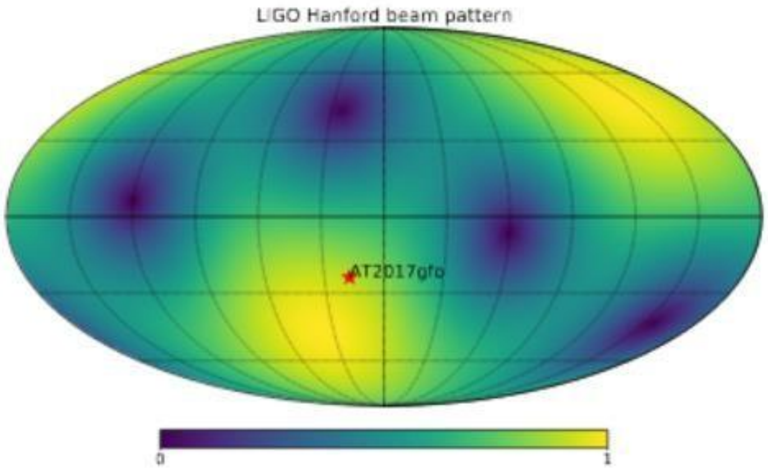
EM FOLLOW-UP

Search EM/neutrino counterpart candidates after GW identification

The principle of localization with GWs



Source localization by timing using triangulation for the Advanced LIGO – Advanced Virgo network

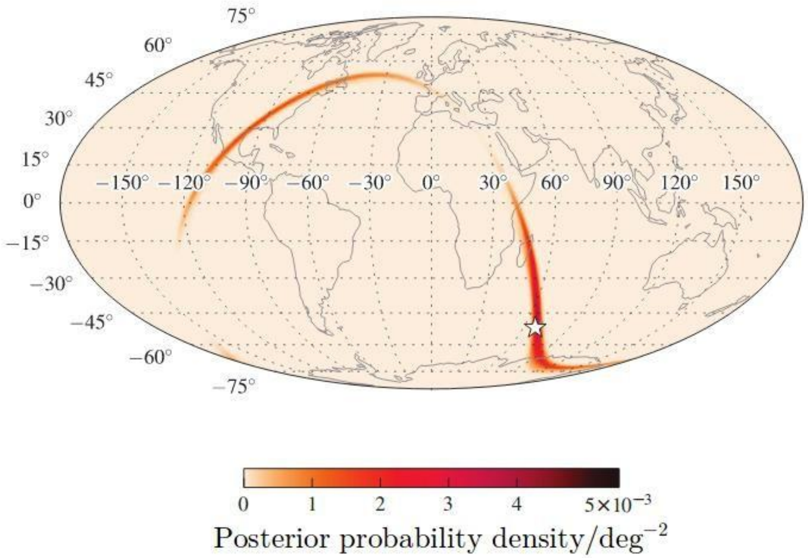


Antenna pattern of Livingston at the time of GW170817

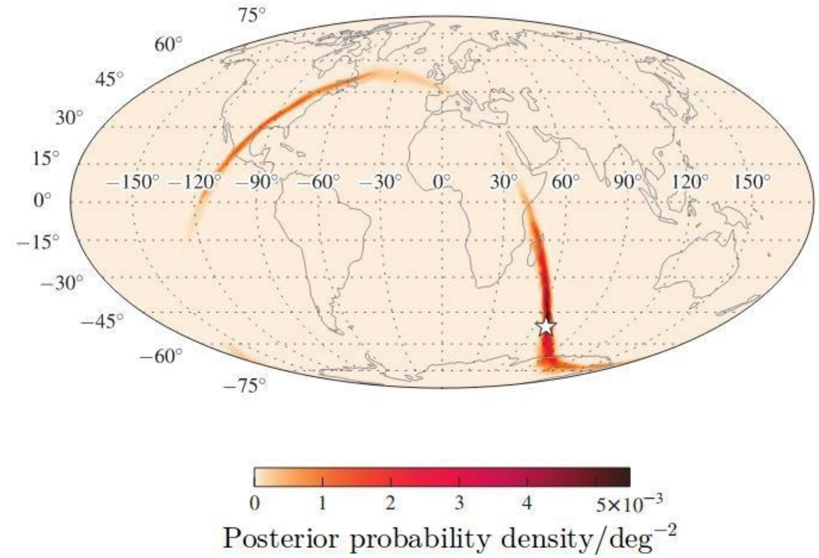
Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA

Localization of GW

BAYESTAR



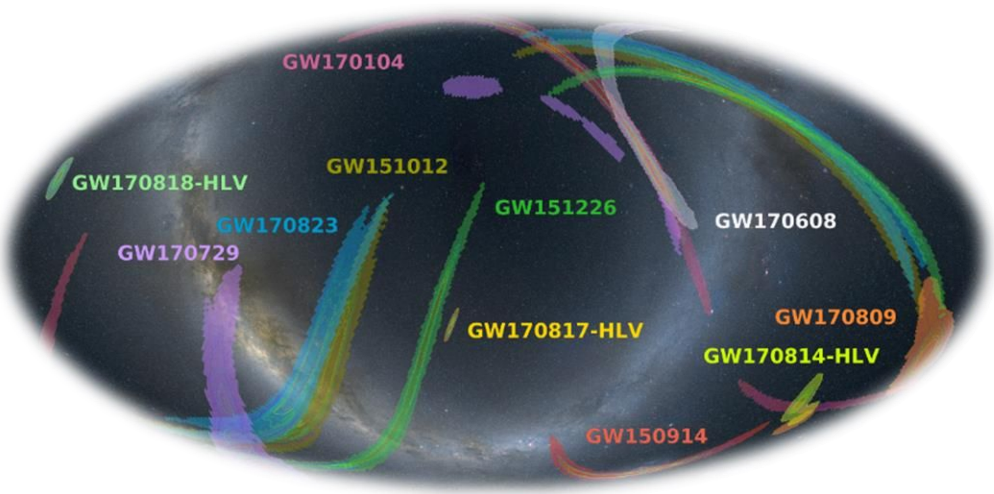
LALINFERENCE

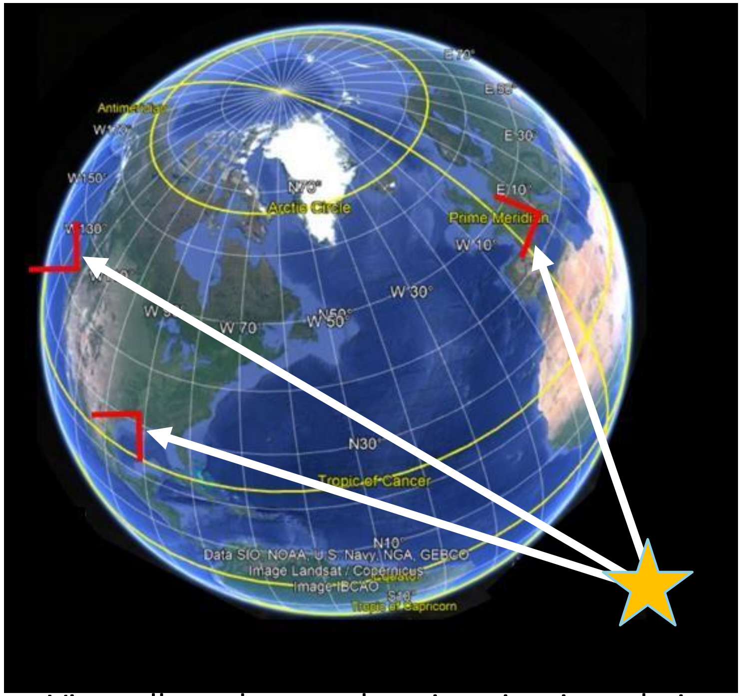


Posterior probability density for sky location with a simulated example. The source is at a distance of 266 Mpc and has a signal-to-noise ratio of 13.2

Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA

Localization of GW events





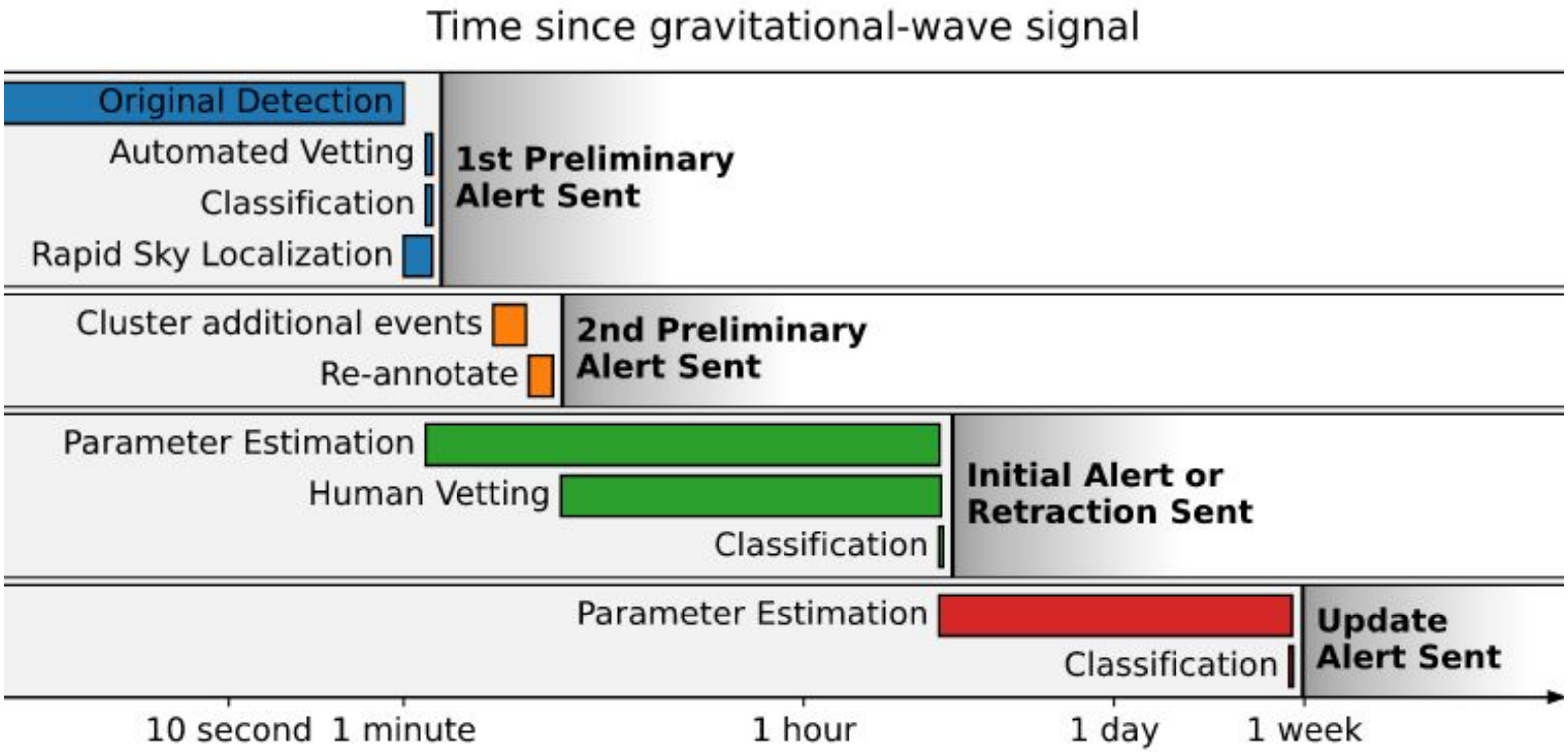
14 alerts sent during O2, 6 confirmed to be real!
GW170817 first arrived at Virgo, after 22 ms it arrived at LLO, and another 3 ms later LHO detected it

Virgo allowed source location via triangulation

Low latency gravitational wave alerts for multi-messenger astronomy during the second advances LIGO and Virgo observing runs APJ, 2019

Timeline of the **PUBLIC** alerts

Early warning alerts



Follow-up strategy

COINCIDENCE SEARCH – EARLY SEARCH

Neutrinos

Ice-cube + Antares
Monitor the all sky
Model dependant

Gamma-ray

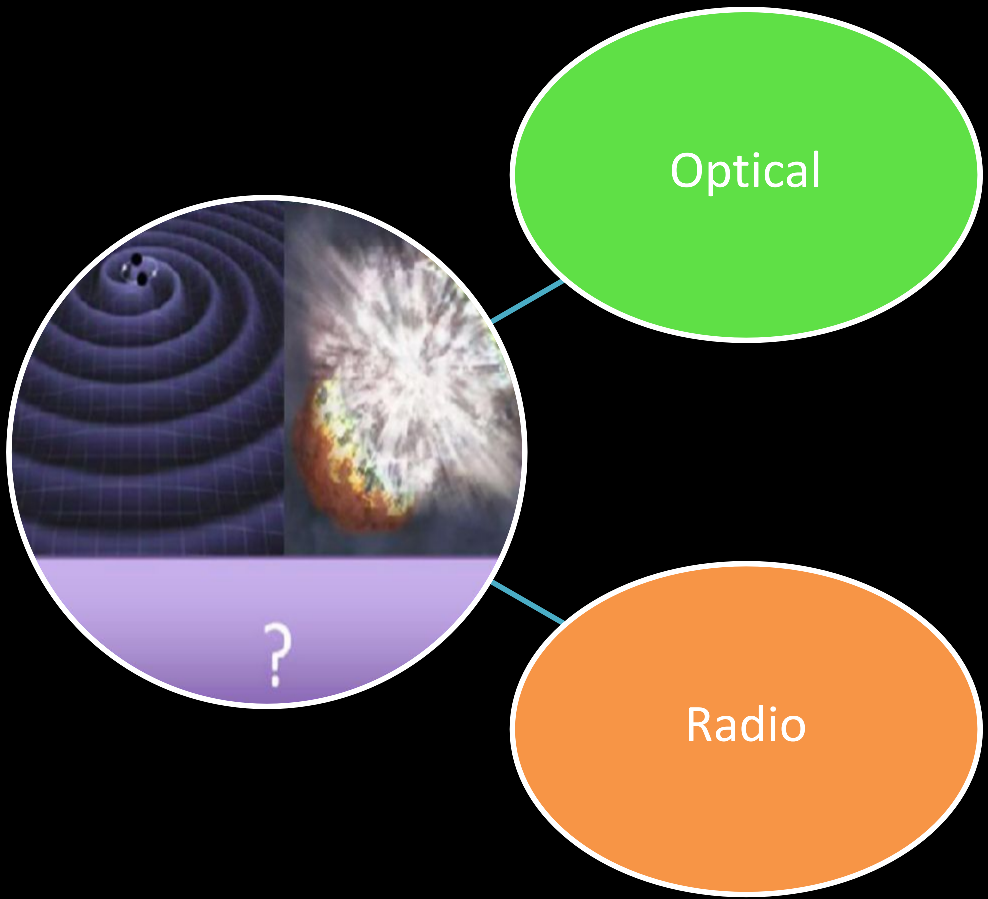
less contaminants
all-sky survey
Beamed emission

X-ray

less contaminants
No wide-field telescope

TRACK the em/neutrino counterpart of GW ALERTS

EARLY SEARCH

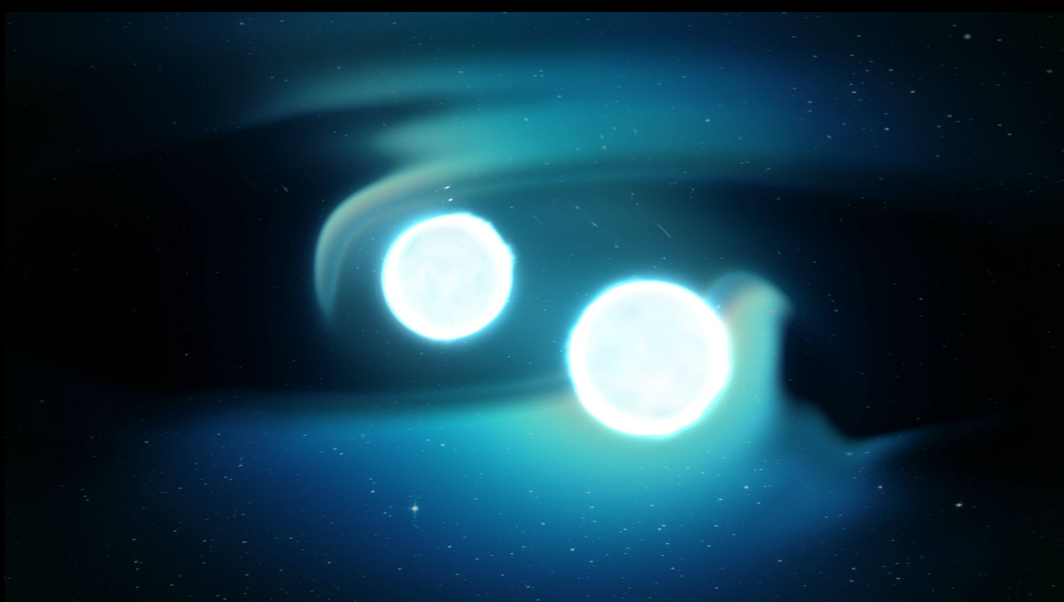


Lot of contaminants
10^4-10^5 variable objects
over 100 sq. degrees
Difficult to monitor the whole sky

Less contaminants
Wide-field array at low frequencies (MHz) Faint sources
Long delay between GW and radio emission

Two massive stars

A long time ago in a galaxy far, far away....

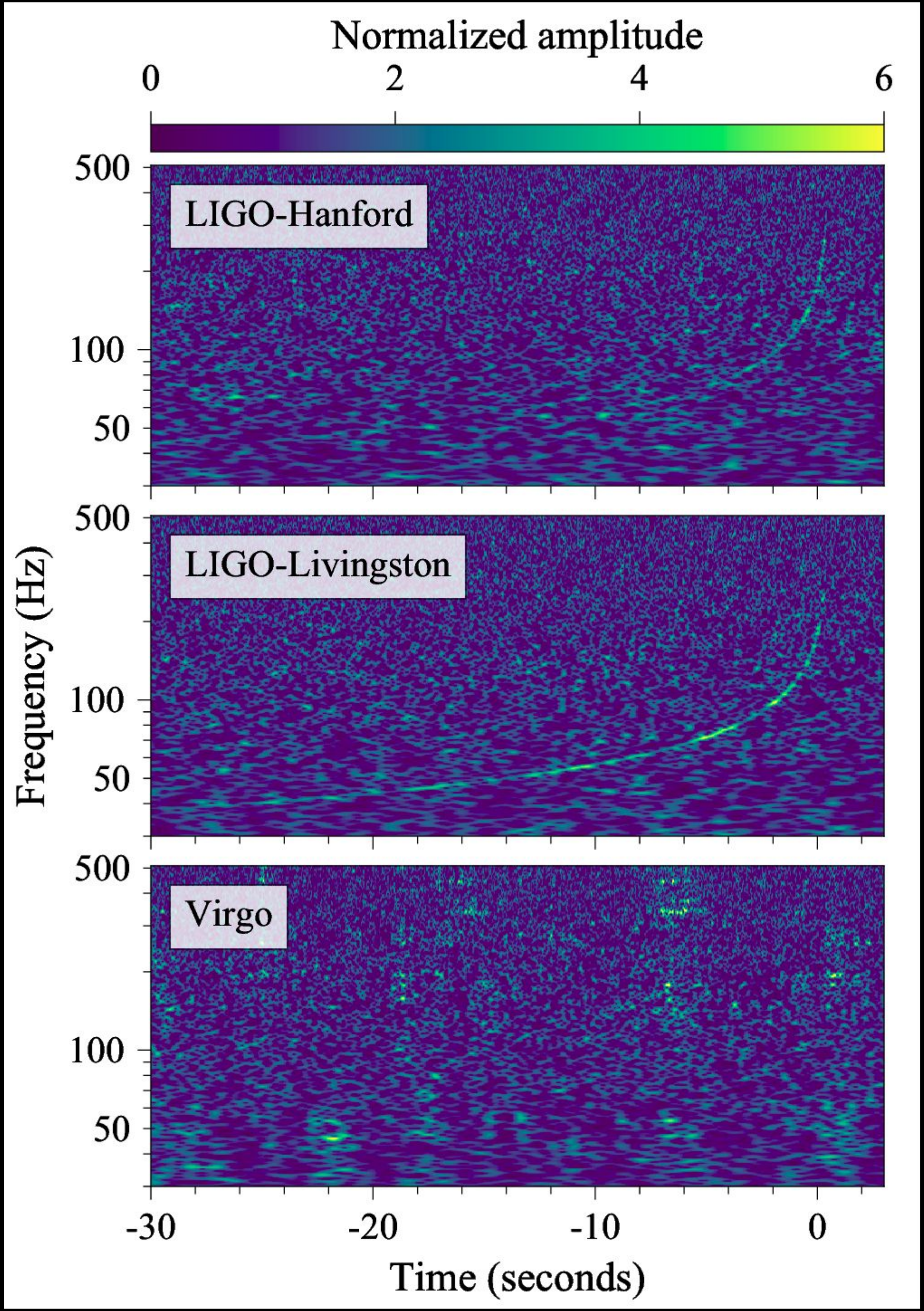


NGC 4993

127 M light yr - 40 Mpc

Spheroidal galaxy

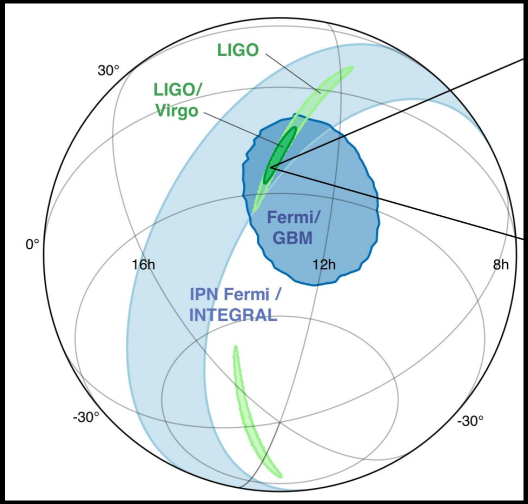
Low star formation rate



12:41:04.4 UTC

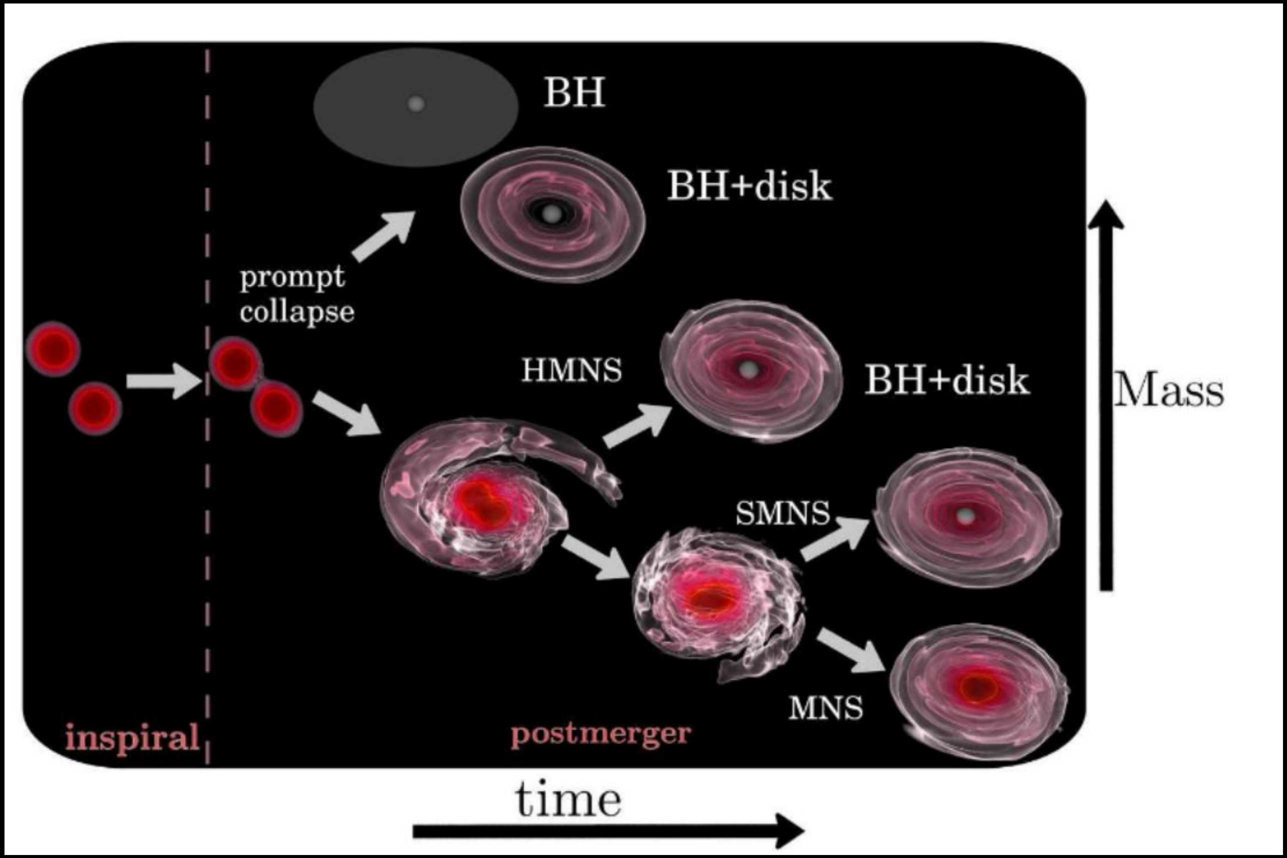
~3000 cycles from 30 to 1000 Hz
Chirp mass: 1.19 solar Mass
(component masses: 1.2 - 1.4 solar Mass)

Viewing angle ~ 28 degrees
D ~ 40 Mpc



Merger product

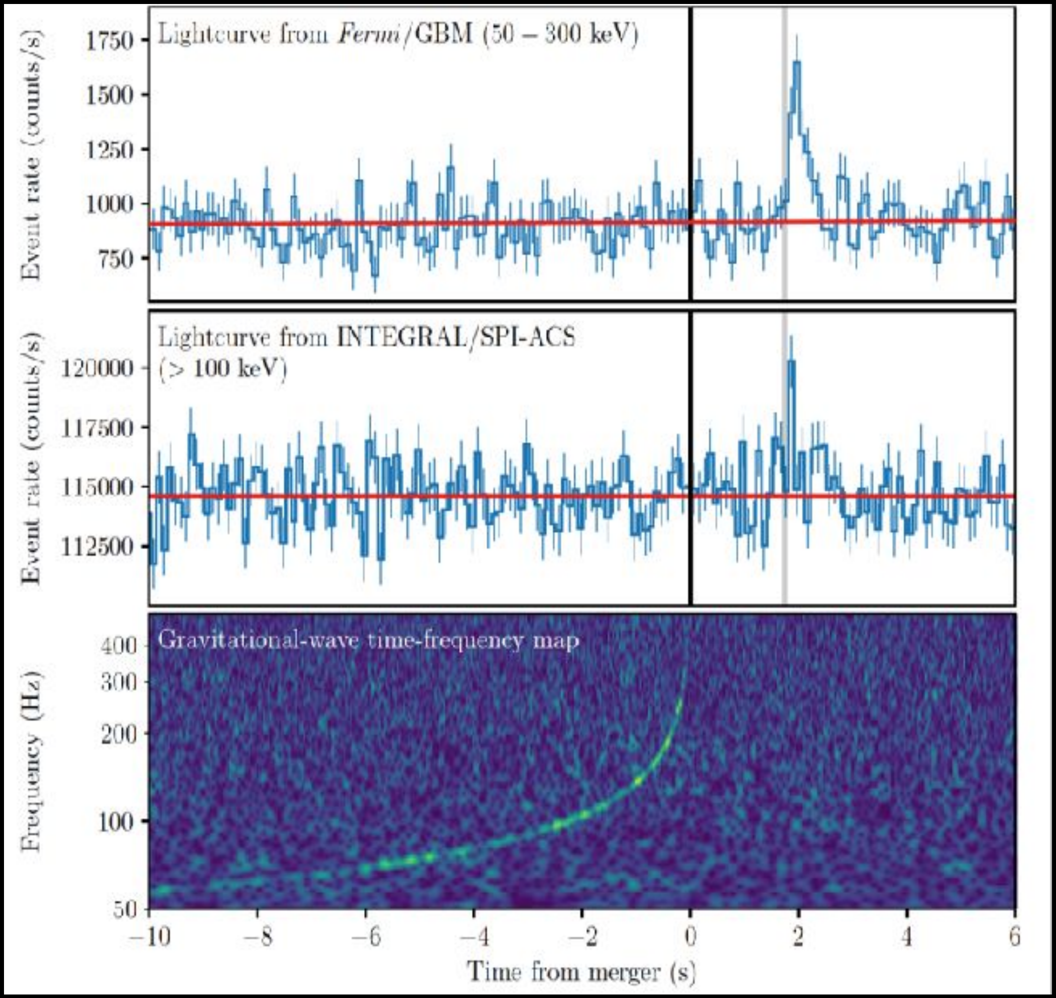
NS Mass : [1.0 , 2.2] solar mass   and NS Radius: [10 15] km



Central core : ~2.5 solar mass

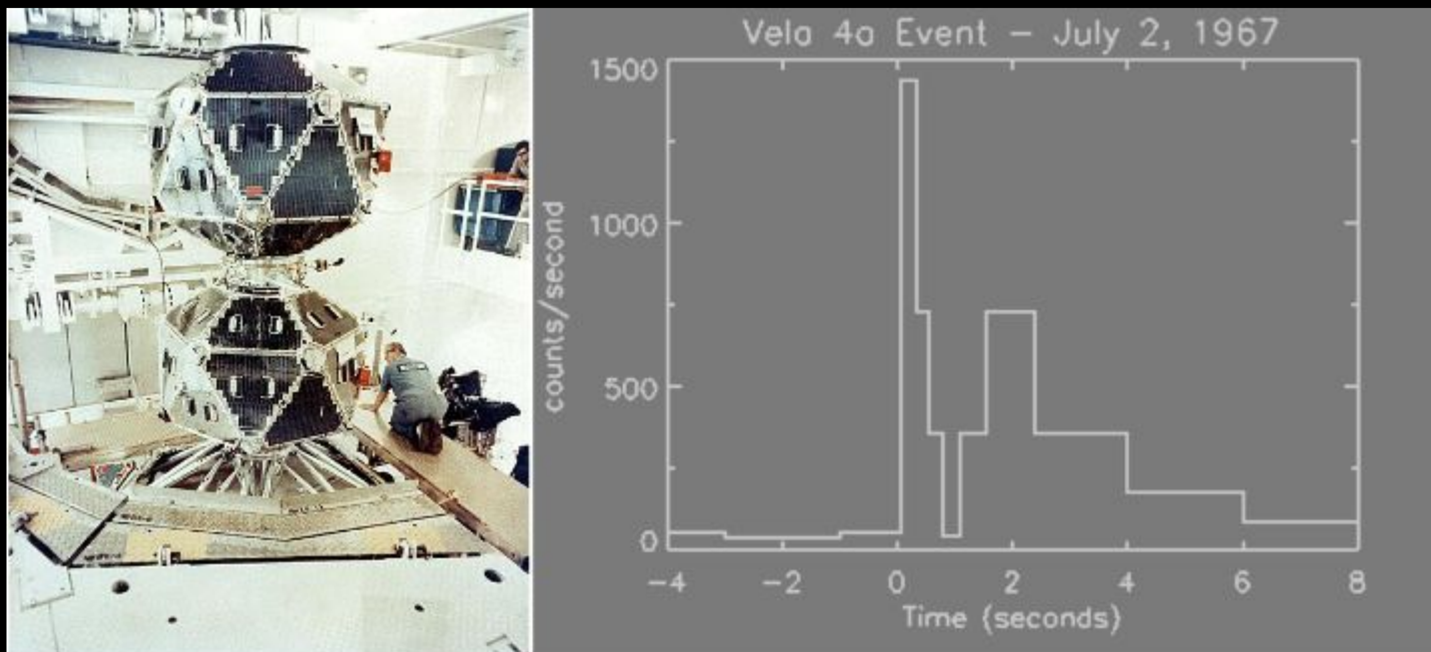
Direct collapse BH or massive long-live rapidly spinning NS (magnetar)
Accretion torus ~ 0.3 solar mass
mass loss (tidal tails, polar outflow): 0.01 to 0.1 solar mass

GRB170817A



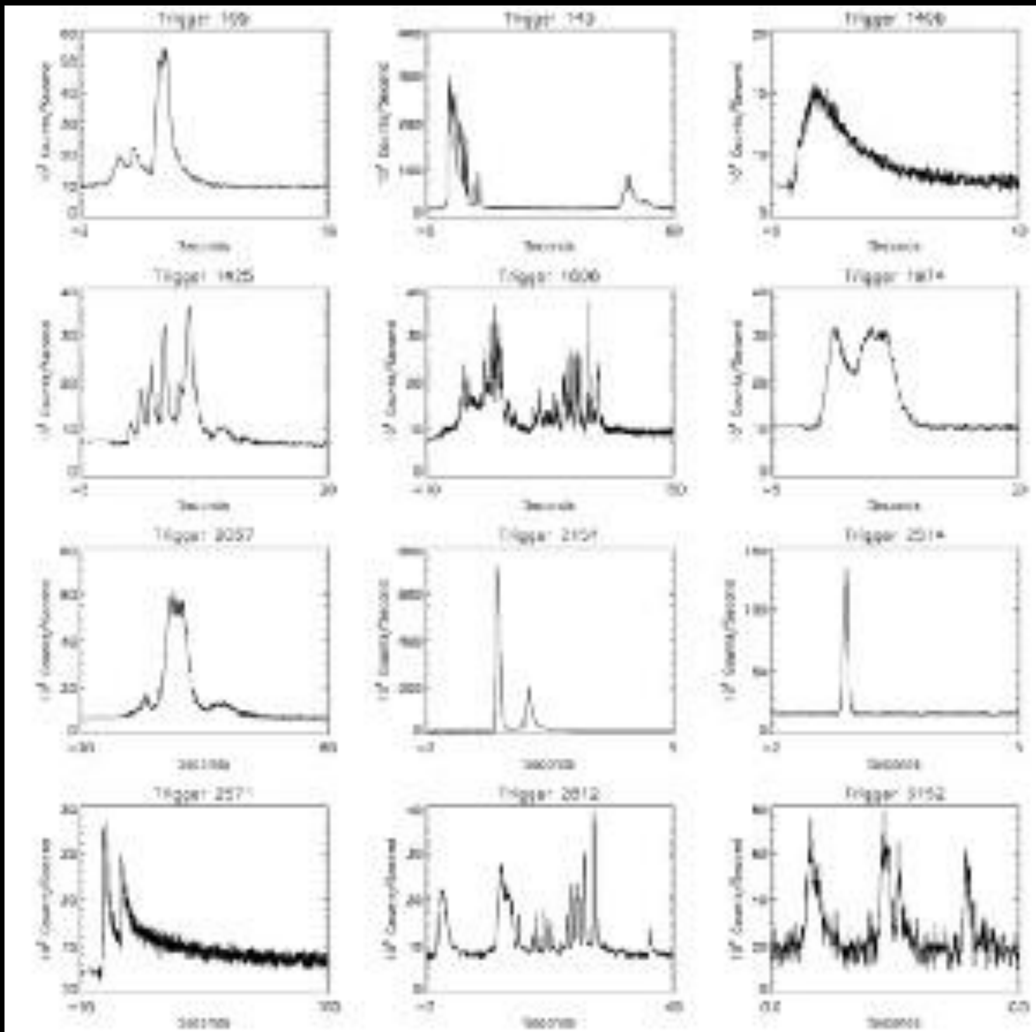
Lightcurve from Fermi/GBM (50 – 300 keV)
Event rate (counts/s)
1750
1500
1250
1000
750
Lightcurve from INTEGRAL/SPI-ACS
(> 100 keV)
Event rate (counts/s)
120000
117500
115000
112500
Gravitational-wave time-frequency map
Frequency (Hz)
400
300
200
100
50
−10
−8
−6
−4
−2
0
2
4
6
Time from merger (s)

Gamma-ray bursts

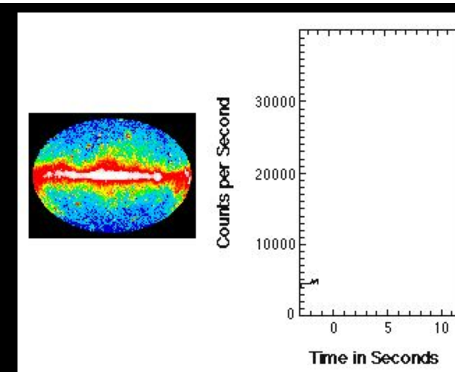


Vela satellites

Gamma-ray bursts



Fishman et al. 1995



High variability : ms → 100 ms

- Short duration: a few ms to a few min
- Two classes: short & long GRBs

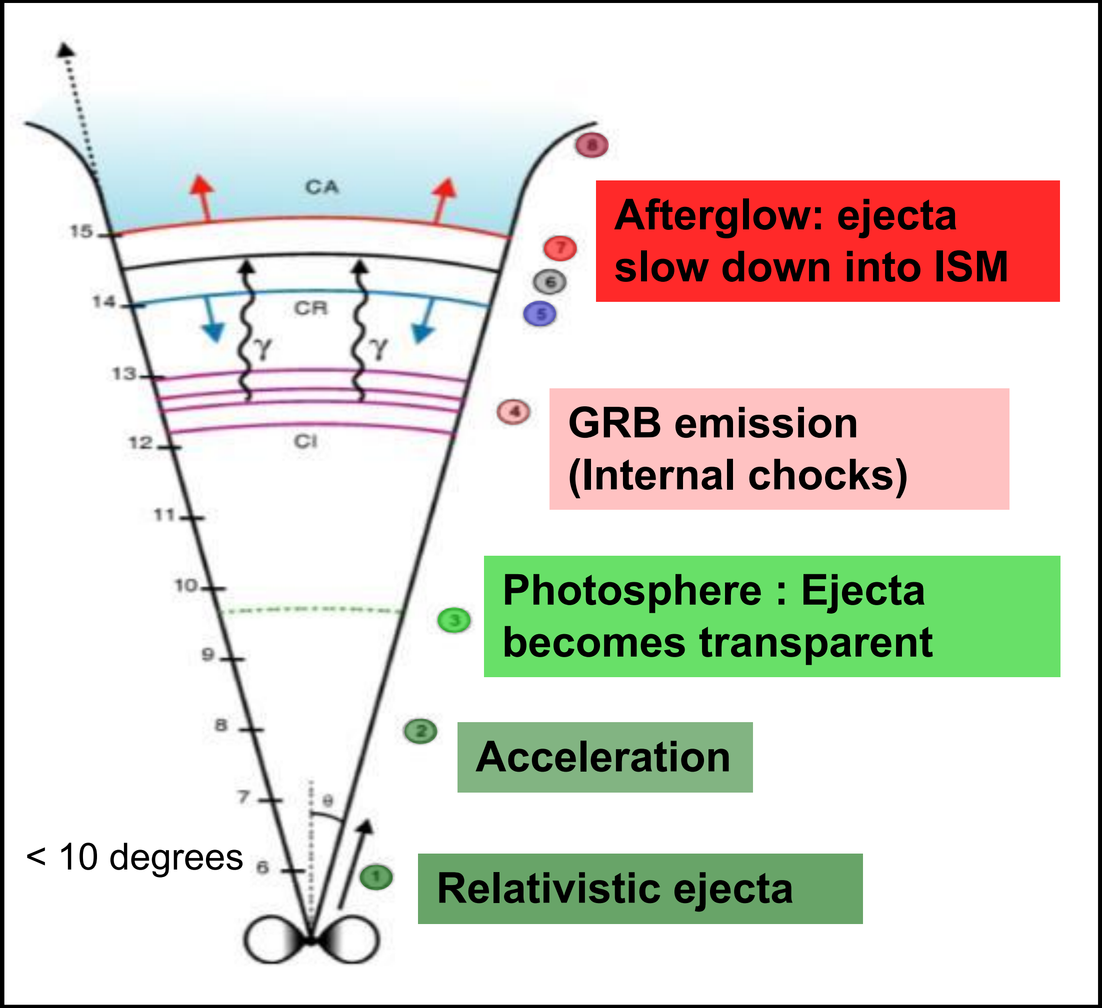
Great diversity of light curves :
→ Pulses: 100 ms → 10 s

Non-thermal spectrum: peak energy :
→ 100 keV → 1 MeV

Spectral evolution

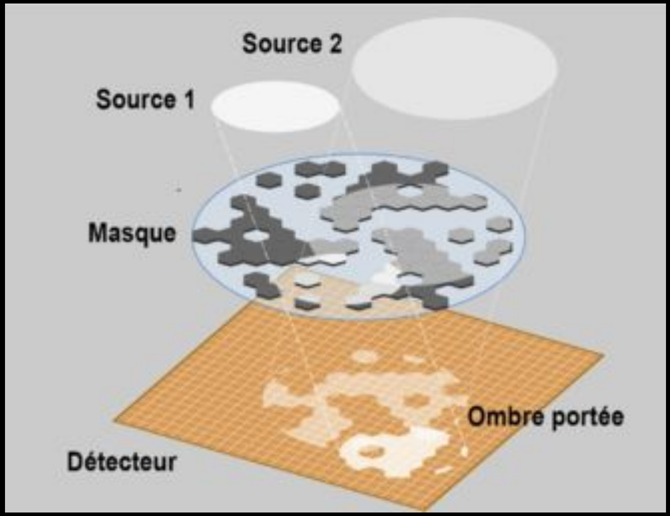
Spectral diversity: classical GRBs, X-ray rich GRBs, X-ray Flashes, etc.

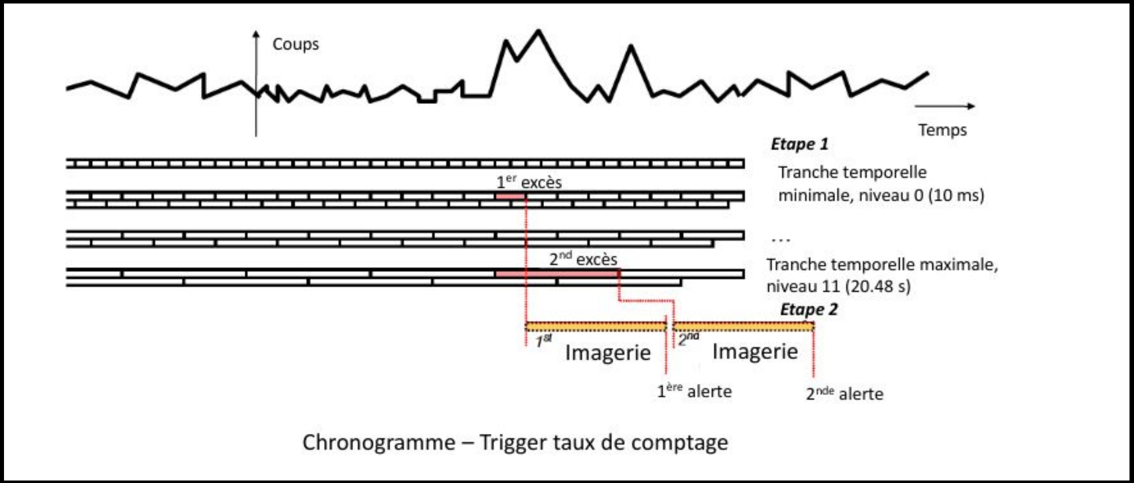
Gamma-ray bursts



Cosmological distance: huge radiated energy (Eiso ~ 10^50 -10^55 erg)

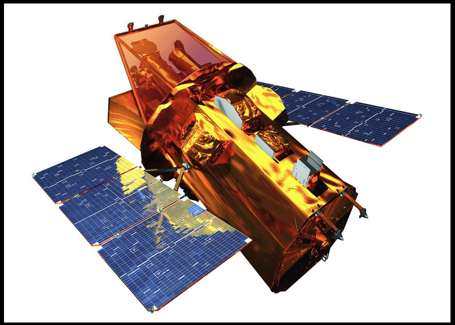
Detecting and localizing with Gamma-ray bursts





Coded mask technics

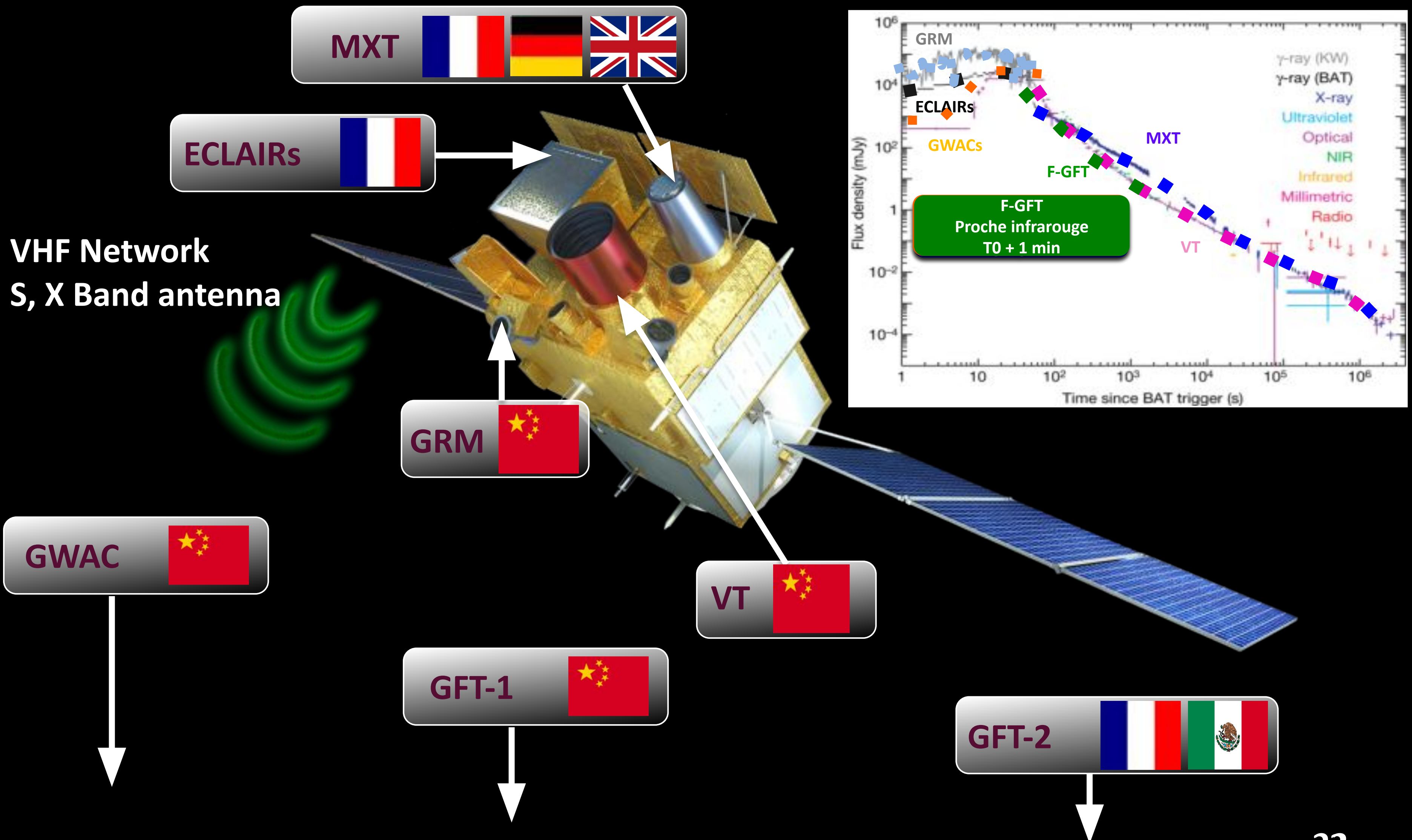
Trigger en Swift



Swift satellite

SVOM: Space-based multiband astronomical Variable Objects Monitor

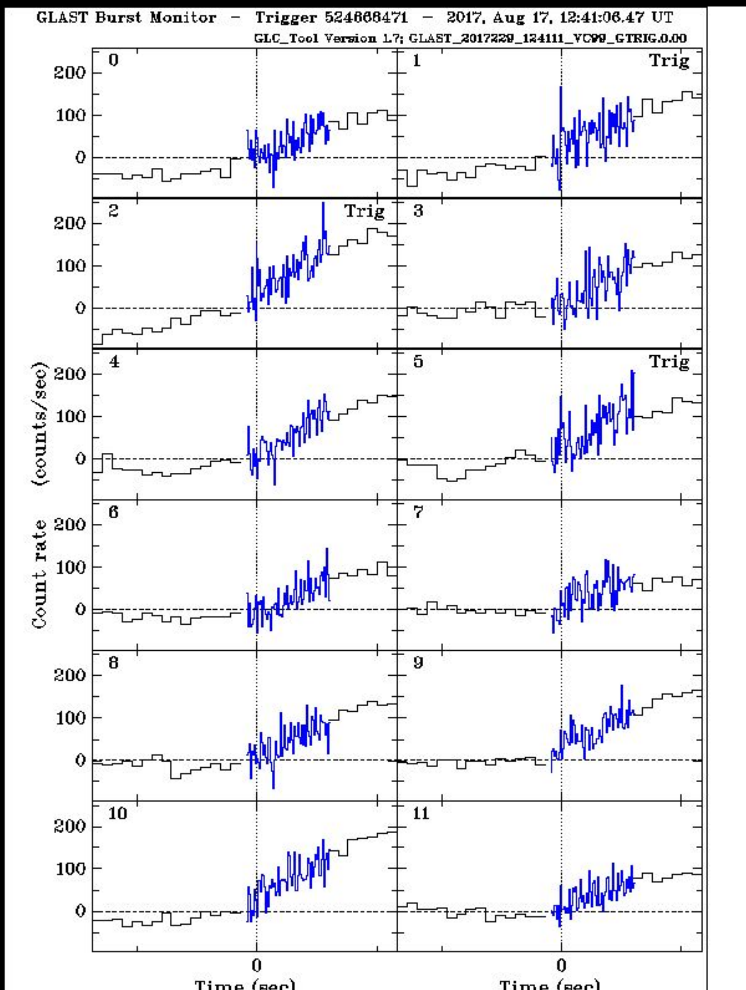
Satellite to be launched in 2024

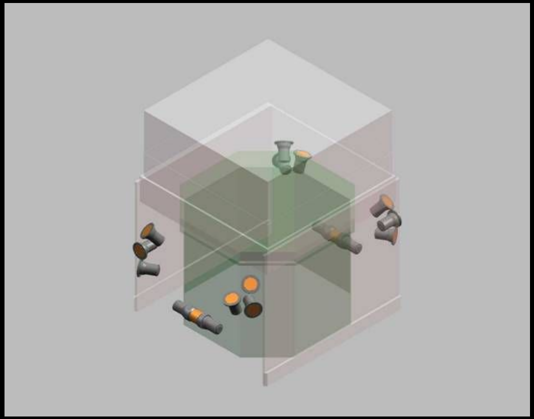


Cordier et al., PoS, *Swift:10* (2015)

Look at GRB170817A with Fermi-GBM

https://heasarc.gsfc.nasa.gov/FTP/fermi/data/gbm/triggers/2017/bn170817529/quicklook/





```
//////////////////////////////////////////////////////////////////////
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
DETECTORS:       0,1,1, 0,0,1, 0,0,0, 0,0,0, 0,0,
LC_URL:          http://heasarc.gsfc.nasa.gov/FTP/fermi/data/gbm/triggers/2017/bn170817529/quicklook/glg_lc_medres34_bn170817529.
COMMENTS:        Fermi-GBM Trigger Alert.
COMMENTS:        This trigger occurred at longitude,latitude = 321.53,3.90 [deg].
COMMENTS:        The LC_URL file will not be created until ~15 min after the trigger.
```

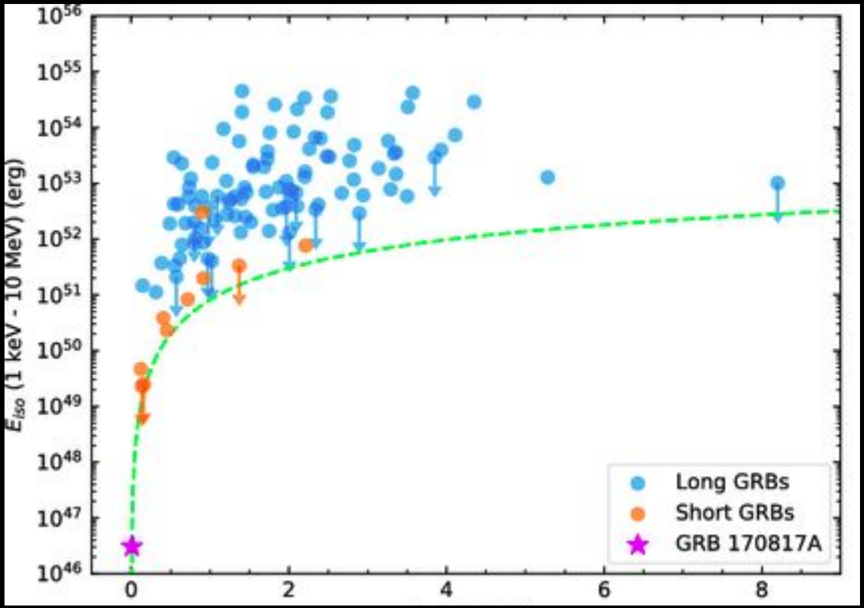
in blue 1s resolution

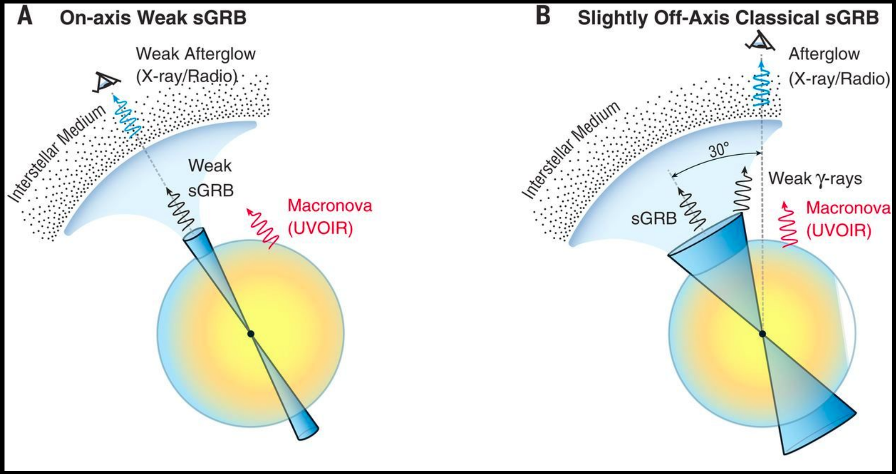
Why GRB170817A particular ?

Start 1.7s after GW signal; 1.5 duration

GRBs: photons above 100 keV
From 0 - 0.7s: non thermal spectrum possibly followed by a thermal tail

Very underluminous : Egamma,iso ~ 10 E 46 erg





Follow-up optical strategies of GW follow-up

GW sky localisation error box (hundreds deg^2)

Wide Field of view instruments

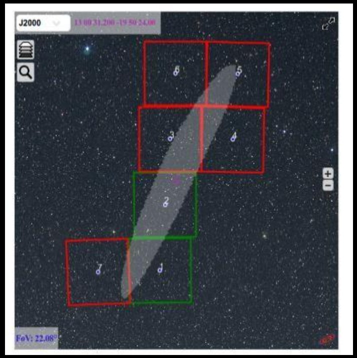
Trigger candidates

Follow-up with narrow fields instruments

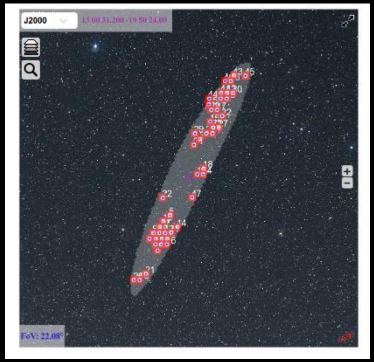
Caracterisation of the counterparts candidates

NEEDS A LARGE ASTRONOMICAL COLLABORATION

NEEDS SPECIFICS OBSERVATIONAL STRATEGIES



Tiling stategy



Galaxy-targeting (with distance)

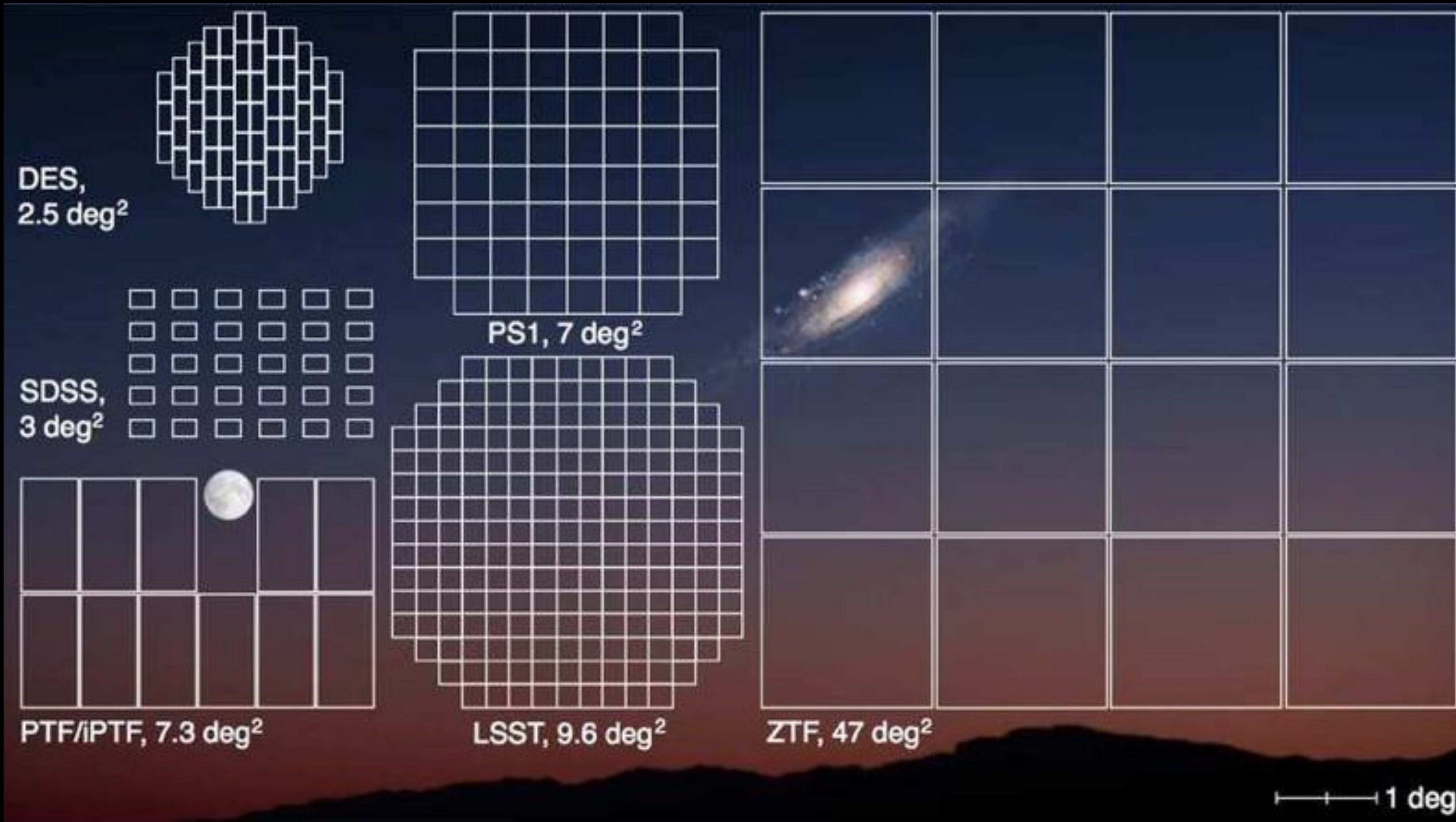
Observing

1.

2.

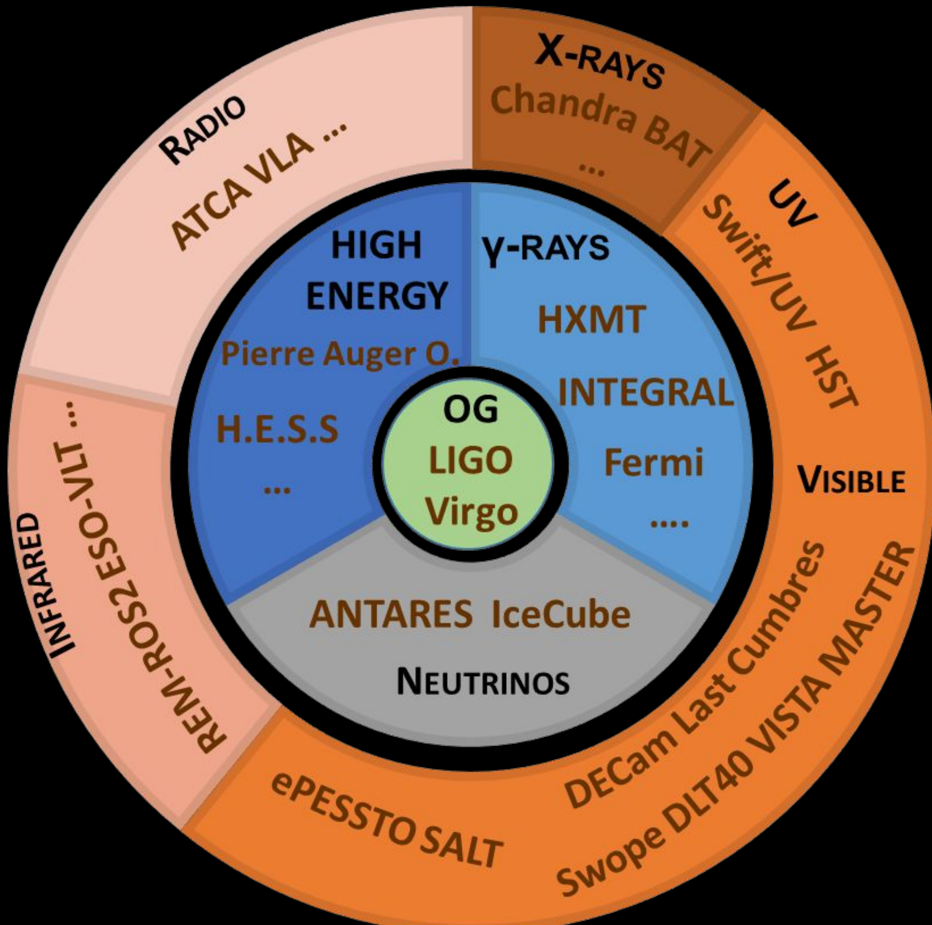
3.

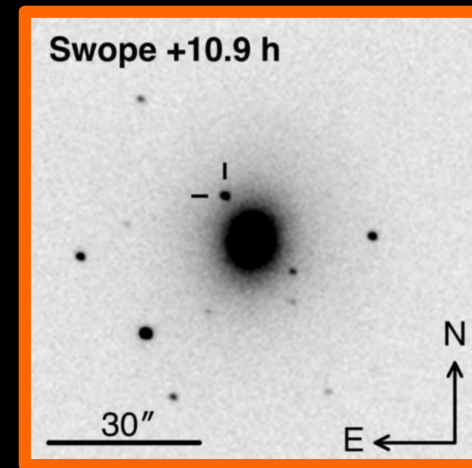
The Optical Time Domain

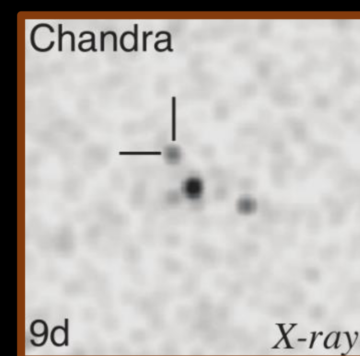


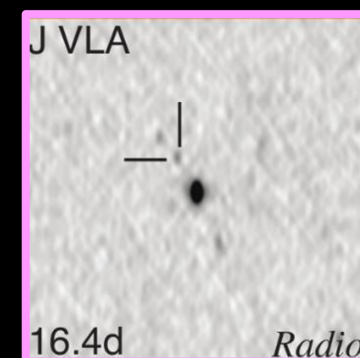
Many surveys: ZTF, PTF, CRTS, ATLAS, Pan-STARRS, LSST, Gaia, TESS, Kepler, ASAS-SN, etc

GW170817- Alert



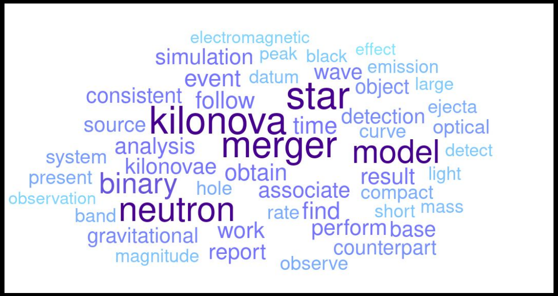


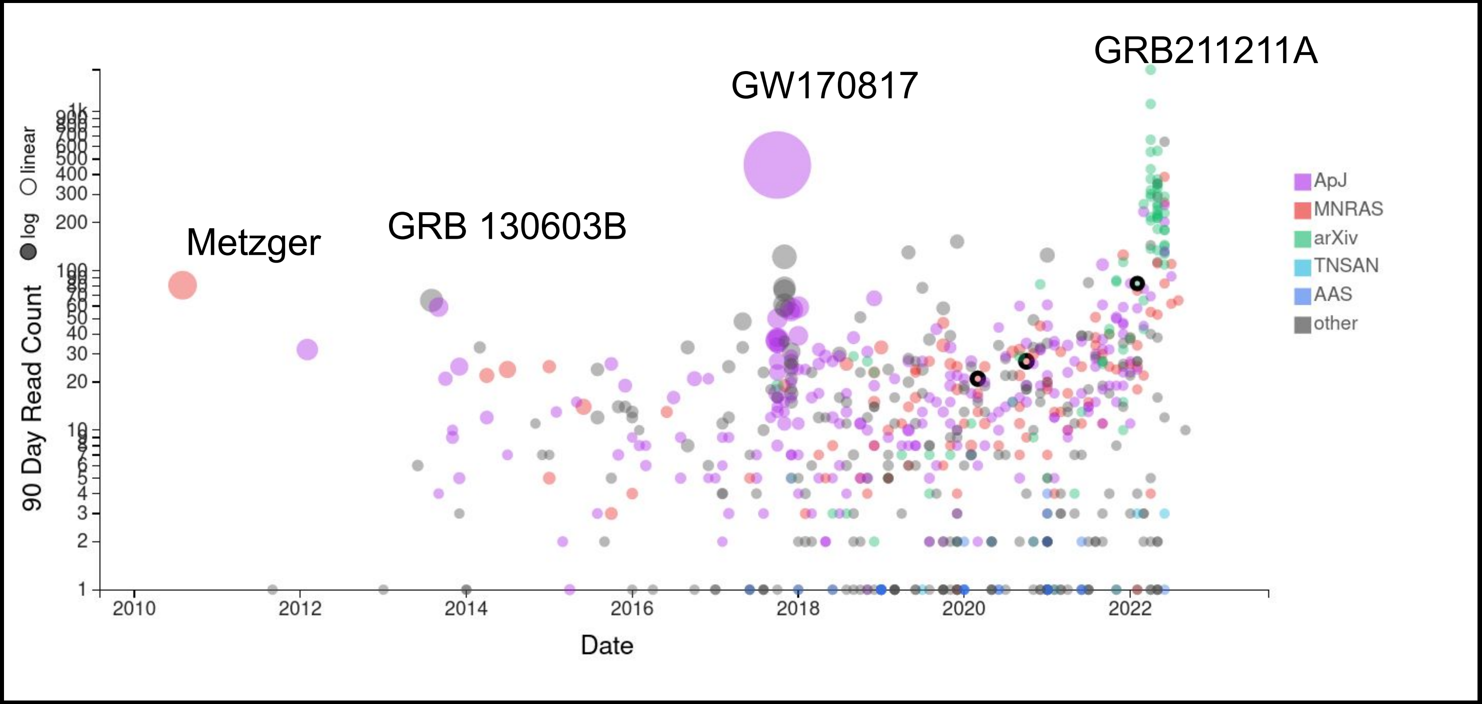




T0 GW detecti → +2 s GRB170817A → +5h GW localiz. → +11h Optical counter → +11h Host galaxy NGC499 → +9d X-ray counter part → +16d Radio counter part

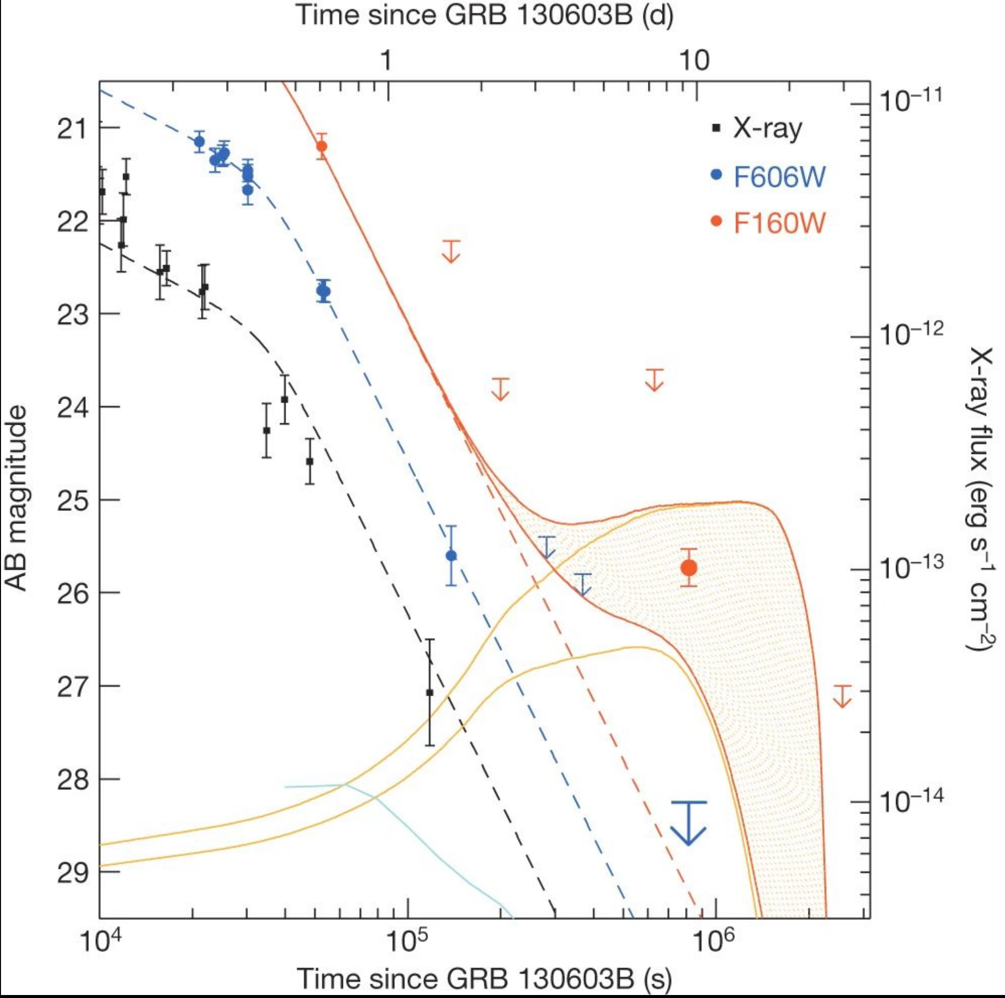
Kilonovae a very short story in astronomy





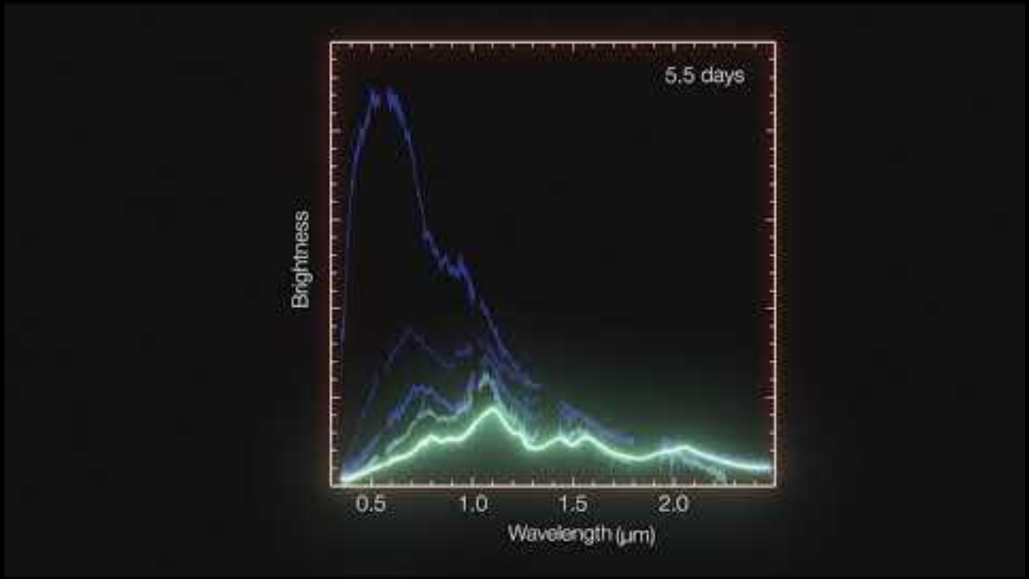
(Lattimer & Schramm) 1974

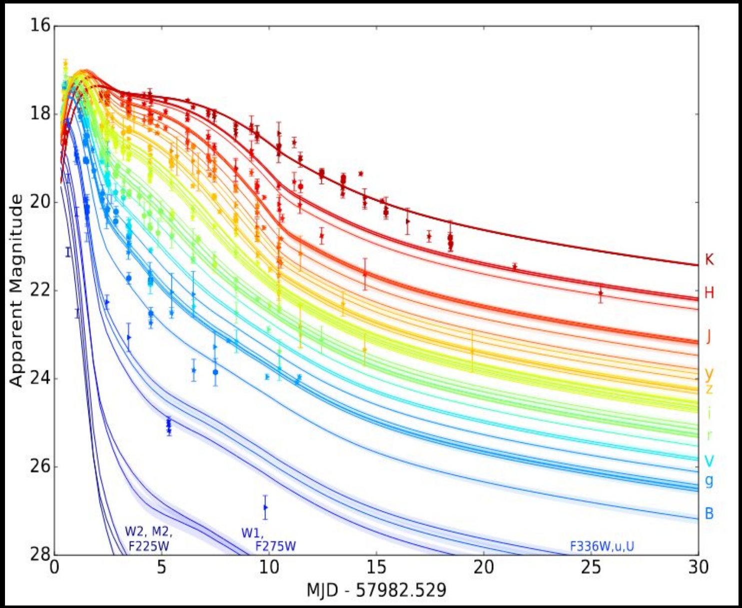
Kilonovae



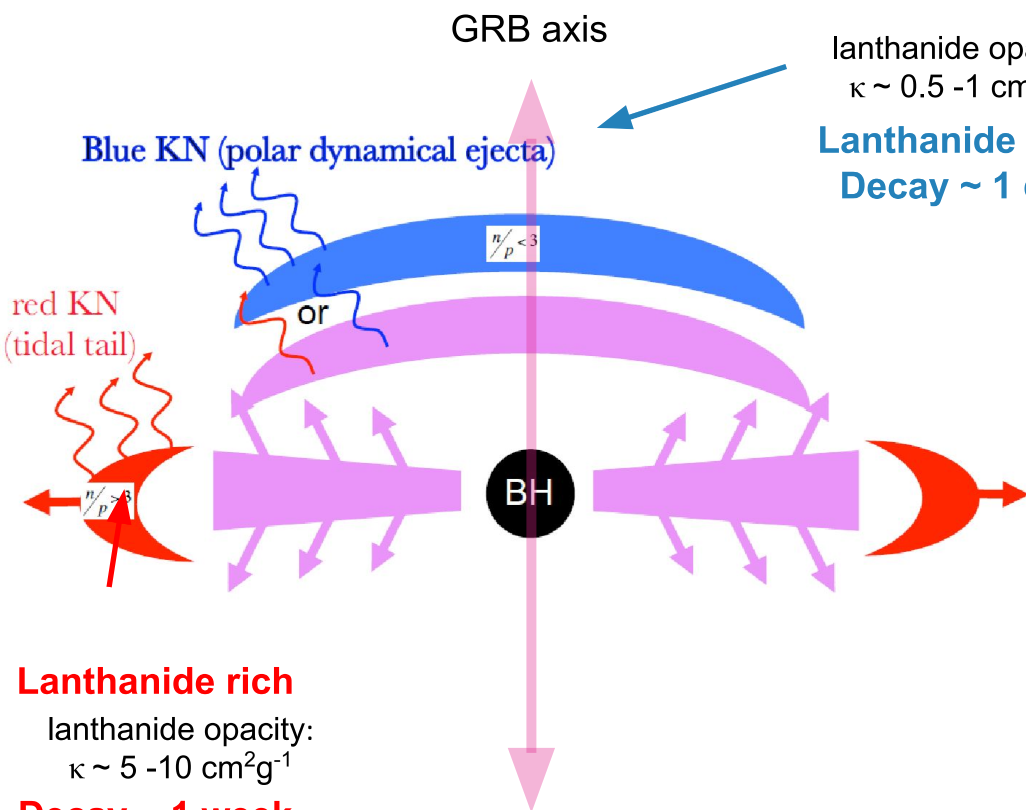
and other cases in GRB 060614, GRB 050709, GRB 150101B, GRB 070809, GRB160821B

Detecting new optical sources



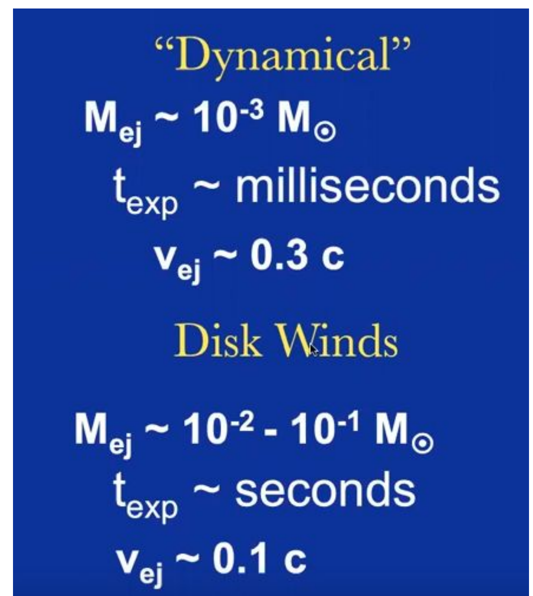


Kilonovae Modelisation



Observed properties change with:

- mass ratio
- equation of state of NS
- Lanthanide fraction
- nature of the post-merger



EX: GW170817

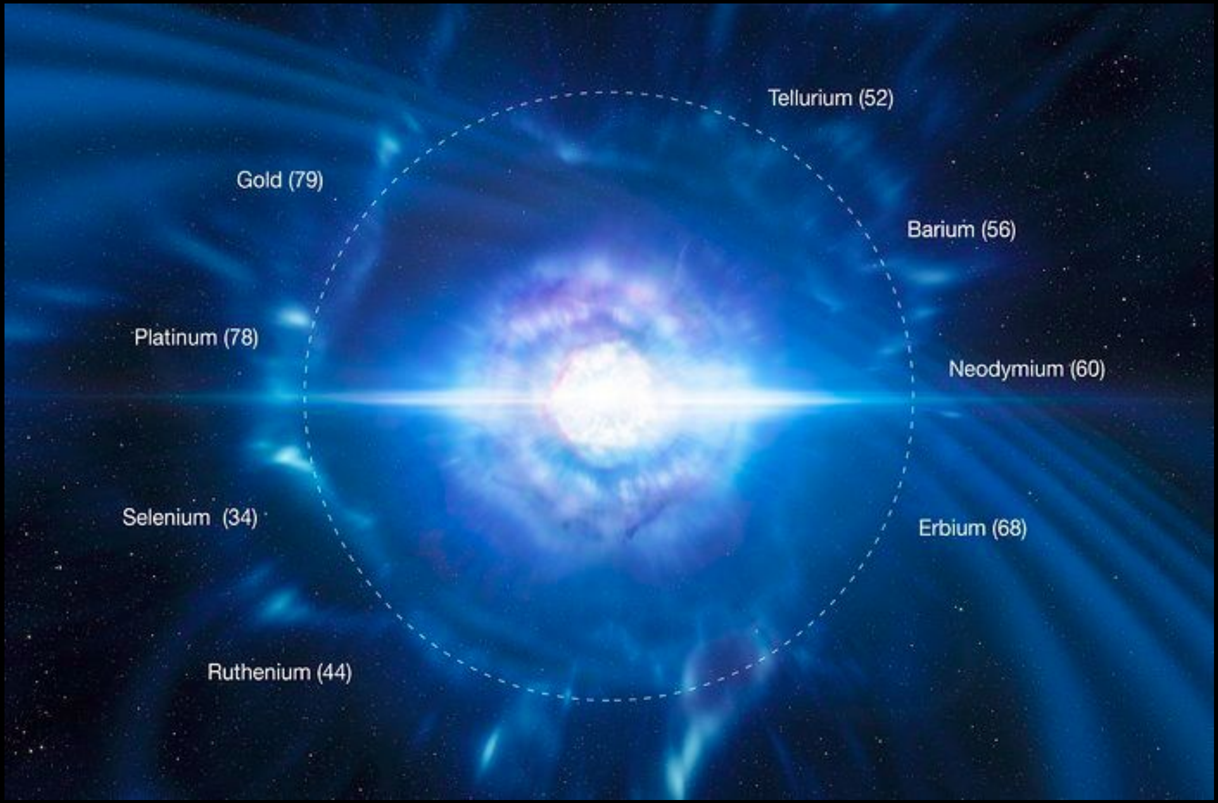
Kilonova (KN): **Optical** and **NIR** transient **powered by r-process** in **neutron rich** environment. Only **one** clear confirmed event (**AT2017gfo**)

100 millions times the sun → 1000 novae

Heating up through beta decay (n → p + electron + neutrino elec.)

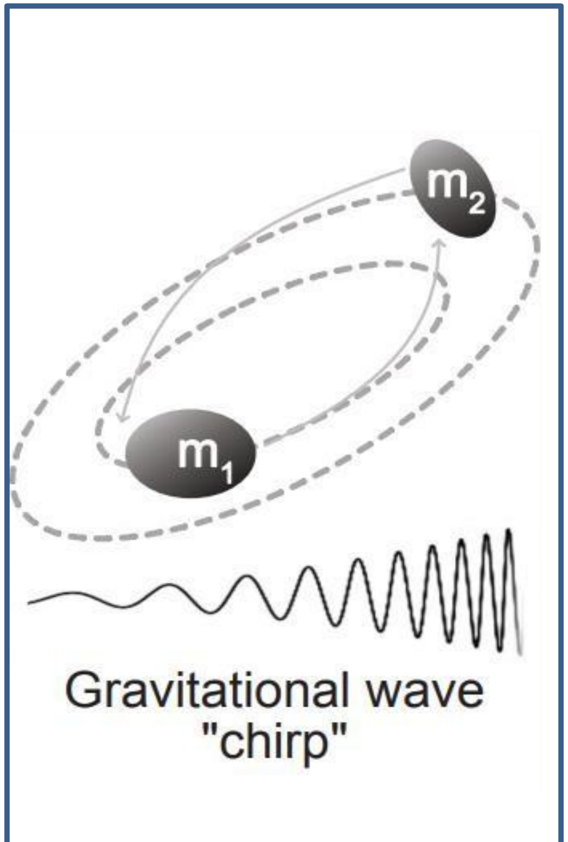
Production of heavy elements

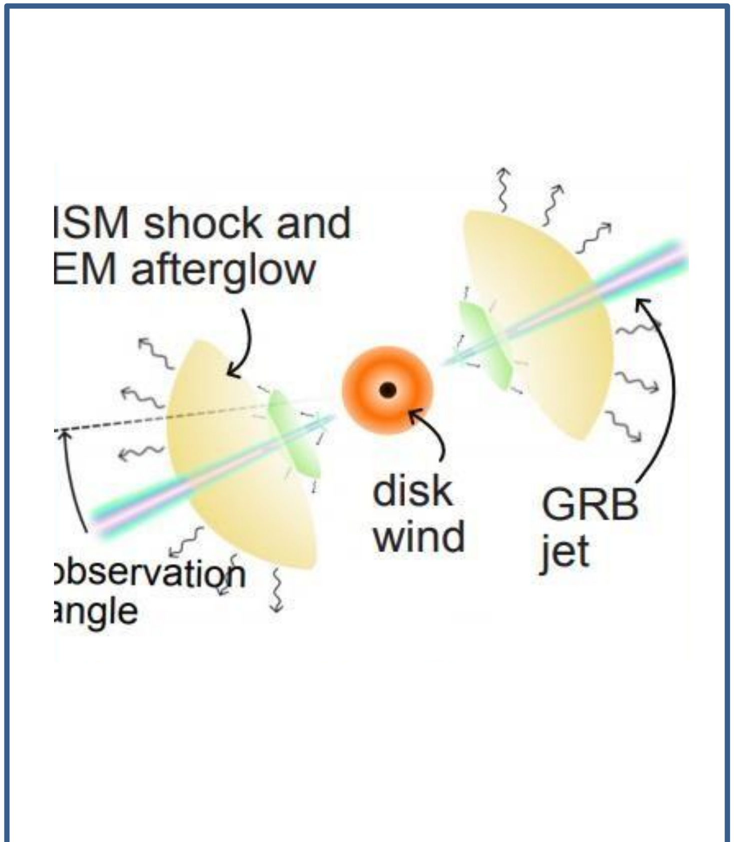
r-process nucleosynthesis is catalyzed by very intense neutron bombardment

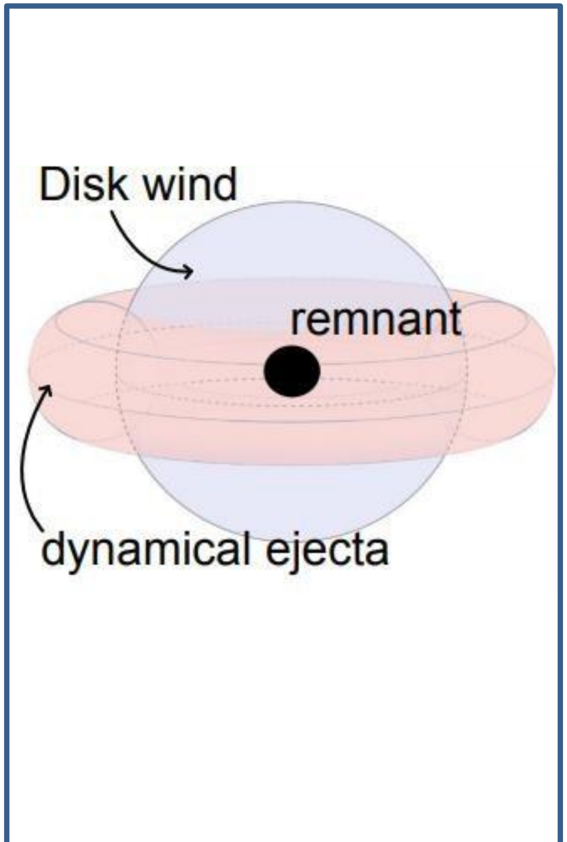


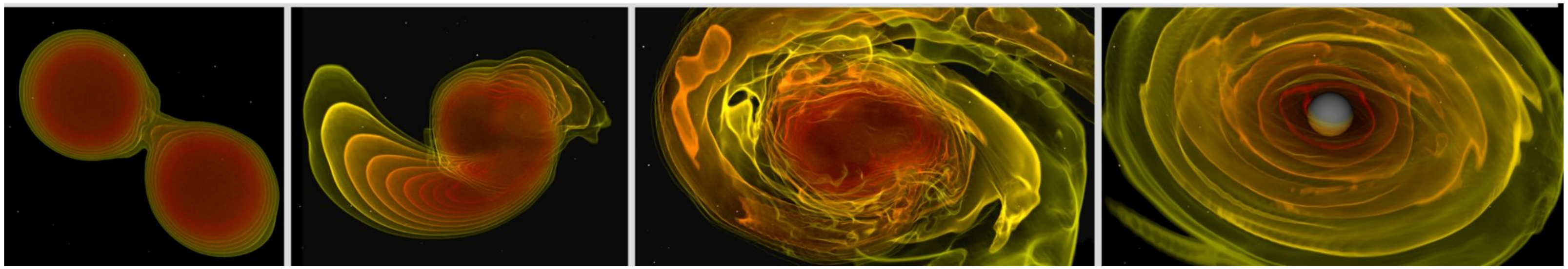
Combining multiple messengers

Merger Event → Gamma Ray Burst → Kilonovae









Science impact

FUNDAMENTAL PHYSICS

Access to dynamic strong field regime, new tests of General Relativity
Black hole science: inspiral, merger, ringdown, quasi-normal modes
Lorentz-invariance, equivalence principle …

ELECTROMAGNETIC EJECTA TO GW EVENTS

First observation for binary neutron star merger, relation to sGRB
Evidence for a kilonova, explanation for creation of elements heavier than iron

POPULATIONS STUDIES

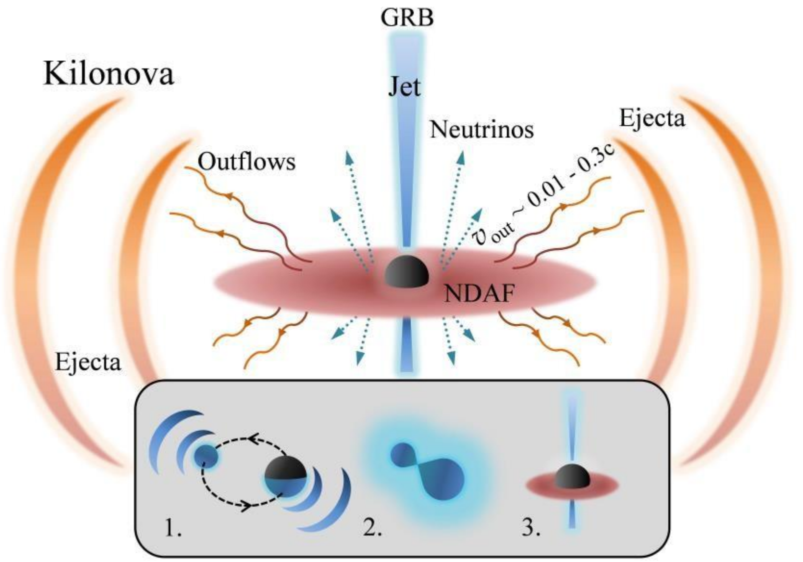
Start of gravitational wave astronomy, population studies, formation of progenitors, remnant studies
Gap between NS and BH

COSMOLOGY

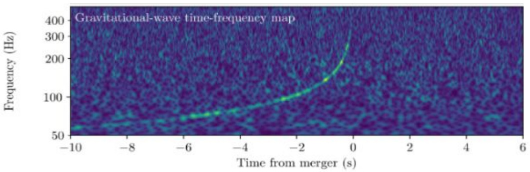
Binary neutron stars can be used as standard "sirens"
Dark Matter and Dark Energy, stochastic background

NUCLEAR PHYSICS

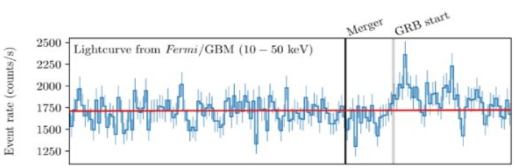
Tidal interactions between neutron



GW170817- First multi-messenger event

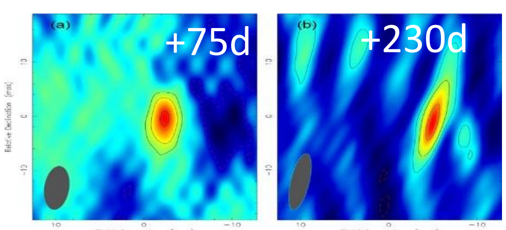


Ondes gravitationnelles
Système Initial

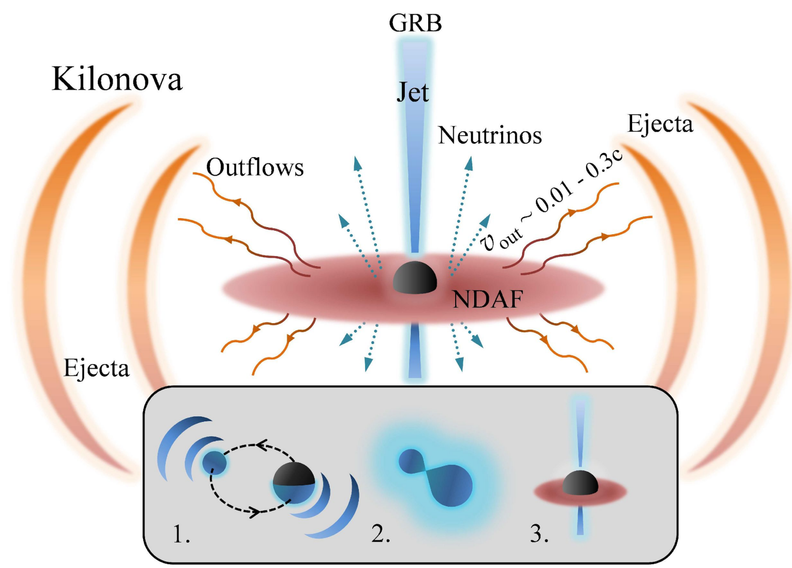


GRB
Jet
Mécanismes d'accélération

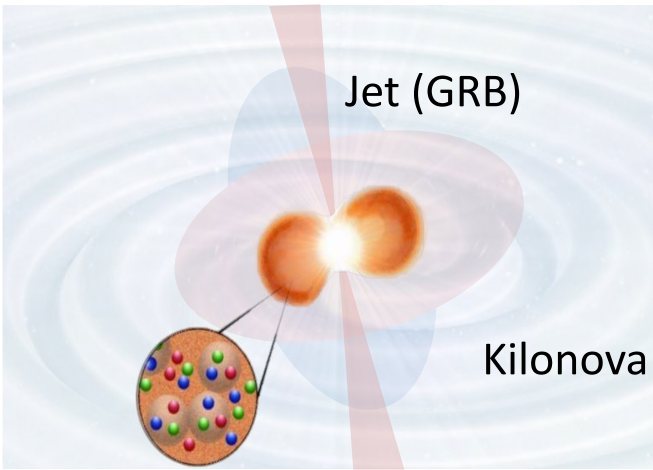
Kilonova
Localisation (arcsec)
Galaxie hôte
Décalage vers le rouge



Rémanence
Géométrie de l'émission



Multi-physics framework



GW / EM facilities

Chemical evolution
R-process

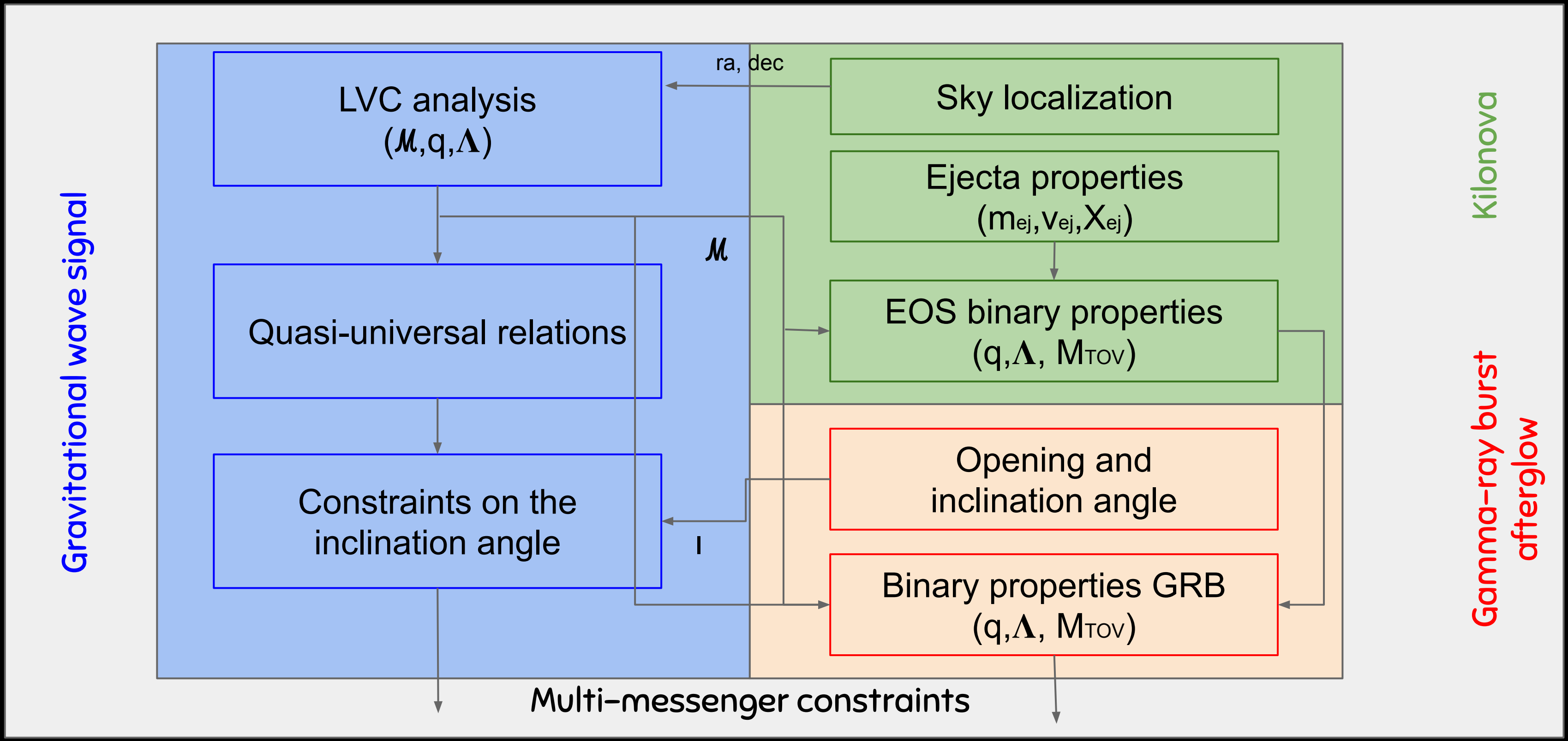
Global astrophysical modeling

GW modeling

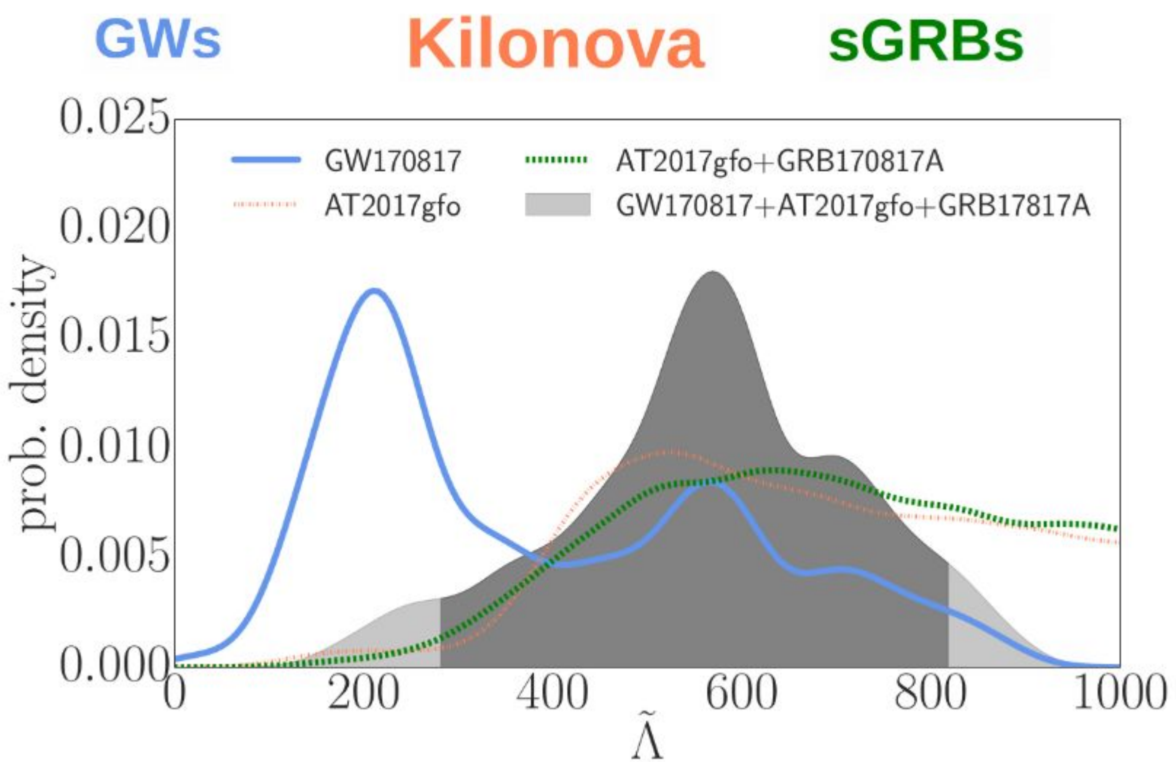
Nuclear Physics
Theory of dense matter

Neutron stars mergers

Combining the informations



Combine the informations



Multimessenger Bayesian parameter inference of a binary neutron star merger

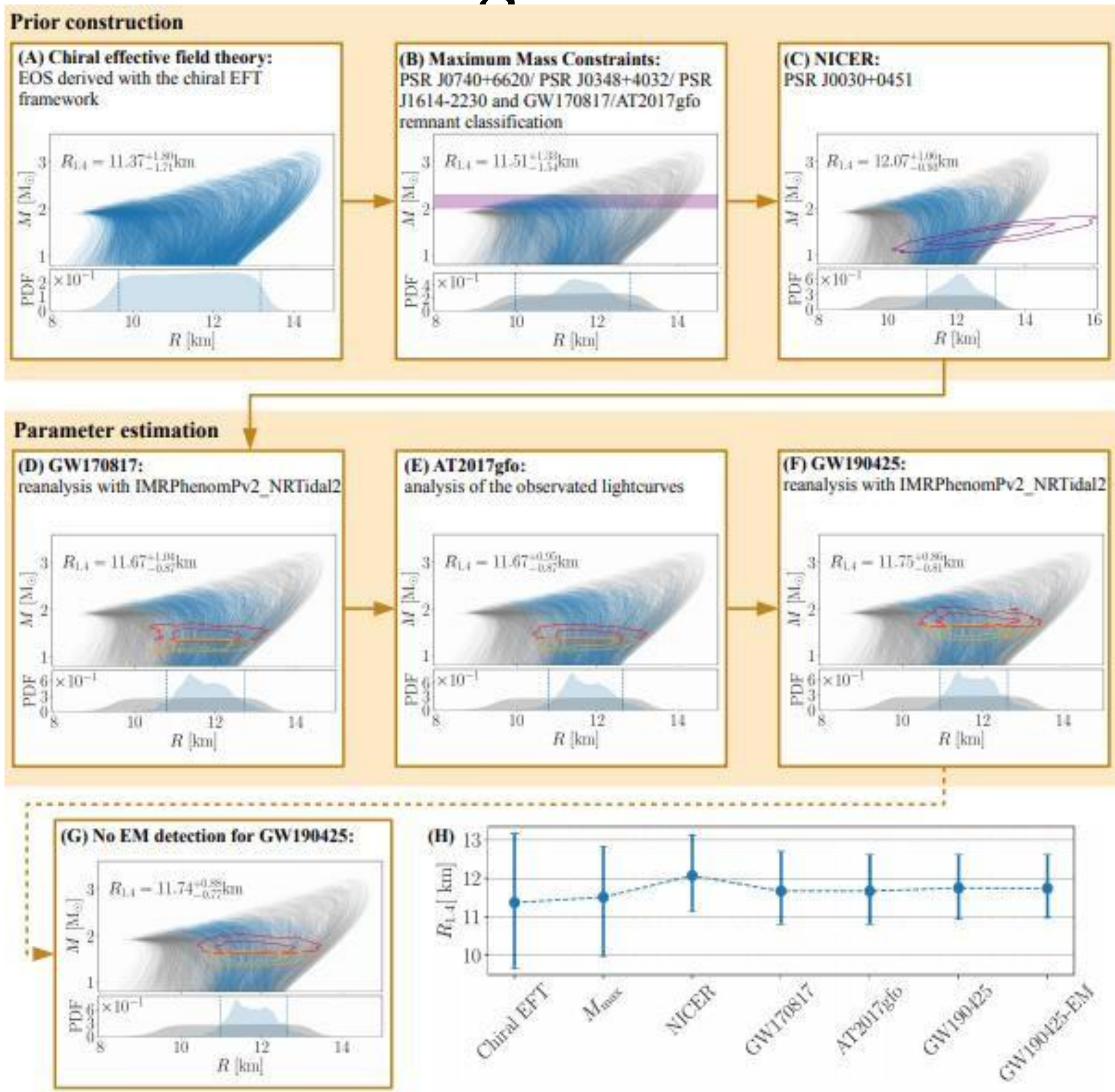
Michael W Coughlin, Tim Dietrich, Ben Margalit, Brian D Metzger Author Notes

Monthly Notices of the Royal Astronomical Society: Letters, Volume 489, Issue 1, October 2019, Pages L91–L96, https://doi.org/10.1093/mnrasl/slz133

Published: 29 August 2019 **Article history ▾**

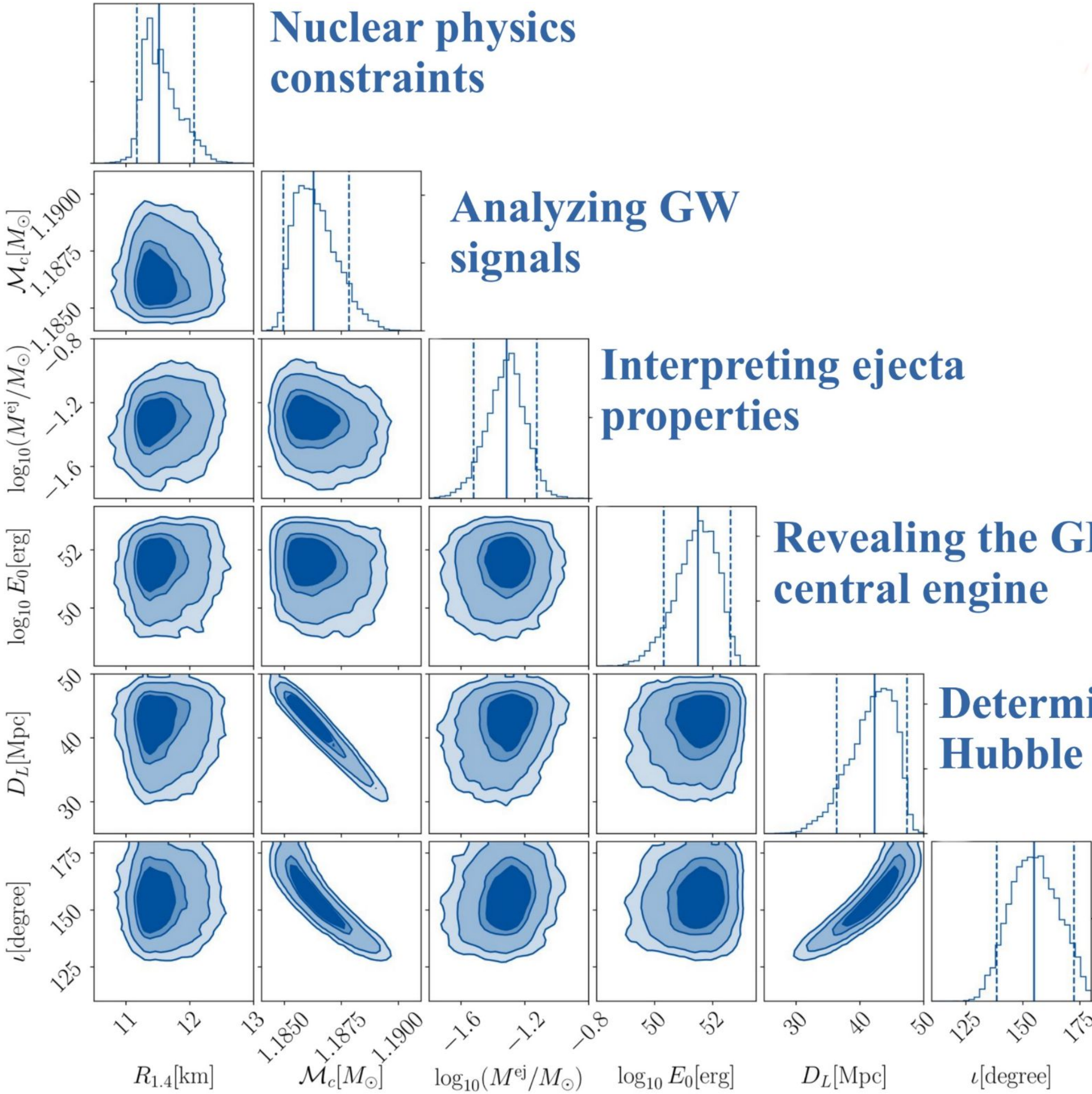
Parameter	90% confidence interval
M	$[2.722, 2.755] M_\odot$
q	$[1.00, 1.29]$
$\tilde{\Lambda}$	$[279, 822]$
R	$[11.1, 13.4]$ km

Multi-messenger framework



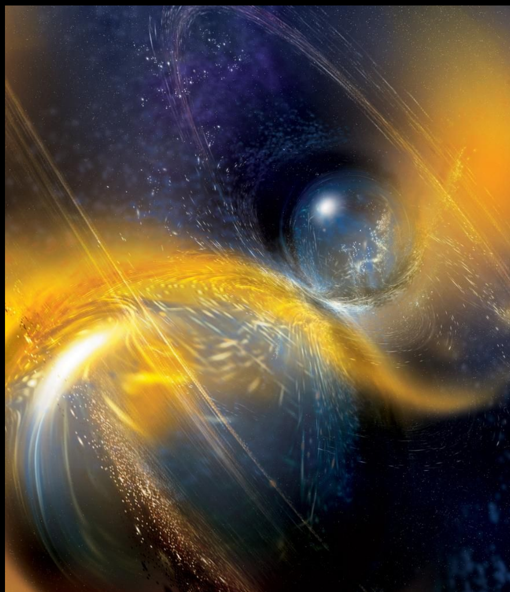
Dietrich T et al., New Constraints on the Supranuclear Equation of State and the Hubble Constant from Nuclear Physics – MMA

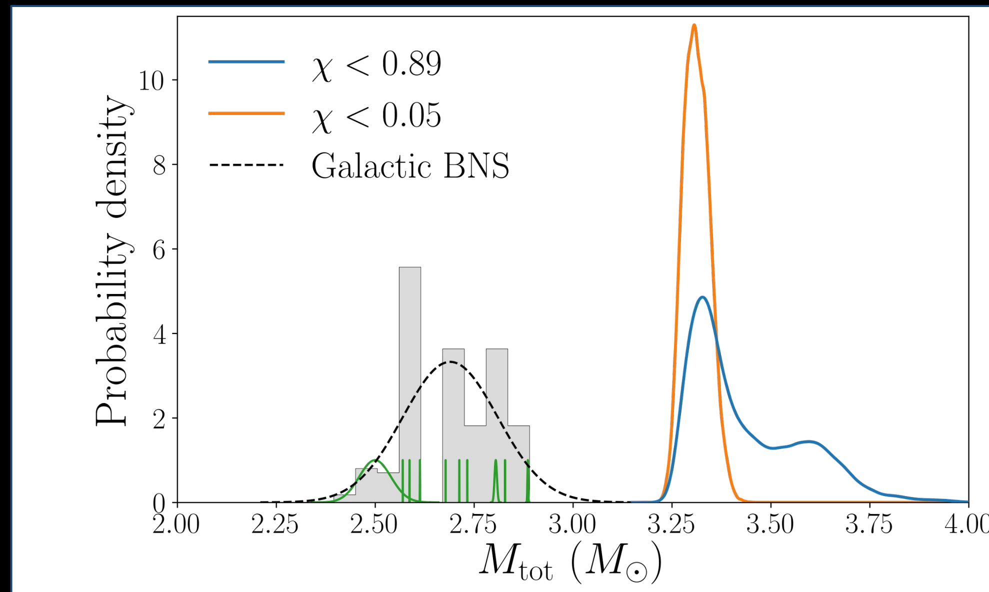
Constrains from the source



Pang et al., arXiv: 2005.08513

GW190425





On 08:18:05 UTC, L1 single detection, 8000 deg2 for 90% sky area localization, 156 Mpc +/– 41 Mpc
FAR: one chance event in 69,000 years
initial m1: 1.61 and 2.52 solar mass and initial m2: 1.12 and 1.68 solar masses
total mass: 3.0 – 3.7 solar masses

GW190425: Observation of a Compact Binary Coalescence with Total Mass $\sim 3.4 M_\odot$

The LIGO Scientific Collaboration, the Virgo Collaboration: B. P. Abbott, R. Abbott, T. D. Abbott, S. Abraham, F. Acernese, K. Ackley, C. Adams, R. X. Adhikari, V. B. Adya, C. Affeldt, M. Agathos, K. Agatsuma, N. Aggarwal, O. D. Aguiar, L. Aiello, A. Ain, P. Ajith, G. Allen, A. Allocca, M. A. Aloy, P. A. Altin, A. Amato, S. Anand, A. Ananyeva, S. B. Anderson, W. G. Anderson, S. V. Angelova, S. Antier, S. Appert, K. Arai, M. C. Araya, J. S. Areeda, M. Arène, N. Arnaud, S. M. Aronson, K. G. Arun, S. Ascenzi, G. Ashton, S. M. Aston, P. Astone, F. Aubin, P.

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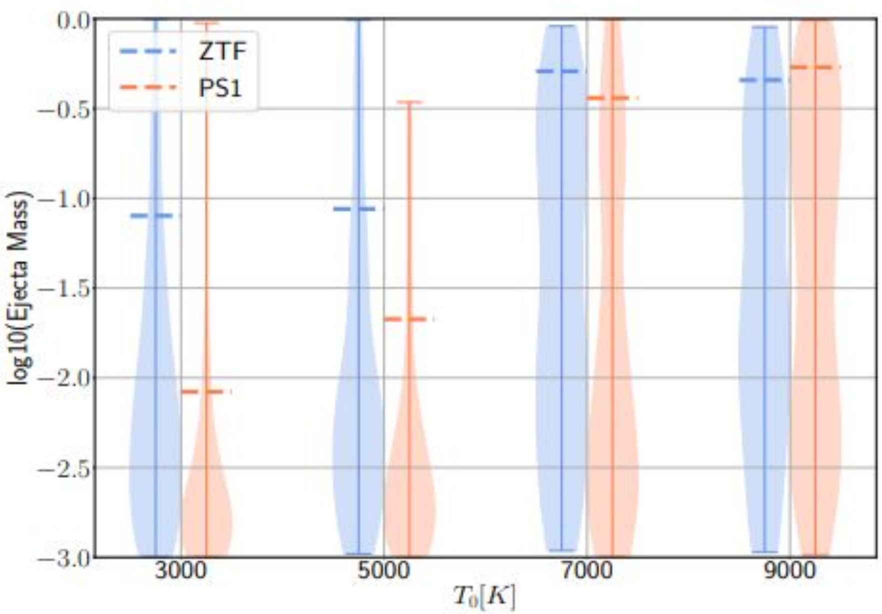
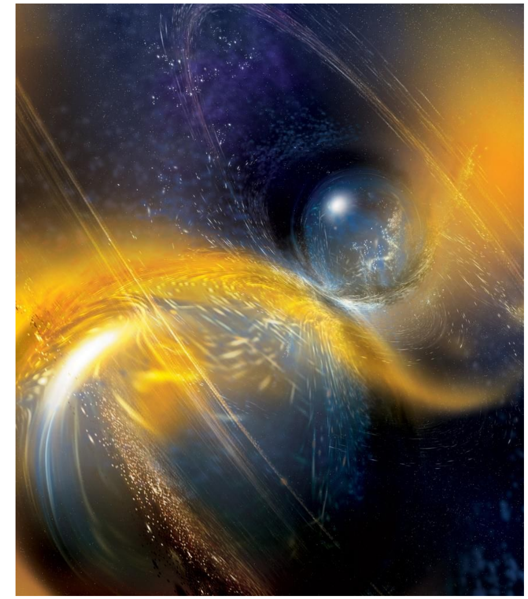
When there is no EM detection

Quantité de matière éjectée



Température de l'éjecta

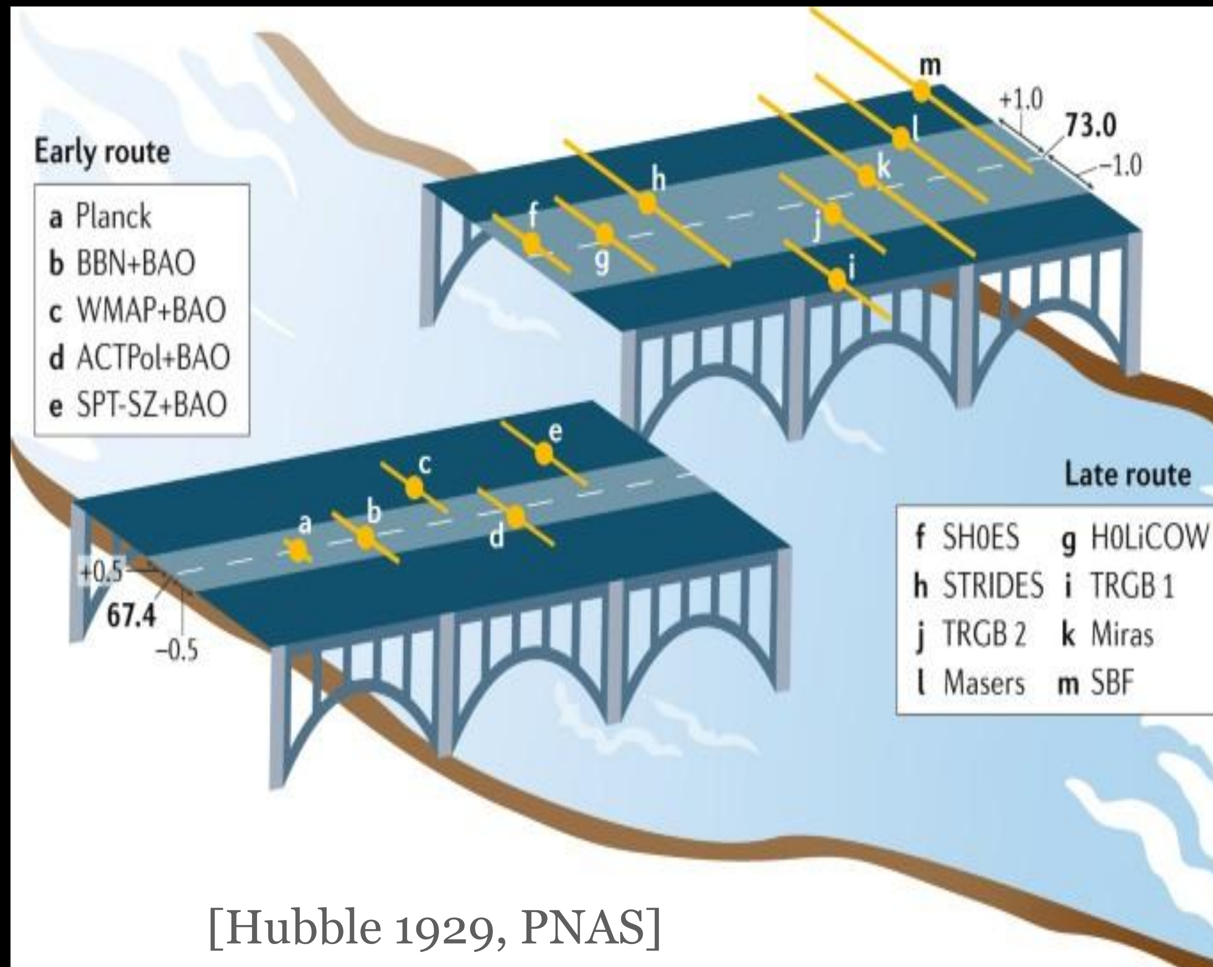


GW190425: Analyse du signal gravitationnel	
Temps du trigger	25 April 2019, 08:18:05 UTC
Détecteurs impliqués	L1 (SNR 12.9), V1 (SNR 2.5)
Distance	156 Mpc +/− 41 Mpc
Masse totale système	3.3 to 3.7 M⊙
Masse première NS	1.61 to 2.52 M⊙
Masse seconde NS	1.12 to 1.68 M⊙

Application 2 - Cosmology

$$H_0 = \frac{\text{Velocity}}{\text{Distance}}$$

The Hubble tension

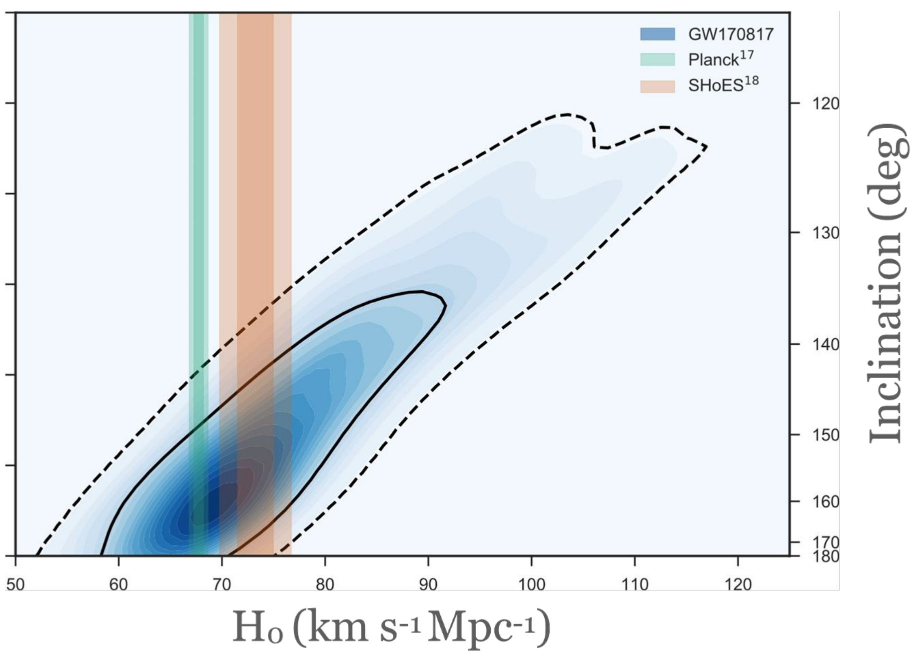


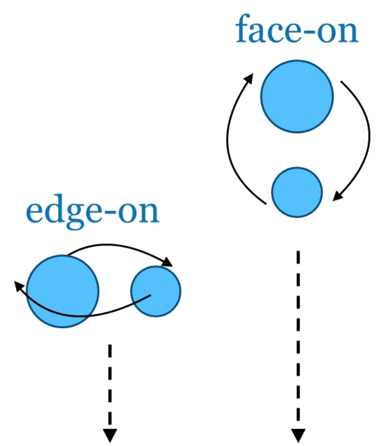
[Hubble 1929, PNAS]

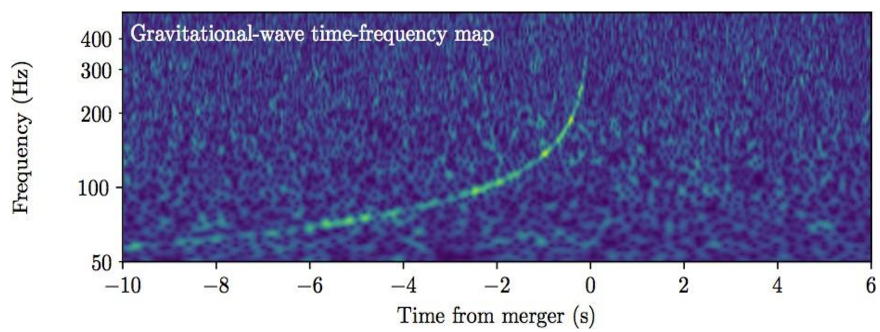
Gravitational Waves as Standard Sirens

[Schutz 1986, Nature; Holz & Hughes 2005, ApJ]

$$H_0 = \frac{\text{Velocity}}{\text{Distance}} = \frac{\text{[speed of light]} \cdot \text{Redshift}}{\text{Distance}}$$

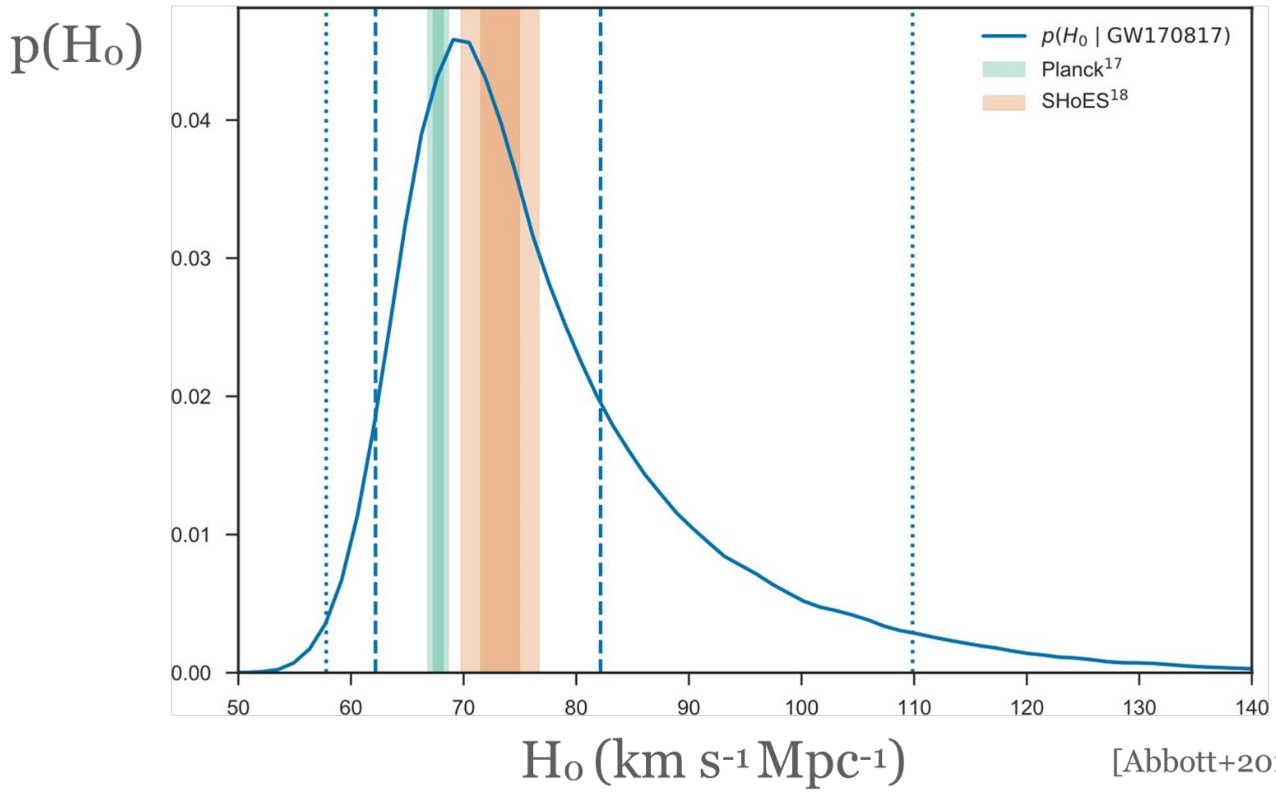






Gravitational Waves as Standard Sirens

[Schutz 1986, Nature; Holz & Hughes 2005, ApJ]

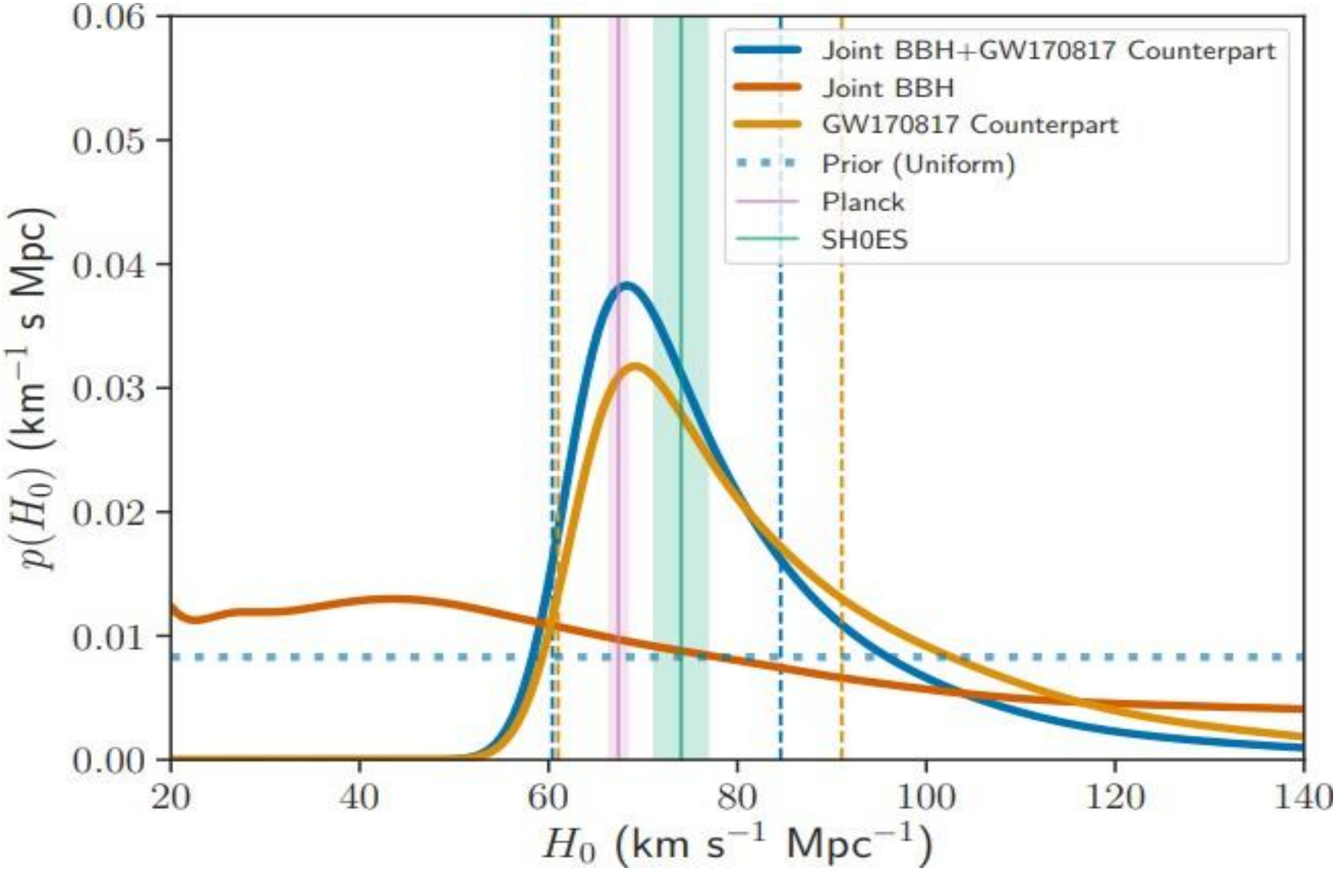


[Abbott+2017, Nature]

$$H_0 = 70.0^{+12.0-8.0}\ \mathrm{km.s^{-1}\,Mpc^{-1}}$$

Gravitational Waves as Standard Sirens

[Schutz 1986, Nature; Holz & Hughes 2005, ApJ]

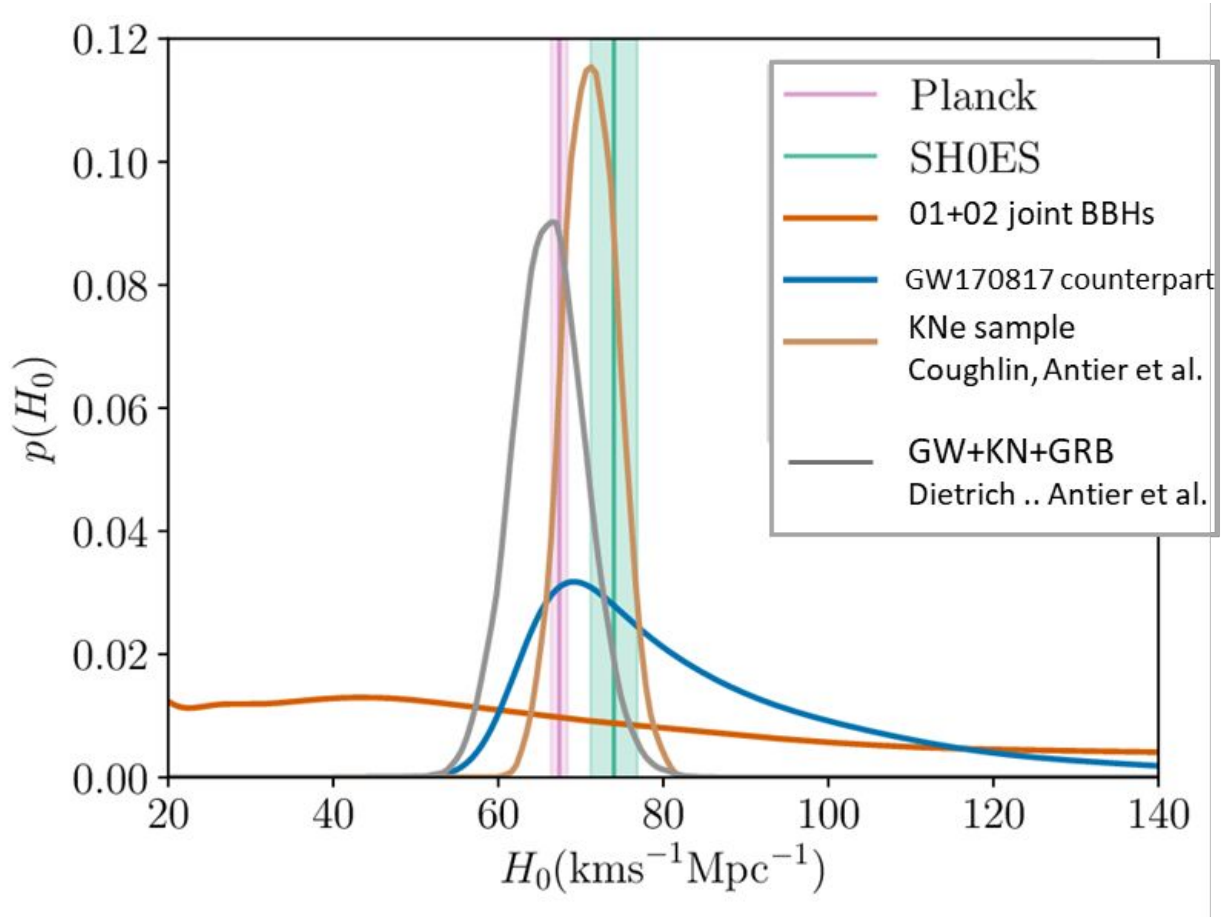


A gravitational-wave measurement of the Hubble constant following the second observing run of Advanced LIGO and Virgo, O2 run, LVC

- Method 1 : GW + KN
- Method 2 : Statistical approchs with BBH (prob loca and catalogs)

Gravitational Waves as Standard Sirens

[Schutz 1986, Nature; Holz & Hughes 2005, ApJ]



- Method 1 : GW + KN + **help the degenary of the distance – inclination**
- Method 2 : Statistical approchs with BBH (prob loca and catalogs)
- **Method 3 : KNe as standard canddles**

O4 expectations

LIGO, VIRGO, AND KAGRA OBSERVING RUN PLANS as of 17 June 2021 update;

Observing Run in March 2023

Target sensitivity: LIGO: 160-190 Mpc, Virgo: 80-115 Mpc, Kagra: 1 Mpc with a plan to improve to 3-25 Mpc during O4

Ligo O3 sensitivity ~115 Mpc Hanford and ~133 Mpc Livingston => (160/115)**3 ~ 2.7 in Volume
Virgo O3 sensitivity~50 Mpc => ~4 in Volume

We do expect a factor 3 in the number of events:

We should reasonably expect (since we had reported 79 confident GW events and 81 OPA) to have:

~ 240 OPA , ~ 240 GW events.

That is almost 1 detection per day.

The detection rate, localization does not evolve as fast as expected

Epoch			2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration			4 months	6 months	9 months	(per year)	(per year)
Burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 80	80
BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	200	200
		Virgo	—	20 – 60	60 – 85	65 – 115	130
Estimated BNS detections			0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400
90% CR	% within	5 deg^2	< 1	2	$> 1 - 2$	$> 3 - 8$	> 20
		20 deg^2	< 1	14	> 10	$> 8 - 30$	> 50
	median/deg^2		480	230	—	—	—
searched area	% within	5 deg^2	6	20	—	—	—
		20 deg^2	16	44	—	—	—
	median/deg^2		88	29	—	—	—

2015

Predictions 04

34 (+78 – 25) BNS and 72 (+75 – 38) NS-BH

Median Luminosity distance : 350 (+/- 10) Mpc for BNS and 620 (+/- 15 Mpc)

90 % c.r region : 1800 (+/-200) deg2 for BNS

Predictions 05

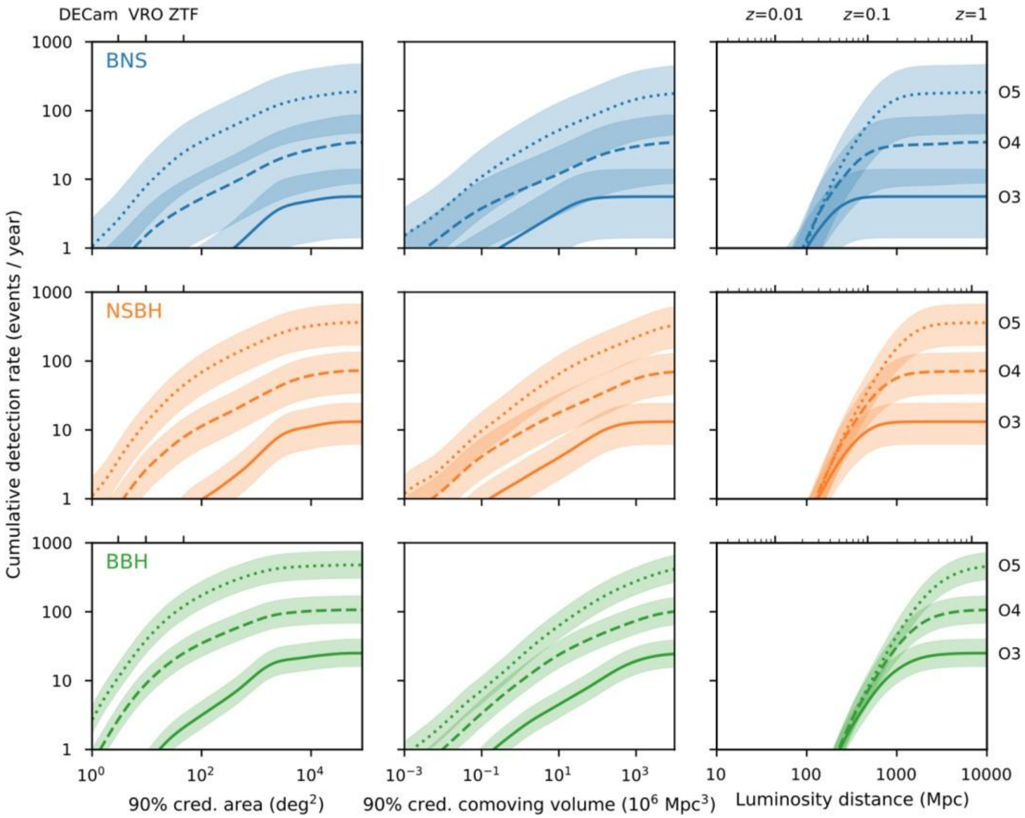
190 (+410 – 130) BNS and 360 (+360 – 180) NS-BHs

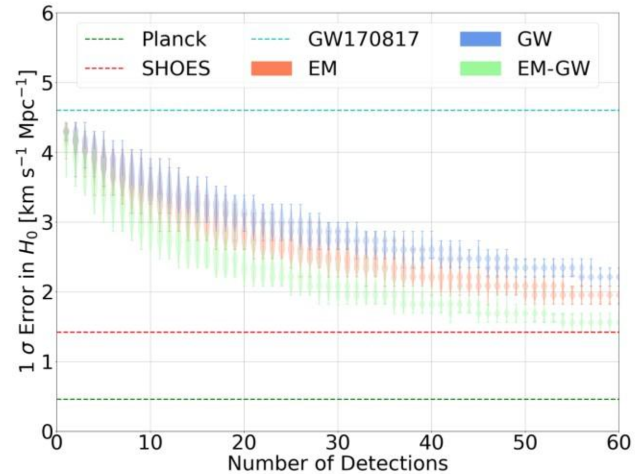
Median Luminosity distance : 620 (+/- 16) Mpc for BNS and 1130 (+/- 20 Mpc)

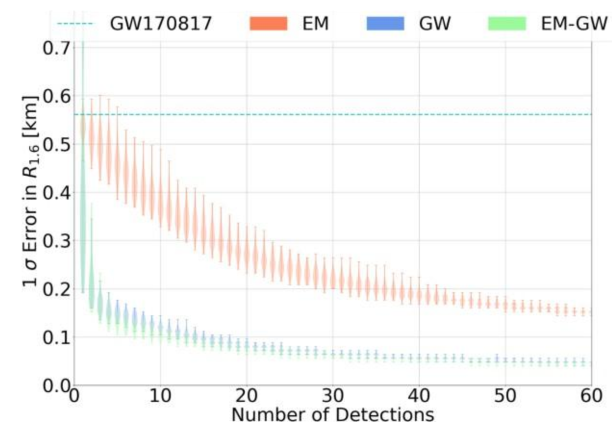
90 % c.r region : 1300 (+/120) deg2 for BNS

Data-driven expectations for electromagnetic counterpart searches based on LIGO/Virgo public alerts, Petrov 2021

Prospects for multi-messenger detections







Data-driven expectations for electromagnetic counterpart searches based on LIGO/Virgo public alerts, Petrov 2021

Coughlin, SA et al., in preparation: Prospects for H0 and EOS based on updates