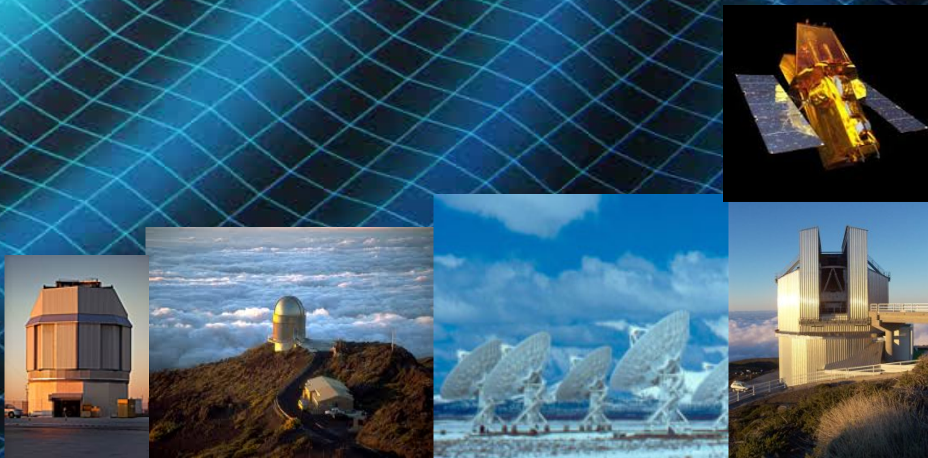
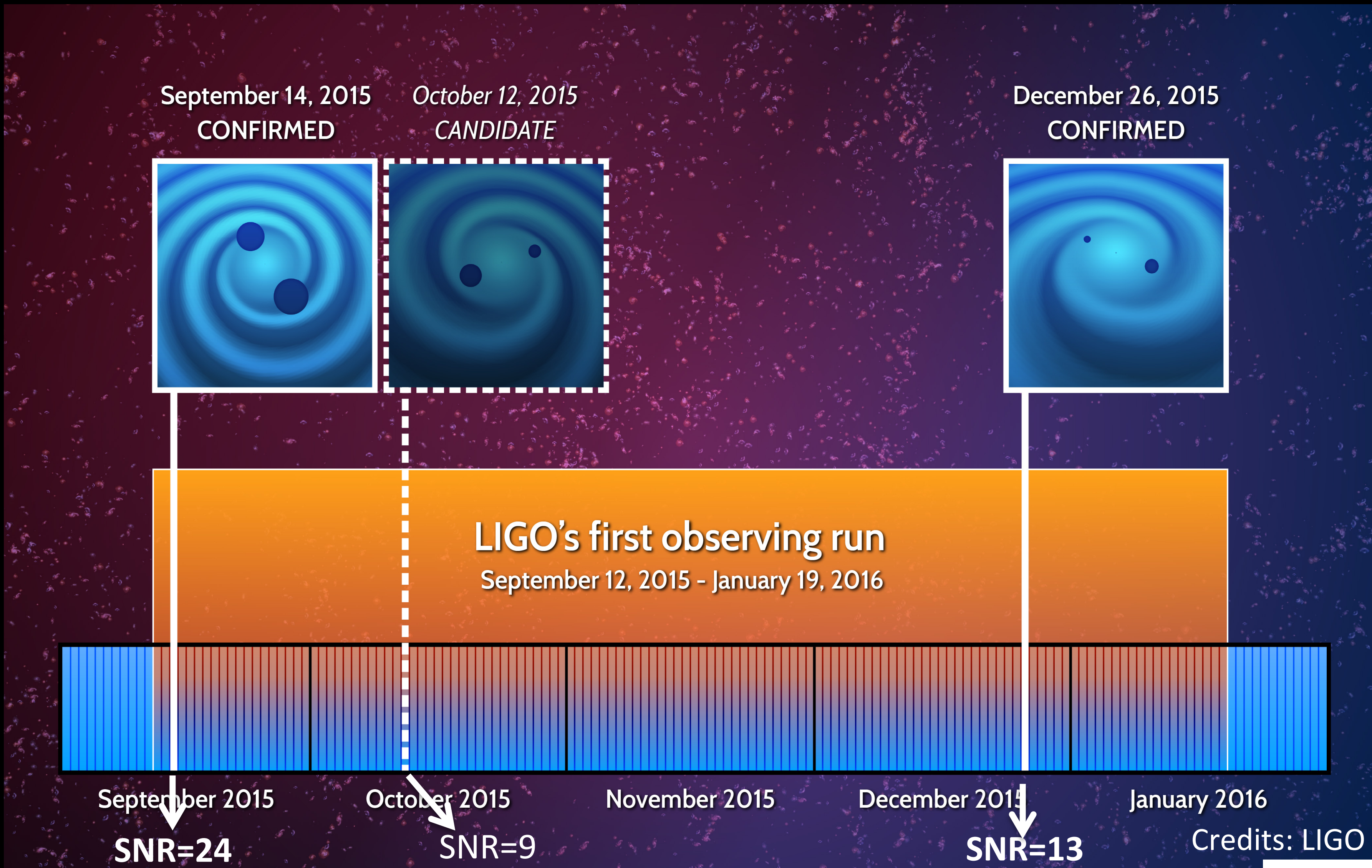
Unveiling the physics of the transient sky through gravitational-wave and electromagnetic observations

M. Branchesi

Università di Urbino/INFN-Firenze



The era of GW astronomy started!

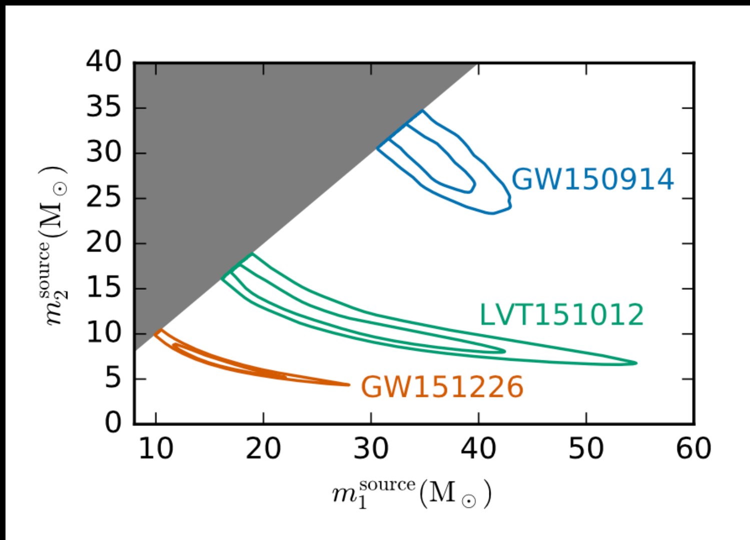


FAR < 6 x 10^{-7} yr^{-1}
Significance > 5.3 σ

FAR 0.37 yr^{-1}
Significance = 1.7 σ

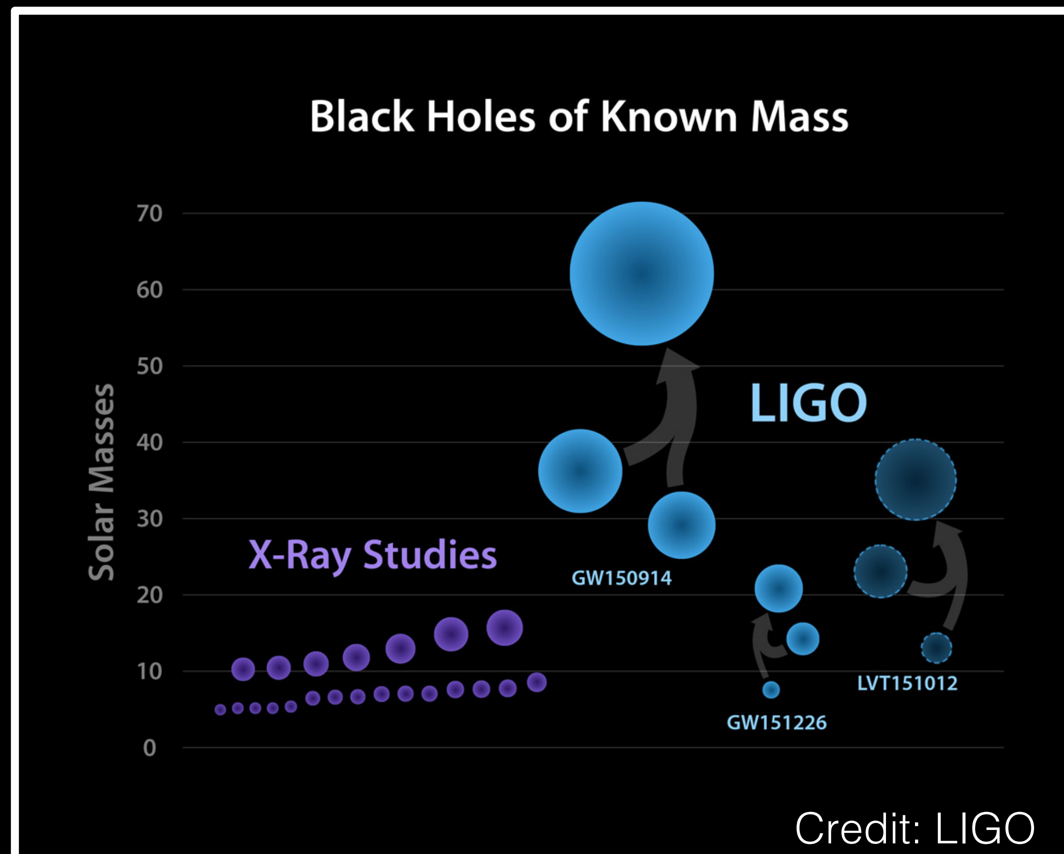
FAR < 6 x 10^{-7}
Significance > 5.3 σ

Parameters of the BBH systems



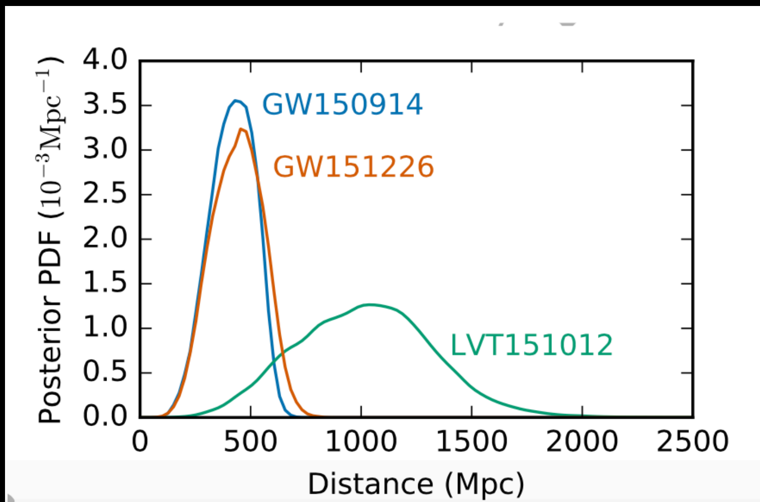
Component masses

Event	GW150914	GW151226	LVT151012
Primary mass $m_1^{source}/M_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{source}/M_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}



LVC 2016 Phys. Rev. Lett. 116, 061102
LVC 2016 ApJL, 818, 22
LVC 2016 Phys. Rev. Lett. 116, 241103
LVC 2016 Phys. Rev. X, 6

Challenges to identify the host galaxy



Distances

Event	GW150914	GW151226	LVT151012
Luminosity distance D_L/Mpc	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}

LVC 2016 Phys. Rev. X, 6

Sky localizations

90% credible areas of about

600 deg^2 GW150914

1600 deg^2 LVT15012

1000 deg^2 GW151226

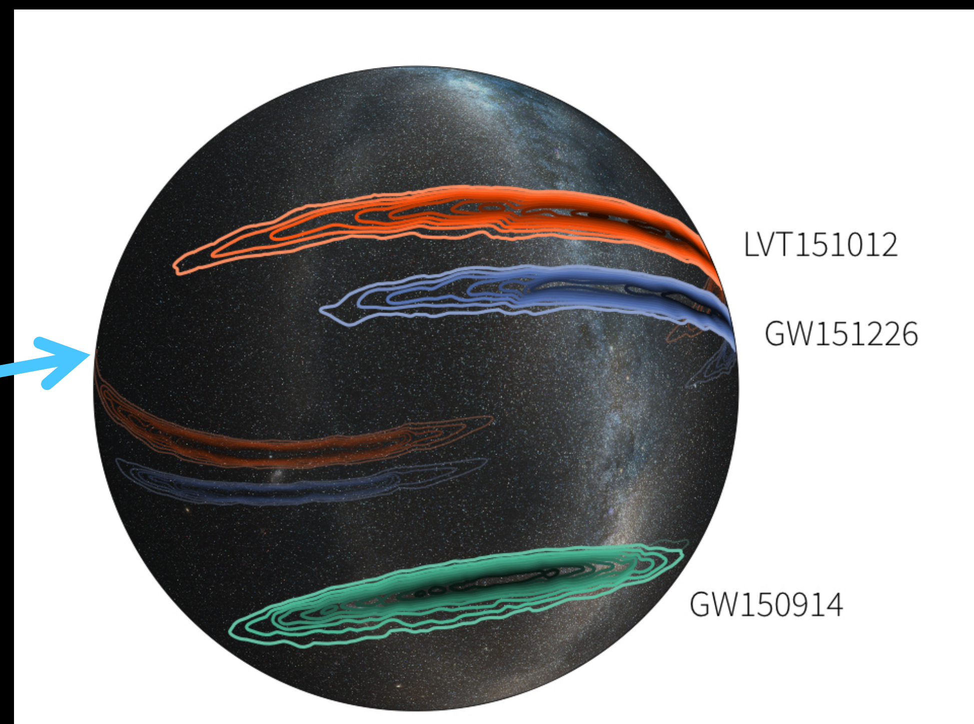
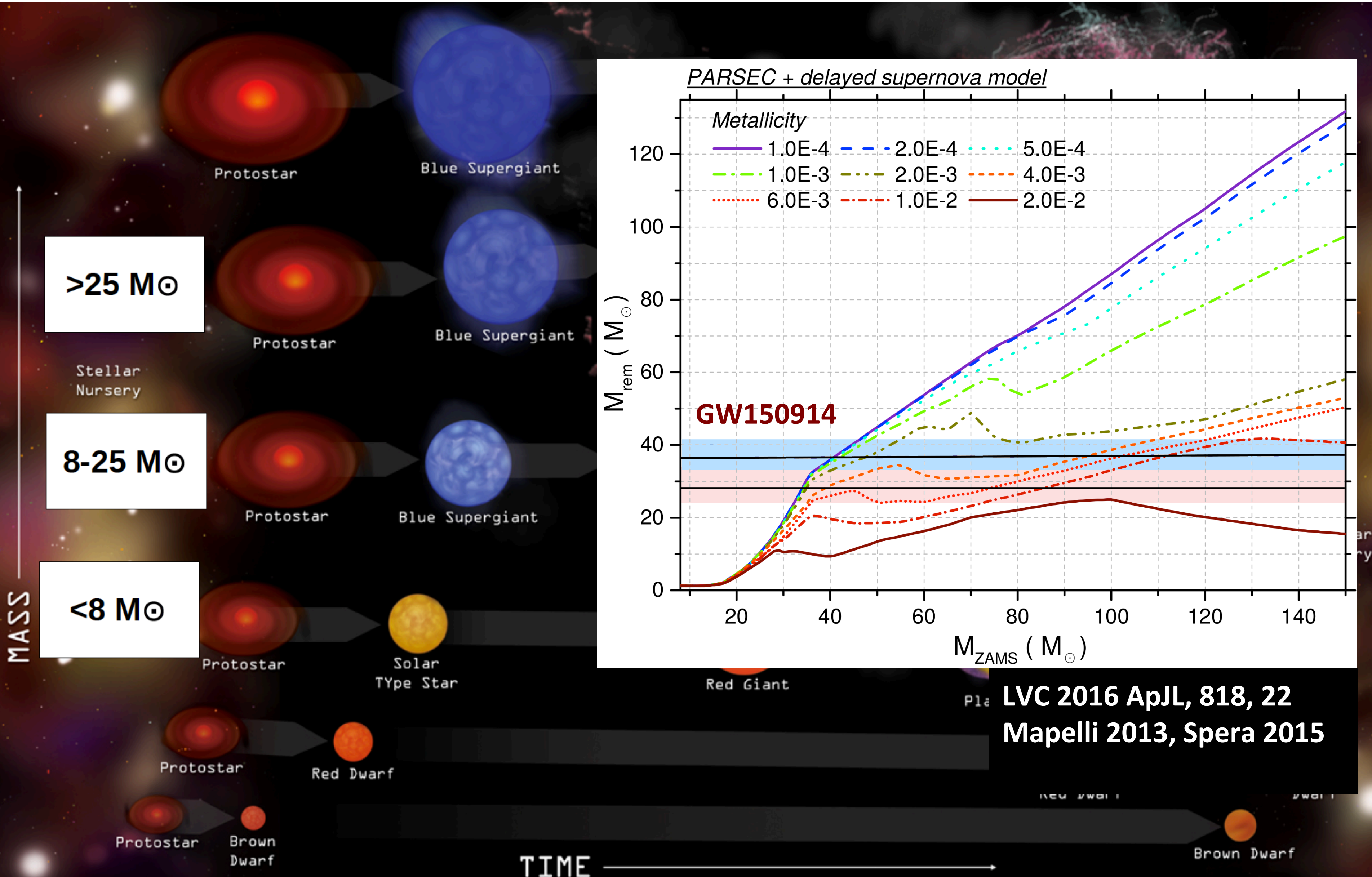


Image credit: LIGO/L. Singer/A. Mellinger

How do black holes form?

Credit: Chandra



Where do black holes form?

Galaxy field

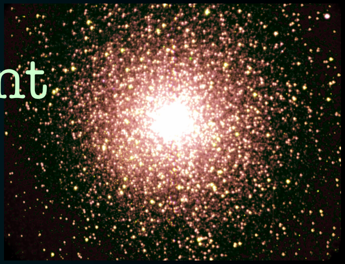
R ~ 10 kpc,

N ~ 10^{10} stars

Dense environment star clusters

R ~ 1-10 pc,

N ~ 10^{3-7} stars



How do they form binary systems?

Isolated binary

Dynamical interactions

Both formation paths are consistent with GW150914 and GW151226

For GW150914, low metallicities are necessary

Where do black holes form?

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N ~ 10^{10} stars

Dense environment

star clusters

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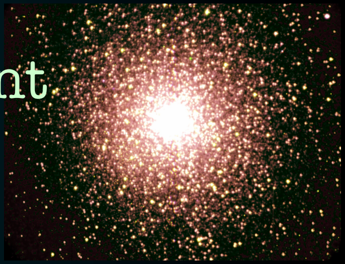


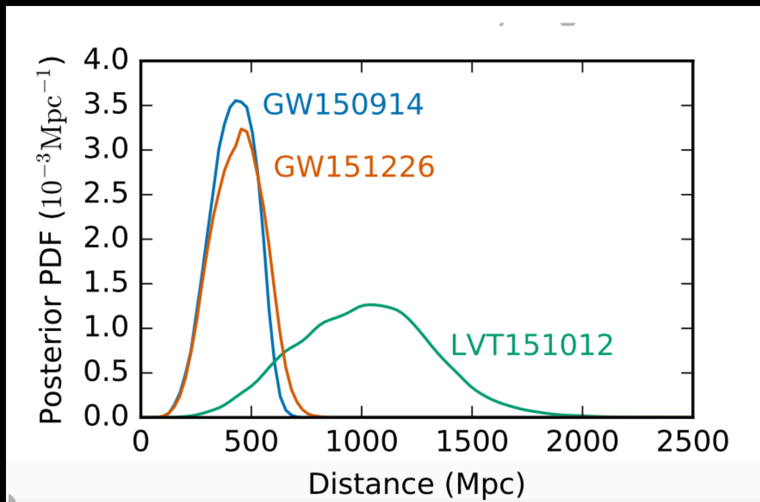
How do they form binary systems?

Isolated binary

Dynamical interactions

Crucial: identify the host galaxy and study the GW source environment

Challenges to identify the host galaxy



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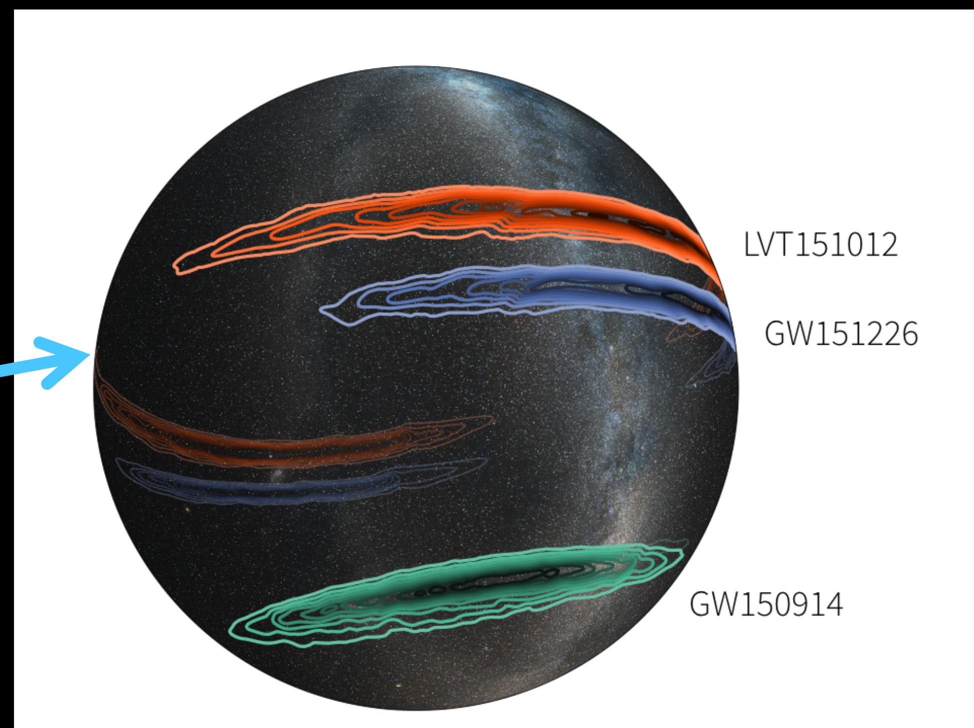
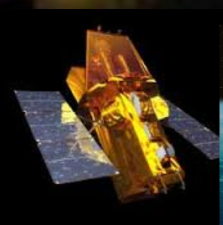


Image credit: LIGO/L. Singer/A. Mellinger

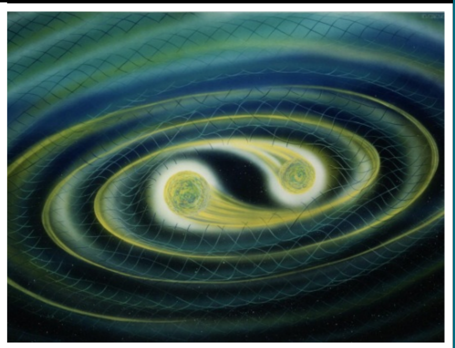
In the volume of the Universe corresponding to GW150914, LVT151012, GW151226 there are 10^5-10^6 galaxies



The multi-messenger astronomy is required...

ASTROPHYSICAL SOURCES emitting transient GW signals detectable by LIGO and Virgo (10-1000 Hz)

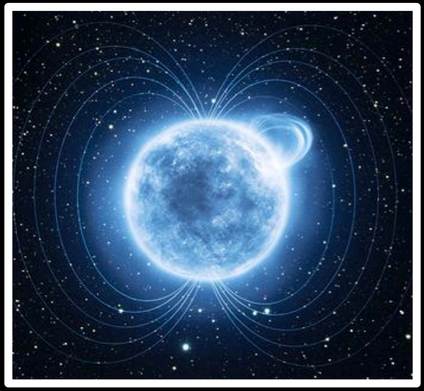
Coalescence of binary system of neutron stars (BNS) and NS-BH



- Orbital evolution and GW signals accurately modeled by post-Newtonian approximation and numerical simulations
  → precise waveforms
- **Energy emitted in GWs (BNS): ~$10^{-2} M_o c^2$**

Core-collapse of massive stars

Isolated NSs instabilties



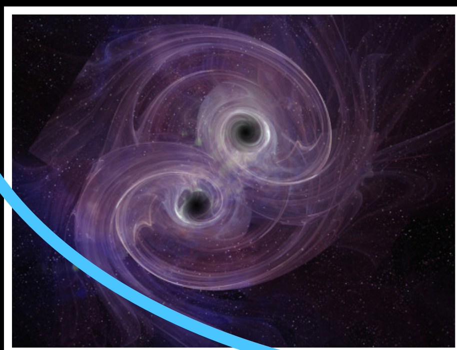
- Modeling of the GW shape and strength is complicated → **uncertain waveforms**
- **Energy emitted in GWs:**

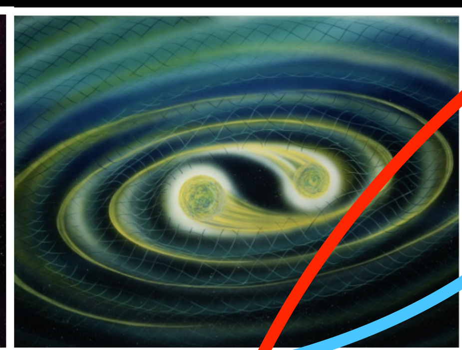
~10^{-8} – 10^{-5} $M_o c^2$ for the core-collapse

~10^{-16} – 10^{-6} $M_o c^2$ for isolated NSs

ASTROPHYSICAL SOURCES emitting transient GW signals detectable by LIGO and Virgo (10-1000 Hz)

Coalescence of binary system of neutron stars and/or stellar-mass black-hole

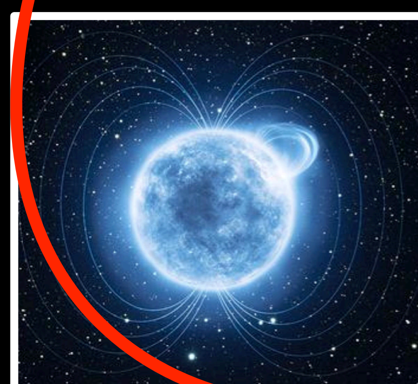




→ MATCHED-FILTER MODEL SEARCHES

Core-collapse of massive stars

Isolated neutron-star



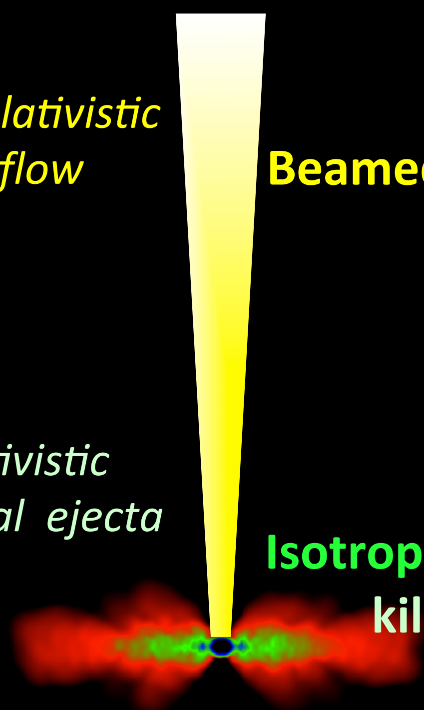
UNMODELED SEARCHES

EM emissions

NS-NS and NS-BH mergers

Short Gamma Ray Burst (sGRB)

Ultra-relativistic outflow



Beamed emission

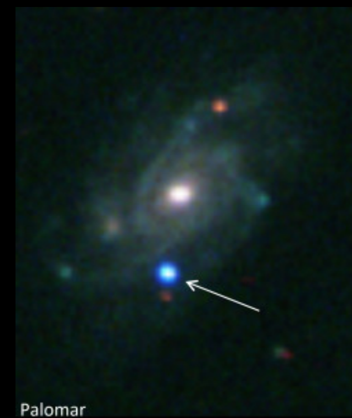
Sub-relativistic dynamical ejecta

Isotropic emission
kilonova

disk wind outflow

Spin-down luminosity

Core-collapse of massive stars



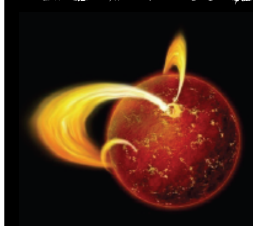
SBO X-ray/UV

Optical

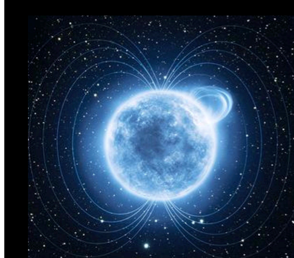
Radio

+ Long GRB

Isolated NS instabilities

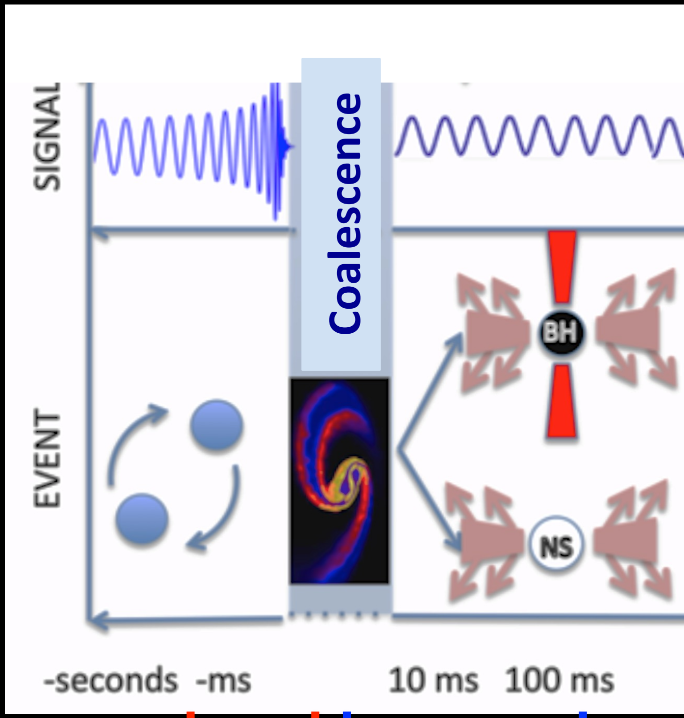


Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars



Radio/gamma-ray Pulsar glitches

NS-NS and NS-BH inspiral and merger



Dynamical Phase

Accretion phase

Fernandez & Metzger 2016, ARNPS, 66

The merger gives rise to:

- dynamically ejected unbound mass
- ejected mass gravitationally bound to the central remnant either falls back or circularizes into an accretion disk

NS-BH binary → <u>unbound mass</u> up to 0.1 Mo depends on **ratio of the tidal disruption radius to the innermost stable circular orbit**

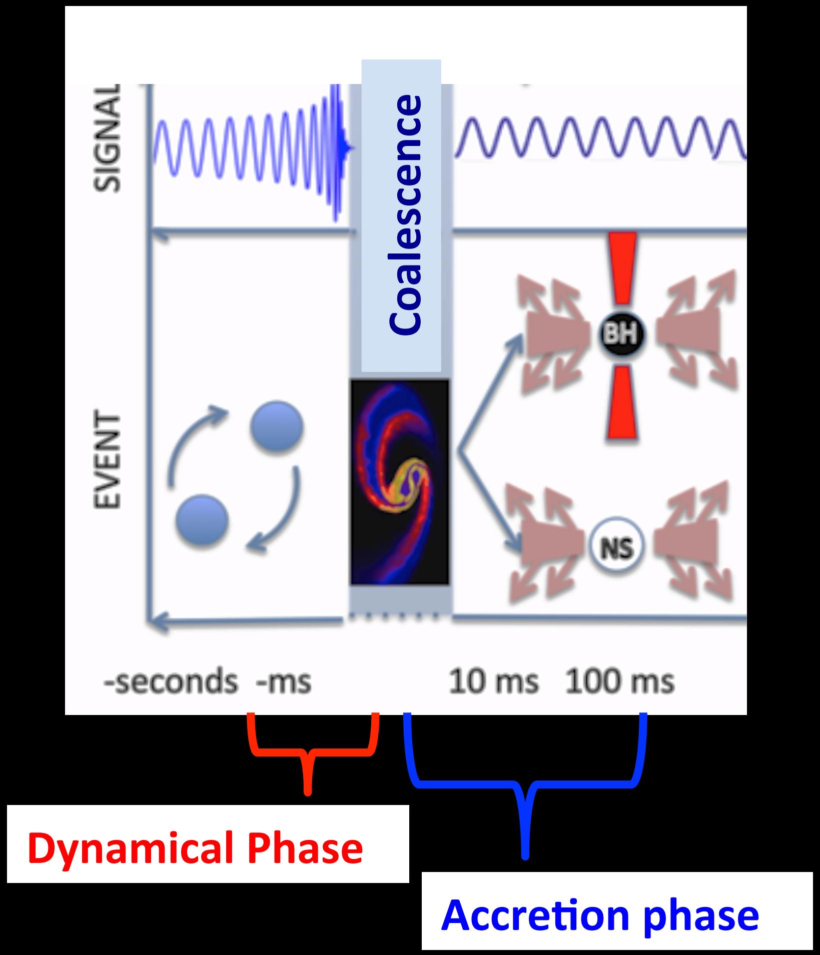
If < 1 → NS swallowed by the BH no mass ejection

If > 1 NS → tidally disrupted, long spiral arms

which depends on **the mass ratio, the BH spin and the NS compactness**

See Kawaguchi et al. 2016,ApJ, 825, 52

NS-NS and NS-BH inspiral and merger



Fernandez & Metzger 2016, ARNPS, 66

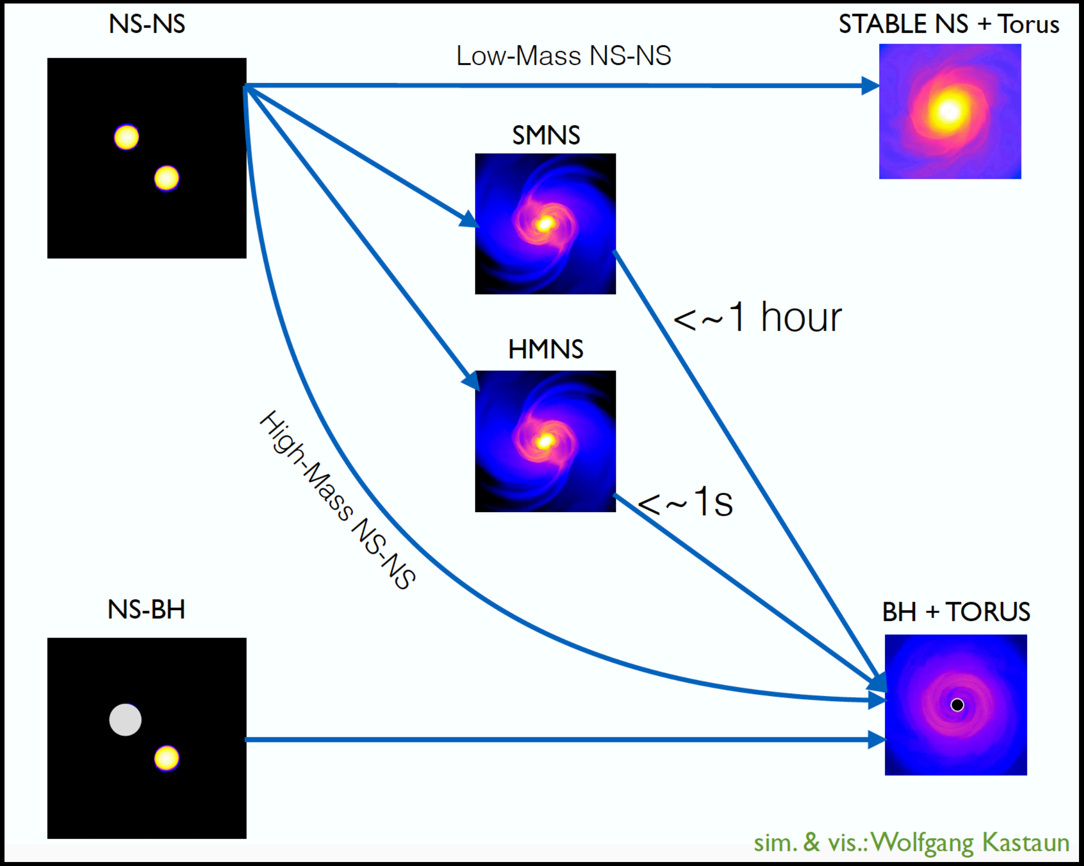
- Ejected material gravitationally bound from the central remnant can fall back or circularizes into an accretion disk

Disk mass up to ~ **0.3Mo**
Disk mass depends on the **mass ratio of the binary, the spins of the binary components, the EOS, and the total mass of the binary**

For NS-BH see e.g. Foucart 2012, PhRvD, 86;
Maselli & Ferrari, PhRvD, 89;
Pannarale & Ohme, ApJL, 791

Outflow mass and geometry influence the EM emission

Central remnant of NS-NS or NS-BH merger



The central remnant influences GW and EM emission

What is central remnant?

- It depends on the total mass of the binary
- The mass threshold above which a BH forms directly depends on EOS

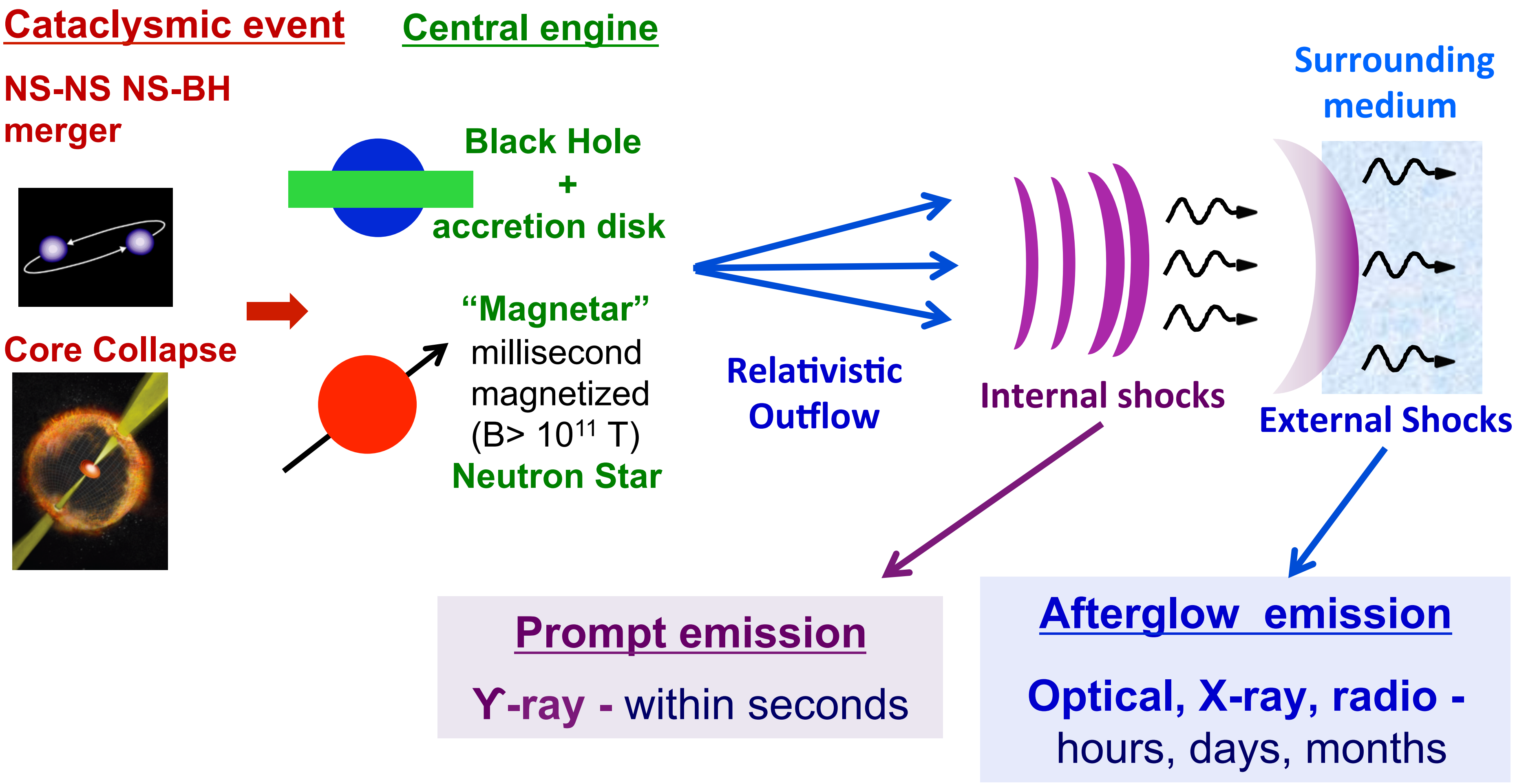
GWs

- Mass
- Spins
- Eccentricity
- NS compactness and tidal deformability
- System orientations
- Luminosity distance

EM emission

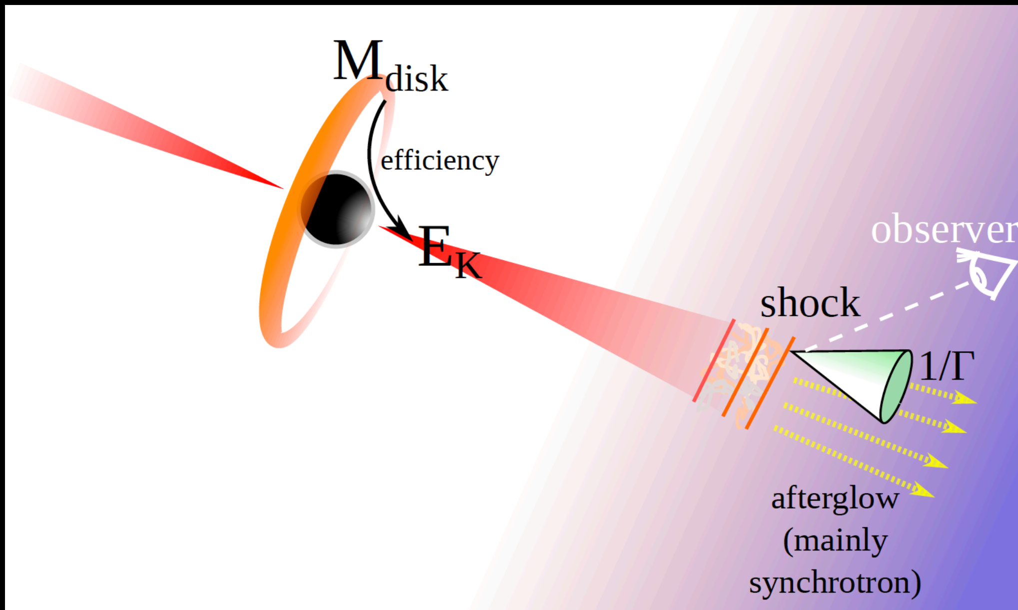
- Beamed and isotropic EM emissions
- Energetics
- Nuclear astrophysics

GRBs emission - Fireball Model



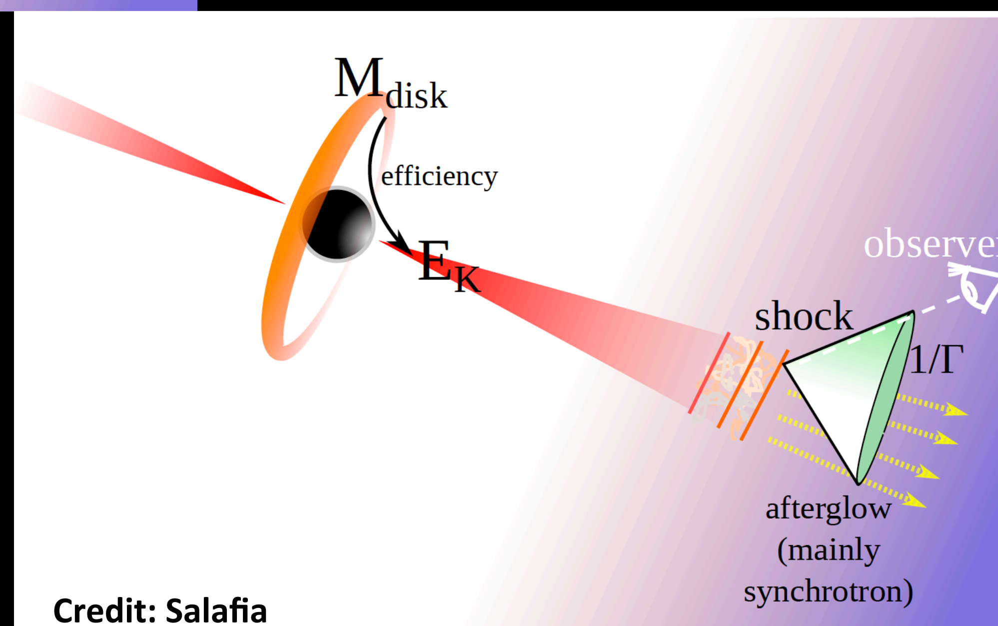
Kinetic energy of the relativistic jet converted into radiation

Mjet = 10^{-7}-10^{-5} Mo, $\Gamma \geq 100$, E=10^{48}-10^{51} erg

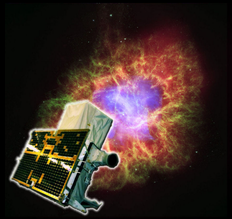


EM emission detectable only by on-axis observers

EM emission detectable also by off-axis observers



How many on-axis/off-axis short GRB?



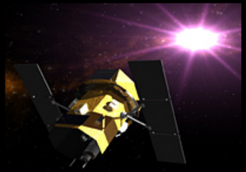
Short GRB rate → GW/sGRB detections by aLIGO/Virgo in full sensitivity

R_{GRB} = 0.2-10 Gpc^{-3} yr^{-1} (e.g. Ghirlanda et al 2016, Wanderman & Piran 2015)

→ $R_{GRB/GW}$ (300* Mpc) = 0.02-1 yr^{-1}

→ $R_{GRB/GW}$ (600* Mpc) = 0.2-10 yr^{-1}

(*Distance range for NS-NS 200 Mpc and for NS-BH 400 Mpc expected times 1.5 for face-on systems)

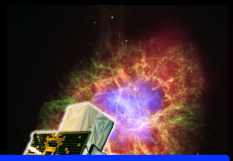


sGRB rate → NS-NS aLIGO/Virgo detection rate

Assuming NS-NS progenitor of short GRB:

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

How many on-axis/off-axis short GRB?



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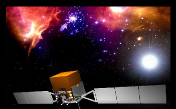
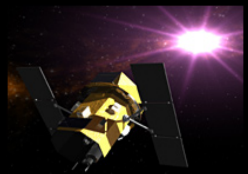
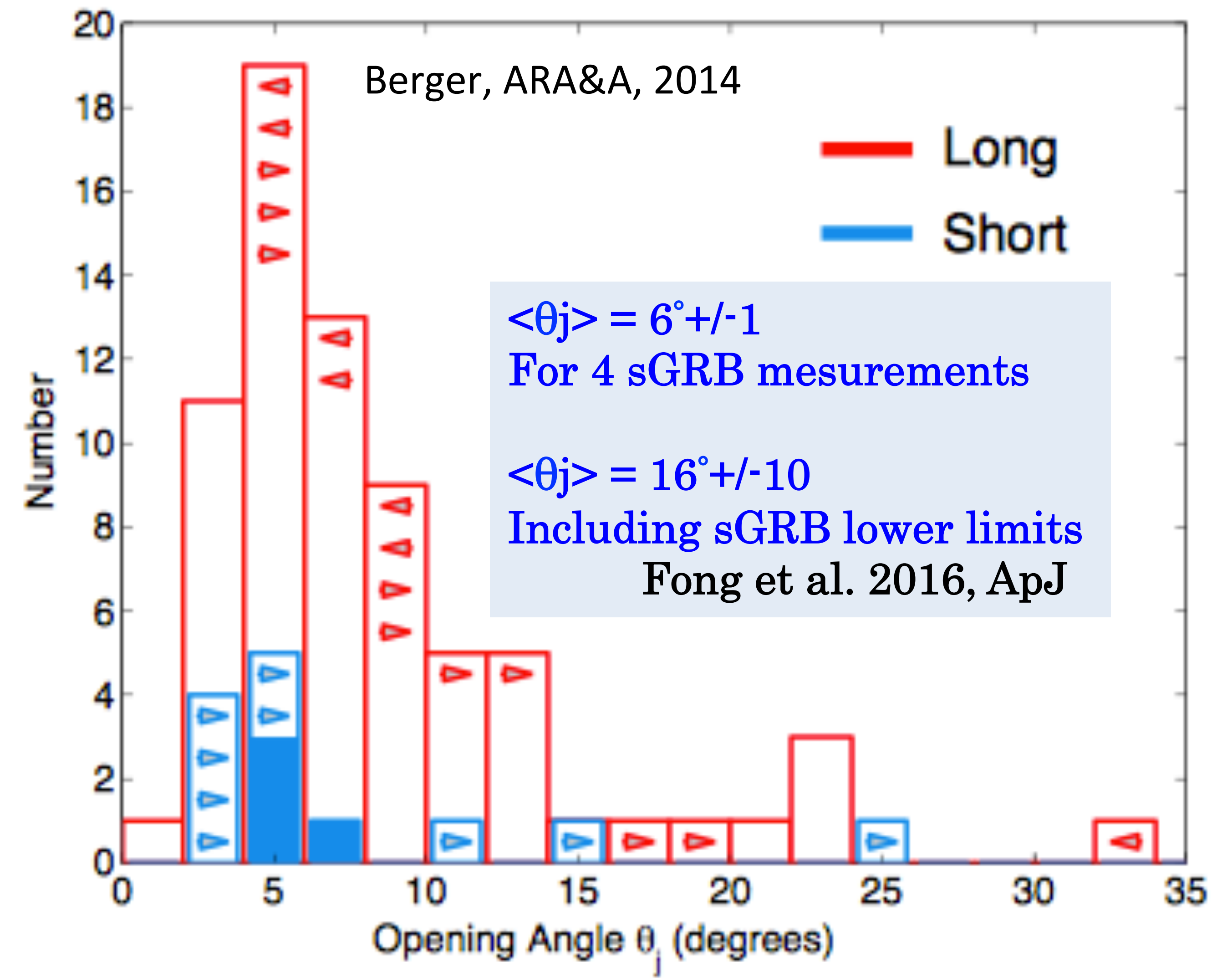


sGR

Assum





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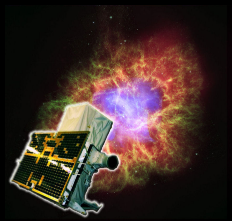

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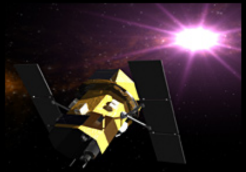

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Assuming NS-NS progenitor of short GRB:

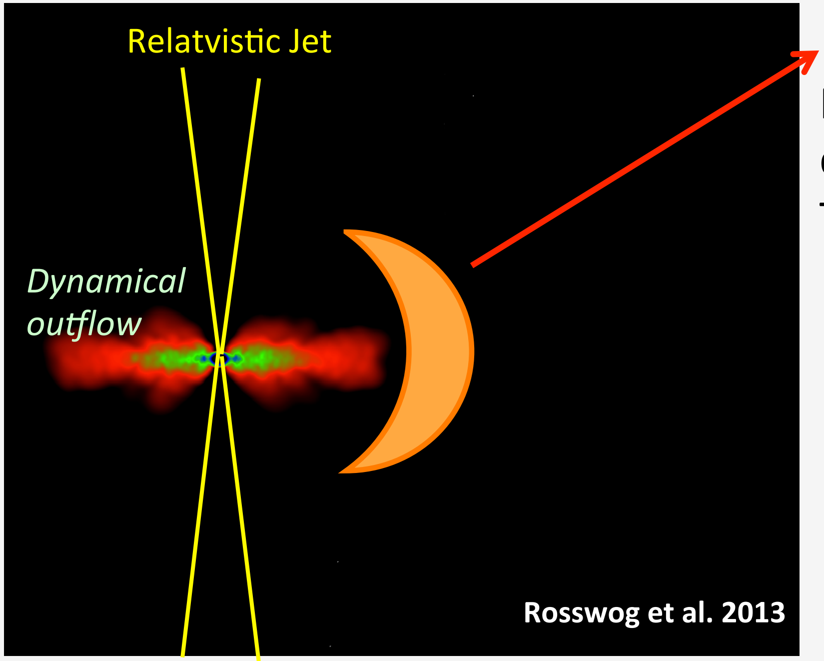
$$R_{NS\text{-}NS}=R_{GRB}/(1-\cos(\theta j))$$

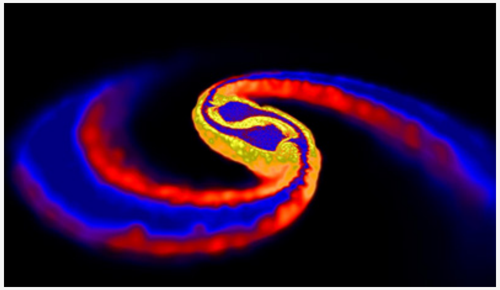
For θj = 10 deg → $R_{NS\text{-}NS}$ (200* Mpc) = 0.4-20 yr^{-1}

For θj = 30 deg → $R_{NS\text{-}NS}$ (200* Mpc) = 0.04-2 yr^{-1}

Macronova/Kilonova-Radio remnant

Significant **mass (0.01-0.1 M_o)** is **dynamically ejected** during **NS-NS NS-BH mergers** at **sub-relativistic velocity (0.1-0.3 c)**





r-process

Neutron capture rate much faster than decay, special conditions:
T > 10^9 K, high neutron density 10^{22} cm^{-3}

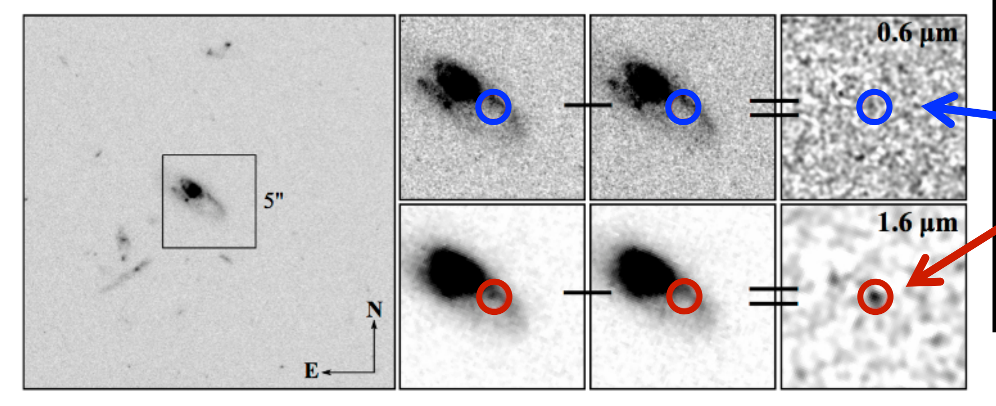
nucleosynthesis of heavy nuclei

radioactive decay of heavy elements

Power MACRONOVA
short lived IR-UV signal (days)

Are neutron stars mergers the primary source for the production of heavy elements in the Universe?
[Beniamini et al. 2016, APJL 2016]

Possible HST kilonova detection for short GRB130603B after 9.4 days (Tanvir et al. 2013, Nature ,500)



HST two epochs (9d, 30d) observations

F606W/optical

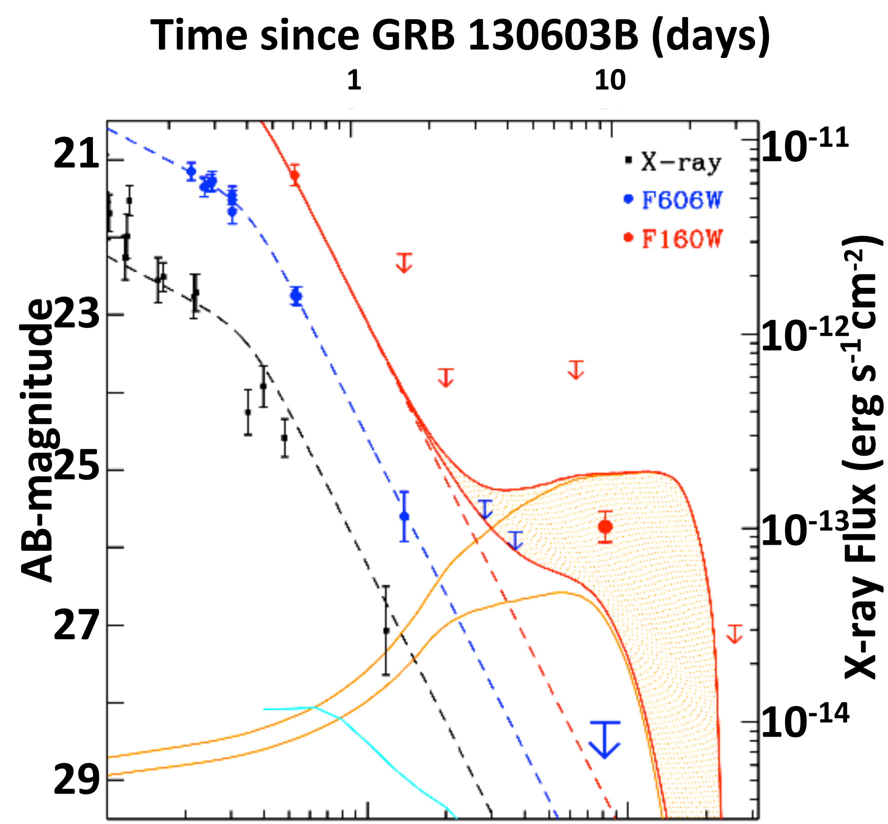
NIR/F160W

Afterglow and host galaxy z=0.356

Orange curves → kilonova NIR model
ejected masses of 10^{-2} Mo and 10^{-1}Mo

Solid red curves → afterglow +kilonova

Cyan curve → kilonova optical model



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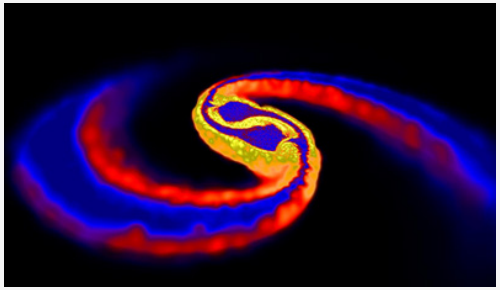

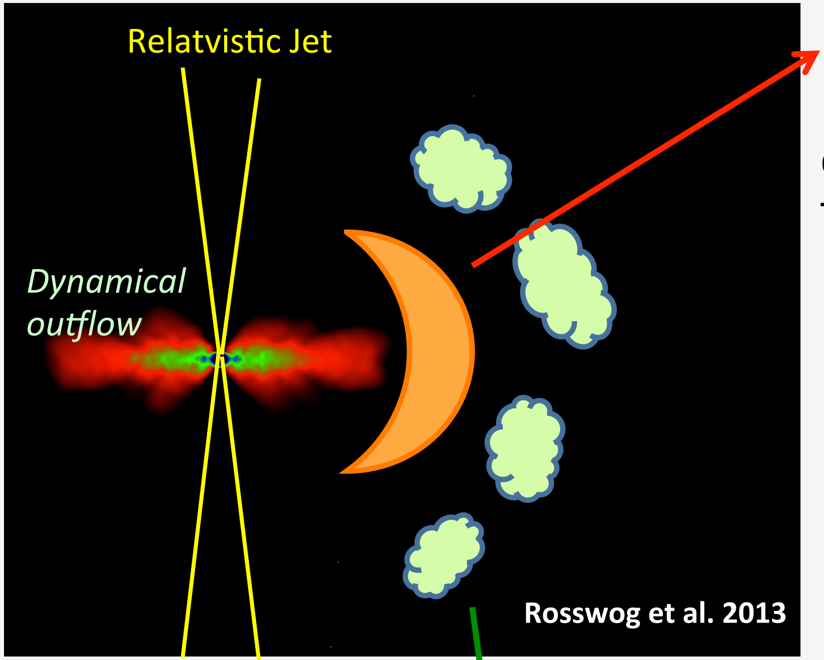

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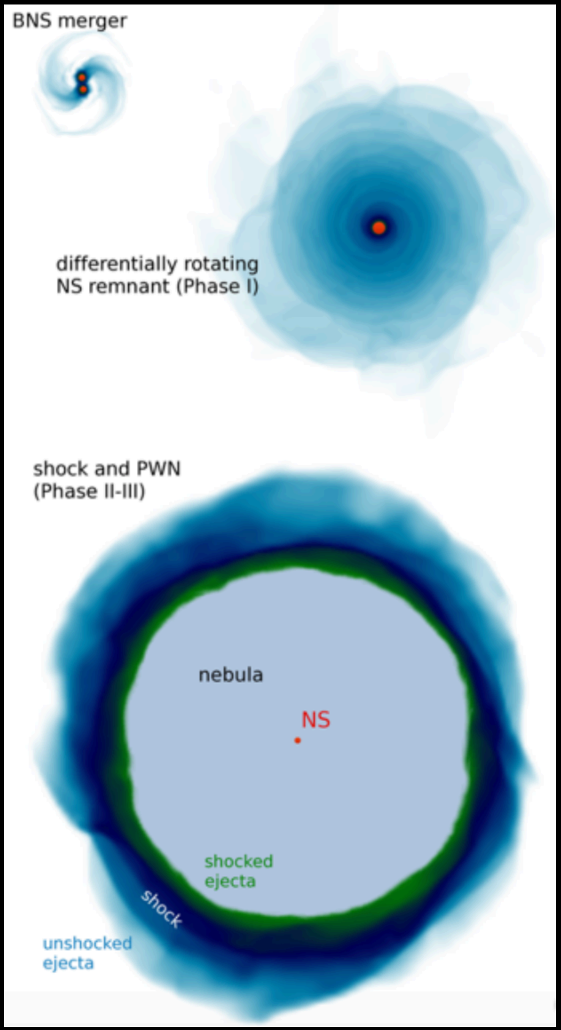
Power MACRONOVA
short lived IR-UV signal (days)

Kulkarni 2005, astro-ph0510256; Li & Paczynski 1998,ApJL, 507 Metzger et al. 2010, MNRAS, 406; Tanaka et al. 2014 ApJ, 780; Barnes & Kasen 2013, ApJ, 775. See Kasen et al. 2015, MNRAS, 450 for the accretion disk wind outflow component.

RADIO REMNANT
long lasting radio signals (years)
produced by interaction of sub-relativistic outflow with surrounding matter

Piran et al. 2013, MNRAS, 430
Hotokezaka 2016, ApJ, 831, 190

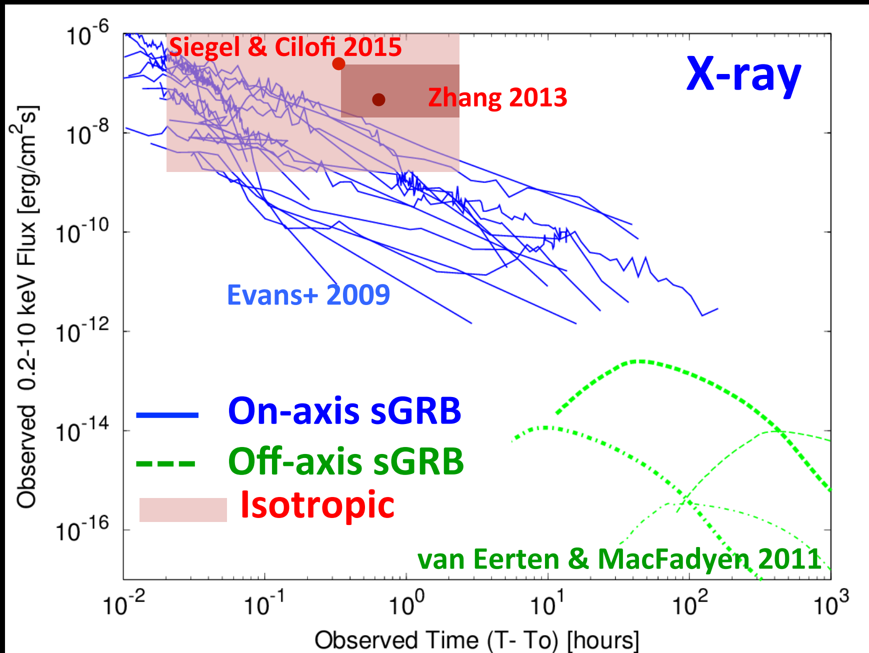
X-ray emission from the long-lived NS remnant

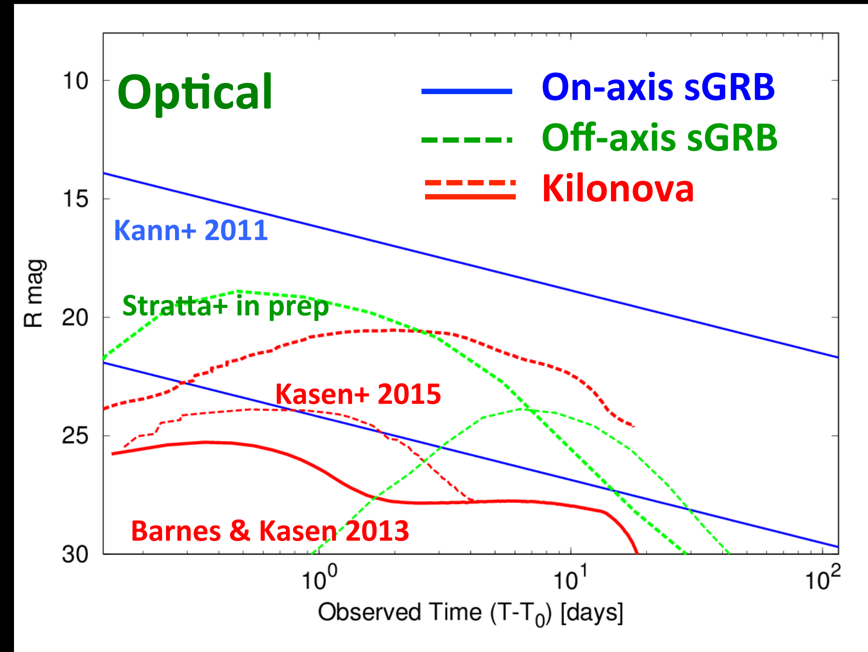


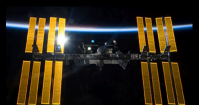
- X-ray afterglow radiation produced by spin-down energy extracted from the NS prior to collapse, slowly diffusing through optically thick environment composed of a pulsar wind nebula (PWN) and outer shell of ejected material
- signal peaks at 10^2-10^4 s after the merger
- luminosities 10^{46}-10^{49} erg/s
- mostly in the soft X-rays (0.2-10 keV)

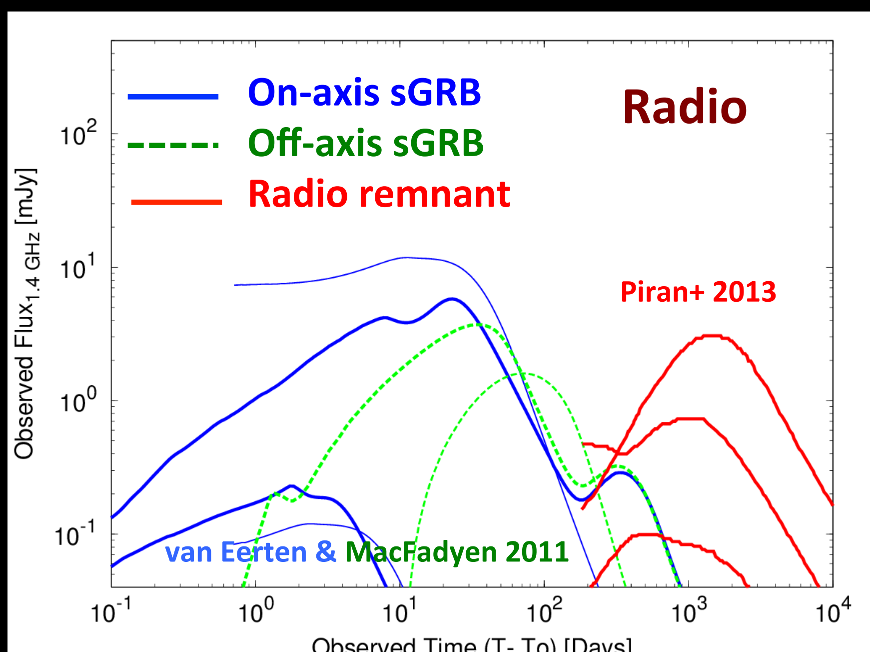
Siegel & Ciolfi 2016, ApJ, 819, 14
Siegel & Ciolfi 2016, ApJ, 819, 15

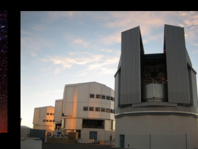
NS-NS merger EM-emissions











Source at 200 Mpc

Different timescale

NS-NS and NS-BH mergers

GRB → prompt gamma (sec)

→ Afterglows X-ray, optical, radio

(minutes, hours, days, months)

Off-axis afterglow

Kilonov

(d

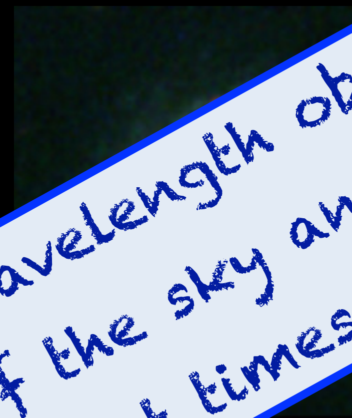
on

adio remnants

(months, years)

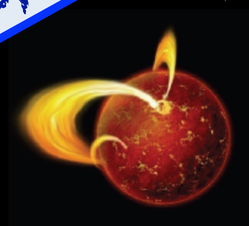
Core-collapse

SBO

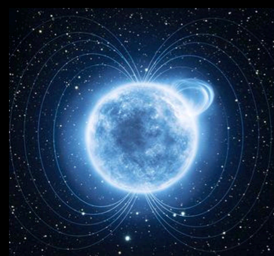


+ Long GRB

olated NS instabilities



Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars



Radio/gamma-ray Pulsar glitches

Request for network of multi-wavelength observatories which cover huge region of the sky and repeat observations over different timescales...

Multi-Messenger Searches with GWs

LIGO & Virgo have signed MOUs with 92 groups for rapid EM/neutrino follow-up of GW candidate events found in low-latency

INVOLVED:

- **About 200 EM instruments** - satellites and ground based telescopes covering the full spectrum from radio ti very high-energy gamma-rays
- ***Worldwide astronomical institutions, agencies and large/small teams of astronomers***

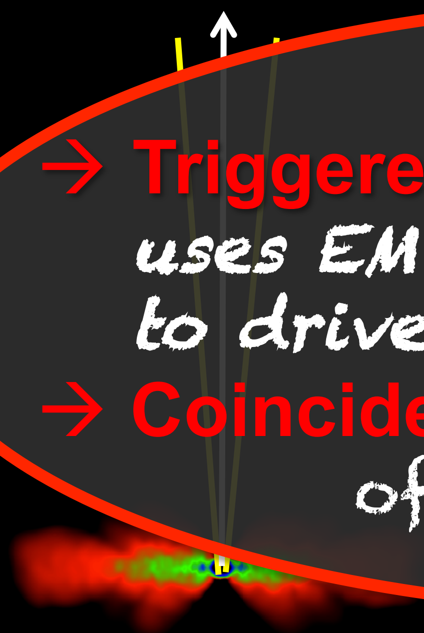
\+ In addition a number of triggered / joint search MOUs

Multi-messenger searches

NS-NS and NS-BH mergers

GRB → prompt gamma

HEN Neutrinos



Core-collapse of massive stars

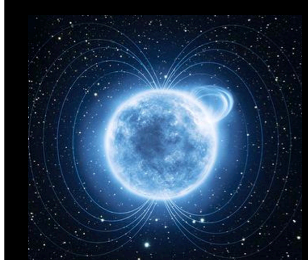
SBO X-ray/UV
(minutes,days)

Optical
(weeks, months)

Low-energy Neutrinos

Isolated NS instabilities

Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars

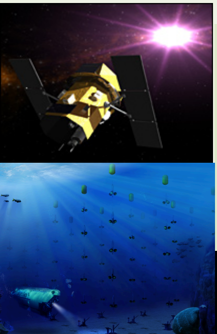


Radio/gamma-ray Pulsar glitches

→ **Triggered Analysis:** search that uses EM or neutrino observations to drive the detection of GWs

→ **Coincident searches:** compare sets of candidate events

GRB prompt emission, SN explosion in local galaxies, flares SGR, pulsar glitches, low and high energy neutrino → GW TRIGGERED ANALYSIS

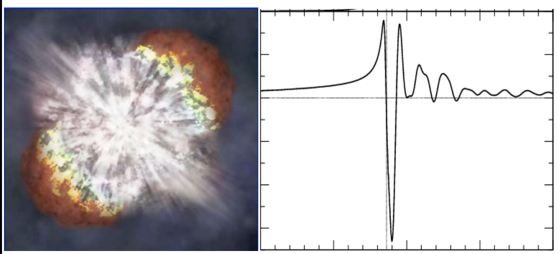


Known **event time** and **sky position:**

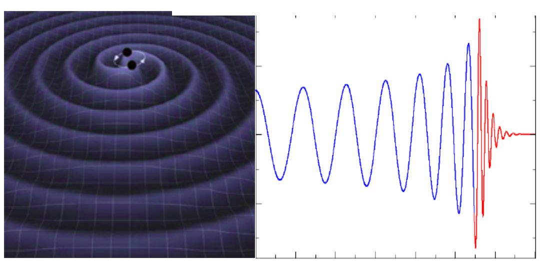
→ reduction in search parameter space
→ gain in search sensitivity

Abadie et al. 2012, ApJ, 760
Aasi et al. 2014,PhRvL, 113
Abadie et al. 2012, ApJ, 755
Adrián-Martínez et al. 2013, JCAP
Aartsen et al, PhysRevD, 90, 102002

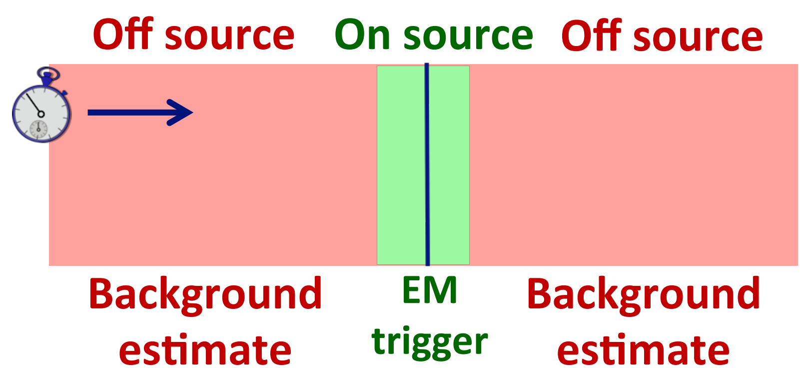
GW transient searches

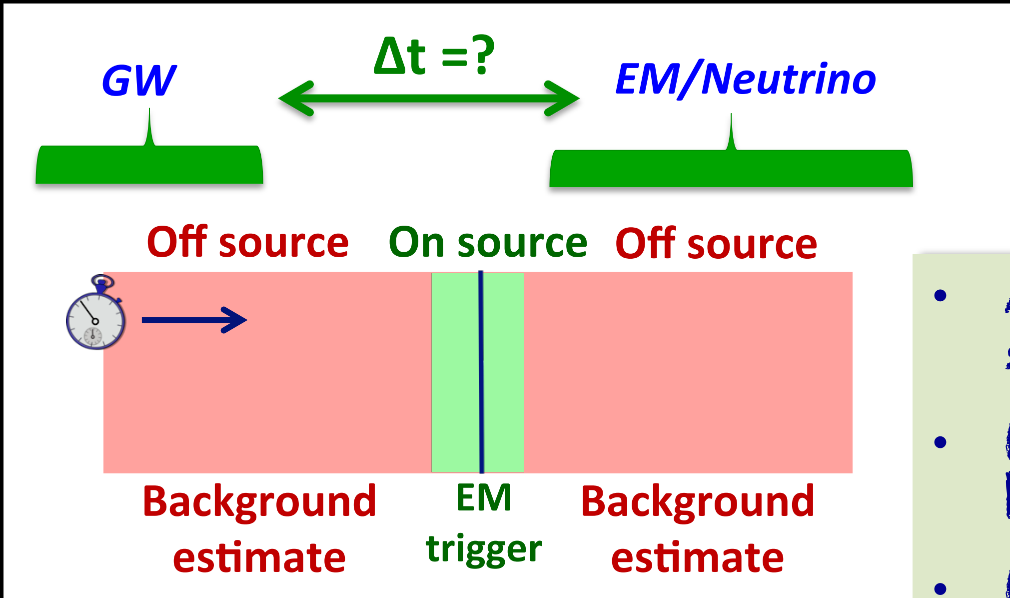


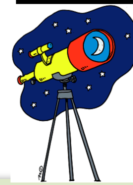
Unmodeled GW burst
(< 1 sec duration)
Arbitrary waveform
→ **Excess power**

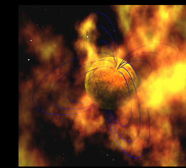


Compact Binary Coalescence
Known waveform
→ **Matched filter**

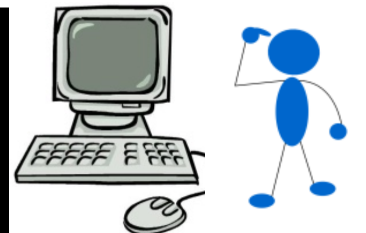




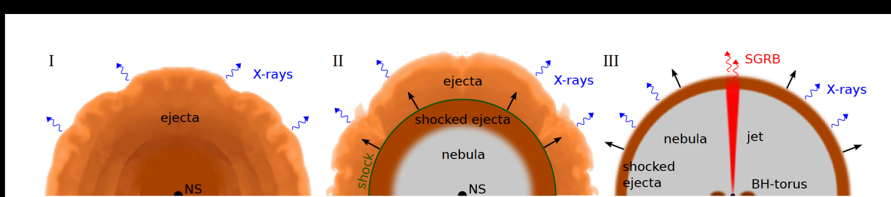




- Are the GW and EM emissions simultaneous?
- What is the possible time delay between GW and EM?
- What are the uncertainities in the observed EM event time?
- What is the temporal on-source window to use?

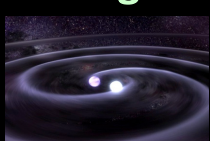


→ ***"Time-reversal" scenario for NS-NS merger*** (Ciolfi & Siegel 2014)***:***



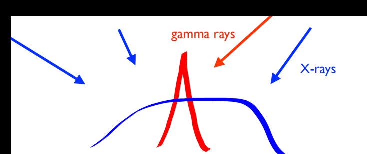
GWs → X-ray → Gamma-ray

Merger



Supramassive NS lifetime **10^3 s**

Collapse to BH

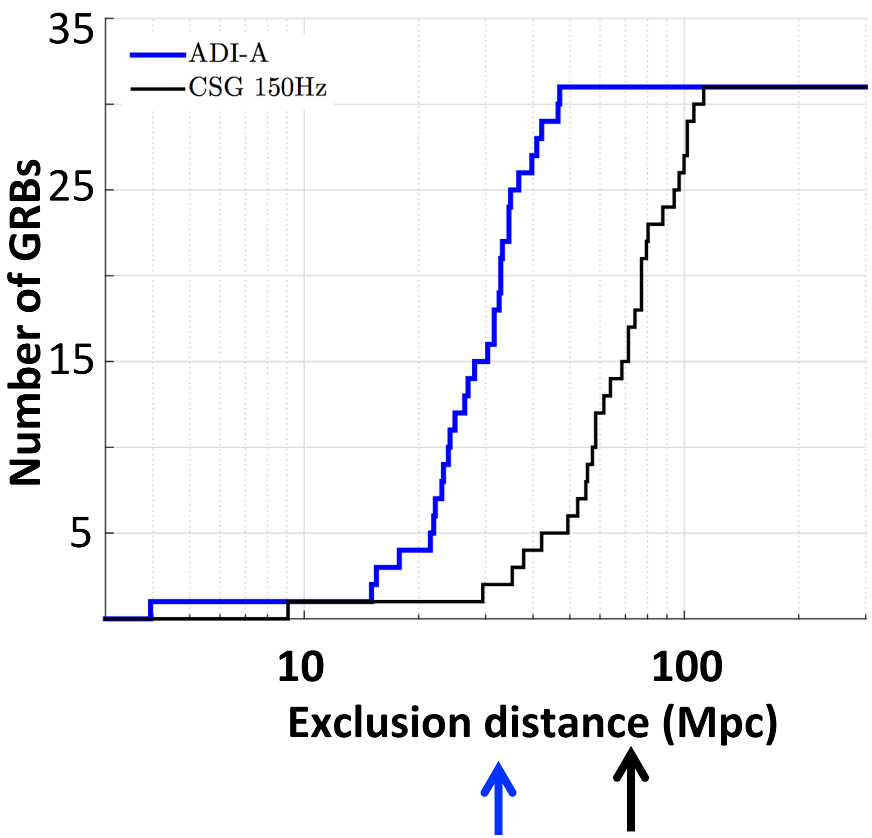


O1 GRB prompt emission Triggered Search

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

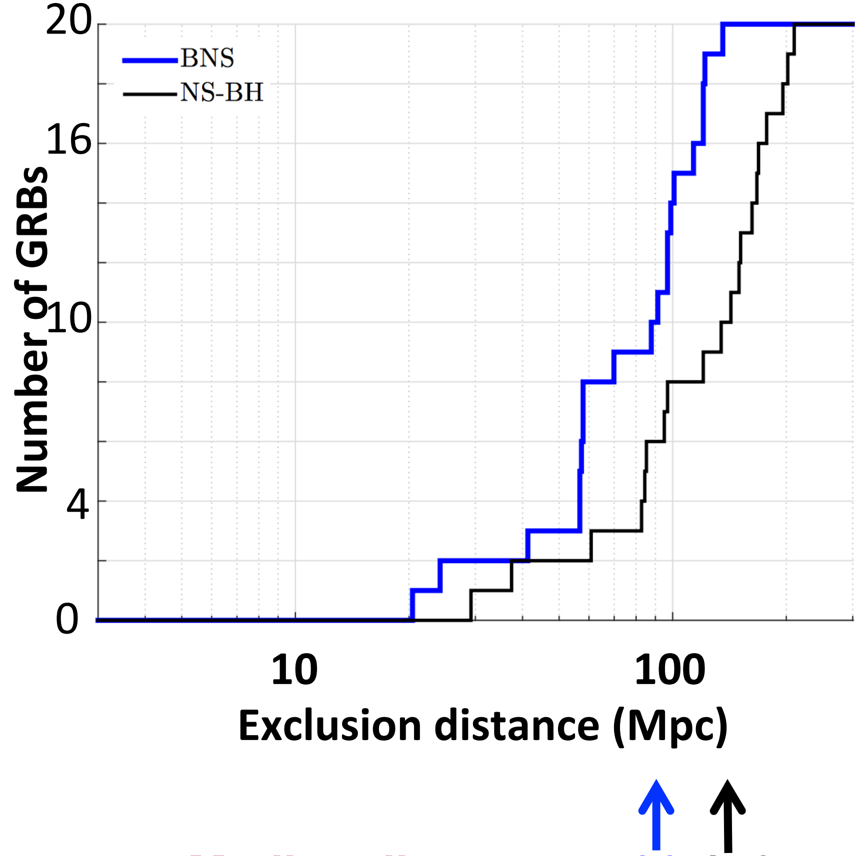
Abbott et al. 2016, ApJ in press, arXiv:1611.07947

Unmodeled GW burst (31 GRBs)
with **10^{-2} Moc^{2} energy in GW** (optimistic)



Median distances: 31 **71** Mpc

Binary system coalescence
(19 short GRBs)



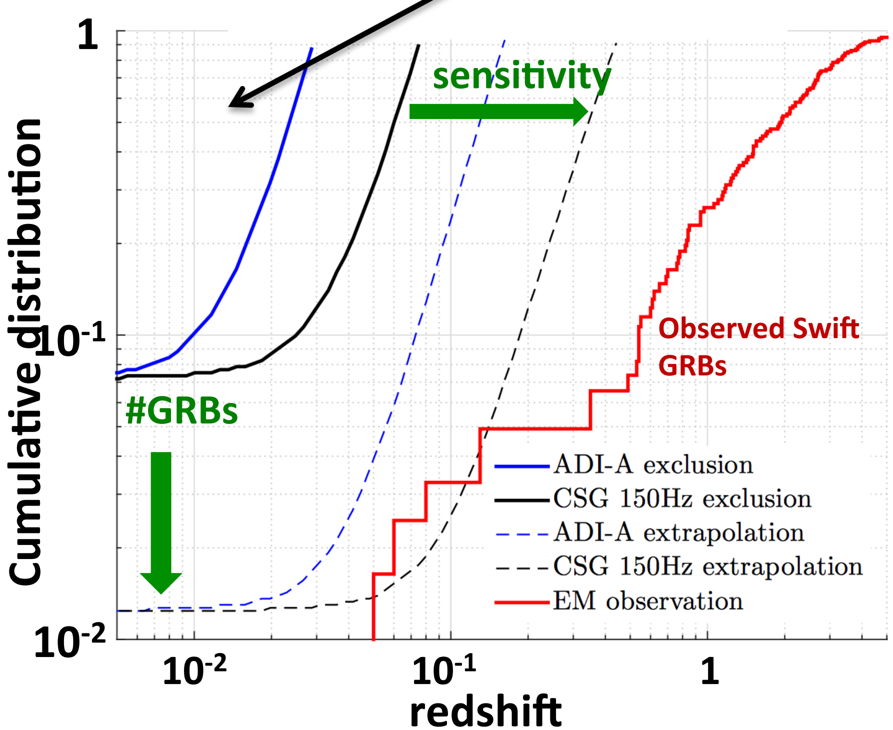
Median distances: 90 **150** Mpc

Population exclusion on cumulative redshift distribution

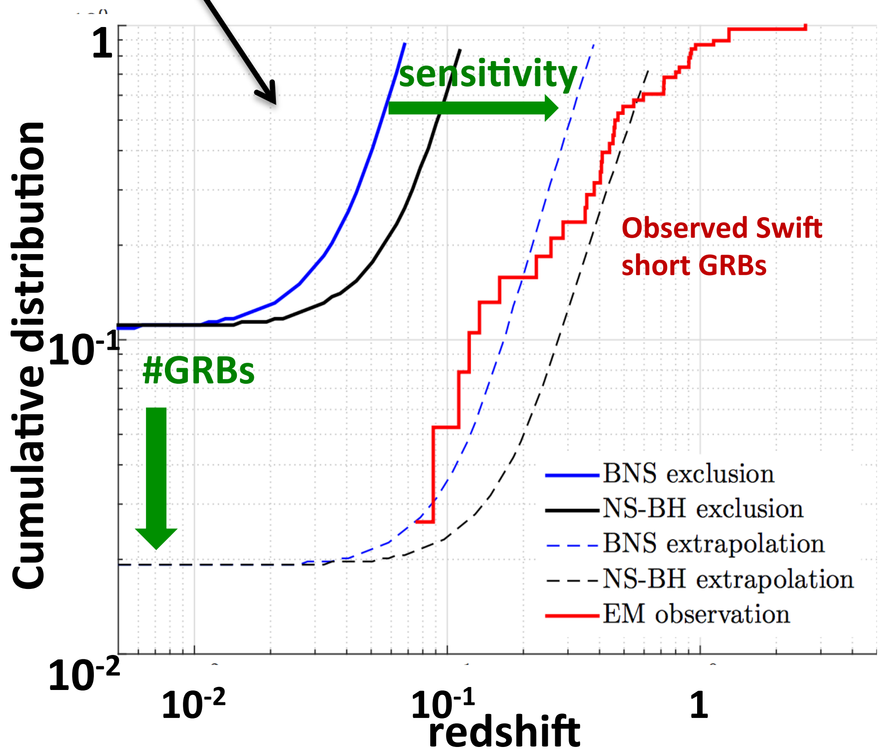
O1 results & prospects for 2 yrs of Advanced LIGO/Virgo design sensivity

90% confidence exclusion region

Unmodeled GW burst



Binary system coalescence



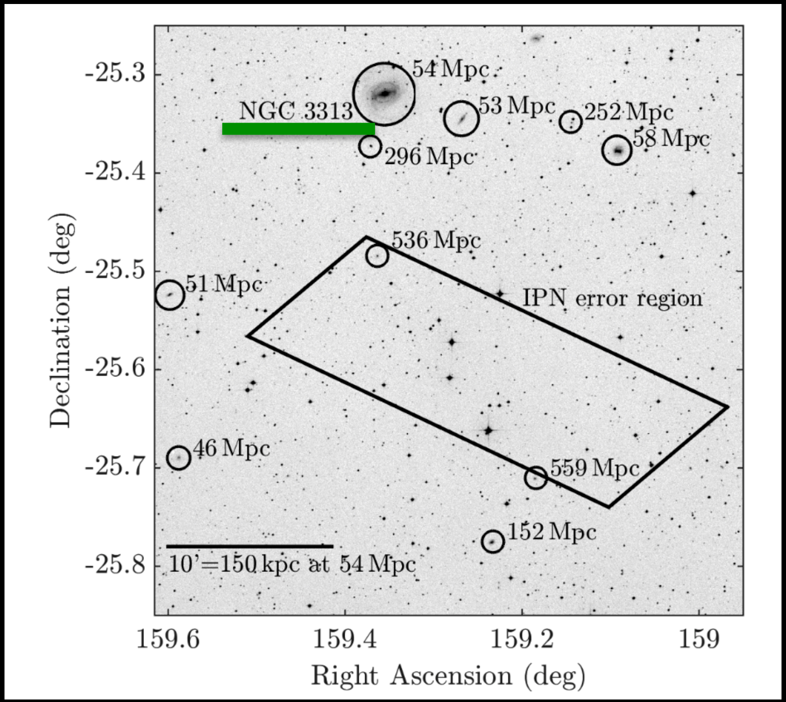
2yrs Advanced LIGO and Virgo

Long GRBs→ lack of detection constrain most extreme scenario

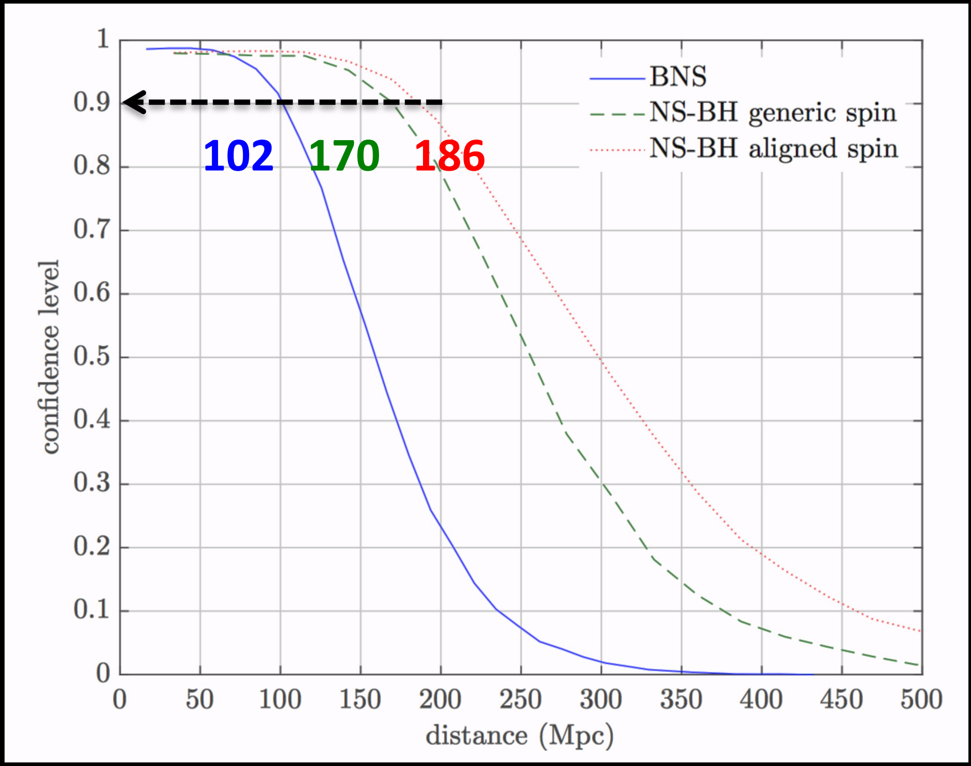
Short GRBs→ likely detection or no detection in tension with BNS merger progenitor

Abbott et al. 2016, ApJ in press, arXiv:1611.07947

GRB150906B BNS or NS-BH merger in NGC3313?
Triggered Search



- ❖ GRB 150906B – Sep 06, 2015 at 08:42:20 UTC, detected by IPN
- ❖ Short-duration/hard-spectrum GRB close to the local galaxy NGC3313 (D=54Mpc)
- ❖ Only LIGO Hanford on at the time



- ❖ Assuming a jet half-opening angle ≤ 30° → BNS and NS-BH progenitors in NGC 3313 excluded at >99%
- ❖ No evidence for NS-NS/BH GW signals up to 102/170 Mpc

Abbott et al. 2016, ApJ in press, arXiv:1611.07947

Multi-messenger searches

NS-NS and NS-BH mergers

GRB → prompt gamma (sec)
→ Afterglows X-ray, optical, radio
(minutes, hours, days, months)

Off-axis afterglow

Isotropic emission
Kilonovae (days)

Radio remnants
(months, years)

Siegel & Ciolfi 2016, ApJ → X-ray (min, hrs)

Core-collapse of massive stars

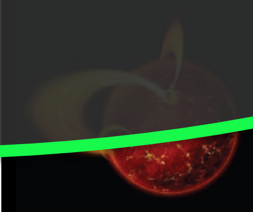
SBO X-ray/UV
(minutes,days)

Optical
(weeks, months)

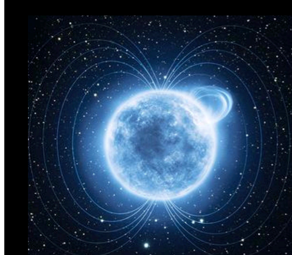
Radio
(years)

→ EM follow-up: *low-latency GW candidate events to trigger prompt EM observations and* → archival searches

Isolated NS instabilities



Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars



Radio/gamma-ray Pulsar glitches

BH-BH mergers ?

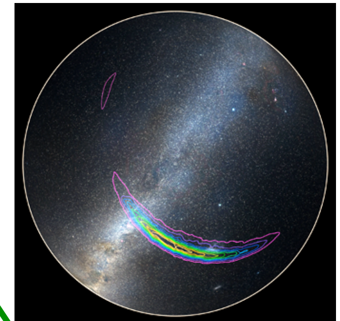
Low-latency GW data analysis pipelines to promptly identify GW candidates and send GW alert to obtain EM observations

Branchesi 2016 on behalf of LVC, Ricap2016 conference

GW candidates **Sky Localization** **EM facilities**

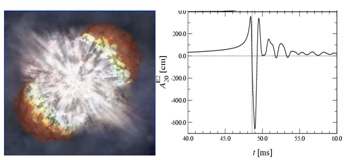
LIGO-H LIGO-L

Virgo

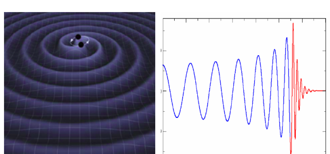


Event validation

Low-latency Search
to identify the GW-candidates

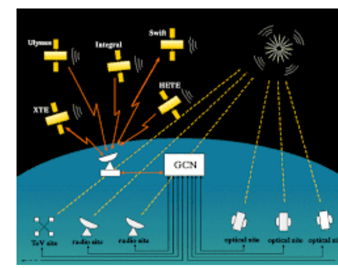


Unmodeled GW burst search



Matched filter with waveforms of compact binary coalescence

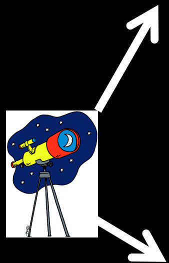
Software to
- select statistically significant triggers wrt background
- check detector sanity and data quality
- determine source localization



a few min → **15/30 min**

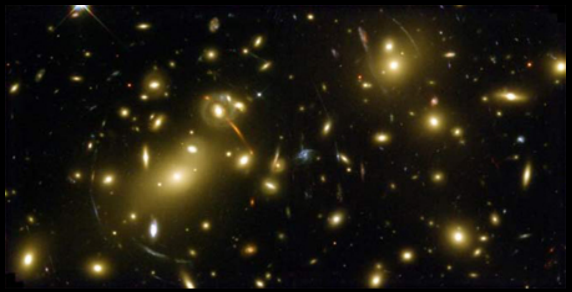
Parameter estimation codes → **Hours,days** → **GW candidate updates**

Hunt the elusive EM-counterpart!

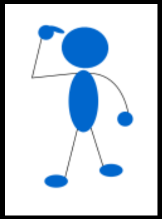


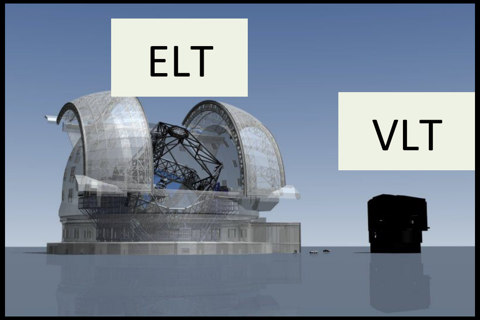
Wide-field telescope
FOV >1 sq.degree

Not easy to cover hundreds of square degrees with FOV 1-10 sq. degrees!



"Fast" and "smart" software to select a sample of candidate counterparts





Larger telescope to **characterize** the candidate nature

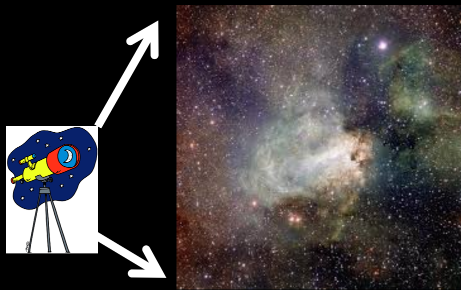
The EM Counterpart!

Galaxy-targeting observational strategy

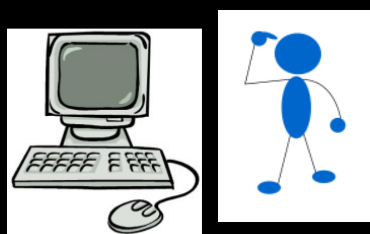
Nissanke et al. 2013, ApJ, 767
Aasi et al. 2014, ApJS, 211
Gehrels et al. 2016, ApJ, 820

Hunt the elusive EM-counterpart!

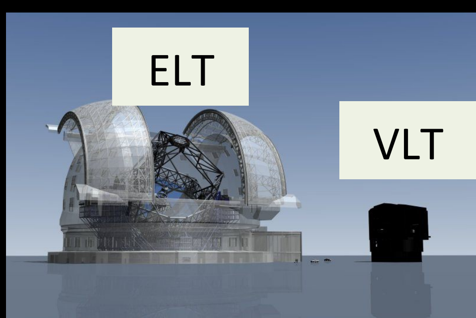
Optical/NIR band



Wide-field telescope
FOV >1 sq.degree



“Fast” and “smart” software to select a sample of candidate counterparts



Larger telescope to **characterize** the candidate nature

The EM Counterpart!

10^4-10^5 variable objects over 100 sq. degrees

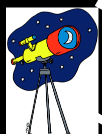
Artifacts and many astrophysical contaminants

M-dwarf flares (min to hrs)
3 (0.3) deg^{-2} up to red mag 24
at 20 (80) deg latitude
(Ridgway et al., 2014)

Supernovae (days to month)
7 deg^{-2} up to red mag 24
(Graur et al., 2014; Dahlen et al., 2012Cappellaro, 2014)

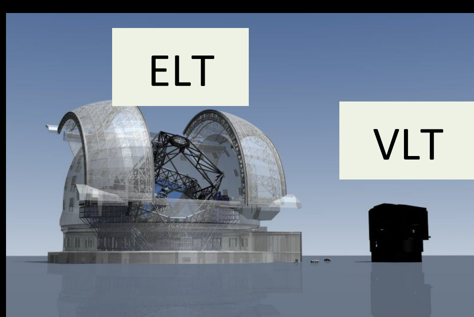
A few tens of candidate counterparts

Hunt the elusive EM-counterpart!



Wide-field telescope
FOV >1 sq.degree

"Fast" and "smart" software to select a sample of candidate counterparts



Larger telescope to **characterize** the candidate nature

The EM Counterpart!

X-rays

✓ less contaminants

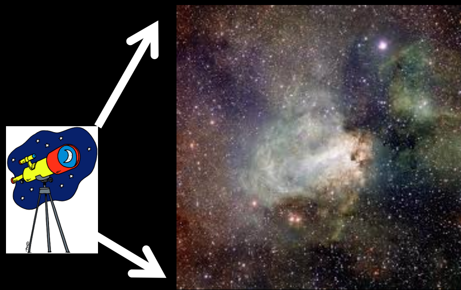
Transient rate **2.5×10^{-3} deg^{-2}**
$flux_{0.2-2KeV} > 3 \times 10^{-12} ergs^{-1} cm^{-2}$
(Kanner et al. 2013)

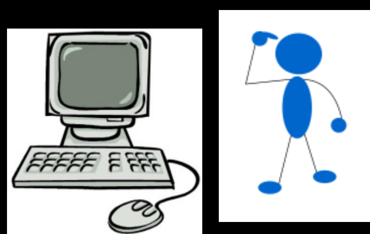
x no wide-field telescope

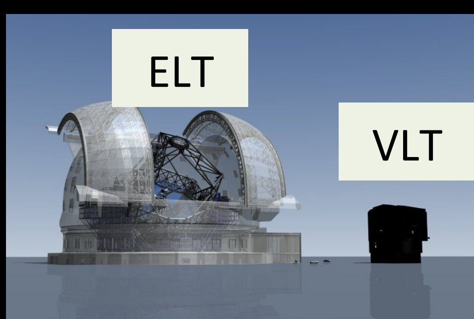
Gamma-rays

✓ less contaminants
✓ all-sky monitors
x beamed emission

Hunt the elusive EM-counterpart!







Wide-field telescope
FOV >1 sq.degree

"Fast" and "smart" software to select a sample of candidate counterparts

Larger telescope to **characterize** the candidate nature

The EM Counterpart!

Radio

✓ less contaminants

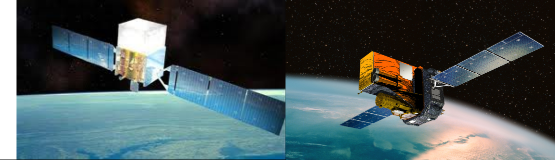
Transient rate < 0.37 deg^{-2}
peak-flux_1.4 GHz > 0.21 mJy
timescales 1 d – 3 m
(Mooley et al., 2013)

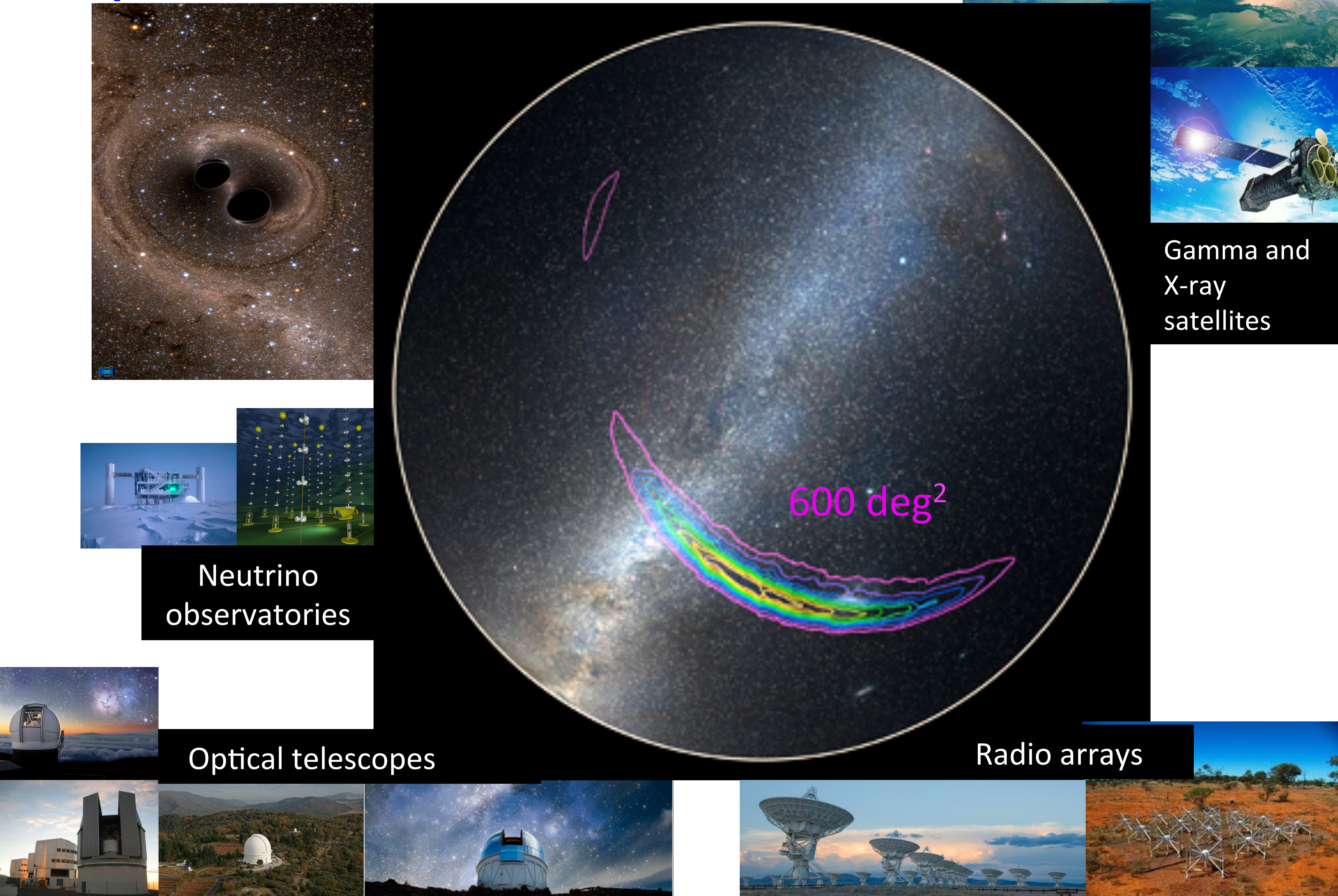
✓ wide-field array at low frequencies (MHz)

x faint sources

x long delay GW → radio emission

The first multi-messenger campaign including GW/photons and neutrinos…..



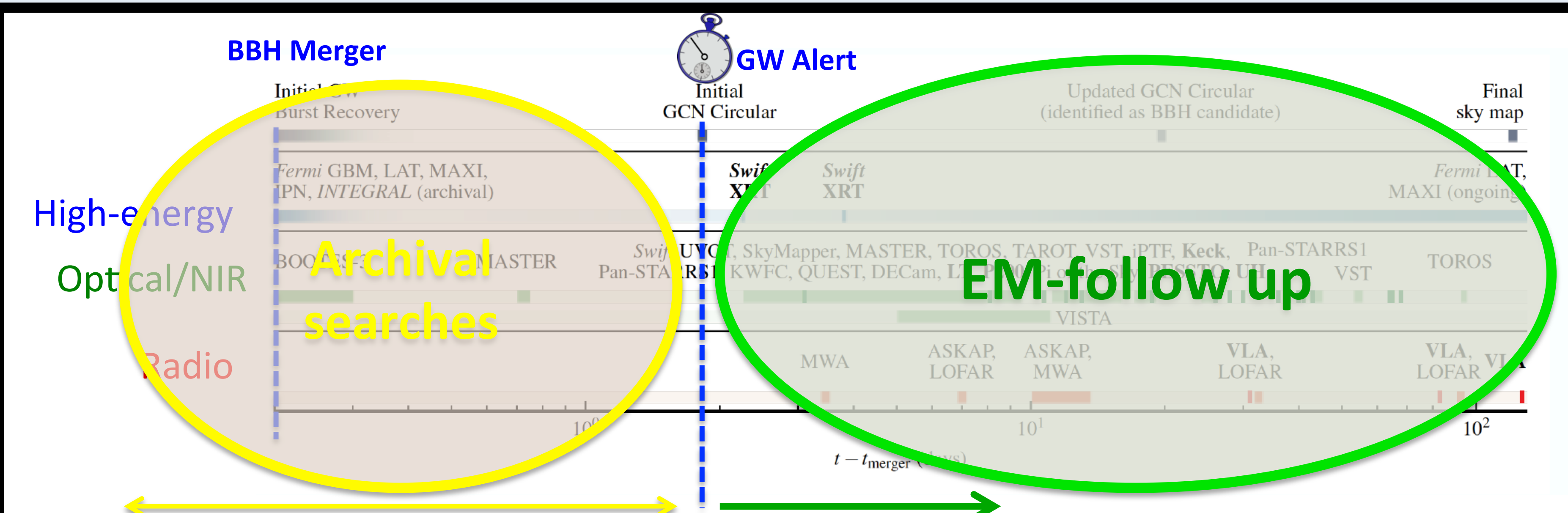


GW150914

EM follow up observations and archival searches

- ***Twenty-five teams*** *of observers responded to the GW alert*

- *The EM observations involved* ***satellites and ground-based telescopes*** *around the globe spanning 19 orders of magnitude in frequency across the EM spectrum*

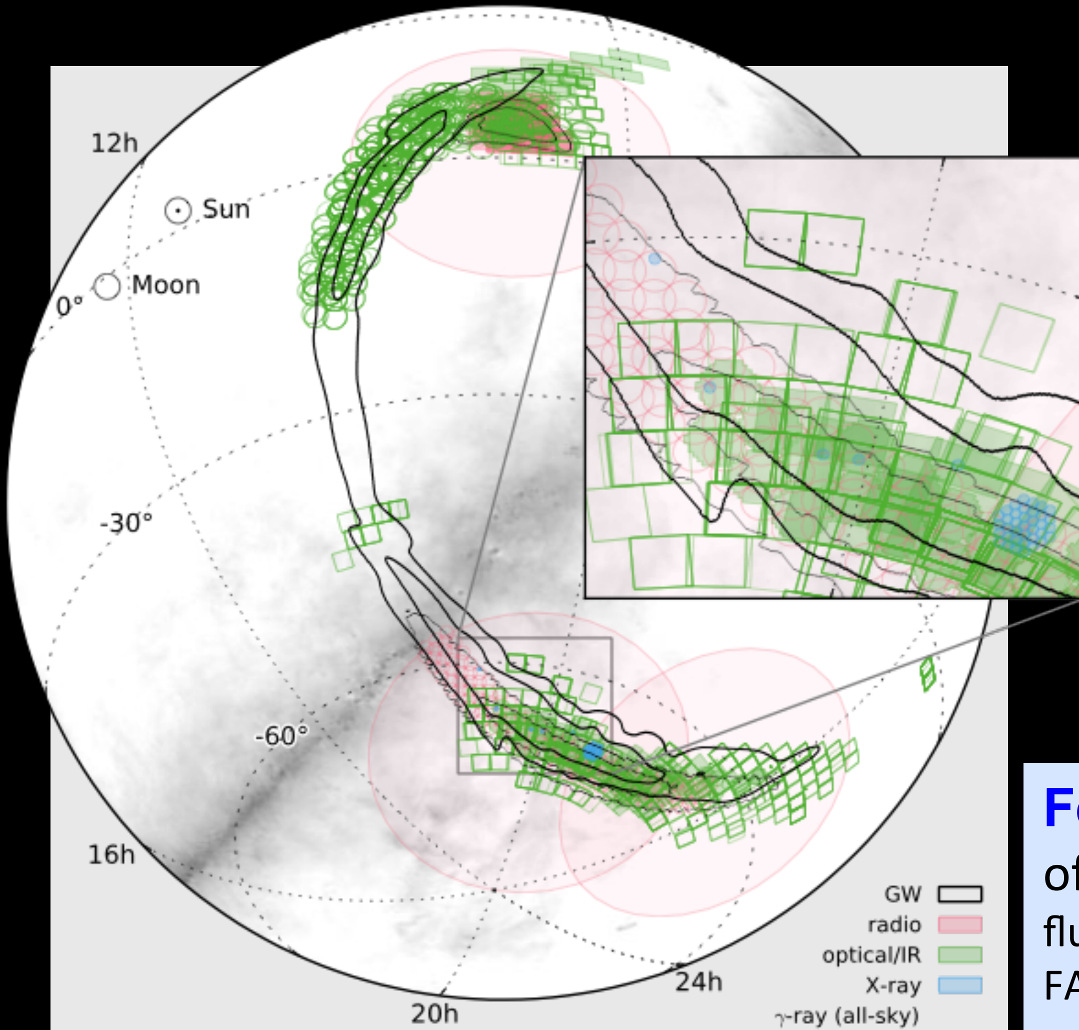


LVC+astronomers, ApJL, 826, 13
LVC+astronomers ApJS, 225,8
Connaughton et al. ApJL, 826, 6
Savchenko et al. 2016 ApJL 820, 36
Fermi-LAT collaboration ApJL, 823,2
Hurley et al. ApJL, 829, 12

Evans et al. MNRAS 460, L40
Morokuma et al. PASJL, 68, 9
Lipunov et al. arXiv:1605.01607
Soares-Santos et al. ApJL, 823, 33
Annis et al. ApJL, 823, 34
Smartt et al. MNRAS, 462, 4094

Kasliwal et al. ApJL, 824, 24
Diaz et al. ApL 828, 16
Greiner et al. ApJL, 827, 38
Tavani et al. ApJL, 825, 4
Troja et al. ApJL, 827, 102

Sky map coverage



- Covered sky map contained probabilty:
  100% gamma-ray
  86% radio
  50% optical
- ***In the optical***, *candidate counterparts rapidly characterized and identified to be normal population SNe, dwarf novae and AGN*

LVC+astronomers ApJL, 826, 13
LVC+astronomers ApJS, 225, 8

Fermi-GBM → **weak signal**
of 1 sec 0.4 s after GW15014

fluence(1 keV-10 MeV) = 2.4×10^{-7} erg cm^{-2}
FAR 4.79×10^{-4} Hz, FAP 0.0022
(**Connaughton et al. 2016 ApJL, 826**)

INTEGRAL → no signal but
stringent upper limit
(**Savchenko et al. 2016 ApJL, 820**)

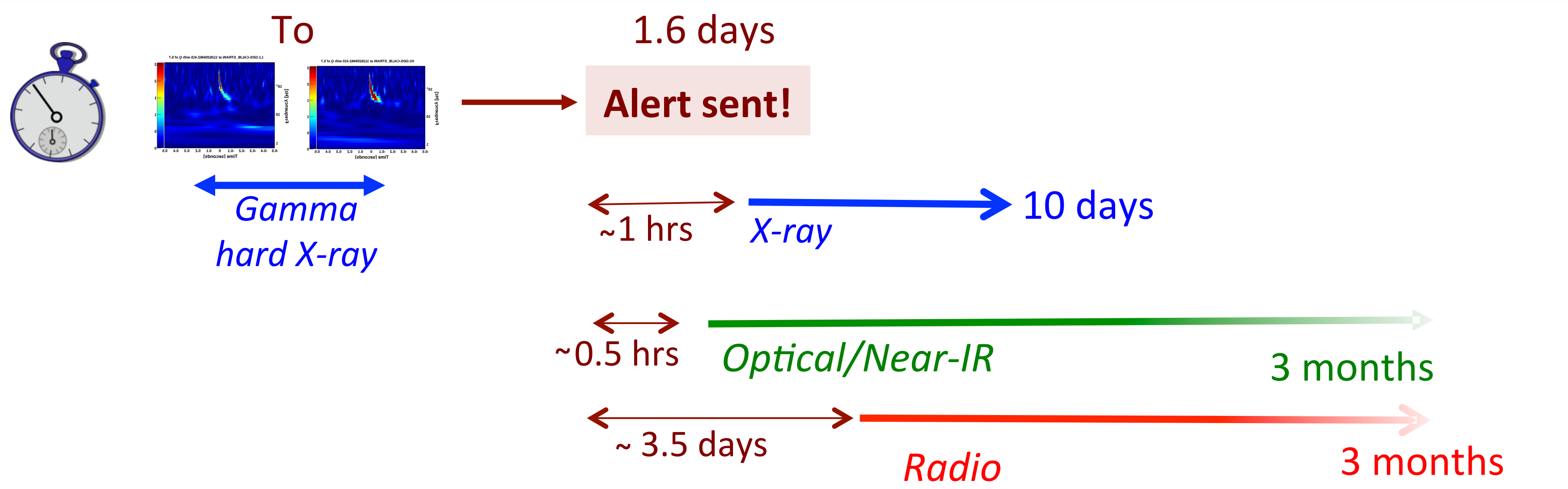
GW151226

***Thirty-one groups** responded to the GW alert:*

High-energy and Very high-energy→ Swift, XMM-Slew, MAXI, AGILE, Fermi, CALET, CZTI, IPN, MAGIC, HAWC

Optical-NIR → MASTER, GRAWITA, GOTO, Pan-STARRS1, J-GEM, DES, La Silla–QUEST, iPTF, Mini-GWAC SVOM, LBT-Garnavich, Liverpool Telescope, PESSTO, VISTA-Leicester, Pi of the Sky observations, LCOGT/UCSB, CSS/CRTS, GTC

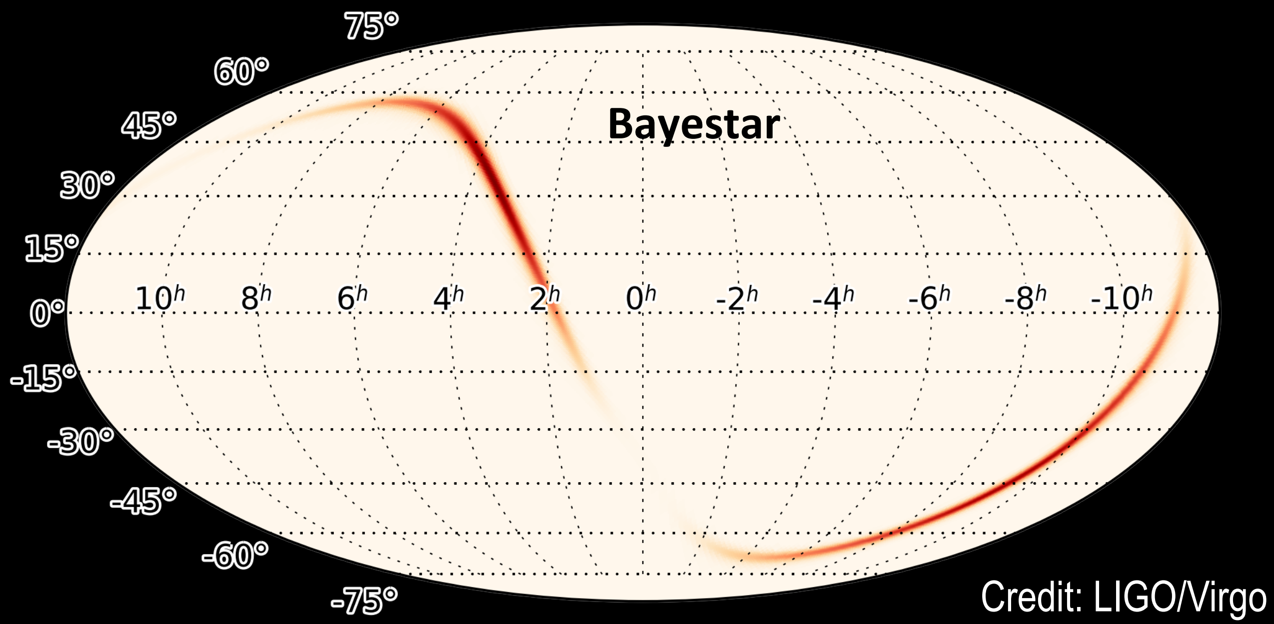
Radio → VLA-Corsi, LOFAR, MWA



All the info from public GCNs: http://gcn.gsfc.nasa.gov/gcn3_archive.html

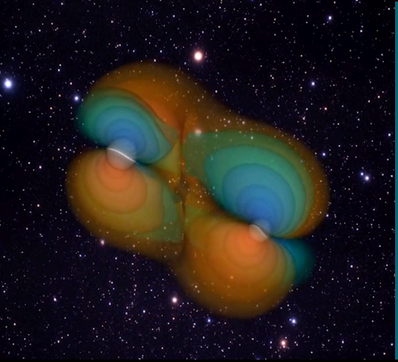
Racusin et al. arXiv:1606.04901
Smartt et al. arXiv:1606.04795
Copperwheat et al. MNRAS, 462, 3528
Cowperthwaite et al., ApJL, 826, 29
Evans et al. MNRAS, 462, 1591
Adriani et al.ApJL, 829, 20
Palliyaguru et al. ApJL, 829, 28

GW151226



- *Large portions of the GW sky map observed*
- *Candidate counterparts rapidly characterized*
- *In the optical, candidate counterparts identified to be normal population SNe, dwarf novae and AGN*
- ***No EM counterpart reported***

GCNs: http://gcn.gsfc.nasa.gov/gcn3_archive.html



The O1 EM follow-up demonstrates the capability to cover large area, to identify candidates, and to rapidly chracterize them.

No stellar-BBH EM emission expected due to the absence of the accreting material
...but some mechanisms that could produce unusual presence of matter around BHs recently discussed
(e.g. Loeb 2016 ; Perna et al. 2016 ; Murase et al. 2016, Bartos et al. 2016)

Future EM follow-ups of GW will shed light on the presence or absence of firm EM counterparts for BBH

The follow-up campaign sensitive to emission expected from BNS mergers at 70 Mpc range

The widely variable sensitivity across the sky localization is a challenge for the EM counterpart search

GCN Alerts contents to support observing startegy

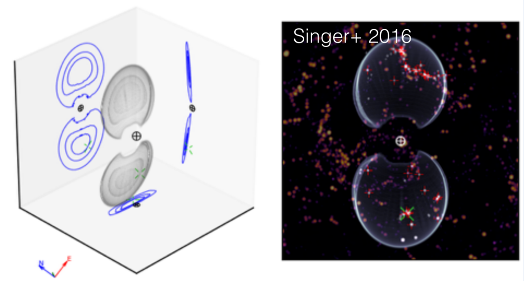
- Event **time** and **probability sky map** (HEALPix FITS file)
- Estimate of **False Alarm Rate** of event candidate (FAR < 1/1month)
- **Basic source classification**: found by CBC, Burst, or both pipelines;

For CBC candidates LVC GCN will have:

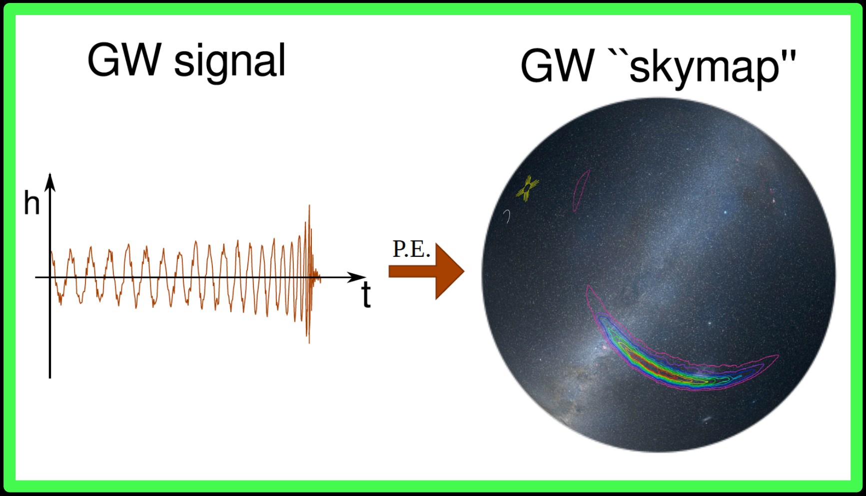
- ***"EM bright" indicators:***
  - **Source classifier** → Probability of **presence of a NS** in the binary (object m<3.0 solar mass)
  - **Remnant mass classifier** → Probability of **presence of any NS tidally disrupted mass left outside the BH**

(*Foucart 2012, PhRvD, Pannarale* & Ohme, 2014, ApJ)

- ***Luminosity distance*** marginalized over whole sky (mean+/-standard deviation)
- ***3D sky maps with direction-dependent distance*** (e.g. Singer et al. 2016, ApJL 829, L15)



Optimizing the observational strategy: when and where?



3D sky map

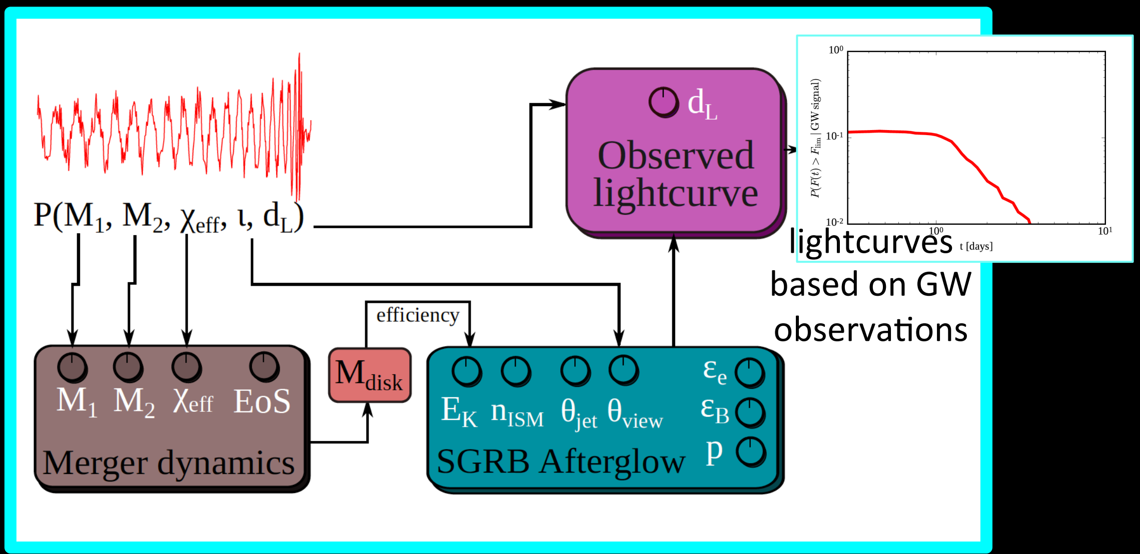
Sky localization probability with direction-dependent distance and its distribution

Singer et al. 2016 ApJL, ApJS

Detectability map
P (F(t) > Flim |RA,DEC, D_L)

Posterior distributions of GW parameters

The same signal can be produced by different combinations of the parameter values

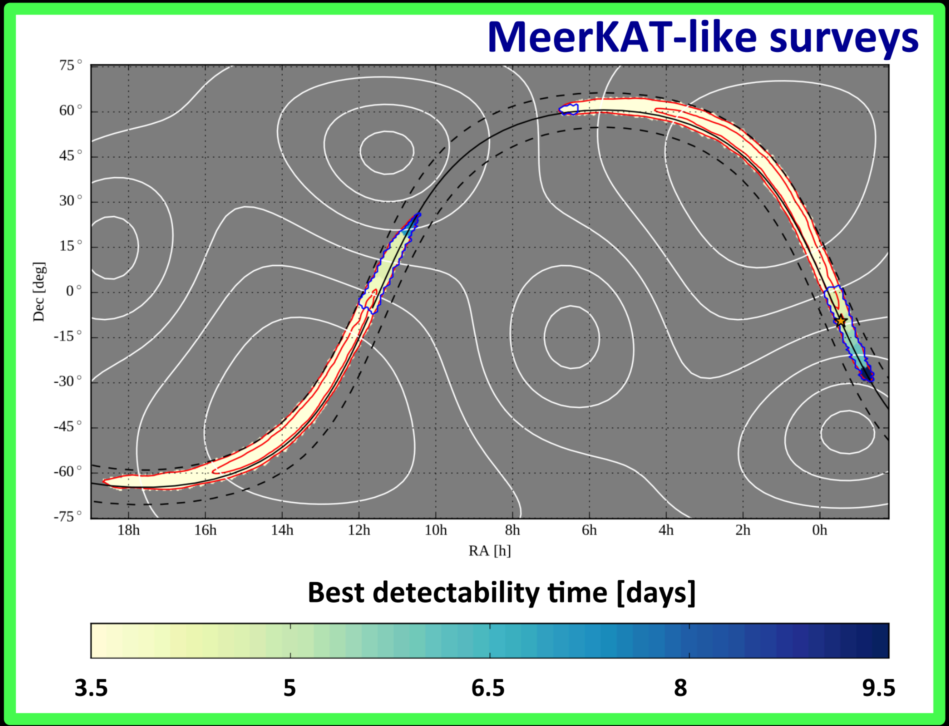


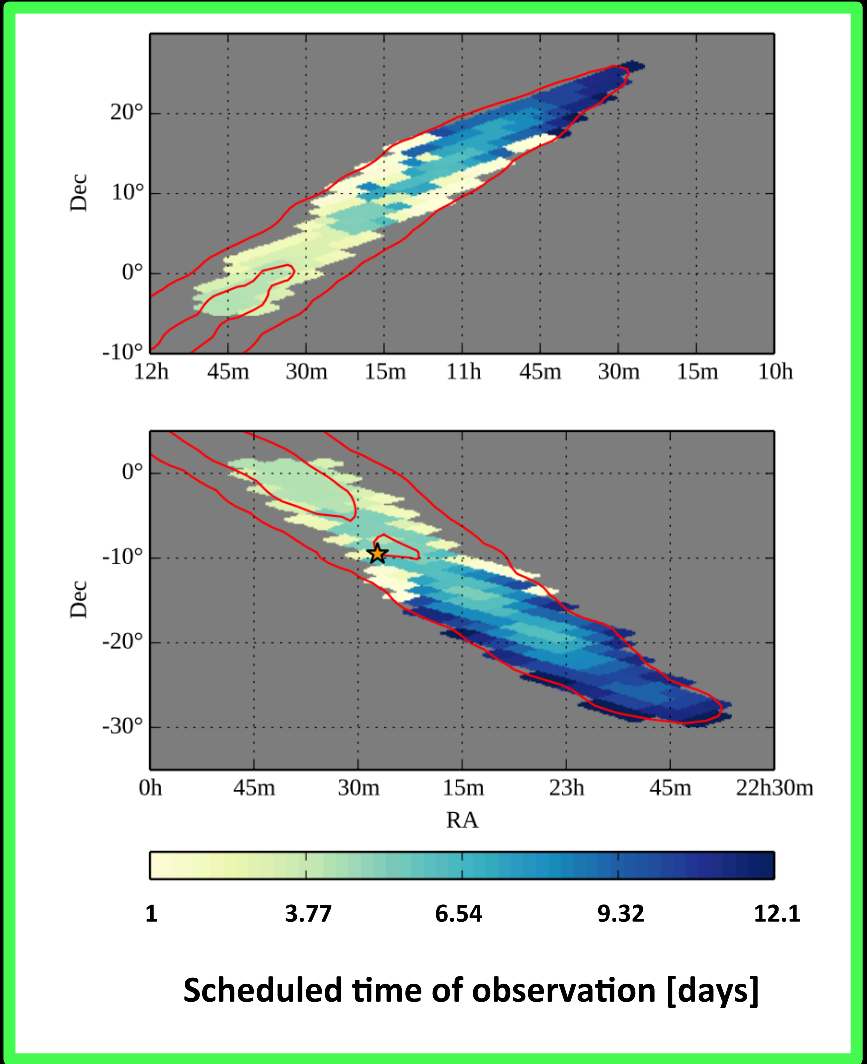
A posteriori detectability
P (F(t) > F_{lim} |GWsignal)

Salafia et al. arXiv:1704.05851

Sky-position-conditional posterior distribution

→ Detectability map P (F(t) > Flim |RA,DEC, GW signal)





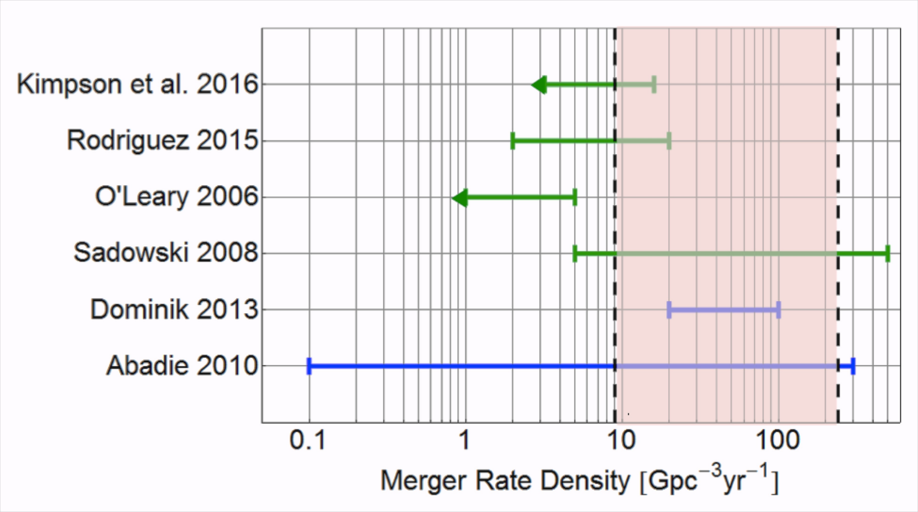
Salafia et al. arXiv:1704.05851

→ Optimize the sequence of tiles and observational epochs
→ Reduce area to be observed and telescope time

Prospects of observing and localizing GWs in the next LIGO and VIRGO scientific runs

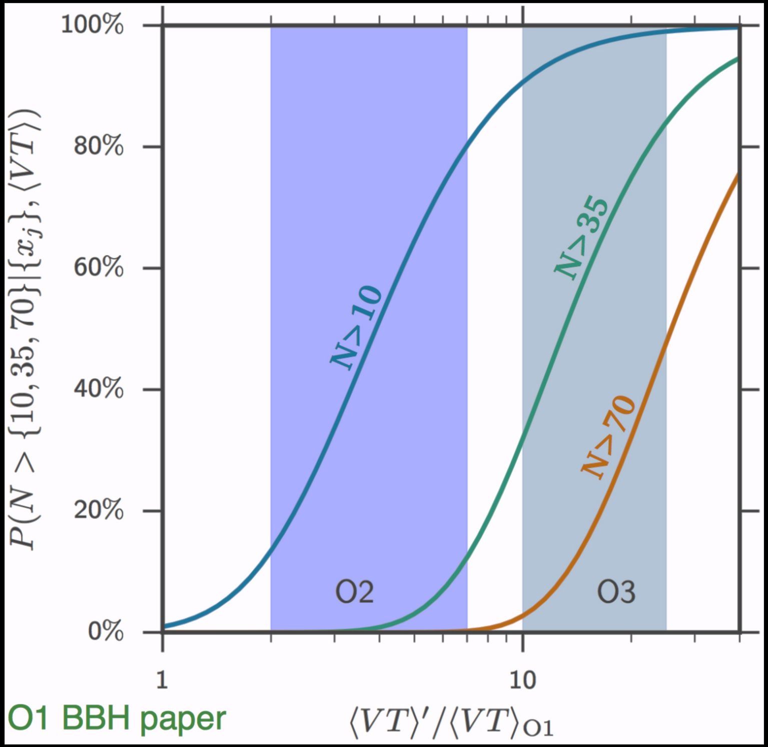


BBH merger rate based on O1 observations



9-240 Gpc^{-3} yr^{-1}

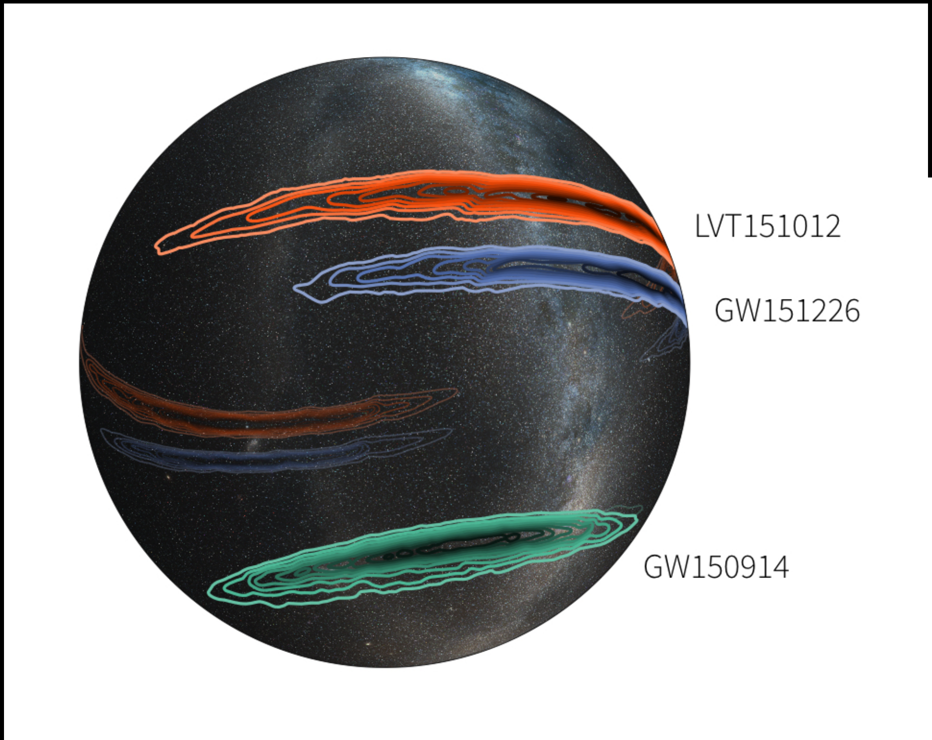
Number of expected highly significant detections (FAR < 1/century)



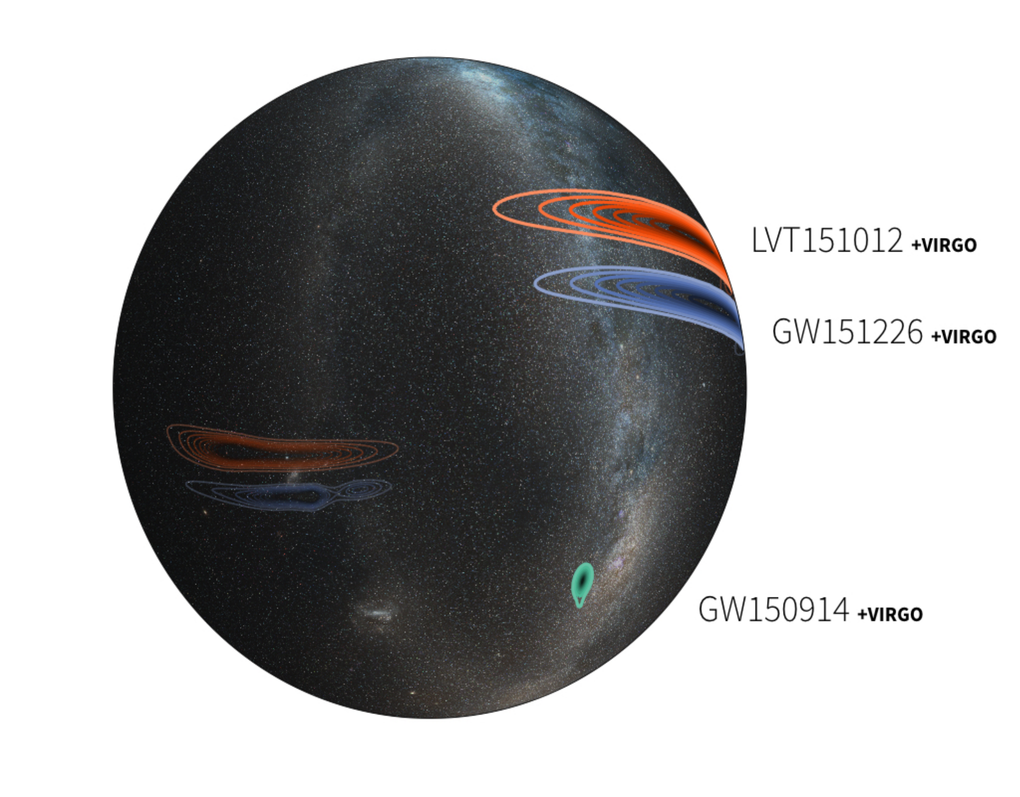
LVC 2016 Phys. Rev. X, 6

Sky localization with Virgo

Actual estimates



Simulated estimates with Virgo



Virgo is expected to join O2 run in Summer!

Image credit: LIGO/L. Singer/A. Mellinger

No detection of either NS-NS or NS-BH mergers in O1

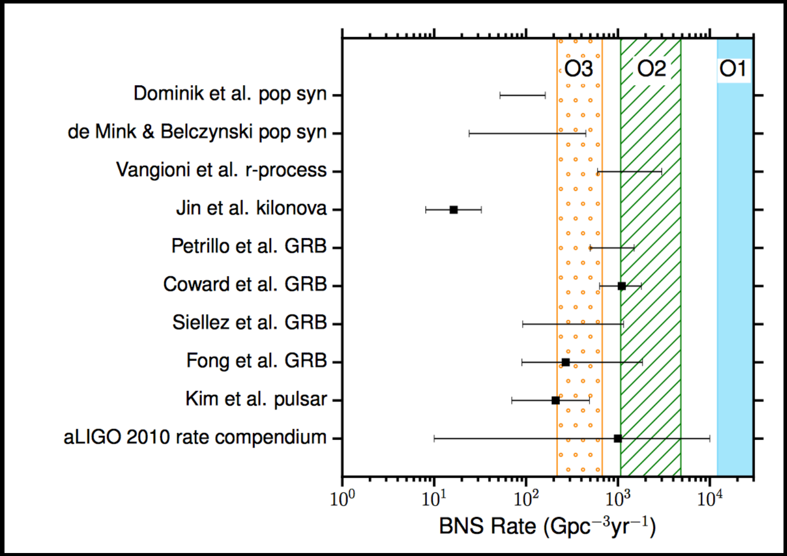
Reached distance range:

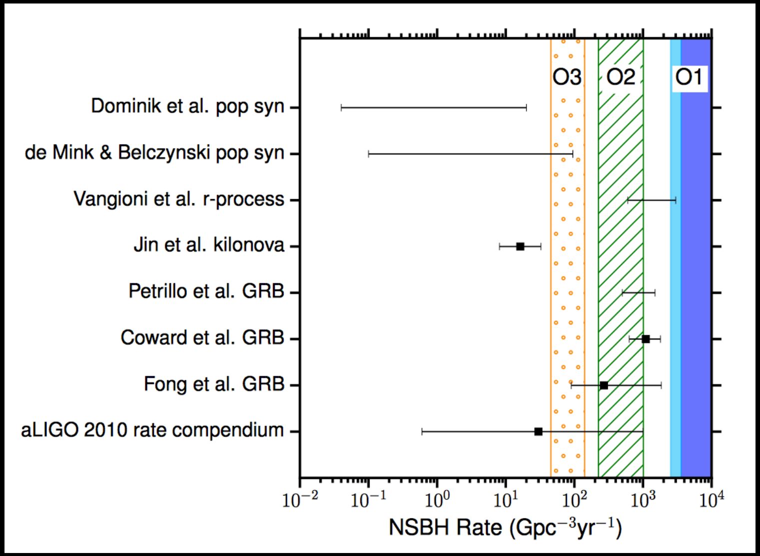
- **70 Mpc** for NS-NS 1.35±0.13 $M_\odot$
- **110 Mpc** for NS 1.4 $M_\odot$ -BH 5 $M_\odot$

Upper limits on the merger rates in the local Universe:

- **< 12600** Gpc^{-3} yr^{-1} for NS-NS 1.35±0.13 $M_\odot$
- **< 3600** Gpc^{-3} yr^{-1} for NS 1.4 $M_\odot$ -BH 5 $M_\odot$

The upcoming Advanced LIGO and Virgo observing runs would place significant constraints on the merger rates

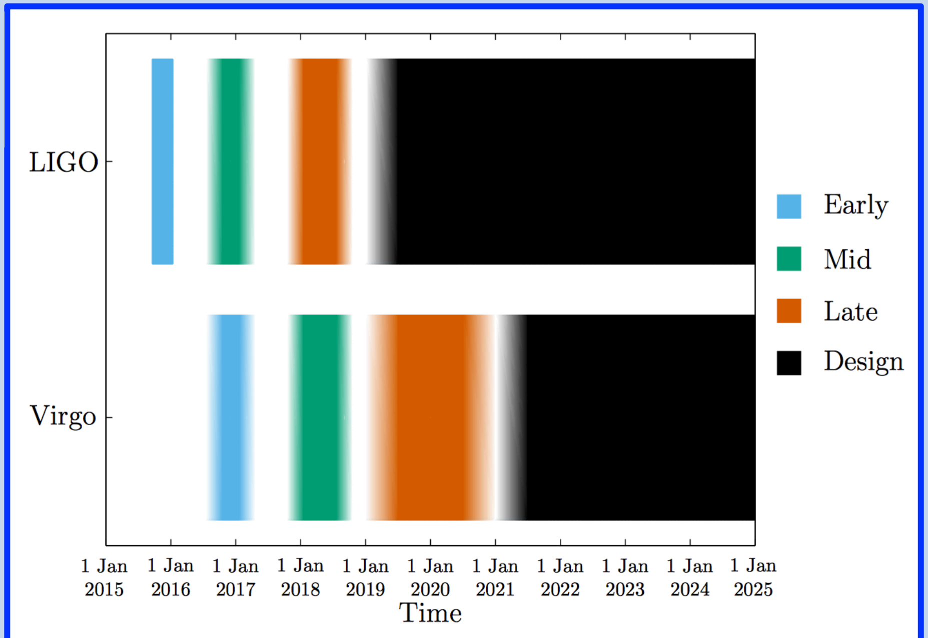




LVC 2016, ApJL, 832

Prospects of Observing and Localizing GWs

Sensitivity evolution and observing runs

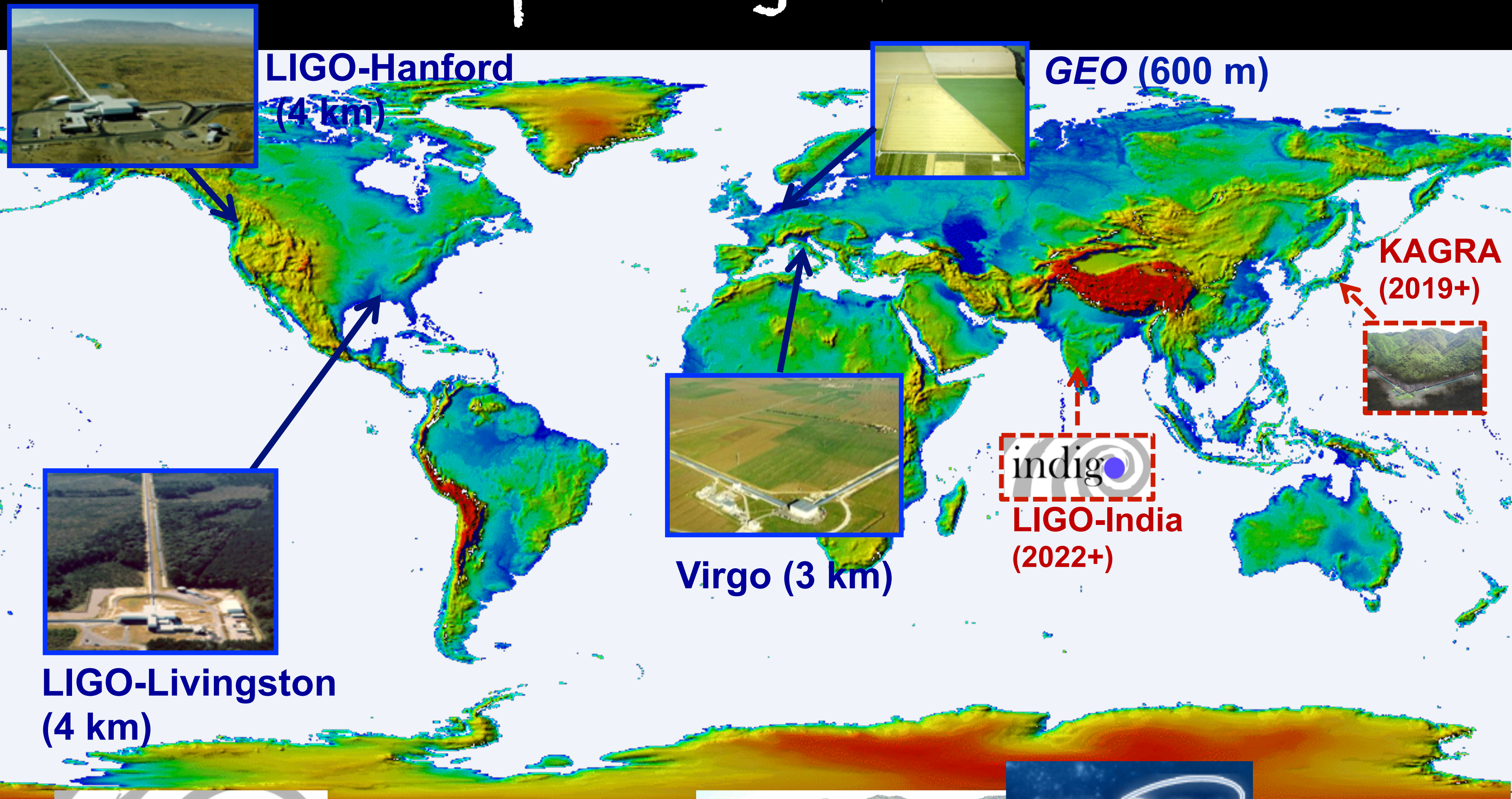


LVC 2016, LRR, 19, 1

Observing schedule, sensitivities, and source localization for BNS

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	—	—	—

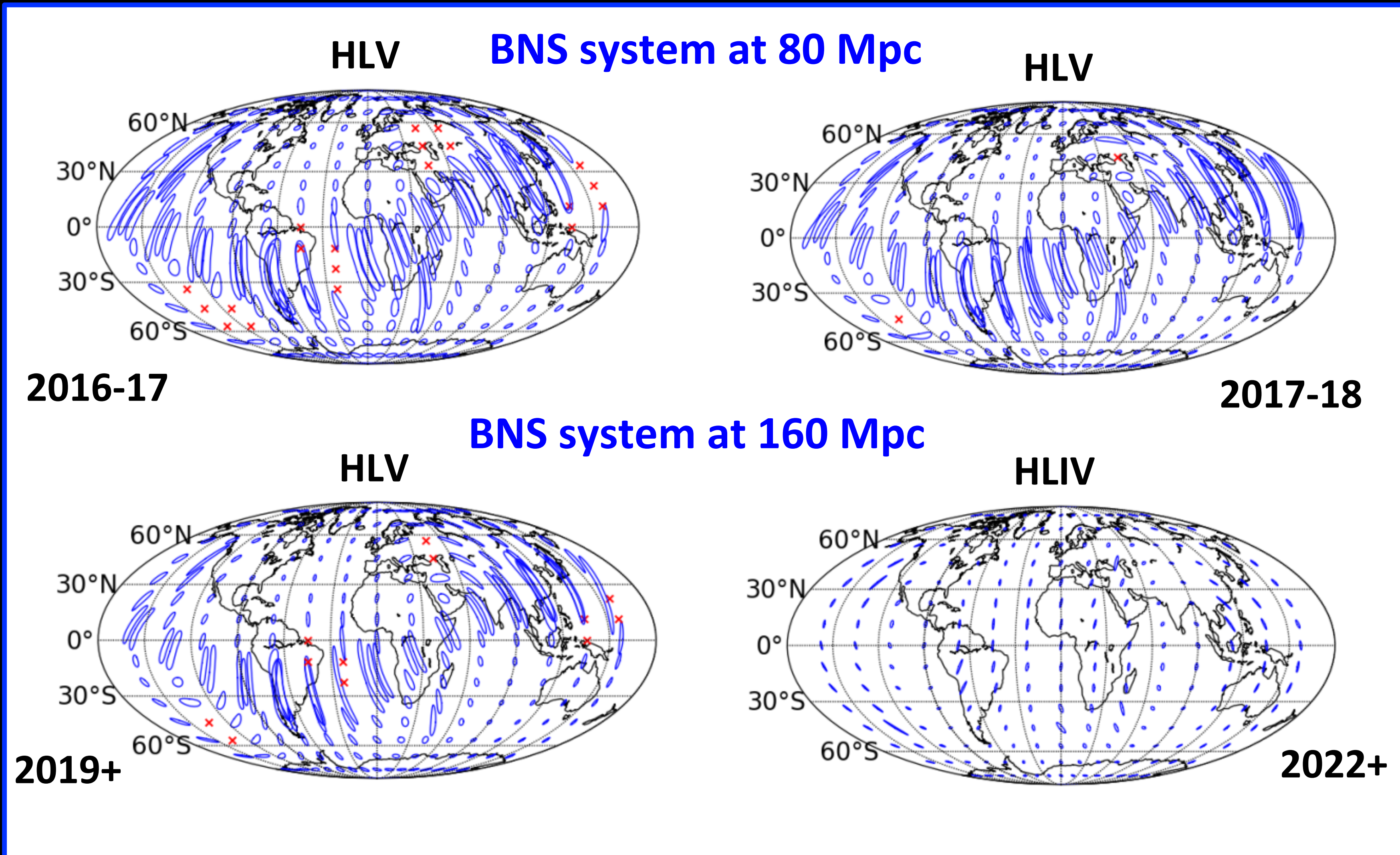
Upcoming network



LIGO detector in India
(4 km)

Underground detector in
Kamioka mine (3km)

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

LVC 2016, Living Reviews in Relativity, 19

O2 run – triggers shared

NEWS

MAY 2017 UPDATE ON LIGO'S SECOND OBSERVING RUN

3 May 2017 -- The second Advanced LIGO run began on November 30, 2016 and is currently in progress. As of April 23 approximately 67 days of Hanford-Livingston coincident science data have been collected. The average reach of the LIGO network for binary merger events has been around 70 Mpc for 1.4+1.4 Msun, 300 Mpc for 10+10 Msun and 700 Mpc for 30+30 Msun mergers, with relative variations in time of the order of 10%.

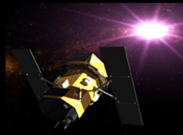
As of April 23, 6 triggers have been identified by the online analysis, using a loose false-alarm-rate threshold of one per month, and shared with astronomers who have signed memoranda of understanding with LIGO and Virgo for electromagnetic followup. A thorough investigation of the data and offline analysis are in progress; results will be shared when available.

http://ligo.org/news/index.php

- About 67 days of coincident Handford and Livingston science data
- Range: BNS 70 Mpc,
  BBH (M=10+10 Mo) 300 Mpc,
  BBH (M=30+30 Mo) 700 Mpc
- 6 triggers (FAR < 1/month) sent to astronomers

Loose FAR threshold → these are not all real events!

Multi-messenger astronomy with the advanced GW detectors



GWs

- Mass
- Spins
- Eccentricity
- NS compactness and tidal deformability
- System orientations
- Luminosity distance
- Compact object binary rate

EM emission

- Energetics
- Magnetic field strength
- Precise (arcsec) sky localization
- Host galaxy
- Redshift
- Nuclear astrophyisics

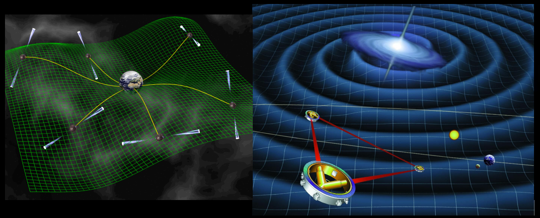
→ To confirm the short GRB progenitor

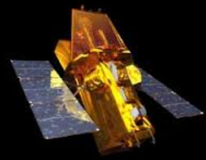
→ To probe geometry of the systems and emission models

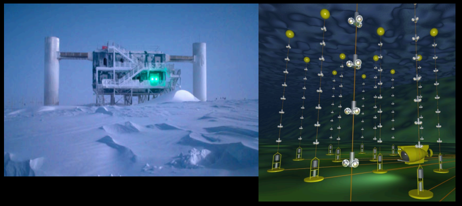
→ To probe birth and evolution of compact objects

→ To investigate the origin of the heavy elements in the Universe

→ To probe the NS equation of state







We are only at the dawn of the multi-messenger era

Many challenges to overcome but our exploration of the exciting frontier of the multi-messenger astronomy started!

LSST
Large Synoptic Survey Telescope

SKA
SQUARE KILOMETRE ARRAY